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ELECTRICAL & COMPUTER ENGINEERING DEPARTMENT
COLLEGE OF ENGINEERING & TECHNOLOGY
OLD DOMINION UNIVERSITY
NORFOLK, VIRGINIA 23529

ELECTRON-BEAM CONTROLLED SEMICONDUCTOR SWITCHES

By

Karl Schoenbach, Principal Investigator

Final Report
For the period ended August 31, 1993

Prepared for
Department of the Army
Army Research Office
P.O. Box 12211
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Under
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FINAL REPORT

ELECTRON-BEAM CONTROLLED SEMICONDUCTOR SWITCHES

ARO DAAL03-90-G-0018-POOO4
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The final report consists of an overview of the experimental and modeling studies on electron-beam controlled semiconductor switches and, for more details, reprints of paper published under this contract. Also included in the final report are results of those studies which have not yet been published in the open literature.

I would like to thank the technical monitors at ARO and AFOSR for their support on this project. The success of the research on electron-beam controlled switches can be seen in the increasing number of research groups who utilize this concept of switching and by the fact that the electron-beam controlled GaAs switch, the topic of our study, is now being developed in a SBIR phase 2 project for industrial applications.

INTRODUCTION

The use of electron-beams instead of lasers to activate gallium arsenide switches offers the possibility to modulate the switch conductance on a timescale of nanoseconds through modulation of the electron-beam intensity and to operate it in a burst mode at a MHz or even GHz pulse rate. Other advantages compared to laser activation of solid state switches are the high efficiency, relatively low cost, and the reliability of electron guns, and the possibility to introduce the electron-beam through the metallic contact into the switch. The use of cold cathodes for the electron gun will allow us to further simplify the switch system.

An obstacle for the use of electron-beam activation of solid state switches is the small range of electrons in solids. For an electron energy of 50 keV, for example, the range is on the order of 10 μm. In a switch configuration, as shown in figure 1, where the electron-beam is injected through one of the contacts, full activation of the switch material requires the use of thin films with high dielectric strength. Experiments with diamond films[1,2] and silicon dioxide[3,4] have demonstrated the *validity of this concept*. However, even withthese large bandgap materials, the voltage for this mode of operation is limited to several kilovolts. In order to extend the concept of electron-beam control of solid state switches to higher voltages, which requires switches of much increased thickness, it was proposed to utilize the electron-beam induced radiation (cathodoluminescence) in a direct semiconductor, such as GaAs, for bulk ionization of the switch.[5]

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[1]R.P. Joshi, M.K. Kennedy, K.H. Schoenbach, and W.W. Hofer, "Studies of High Field Conduction in Diamond for Electron-Beam Controlled Switching," J. Appl. Phys. 72, 4781 (1992).
[2] R.P. Joshi, K.H. Schoenbach, C. Molina, and W.W. Hofer, "Studies of Electron-Beam Penetration and Free Carrier Generation in Diamond Films," J. Appl. Phys. 74, 1568 (1993).
[3]W. Jiang, K. Zinsmeyer, M. Less, M. Kristiansen, and K.H. Schoenbach, "Electron-Beam Controlled Switching Using Quartz and Polycrystalline ZnSe," Proc. 9th Pulsed Power Conf. Albuquerque, NM, June 1993. ENCLOSED
[4]W. Jiang, K. Zinsmeyer, M. Less, K.H. Schoenbach, and M. Kristiansen, "Electron-Beam Controlled Switching Using Quartz and Polycrystalline ZnSe," to appear in IEEE Trans. Electron Devices. ENCLOSED
[5]K.H. Schoenbach, V.K. Lakdawala, D.C. Stoudt, T.F. Smith, and R.P. Brinkmann, "Electron-Beam Controlled High Power Semiconductor Switches," IEEE Trans. Electron Devices 36, 1793 (1989).

Figure 1 shows the principal configuration of a switch activated by secondary radiation. It consists of a sample of compensated direct semiconductor material (semi-insulating GaAs) between metal contacts, with a p-doped layer at the side which faces the electron-beam. In the non-activated state, the electron and hole density

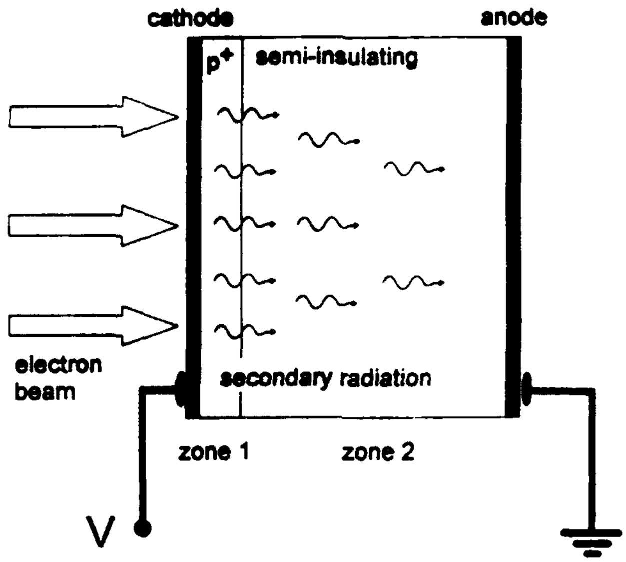

Fig. 1. Switch Activated by Secondary Radiation

is determined by thermal emission only and by carrier injection through the contacts. For semi-insulating material at voltages below the so-called trap-filled-limited voltage, the concentration of free carriers in the bulk is very small and the switch resistance therefore high. Under electron-beam irradiation, the incident electrons are stopped within a shallow layer at the cathode, the electron range, and their energy is utilized to about one third for the generation of electron-hole pairs. In a pure direct semiconductor, the annihilation of these electron-hole pairs would be through radiative recombination only. In a semi-insulating semiconductor, characterized by a large concentration of recombination centers and traps, the direct radiative recombination is in competition with trapping and recombination through recombination centers, respectively. The presence of the p-doped layer ensures that most of the electrons recombine with shallow acceptors, thus providing photons with a quantum energy only slightly lower than the bandgap energy. The photons, which due to their relatively low quantum energy can penetrate deep into the semi-insulating material, will activate the bulk of the switch through impurity ionization. This type of electron-beam controlled switch can therefore be considered as a photoconductive switch with a cathodoluminescent activation source of high efficiency (up to 30%) and the possibility to modulate its conductance up to the MHz or even GHz range.

FIGURE OF MERIT FOR ELECTRON-BEAM CONTROLLED SWITCHES

A simple model of the switch assumes a constant source function for the electron-beam ionization over the electron range and a constant secondary ionization in the bulk of the semiconductor, with the entire radiation being absorped in the semiconductor. The efficiency of the luminescence generation is described by a constant k_{int}. Based on these assumptions it is possible to define a number of merit for the switch, Q:[6]

$$Q = \frac{e\mu\tau k_{int} V_0^2}{L^2 \xi_{ion}}$$

where e is the electronic charge, μ is the carrier mobility, τ is the mean carrier lifetime, V_0 the applied voltage, L the depth of the switch, and ξ_{ion} the effective ionization energy. The quality, Q, can be interpreted as the power gain (ratio of switched power to control power) times the ratio of load resistance, R_L, to switch resistance, R_S. This equation holds if the switch resistance in the on-state is very small compared to a load resistance. The inverse of the switch resistance, the switch conductance, G_S, is given as:[6]

$$G_s = \frac{e\mu k_{int} \tau P_b}{\xi_{ion} L^2}$$

with P_b being the electron-beam power density.

A physical parameter which determines the quality, Q, of the switch strongly is the cathodoluminescent efficiency, k_{int}. This factor is determined in part by the quantum efficiency in the

[6]R.P. Brinkmann and K.H. Schoenbach, "Electron-Beam Controlled Switching with Wide Bandgap Semiconductors," Proc. 8th IEEE International Pulsed Power Conf., San Diego, CA, 1991, p. 94. ENCLOSED

cathodoluminescent layer, η_{int}. By using p-doped GaAs as cathodoluminescent material, the internal quantum efficiency (defined as the ratio of radiative among all recombination events) approaches unity.[7] The second contribution to k_{int} is determined by the degree of absorption of the cathodoluminescent radiation in the bulk of the semiconductor. The absorption depends on the wavelength of the emitted radiation relative to the absorption spectrum of the semiconductor and can be expressed in terms of an absorption coefficient, α. In order to include the effect of incomplete absorption in the equation for Q, k_{int} is replaced by $\eta_{int}\alpha L$, with the condition that αL must be less than one; this means that in order for the switch to conduct, the minimum absorption length, $1/\alpha$, must be about the thickness of the switch. For αL approaching unity we have optimum coupling of light into the switch. The equation for the figure of merit, Q, which takes this into account, reads:

$$Q = \frac{e\mu\eta_{int}\alpha\tau V_0^2}{\xi_{ion}L}$$

SWITCH OPTIMIZATION

In order to optimize the switch, that means to operate it at high Q, the switch material needs to have a high mobility, low ionization energy, and long carrier lifetime. On the other hand, since the carrier lifetime also determines the temporal response of the switch it might be necessary, depending on the application, to choose materials with short carrier lifetimes. The various aspects on material selection are discussed in more detail in reference 6. Semi-insulating gallium arsenide with its high electron mobility, relatively low ionization energy, and carrier life time on the order of nanoseconds is a good candidate for electron-beam controlled switch material. Even more important is the fact that GaAs is a direct semiconductor with consequently high quantum efficiency, η_{int}, which is enhanced by p-doping of the cathodoluminescent layer.

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[7] W.N. Carr, IEEE Trans. Electron Devices 12, 531 (1965).

A very important switch parameter is the maximum applicable voltage, the hold-off voltage V_o. Due to carrier injection and trapfilling, this voltage cannot be assumed to be the product of dielectric strength, E_d, and the switch length, L. It is a complex function of the type of deep traps, trap densities, trap activation energies, and the switch dimensions.[8] Because of the effect of traps on the hold-off voltage, it is possible to influence it by controlling the trapfilling through control of the carrier injection through the contacts. Using blocking contacts (reverse biased junctions) it was shown to be possible to obtain higher values for the hold-off voltage, compared to switch systems with injecting contacts.[9,10]

EXPERIMENTAL AND THEORETICAL EFFORTS TO OPTIMIZE THE GaAs SWITCH (DETAILS IN ENCLOSED PUBLICATIONS)

In order to optimize the electron-beam controlled GaAs switch, with respect to hold-off voltage, we have studied experimentally and theoretically the dark current characteristics of various semi-insulating GaAs samples ranging in thickness from 0.5 mm to 5 mm.[11,12] The samples were either undoped or p-doped over a depth of several μm with Zn. This p-doped layer serves both as a cathodoluminescent layer and as a blocking contact for electrons. The cathodoluminescent yield and the absorption of the secondary radiation in the bulk of the semiconductor were studied for electron-beam current densities on the order of 20 mA/cm^2, and pulse durations of μs. Also the temporal response of the switch current and voltage to electron-beam activation and the recovery

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[8]R.P. Brinkmann, "The Current-Voltage Characteristics of Semi-Insulating Gallium Arsenide," Physical Electronics Research Institute, Old Dominion University, Norfolk, VA, Report 105, 1989.

[9]M. Kennedy, R.P. Brinkmann, K.H. Schoenbach, and V.K. Lakdawala, "Switching Properties of Electron-Beam Controlled GaAs Pin Diodes," Proc. 8th Intern. IEEE Pulsed Power Conf., June 1991, San Diego, CA, p. 102. ENCLOSED

[10]M.K. Kennedy, K.H. Schoenbach, and R.P. Brinkmann, "Influence of Contacts on the Hold-Off Voltage and Recovery of Electron-Beam Activated Gallium Arsenide Switches," submitted to IEEE Trans. Electron Devices. ENCLOSED

[11]D.C. Stoudt, K.H. Schoenbach, R.P. Brinkmann, V.K. Lakdawala, and G.A. Gerdin, "The Recovery Behaviour of Semi-Insulating GaAs in Electron-Beam Controlled Switches," IEEE Trans. Electron Devices 37, 2472 (1990). ENCLOSED

[12]R.J. Allen, K.H. Schoenbach, J. Hur, and G. Kirkman, "Optimization of Electron-Beam Activated GaAs-Switches," Proc. 9th Intern. IEEE Pulsed Power Conf., paper PII-55, Albuquerque, NM, June 1993. ENCLOSED

behavior of the switches after termination of the electron-beam pulse were studied experimentally and theoretically.[9,10,12,13,14]

NEW MATERIALS

Acccording to our considerations on the switch efficiency (section: Figure of Merit for Electron-Beam Controlled Switches) materials with high dielectric strength and high mobility are optimum. In case the materials are indirect semiconductors, the electron-beam needs to have sufficent energy to penetrate the entire switch. This requires the use of thin films. In case of direct semiconductors, the cathodoluminescent efficiency needs to be high.

An indirect semiconductor with both high dielectric strength and high mobility is diamond. As a spin-off of this contract, we have performed extensive studies of the performance of diamond as switch material under contracts with DARPA and LLNL. Results are published in references 1, 2 and 15. Another material with extremely high dielectric strength but moderate mobilities is silicon dioxide (SiO_2). The response of silicon dioxide to electron irradiation was explored in cooperation with Texas Tech University. The results are published in references 3 and 4. Besides GaAs as direct semiconductor we have also studied zinc selenide (ZnSe) under a contract with DARPA, and in cooperation with TTU. ZnSe has a higher dielectric strength than GaAs, but a lower mobility. Since, however, the hold-off voltage affects the efficiency of the switch quadratically, the mobility only linearly, ZnSe is an attractive alternative to GaAs. Experiments were performed on single crystal and polycrystalline ZnSe and are published in references 3, 4 and 15.

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[13] R.P. Brinkmann and K.H. Schoenbach, "Electron-Beam Controlled Switching with Wide Bandgap Semiconductors," Proc. 8th Intern. IEEE Pulsed Power Conf., June 1991, San Diego, CA, p. 94. ENCLOSED

[14] R.P. Brinkmann, K.H. Schoenbach, D.C. Stoudt, V.K. Lakdawala, G.A. Gerdin, and M.K. Kennedy, "The Lock-On Effect in Electron-Beam Controlled Gallium Arsenide Switches," IEEE Trans. Electron Devices, 38, 701 (1991). ENCLOSED

SUMMARY

During this funding period we concentrated on two topics. The first was the influence of heavily doped contacts on dark current, cathodoluminescence, and switch kinetics. The use of a shallow p-doped layer on the electron-beam irradiated face of an electron-beam controlled GaAs switch was shown to improve the gain of the switch, Q, dramatically. For one, the junction of the p-layer with the intrinsic material prevents, if negatively biased, the injection of holes into the intrinsic region. This prevention of double injection allows us to apply a factor of two higher voltages than with samples having just ohmic contacts. Because of the quadratic dependance of the gain on the hold-off field, this amounts to a factor of four increase in gain. Secondly, the increased cathodoluminescence of p-doped GaAs promises to give an order of magnitude improvement in the switch gain. An additional advantage of using p-doped layers is the expected, and for the case of 0.5 mm thick samples experimentally verified,[8] suppression of the lock-on effect for voltages up to about twice the usual lock-on voltage. The use of low energy electron-beams for these kinds of switches, as discussed in the previous section, promises to make these devices easily controllable closing and opening switches for high reprate pulse power applications.

The second research topic was the development of a criterion for the efficiency of electron-beam controlled switches. This criterion, which is discussed in the second section of this report, allowed us to extend the switching concept to new materials such as diamond, zinc selenide, and silicon dioxide. Experiments performed with these materials have demonstrated the applicability of our concept for the development of high duty cycle closing and opening switches where the switch material parameters (such as thermal conductivity, dielectric strength, carrier life time) can be selected to match a specific application.

TECHNOLOGY TRANSFER

The development of electron-beam controlled GaAs switches for military and industrial applications is the topic of an SBIR from Integrated Applied Physics, Inc. in Waltham, MS supported by BMDO. IAP has particularly concentrated on minimizing the electron energy for switching. The project is presently in phase II.

APPENDIX

CATHODOLUMINESCENCE: CONVERTING ELECTRON ENERGY INTO PHOTON ENERGY FOR BULK IONIZATION OF GaAs

Our switch concept, the electron-beam controlled activation of thick GaAs samples, depends on the conversion of electron energy into photon energy. In order to obtain information on the cathodoluminescence in GaAs, we have studied the light emission side-on and end-on. The first type of measurement yields information on the spatial distribution of the cathodoluminesce; the second one allows us to measure the absorption coeffient and to study the generation of light in samples with different doping.

The experimental set-up for the spatial profile distribution measurement is shown in figure 2.[15] The electron-beam hits the sample and generates band-edge radiation over a distance given by the electron-range. This radiation (cathodoluminescence) is recorded by means of a photomultiplier with an S20 or S1 cathode. In order to record only light which is generated in the region determined by the range of the electron-beam we have used a telescope arrangement. The optical arrangement allows only light

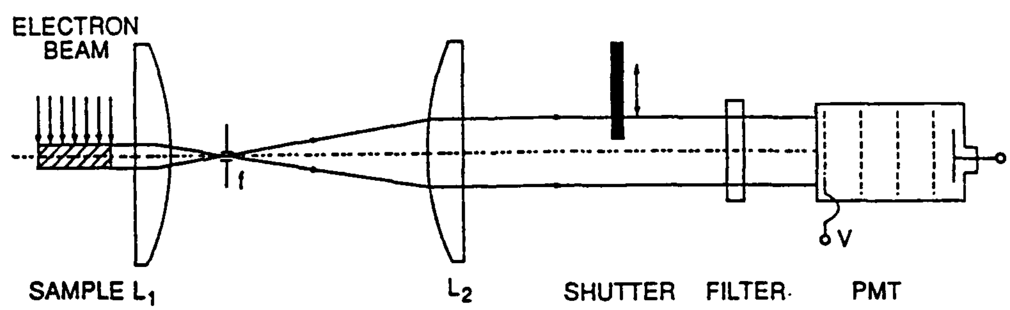

Fig. 2. Experimental Set-Up for Cathodoluminescence Measurements

[15]M. Kale, Thesis, Old Dominion University, Department of Electrical and Computer Engineering, 1991.

which is generated along the line of sight (parallel light beams) to reach the detector. Light which is emitted from the sample under an angle larger than 0.014, determined by the diameter of the pinhole (250 μm, located at distances f from both lenses), and might possibly be originated in the region outside the electron-range is blocked out. The two lenses with the focal length f of 40 mm and 200 mm, respectively, create a 2.5 mm image of the 0.5 mm size sample on the photomultiplier window.

A mechanical shutter was used to block the light partially. By moving the shutter across the light beam emitted from the sample, a signal was obtained which contained information on the integral value of the intensity emitted by the sample over a thickness x from the electron-beam irradiated face. Measurements were performed by varying values of x, and the obtained signal

$$S(x) = \int_0^x I(x)\,dx$$

was then differentiated to get the intensity I(x) of the cathodoluminescence. The method was applied to zinc-doped GaAs as cathodoluminescent material. Measured cathodoluminescent profiles are shown in figure 3 for three different electron-beam energies. There is clearly a layer of less than 50 μm thickness at the cathode (x=0) with enhanced light emission, the cathodoluminescent layer.

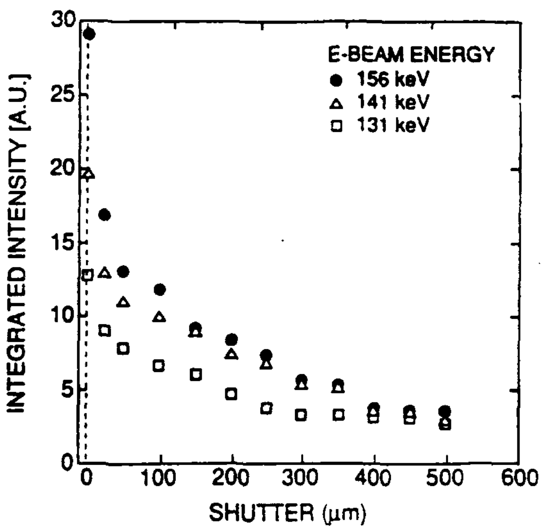

Fig. 3. Cathodoluminescence as a Function of Distance from the Electron Irradiated Face of the GaAs Sample

The relative cathodoluminescent yield, an important parameter for an electron-beam controlled switch with secondary optical excitation, was measured by recording the electron-beam induced transmitted through the sample. A typical light pulse (compared to the electron-beam diode voltage) is shown in figure 4 for the 2 mm sample with the p-doped layer facing the electron-beam. The temporal development of the light emission follows clearly the shape of the electron-beam voltage pulse. The intensity of the transmitted light depends on the electron-beam energy as shown in figure 5. There is no light recorded below 50 kV. For higher values of the electron-beam voltage, it increases linearly with voltage.

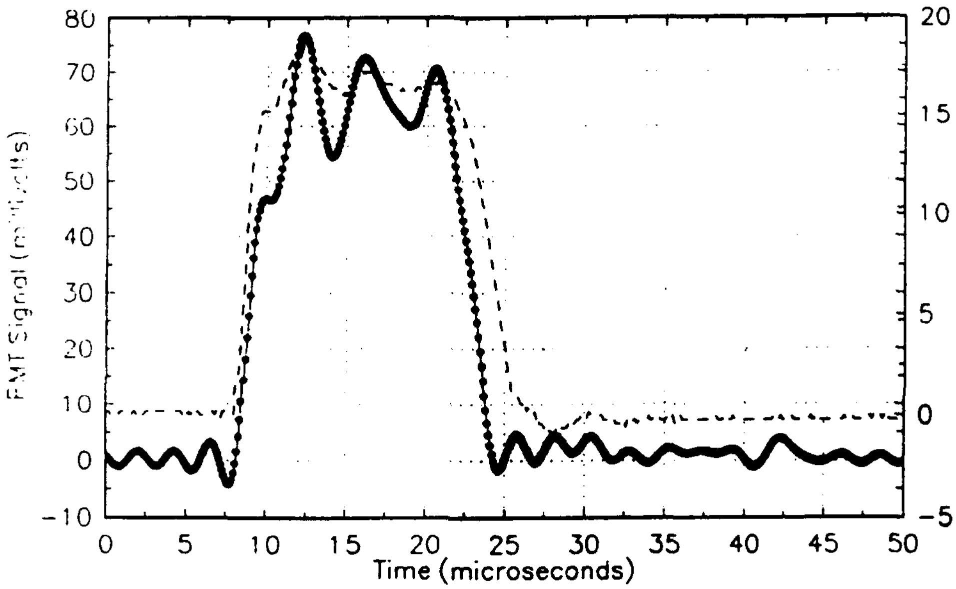

Fig. 4 Temporal Development of the Cathodoluminescence Measured through a 2 mm Thick GaAs Switch with a p-Layer (solid curve) compared to the Electron-Beam Activation (dashed curve). The Peak Electron Energy is 140 keV.

When the electron-beam irradiates the undoped face of the 2 mm sample, the intensity of the transmitted light is lower by about an order of magnitude compared to that emitted from the electron-beam irradiated p-doped layer (Fig. 5). It is also higher than that emitted through an electron-beam activated, 0.5 mm thick undoped GaAs sample. These results confirm our hypothesis that the presence of a p-doped layer on the electron-beam irradiated face of the GaAs-switch has a strong impact on the efficiency of luminescence generation.

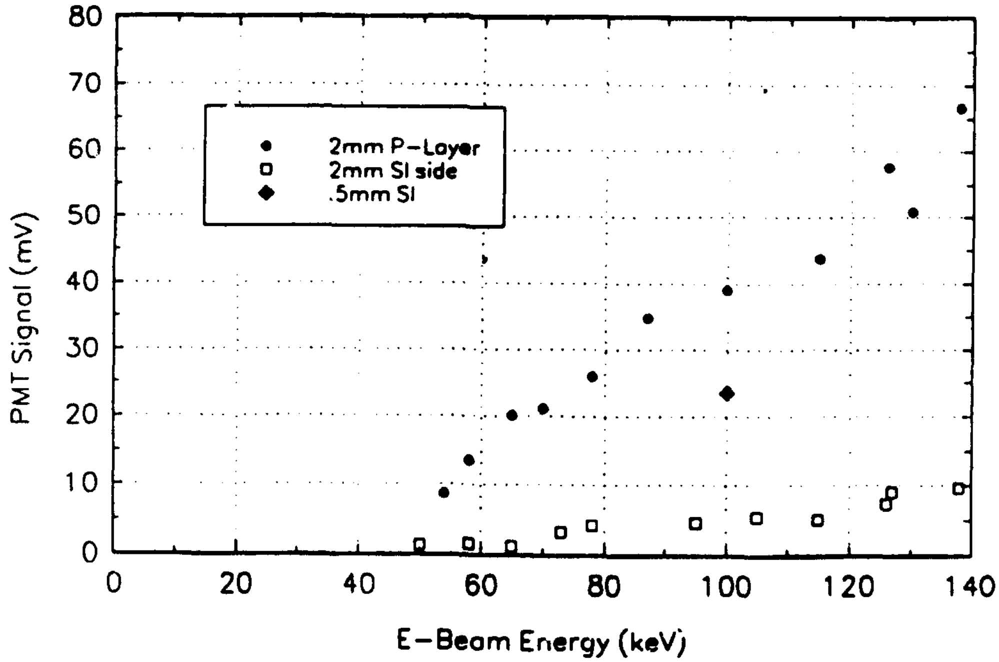

Fig. 5. Cathodoluminescence Measured through a 2 mm GaAs Switch with a p-Layer (closed circles) compared to that Obtained without p-Layer (open circles). For Comparison, one Result with 0.5 mm undoped GaAs is plotted.

LIST OF PUBLICATIONS (published under this contract)

R.P. Brinkmann, K.H. Schoenbach, D.C. Stoudt, V.K. Lakdawala, G.A. Gerdin, and M. Kennedy, "The Lock-On Effect in Electron-Beam Controlled Gallium Arsenide Switches," Records of the Nineteenth Power Modulator Symposium, San Diego, CA, June 1990, p. 334.

K.H. Schoenbach, "Electron-Beam Controlled Semiconductor Switches," High Average Power Switch Workshop, Lawrence Livermore National Laboratories, CA, October 1990, published in Proc. Fourth SDIO/ONR Pulse Power Meeting 1991, Los Angeles, CA, p. 212.

R.P. Brinkmann, K.H. Schoenbach, R.A. Roush, D.C. Stoudt, V.K. Lakdawala, and G.A. Gerdin, "High Power Switching with Electron-Beam Controlled Semiconductors," Proc. OPTCON'90, Boston, November 1990, p. 203.

D.C. Stoudt, K.H. Schoenbach, R.P. Brinkmann, V.K. Lakdawala, and G.A. Gerdin, "The Recovery Behavior of Semi-Insulating GaAs in Electron-Beam Controlled Switches," IEEE Trans. Electron Devices, 37, 2472 (1990).

M. Kennedy, R.P. Brinkmann, K.H. Schoenbach, and V.K. Lakdawala, "Switching Properties of Electron-Beam Controlled GaAs Pin Diodes, Proc. 8th Intern. IEEE Pulsed Power Conf., June 1991, San Diego, CA, p. 102.

R.P. Brinkmann and K.H. Schoenbach, "Electron-Beam Controlled Switching with Wide Bandgap Semiconductors," Proc. 8th Intern. IEEE Pulsed Power Conf., June 1991, San Diego, CA, p. 94.

R.P. Brinkmann, K.H. Schoenbach, D.C. Stoudt, V.K. Lakdawala, G.A. Gerdin, and M.K. Kennedy, "The Lock-On Effect in Electron-Beam Controlled Gallium Arsenide Switches," IEEE Trans. Electron Devices, **38**, 701 (1991).

W. Jiang, K. Zinsmeyer, M. Less, M. Kristiansen, and K.H. Schoenbach, "Electron-Beam Controlled Switching Using Quartz and Polycrystalline ZnSe," Proc. 9th IEEE Intern. Pulsed Power Conf. Paper 17-6, Albuquerque, NM, June 1993.

R.J. Allen, K.H. Schoenbach, J. Hur, and G. Kirkman, "Optimization of Electron-Beam Activated GaAs-Switches," Proc. 9th Intern. IEEE Pulsed Power Conf., paper PII-55, Albuquerque, NM, June 1993.

W. Jiang, K. Zinsmeyer, M. Less, K.H. Schoenbach, and M. Kristiansen, "Electron-Beam Controlled Switching Using Quartz and Polycrystalline ZnSe," to appear in IEEE Trans. Electron Devices.

M.K. Kennedy, K.H. Schoenbach, and R.P. Brinkmann, "Influence of Contacts on the Hold-Off Voltage and Recovery of Electron-Beam Activated Gallium Arsenide Switches," submitted to IEEE Trans. Electron Devices.

STUDENTS SUPPORTED BY THIS PROGRAM

Tyler Smith, graduated Fall 1991; "Cathodoluminescence of GaAs".

Mandakini Kale, graduated Fall 1991; "Study of Cathodoluminescence in Semiconductors".

Michael Kennedy, graduated in Fall 1992; "The Effect of Contacts on the Performance of Electron-Beam Controlled GaAs and Diamond Switches".

Raymond Allen, expected to graduate in Spring 1994; "Optimization of Electron-Beam Controlled GaAs Switches".

THE LOCK-ON EFFECT IN ELECTRON-BEAM CONTROLLED GALLIUM ARSENIDE SWITCHES

R.P. Brinkmann, K.H. Schoenbach, D.C. Stoudt,
V.K. Lakdawala, G.A. Gerdin, and M.K. Kennedy
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Old Dominion University, Norfolk, Virginia

The term "lock-on effect" describes the inability of optically or electron-beam controlled semiconductor switches to recover to their initial hold-off voltage following the application of the trigger pulse; after turn-off of the ionization source the current is instead "locked on" to a constant voltage with average electric fields ranging from 4 kV/cm to 12 kV/cm [1]. This paper paper is concerned with an investigation into the lock-on effect in gallium arsenide based electron-beam controlled switches and power modulators. Our experimental results indicate that the lock-on current of the system is actually identical with the time asymptotic dark current under double injection conditions. They show that the pre-illumination of the sample with an ionization source does not influence the amplitude of the current but causes only a reduction in the time neccessary to reach its final value. In particular, it is demonstrated that the initial highly resitive state is not an actual steady state but rather a transient phase characterized by a non-equilibrium distribution in the electron and hole trap occupation. Based on these experimental results, a scenario is developed which describes the lock-on effect in terms of current injection through the contacts and carrier trapping in deep intraband levels. The proposed scenario explains all major characteristics of the lock-on effect and is further supported by the good qualitative agreement of the experimental data with current voltage curves calculated on the basis of a recently developed self-consistent device model [2].

I. Introduction

Attempts to utilize electron-beam controlled semiconductor switches have already been made in the sixties [3] and the seventies [4], but only recently research in this field has gained new momentum due to an improved concept [5,2]. This switch concept is based on the generation of free charge carriers in the bulk of a semi-insulating semiconductor like gallium arsenide (GaAs) by cathodoluminescence. Once the electron-beam is terminated, the switch will open due to electron-hole recombination, and trapping of free carriers, on a time scale of nanoseconds or less if the current injected through the contacts is negligible [6]. Besides switch closing and opening the processes of electron-hole generation and recombination allow modulation of the switch current with an electron-beam. With the observed linear characteristics of the electron-beam controlled switches in an electric field range up to about 4 kV/cm [5], these devices promise to be useful for the modulation of the electrical power into a temporally varying load. The modulation of electron-beam currents can easily be done with gated vacuum tubes, which makes compact and economic switch design possible.

An obstacle for the use of GaAs switches as opening switches or modulators in high voltage systems, however, is the so called "lock-on" effect. This effect is manifested by the inability of the switch to recover to its initial hold-off voltage following the application of an electron-beam or laser pulse [7,1]. After turn-off of the driving source the current is "locked-on" to a constant voltage with average electric fields in the range from 4 kV/cm to 12 kV/cm (1). The effect of "lock-on" on voltage and current after termination of the sustaining electron-beam is shown schematically in Fig. 1 (case $V > V_{cr}$).

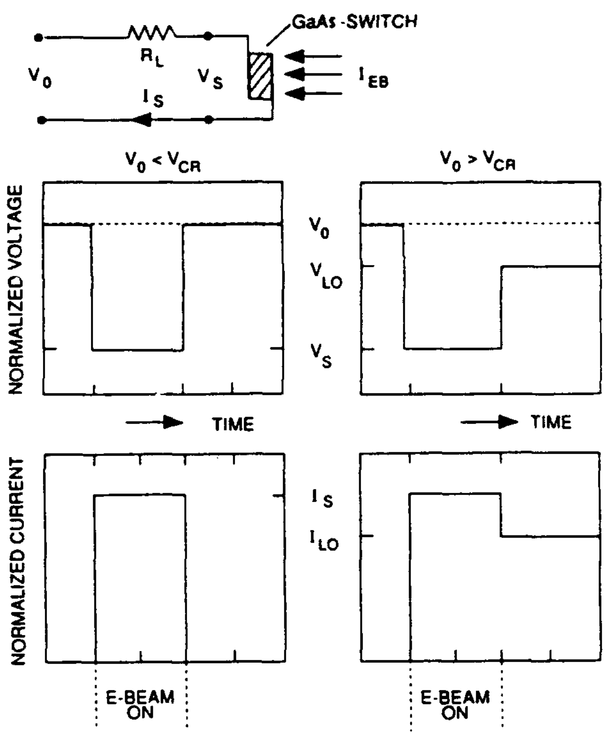

Figure 1: Schematic illustration of the lock-on effect.

II. Experiments

To study the lock-on effect we have concentrated on semi-insulating GaAs as switch material. Particularly for the experimental investigations as-grown (EL2-compensated) material with a resistivity of 6×10^6 Ωcm was used. The sample geometry consisted of a bulk region with aligned parallel plate contacts. The thickness of the bulk was 0.065 cm, the area of the contacts about 1.1 cm^2. The contacts were manufactured by thermally depositing a Au(88%)-Ge(12%) alloy to a thickness of 100 nm. The sample was then annealed at 450°C in N_2 at atmospheric pressure for a period of 15 minutes.

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A set of experiments was conducted using the circuit shown in Fig. 2, where the GaAs sample was irradiated through the cathode contact with an electron-beam pulse of 15 μs duration, as schematically shown in Fig. 1. The electron-beam was produced by a pulsed thermionic diode [8]. The energy of the electrons was about 150 keV and the current density was in the range of up to 30 mA/cm^2. In the circuit shown in Fig. 2, the 15 Ω PFN load resistance is used to provide a constant voltage across the series combination of the 50 Ω load and the sample. As the resistance

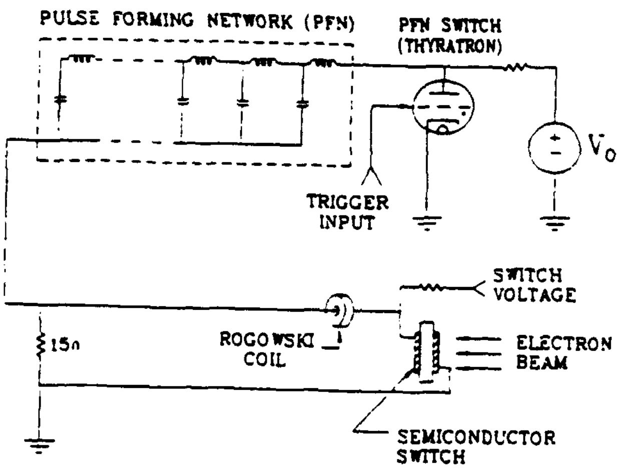

Figure 2: Experimental set-up of the system used to measure the switch I-V-characteristics.

of the sample drops due to electron-beam ionization, the voltage neccessary to sustain the current would remain across the sample, while the sample current is limited by the 50 Ω resistance.

The results of current voltage measurements are shown in Fig. 3. The current density in the on-state (during electron-beam irradiation) increases linearly with voltage up to about 200 V, which corresponds to an average field intensity of 4 kV/cm. Above this voltage the current density rises steeply to values greater than 20 A/cm^2, values which correspond to a current gain (switch current/ electron-beam current) of about 1000. In that regime, the sample does not return to the initial applied voltage after termination of the electron-beam, but rather to a value which appears to be independent of it. This "lock-on" effect is very similar to the results obtained when GaAs samples are irradiated with a high power laser [7].

The lock-on current increases strongly with the voltage across the sample. The values for this current are also plotted in Fig. 3 as a function of the switch voltage. The lock-on voltage corresponds to an average electrical field of about 3.7 kV/cm. The value of this lock-on field depends on the deep level configuration of the switch material. It increases with the density of deep traps or recombination centers and with the trapping cross sections. When chromium doped semi-insulating GaAs was used the critical field was increased by a factor of two compared to the lock-on field of as-grown GaAs.

The electron-beam current determines the current-voltage characteristics of the switch in the on-state, as shown in Fig. 3. It does not, however, seem to influence the lock-on curve. Because of the independence of the lock-on current on the previous illumination it can be considered the dark current of the device. In order to prove this, dark current measurements on

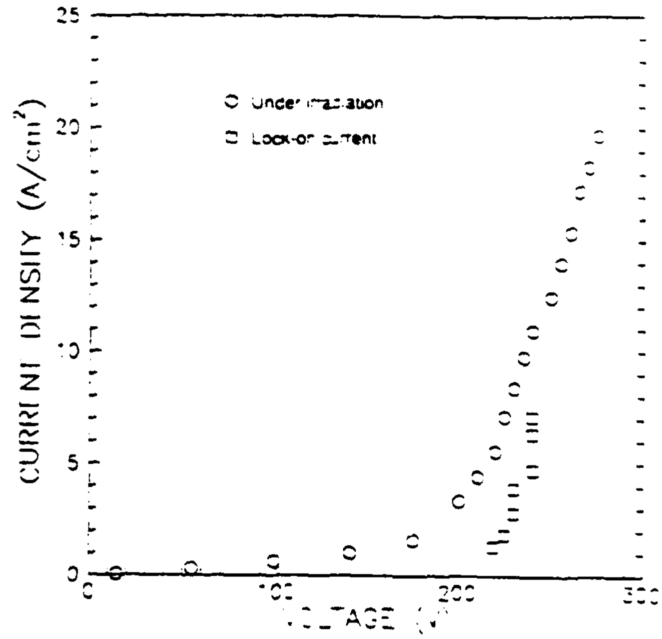

Figure 3: The I-V-curves for the switch under electron-beam irradiation and in the lock-on state.

semi-insulating GaAs were performed with applied voltages of up to 110 V, corresponding to fields of 1.7 kV/cm. To study the dark current at higher applied voltages, especially its temporal development, a hard tube pulser was used which allows to apply voltage pulses of up 3 kV for hundreds of ms across a high impedance load (> kΩ's). Pulsing the sample allowed to measure the dark current at higher voltages than are possible with a dc bias, because the limited pulse duration reduced the problem of Joule heating. The circuit consisted of a storage capacitor which is charged to the desired voltage and discharged through a resistor (100 kΩ) that is in paralell with the sample. The switch used to control the pulse width is an RCA 6293 beam-power amplifier vacuum tube with a maximum plate voltage of 3.5 kV. As the voltage across the sample is increased further, the sample impedance becomes too low to be driven by the hard tube circuit. Therefore, the pulse circuit shown in Fig. 2 was used to allow the dark current to be measured at lower sample impedances. The circuit uses a 15 Ω pulse forming network which provides a 15 μs voltage pulse.

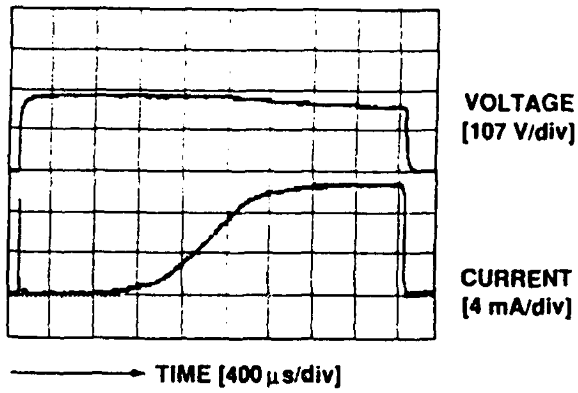

Figure 4: The temporal evolution of the dark current.

A typical current and voltage waveform using the hard tube pulser in shown in Fig. 4. The current spike after the initial application of the step voltage is attributed to the displacement current. After the displacement current, the dark current remains very low for an "onset time" and then increases monotonically up to a steady state value. The onset-time which is defined as the time neccessary to reach a current value of 5% of the final, steady state current, is found to be a strong function of the amplitude of the applied voltage as shown in Fig. 5.

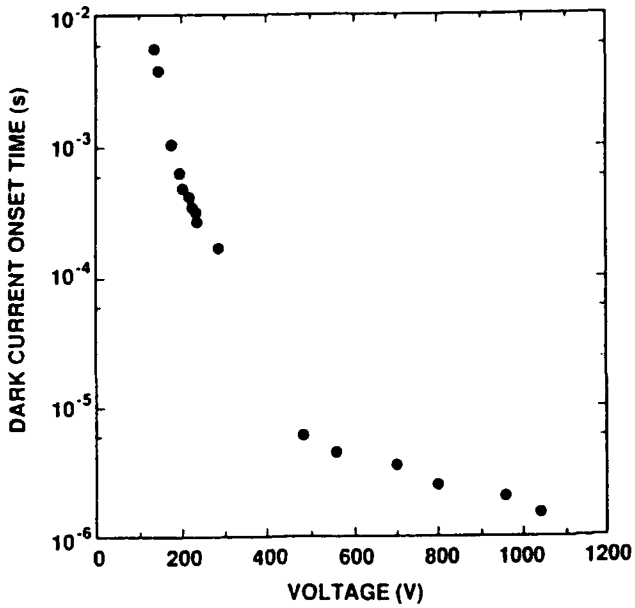

Figure 5: The onset time as a function of the applied voltage.

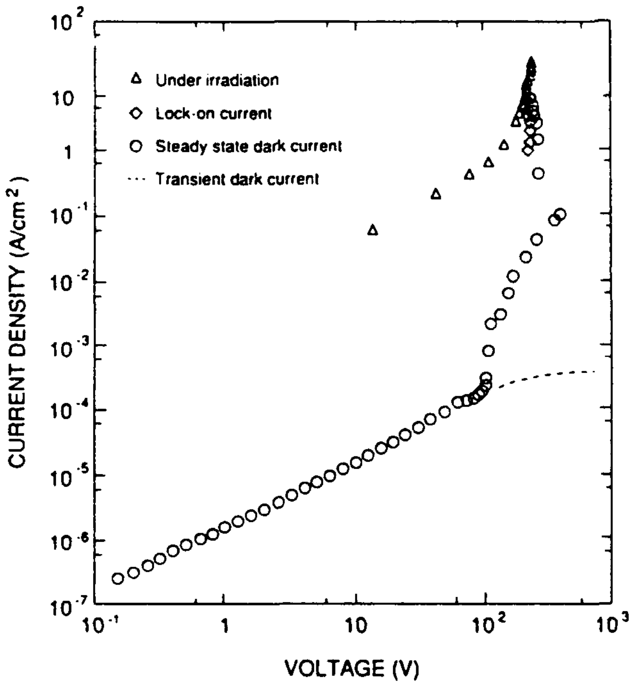

Figure 6: The I-V-curves corresponding to the steady state dark-current, the transient dark current, the lock-on current and the current under electron-beam irradiation.

Fig. 6 shows the steady state currents obtained with both the dc and the pulsed bias measurements at room temperature. There is a steep increase in current over four orders of magnitude at about 200 V in a voltage range of several ten's of volts. The current values obtained in the "lock-on" experiment (Fig. 2) are plotted for comparison with the time asymptotic values of the dark currents; the two groups of currents are virtually identical. Also plotted is the I-V-characteristics of the on-state, and the transient values the dark current assumes during the onset time.

III. Modeling

In order to understand the experimental results outlined above, we focus now on a theoretical description of the switch configuration. We assume that the switch diameter is large compared to its thickness, such that a one-dimensional model can be employed to describe the electron and hole flow though the switch. Our model includes the generation of free charge carriers through radiative, thermal or impact ionization, their transport under the influence of the electrical field, and their recombination or trapping in intraband traps. These deep traps are responsible for the high resistance of semi-insulating GaAs and determine largely, as will be shown, the I-V-characteristics of this material. Denoting the number of electrons in the conduction band and the number of holes in the valence band by n and p, respectively, the densities of the various carrier traps by N_i and their relative occupation number by r_i, the system of dynamical equations reads

$$\frac{\partial n}{\partial t} - \frac{\partial}{\partial x}(v_n(E)n) = \dot{n}_{cv} - \sum_i N_i \dot{r}_{ci} + S, \qquad (1)$$

$$\frac{\partial p}{\partial t} + \frac{\partial}{\partial x}(v_p(E)p) = \dot{n}_{cv} + \sum_i N_i \dot{r}_{vi} + S, \qquad (2)$$

$$\frac{\partial r_i}{\partial t} = \dot{r}_{vi} + \dot{r}_{ci}. \qquad (3)$$

In these expressions, v_n and v_p stand for the absolute values of the field dependent carrier drift velocities, the diffusion contributions have been neglected. The terms on the right hand side denote the balances of direct recombination, thermal pair generation and impact ionization ($\dot{n}_{cv}$), trapping and thermal release of electrons or holes ($\dot{r}_{ci}$ and $\dot{r}_{vi}$), and the carrier generation due to the external source (S). The description is completed with Poisson's equation connecting the electrical field E to the excess charge in the crystal; the quantites N_d, ϵ_0 and ϵ_r stand for the effective shallow doping density, the absolute and the relative dielectric constant, respectively:

$$\epsilon_0 \epsilon_r \frac{\partial E}{\partial x} = e(n - p + \sum_i N_i r_i - N_d). \qquad (4)$$

We have solved the equations numerically under the assumption of steady state, closely following a procedure which will more extensively be discussed in reference [2]. The contacts have were assumed to be injective (ohmic). It turned out that the results vary considerably depending on the deep level configuration. However, there are some features which appear to be characteristic for most types of compensated GaAs and other semi-insulating material. They are discussed in the following, using a relatively simple deep level configuration. Figure 7 shows the I-V-characteristics of an 0.5 mm switch assuming the presence of one dominant recombination center with

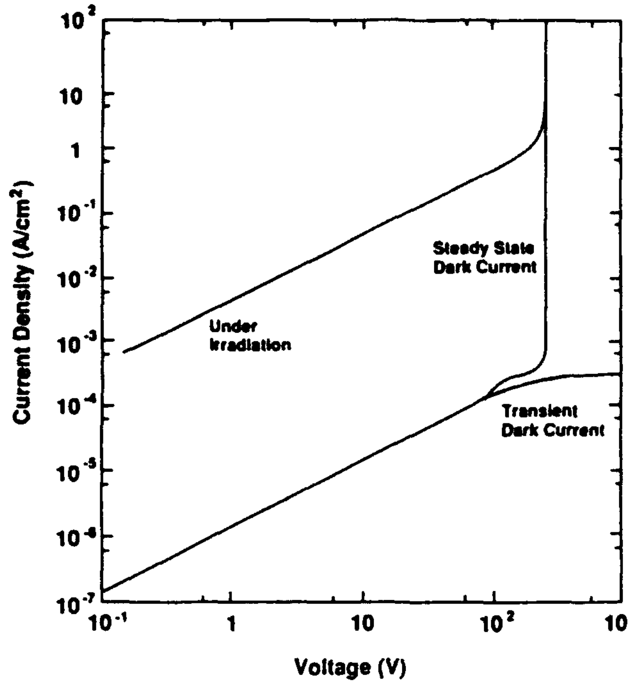

Figure 7: The I-V-characteristics according to the numerical calculations

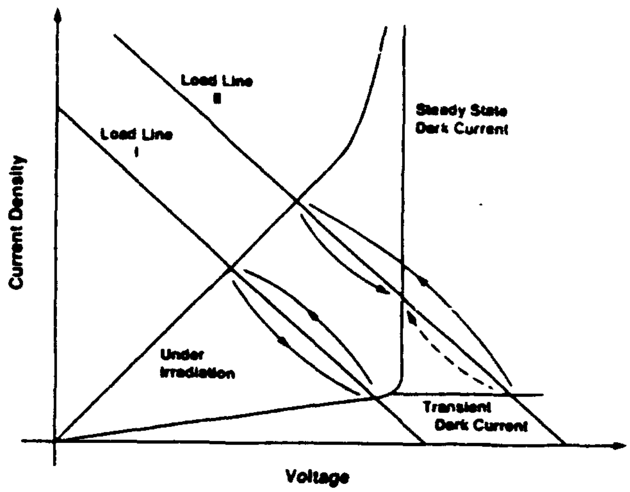

Figure 8: The switching cycles in a load-line diagram

a density of $N = 10^{17}$ cm^{-3}, an energy of 0.85 eV above the valence band, and electron and hole capture cross sections of $\sigma_n = 2\times10^{-19}$ cm^2 and $\sigma_p = 5\times10^{-17}$ cm^2, respectively. Curve I corresponds to the dark current ($S = 0$), curve II to the current *under irradiation* ($S = 10^{17}$ $cm^{-3}s^{-1}$).

A comparison of the numerically obtained curves with the experimental results displayed in figure 6 shows a very good qualitative agreement. (The quantitative deviations are probably due to the relatively simple representation of the deep level structure in our model.) In particular, the calculations reproduce well the initially linear behavior of the current both in the dark and in the irradiated state, and their subsequent steep increase above the critical voltage of 200 V. At low voltages, the dark current shows an ohmic behavior. The resistance, measured in this range, corresponds to the value given by the manufacturer. At a certain, critical voltage the current rises drastically; in this material over seven orders of magnitude. This effect will extensively be discussed in reference [2], it is essentially due to the injection of electrons and holes at the contacts (double injection) and involves a considerable build-up of charges in the deep levels.

From the fact that the strong increase in the current is due to trap filling, we can explain the relatively long onset time of the dark current before it rises to its final value. Initially, most of the charge carriers that are injected from the contacts will become trapped in electron or hole traps which have a relative high density in semi-insulating gallium arsenide, to the effect that free carrier densities remain very low during the onset time. It is only after the traps are completely filled that the current can rise to its final value. The neccessary time span can be considerable if only charges injected through the contacts are available to fill the traps. Under irradiation with the beam, however, the onset time will be much shorter due to the large source function for electrons and holes in the bulk of the switch. More quantitative results which are based on a transient simulation of equations (1) - (4) will be published elsewhere.

IV. The Lock-On Scenario

Based on the results of the numerical calculation described above, we can now establish a scenario which explains the main features of the lock-on effect. Consider the linear I-V-diagram in figure 8, where we have schematicly drawn the three different I-V-curves discussed above, namely a) the transient dark-current I-V-curve that is valid during the onset time, b) the steady state dark-current which is reached in the time asymptotic limit, c) and the current-voltage characteristic of GaAs under electron-beam irradiation.

Let us consider two switch experiments with the same load resistor R, but different initial voltages V_0, characterized by the two load lines I and II in figure 7. In the first experiment, the switch starts in the highly resistive off-state at point a_I where the current is low and the voltage is very close to the voltage V_0. Under irradiation with the electron beam, the switch becomes quickly ionized and the load point moves to the low resistivity regime b_{II}, the on-state of the switch. After turn-off of the beam, the charge carriers recombine and the switch moves to the point c_I, which is identical with the point a_I. It is clear that this case does not exhibit a lock-on effect.

Consider next the load line II with a source voltage V_0 that lies over the critical value V_c. In the initial off-state, the load point is located at a_{II}, which characterizes the transient state with a small electrical current. The load point begins to move along the load line, but according to our argumentation above (and the experimental curve 5), this time development is rather slow and might take a time that is long compared to the duration of the applied pulse. Under irradiation with the electron beam, however, the load point moves very quickly to b_{II}, i.e. to the on-state with a high current and a small voltage. Due to the high carrier density generated by the e-beam, the traps will be filled very quickly. But now, after the turn-off of the beam, the load point will not return to the initial value b_{II} but rather to the steady state value c_{II}, with a considerably higher current, the lock-on current.

V. Discussion

A current lock-on at a constant voltage was observed in electron-beam controlled GaAs switches. Its essential features are equivalent with the ones found in optically controlled GaAs switches. It has been demonstrated, that the amplitude of the lock-on current only depends on the voltage of the driving circuit, and not on the electron beam power. In fact, even without irradiation the same current could be established. The only effect that e-beam irradiation has is the reduction of the onset time of the current flow.

Based on these observations and on supporting numerical calculations of the dark current in GaAs, we propose a model which is able to explain the main features of the lock-in effect: It appears only above a certain voltage threshhold, it is essentially independent of the initial e-beam (or laser) irradiation, and the voltage across the sample is independent of the current density.

What is the practical importance of the lock-on effect? Clearly, it must be regarded as an unwanted effect for opening switches, as it prevents the recovery of electron-beam or optically controlled semiconductor switches to their initial hold-off voltage following the application of the trigger pulse. However, it might be a very desirable effect for closing switches, as its allows to close a circuit indefinitely by using a short trigger pulse.

VI. Acknowledgement

This work was supported by the U.S. Army Research Office and the Air Force Office for Scientific Research under Contract No. DAAL03-90-G-0018

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Proceedings of the

FOURTH SDIO/ONR PULSE POWER MEETING 1991

June 20–21, 1991

University of Southern California
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High Average Power Switching for Linear Induction Accelerators

A Summary of the Workshop held at the Wente Conference Center in Livermore, California on October 10-11, 1990

by:
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ABSTRACT

This report summarizes the presentations and the findings of the Workshop on High Average Power Switching (WHAPS) that took place in Livermore, CA on October 10–11, 1990. The WHAPS discussed switching technologies that could meet requirements that arise in applications of linear induction accelerators also known as induction linacs. Induction linacs require a switch that will hold-off 250 kV, conduct 30 kA for 150 to 200 ns, operate at 1 to 2 kHz for several second bursts, have better than 1 ns jitter, and last in excess of 10^8 pulses. The workshop reviewed the state-of-the-art of Super-Emissive Cathode Switches, Magnetically Delayed Vacuum Switches and Solid State Switches and considered research and development steps that would allow these technologies to meet these requirements.

Zutavern, F.J., et al., "Photoconductive Semiconductor Switch. (PCSS) Recovery," Proceedings of the 7th IEEE Pulsed Power Conference (1989) 412-417; also: Proc. 19th Mod. Symp., IEEE CH 2839-9 (1990) 385-390.

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Mazzola, M.S., et al., "Investigation of a Photoconductive Closing and Opening Bulk GaAs Semiconductor Switch," Proceedings of the 7th IEEE Pulsed Power Conference (1989) 418-421.

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Thomas, B.L., et al., "Investigation of Surface Flashover in Silicon Photoconductive Power Switches," Proceedings of the 6th IEEE Pulsed Power Conference (1987) 149-152.

7.2 Electron-Beam Controlled Semiconductor Switches [7]

Electron-beam controlled GaAs switches operating either in the linear mode or triggered into a semi-permanent conductive state, can switch, like photoconductive switches at high powers, with nanosecond risetimes and very low jitter. Since electron beam sources have higher efficiencies, higher repetition rates, and are less expensive than lasers at comparable power levels, electron beam controlled semiconductor switches could be competitive with photoconductive switches in high average power switching applications. In addition the use of electron beams as drivers for switches operated in the linear mode allows pulse shaping by modulating the electron beam current in a gated vacuum tube.

7.2.1 Electron-Beam Sustained GaAs Switch

The concept of electron-beam sustained semiconductor switches (1, 2) is based on irradiating a wide-bandgap, direct semiconductor material, such as GaAs or ZnSe, with a high energy electron-beam. The electron-beam creates a high density

[7] K. Schoenbach contributed this section. Work supported by USARO and AFOSR

electron-hole carrier in a surface layer with a depth in the range of several tens to hundreds of micrometers. The electron-beam-generated secondary ionizing radiation (x-rays and band-edge radiation from recombining electron-hole pairs) can penetrate deep into the bulk of the semiconductor. Band-edge radiation, with an emission characteristic which is well matched to the absorption spectrum of the semiconductor, is the dominant source of ionization. The physics of the switching process is therefore similar to that of a laser-driven photoconductive switch.

A sketch which shows schematically how the switch can be integrated in an electron-beam driver is shown in Figure 7.2.1. The switch consists of a cylindrical piece of semi-insulating GaAs or any other wide-bandgap, direct semiconductor. It is doped on the cathode side with acceptor material to a depth equal to the penetration depth of the electron-beam. For 200 keV this depth is on the order of 100 µm. At the anode the semiconductor is doped with a donor material, generating a P-layer, intrinsic, N-layer (PIN) structure.

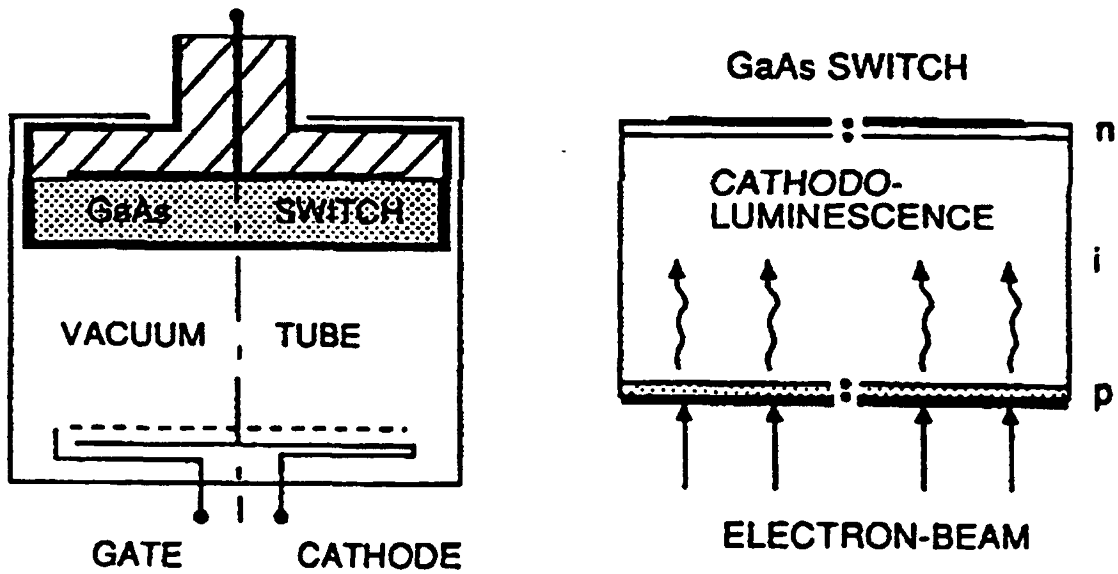

Figure 7.2.1: Schematics of an electron beam controller switch with the GaAs switch integrated in a gated electron tube. The figure on the right shows the design of the solid state switch (PIN structure) and indicates the process of electron energy conversion into band edge radiation.

In the open state (no irradiation), the bulk material has a high resistivity, with measured hold-off field strengths of more than 150 kV/cm. The PIN structure prevents current injection into the bulk of the switch and insures therefore a low dark current.

To turn the switch into the conducting state, closing the switch, an electron-beam with an energy below the damage threshold of 250 keV, is injected at the cathode side of the sample. Due to the small penetration depth of the electron-beam, the electrons that stop in the p-type layer of the switch create a high concentration of electron-hole pairs by direct ionization. Subsequently, these pairs recombine emitting band-edge radiation (in GaAs: $h\nu = 1.42$ eV) which then penetrates deep into the material, ionizing the bulk of the switch. The electron-hole plasma in the bulk zone allows large currents to flow during electron-beam irradiation. Modulation of the electron-beam current will cause linear changes in electron-hole plasma density and therefore the switch current.

The strong p-type doping of the electron impact region has two effects on the switch efficiency. First, it enhances the probability of electron energy conversion into photon energy and second, it reduces the bandgap. Consequently, the resulting band-edge radiation undergoes less absorption in the intrinsic material and penetrates deeper into the bulk. Proper doping of the p-type layer allows tailoring of the 1/e depth of the band-edge radiation with respect to the switch geometry, in a similar way to that attainable with a tunable laser.

Early experiments were performed with 0.5 mm thick semi-insulating GaAs wafers without the PIN structure. Electron-beam current densities were in the range of 10 mA / cm^2 with pulse durations in the 10 μs range. Figure 7.2.2 shows the results of the electrical measurements. In the linear range, currents of up to 10 A have been switched with 36 mA electron beams corresponding to a current gain (switch current/electron-beam current) of about 300. Gains of more than 10,000 have been reached in the nonlinear range at applied fields in excess of 5 kV/cm. Also shown in this figure are results of modeling (solid lines) which indicate that linear switch operation, where the switch current is proportional to the applied voltage, is well understood.

Improvements in current gain by more than an order of magnitude are possible by using PIN structures. Also, modeling results indicate that it should be possible to extend the linear range to much higher field strengths, avoiding the lock-on effect [3], and therefore keeping the switch controllable over a wide range of voltages. This would allow the switch to open even at high applied voltages by turning off the electron-beam. Experiments with GaAs in a PIN structure have confirmed this prediction [3a]. It was possible to apply five times higher voltage to the switch than to an intrinsic one without going into the lock-on state. Also, the switch gain improved by about a factor of four, even though the p-type layer in the GaAs did not have the optimal thickness. Because the proposed switch would operate in the linear regime, currents and voltages should scale linearly with switch dimensions and source intensities. Modeling results [2], which are experimentally verified for lower current and voltage levels, led to the scenario generated by the discussion group on solid state switches [Table 10.1].

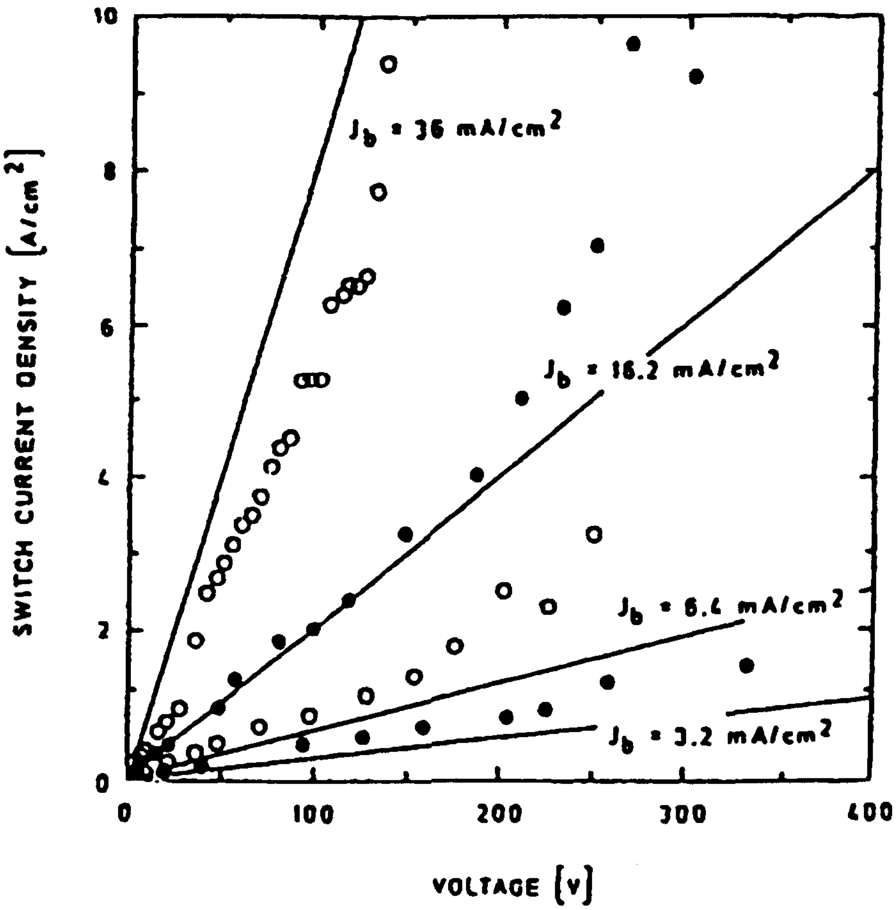

Figure 7.2.2: Comparison of experimentally obtained J-V characteristics with computed J-V curves for 0.5 mm-thick semi-insulating GaAs switches. The modeling results hold for low voltages only.

7.2.2 Electron-Beam Triggered GaAs:Si:Cu Switch

The development of a new type of semi-insulating GaAs at Old Dominion University (ODU), which has decay time constants far exceeding those of GaAs and even Si, offers the possibility to use this material as a low jitter closing switch. This switch can be triggered with either a Nd:YAG laser, as it was done at ODU, or with an electron beam. It has hold-off voltages and dark currents comparable to those at GaAs, but the current decays with 1/e times that are long compared to the pulse duration requirements of Linear Induction Accelerators (Figure 7.2.3). This persistence of the current after switching into the conducting state is *not* due to the lock-on effect. Rather, it is a linear effect, which results from the slow trapping of electrons into ionized deep Cu centers. Unlike the lock-on case, where the switch current is locked to a certain voltage, the forward voltage is only determined by the source function and can therefore attain very low values. The new material, silicon doped, copper compensated GaAs (GaAs:Si:Cu) and its applications are discussed in [4, 5, 6, and 7]. One of the most attractive features of this new material is its use as an opening switch, where the current is optically quenched: GaAs:Si:Cu switches can be closed *and* opened by means of laser radiation.

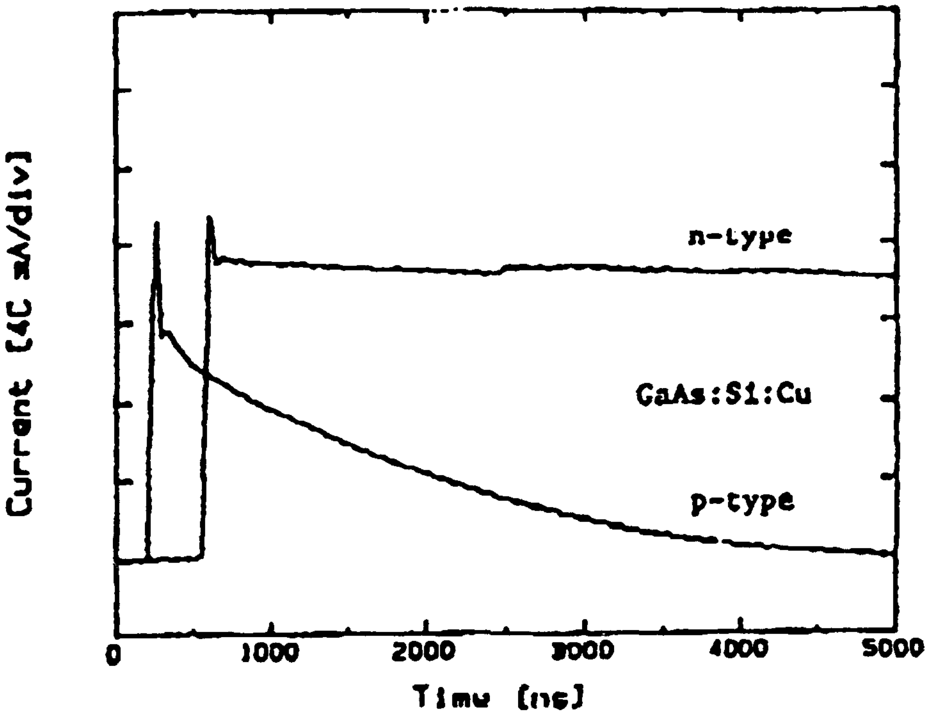

Figure 7.2.3: Photocurrent decay curves for slightly undercompensated (n-type) GaAs:Si:Cu and slightly overcompensated (p-type) GaAs:Si:Cu. Un-doped GaAs or chromium doped GaAs has decay times of nanoseconds and less. Current scale is 40 mA div^{-1}, time scale is 1000 ns div^{-1}. (M. Mazzola, Dissertation, ODU, 1990)

The properties of GaAs:Si:Cu, its high optical gain together with its low dark current, make it the best available switch material for photoconductive closing switches, operating at voltages far below the lock-on voltage. The closing switch based on e-beam triggering of the GaAs:Si:Cu has been modeled and results are discussed in [8]. Results show that subnanosecond switching of a GaAs:Si:Cu switch into a conductive state with less than 0.1 Ω/cm^2 (Figure 7.2.4) is possible with electron-beam pulses which generate carriers at a rate of 10^{25} cm^{-3} s^{-1}. This corresponds to an electron current density of 100 A/cm^2 at an electron energy of 150 keV. Although these values seem high, it should be considered that handheld, battery driven e-beam guns with 2 ns e-beam pulses, which generate several hundred amperes at the required electron energy are available [10, also: M. Kristiansen, Texas Tech University].

The calculation of Figure 7.2.4 was performed for a 0.5 mm sample. However, it can be expected, that by relaxing the condition for the risetime from ps to ns, it becomes possible to switch thick samples with about the same e-beam flux as used in the model. The advantages of using such a switch in Linear Induction Accelerators would lie in the relatively inexpensive (compared to lasers) construction of switch drivers, which allow precise switch triggering at high repetition rates. In addition, the reduced thermal loading of the switch due to the low forward voltage (far below the lock-on voltage) and the small amount of trigger energy should allow easier thermal management of the repetitively operated solid state switch.

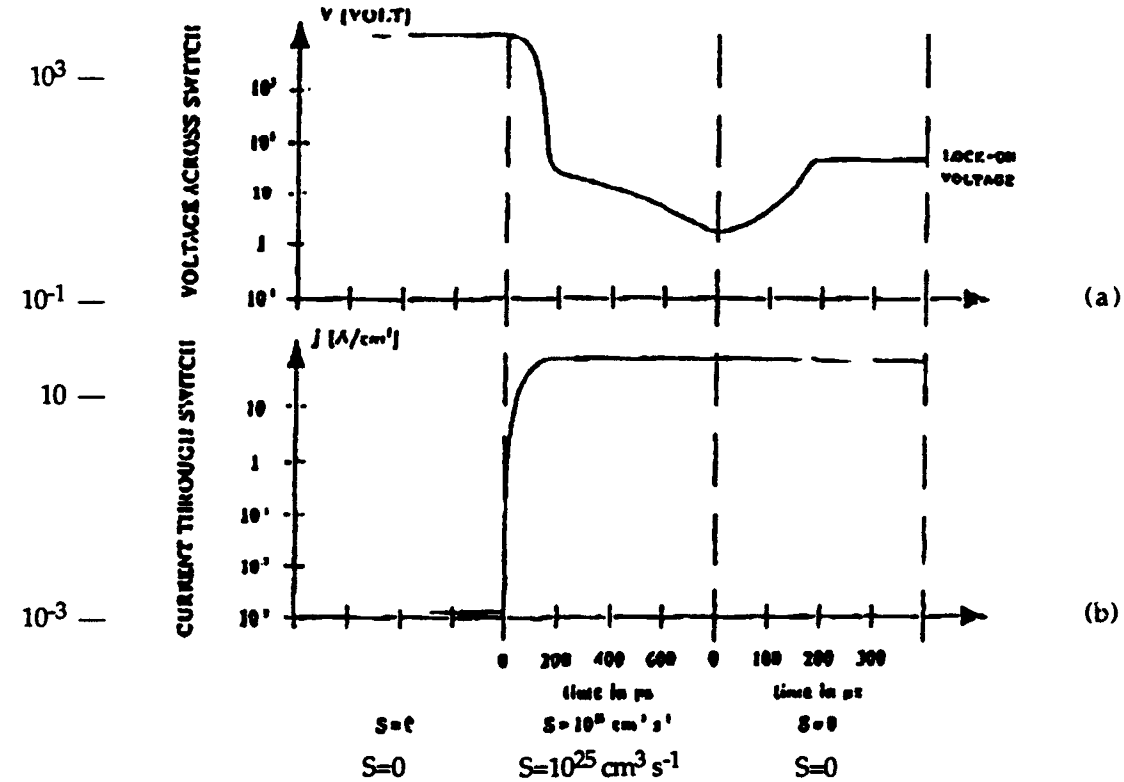

Figure 7.2.4: Calculated temporal development of switch voltage (a) and current density (b) in a 0.5 mm GaAs switch during (time scale 200: ps div^{-1}) and after (time scale 100: µs div^{-1}) electron beam radiation. The forward voltage during the first 100 µs is far below the lock-on voltage. It reaches the lock-on voltage level after about 200 µs.

Although this switch concept, as the first one, is not yet tested at high power levels, it should be scalable because it does not rely on nonlinear effects, such as the lock-on effect, for the conduction phase. The novel idea in both type of switches is the use of electron-beams with their inherent high efficiency and controllability, and in the triggered switch case, the utilization of "tailored" switch materials. In both cases it is not even necessary to generate the cathodoluminescence in the switch itself. It is possible to have the electron-beam controlled light source separated from the switch and to couple the light through fibers from source to switch [9]. This, although less efficient than having the light source integrated in the switch, might have advantages in switching parallel systems with low jitter.

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HIGH POWER SWITCHING WITH ELECTRON-BEAM CONTROLLED SEMICONDUCTORS

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Measurements and model calculations on semi-insulating GaAs as material for optically and electron-beam controlled semiconductor switches have shown that the steady state current is a strongly nonlinear function of both the applied voltage and the radiation intensity. The nonlinear shape of these curves can be influenced over a wide range by doping with suitable deep acceptors or donors, a result which opens the possibility of "tailoring" the materials to meet specific demands. As an example, it is discussed how a current-controlled negative differential conductivity due to Cu-doping can be utilized for a fast (sub-nanosecond) e-beam controlled switch which operates at low dark current, high hold-off voltage and a forward resistance which lies considerably below the lock-on resistance.

I. INTRODUCTION

The concept of electron-beam controlled semiconductor switches is based on the generation of free charge carriers in the bulk of a semi-insulating semiconductor, utilizing both the direct and the indirect ionizing effects of high-energy electrons. A beam of such electrons with a current of up to 100 A/cm^2 and an energy of up to 150 keV can easily be generated with standard vacuum technology, making a compact and economic switch design possible. A thorough analysis of the device in the linear regime has been given in references [1] and [2].

Recently, much attention has been focused on the non-linear behavior of optically and electron beam controlled semiconductor switches, concentrating on features like the non-linear dark current characteristics, the break-down voltage, and on the so-called lock-on effect [3,4,5]. The experimental results of different groups vary considerably. This indicates that the named characteristics are essentially determined by the non-ideal features of the semiconductor, in particular by the localized deep energy levels generated by impurities or defects.

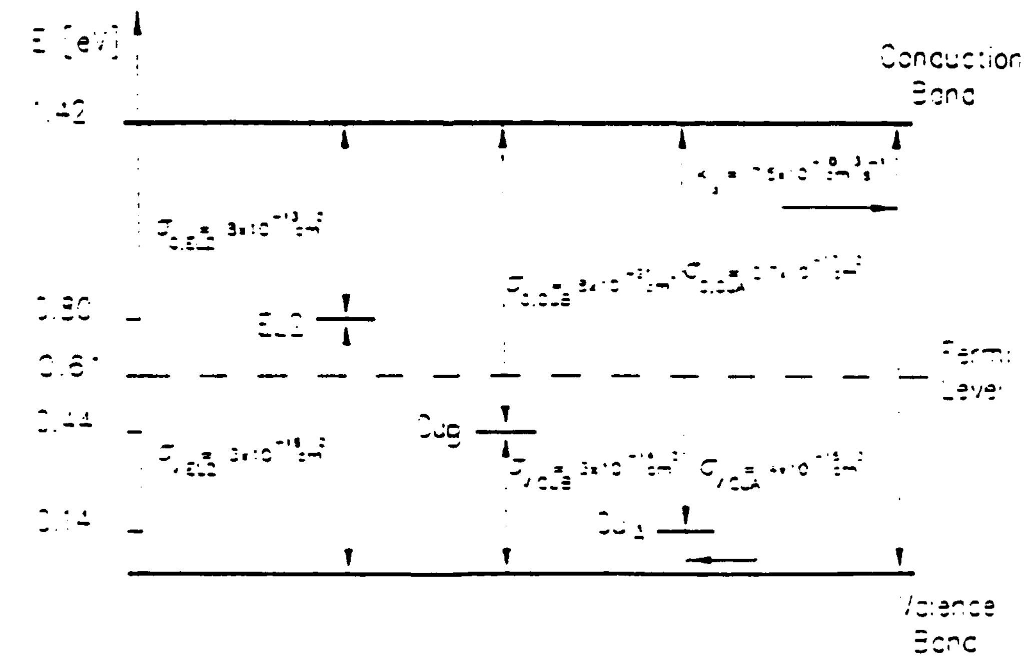

Figure 1: Model of the Level Structure of Cu:Si-Doped Semi-Insulating GaAs.

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The strong dependence of the switch characteristics on impurities and defects is on one hand an obstacle for standardization of semiconductor switches, but can also be seen as an opportunity: "Tailoring" of the switch material becomes possible. Deep traps in the band gap are responsible for the high resistance of semi-insulating GaAs and determine largely the I-V-characteristics of the material [4]. Some of them, like the generally dominant electron trap EL2, are related to defects resulting from the composite nature of GaAs and are hence intrinsic to the material, others however, can be introduced by doping the crystal with suitable acceptors or donors. The strong dependence of the material properties on these dopants opens the possibility of shaping the conductance of the semiconductor to meet specific demands. In the following, we discuss the example of a current-induced negative differential conductivity due to copper doping and how it may be utilized to design a fast (sub-nanosecond) on-switch which operates at low dark current, has a high hold-off voltage and shows forward resistance which is considerably below that obtained under lock-on conditions. The assumed energy level structure is given in figure 1. It consists of the two copper levels Cu_A and Cu_B which act as hole traps, and of the intrinsic electron trap EL2.

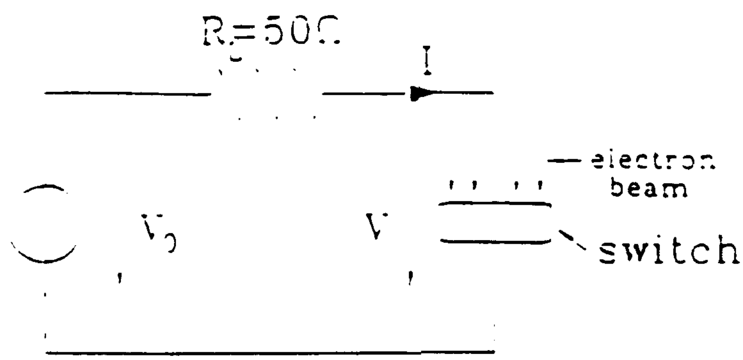

Figure 2: Schematic Representation of the Switch Circuit.

II. MODELING THE SWITCH CONFIGURATION

In order to analyze the performance of electron-beam controlled semiconductor switches, we have developed a model based on the idealized configuration shown in figure 2. The voltage source represents a pulse forming line with an internal resistance of $R = 50\ \Omega$. We assume that the switch diameter ($A = 1\ \mathrm{cm}^2$) is large compared to its thickness ($L = 0.5$ mm), such that a set of one-dimensional equations can be employed to describe the electron and hole transport. Our model includes the generation of free charge carriers through radiative, thermal or impact ionization, their transport under the influence of the electrical field, and their recombination or trapping in intraband traps. Denoting the number of electrons in the conduction band and the number of holes in the valence band by n and p, respectively, the densities of the various carrier traps by N_i and their relative occupation number by r_i, the system of dynamical equations reads

$$\frac{\partial n}{\partial t} + \frac{\partial}{\partial z}(v_n(E)n - D_n\frac{\partial n}{\partial z}) = \dot{n}_{cv} - \sum_i N_i\dot{r}_{ci} + S, \tag{1}$$

$$\frac{\partial p}{\partial t} - \frac{\partial}{\partial z}(v_p(E)p + D_p\frac{\partial p}{\partial z}) = \dot{n}_{cv} + \sum_i N_i\dot{r}_{vi} + S, \tag{2}$$

$$\frac{\partial r_i}{\partial t} = \dot{r}_{vi} + \dot{r}_{ci}. \tag{3}$$

In these expressions, v_n and v_p stand for the field dependent drift velocities of the electrons and ther holes, respectively, D_n and D_p are the diffusion coefficients. The dottet terms on the right hand side denote the balances of direct recombination, thermal pair generation and impact ionization ($\dot{n}_{cv}$), and trapping and thermal release of electrons or holes ($\dot{r}_{ci}$ and $\dot{r}_{vi}$). Together with the corresponding cross sections, they are visualized in the band structure model if figure 1. The source function S represents the generation of electron-hole pairs due to the external source (S); for the sake of simplicity we assume it to be spatially constant. For an electron beam of 150 keV energy, S is $10^{23}\ \mathrm{cm}^{-3}\mathrm{s}^{-1} \times j_{beam}/\mathrm{Acm}^{-2}$.

The description of the system is completed with Poisson's equation which connects the electrical field E to the excess charge in the crystal; the quantities N_d, ϵ_0 and ϵ_r stand for the effective shallow doping density, the absolute and the relative dielectric constant, respectively:

$$\epsilon_0\epsilon_r \frac{\partial E}{\partial x} = e(n - p + \sum_i N_i r_i + N_d). \quad (4)$$

We have solved the equations numerically under the assumption of steady state, closely following a procedure which is more extensively discussed in reference [2], and in the transient case where we have implemented a hybrid code which combines a Lagrangian treatment of the free carriers with an Eulerian description of the trapped charges. (This approach, which virtually eliminates the spurious numerical diffusion inherent to finite differencing methodes, ensures a satisfactory accuracy even for a relatively small number of discretization points.) For all calculations, the contacts have been assumed to be injective with negligible contact resistance.

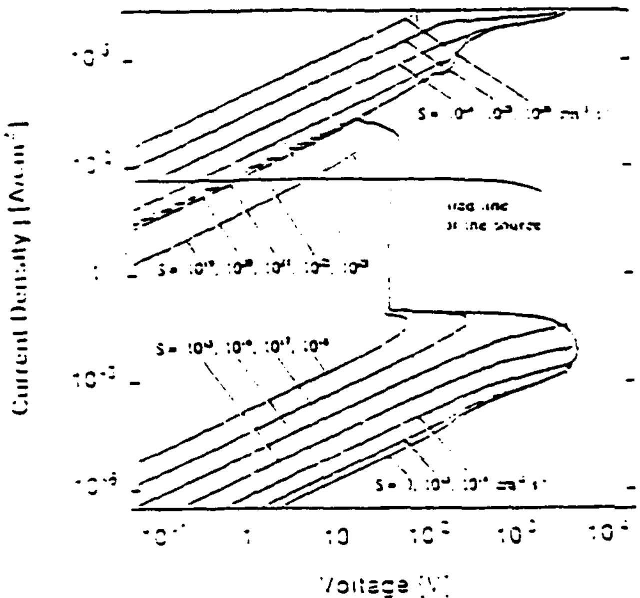

Figure 3: The Steady State I-V-Curves with and whithout Electron-Beam Irradiation, and the Load Line of the Voltage Source.

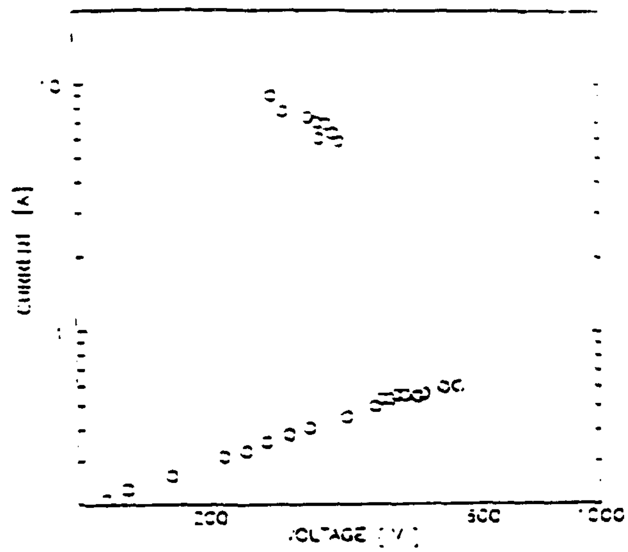

Figure 4: The Experimentally Obtained Dark Current Curve for GaAs:Cu:Si.

III. STEADY STATE CURRENT-VOLTAGE CHARACTERISTICS

First, we consider the time-independent current-voltage characteristics of the switch. We have calulated the I-V-curves for the case $S = 0$ (dark current), and for every power of ten between 10^{14} cm^{-3}s^{-1} and 10^{25} cm^{-3}s^{-1}, corresponding to e-beam currents between 1 nA/cm^2 and 100 A/cm^2. The familiy of curves is displayed in figure 3, together with the load line $V = 4$ kV $- j * 50\,\Omega$cm^2 of the assumed voltage source.

Let us focus first on the dark current curve $S = 0$. For low voltages, $V \lesssim 100$ V, it exhibits a linear ohmic behavior with $j = e(\mu_n n_{eq} + \mu_p p_{eq})V/L = G_0 V$, the conductivity being determined by the carrier concentration in the thermodynamic equilibrium. For higher voltages, 100 V $\lesssim V \lesssim 5$ kV, deviations from this relation arise which are due to the nonlinear dependence of the drift velocities on the electrical field, but the current voltage curve is still monotonic. At about 5 kV, however, the current slope begins to rise steeply and finally bends back to lower voltages. The occurrance of such a current-controlled negative differential conductivity has first been predicted by Lampert et al. [6]. It can be understood as a phenomenon resulting from the effects of trap filling and double-current-injection: In the low current regime, any injected charge carriers are quickly trapped in the vicinity of the contacts so that they create a considerable space charge (and hence voltage drop) but do not contribute to the current flow. At currents above 10 mA/cm^2, however, the deep traps are essentially filled, leading to a drastically increased effective carrier lifetime, a more homogeneous charge distribution and hence to a reduced forward voltage.

An important effect resulting from the negative differential conductivity of the sample is that the dark current characteristic crosses the load-line of the voltage source at three different points which determine three distinct steady states of the system, denoted by I, S_1 and S_2 in figure 3. The state I is externally unstable because of $R + \frac{\partial V}{\partial j} > 0$, the two states S_1 and S_2 are externally stable. Assuming also internal stability, we can conclude that the configuration of figure 2 shows a pronounced bistable behavior with a low-current (or hold-off) state S_1 and a high-current (or lock-on) state S_2.

At this point, it is interesting to compare the numerical results with some experimentally obtained data. Figure 4 shows the dark current I-V-curve for a sample which was manufactured by electrically compensating silicon doped gallium arsenide through thermal diffusion of copper into the host crystal. The two curves show a satifactory qualitative agreement with respect to the current controlled negative differential conductivity, but a rather poor quantitative correspondence in terms of the maximum hold-off voltage and the minumum sample voltage at higher currents. The reason for this is probably that the deep level structure used in our calculations gives only an approximate (and simplified) representation of the real material, mainly because collisional processes which lead to trap emptying are not yet considered in the model. Processes of this type, which are difficult to include in the model because of the lack of basic data, are at least partially to blame for the still existing gap between experimental and theoretical results.

Let us now turn to the current voltage characteristics under irradiation. As one should expect, they also show a linear behavior for low voltages, $j = e(\mu_n n + \mu_p p)V/L = G_S V$, corresponding to a homogeneous field distribution. At higher voltages, hovever, deviations from the linear slope become significant because the effects of the external source function are no longer dominant compared to those of internal electron-hole-pair generation and current injection through the contacts. Finally, the I-V-curves under irradiation merge with the dark current curve.

From the family of I-V-curves in figure 3 and the load line of the assumed voltage source we can already infer the essential characteristics of a switching scenario: Assume the system to be in the hold-off mode with an applied voltage of 4 kV and a currrent of about 1 mA/cm^2. Starting from $S = 0$, we may imagine a slow (adiabatic) increase of the source function and a corresponding rise in the conductance. At first, the state of the system will follow the intersection of the load line and the I-V-curves quasistatically; at $S \approx 10^{16}$ cm^{-3}s^{-1}, this intersection and also the corresponding steady state vanish: The system cannot react adiabatically anymore, it has to undergo a transition into a dynamical state and will finally reach the high-current mode. From there, it can follow any subsequent changes in the source function quasistatically again; in particular, it will go into the lock-on state S_2 when the source function is switched off.

From the expected bi-stable behavior of the switch we conclude that doping of GaAs with deep acceptors such as copper opens the possibility to design a very economical switch. Source functions as low as 10^{16} cm^{-3}s^{-1} which correspond to an electron beam of 0.1 μA/cm^2 and 150 keV energy, or to a GaAs laser diode of 10 mW/cm^2 can be used to trigger the switch into a low impedance mode, followed by the lock-on mode with slightly higher impedance.

IV. TRANSIENT SIMULATION

Unfortunately, a quasistatic investigation alone does not allow us to conclude on the temporal characteristics of the switching process. As the transition to the lock-on mode is related to the filling of the deep carrier traps, we can roughly estimate the closure time by $\tau = N/S$, where $N \approx 10^{15}$ is a typical trap density. To obtain a more quantitative formulation, we have to employ a complete transient simulation of equations (1) - (4). For the sake of conciseness, we confine ourselves to the discussion of one case which is typical for our experimental results.

Figure 5 shows a synopsis of the simulation, i.e., the voltage of the source, the voltage across the switch, and the current density as a function of time. (Note the different scales for the t-axis.) We start the system at $t = 0$ from the thermodynamic equilibrium, i.e., from the state with no voltage and no source function applied. First, the source voltage is increased within about 10 ns to a value of 4 keV, to which the switch responds with the dielectrical displacement current. After the final voltage has been reached, this current dies rapidly off and the system reaches steady state; comparison with figure 3 shows that this is indeed the low-current hold-off state S_1.

After 40 ns, we apply a source function of $S = 10^{25}$ cm^{-3}s^{-1} for a time span of 750 ps. The system reacts within about three hundreds ps by increasing the conductivity such that the voltage at the switch breaks down to about 1 V, a value which corresponds almost to the steady state value. During irradiation, the deep centers trap charges form the conduction and the valence band, respectively, so that at the end of the 750 ps the electron trap is nearly completely filled, and the dominant hole is trap filled to about 50%.

After the source function has been switched off again, we now follow the relaxation of the system on a much longer time scale. First, the remaining hole sites in the Cu-level trap the holes in the valence band and form an immobile

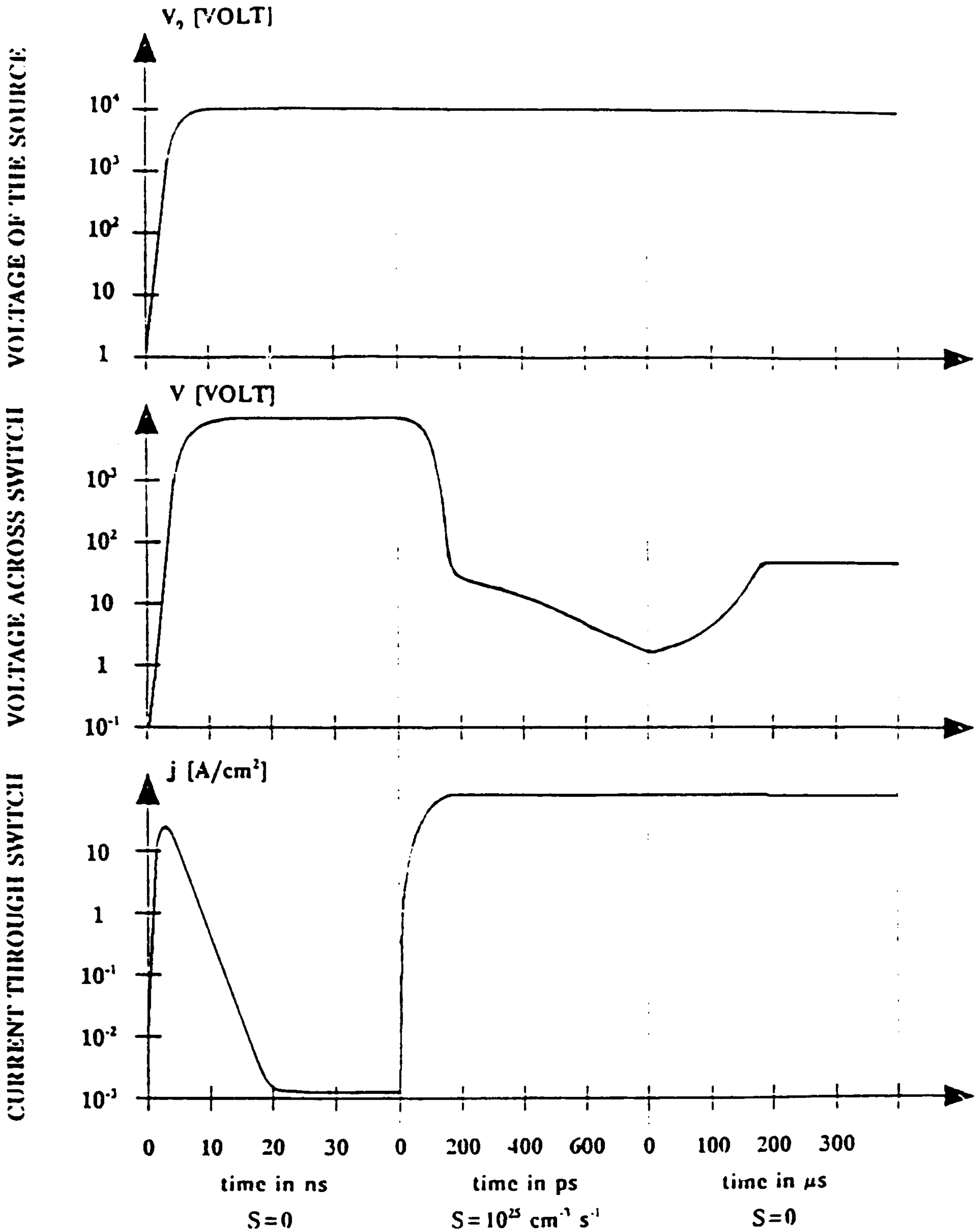

Figure 5: Temporal Representation of a Transient Simulation Run.

positive space charge, wheras electrons stay in the conduction band because the EL2-trap is already completely filled. As a consequence, the system is now "dynamically" n-type, and it remains in a highly conductive state for a considerable time. (This effect was first used by Schoenbach et al. [7] in the BOSS concept. As in this concept, the current could be quenched by releasing the holes with laser irradiation.)

After a time span of some hundred μs, the trapping of electrons in the Cu-levels starts to make an impact on the conductance of the switch. It decreases to a certain extent, and the voltage increases to a value of about 50 V. Comparison with figure 3 shows that this is actually the lock-on state as discussed in the previous section.

V. SUMMARY AND DISCUSSION

Our considerations have shown experimentally and theoretically that the current-voltage curves of semi-insulating GaAs can be tailored by doping the material with deep acceptors or donors. The use of copper as a dopant induces a pronounced current controlled negative differential conductivity which leads to a bistable behavior of the system. This characteristic feature offers the possibility to design an on-switch which combines a high hold-off voltage and low forward resistance and hence reaches a very favorable efficiency. Two limiting cases are of interest:

- If delay times of μs and more are of no concern, switching with large current rise can already be achieved with source functions as low as $S = 10^{16}\ cm^{-3}s^{-1}$, corresponding to e-beam or laser power of the order of 10 mW/cm^2.
- With source functions of $S = 10^{25}\ cm^{-3}s^{-1}$ switching can be obtained on a sub-nanosecond time scale. The beam power in this case is relatively high, $P = 10^7 W/cm^2$, but easily obtainable with electron beam guns. It corresponds to beam currents of about 100 A/cm^2 at 150 keV; the corresponding pulse energy, however, is still only of the order of $10^{-2} J/cm^2$.

These examples show that the electron-beam controlled semiconductor switches promises to be a very attractive alternative to optically controlled semiconductor switches as well as to conventional thyratrons. It should be emphasized that the properties of the devices can be improved even more by employing semiconductors with higher band gap. Materials like ZnSe promise to yield superior performance in terms of leakage current, hold-off voltage and temperature stability, a perspective which will undoubtedly motivate increased research effort into that direction.

VI. ACKNOWLEDGEMENT

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Abstract—The conductivity of wide-bandgap semiconductors can be effectively controlled by electron-beam excitation thereby allowing these materials to be used as closing and opening switches in high-power, high-repitition rate systems. Semi-insulating GaAs is experimentally studied with respect to its application in electron-beam-controlled switches. The dark current through the switch is measured both before and after electron-beam irradiation. A "lock-on" effect, similar to that seen in photoconductive switches, is observed after the electron beam is terminated. This effect is characterized by the switch current continuing to flow, locked to a certain voltage, as long as the voltage is applied across the switch. A possible explanation for this effect, based on the process of electron and hole injection at the contacts is presented. A method to minimize double injection is offered to make the electron-beam-controlled switch, along with the photoconductive switch, practical for use as both an opening and closing switch.

I. Introduction

RESEARCH on photoconductive semiconductor switches has evolved rapidly during the past few years. Whereas most of the research initially has been concentrated on silicon (Si) as the switch material, there is recently more and more interest in semi-insulating (SI) gallium arsenide (GaAs). Some of the benefits of using SI GaAs in a high-power switch instead of Si are that it has a higher electron mobility, higher dark resistance, higher dielectric strength, and a faster recombination time. Besides these material properties, GaAs has an additional advantage in that copper-compensated silicon-doped GaAs can be utilized as a material for optically controlled closing and opening switches [1].

Although photoconductive, high-power switches have been studied for less than a decade [2], they have gained much more attention than electron-beam-controlled pulsed-power switches which were studied for a much longer time [3], [4]. Recently, research in this field has gained new momentum due to an improved switch concept [5]–[7]. This concept is based on the generation of free charge carriers in the bulk of the semiconductor by induced cathodoluminescence. Using an electron beam to ionize the semiconductor allows the switch to be closed for microsecond or even millisecond time durations. Once the electron beam is terminated, the switch will open due to electron–hole recombination, trapping of free carriers, diffusion, and carrier sweep-out. The recovery time of photoconductive GaAs switches was measured to be nanoseconds and less for low applied voltages [8]. It should not be different for electron-beam excitation. Therefore, the electron-beam switches should be useful in systems where high repetition rates are required or where switches are needed to operate in a burst mode.

Some of the advantages of electron-beam-controlled switches compared to conventional photoconductive (laser controlled) switches are as follows:

- Compared to high-power lasers, electron beams allow easy temporal control of the beam current. When combined with the linear characteristics of the electron-beam-controlled semiconductor switch, a device which promises to be very useful for the purpose of high-power modulation can be developed. This could have applications in inductive energy storage devices where it is desirable to control the conduction phase of the opening switch to optimize the power transferred into the load.
- Electron beams with power densities in the 1- to 100-kW range can be generated with relatively uncomplicated devices like vacuum tubes. Therefore, compact and economical integrated switch designs are possible.

An obstacle for the use of GaAs switches as opening switches in high-voltage systems, however, is the so-called "lock-on" effect. This effect is manifested by the inability of the switch to recover to its initial hold-off voltage following the application of an electron beam or laser pulse and results in a current which persists after the source of irradiation has been removed [9], [10]. In order to investigate the lock-on effect in electron-beam-controlled semiconductor devices, the dark current was measured under both steady-state and transient conditions for a range of applied voltages. From the results of these measurements: a) the nature of the semiconductor material may be established and b) its application to high-power switching can be assessed. The purpose of this work is to study the lock-on phase of the switch cycle,

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after termination of the excitation source, and compare it with the dark-current characteristics of the switch.

II. The Dark Current at Low Voltages

The material used in the experimental investigation was as-grown (or EL2-compensated) SI GaAs [11] with a resistivity of $6 \times 10^6\ \Omega \cdot$ cm. The thickness of the switch bulk was 0.065 cm with a contact area of about 1.1 cm^2. The sample geometry consisted of the bulk region with aligned parallel-plate contacts. The contacts were manufactured by thermally depositing a Au(88%)-Ge(12%) alloy to a thickness of 100 nm. The sample was then annealed at 450°C in N_2 at atmospheric pressure for a period of 15 min.

The low-voltage steady-state I-V characteristics of the material were measured with a Keithley 617 electrometer which measured the current and supplied the voltage up to 100 V. Potentials above 100 V were supplied by a Bertan 3-kV dc power supply. All measurements were conducted with the sample in the dark and in a vacuum of about 5 mtorr. The vacuum was used to provide thermal isolation from the environment when the temperature of the sample was varied.

The I-V characteristics of the material are shown in Fig. 1 with the curves being generated at a constant temperature (±1°C). The most noticeable feature of these curves is the existence of a linear "ohmic" region which shifts uniformly with temperature. This shift with temperature is a function of the deep-level configuration of the material rather than a simple exponential function of the bandgap energy. A more detailed study of the temperature effect on this material can be found in [12]. When a certain voltage level is reached, the current rapidly increases with a small change in sample voltage. The voltage at which this transition occurs is called the trap-filled-limit voltage (V_{TFL}). This transition occurs at a V_{TFL} of 100 V (1.5 kV/cm) for a temperature of 24°C. A switch can only be operated up to this voltage under static bias conditions without excessive leakage current.

The theoretical analysis of the low-voltage characteristics is based on the single-carrier-injection model developed by Lampert et al. [13]. For this analysis, the effect of hole injection is neglected because the material is n-type, i.e., $n_0 >> p_0$, and the electron mobility is much greater than the hole mobility. For low voltages, the I-V characteristic is determined by Ohm's law. The rapid increase in the measured current occurring at V_{TFL} is a trap-filling effect resulting from the electron lifetime becoming greater than the electron transit time.

The value of V_{TFL} contains information on the concentration of the dominant empty traps at thermal equilibrium (p_{t0}), therefore, it is possible to calculate the value of V_{TFL} from basic data on deep centers in GaAs. According to Lampert and Mark [14], p_{t0} is given by

$$p_{t0} = (2\epsilon V_{TFL})/(eL^2) \tag{1}$$

where ϵ is the material permittivity, e is the electron charge, and L is the distance between the contacts.

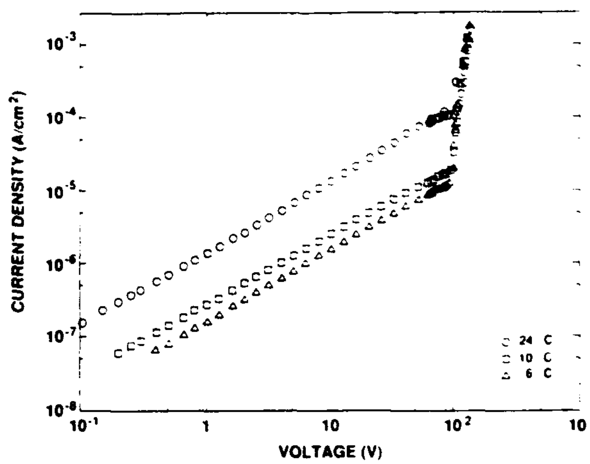

Fig. 1. DC I-V characteristics of semi-insulating GaAs ($6 \times 10^6\ \Omega \cdot$ cm) with temperature as the variable parameter.

Using the experimentally obtained value of V_{TFL} in (1) yields an empty trap concentration of $p_{t0} = 3.4 \times 10^{11}$ cm^{-3}. From p_{t0} we can obtain the total trap concentration (N_t) from the relation

$$p_{t0} = \frac{N_t}{1 + g \exp\left[(E_f - E_t)/kT\right]} \tag{2}$$

where T is the temperature in kelvins, k is the Boltzmann constant, E_t is the activation energy of the trap, E_f is the Fermi energy, and g is the ground-state degeneracy of the deep level. For our analysis we assume the deep level to have a degeneracy of 2.

To determine the Fermi energy (E_f), the thermal free-electron concentration (n_0) is found by fitting Ohm's law to the linear region of Fig. 1 for a temperature of 24°C. The electron mobility is given as 6653 cm^2/V · s [11]. With a value of $n_0 = 5.8 \times 10^7$ cm^{-3} the location of the Fermi level was calculated to be $E_c - E_f = 0.58$ eV. Assuming that EL2, which is located at 0.825 eV below the conduction band [15], determines the value of V_{TFL}, a trap density of $N_t\{\text{EL2}\} = 9.7 \times 10^{15}$ cm^{-3} was obtained which is close to the values normally quoted for EL2 in SI GaAs [16]. It is generally considered that EL2 exhibits donor-like tendencies in SI GaAs [17]. Therefore, in order to make the material semi-insulating, there must be some acceptor-like impurities in the material to compensate the donors. These acceptors may be located close to the valence band (i.e., carbon) and play no role other than to provide compensating holes for the trapping centers. Or, they may be located deep in the bandgap (i.e., chromium) and act as both a compensating level and a hole trap.

III. Transient Dark Current Response

In order to investigate the temporal characteristics of the dark current, the transient response to a step voltage, a hard-tube pulse generator was constructed which would

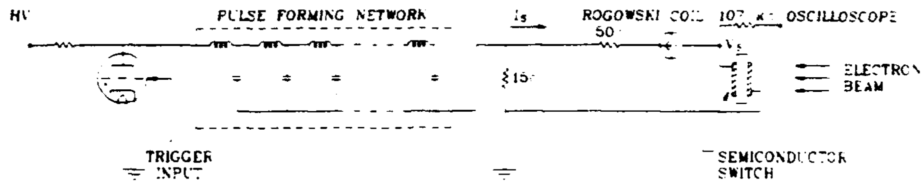

Fig. 2. Experimental setup of the system used to measure the I-V characteristics with a 15-μs voltage pulse.

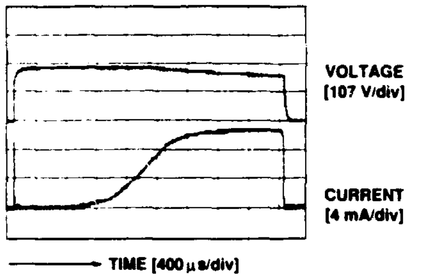

Fig. 3. Temporal development of the switch dark current using the hard-tube pulser. (Sample resistivity: $6 \times 10^6\ \Omega \cdot$ cm.)

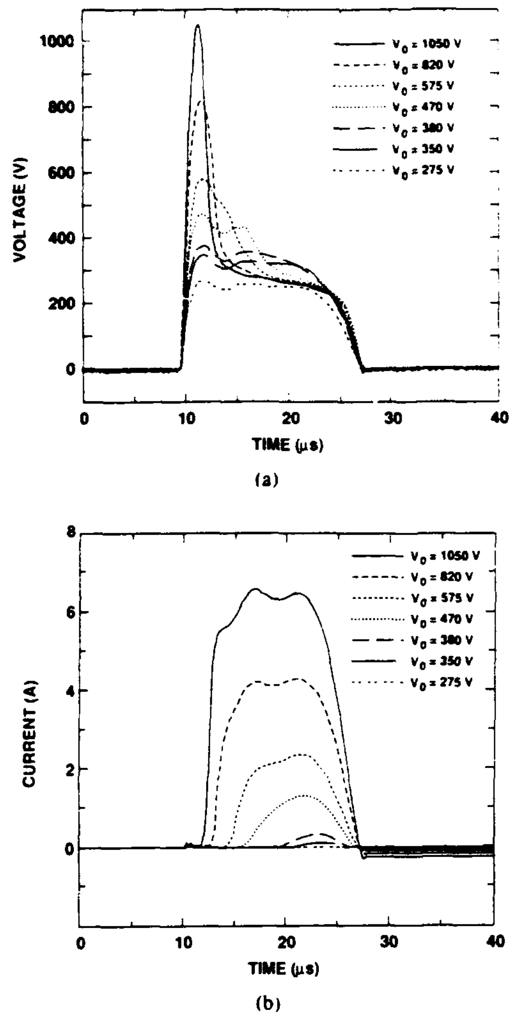

Fig. 4. Temporal behavior of the switch voltage (a) and switch current (b) using the circuit shown in Fig. 2 with the initial applied voltage (V_0) as the variable parameter (without electron-beam irradiation).

apply voltage pulses of up to 3 kV for hundreds of milliseconds across a high-impedance load (> kΩ's). This pulser allowed higher voltages to be applied across the sample than would be possible with a dc bias because the limited pulse duration reduced the problem of heating caused by high dark currents. The circuit consisted of a storage capacitor which is charged to the desired voltage and discharged through a resistor (100 kΩ) that is in parallel with the sample. The switch used to control the pulse width is an RCA 6293 beam-power amplifier vacuum tube with a maximum plate voltage of 3.5 kV.

As the voltage across the sample is increased, the sample impedance becomes too low to be driven by the hard-tube circuit for a sufficient time to allow the full development of the current. Therefore, a second pulse circuit, shown in Fig. 2, is used to allow the dark current to be measured at lower sample impedances. The circuit uses a 15-Ω pulse-forming network which provides a 15-μs voltage pulse.

A typical voltage and current waveform using the hard-tube pulser is shown in Fig. 3. After the initial application of the voltage step there is an initial current spike which is attributed to the displacement current. After the displacement current, the dark current remains very low for an "onset time," which is defined as the time delay for the dark current to reach roughly 1% of the peak current, and then monotonically increases up to a constant value.

Fig. 4 shows the current and voltage waveforms that are measured using the circuit shown in Fig. 2 without electron-beam irradiation. It clearly shows a decrease in the onset time that occurs with an increase in the applied voltage. The onset time is a strong function of the amplitude of the applied voltage pulse as shown in Fig. 5. In Fig. 3, the onset time is about 900 μs and the time to reach the steady-state value is about 2.9 ms for an applied voltage of 200 V. This effect is also found to occur in p-SI-n structures where the p and n regions are epitaxially grown on a SI GaAs substrate [18]. The SI region on these structures is in the range of 20 to 60 μm thick.

The onset time was also found to be a function of the deep-level configuration of the material as well as the applied voltage and temperature. This was found when the same experiment was conducted on SI GaAs which was compensated with carbon such that the material resistivity was $3 \times 10^8\ \Omega \cdot$ cm [19], compared to $6 \times 10^6\ \Omega \cdot$ cm for as-grown SI GaAs. For this material and for an applied voltage of about 650 V, the onset time was found to be 120 ms and the steady-state current was reached in

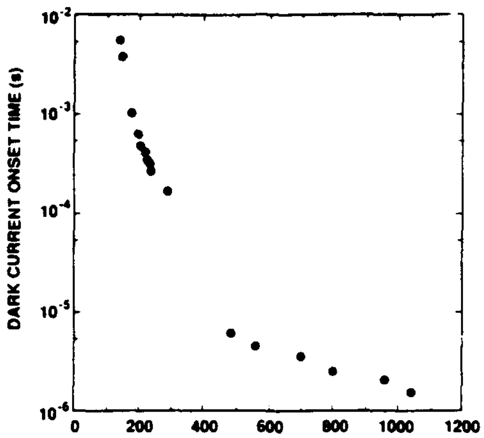

Fig. 5. Dark current "onset" time versus applied voltage.

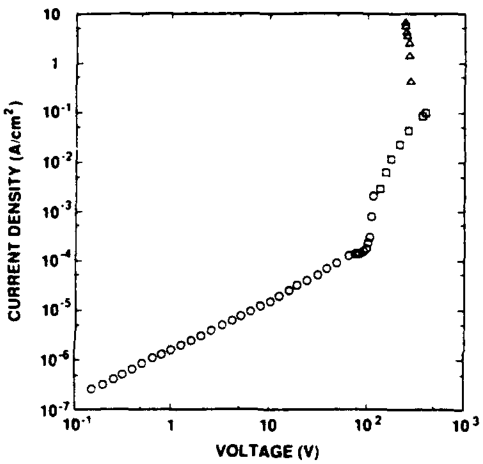

Fig. 6. Dark current density versus applied voltage for semi-insulating GaAs.

about 320 ms at room temperature. Therefore, this material had an onset time that was more than two orders of magnitude longer than the 6×10^6 $\Omega \cdot$ cm material for an applied bias that was about a factor of three higher than that shown in Fig. 3.

Fig. 6 shows the steady-state currents in SI GaAs obtained with both the dc and the pulsed bias measurements at room temperature. The circles represent dc measurement results as shown in Fig. 1 at 24°C. The squares show the data obtained using the hard-tube pulser. The slope of the square data points appears to be saturating into an $I \propto V^2$ dependence. The triangles in Fig. 6 depict the data taken using the circuit shown in Fig. 2 and correspond to the peak in the sample current and the sample voltage during that peak. In this range the current increases with little change in voltage. The apparent negative slope is possibly the result of the current not reaching a steady state in the 15-μs voltage pulse provided by the circuit.

Double-pulse experiments, using the hard-tube circuit, were conducted to determine the recovery of the material after the removal of the voltage. These measurements, which are important for the repetitive operation of the switch, were done by applying two identical voltage pulses, with a variable time delay between them, to the sample while measuring the current. It was found that when the second pulse was applied the onset time was much shorter than that measured for the first pulse. In fact, it normally took more than a 1-s delay between pulses for the sample current to show the same temporal development as the first pulse at room temperature. This effect was investigated by Brodovoi *et al.* [20] who found that for SI GaAs:Cr material at 77 K, the material did not return to its initial resistivity for 2 to 3 h after the voltage was removed. However, if the temperature was raised back up to room temperature, or the sample was illuminated with infrared radiation of 0.3–0.5 eV, the sample again became highly resistive. These results strongly indicate that carrier trapping and emission in the bulk of the material determines the recovery behavior of the switch.

IV. Influence of Electron Irradiation on the Dark Current

Similar to optically activated semi-insulating GaAs switches [21], the activation source strongly influences the temporal development of the dark current after the source is terminated. This influence was studied by means of an electron beam as an activation source. The electron beam used in these experiments was produced by a pulsed thermionic diode [22]. The energy of the electrons was about 150 keV and the current density was about 30 mA/cm^2. The pulse width of the beam was 15 μs.

The effect of electron-beam pre-irradiation on the time development of the dark current was first measured using the hard-tube circuit as a voltage source for the GaAs switch. For these measurements the voltage across the switch was held nearly constant by the circuit as shown in Fig. 7. In Fig. 7(a) the temporal development of the dark current without electron-beam irradiation is shown, while in Fig. 7(b) the effect of electron-beam irradiation occurring about 1.7 ms after the voltage was applied is shown. During the electron-beam pulse, the sample current reaches a value which is far above the scale and the sample voltage drops. After irradiation the sample voltage returns back to a value slightly less than what was initially applied and the current settles back to a value which is about 30% greater than that seen at the same time in Fig. 7(a). When the current immediately after electron-beam irradiation in Fig. 7(b) is compared to the sample current, at the same time, in Fig. 7(a), it becomes clear that by irradiating the sample, the onset time of the sample current is reduced.

A second set of experiments were conducted using the circuit shown in Fig. 2 where the sample was irradiated through the cathode contact with an electron-beam pulse which was terminated during the first half of the 15-μs voltage pulse. As with the previous measurements, this experiment was also done to measure the dark current after electron-beam irradiation although at elevated-current levels. In the circuit shown in Fig. 2, the 15-Ω PFN load

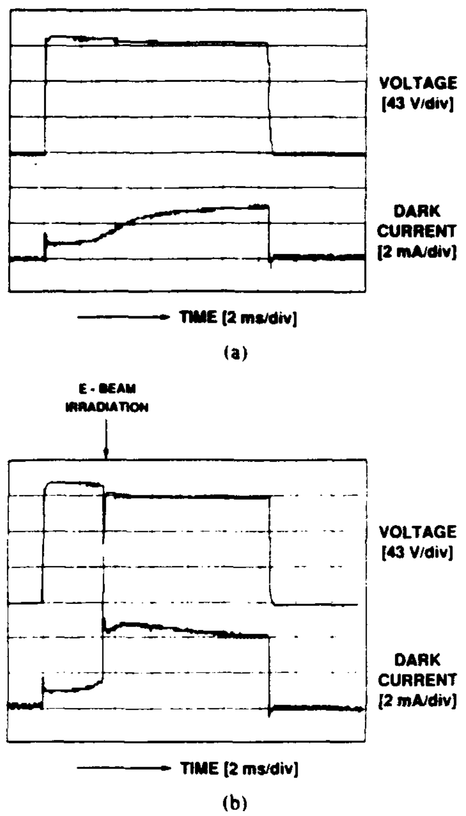

Fig. 7. Temporal development of the switch dark current (a) without electron-beam irradiation and (b) with electron-beam irradiation occurring at the point indicated.

resistance is used to provide a constant voltage across the series combination of the 50-Ω load and the sample. For these high-current measurements, as the resistance of the sample dropped, the voltage necessary to sustain the current would remain across the sample while the sample current was limited by the 50-Ω load resistance.

The results of this experiment are shown in Fig. 8 where the sample voltage is shown in Fig. 8(a) and the sample current in Fig. 8(b). During the first half of the voltage pulse, when the electron beam is turned on, the sample voltage is at a minimum (shown in Fig. 8(a)) while the corresponding current is high. At the time when the electron-beam irradiation is terminated, at 15 μs, an increase in the sample voltage occurs along with a decrease in the sample current.

The most interesting result in Fig. 8(a) is that after the termination of the electron beam, the sample voltage does not return to the initial applied voltage but rather to a value which appears to be independent of that initial voltage. The sample current, on the other hand, returns to a value which is roughly proportional to the initially applied voltage. The I–V values for this state are plotted in Fig. 9 as diamonds. The sample voltage shows up as a vertical line in the I–V characteristics indicating a current-independent voltage at an electric field of about 3.7 kV/cm. This voltage "lock-on" is very similar to the results obtained after GaAs samples are irradiated with a high-power laser [9].

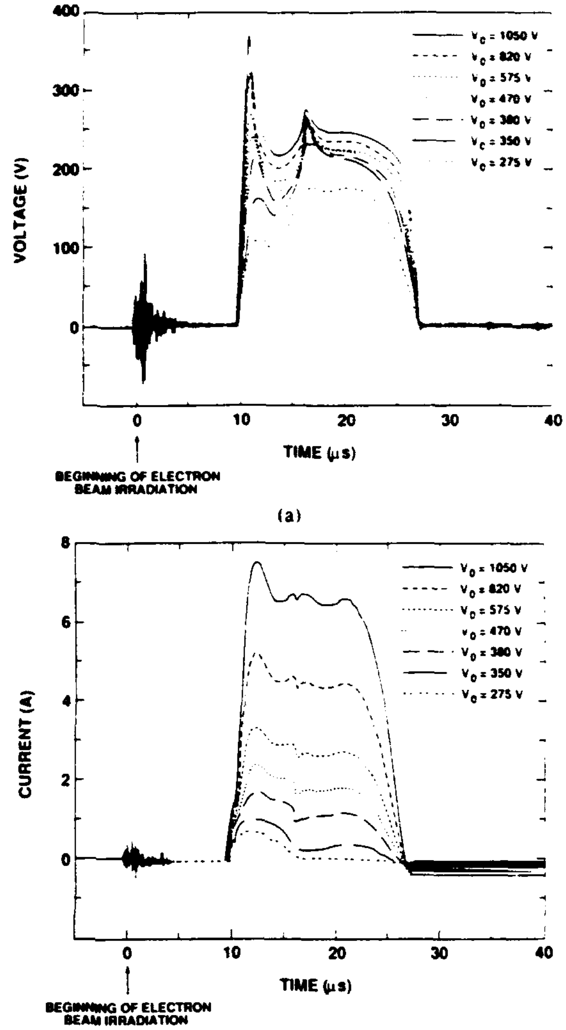

Fig. 8. Recovery of the switch voltage (a) and current (b) following the termination of the electron-beam pulse.

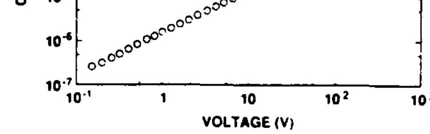

Fig. 9. Dark current density versus applied voltage for semi-insulating GaAs. Diamonds indicate current and voltage measured after the electron-beam irradiation as shown in Fig. 8.

V. Discussion

The results shown in Fig. 1 illustrate the low-voltage dc I–V characteristics of the SI GaAs material that was investigated. The material resistivities that are usually quoted in the literature for high-power, solid-state switches, made from both SI GaAs and high-resistivity Si, correspond to the linear portion of the dc I–V characteristics. The values in the ohmic range, however, only characterize the material up to field strengths of several kilovolts per centimeter the value where the slope changes in the dc I–V characteristics (i.e., 1.54 kV/cm at 24°C for the $6 \times 10^6\ \Omega \cdot$ cm material used in this study). The value of this critical electric field depends strongly on the deep-level configuration of the material and increases with the recombination rate coefficient, which is a function of the number of recombination centers and the electron and hole trapping cross sections. However, even when the SI GaAs was compensated with chromium to resistivities greater than $1 \times 10^8\ \Omega \cdot$ cm, the V_{TFL} was only increased by a factor of two (i.e., $V_{TFL} = 160$ V or an electric field of 2.54 kV/cm) [12]. The fact that a sharp break occurs in the I–V characteristics must be considered when a high-power, solid-state switch is to be designed using the bulk properties of the semiconductor material. This is particularly true if the switch is to hold off a substantial dc voltage.

The steady-state-current values are reached after an "onset time" which ranges from milliseconds down to fractions of microseconds. After a delay time, or onset time with negligible current, the current increases up to a value which appears to saturate into a $I \propto V^2$ dependence as shown in Figs. 6 and 9 using the hard-tube pulser results for voltages up to about 400 V corresponding to an average electric field of $E \approx 6$ kV/cm. Furthermore, when still higher voltages are applied, the I–V characteristics appear to go through a negative resistance excursion to a point of circuit-limited current with a nearly constant voltage across the switch as shown in Figs. 6 and 9 using the data from the circuit shown in Fig. 2.

When discussing the low-voltage I–V characteristics shown in Fig. 1, a single-carrier-injection model appears to yield a sufficient explanation. However, in order to explain the time development and the current-independent voltage characteristics shown in Fig. 3 and Fig. 9, respectively, the effects of increased hole injection must be included. For this discussion, the contacts are assumed to have infinite charge reservoirs at both the cathode and the anode. If the charge injection efficiency of the contacts is low, a transition from a bulk-limited response to a contact-limited response may occur at higher switch current densities.

In terms of charge-carrier mobility and lifetime, the properties of commercially available semi-insulating GaAs differ considerably from those of an ideal material. The deviation is mainly due to the presence of deep localized energy states within the fundamental gap which are generated by impurities and defects of the crystal structure. The properties and relative densities of these additional energy states strongly depend on the details of the material composition and the manufacturing process, so that the physical behavior of the available material exhibits a broad spectrum of variation. The following scenario, which depends on a particular distribution of the deep energy levels, might therefore be viewed as only one possible scenario among others to explain the experimental data.

The double-injection mechanism is examined for a varying-lifetime, negative-resistance problem involving an additional deep-acceptor level, which, in equilibrium, is partially occupied by electrons [23]. This deep acceptor is considered to be a "hole trap" or a level for which the cross section for hole capture (σ_p) is much greater than that for electron capture (σ_n). This discussion is concerned with the transition made in the I–V characteristics (shown in Fig. 9) from an ohmic behavior to a nearly current-independent voltage by following arguments described in [14].

At low electron and hole injection levels, the current will follow Ohm's law because both injected charge carriers are being trapped leaving the current to be carried by the thermally generated carriers. If the concentration of "empty" electron traps is assumed to be less than the concentration of "empty" hole traps, and both trap concentrations are large compared to the thermally generated carrier densities, it is reasonable to speculate that a transition will occur in the I–V characteristics at a voltage corresponding to an electron trap-filled-limit voltage (V_{ETFL}) which results from the electron lifetime (τ_n) becoming longer than the electron transit time through the bulk. The holes, however, will still not contribute appreciably to the current because the remaining empty hole traps, combined with electron–hole recombination, will serve as a "recombination barrier" causing the hole lifetime (τ_p) to be less than the hole transit time through the bulk region. After the transition at V_{ETFL}, the current should start to follow a V^2 dependence similar to a trap-free space-charge-limited current which recombines with injected holes at the anode contact [24]. In this square-law segment of the characteristic, the current is being carried by both the injected electrons (n) and the thermally induced holes (p_0), with $n \gg p_0$. As the voltage is increased, the injected electron concentration will also increase while the hole concentration (p) will remain near p_0 as a result of hole trapping.

When the voltage is high enough to drive the holes across the bulk region, a sharp increase in the current will result. This threshold voltage (V_{th}) would correspond to a value where the hole lifetime is approximately equal to the hole transit time (t_p) or

$$t_{p,th} \approx L^2/\mu_p V_{th} \approx \tau_p \tag{3}$$

where μ_p is the hole mobility. At this point, the hole trap will preferentially fill up with holes causing the hole lifetime to further increase. The result is that it will allow the switch to carry higher currents at the same voltage. The current may even increase through a negative resistance region allowing the voltage to reach a lower value. A more rigorous treatment of the carrier transport in GaAs shows that as the length of the sample increases, the L^2 dependence of the threshold voltage decreases and eventually transitions into a linear $V_{th} \propto L$ dependence [25].

The effect of the observed steep rise in current at a threshold voltage (V_{th}) could explain the lock-on effect. This effect results from the current through the semiconductor being locked to a certain voltage after a time necessary to fill the hole traps. The time to establish this condition in the bulk of the semiconductor by double injection can be shortened by optical or electron-beam injection of electron-hole pairs to such an extent that immediate "lock-on" of the dark current is observed. A theoretical treatment of this model will be published elsewhere [25].

The discussion given here and in [25] is for the case of a homogeneously distributed current in the bulk of the material. Another possible scenario may include the formation of current filaments in the bulk region. This possibility has not yet been ruled out and requires more investigation.

VI. Conclusion

Experiments have been conducted to investigate the recovery behavior of the electron-beam-controlled semiconductor switch. It was found that the switch exhibits a "lock-on" behavior similar to that found in high-power, photoconductive switches. This behavior results in unacceptably high dark currents through the switch in the off-state. A possible explanation for this effect is double injection, the process of electron and hole injection at the contacts. The I-V characteristics of the sample were measured and their implication discussed in the context of a process using electron and hole capture in the bulk region of the switch. This process of double injection combined with charge trapping at deep centers may be useful in explaining the oscillations which are sometimes measured in conjunction with the lock-on effect [9], [21], [26], [27].

The ability to understand, and control, the lock-on effect in bulk switches is necessary if these switches are to be used in high-power, high-repetition-rate systems. If double injection is, in fact, responsible for the lock-on effect, proper sample geometries should reduce the dark current down to an acceptable level. One such sample geometry would be to use a reverse-biased p^+-SI GaAs-n^+ structure. The purpose of the n^+ and p^+ regions is to greatly reduce the electric field and the minority-carrier concentrations at the contacts, thereby, minimizing any current injection into the bulk region [28]. This technique applies not only to electron-beam-controlled semiconductor devices but to photoconductive switches as well.

Given that the problem of lock-on can be overcome, the electron-beam-controlled switch concept shows great promise for use as both a closing and opening switch. The possible current gains achievable and the ability for each modulation of the switch conductance also indicate that this device would have applications in high-power modulators, inductive-energy-storage systems, and many other repetitively operated, pulsed-power systems.

Acknowledgment

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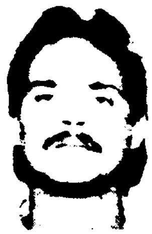

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SWITCHING PROPERTIES OF ELECTRON-BEAM CONTROLLED GaAs pin-DIODES

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Abstract - The electron-beam induced conductance and the recovery behavior of bulk GaAs switches (with ohmic contacts) was compared with pin diodes made of an identical semiconductor material and with the same dimensions. The conductance of pin diodes can be tailored to exceed that of bulk switches by more than an order of magnitude due to the enhanced cathodoluminescence in the heavily doped p-layer of the diode. The "lock-on" effect which was observed in the bulk switch and in the forward biased p-i-n switch at field strengths exceeding 9.2 kV/cm, was suppressed in the reverse biased pin diode. This result indicates that double injection of carriers through the contacts is at least in part responsible for the "lock-on" effect.

I. INTRODUCTION

The efficient conversion of electron energy into photon energy in cathodoluminescent materials makes electron-beam controlled light sources very attractive as ionization sources when applied to "photoconductive" solid state switches. By making use of cathodoluminescence, it is therefore possible to integrate the ionization source and the switch into the same device. Standard vacuum technology could allow for the design of a device where the electron beam and the switch are enclosed in the same vacuum tube, making a compact and economic switch design possible. Switching by means of cathodoluminescence offers an additional advantage, compared to laser switching, in the possibility to modulate the ionization source easily, eg. to generate pulse trains with variable duty cycles or pulse shapes which allow temporal matching of the load to the power source.

An obstacle to using electron-beam and optically controlled switches as modulators or opening switches is the so-called "lock-on" effect. This effect describes a photoconductive or electron-beam controlled switch as unable to recover to its initial high hold-off voltage after the termination of the ionization source. This type of switch is ideal as a closing switch, where a short pulse could trigger the closure, rather than having to sustain the ionization source. The "lock-on" effect however presents a problem to the opening switch, where the duration of the source should exactly determine the closure of the switch. Experiments have shown that it is possible to suppress the "lock-on" effect and obtain an electron-beam controlled opening switch.

II. CONCEPT OF THE SWITCH

By irradiating a bulk semiconductor sample with a high energy electron beam, a large number of free charge carriers is generated by both direct and indirect ionization processes. This concept of switch activation has been applied to semi-insulating GaAs as the switch material [1], [2]. The semiconductor is already a good cathodoluminescent material, but its conversion efficiency (light intensity/electron-beam intensity) can be improved by doping with high concentrations of shallow acceptors or donors. Zinc-doped GaAs was chosen because at high doping concentrations it is seen that the bandgap is reduced compared to semi-insulating GaAs [3]. This will result in a lower emission peak, hence the light generated will penetrate deeper into the material and ionize larger volumes.

The switch is supposed to open after termination of the ionizing source, the e-beam. However, at voltages, corresponding typically to electric fields above 4 kV/cm, the photocurrent continues to flow, which is detrimental to the opening of both photoconductive and electron-beam controlled switches. This so-called "lock_on" effect is assumed to be due to double injection of electrons and holes and to trap filling processes [4]. If double injection can be prevented, it should therefore be possible to suppress the "lock-on" effect. To test this hypothesis, a p-i-n structure was used. The device, shown in Figure 1, consists of a bulk slab of semi-insulating GaAs, with n and p-type epitaxial layers grown on opposite sides. The zinc-doped cathode region (zone I) is used to provide efficient cathodoluminescence. The anode (zone III) is silicon-doped and completes the p-i-n structure. Both layers are 20 μm, which are very thin compared to the 600 μm bulk zone II thickness. Metal is then deposited and annealed to both sides of the device to form ohmic contacts.

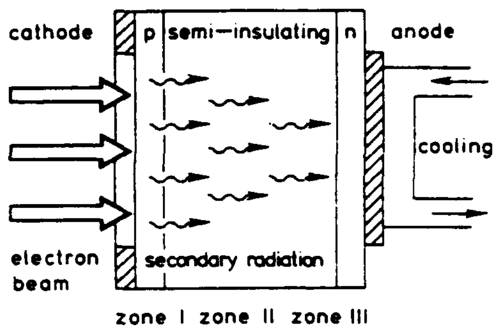

Fig. 1. Schematic representation of the proposed device goemetry.

III. CURRENT-VOLTAGE CHARACTERISTICS

In order to study the influence of carrier injection through the contacts and its relation to the "lock-on" effect, we have compared the switching properties of a semi-insulating GaAs bulk switch with ohmic contacts with those of a p-i-n diode fabricated from an identical semiconductor material. The bulk material was as-grown GaAs with a resistivity of 6×10^6 Ω·cm.

First, the dark current response (without electron-beam irradiation) to an applied DC voltage was measured. The dynamics of the dark current occur in the intrinsic region of the device, hence zones I and III only serve as injecting or blocking contacts depending on the bias. The normal mode of the switch device will be under reversed bias conditions, hence the extrinsic regions will be blocking contacts to minority carriers. It is therefore expected that the reverse biased switch would have a much higher hold-off voltage than the forward biased, limited by the breakdown voltage of the material. Experimentally, however, only a factor of two increase in hold-off voltage was found, as seen in Figure 2.

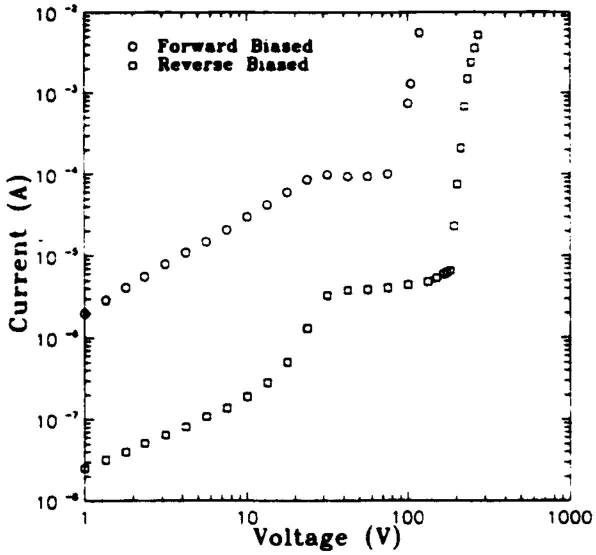

Fig. 2. DC current-voltage characteristics of forward and reverse biased p-i-n switch structure.

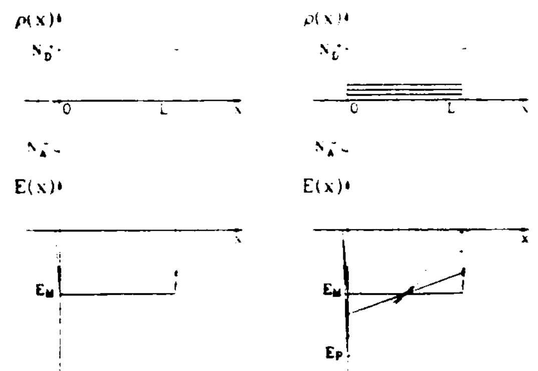

Fig. 3. Charge density and electric field profile for reverse biased p-i-n switch at a) time of charge sweep out and b) time after charge sweep out.

An analysis showed that a high DC hold-off voltage cannot be achieved with such a system. Initially, the device is in thermodynamic equilibrium, thus $n = n_o$ and $p = p_o$. There are four trap assisted processes that occur within the bulk material between various energy levels. These processes are 1) electron capture from the conduction band to a deep level, 2) electron emission from a trap level to the conduction band, 3) hole capture from the valence band, and 4) hole emission from the trap. In equilibrium, these processes balance each other.

In the phase where a reversed bias is applied to the device, the mobile carriers are swept out of the intrinsic region, creating a depletion region over the entire zone II. In addition to this depletion zone, space charge regions are created in zones I and III. In the p-type region, the removal of positive charges creates a negative space charge of ions with a density N_A^- equal to the initial doping concentration in the region. A similar positive space charge is created in the n-type region with a density N_D^+. The time of the charges to be swept out is given by the sample length divided by the field-dependent drift velocity of the charges. The current due to this sweep out of both types of charge carriers for the material used in our experiments is on the order of 3 - 4 μA.

Since the charge densities of the small depletion layers in zones I and III are much larger than the background charge in zone II, the junctions can be treated as one-sided abrupt junctions. The junctions are abrupt because the extrinsic regions are epitaxial layers rather than diffused or implanted layers. The electric field is the spatial integral of the charge density, and since the background charge is very small and can be neglected, the electric field is constant over the intrinsic region. Figure 3a shows the charge density and electric field profile.

After the depletion regions have been created, the electron and hole capture terms will no longer be present since the mobile charges previously located in the conduction and valence bands have been swept out. The emission terms due to background charges in deep levels will still however be present. The most likely case is that the electron and hole emission cross-sections are not equal, causing a build-up of the charge carrier with the smaller cross-section. This build-up of charge then begins to alter the electric field. The background charge also continually becomes larger in zone II. As seen in Figure 3b the electric field changes from the initial case ($E=E_M$) to and even beyond the case where $E(x=L)=0$, where the peak value is $E_P=2E_M$. As the electric field further reduces at x=L below E=0, charges begin to move back into the intrinsic region, effectively shortening zone II.

This effect takes a certain amount of time to occur, which is determined by the cross-sections and emission rates. By shortening zone II, this effect will lower the steady state hold-off voltage of the device. Experimental results indicate that this effect takes on the order of milliseconds to occur. Therefore, if a pulsed bias is applied, with a pulse shorter than the time of this effect, the problem can be overcome.

In order to prove this theory, the current-voltage characteristics were studied under pulsed conditions, using an applied voltage with a pulse width of 30 μs. The forward biased switch displayed a hold-off voltage of 260 V. This is a larger value than the DC hold-off value, which can be expected due to the dark current onset time [4]. In reverse bias, the switch held off more than 960 V which corresponds to an electric field of 17 kV/cm. At this point, problems with surface flashover prevented the voltage from being increased further.

IV. ELECTRON-BEAM SWITCHING

Switching experiments were performed with an electron beam of 15 μs pulse duration, ranging in energy to about 180 keV. This energy corresponds to a penetration depth of 60 - 65 μm [1]. The electron-beam current ranged up to 30 mA/cm². The sample was pulse biased with a 30 μs pulse at voltages up to 550 V, which correspond to field strengths of up to 9.2 kV/cm.

For the forward biased switch it is expected that the "lock-on" effect should become evident at about the same voltage as the bulk GaAs switch that doesn't utilize the p-i-n geometry. It is, however, expected that the switch conductance for the p-i-n structure should increase due to more efficient cathodoluminescence. The switch conductance for the bulk GaAs switch was 2.3×10^{-2} S/cm². The forward biased p-i-n diode displayed a switch conductance of 4.5×10^{-2} S/cm². The "lock-on" effect was observed for the bulk GaAs switch and the forward biased p-i-n switch for applied voltages above 170 V, corresponding to field strengths of 2.8 kV/cm.

Under reverse bias conditions, the conductance was slightly less than for forward bias, however, the "lock-on" effect disappeared completely. The switch displayed a completely open behavior after the termination of the electron beam, up to applied fields of 9.2 kV/cm where surface flashover presented a further increase in voltage. Figure 4 shows the temporal development of the pulsed voltage across the switch. The electron beam irradiated

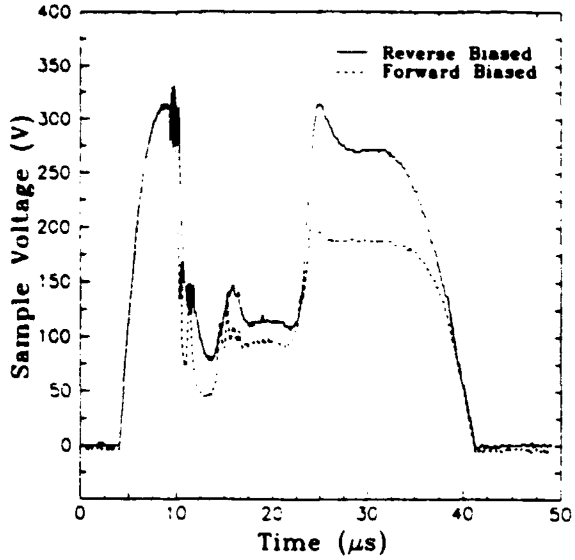

Fig. 4. The temporal development of the pulsed voltage across the switch. The e-beam hit the switch at about 10 μs for a duration of 15 μs.

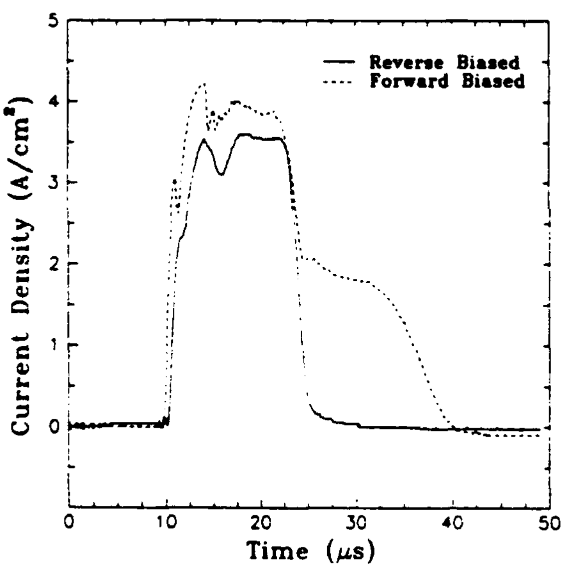

Fig. 5. The temporal development of the switch current. The e-beam hit the switch at about 10 μs for a duration of 15 μs.

the switch at about 10 μs for a duration of 15 μs. The figure shows a forward and reverse applied voltage of 320 V with all other parameters the same. It is seen that the forward biased switch recovers to a "lock-on" voltage rather than the initial hold-off voltage. Figure 5 shows the corresponding switch current. The reversed bias switch opens completely, opposed to the forward biased switch which locks on to some non-zero current. At the highest applied field of 9.2 kV/cm, the current gain (switch current/e-beam current) is about 540.

V. DISCUSSION

Although the tested p-i-n structure only displayed a factor of two increase in conductance compared to the bulk GaAs device, by optimizing geometry and doping of the zinc-doped cathode region, it should be possible to increase this efficiency by one or two orders of magnitude. The two parameters that can be altered are 1) the doping density, and 2) the thickness of the doped region. For the experiments performed here, the zinc-doped layer had a concentration of 7 x 10^{19} cm^{-3} carriers and was 20 μm thick. The electron beam deposited energy over a range of 60 μm. This is an approximate factor of three increase that could be gained by matching the electron penetration depth (electron energy) to the thickness of the doped layer. It is seen by extrapolating curve 1 of Figure 6 that for a doping concentration of 7 x 10^{19} cm^{-3} the internal quantum efficiency drops below 10%. This is more than a factor of 10 decrease from a concentration of 10^{18} cm^{-3}. By optimizing both parameters, it should therefore be possible to increase the conductance of the p-i-n switch to more than a factor of 60 above the bulk GaAs switch. By studying the curves of Cusano [3] for emission peak and Garbuzov [5] for internal quantum efficiency, it appears that the optimum range for doping concentration of the zinc-doped layer is from 5 x 10^{18} cm^{-3} to 1 x 10^{19} cm^{-3}.

The experimental results are in accordance, qualitatively and quantitatively, with results of a model developed by Brinkmann *et al.* [4]. It was demonstrated that a) the switch efficiency (power switched/control power) can be optimized by proper doping of the cathode face of the switch and that b) the "lock-on" effect which prevents opening of photoconductive GaAs switches can be suppressed by preventing double-injection of electrons and holes through the contacts.

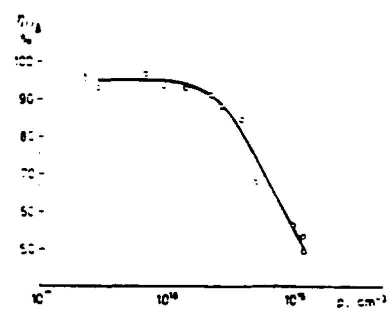

Fig. 6. Internal quantum efficiency in p-materials. (After D.Z. Garbuzov, [5])

ACKNOWLEDGEMENTS

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ELECTRON-BEAM CONTROLLED SWITCHING WITH WIDE BANDGAP SEMICONDUCTORS

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Abstract

Wide bandgap semiconductors are discussed as materials for electron-beam controlled semiconductor switches. Based on a figure of merit which allows to compare materials with different carrier mobility, dielectric strength, and ionization energy, gallium arsenide (GaAs), zinc selenide (ZnSe) and diamond are identified as the most promising materials for high-power electron-beam switching. A mathematical model is presented which allows the calculation of both the steady-state current voltage characteristics and the transient response of these switches to an electron-beam. The results of the simulation and switching experiments with GaAs, ZnSe, and diamond indicate that an electron-beam switching of wide bandgap semiconductors offers and attractive alternative to conventional photoconductive switching.

Introduction

Over the last decade photoconductive semiconductor switches have become serious competitors to more conventional high power switches, such as spark gaps and thyratrons. The increasing interest of the pulse power community in these switches is mainly due to their jitterfree operation with optical isolation of the trigger, and their switching speed, which is limited only by the optical trigger speed [1]. Generally nanosecond or picosecond lasers are used as trigger sources or to sustain the photoconductivity.

Less common is the use of electron-beams as control sources for bulk semiconductor switches, although there are some distict advantages of using electron-beams versus lasers to ionize the semiconductor. Electron beam generators are generally less expensive and have a simpler design than lasers at comparable power levels. The wall-plug efficiency, when used in conjunction with a semiconductor switch, is higher than that of most solid state lasers, and comparable to semiconductor lasers [2]. High speed operation in the subpicosecond range is possible [3]. Further, the use of electron-beams as drivers for semiconductor switches operated in the linear mode, allows to generate pulse trains with variabe duty cycles or pulse shapes. Repetition rates of MHz in a burst mode can be achieved this way [4]. And, any semiconductor material, independent of the bandgap can be switched with the same electron-beam gun.

There are basically three modes of operation for such an electron beam controlled semiconductor switch, namely:

- generation of an electron-hole plasma in the entire bulk of the semiconductor by electron-beam ionization only,
- generation of an electron-hole plasma in the contact area, with switch closure by space charge limited flow to the opposite contact, and
- generation of an electron-hole plasma in the entire bulk by means of secondary ionization due to cathodoluminescence radiation.

The applicability of the first method, the direct beam ionization of the active medium, is restricted by the high electron energies which are required for reasonable switch dimensions. For example, in order to penetrate switch samples of one millimeter thickness, electrons in the MeV range are needed. The maximal beam energy is not only limited by obvious practical considerations but also by the fact that over-energetic electrons will degrade the semiconductor by inducing irreversible damage to the crystal structure. For GaAs this damage threshold is at about 230 keV, which corresponds to a penetration depth of just about 100 µm. Only for materials with extremely high dielectric strength, direct electron-beam ionization will allow to switch high voltages with reasonable electron-beam energies. Diamond, for example, has a dielectric strength of over 1 MV/cm, so that even with thin films in the tens of micrometer range voltages of several kV can be switched.

The second concept forms the basis of the so-called Electron-Bombarded Semiconductor (EBS) devices [5] which rely on the generation of an electron-hole plasma close to the negatively biased contact. Due to the high field in the separation zone, the electrons are quickly swept across the switch towards the anode, the (generally less mobile) holes recombine in the cathode and provide merely the continuity of the current. EBS-devices have a response speed which is only constrained by the time the electrons need to get from cathode to anode and which can be in the nanosecond range. Their conductance, however, is limited by space charge effects so that high voltages are needed to obtain sufficient current densities. For an 0.5 mm thick GaAs switch, e.g., biased at 100 V, the maximum current density that can be obtained is 0.4 A/cm^2 [6].

In the following we will focus mainly on the third and most promising approach to electron-beam controlled high voltage, direct semiconductor switches. This concept [6], which is based on utilizing the secondary ionization effects of cathodoluminescence radiation, avoids current limitations due to space charge effects and enables the realization of switches with high on-state conductance. Figure 1 shows the principal configuration of such a switch, consisting of a sample of compensated direct semiconductor material with ohmic contacts at the opposing sides. In the dark state, the electron and hole densities in the bulk have their intrinsic values and the switch shows a high resistivity. Under e-beam irradiation, the incident electrons are stopped within a shallow layer at the cathode, and their energy is utilized for the generation of electron-hole pairs. Due to the high carrier density and the fact that the material is a direct semiconductor, a substantial part of the electron-hole pairs recombines radiatively under emission of band-edge photons which then penetrate deeper into the bulk and ionize also the remainder of the crystal. Obviously, the main mechanism of energy transport into the active region is not of electronic but of radiative nature, so that we may characterize this kind of configuration as an optically controlled semiconductor switch with integrated radiation source.

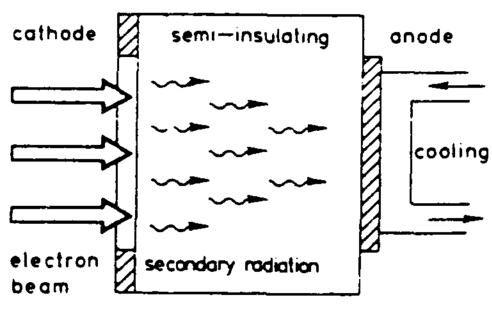

Figure 1. Schematic representation of the proposed device geometry.

The following part of this paper is organized as follows: In the next sections, we give a short review of the current state of the electron-beam generating devices, and analyze the requirements for a semiconductor to be suitable as a high power, electron-beam controlled switch. We will then present a mathematical model which allows to simulate these electron-beam controlled switches both under steady state and transient conditions, and finally discuss the strengths and limitations of electron-beam controlled semiconductor switches in pulsed power circuits.

Electron-Beam Considerations

Electron beams with power densities comparable to that of high power lasers are routinely used for laser excitation and microwave generation. Most of these high current electron sources utilize field emission from felt emitters as the electron generation mechanism. Current densities of several hundred A/cm^2 can be obtained [7], at the expense, however, of limited pulse duration due to diode closure. Diode closure is caused by plasma formation at the anode which closes the diode gap in typical times of microseconds.

A special type of field emission cathode is the "Spindt" cathode [8]. It consists of an array of micrometer size field emission devices. The conducting silicon base supports up to 5000 Molybdenum cones per mm^2. With dc currents of 10 to 500 µA per cone, the achievable current density is in the range of severals tens of A/cm^2. These cathodes can be driven by voltages in the range of 50 to 150 V [9].

A new method for high current cold electron generation is based on the ejection of electron from prepoled ferroelectric samples [10]. By applying an electrical field across a ferroelectric sample, the material is polarized with surface charge densities reaching 100 µC/cm^2, which are compensated by charge carriers injected through the contacts. When a fast rising electric field of opposite polarity is applied, the polarization of the ferroelectric sample is reversed and the surface charge is ejected. Electron-beam current densities of greater than 100 A/cm^2 were obtained with PLZT ceramics. In other experiments [11], regular electron emission from ferroelectric samples was observed at repetition rates of up to 2 MHz, showing that the recovery of the emitting sample may occur in less than one microsecond.

In order to obtain electron-beam pulses in the subnanosecond range, laser driven diodes must be used. The electron generation in such diodes can be either based on thermionic emission or on the photoelectric effect. For instance, electron-beam pulses of 10 ps duration in excess of 1 kA/cm^2 were generated by irradiating metal surfaces with picosecond, 266 nm laser pulses (12). The highest quantum efficiency obtained was 7.25 x 10^{-4} with samarium photocathodes. For applications were lower electron-beam currents are required, photocathodes with quantum efficiencies exceeding 0.1 are available (13).

The most common cathodes in electron-beam diodes are thermionic emitters. Compared to field emitting cathodes using felts, they offer the advantage of decoupling electron generation (cathode temperature) and acceleration (applied field) with in principle unlimited pulse length. The generation of pulse trains is possible by using a triode or tetrode configuration. In a tetrode with thoriated tungsten electrodes, multiple electron-beam pulses with current densities of up to 4 A/cm^2 were obtained [4]. With dispenser type thermionic cathodes, values of 300 A/cm^2 were reached [14].

Material Considerations

The right choice of the semiconductor material is of essential importance for the electron-beam controlled switches. It is clear that this performance will not depend on one single but rather on a combination of several material parameters; the following quantities are obviously of importance:

- **Dielectric strength** [E_d]. The quantity E_d denotes the characteristic electrical field strength of a material above which carrier multiplication due to impact ionization leads to dielectrical breakdown. A higher E_d is obviously of advantage because it allows to decrease the thickness of a switch for a given hold-off voltage V_{ho}. In tendency, the dielectric strength is an increasing function of the band gap energy E_g. Experimental data suggest that the breakdown field scales with $E_g^{3/2}$ (15). Based on theoretical considerations one can also expect a (roughly logarithmic) dependence of E_d on the trap density in the material.

- **Effective Ionization Energy** [ξ_{ion}]. The effective ionization energy ξ_{ion} of a semiconductor is the average kinetic energy that a beam electron looses per electron-hole pair generation event. Experimental data [16] suggest that it is dependent on the bandgap energy in the form $\xi_{ion} = 2.1\ E_g + 1.3$ eV. About one third to one half of the electron energy is used for electron-hole pair generation, the rest is converted into kinetic energy of the free charge carriers and quickly dissipated.

- **Cathodoluminescence yield**. We define the cathodoluminescence yield in an indirectly ionized semiconductor switch as the ratio of secondary electrons generated by bandedge radiation to the number of primary electrons generated by the e-beam. Up to a scale invariant geometry factor k (which measures the fraction of photons absorbed in the "right place"), it is identical to the internal quantum efficiency η_{int}, i.e., the percentage of radiative among all recombination events. This number can vary by several orders of magnitude for different materials. For very pure direct semiconductors, or semiconductors doped with a high concentration of shallow donors or acceptors, it can reach values close to one [17]; for less pure materials or for indirect semiconductors it is considerably lower.

- **Carrier mobility** [µ]. For a given carrier density, the conductivity of a semiconductor is directly proportional to the mobility µ of the free charge carriers. For electrons, being usually the more mobile species, this number can vary within a wide range, from several hundred cm^2/Vs to several thousand cm^2/Vs for semiconductors of interest for switch applications. Unfortunately, the mobility is generally lower for higher band gap energies and breakdown voltages.

- **Mean carrier lifetime** [τ]. Immediately after irradiation onset, the conductance of an e-beam controlled switch increases linearly with time as free charge carriers are generated. The increase levels off to a steady state when the carrier generation reaches a balance with the recombination losses. For a given e-beam power, the dc conductance of a switch is obviously proportional to the mean free carrier lifetime τ. That means that there is a trade-off between efficiency and speed in photoconductive and electron-beam controlled semiconductor switches.

It is clear that the performance of electron-beam controlled semiconductor switches is influenced by all these parameters simultaneously. For a quantitative comparison of different materials, however, it is necessary to define a figure of merit which combines all parameters into one single (and meaningful!) number. We start to derive such a number of expressing the conductance per area of an ionized switch in the usual way as a function of the mobility µ, the carrier density n and the thickness L,

$$G = e\mu n/L. \tag{1}$$

Under steady state conditions, the value of n is given by the product of the beam power P_b and the carrier life time, τ, divided by the mean ionization energy ξ_{ion} and the switch thickness L. For indirectly ionized switches, it contains also the cathodoluminescence efficiency $k\eta_{int}$ as a factor. The conductance per area is thus

$$G = \begin{cases} \dfrac{e\mu P_b \tau}{\xi_{ion} L^2} & \textit{for directly ionized switches,} \\[2ex] \dfrac{e\mu k\eta_{int} P_b \tau}{\xi_{ion} L^2} & \textit{for indirectly ionized switches.} \end{cases} \tag{2}$$

The efficiency of a switch increases obviously with decreasing thickness. For a fixed hold-off voltage, the minimal (and optimal) value of L is given by the dielectric strength to $L = V_{so}/E_d$, so that the maximal switch conductance can be written as the product of external parameters and an material factor, $G = P_s/V_{so}^2 \times Q$. It seems reasonable to define this material factor as the figure of merit for the semiconductor in electron-beam controlled switches.

$$Q = \begin{cases} \dfrac{e\mu\tau E_d^2}{\xi_{ion}} & \textit{for directly ionized switches,} \\ \dfrac{e\mu\tau\eta_{ce}E_d^2}{\xi_{ion}} & \textit{for indirectly ionized switches.} \end{cases} \qquad (3)$$

If we neglect the saturation of the carrier mobility for higher electrical fields, we can give a very illustrative meaning to this number: For constant conductance, the current density through the switch at V_{so} is $j = GV_{so} = Q \times P_b/V_{so}$, so that Q can be interpreted as the ratio between the switch power P_s and the controlling beam power P_b, i.e., as the (formal) power gain of the material.

The following table shows a compilation of material data and the figure of merit for the three materials which seem to be most promising for electron-beam controlled semiconductor switches, namely gallium arsenide (GaAs), zinc selenide (ZnSe), and diamond. The values for silicon (Si), another common photoconductive switch material also is given for comparison. The maximal voltage up to which the switch concept is feasable, is calculated as the product of the dielectric strength and the penetration depth of the electron beam at the radiation damage threshold (for silicon and diamond), or with the typical range of the band edge radiation (for GaAs and ZnSe).

The numbers in the table indicate that diamond is the most suitable of the listed semiconductor materials for direct beam-ionization. Due to its extremely high dielectric strength even thin films of several ten's of µm thickness can be utilized as electron-beam switches in pulse power circuits. On the other hand, in order to operate at high power gain the thickness cannot exceed the penetration depth of the high energy electrons in the electron-beam. For electrons with an energy of 100 keV this depth is about 40 µm, corresponding to a maximum switch voltage of 12 kV.

For switches operating with indirect ionization (conversion of electron energy into photon energy), gallium arsenide and zinc selenide are very promising materials. Both are direct semiconductors with high dielectric strength and a high electron mobility: especially what mobility concerns, they outperform any other direct semiconductor material. Diamond, although it has a high electron mobility, cannot be used in this mode of operation because of its small quantum efficiency due to its nature as an indirect semiconductor.

From the three materials which seem to be the most promising for electron beam controlled switching, only gallium arsenide has found greater interest so far, having the advantage of a relatively low price and a well established manufacturing technology. Zinc selenide on the other hand allows us to extend the voltage range over that of GaAs: in the case of dc bias, as will be shown, this is an order of magnitude effect. And diamond, in the form of thin films could, due to its high power gain and the excellent thermal properties play an important role for high repetition rate switching at moderate power and voltage levels [18]. In the following section we discuss briefly some experimental studies performed on these three materials.

Experimental Results

In order to characterize the three materials with respect to their use in electron-beam controlled switches dark current measurements over an extended range of voltages and currents and measurements of the electron-beam induced conductance as a function of the beam intensity and the applied voltage have been performed. At the two direct semiconductor materials, GaAs and ZnSe, we have studied the concept of secondary beam ionization (via cathodoluminescence radiation) by testing samples which were considerably thicker than the e-beam penetration length (0.5 mm and 1 mm, respectively). Thin (1µm) diamond films with a thickness less than the electron range have been employed to investigate the direct ionization mode. To obtain comparable results, we have restricted ourselves to materials with about the same mean free carrier lifetime, all samples having a τ of less than 1 ns. (For GaAs this means that we have used material with a chromium doping of about 10^{17} cm^{-3}, denoted GaAs:Cr.)

The results of the dc-dark current measurements are shown in Figure 2. Generally, as it is shown for GaAs:Cr and ZnSe, the samples showed a linear (ohmic) behavior at low voltages. The extent of the linear range value of the corresponding resistance is related to the bandgap energy. The unusually high conductance measured for the diamond sample is probably due to its very small thickness of only 1 µm. An order-of-magnitude estimate shows that the current in this regime is carried by diffusion rather than by drift. This effect should become negligible for diamond films with large thicknesses, for such samples we expect resistivities well above 10^{10} Ω cm.

The diagram also shows that the current rises drastically over the ohmic regime once the voltage is increased above a critical threshold value V_{cr} which varies from material to material (and even from sample to sample). This transition to a low resistivity has the appearance of dielectric breakdown, a comparison with Table I below, however, shows that it occurs at electrical fields much below the listed dielectric strength.

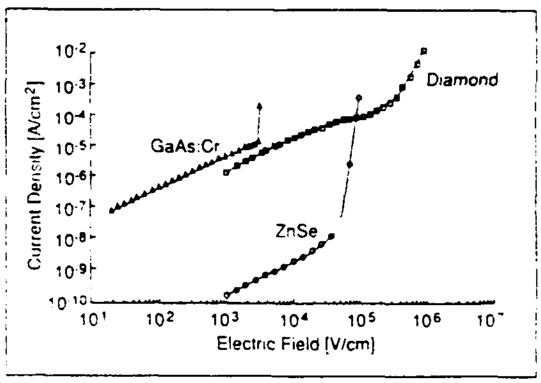

Figure 2. The dark current characteristics for GaAs:Cr, ZnSe, and Diamond.

Table I.

Material	$E_g[eV]$	μ_e[cm²/Vs]	μ_h[cm²/Vs]	E_d[V/cm]	ξ_{ion}[eV]	eV_d[keV]	Q/η	V_{max}[kV]
Si	1.12	1500	450	$3\cdot10^5$	3.7	250...350	$4.7\cdot10^4$	5
GaAs	1.42	8500	400	$4\cdot10^5$	4.3	~ 230	$3.3\cdot10^5$	400
ZnSe	2.7	500	30	$1\cdot10^6$	7.0	~ 230	$7.5\cdot10^4$	1000
Diamond	5.47	1800	1200	$3\cdot10^6$	12.8	150...350	2.1·10[illegible]	30

This characteristic behavior poses a severe limitation on the dc operation of electron-beam (and photoconductively) controlled semiconductor switches. it is obviously not possible to apply a higher voltage than V_{cr} at the contacts for an unlimited time. In other words, the dc hold-off voltage of these devices may be considerably lower than the value $L \times E_d$ assumed in the order of magnitudes estimation presented above.

Transient measurements which were mainly performed on semi-insulating GaAs (19), on the other hand, showed that for short pulse applications it is possible to achieve hold-off voltages that exceed V_{cr} considerably. The current density stayed initially very close to the value expected from extrapolating Ohm's law, only after a characteristic delay time it increased and rose finally to the much higher dc value (Fig. 3). The measured delay time was observed to be a strong function of the applied voltage, it was in the order of ms for voltages just above V_{cr} and was considerably shorter at higher voltages. (See Figure 4.)

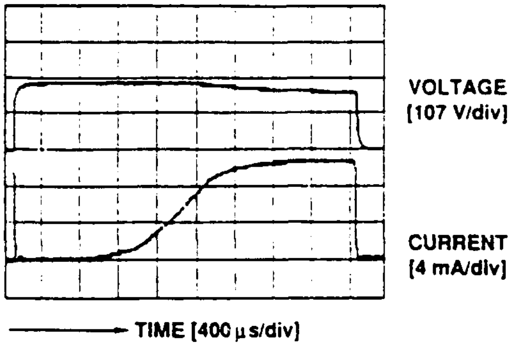

Figure 3. Temporal development of the switch dark current in semi-insulating GaAs.

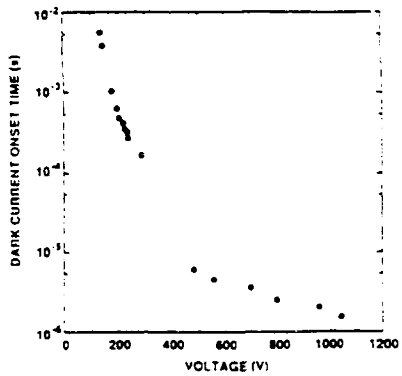

Figure 4. Dark current "onset" time versus applied voltage.

The experiments with an electron beam applied (of 100 to 150 keV energy and current densities of up to 30 mA/cm^2, however, revealed that even for pulse applications the critical voltage V_{cr} has it significance: At applied voltages below the value of V_{cr} (Figure 5a), the switch current and switch voltage followed the sustaining electron-beam pulse, that means the voltage recovered completely after turn-off of the e-beam and the current approached zero. For applied voltages above V_{cr} (Figure 5b), however, the current did not return to zero, and the voltage recovered only partially and stayed constant for the duration of the applied PFN pulse. This behavior which was observed previously is known as lock-on effect. Figure 6 (20) summarizes these results in current voltage curves for the dark condition, for electron-beam ionization, and for the phase following the termination of the e-beam. At voltages above V_{cr}, the lock-on and the dark current curve seem to be almost identical and both are merging with the electron-beam controlled current at higher voltages.

Similar switching experiments as with GaAs have been performed with different samples of ZnSe For poly-crystalline material, the measured power gain was far below the expected value as listed in Table I, an effect that we blame on the poor quantum efficiency due to increased non-radiative recombination at the grain boundaries. For mono-crystalline samples, the results were much better and more in accordance with the expectations. Doping of the material with shallow donors or acceptors, a concept which was successfully applied to GaAs (2), should increase the quantum efficiency even further. Also in ZnSe, we have observed the lock-on effect.

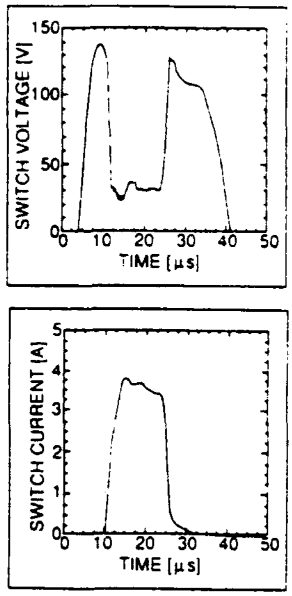

Figure 5. (a) Switch voltage and switch current for switch operation in the linear mode.

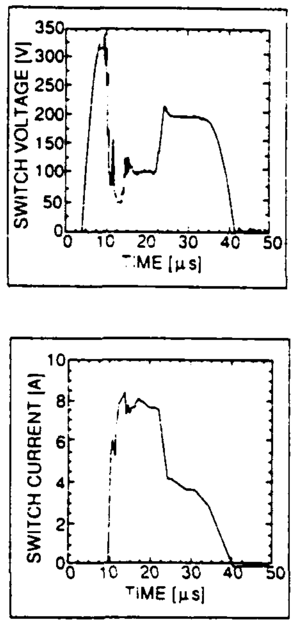

Figure 5. (b) Switch voltage and switch current for switch operation in the lock-on mode.

Thin diamond films of 1 μm thickness showed the expected results in the switching experiments; again the lock-on effect was observed. We believe that the matching of film thickness to electron penetration depth will make diamond electron-beam controlled switches extremely efficient for applications which require to switch voltages in the kV-range.

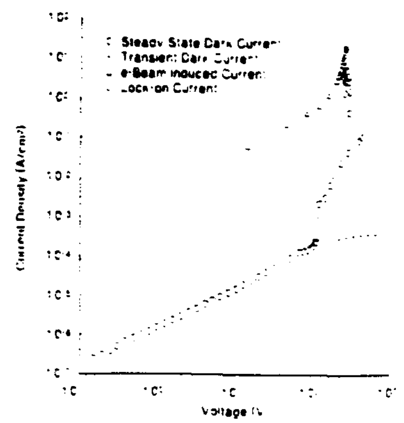

Figure 6. The steady-state dark current, the transient dark current, the lock-on current, and the current under electron-beam irradiation versus applied voltage.

Modeling of the Switches

To gain a better understanding of the behavior of electron-beam controlled switches both under steady state and transient conditions, it is instructive to confront the experimental results of the last chapter with the outcome of a mathematical simulation. Although our currently employed switch model is not yet realistic enough to allow quantitive predictions, mainly because of the poor knowledge of several essential material parameters, it is nonetheless able to provide qualitative insight into the operation principles of the switches. In particular, it can account for the breakdown-like behavior of the devices at electrical fields considerably below the dielectric strength, and it can give a plausible explanation for the lock-on effect.

For the following, we consider a switch sample with an area of A = 1 cm^2 and a thickness of L = 0.5mm, connected to a voltage source as depicted in Figure 7. We describe the electron and hole transport in the device with a set of one-dimensional equations that include the generation of free charge carriers through radiative, thermal or impact ionization, their transport under the influence of the electrical field, and their recombination or trapping in intraband levels; we also allow for charge carrier injection at the contacts. The number of electrons in the conduction band and the number of holes in the valence band are denoted by n and p, respectively, and the densities of the various deep levels by N_i and their relative occupation number by r_i. To be specific, we consider a "generic" GaAs-like material with three deep levels, namely a dominating recombination center in the middle of the band gap, and two additional levels in 0.3 eV distance from the conduction and the valence band which act as electron and hole traps. The mean free carrier lifetimes are 1.2 ns for the electrons and 3.5 ns for the holes, and the dielectric strength is 215 kV/cm.

$$\frac{\partial n}{\partial t} + \frac{\partial}{\partial x}\left(v_n(E)n - D_n\frac{\partial n}{\partial x}\right) = S + \dot{n}_{cv} + \sum_i N_i \dot{r}_{ci} , \quad (4)$$

$$\frac{\partial n}{\partial t} - \frac{\partial}{\partial x}\left(v_p(E)p - D_p\frac{\partial p}{\partial x}\right) = S + \dot{n}_{cv} + \sum_i N_i \dot{r}_{vi} , \quad (5)$$

$$\frac{\partial r_i}{\partial t} = \dot{r}_{vi} - \dot{r}_{ci} . \quad (6)$$

In these expressions, v_n and v_p stand for the field dependent carrier drift velocities, D_n and D_p are the diffusion coefficients. The terms on the right hand side denote the balances of direct recombination, thermal pair generation and impact ionization (n_{cv}), trapping and thermal release of electrons or holes (r_{ci} and r_{vi}), and the carrier generation due to the external source (S). The description is supplemented with Poisson's equation connecting the electric field E to the excess charge in the crystal, the quantities N_d, ε_0 and ε_r stand for the effective shallow doping density, the absolute and the relative dielectric constant, respectively

$$\varepsilon_0\varepsilon_r\frac{\partial E}{\partial x} = e\left(n - p + \sum_i N_i r_i + N_d\right) . \quad (7)$$

For the completion of the system, we assume ideal injection conditions at both contacts, i.e., we require $E|_0 = E|_L = 0$ in addition to the voltage condition $\int_0^L E dx = V$.

These assumptions - which have first been introduced by Lampert [21] - express the fact that the overall voltage drop across the switch is dominated by the highly resistive semi-insulating bulk material, they also lead to a satisfactory phenomenological description of the current injection through the contacts at higher applied voltages.

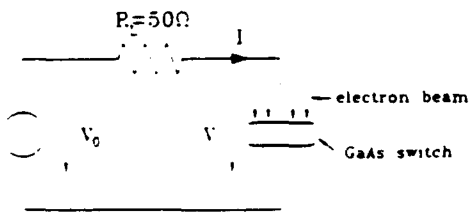

Figure 7. Schematic representation of an electron-beam-controlled switch connected to an external load circuit of 50-

The Steady-State Characteristics

To calculate the steady state I-V curves of the switches, we have employed a numerical code which solves (1) to (5) iteratively on the basis of a modified shooting scheme. (See reference [22] for a more extensive discussion of our method.) An investigation of several different cases has demonstrated that the quantitative details of the current-voltage curves depend strongly on the physical parameters of the simulation, especially on the density and the trapping cross sections of the deep levels in the material. A detailed cartography of this multi-dimensional parameter space is beyond the scope of the current work; we will instead base the following analysis on the "generic" configuration introduced above and discuss the influence of possible parameter variations only qualitatively.

The results of our dark current simulation agree qualitatively very well with the measured values (Fig. 2). For low voltages, V < 200 V, the I-V-curve exhibits a linear ohmic behavior with $j = e(\mu_n n_{eq} + \mu_p P_{eq})V/L = G_0 V$, with the conductivity being determined by the carrier concentrations in the thermodynamic equilibrium. For higher voltages, 200 V < V < 2 kV, deviations from this relation arise which are due to the saturation of the drift velocities at higher electrical fields, but the current voltage curve is still monotonic. At about 2 kV (the critical voltage V_c), however, the current slope begins steeply to rise over several orders of magnitude, and bends even slightly back to lower voltages.

Theory and experiment coincide in that the numerical value of the critical voltage V_{cr} is considerably lower than what one would expect from a simple calculation on the basis of the dielectric strength, $V_{cr} \approx LE_d \approx$ 10 kV. A detailed investigation of the field configuration at different voltages [22] has revealed the cause of this apparent contradiction: The steep increase of the current at V_{cr} is not at all related to the usual dielectric breakdown, i.e. to impact ionization and avalanche multiplication in the bulk, but rather to the injection of charge carriers through the contacts and the subsequent formation of an electron-hole plasma. The existence of the voltage threshold results from the fact that small amounts of injected charge carriers are quickly trapped in the vicinity of the contacts so that they cannot contribute to the conductance (which remains determined by the equilibrium carrier concentration). At higher injection levels, however, the deep traps become essentially filled, and the effective lifetime of the charge carriers increases considerably. (In the considered generic material, this increase amounts to a factor of four for the electrons, and a factor of two for the holes). Consequently, the concentration of charge carriers in the conductive bands also goes up and leads to a drastic current increase at constant or even reduced forward voltages.

Our scenario is independently confirmed by the already mentioned observation that the quantitative and qualitative characteristics of the I-V curves depend strongly on the details of the deep level structure of the material. In particular, the value of the critical voltage can be considerably higher for a semiconductor with a higher concentration of recombination centers, i.e., with a shorter free carrier lifetime τ. In suitably (for instance, strongly chromium) doped material, V_{cr} can even be increased up to the value given by the dielectric strength (which then, of course, sets a limit to further improvement).

We calculated for our sample configuration also the current-voltage curves under electron-beam irradiation, assuming a constant source function for the sake of simplicity. At low fields, the relation between the voltage and the current is approximately linear and can be described by a conductance G, $j = e(\mu_n n + \mu_p p)V/L = G(S)V$. Under higher stress, however, deviations from the linear slope become significant, and a the critical voltage the I-V-curves increase non-linearly due to charge carrier injection until they merge with the dark current curve.

The Transient Behavior of the Switches

A deeper analysis of the modeling results obtained so far reveals that they are not only able to explain the quasi-breakdown at fields below E_c, but can also give a plausible scenario for the transient behavior of the switches: If the high current above V_{cr} is related to increased carrier lifetimes because of filled traps, then it is clear that this state cannot be reached instantaneously. Immediately after the application of the voltage, the traps are still in their equilibrium occupation state, i.e., they can still trap the injection charges from the valence and conduction band and maintain the high resistivity of the material. It is only after a relatively slow evolution during which the traps are filled by the injected charges that the current can assume its higher dc value. Obviously, this temporal development can be accelerated considerably if the charges necessary to fill the traps are not only injected from the contacts but also directly generated in the bulk: An order of magnitude estimation shows that a reasonably strong external source function can shorten the trap filling time down to the ns range.

Consider now the linear I-V-diagram in Figure 8, where we have schematically drawn the three different I-V-curves discussed above, namely a) the transient dark-current I-V-curve that is valid during the onset time, b) the steady state dark-current which is reached in the time asymptotic limit, c)and the current-voltage characteristic of GaAs under electron-beam irradiation. Imagine two switching experiments with the circuit depicted in Figure 7, i.e., with the same load resistor R, but different initial voltages V_0. The corresponding load lines I and II are drawn in Figure 8.

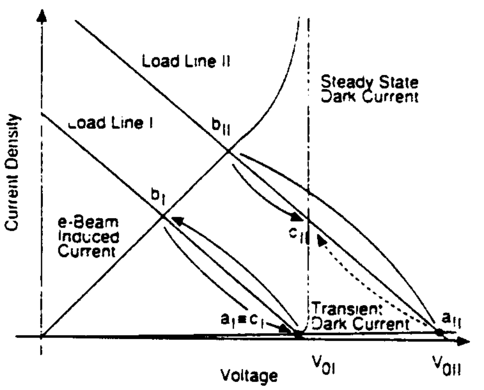

Figure 8. Schematic switching cycles in a load-line diagram for two different applied voltages. Cycle I shows no lock-on current; in cycle II, the current locks on at point c_{II}.

In the first experiment, the switch starts in the resistive off-state at point a_I where the current is low and the voltage is very close to the voltage V_{0I}. Under irradiation with the beam, the switch becomes quickly ionized and the load point moves tot he low resistivity regime b_I, the on-state of the switch. After turn-off of the beam, the charge carriers recombine and the switch moves to the point c_I, which is identical with the point a_I. It is clear that this case does not exhibit a lock-on effect.

In the second experiment, the load line II corresponds to a source voltage V_{0II} that lies over the critical value V_{cr}. In the initial off-state, the load point is located at a_{II}, i.e., in the transient state with a small electrical current. The load point begins to move along the load line, but according to our argumentation above, this time development is rather slow and might take a time that is long compared to the duration of the applied pulse. Under irradiation with the electron beam, however, the load point moves very quickly to b_{II}, i.e. to the on-state with a high current and a small voltage. Due to the high carrier density generated by the e-beam, the traps will be filled very quickly. Now, after the turn-off of the beam, the load point will not return to the initial value b_{II} but rather to the steady state value c_{II}, with a considerably higher current, the lock-on current.

To demonstrate this conjected behavior of the switch explicitly, we have implemented the dynamical equations on the basis of a specially adapted transient scheme. Our code, which combines a Lagrangian treatment of the free electrons and holes with an Eulerian description of the trapped charges, eliminates virtually all errors due to spurious numerical diffusion and ensures a satisfactory accuracy even for a relatively small number (220) of discretization points.

Figure 9a and 9b shows a synopsis of a typical simulation run, i.e., the applied voltage V_0, the voltage across the switch V (Fig. 9a), and the current density j (Fig. 9b) as a function of the elapsed time t. The system starts $t = 0$ from the thermodynamic equilibrium, i.e., from the state with no voltage and source function applied. First, the applied voltage is increased within about 10 ns to a value 4 keV, to which the switch responds with the dielectric displacement current. After the final voltage has been reached, the current dies rapidly down and the system settles down to a highly resistive state. A comparison with the I-V-characteristics in Figure 6, however, shows that because of $V_0 < V_C$ this state does not correspond to a true equilibrium, but rather to an intermediary phase which still evolves on comparatively long time scale.

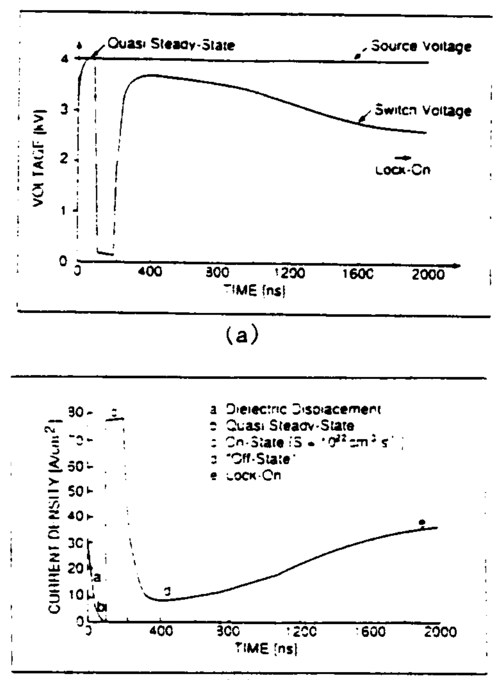

Figure 9. The temporal development of switch voltage (a) and current density (b) in an electron beam control GaAs switch.

After 100 ns, we apply for a time span of 100 ns a source function of $S = 10^{22}\ cm^{-3}cm^{-1}$. The system reacts within a few ns by increasing the conductivity drastically. The current jumps nearly to the maximal value of 80 A determined by the external circuit, and the voltage across the switch breaks down to about hundred volts. At the same time, the deep levels trap charges form the conduction and valence band, respectively, so that at the end of the 100 ns the electron trap is about half filled, and the hole trap to about 5%.

After the source function has been switched off again, the remaining traps in the band gap absorb most of the charge carriers of the conduction bands, such that resistivity of the bulk increases and the current density drops to less than 10%. The initially highly resistive state, however, is not completely recovered, the system exhibits instead a slow rise of the current density due to the continuing filling of the traps by injected charges, and finally relaxes into the true equilibrium, the lock-on state.

In the light of these results, what is now the significance of the figure of merit Q, the so-called power gain? Clearly, as defined above, it is strictly applicable only for switches where the hold-off voltage is close to the value given by the dielectric strength, i.e., where the effect of current is negligible. This is the case either for samples that have a sufficient concentration of recombination centers, or in situations where the electrical stress is applied merely for a short time before the electron beam irradiation starts. In other cases, the power gain will lose its strict meaning, but we can still view it as a heuristic tool to obtain a first idea of the suitability of different materials.

Discussion

The concept of electron-beam controlled semiconductor switches is based on the generation of free charge carriers in a semi-insulating semiconductor sample by ionizing it with a high-energy electron-beam. Based on an expression which combines the relevant parameters of a material to one dimensionless figure of merit, the maximal power gain Q, we have concluded that three different semiconductor materials are singled out with respect to their performance in e-beam controlled switches: For the concept of direct beam ionization, it is diamond which seems to be the most promising material. In the form of thin films of up to about 100 μm thickness, diamond switches can withstand voltages of up to 5 kV for dc operation and 30 kV in pulse charged systems. Combined with their good thermal properties which enables high repetition rate operation this is reason enough to expect a bright future for diamond based electron-beam switches in the control of low to moderate power densities.

For higher electrical stress, the concept of indirect bulk ionization with cathodoluminescence is more appropriate. Our investigations have shown that two materials are particularly promising, namely the direct semiconductor materials of GaAs and ZnSe. Due to their nature as direct semiconductors, both materials have a high conversion factor of beam energy into photons and allows therefore the control of semiconductor bulk switches of up to several mm thickness.

The particular advantages of electron-beam controlled semiconductor switches are other types of photoconductive switches are:

- Due to the possibly small volume and low cost of high-intensity electron beam guns based on standard vacuum technology, compact and economic designs of e-beam controlled switch systems are possible.
- Photocathode emitters offer possibilities for generating electron-beam pulses with very short pulse duration.
- Because of the strong influence of the deep traps on the switch behavior in both the steady state an the transient case, a tailoring of the material to maximize the performance is possible.
- Any semiconductor switch, independent of the bandgap, can be ionized.
- Especially promising is that the concept does not allow for fast and repetitive opening and closing cycles but also for the use as a linear power modulator controlled by the electron-beam current. The closed switch behaves very similar to an externally controlled ohmic resistor as long as the applied electrical fields are moderate; the current density is essentially proportional to the forward voltage drop and can reach up to thousand times the value of the controlling electron-beam current.

Our discussion would not be complete without mentioning also the negative aspects of electron-beam controlled switches. Most of these drawbacks are problems that they share with the other types of photoconductive switches, such as the occurrence of the lock-on effect and the possibility of thermal breakdown. It is, as many post-mortem investigations indicate, in particular the formation current filaments and the related inhomogeneity in the energy dissipation which can lead to local overheating and a catastrophic device failure. It is not yet completely clear if (or how) the filamentation is related to the lock-on effect, possibly it is due to a symmetry-breaking instability caused from the negative differential conductivity discussed above, or it is the consequence of thermal runaway. There is however, one possible problem which is indigenous only to the concept of indirectly ionized e-beam controlled switches: Due to the fact that only about one third of its kinetic energy is converted into band edge radiation, the e-beam irradiation causes a considerable energy dissipation in a thin layer close to the semiconductor surface. While the overall contribution of energy to the total dissipation is relatively small, it is its concentration on the small conversion layer which can lead to considerable local overheating.

Some of the named limitations of electron-beam controlled semiconductor switches can be overcome by pulse charging the power system. Since the filling of the electron and hole traps requires a certain time, the transition into the trap-filled state can be extended to higher fields if the pulse duration of the applied voltage and with it the number of injected charges is reduced. For very short pulses and a sufficient density of deep traps, the critical voltage V_c can approach the breakdown field of the semiconductor as listed in Table I. That means for fast pulse charged systems, GaAs could be almost as efficient as diamond and even surpass ZnSe.

The effect of trap filling on switch resistance and consequently on the maximum applicable voltage is demonstrated in Figure 10 which show the computed current voltage characteristics of semi-insulating GaAs. It covers the range from ohmic behavior at low voltages through the range where deep traps determine the dark current up to the onset of dielectric breakdown through impact ionization. Initially, in the ohmic range, most of the charge carriers that are injected from the contacts will become trapped in electron or hole traps which have a relative high density in semi-insulating gallium arsenide, to the effect that free carrier densities remain very low during the onset time. It is only after the traps are completely filled that the current can rise to a higher value. The necessary time span can be considerable if only charges injected through the contacts are available to fill the traps. However, for short pulses it is possible to stay in the regime where traps are not completely filled even at high voltages. Then it is possible to extend the switch voltage range to the value of the dielectric breakdown voltage, which can be orders of magnitude above the dc trap filled voltage.

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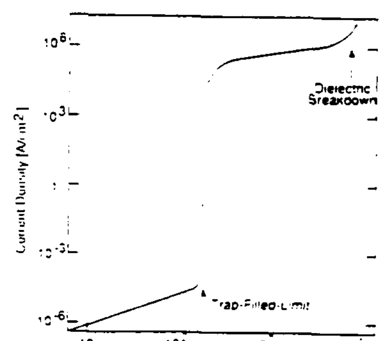

Figure 10. Dark current characteristics of semi-insulating GaAs.

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The Lock-On Effect in Electron-Beam-Controlled Gallium Arsenide Switches

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***Abstract*—The term "lock-on effect" describes the inability of photoconductive or electron-beam-controlled semiconductor switches to recover to their initial hold-off voltage following the application of the laser or electron-beam pulse, if the applied voltage exceeds a certain value. For GaAs, this threshold voltage corresponds to average electric fields in the range from 4 to 12 kV/cm. Experimental results on semi-insulating GaAs switches indicate that the corresponding lock-on current after e-beam irradiation is identical with the steady-state dark current. The highly resistive state of the switch before e-beam irradiation is shown to be a transient phase towards the much lower steady-state dark resistance, with a duration which depends on the impurity content of the switch material and the applied voltage. The irradiation of the GaAs samples with electrons or photons causes an acceleration of this temporal evolution; at sufficiently high laser or e-beam intensities "lock-on" of the dark current after termination of the driving ionization source is observed. Based on the experimental results, a model is developed which describes the lock-on effect in terms of double injection and carrier trapping in deep intraband levels. The model explains the major characteristics of the lock-on effect and is supported by the qualitative agreement of the calculated current–voltage curves with the experimental data.**

I. Introduction

Attempts to utilize electron-beam-controlled semiconductor switches have already been made in the 1960's [1] and the 1970's [2], but only recently research in this field has gained new momentum due to an improved concept [3], [4]. This switch concept is based on the generation of free charge carriers in the bulk of a semi-insulating semiconductor such as gallium arsenide (GaAs) by cathodoluminescence. Once the electron-beam is terminated, the switch will open due to electron–hole recombination and trapping of free carriers on a time scale of nanoseconds or less if the current injected through the contacts into the bulk of the switch is negligible [5]. With the observed linear dependence of the switch current on the electron-beam current in an electric field range up to about 4 kV/cm [3], these devices promise also to be useful for the modulation of the electrical power into a temporally varying load. The modulation of electron-beam currents can easily be achieved with gated vacuum tubes which makes compact and economic switched designs possible.

An obstacle for the use of the GaAs switches as opening switches or modulators in high-voltage systems, however, is the so called "lock-on" effect which determines the device behavior when the initially applied voltage V_0 is greater than a certain critical value V_{cr}. This effect is manifested by the inability of

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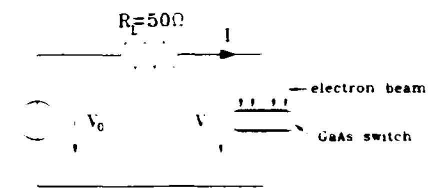

Fig. 1. Schematic representation of an electron-beam-controlled switch connected to an external load circuit of 50-Ω impedance.

the switch to recover to its initial hold-off voltage following the application of an electron-beam or laser pulse; after turn-off of the driving source the voltage is "locked-on" to a constant value corresponding to an average electric field strength in the range from 4 to 12 kV/cm [6], [7].

The effect of "lock-on" on the voltages and current curves of a switching cycle is shown schematically in Fig. 2 (case $V_0 > V_{cr}$) in comparison to a cycle without lock-on (case $V_0 < V_{cr}$); Fig. 1 shows schematically the corresponding external circuit. In both cases, the switch is initially in a highly resistive state with $V \approx V_0$ and the dark current is very small. Due to the electron-beam excitation the switch then turns on, i.e., the switch voltage collapses and the current reaches a value which is determined by the e-beam-generated conductance and by the external circuit. After the termination of the electron-beam, however, it is only in the case of $V_0 < V_{cr}$ that the voltage recovers to its initial value V_0 and the current returns to the small dark current value. In the case of $V_0 > V_{cr}$, the voltage does not recover completely, but settles on a value $V_{lo} < V_0$, the lock-on voltage. The name lock-on indicates that this voltage is virtually independent of the current, a characteristics which has been compared to that of a Zener diode.

II. Experiments

In order to study the lock-on effect we have concentrated semi-insulating GaAs as the switch material. Particularly for the experimental investigations, as-grown (EL2-compensated) material with a resistivity of $6 \times 10^6\ \Omega \cdot$ cm was used. The sample geometry consisted of a bulk region with aligned parallel-plate contacts. The thickness of the bulk was 0.065 cm, the area of the contacts about 1.1 cm^2. The contacts were manufactured by thermally depositing a Au(88%)-Ge(12%) alloy to a thickness of 100 nm. The sample was then annealed at 450°C in N_2 at atmospheric pressure for a period of 15 min.

A set of experiments [8] was conducted where the GaAs sample was irradiated through the cathode contact with an electron-beam pulse of 15-μs duration as schematically shown in Fig. 1. The electron-beam was produced by a pulsed thermionic diode.

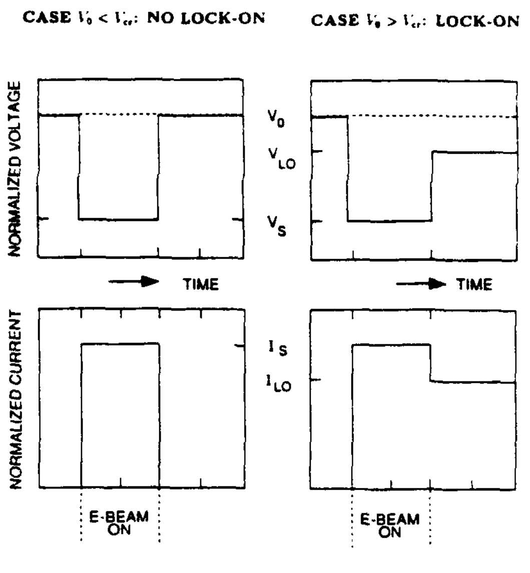

Fig. 2. Schematic illustration of switching cycles without and with the lock-on effect ($V_0 < V_{cr}$ and $V_0 > V_{cr}$, respectively).

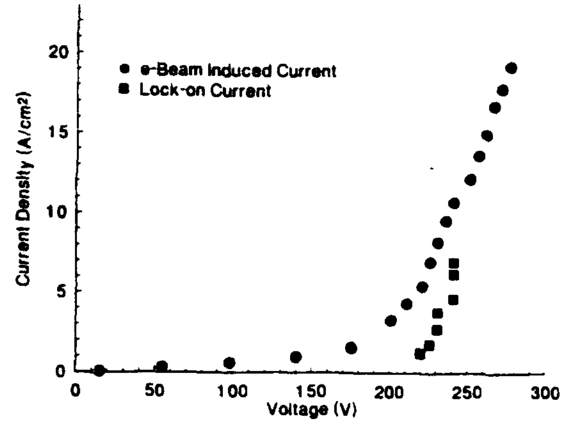

Fig. 3. The current-voltage characteristics of the GaAs switch under electron-beam irradiation (circles) and in lock-on phase (squares). The electron beam current density was 20 mA/cm^2.

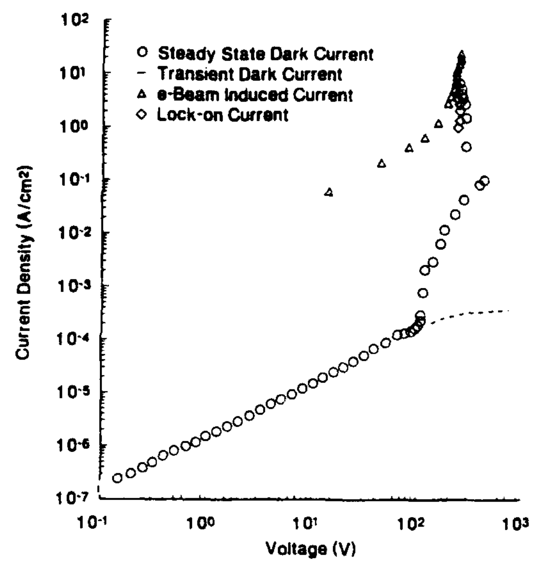

Fig. 4. The steady-state dark current, the transient dark current, the lock-on current, and the current under electron-beam irradiation versus applied voltage.

The energy of the electrons was about 150 keV and the e-beam current density was in the range of up to 30 mA/cm^2.

The results of the current-voltage measurements which are described in more detail in [8] are shown in Fig. 3. The current density in the on-state (during electron-beam irradiation) increases linearly with voltage up to about 200 V which corresponds to an average field intensity of 3 kV/cm. Above this voltage the current density rises steeply to values greater than 20 A/cm^2. In that regime the sample does not return to the initial applied voltage after termination of the electron beam but rather to a value which appears to be almost independent of the initial conditions [8]. The values of this "lock-on" current are plotted in the same diagram (Fig. 3) as squares. The lock-on onset occurs at an average electrical field of about 4 kV/cm and rises very steeply, i.e., the voltage is almost independent of the current. When chromium-doped semi-insulating GaAs was used, the critical field was found to be higher by a factor of two compared to the lock-on field of as-grown GaAs. The effect is very similar to the results obtained on GaAs samples irradiated with a high-power laser [6], [7], where it was also found that the value of the lock-on field depends on the impurity content of the switch material.

In the on-state, an increase of the electron-beam current causes a nearly linear increase in the switch current. The amplitude of the lock-on current, however, does not seem to be dependent on the intensity of the previous e-beam irradiation. The lock-on current is therefore determined only by material-dependent transport processes occurring at high fields; in our opinion it is actually the steady-state dark current of the device. In order to prove this concept, dark current measurements on semi-insulating GaAs were performed with applied voltages of up to 1000 V, corresponding to average fields of up to 15 kV/cm. Fig. 4 shows the steady-state current obtained with both the dc and the pulsed bias measurements at room temperature [8]. There is a steep increase in current over four orders of magnitude at about 200 V in a voltage range of several tens of volts. The current values obtained in the "lock-on" experiment (Fig. 3) are plotted for comparison with the steady-state values of the dark current; the two current curves are virtually identical. Also plotted are the I–V characteristics of the on-state, when the GaAs switch was irradiated by an electron beam.

The temporal development of the dark current was also studied [8]. It turned out that this current remains very low for an "onset time" and then increases monotonically up to a steady-state value (Fig. 5). The onset time, which is defined as the time necessary to reach a current value of 5% of the final steady-state current, is found to be a strong function of the amplitude of the applied voltage as shown in Fig. 5. Any electron-beam illumination shortly before or during the onset time shortens the transient phase drastically. In particular, by sufficiently irradiating the sample with an electron beam or laser it is possible to reduce the time necessary to reach the final value of the dark current such that the dark current then locks on immediately after the application of the voltage pulse (Fig. 6).

III. Modeling

In order to understand the experimental results outlined above, we focus now on a theoretical description of the switch configuration. We assume that the switch diameter is large com-

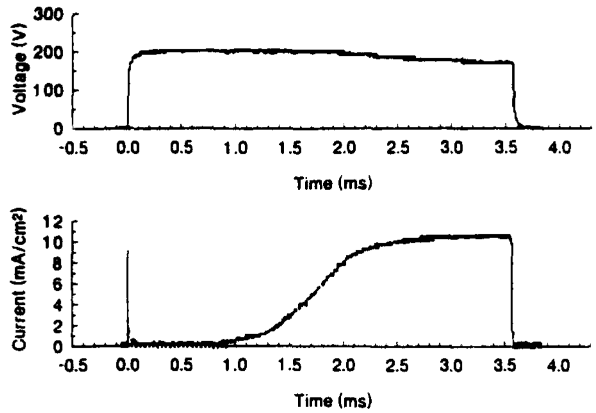

Fig. 5. The temporal evolution of the dark current with a square-pulse voltage applied [8]. The peak at $t = 0$ corresponds to the displacement current, it is followed by the transient dark current ($0 < t < 1$ ms), the onset phase current (1 ms $< t < 2.5$ ms), and by the steady-state dark current (2.5 ms $< t < 3.5$ ms).

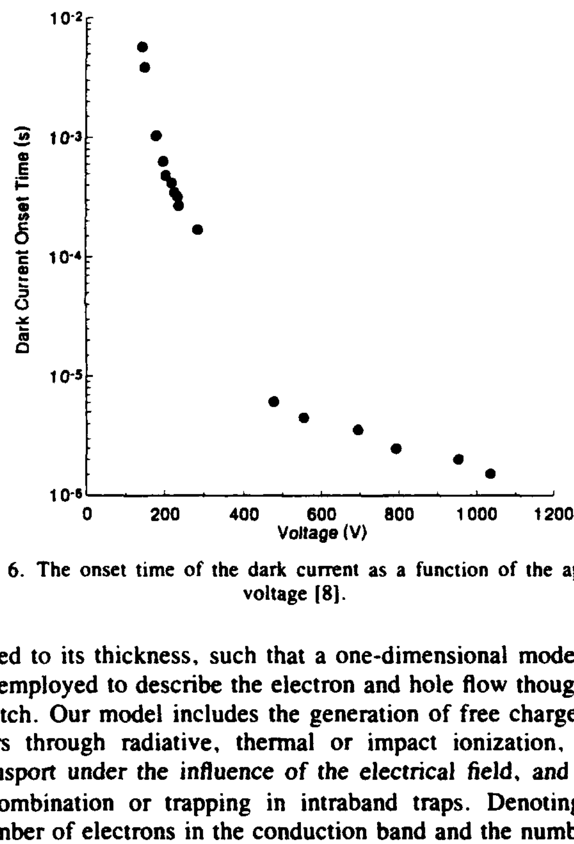

Fig. 6. The onset time of the dark current as a function of the applied voltage [8].

pared to its thickness, such that a one-dimensional model can be employed to describe the electron and hole flow though the switch. Our model includes the generation of free charge carriers through radiative, thermal or impact ionization, their transport under the influence of the electrical field, and their recombination or trapping in intraband traps. Denoting the number of electrons in the conduction band and the number of holes in the valance band by n and p, respectively, the densities of the various carrier traps by N_i, and their relative occupation number by r_i, the system of dynamical equations reads

$$\frac{\partial n}{\partial t} - \frac{\partial}{\partial x}(v_n(E)n) = \dot{n}_{cv} - \sum_i N_i \dot{r}_{ci} + S \qquad (1)$$

$$\frac{\partial p}{\partial t} + \frac{\partial}{\partial x}(v_p(E)p) = \dot{n}_{cv} \sum_i N_i \dot{r}_{vi} + S \qquad (2)$$

$$\frac{\partial r_i}{\partial t} = \dot{r}_{vi} + \dot{r}_{ci}. \qquad (3)$$

In these expressions, v_n and v_p stand for the absolute values of the field-dependent carrier drift velocities. The diffusion contributions have been neglected. The terms on the right-hand side denote the balances of direct recombination, thermal pair generation and impact ionization ($\dot{n}_{cv}$), trapping and thermal release of electrons or holes ($\dot{r}_{ci}$ and $\dot{r}_{vi}$), and the carrier generation due to the external source (S). The description is completed with Poisson's equation connecting the electrical field E to the excess charge in the crystal; the quantities N_d, ϵ_0, and ϵ_r stand for the effective shallow doping density, the absolute and the relative dielectric constant, respectively

$$\epsilon_0 \epsilon_r \frac{\partial E}{\partial x} = e\left(n - p + \sum_i N_i r_i - N_d\right). \qquad (4)$$

For the completition of the system we assume ideally ohmic conditions at both contacts, i.e., we require $E|_0 = E|_L = 0$ in addition to the voltage condition

$$\int_0^L E\,dx = V. \qquad (5)$$

These assumptions—which have been introduced first by Lampert [9]—express the fact that the overall voltage drop across the switch is dominated by the highly resistive semi-insulating bulk material; they also lead to a satisfactory phenomenological description of the current injection through the contacts.

We have developed a code which solves (1)-(4) numerically under the assumption of steady state, closely following a procedure which is more extensively discussed in [10]. An investigation of several different cases has demonstrated that the quantitative details of the resulting current-voltage curves depend strongly on the physical parameters of the simulation, especially on the density and the trapping cross section of the deep intraband traps. It is beyond the scope of this work to give a detailed carthography of the multi-dimensional parameter space of the problem, and we will instead restrict ourselves to the discussion of one simple deep-level configuration which nonetheless shows features that are typical for most types of compensated gallium arsenide and other semi-insulating materials.

Fig. 7 shows the I-V characteristics of 0.65-mm switch assuming the presence of one dominant recombination center with a density of $N = 10^{17}$ cm^{-3}, an energy of 0.85 eV above the valence band, and electron and hole capture cross sections of $\sigma_n = 2 \times 10^{-19}$ cm^2 and $\sigma_p = 5 \times 10^{-17}$ cm^2, respectively. These values have been chosen to match the dark resistance and the lock-on voltage of the sample under consideration, using a set of simple analytical expressions that will be discussed in [10]. Curve I corresponds to the dark current, curve II to the current under electron-beam irradiation. A comparison of the numerically obtained curves with the experimental results displayed in Fig. 4 shows a good agreement not just in the values of the dark current at low voltages and in the onset of the lock-on regime (which is expected from our assumptions), but also in the shape of the curves. In particular, the calculations reproduce the initially linear (ohmic) behavior of the current both in the dark and in the irradiated state, and their subsequent steep increase of nearly six orders of magnitude above the critical voltage of 200 V. The nature of this effect is extensively discussed in [10]; it is, according to our model, essentially a result of the injection of electrons and holes through the contacts (double injection) and the subsequent buildup of charges in the deep levels.

From the assumption that the strong increase in the current is due to trap filling, we can explain the relatively long onset time of the dark current before it rises to its final value. Initially,

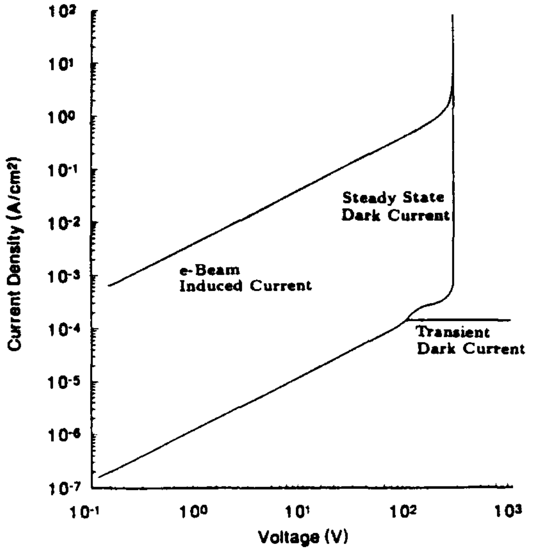

Fig. 7. The computed current-voltage curves for a 0.65-mm GaAs switch. The assumed source function of $S = 10^{17}$ $cm^{-3} \cdot s^{-1}$ corresponds to an electron-beam irradiation of 20 mA/cm^2.

most of the charge carriers that are injected from the contacts will become trapped in electron or hole traps which have a relatively high density in semi-insulating gallium arsenide, to the effect that free carrier densities remain very low during the onset time. It is only after the traps are completely filled that the current can rise to its final value. The necessary time span can be considerable if only charges injected through the contacts are available to fill the traps. Under irradiation with the electron beam or a laser, however, the onset time will be much shorter due to the large source function for electrons and holes in the bulk of the switch. More quantitatives results which are based on a transient simulation of (1)–(4) will be published elsewhere.

IV. The Lock-On Scenario

Based on the results of the numerical calculation described above, we can now establish a scenario which explains the main features of the lock-on effect. Consider the current–voltage diagram in Fig. 8, which shows schematically the three different I-V curves discussed above, namely a) the transient dark-current I-V curve that is valid during the onset time, b) the steady-state dark current which is reached in the time asymptotic limit, c) and the current-voltage characteristic of GaAs under electron-beam irradiation.

Let us consider two switching experiments with the same load resistor R, but different initial voltages V_0, characterized by the two load lines I and II in Fig. 8. In the first experiment, the switching cycle starts in the highly resistive off-state at point a_I where the current is low and the voltage is very close to the voltage V_{0I}. Under irradiation with the electron beam, the switch quickly becomes ionized and the load point moves to the low resistivity regime b_I, the on-state of the switch. After turn-off of the beam, the charge carriers recombine and the switch moves to the point c_I which is identical with the point a_I: The switch opens and does not exhibit a lock-on effect.

Next, consider the load line II with a source voltage V_{0II} that lies above the critical value V_{cr}. In the initial off-state, the load point is located at a_{II} on the transient I-V curve, the sample hence carries a relatively small current. As a_{II} is not a steady state, the load point begins to move along the load line with a time constant determined by the trap filling process (dashed

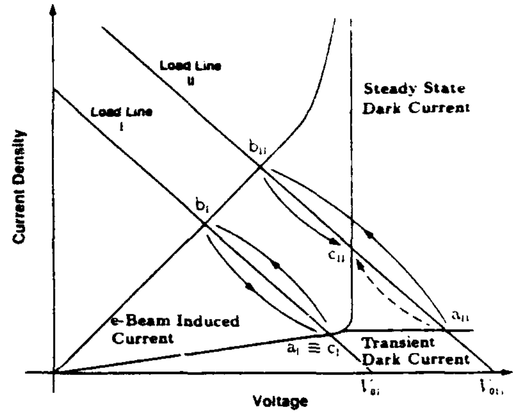

Fig. 8. Schematic switching cycles in a load-line diagram for two different applied voltages. Cycle I shows no lock-on current; in cycle II, the current locks on at point c_{II}.

line). According to our argumentation above (and the experimental curve 5), however, this temporal development is rather slow and will take a time that is long compared to the duration of the applied pulse. The situation changes when the switch is irradiated with the electron beam. The load point moves very quickly to the on-state b_{II} with a high current and a small voltage drop, and, due to the high carrier density generated by the e-beam, the traps will be filled very quickly. After the turn-off of the beam, however, the load point will not return to the initial low current value a_{II} but locks on to a higher current value c_{II}, a current which is identical with the steady-state dark current.

V. Discussion

Our experimental and theoretical investigations have established a concise scenario for the lock-on effect in ionization-controlled high-power semiconductor switches. (As the basic mechanisms that lead to lock-on are obviously independent of the actual physical source of the ionization, we expect the description to hold not only for electron-beam-controlled switches but also for devices which are optically triggered.) These are the essential features of lock-on that the model can explain:

i) The phenomenon appears only above a certain threshold value V_{cr} of the applied voltage, below V_{cr} the switch recovers after irradiation.

ii) The current–voltage relation in the lock-on state is characterized by a very low differential resistance, i.e., by a voltage which is virtually independent of the current.

iii) The lock-on characteristics are independent of the intensity of the initial electron-beam (or laser) irradiation as long as this intensity is sufficient to trigger the switch into the lock-on state during the e-beam or laser-pulse duration.

iv) The numerical value of the lock-on voltage depends crucially on the impurity content of the semiconductor which varies considerably in different materials. In particular, semiconductors with a low intrinsic impurity concentration like silicon are expected to have a very different threshold for lock-on.

v) The lock-on effect can be suppressed by using blocking contacts which prevent carrier injection into the semiconductor. These contacts can be manufactured by growing highly doped boundary layers on the surface to create a p-i-n structure for the device.

It should be emphasized, however, that the numerical calculations which we have used to illustrate our lock-on scenario are based on a very simplified deep-level structure. It is therefore not surprising that the theoretically obtained curves do not fully match the experimental data. Combinations of deep traps with various concentrations, energy levels, and cross sections can introduce rather complicated structures in the current–voltage characteristics of semi-insulating semiconductors. In particular, preliminary investigations into the subject have shown that doping of GaAs with impurities such as Cu can lead to an S-shaped "back-bending" of the *I-V* curves of the material, i.e., a current-controlled negative differential resistivity [12]. This effect might explain why some switching experiments with semiconductors that had a high concentration of deep traps have yielded hold-off voltages that were considerably higher than the corresponding lock-on values [6]. Also, it should be noted that a negative differential resistivity in a material generally leads to the onset of current filamentation, a phenomenon which has recently been related to the lock-on effect [11].

What is the practical importance of the lock-on effect? Clearly, it must be regarded as an unwanted effect for opening switches, as it prevents the recovery of electron-beam or optically controlled semiconductor switches to their initial dielectric strength following the application of the irradiation. However, it is a very desirable effect for closing switches, because it allows the circuit to be closed indefinitely by using a short trigger pulse [7]. The possibility of influencing the current-voltage characteristics of semi-insulating material through doping with deep-level impurities might therefore open ways to "tailor" materials for particular applications.

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Michael K. Kennedy (S'91), photograph and biography not available at the time of publication.

Electron–Beam Controlled Switching using Quartz and Polycrystalline ZnSe

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Abstract — **Results of electron–beam controlled switching experiments with switch samples of quartz crystal and polycrystalline zinc selenide (ZnSe) are presented. For switch samples of both materials, drastic reductions of the switch resistance were induced by the electron beam. The quartz sample showed very fast temporal response (less than 1 ns) with potential applicability for current control. The ZnSe samples, on the other hand, showed longer current transients (on the order of 10 ns) with exponential development of the switch resistance after the electron beam pulse.**

I. Introduction

Electron–beam controlled solid switches have very interesting potential applications in pulsed power technology [1]–[7]. For these switches, high power gain and fast response are the major subjects of interest.

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Electron–beam controlled switches are similar to optically controlled switches which have been developed for decades. The advantage of using an electron beam for switching control is the high efficiency of source, compact switch arrangement, pulse shaping and high repetition rate [5].

There are basically two configurations of electron–beam controlled switches [1]. In one configuration (A), the switch current flows along the surface of the switch sample in the direction perpendicular to that of electron beam. In another configuration (B), the switch current flows through the sample in the direction parallel to that of electron beam. In the second configuration, there are two modes. In one mode (B–1), free charge carriers are generated by electron beam ionization only. In another mode (B–2), free charge carriers are generated by both electron beam and secondary radiation.

For configurations A and B–2, we have selected polycrystalline zinc selenide (ZnSe) as the switch material mainly because of its low steady state dark current. Lower dark current is very important to our experimental setup where, as shown below, the charging on the switch is a DC voltage.

For configuration B–1, the thickness of the switch must be smaller than the range of electrons in the sample. That requires a high dielectric strength of the switch material. We have found that silicon dioxide (SiO_2) has both high breakdown field and high possible power gain. In order to show the switching properties of SiO_2, we have used thin quartz crystals as our switch samples for configuration B–1. More ideal, specially designed SiO_2 samples are presently being manufactured for us by an industrial company.

II. Switch Samples and Experimental Setup

The specification of our switch samples are as follows:

Sample No. 1, material: quartz crystal; switching configuration: B–1; thickness: ~80 μm; contact: ϕ 3 mm, thickness < 1 μm, Ag.

Sample No. 2, material: polycrystalline ZnSe; switching configuration: A; surface gap: length 2 mm, width 6 mm; thickness: 0.9 mm; contact: conducting epoxy.

Sample No. 3, material: polycrystalline ZnSe; switching configuration: B–2; thickness: 0.9 mm; contact: 4 mm × 2.1 mm, 0.01 μm Cr + 0.2 μm Au.

The quartz crystals we have used were originally electronic parts for frequency control with a characteristic frequency of nearly 100 MHz. The ZnSe samples were obtained from II–VI Inc., Saxonburg, PA.

The electron source (150 kV, 200 A, 2 ns) used in our experiments was a very compact electron–beam generator (Radan 1502) made by the Institute of Electrophysics, Russian Academy of Sciences. The divergence of the beam was relatively large so that the beam current density changes with the distance from the output window. Figure 1 shows the peak electron–beam current density obtained with a Faraday cup as a function of distance from the source. At each distance, the cross–sectional distribution of the electron current was observed to be uniform over the area of a switch sample.

The experimental setup is shown in Fig. 2 where Fig. 2(a) shows configuration A (sample No. 2) and Fig. 2(b) shows configuration B (samples No. 1 and 3). In order to obtain a fast current rise, the switch was set on a piece of 50 Ω stripline. Connected with the stripline was a 3 m, 50 Ω, DC charged cable which discharges when the switch turns on. The current through the switch was observed downstream with a 50 Ω terminated oscilloscope (Tektronix 7104, 1 GHz).

III. Experimental Results

Typical waveforms of the switch response to the electron beam are shown in Fig. 3 ((a) for sample No. 1 and (b) for samples No. 2 and 3). For configuration A, since the switch current density might vary with the depth, we have used the switch current instead of the current density. For configuration B, since the electron-beam current is uniform over the sample, we obtained switch current density by dividing the current with the area of the sample. It is seen from Fig. 3 that all switch samples reacted very fast (within 1 ns) when the electron beam was turned on. However, after the electron beam pulse, the switch current of each sample decayed on different time scales. The crystal sample (sample No. 1) turned off almost simultaneously with the electron beam. The polycrystalline ZnSe samples (samples No. 2 and 3), however, turned off in times on the order of 10 ns. For sample No. 2, the current collapse at about 30 ns after turning on is clearly due to the end of the voltage pulse.

Figure 4 shows the relation of (a) the peak switch current density (or peak switch current) and (b) maximum switch conductance, versus peak electron current density. The switch conductance was obtained from the switch current density (or the switch current) and the switch voltage which was obtained by subtracting twice the voltage across the termination from the charging voltage. The resistance of the termination was confirmed by measurement while the impedance of the 50 Ω cables was not confirmed directly. The errors in these impedance values may induce error in the switch conductance, especially for large switch current, since we have to calculate the difference between two large numbers to get a relatively small number of the switch voltage. From fig. 4, we see that, at low beam current density, the switch conductance rises nearly linearly with the beam current density. When the beam current density increases, however, the switch current density (or switch current) saturates at a value. This saturation might be caused by the circuit limit and the error in calculating the switch voltage. The minimum switch resistance obtained from Fig. 4 were 160 Ω, 15 Ω and 50 Ω for samples No. 1, 2 and 3, respectively.

Figure 5 shows the waveforms of the switch current density of sample No. 1 with the same electron beam current (18.8 A/cm^2) but different charging voltages. We see from Fig. 5 that higher charging voltages give faster turn-on response. Furthermore, at a voltage of 1500 V, the maximum switch current is much lower than that for the other voltages. Experimentally, no clear switch current was observed at voltages below 1000 V.

Figure 6 shows the waveforms of the normalized switch current density of sample No.3 obtained with the same charging voltage (2000 V) but different electron-beam current density. All waveforms in Fig. 6 are normalized with respect to the peak value in order to compare the shapes. It is seen from Fig. 6 that, for different electron current densities, the switch current decayed on different time scales.

We have tried to measure the steady state dark current of the switch samples. With applied voltages up to 3000 V, however, no switch current larger than 0.01 μA was observed for any sample. This result has shown that the steady state switch resistance is higher than $3 \times 10^{11}\ \Omega$. Therefore, we obtain that the switch resistance was lowered by at least nine orders of magnitude for samples No. 1 and 3 and ten orders of magnitude for sample No. 2.

IV. Discussions

A. Quartz (Sample No. 1)

With a switch sample of quartz crystal (sample No. 1), the temporal response of the switch current to the beam current shows that the mean carrier lifetime is shorter than 1 ns. This result shows that an electron–beam controlled SiO_2 switch has a very high potential to be used as a fast pulsed power switch and/or controllable high power resistor. From Fig. 4(a), we obtain that, with the peak beam current density (J_b) of 3.12 A/cm^2, the peak switch current density (J_s) was 134 A/cm^2 which corresponds to a current gain (J_s/J_b) of ~ 43. For beam current densities below this value, the current gain is nearly constant, which means that the switch current changes linearly with the electron current.

The applied voltage of 3 kV is less than 5 % of the hold–off voltage of the sample (with the dielectric strength of 9 MV/cm). Therefore, the current gain may be increased for tens of times by increasing the voltage across the sample (by raising the applied voltage or reducing other loads in the circuit). Then the power on the switch is expected to be several hundreds of times higher than the power of the electron beam. High dielectric strength and short carrier lifetime show potential applicability of a SiO_2 switch as a pulsed power amplifier.

For SiO_2 the bandgap energy is 9 eV, indicating an effective ionization energy of 20 to 25 eV. Consequently, photoconductive SiO_2 switch needs an X–ray source which is usually inefficient. With electron beam, however, it is very easy to generate electrons with enough energy to ionize SiO_2.

B. Polycrystalline ZnSe (Samples No. 2 and 3)

With switch samples of polycrystalline ZnSe (samples No. 2 and 3), the transient time of switch current shows that the mean carrier life time of ZnSe is relatively long (on the order of 10 ns). This property gives potentially high power gain of a ZnSe switch [5]. The data in Fig. 4(b) show that the maximum switch conductance of ZnSe does not depend strongly on the charging voltage.

For sample No. 2, the maximum switch current was about 17 A which corresponds to a surface current density of 28.3 A/cm. If we suppose an ionization depth of 0.1 mm, the average current density is 2.83 kA/cm^2 which is much larger than that of sample No. 3. However, it is clearly a disadvantage of sample No. 2 that the electric field is limited by possible surface flashover.

For sample No. 3, the thickness of the switch sample is obviously larger than the mean electron range which is on the order of 100 μm. Therefore, it is clear that the secondary radiation played an important role in generating the free charge carriers. The data in Fig. 4 give a maximum current gain of ~ 59. The dielectric strength of ZnSe is about 1 MV/cm, indicating an hold–off voltage of sample No. 3 of about 90 kV. With this voltage on the sample, the current gain may be expected to exceed five thousands. Then the power on the switch may be several thousands of times higher than the power of the electron beam. Furthermore, we may expect higher power gain of the switch with longer pulse of the electron beam than the average carrier lifetime of ZnSe.

After the electron–beam pulse, the decay of the carrier density in the switch is described by the following equation [6]:

$$\frac{dn}{dt} = -an^2 - bn \quad , \tag{1}$$

where a is the coefficient for direct ionization and b is the coefficient for indirect ionization.

The development of the switch resistance after the electron–beam pulse for sample No. 3 is shown in Fig. 7 (solid line), where the data were obtained with a peak electron–beam current density of 13 A/cm^2. Also shown in Fig. 7, by the dashed line, is the curve of a function:

$$\ln(Z) = A_0 + A_1 t \quad , \tag{2}$$

with A_0 = 2.85 and A_1 = 0.14, where Z and t are switch resistance and time, respectively. It is seen from Fig. 7 that the switch resistance increases almost exponentially, which indicates that the first term of the right–hand side of eq. (1) is negligible compared with the second term. Consequently, the dominant carrier loss mechanism is indirect recombination rather than direct recombination. If we neglect other effects, the carrier density n can be written as:

$$\ln\left(\frac{1}{n}\right) = \ln\left(\frac{1}{n_0}\right) + bt' \quad , \tag{3}$$

where t' and n_0 are time relative to the end of the electron–beam pulse and the carrier density at $t' = 0$. For Fig. 7, we have obtained $b = 1.4 \times 10^8$, $n_0 = 1.2 \times 10^{14}$ and the efficiency for generation of carriers by secondary radiation $\eta = 8.3 \times 10^{-4}$. We have used the carrier mobility $\mu = 900$ cm^2/Vs [8].

By comparing the experimental results of ZnSe and that of GaAs [3]–[5], we have found that ZnSe is advantageous in higher hold–off voltage, lower steady–state dark current and possibly higher power gain.

ACKNOWLEDGMENT

We would like to thank L. L. Hatfield and E. Loree of Texas Tech University for their help throughout this work. We would also like to thank A. Guenther of Sandia National Laboratory for his comments and suggestions. This work received support from Japanese Society for Promotion of Science. It was also supported by a graduate fellowship to M. Less from the US Department of Education and by the Texas Tech University Center for Energy Research. K. Schoenbach was supported by the Army Research Office. One of the authors (W. J.) highly appreciates useful discussions with K. Yatsui of Nagaoka University of Technology.

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FIGURE CAPTIONS

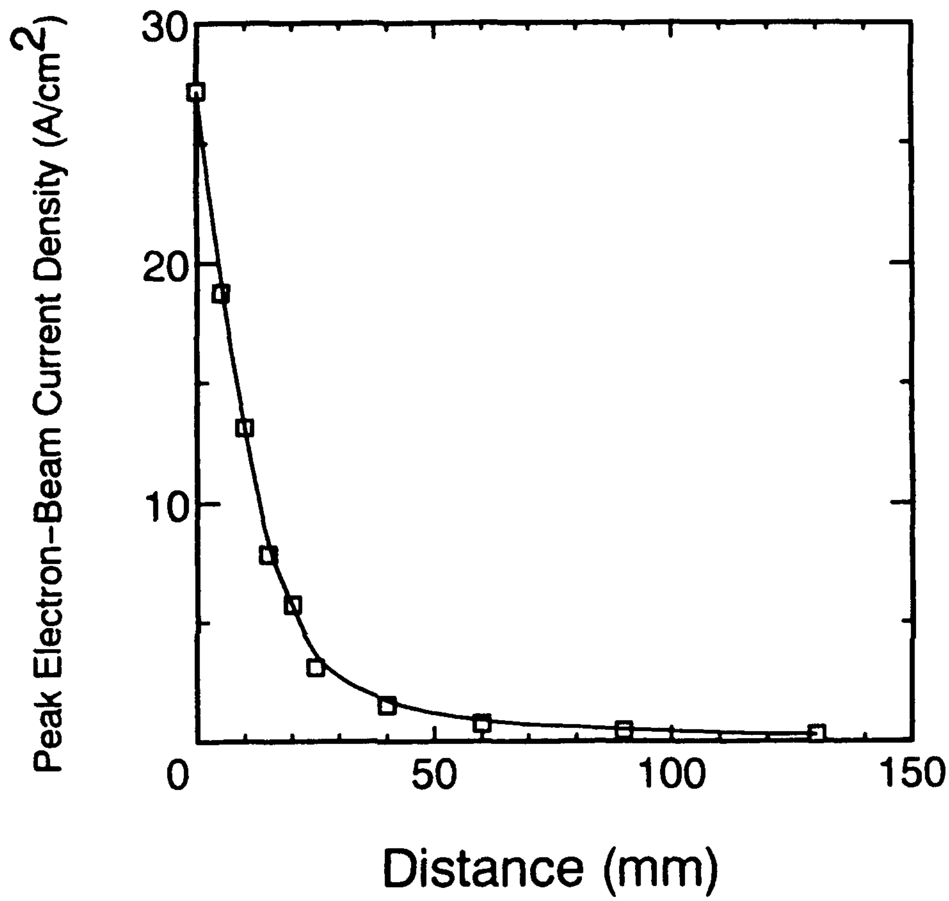
Fig. 1 Peak electron current density as a function of distance from the electron source.

Fig. 2 Experimental setup, (a) for switching along the sample surface and (b) for switching through the sample material.

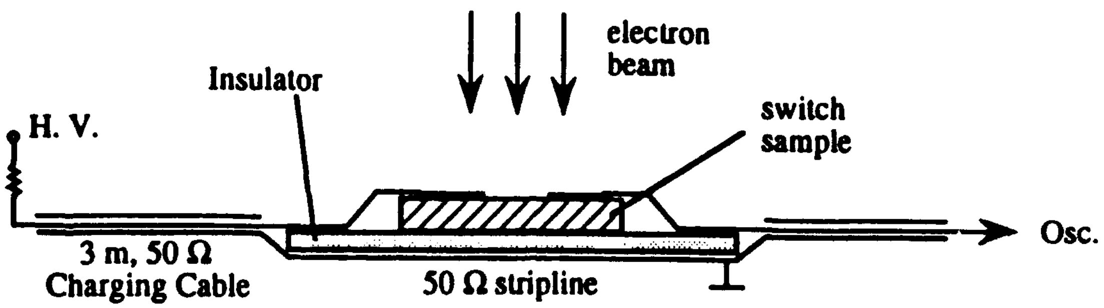
Fig. 3 Typical waveforms of (a) switch current density of sample No. 1 and (b) switch current of sample No. 2 and switch current density of sample No. 3.

Fig. 4 Experimental results of peak switch current density (samples No. 1 and 3) and peak switch current (sample No. 2) versus peak electron-beam current density.

Fig. 5 Calculated results of a) peak switch current of sample No. 2 with carrier mobility $\mu = 350\ cm^2/Vs$, and b) peak switch current density of sample No. 3 with the ratio of carrier density $\eta = n_2/n_1 = 5 \times 10^{-3}$, compared with experimental results.

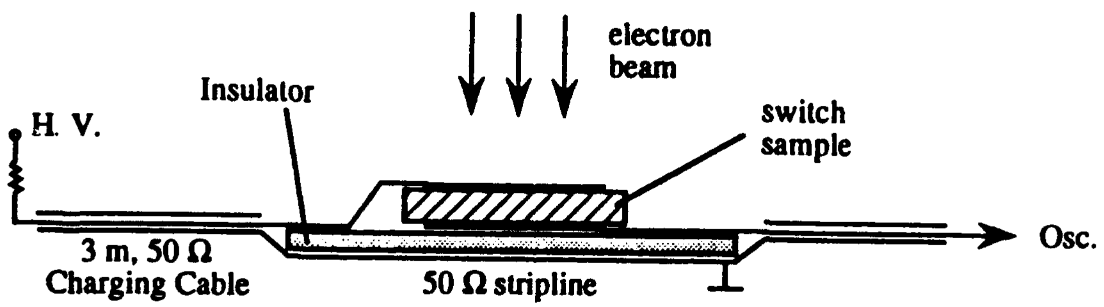


Peak Electron-Beam Current Density (A/cm2)
30
20
10
0
50
100
150
Distance (mm)



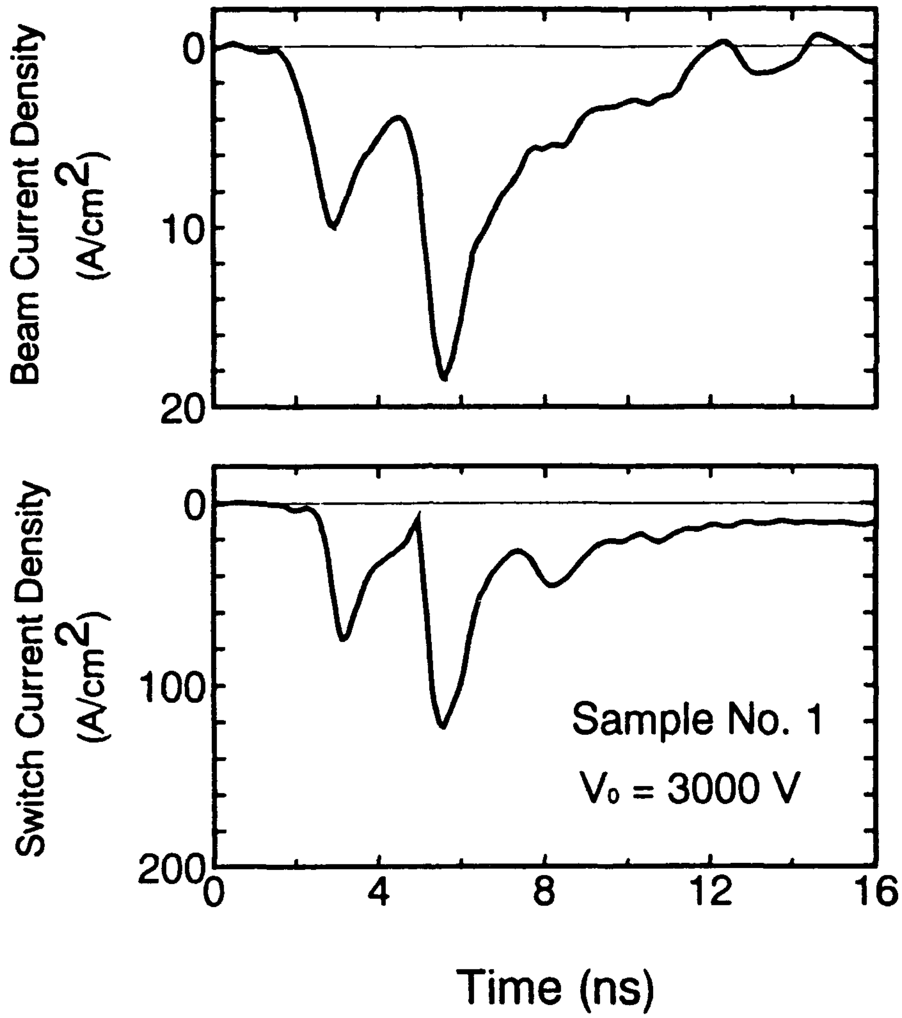
electron
beam
Insulator
switch
sample
H. V.
Osc.
3 m, 50 Ω
Charging Cable
50 Ω stripline

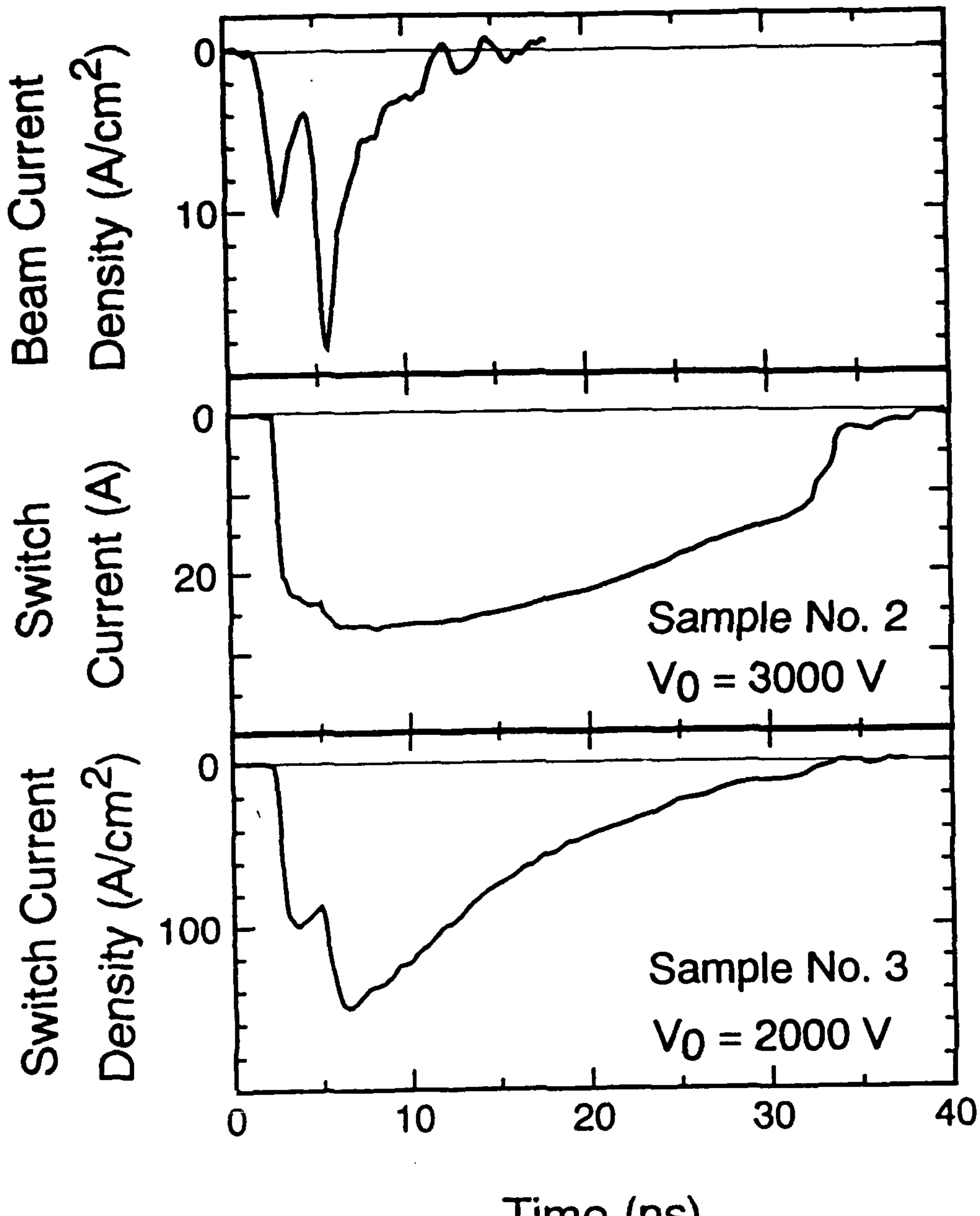
(a)



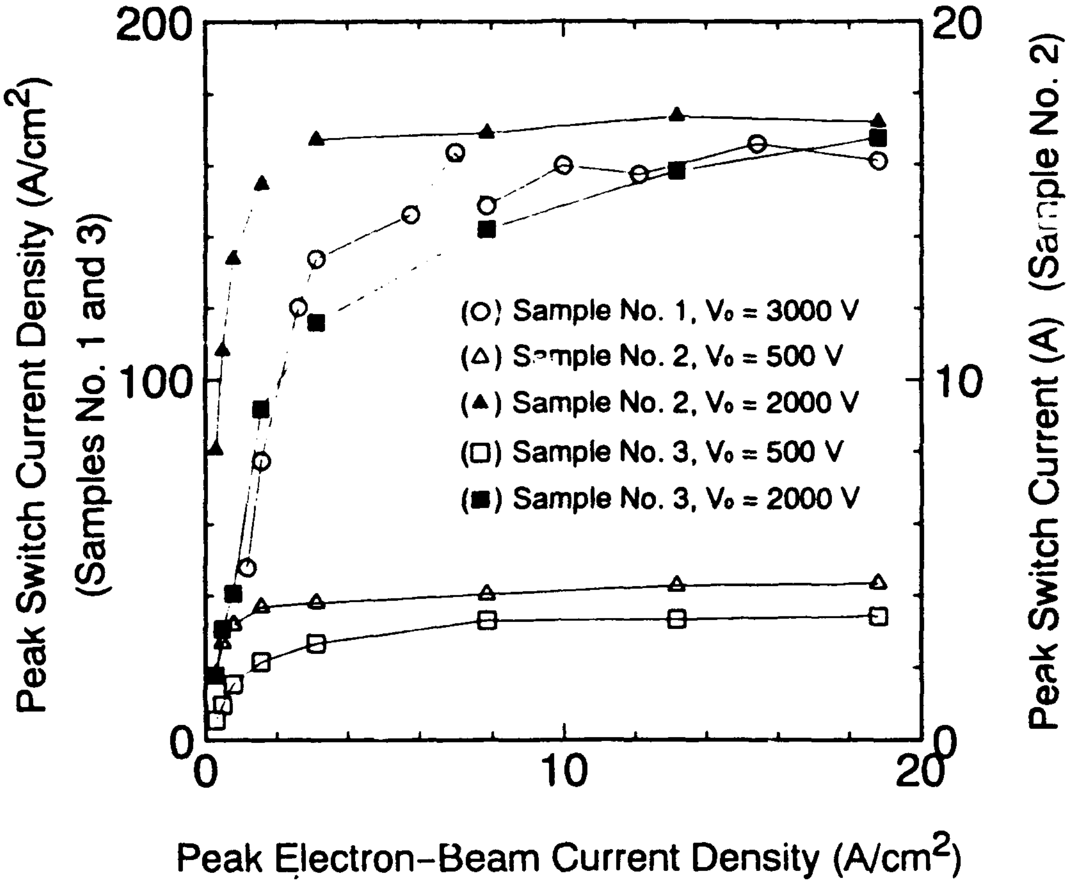
electron
beam
Insulator
switch
sample
H. V.
Osc.
3 m, 50 Ω
Charging Cable
50 Ω stripline

(b)

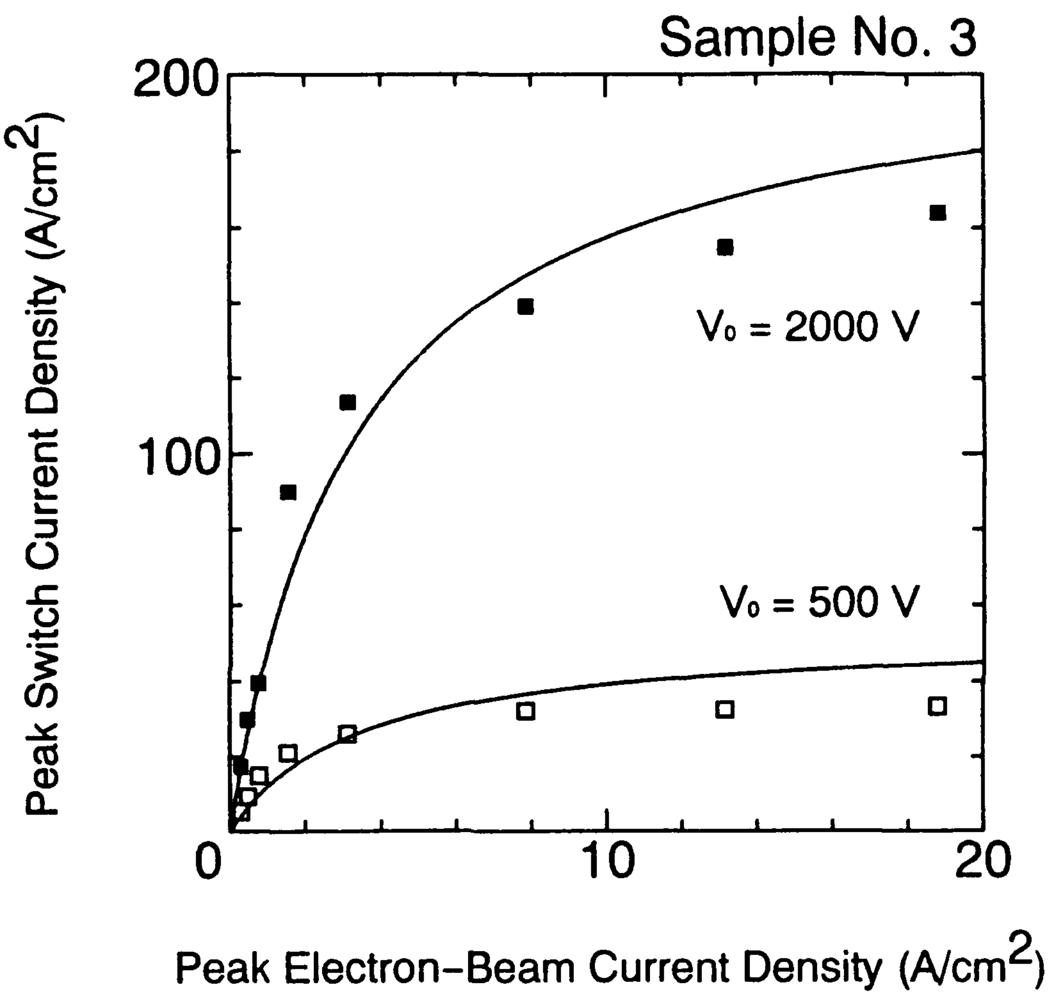

Beam Current Density
(A/cm2)
0
10
20
Switch Current Density
(A/cm2)
0
100
200
0
4
8
12
16
Sample No. 1
V0 = 3000 V
Time (ns)



Beam Current Density (A/cm²)
0
10
Switch Current (A)
0
20
Sample No. 2
V0 = 3000 V
Switch Current Density (A/cm²)
0
100
Sample No. 3
V0 = 2000 V
0
10
20
30
40
Time (ns)



Peak Switch Current Density (A/cm²)
(Samples No. 1 and 3)
Peak Switch Current (A) (Sample No. 2)
Peak Electron-Beam Current Density (A/cm²)
200
100
0
20
10
0
0
10
20
(○) Sample No. 1, V₀ = 3000 V
(△) Sample No. 2, V₀ = 500 V
(▲) Sample No. 2, V₀ = 2000 V
(□) Sample No. 3, V₀ = 500 V
(■) Sample No. 3, V₀ = 2000 V


Sample No. 3
200
100
0
10
20
V_0 = 2000 V
V_0 = 500 V
Peak Switch Current Density (A/cm^2)
Peak Electron-Beam Current Density (A/cm^2)

OPTIMIZATION OF ELECTRON-BEAM ACTIVATED GaAs-SWITCHES

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Abstract

The use of electron-beams instead of lasers to activate gallium arsenide switches offers the possibility to modulate the switch conductance on a timescale of nanoseconds through modulation of the electron beam intensity and to operate it at MHz repetition rates. Other advantages compared to lasers as activation sources are the high efficiency, the relatively low cost, and the reliability of electron beam guns and the possibility to introduce the electron-beam through the metal contacts into the switch. The thickness of the GaAs sample, sandwiched between the two contacts, determines the hold-off voltage and switch gain. Doping of the contact regions allows us to control the carrier injection and, consequently, to reduce the dark current through the switch and increase the hold-off voltage. The p-doped layer serves also as an effective cathodoluminescent emitter. Experiments with semi-insulating GaAs, with a p-type layer as the electron-beam incident face, show that the hold-off voltage increased by a factor of two over switches without this blocking contact and also that the cathodoluminescence increased by almost an order of magnitude.

Introduction

The use of electron-beams instead of lasers to activate gallium arsenide switches offers the possibility to modulate the switch conductance on a timescale of nanoseconds through modulation of the electron-beam intensity, and to operate it in a burst mode at a MHz or even GHz pulse rate. Other advantages compared to laser activation of solid state switches are the high efficiency, relatively low cost, and the reliability of electron guns. Also, it is possible to introduce the electron-beam through the metallic contact and into the switch. The use of cold cathodes for the electron gun will allow us to further simplify the switch system.

An obstacle for the use of electron-beam activation of solid state switches is the small range of electrons in solids. For an electron energy of 50keV, for example, the range is on the order of 10μm. In a switch configuration where the electron-beam is injected through one of the contacts, full activation of the switch material requires the use of thin films with high dielectric strength. Experiments with diamond films[1] and silicon dioxide[2] have demonstrated the validity of this concept. However, even with these large bandgap materials, the voltage for this mode of operation is limited to several kilovolts. In order to extend the concept of electron-beam control of solid state switches to higher voltages, requiring switches of increased thickness, it was proposed to utilize the electron-beam induced radiation (cathodoluminescence) in a direct semiconductor such as GaAs for bulk ionization of the switch.[3]

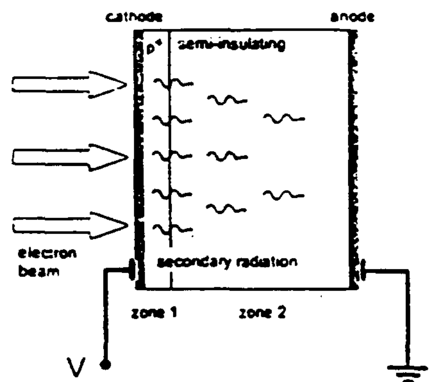

Fig. 1. Switch activated by secondary radiation.

Figure 1 shows the principal configuration of a switch activated by secondary radiation. It consists of a sample of direct semiconductor material (semi-insulating GaAs) between metal contacts, and with a p-doped layer at the side which faces the electron-beam. In the non-activated state the electron and hole density is determined by thermal emission and carrier injection through the contacts only. For semi-insulating material at voltages below the so-called trap-filled-limited voltage the concentration of free carriers in the bulk is very small, and the switch resistance is therefore high. Under electron-beam irradiation, the incident electrons are stopped within a shallow layer at the cathode, the electron range, and their energy is utilized to about one third for the generation of electron-hole pairs. In a pure direct semiconductor the annihilation of these electron-hole pairs would be through radiative recombination only. Semi-insulating semiconductors are characterized by a large concentration of recombination centers and traps. Here, direct radiative recombination is in competition with the trapping and recombination which occurs at the traps and recombination centers, respectively. The presence of the p-doped layer ensures that most of the electrons recombine with shallow acceptors, thus providing photons with a quantum energy only slightly lower than the bandgap energy. These photons which can penetrate deep into the semi-insulating due to their relatively low quantum energy, will activate the bulk of the switch through impurity ionization. This type of electron-beam controlled switch can therefore be considered as a photoconductive switch with a cathodoluminescent activation source of high efficiency (up to 30%) and the possibility to modulate its conductance up to the MHz or even GHz range.

Figure of Merit for Electron-Beam Controlled Switches

A simple model of the switch assumes a constant source function for the electron-beam ionization over the electron range and a constant secondary ionization in the bulk of the semiconductor. All of the radiation is assumed to be absorbed in the semiconductor. The efficiency of the luminescence generation is described by a constant k_{int}. Based on these assumptions it is possible to define a number of merit for the switch, the ratio of the switched power to the control power, Q:[4]

$$Q = \frac{e\mu\tau k_{int} V_o^2}{L^2 \xi_{ion}} \qquad (1)$$

where e is the electron charge, μ is the carrier mobility, τ is the mean carrier lifetime, V_o is the applied voltage, L is the depth of the switch, and ξ_{ion} is the effective ionization energy. This equation holds when the switch resistance in the on-state is very small compared to a load resistance.

In order to optimize the switch, i.e. to operate it at high Q, the switch material needs to have a high mobility, and a low ionization energy. A long carrier lifetime also gives a high Q, however, since the carrier lifetime also determines the temporal response of the switch it may be necessary to choose materials with short carrier lifetimes, depending on the application. The various aspects on material selection are discussed in more detail in reference 4. Semi-insulating gallium arsenide with its high electron mobility, relatively low ionization energy, and carrier lifetime on the order of nanoseconds is a good candidate for electron-beam controlled switch material. Even more important is the fact that GaAs is a direct semiconductor with consequently high quantum efficiency, η_{int}, which can be enhanced by p-doping of the cathodoluminescent layer.

A very important switch parameter is the maximum applicable voltage, the hold-off voltage V_o. Due to carrier injection and trap filling this voltage cannot be assumed to be the product of dielectric strength, E_d, and the switch length, L. It is a complex function of the type of deep traps, the trap densities, the trap activation energies, and the switch dimensions.[5] Because of the effects of traps on the hold-off voltage it is possible to influence it by controlling the trapfilling through control of the carrier injection through the contacts. Using blocking contacts (reverse biased junctions) it seems to be possible to obtain higher values for the hold-off voltage compared to switch systems with injecting contacts.

In order to optimize the electron-beam controlled GaAs switch with respect to hold-off voltage, we have studied both experimentally and theoretically the dark current characteristics of semi-insulating GaAs of 2mm and 5mm lengths. These samples have a p^+ epitaxial layer grown to 3μm with Zn. This p-doped layer serves both as a cathodoluminescent layer, and as a blocking contact for electrons. The cathodoluminescent yield and the absorption of the secondary radiation in the bulk of the semiconductor was studied for electron-beam pulse durations of 15μs and current densities on the order of 20mA/cm^2.

Current-Voltage Characteristics of GaAs Switches

Modeling Results

A drift-diffusion model was used to compute the current-voltage characteristics of the semi-insulating GaAs switches of various thicknesses. The model is described in reference 5. Two types of impurities or defects were assumed; EL2, a deep donor with a concentration of $1\cdot10^{16}$ cm^{-3}, and HL10, a shallow acceptor (possibly cause by carbon) with a concentration of $8\cdot10^{15}$ cm^{-3} which serves to compensate the donors. The data were obtained from experimental studies on semi-insulating GaAs (reference 5). The results of the calculation are shown in figure 2 for samples varying in thickness from .5mm to 10mm.

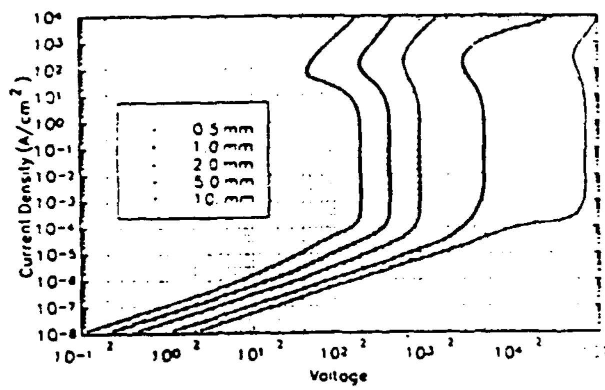

Fig. 2. Modeling results for semi-insulating GaAs.

At voltages below the so called trap-filled-limited voltage the current-voltage characteristics are ohmic, with the resistance determined (in this case) by electron capture in deep traps. Once the traps are filled, the current rises dramatically with voltage. A region of negative differential conductance at higher currents is caused by the formation of an electron-hole plasma due to filling of hole traps (double injection). At higher currents the current varies quadratically with voltage. In this region direct electron-hole recombination is the dominant loss mechanism. The trap-filled-limited voltage increases stronger than linear at small thicknesses (d < 1mm). It becomes linearly dependent on the thickness above 1mm.

Experimental Results

The current-voltage characteristics of two GaAs samples, 2mm and 5mm thick, were measured over a voltage range from 0.1V to 6kV. Both samples have a layer which is doped with Zn, a shallow acceptor, on one side. By forward biasing the resulting junction it acts as a hole emitter, reverse biasing prevents electrons from being injected into the bulk of the semiconductor. In order to avoid heating of the samples DC measurements were performed only with applied voltages less than 100V. At higher voltages the voltage was applied in a pulsed mode. The range from 50V to 2kV was covered by a Velonex pulser with voltage pulses of 150μs duration. For higher voltages a pulse forming network, switched with a thyratron provided a 30μs long pulse.

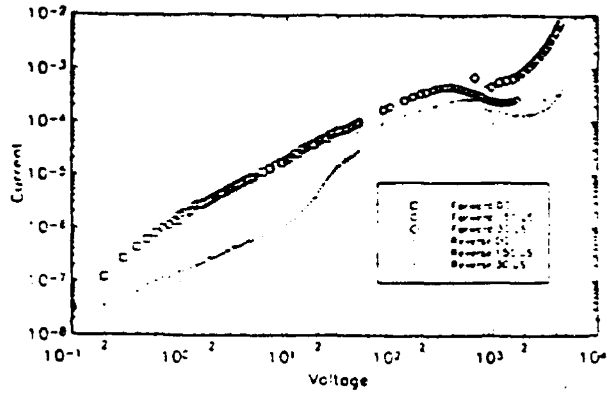

Fig. 3 Measured current-voltage characteristics of a 2mm GaAs switch.

The current-voltage characteristics for forward and reversed biased 2mm thick GaAs switches are shown in Figure 3. The current for the reversed biased case is generally lower than half of that in the forward biased mode. In both cases a region of negative differential conductance is observed at voltages which correspond to average electric fields of 3kV/cm. The current increases again above a voltage of 1.2kV both forward and reverse biased but with quite different slopes. This is shown on a linear scale in figure 4. In this voltage range the effect of non-injecting contacts on the leakage current, and consequently the maximum tolerable voltage is clearly visible. The maximum hold-off voltage of a 2mm GaAs sample with a reverse biased p-i junction was found to be 11kV. At this voltage the sample must be submerged in oil to avoid surface flashover. These and earlier experiments[6] show clearly that the use of reverse biased junctions allow us to extend the voltage range of the switch by more than a factor of two compared to forward biased junctions or simple photoconductive switches with ohmic contacts.

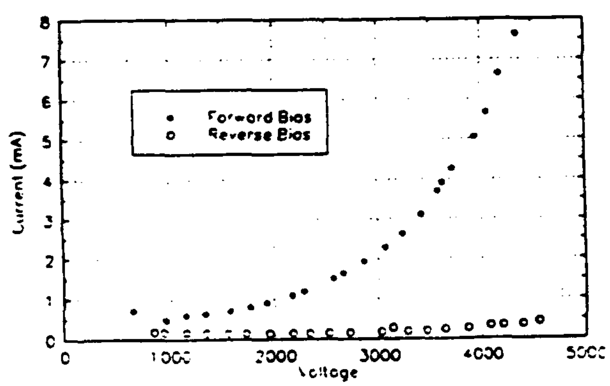

Fig. 4. High-voltage characteristics of 2mm GaAs switch.

A second sample with 5mm thickness was tested in the same way as the 2mm sample. The current-voltage characteristics were similar to the ones obtained with the 2mm sample, however, they were shifted to about two or three times the voltage. In the mm range the DC current-voltage characteristics and consequently the hold-off voltage of the switch seems to depend linearly on the switch thickness. Toward smaller dimensions (below 1mm) the dependence of the hold-off voltage on thickness becomes strongly nonlinear. Measurements with 0.64mm thick GaAs samples gave hold-off voltages below 400V instead of the expected three to four kV. This is possibly due to the stronger influence of space charge limited current which for single carrier injection scales with the inverse cube of the thickness.

Cathodoluminescence of Undoped and P-doped GaAs

The relative cathodoluminescent yield, an important parameter for an electron-beam controlled switch with secondary optical excitation was measured by recording the electron-beam induced light transmitted through the sample. A typical light pulse (compared to the electron-beam diode voltage) is shown in figure 5 for a 2mm sample with a p-doped layer facing the electron-beam. The temporal development of the light emission clearly follows the shape of the electron-beam voltage pulse. The intensity of the transmitted light depends on the electron-beam energy as shown in figure 6. No measurements were made with electron energy below 50keV. For higher values of electron-beam voltage the light output increases linearly with voltage.

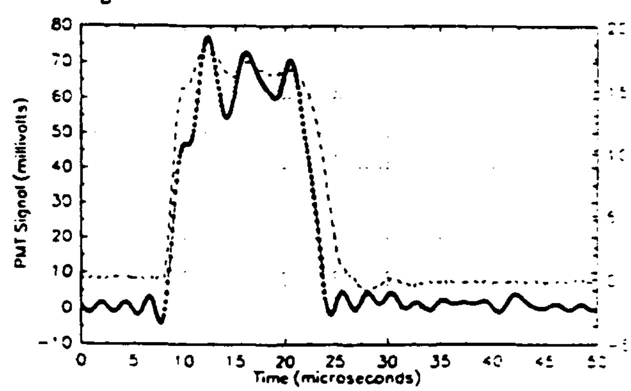

Fig. 5. Light output of 2mm GaAs switch with p-layer with peak electron energy of 140keV.

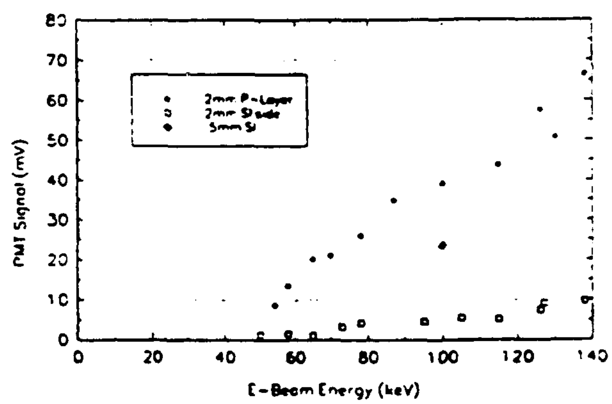

Fig. 6. Light output vs. electron energy of 2mm GaAs with one point taken with .5mm semi-insulating GaAs

When the electron-beam irradiates the undoped face of the 2mm sample, the intensity of the transmitted light is lower by about an order of magnitude compared to that emitted from the electron-beam irradiated p-doped layer (Fig. 6). It is also higher than that emitted through an electron-beam activated, 0.5mm thick undoped GaAs sample. These results support our hypothesis that the presence of a p-doped layer on the electron-beam irradiated face of the GaAs switch has a strong impact on the efficiency of luminescence generation.

Switching Test

The switching characteristic of a GaAs bulk switch controlled with a low energy electron beam (less than 50keV) was studied at Integrated Applied Physics, Inc. The switch unit had a built-in hot-cathode electron-beam source and a GaAs bulk switch in a hermetically sealed, high-vacuum package. The electron gun in the EBCSS unit was designed to provide an electron beam with an energy of 25-50keV, a current density of a few A/cm^2 and a pulse width of 500 nsec. The GaAs bulk switch was an LEC grown semi-insulating wafer with a thickness of 2 mm, a diameter of 2 inches and a resistivity of $2 \cdot 10^7$ Ω-cm.

To study the closing and opening behavior, the EBCSS unit was tested in a pulse forming network (PFN) with a matched load to generate 1-μsec voltage pulses. The switch current profile followed that of the electron-beam pulse, demonstrating the closing and opening capabilities of the EBCSS. The voltage across the EBCSS dropped from a pulsed bias voltage of 250 V to a forward voltage drop of ~50 V. The peak current density in the conduction phase was ~9 A/cm^2 and the switch resistance was 7.6 Ω. Power dissipated in the switch was 325 W which is approximately 20% of the total energy switched. Switching threshold was observed at electron-beam energy of about 30keV. To study the peak current capability, the EBCSS module was tested in a capacitor discharge circuit with a 10-nF capacitor charged to 1.5 kV. An electron-beam with an energy of 45 keV and a beam current density of 5 A/cm^2 was able to switch a peak current of 62 A (a current density of 80 A/cm^2). The current pulse width was ~ 500 nsec demonstrating the closing capability of the switch.

Table 1 summarizes the switching results of the EBCSS. In summary, when switched with a 45-keV, 4-A/cm^2 electron beam, the switch unit exhibited a forward drop voltage of ~50 V in a PFN-circuit, and a peak current density of ~80 A/cm^2 with an opening time of ~250 nsec in a capacitor discharge circuit.

Table 1. *Summary of EBCSS switching results.*

Thickness	0.2 cm
Conducting area diam.	1 cm
E-beam voltage	45 kV
E-beam current density	4 A/cm^2
E-beam pulse width	500 nsec
Capacitor discharge circuit	
Voltage	1.5 kV
Current	62 A
Current density	80 A/cm^2
PFN circuit	
Dissipation	20 %
Forward drop	50 V
Closing/opening time	250 nsec

Summary

The use of a shallow p-doped layer on the electron-beam irradiated face of an electron-beam controlled GaAs switch was shown to improve the gain of the switch, Q, dramatically. First, the junction of the p-layer with the intrinsic material prevents injection of electrons into the intrinsic region when reverse biased. This prevention of double injection allows us two apply a factor of two higher voltages than with samples having just ohmic contacts. Because of the quadratic dependence of the gain on the hold-off field this amounts to a factor of four increase in gain. Secondly, the increased cathodoluminescence of p-doped GaAs promises to give an order of magnitude improvement in the switch gain. Additionally, using p-doped layers suppresses the lock-on effect for voltages up to twice the usual lock-on field. This has been experimentally verified for 0.5mm thick samples. The use of low energy electron-beams for these kind of switches, as discussed in the previous section, promises to make these devices easily controllable closing and opening switches for high repetition rate pulse power applications.

Acknowledgements

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ELECTRON-BEAM CONTROLLED SWITCHING USING QUARTZ AND POLYCRYSTALLINE ZnSe

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Results of electron-beam controlled switching experiments with switch samples of quartz crystal and polycrystalline zinc selenide (ZnSe) are presented. For switch samples of both materials, drastic reductions of the switch resistance were induced by the electron beam. The quartz sample has showed very fast temporal response (less than 1 ns) with potential applicability for current control. The ZnSe samples, on the other hand, showed longer current transients (on the order of 10 ns) with exponential development of the switch resistance after the electron beam pulse.

Electron beam controlled solid switches have very interesting potential applications in pulsed power technology. For these switches, high power gain and fast response are the major subjects of interest.

There are basically two configurations of electron-beam controlled switches. In one configuration (A), the switch current flows along the surface of the switch sample in the direction perpendicular to that of electron beam. In another configuration (B), the switch current flows through the sample in the direction parallel to that of electron beam. In the second configuration, there are two modes. In one mode (B-1), free charge carriers are generated by both electron beam and secondary radiation.

For configurations A and B-2, we have selected polycrystalline zinc selenide (ZnSe) as the switch material mainly because of its low steady state dark current. Lower dark cur rent is very important to our experimental setup where the charging on the switch is a DC voltage.

For configuration B-1, the thickness of the switch must be smaller than the range of electrons in the sample. That requires a high dielectric strength of the switch material. We have found that silicon dioxide (SiO_2) has both high breakdown field and high possible power gain. In order to show the switching properties of SiO_2, we have used thin quartz crystals as our switch samples for configuration B-1. More ideal, specially designed, SiO_2 samples are presently being manufactured for us by an industrial company.

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Abstract

Results of electron-beam controlled switching experiments with switch samples of quartz crystal and polycrystalline zinc selenide (ZnSe) are presented. Switching characteristics of these materials were analyzed. The results showed that both materials are very attractive for applications in electron-beam controlled solid switches.

Introduction

Electron beam controlled solid switches have very interesting potential applications in pulsed power technology [1]-[5]. For these switches, high power gain and fast response are the major subjects of interest.

Under the irradiation of an electron beam, the switch sample might be ionized through either direct ionization by the energetic electrons or secondary ionization by the cathodoluminescence radiation [1]. For materials with small quantum efficiency, direct ionization is the only source of free charge carriers. Hence the thickness of the sample must be smaller than the range of the electrons. This requires high dielectric strength of the switch material. Diamond [6] and SiO_2 are considered to be suitable for this application. On the other hand, for materials with high quantum efficiency, the switching voltage may be raised by increasing the thickness of the switch samples without reduction in switch current, since the secondary radiation generates carriers in the region where beam electrons can not reach. GaAs and ZnSe [7] are promising materials for switches operating with indirect ionization.

In order to show the switching properties of SiO_2 and ZnSe, we have used thin quartz crystals and polycrystalline ZnSe as our switch samples for electron-beam controlled switching experiments.

Switch Samples and Experimental Setup

The quartz samples we have used were originally electronic parts for frequency control with a characteristic frequency of nearly 100 MHz. The sample is nearly 80 μm in thickness, with silver coating of 1 μm in thickness and 3 mm in diameter on both sides.

The ZnSe samples were obtained from II - IV Inc., Saxonburg, PA. The sample is 0.9 mm in thickness, with coating (0.01 μm Cr+0.2 μm Au) in size of 4 mm × 2.1 mm.

The experimental setup is shown in Fig. 1. In order to obtain a fast current rise, the switch was set on a piece of 50 Ω stripline. Connected with the stripline was a 3 m, 50 Ω, DC charged cable which discharges when the switch turns on. The current through the switch was observed downstream with a 50 Ω terminated oscilloscope (Tektronix 7104, 1 GHz). The charging voltage was 3 kV for quartz and 2 kV for ZnSe.

The electron source (150 kV, 200 A, 2 ns) used in our experiments was a very compact electron beam generator (Radan 1502) made by the Institute of Electrophysics, Russian Academy of Sciences. Because of the divergence of the beam, the beam current

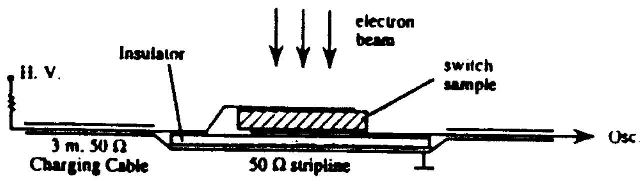

Fig. 1 Experimental Setup

density at the surface of the switch sample can be adjusted from 0.2 to 20 A/cm^2, with the distance from the output window.

Experimental Results

Typical waveforms of the electron-beam current density (J_b) and switch current density (J_s) are shown in Fig. 2. It is seen from Fig. 2 that both samples reacted very fast (within 1 ns) when the

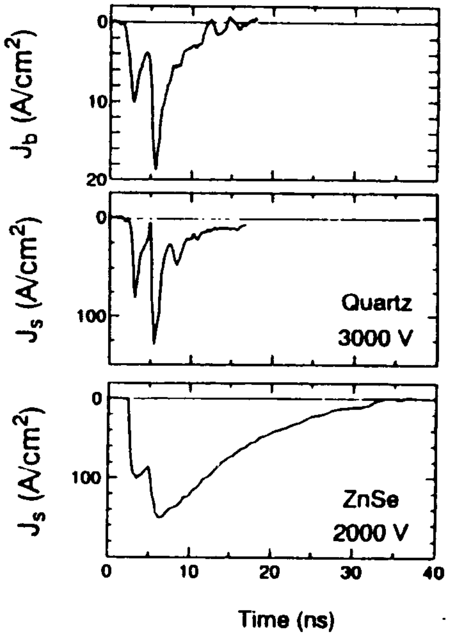

Fig. 2 Typical waveforms of electron-beam current density (J_b) and switch current density (J_s) of both samples.

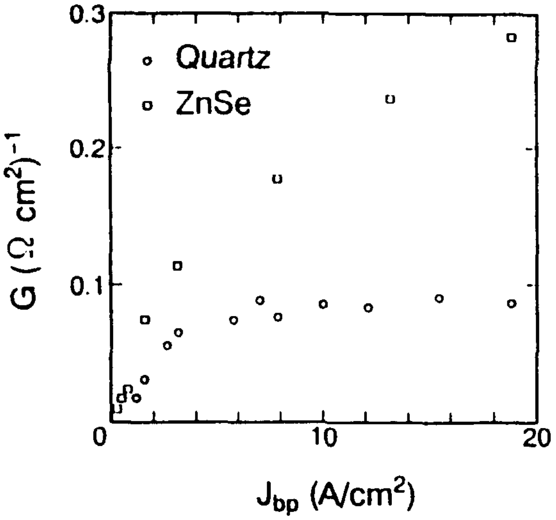

Fig. 3 Peak switch conductance per unit area (G) versus peak electron-beam current density (J_{bp}).

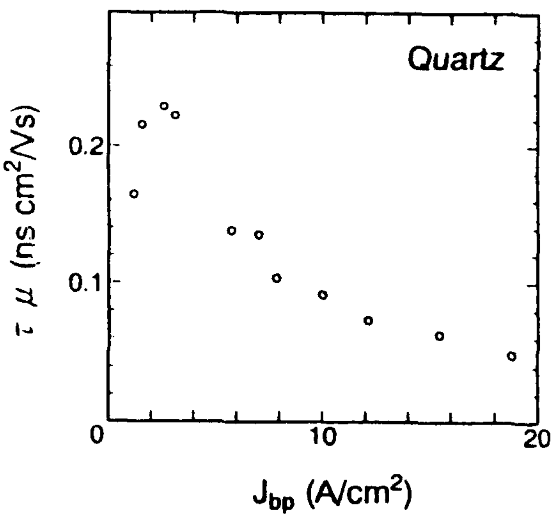

Fig. 4 Calculated results of $\mu\ \tau$, with data shown in Fig. 3, for quartz.

electron beam was turned on. However, after the electron beam pulse, the switch current of each sample decayed on different time scales. The crystal sample turned off almost simultaneously with the electron beam. The ZnSe sample, however, turned off in times on the order of 10 ns.

Figure 3 shows the relation of maximum switch conductance per unit area (G) versus peak electron current density (J_{bp}). G was obtained from the switch current density and the switch voltage which was obtained by subtracting twice the voltage across the termination from the charging voltage.

We have tried to measure the steady state dark current of the *switch samples*. With applied voltages up to 3 kV, however, no switch current larger than 0.01 μA was observed for any sample. This result has shown that the steady state switch resistance is higher than $3 \times 10^{11}\,\Omega$.

Discussions

A. Quartz

For directly ionized switches, under steady state conditions, the conductance per unit area is given by [5]:

$$G = e\mu\,\tau P_b/(\xi_{ion} L^2)\ . \tag{1}$$

where μ is the carrier mobility, P_b is the electron-beam power density, τ is the carrier lifetime, ξ_{ion} is the effective ionization energy and L is the switch thickness. For P_b, we have only informations about the beam current and the peak electron energy (150 keV). Instead of assuming that all electrons have the same energy, we have assumed that the e-beam diode has a constant impedance. This assumption underestimates the beam power at the earlier stage since the dynamic impedance of an e-beam diode usually drops in time.

With Eq. (1), $\mu\ \tau$ of quartz was calculated with G shown in Fig. 3 and the results are shown in Fig. 4, where we have used ξ_{ion} = 25 eV. We see from Fig. 4 that the effective $\mu\ \tau$ obtained from the experimental results changes with the electron-beam curent density and the maximum value is about 0.23 ns cm^2/Vs. Assuming the carrier mobility μ of 20 cm^2/Vs, we obtained the carrier lifetime τ of 11.5 ps. With the maximum value of $\mu\ \tau$, we also obtained the maximum power gain of the quartz switch, whitch is given by $e\mu\ \tau\ E_d^2/\xi_{ion}$, and the result is 745 with an E_d (dielectric strength) of 9 MV/cm. High power gain and short carrier lifetime show the potential applicability of a quartz switch as a pulsed power amplifier.

B. Polycrystalline ZnSe

We considered the ZnSe sample in two regions, 1) direc ionization region and 2) indirect ionization region, and assum uniform distribution in each region. The rate equations for th electron densities are [7]:

$$dn_i/dt = S_i - an_i^2 - bn_i\ , \qquad i = 1,2 \tag{2}$$

where n_i, S_i, a and b are carrier density, source function, direc recombination coefficient and trapping coefficient, respectively. S is due to direct ionization by beam electrons and is given by:

$$S_1 = P_b/(\xi_{ion} L_1)\ , \tag{3}$$

where L_1 is the range of electron in ZnSe. In order to calculate S we assume that carriers in region 2 are generated by radiation du to recombination in region 1. Then S_2 is proportional to th recombination rate in region 1:

$$S_2 = \eta\,(an_1^2 + bn_1)\ , \tag{4}$$

where η is the efficiency of carrier generation in region 2 b recombination in region 1. We solved Eqs. (2)-(4) numerically b fitting the switch current density, which conrresponds to n_2, wit that obtained experimentally to calculate a, b and η. Figure shows the waveforms of the calculated switch current densi (dashed line) obtained with $a = 2 \times 10^{-6}$ cm^3/s, $b = 9 \times 10^7$ /s and $= 1.8 \times 10^{-3}$, and the experimental switch current density (solid

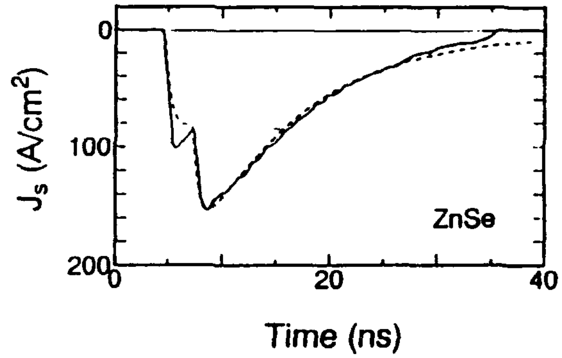

Fig. 5 Waveforms of switch current density obtained from experiment (solid line) and from calculation (dashed line) with $a = 2 \times 10^{-6}$ cm^3/s, $b = 9 \times 10^7$ /s and $\eta = 1.8 \times 10^{-3}$.

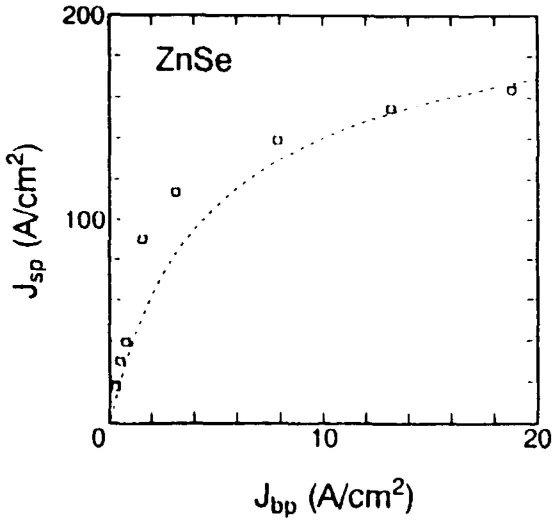

Fig. 6 Experimental and calculated results of peak switch current density (J_{sp}) as a function of peak electron-beam current density (J_{bp}).

line) obtained with a peak electron-beam current density of 13.17 A/cm^2. In the calculation, we have used ξ_{ion} = 7 eV, L_1 = 0.2 mm, and μ = 900 cm^2/Vs [8]. We also used the experimentally obtained electron-beam current density and assumed constant beam-diode impedance. The time step for solving the rate equations was 1 ps. In Fig.5, the difference between the calculated curve and the experimental curve at the earlier stage might be caused by underestimation of the beam power due to the assumption of constant beam-diode impedance.

With the same values of a, b and η, we have calculated the dependance of the peak switch current density (J_{sp}) on the peak electron-beam current density (J_{bp}). The calculated results are compared with the experimental results in Fig. 6.

For electron beam with the pulse width longer than the average carrier lifetime, we calculated the steady state carrier density. With $dn_1/dt = 0$ and $dn_2/dt = 0$, we have:

$$an_2^2 + bn_2 - \eta S_1 = 0 \;, \qquad (5)$$

and then its solution:

$$n_2 = ((b^2 + 4a\,\eta\, S_1)^{1/2} - b)/2a \;. \qquad (6)$$

If $b^2 >> 4a\,\eta\, S_1$, i.e., $J_b << 0.08$ A/cm^2 for an electron energy of 150 keV, Eq. (6) become $n_2 = \eta S_1/b$. Then the maximum power gain of the switch $Q = \mu\,\eta\, eE_d^2 d/(b\,\xi_{ion} L_1) = 1.16\times10^4$, with E_d = 1MV and d = 0.9 mm.

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INFLUENCE OF CONTACTS ON THE HOLD-OFF VOLTAGE AND RECOVERY OF ELECTRON-BEAM ACTIVATED GALLIUM ARSENIDE SWITCHES

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ABSTRACT

The influence of contacts on the dark current, and the gain and recovery behaviour of 0.64 mm thick electron-beam controlled gallium arsenide switches was studied experimentally. With non-injecting contacts the hold-off voltage for pulsed voltage application was found to be higher by more than a factor of four compared to systems with injecting contacts. Also the threshold voltage for current lock-on after switch opening could be increased by at least a factor of three by using non-injecting contacts. The maximum applied voltage to the system with non-injecting contacts was limited by surface flashover. By doping the electron-beam irradiated face of the switch with zinc it was possible to increase the switch gain by a factor of 3.5 over systems with only metal contacts. Optimization of the Zn-doped layer with respect to thickness and concentration should allow us to increase the switch gain further up to a value of about thirty. The experimental results are in accordance with results of a model which explains the lock-on effect as the development of a permanent current due to double injection at voltages above the trap-filled-limited voltage in semi-insulating semiconductors.

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INTRODUCTION

Photoconductive switches with their inherent jitterfree response and high switching speed are increasingly applied in laser controlled ultra wide band radar and high power microwave systems [1]. Less common is the use of electron-beams as control sources fo. bulk semiconductor switches, although there are some distinct advantages of electronic ionization versus optical ionization [2], [3]. Electron-beam generators are generally less expensive and have a higher wall-plug efficiency than lasers. High speed operation in the subnanosecond range is possible [4]. The use of electron-beams as drivers for semiconductor switches allows the generation of pulse trains with variable duty cycles or pulse shapes. Finally, any semiconductor or insulator, independent of the bandgap can be switched with the same high energy electron-beam.

Presently, the most common switch material for pulsed power applications is semi-insulating gallium arsenide (SI-GaAs) because of its high dark resistance and fast recombination (compared to silicon). However, for this material the current response of the switch to optical or electron-beam activation is linear only at low applied field strengths. Above a certain voltage, corresponding to mean electric fields in the range of several kV/cm to several ten's of kV/cm, depending on the defect and impurity concentration of SI-GaAs, nonlinear effects were observed, such as the so-called lock-on effect [5] and current filamentation [6], [7], [8]. The term lock-on describes the fact that a permanent current "locks on" to the photocurrent which is generated by the laser or electron-beam. For low intensities of the activation source or applied voltages just barely above the threshold for lock-on the transition into the permanent current state can be delayed by nanoseconds [7] to milliseconds [9] with respect to the activation pulse.

Whereas this effect is desirable for closing switches because of the low optical or electron-beam energy required to switch into the conductive state, it is certainly undesirable for systems which require operation in the linear mode. These include systems where the optical source or the electron-beam is used to modulate the conductance of the switch, and any system where the optically or electron-beam controlled semiconductor switch is to be used as an opening switch. Besides the inability to recover to their initial state, GaAs switches operated in the lock-on mode seem to be limited in lifetime due to the development of current filaments.

Various attempts have been made to explain the physics of these nonlinear effects, [10], [11], [12] which have been observed not just in gallium arsenide, but also in indium phosphide (InP), [13] zinc selenide (ZnSe) and diamond [14]. The occurance in diamond, which is an indirect semiconductor and does not exhibit a range of negative differential mobility, proves that neither optical transport (reabsorption of recombination radiation) nor the formation of Gunn domains can fully explain the lock-on effect. The strong dependence of the lock-on threshold voltage on the impurity and defect concentration in GaAs indicates that localized energy states (deep traps) in the switch material must be considered in explaining the lock-on effect. The temporal development of the lock-on effect must then be determined by the filling of traps with injected charge carriers.

Besides carrier injection into the bulk, through electronic or optical ionization, carrier injection through the contacts plays an important role in the switching performance, particularly in the development of the lock-on effect. The influence of heavily doped contacts on photoconductive switching was discussed in a recent paper by Thompson and Lindholm (1990) for the case of trap-free photoconductive switches [15]. It was shown, that the influence of the contacts on the switch behaviour is strong for such cases where the photogenerated (or electronically ionized) carriers drift or diffuse a distance on the same order as the switch dimensions. In the case of semiconductors with large trap concentrations, the injection of carriers at the contacts determine the switching characteristics even in the case where the intrinsic region is long compared to the diffusion length. Both the dark current-voltage characteristic of a semiconductor switch which contains large concentrations of deep centers as well as its recovery behaviour is affected by carrier injection at the contacts [16], [10]. The effect of double injection, the injection of both electrons and holes through the contacts, in semiconductors with deep traps was shown to generate current-voltage characteristics with negative differential conductivity, which is a condition for the onset of current filamentation [17]. Other evidence for the influence of contacts on the switch performance are experimental results of studies on photoconductive GaAs switches [18]. It is shown that hole injection, enforced by trap related space charge fields at the anode, in addition to electron injection at a metal cathode, leads to a strong nonlinear behaviour of the switch.

In order to explore the effect of contacts on nonlinear transport processes, such as the lock-on effect, in photoconductive switches, we have studied the dark current behaviour and the temporal development of the current in electron-beam activated semi-insulating (SI) GaAs switches. These studies were performed using a forward and a reverse biased metal/p-type layer/intrinsic semiconductor/n-type layer/metal ($m/p^+/i/n^+/m$) contact system (Fig. 1). The experimental results were compared with observations on SI-GaAs switches with a metal/intrinsic semiconductor/metal (m/i/m) contact system. The electron-beam was injected through the contact (in the case of the non-symmetric system into the p-layer) as shown in figure 1. The cathodoluminescence generated over the range of the electron-beam in the region close to the contact serves to ionize the bulk of the switch [2].

In any of the investigated systems, the intrinsic region, consisting of SI-GaAs, exceeds the diffusion length by orders of magnitude. For injecting, as well as noninjecting contacts, therefore, the current-voltage characteristics of the intrinsic material is expected to determine the system behaviour. For trap-free intrinsic material and switch operation below the space charge limit, this implies a linear current-voltage characteristics. The observed nonlinearities in photoconductive and electron-beam activated GaAs switches, however, indicate the strong influence of traps on the switch kinetics. Consequently, it is expected that the injection of carriers through the contacts, with the purpose of filling deep traps when there is no electron-beam (or laser) activation, and replacing thermally emitted charge carriers after activation, will have a profound influence on the switch performance.

EXPERIMENTS

SWITCH SAMPLES

The material used in the experimental investigations was as-grown (or EL2 compensated) SI-GaAs with a resistivity of 6×10^6 Ωcm. The thickness of the samples was 0.64 mm. The switch geometry consisted of the bulk region with aligned parallel plate contact regions. In the m/i/m type switch sample the contacts were manufactured by thermally depositing a gold-germanium alloy to a thickness of 100 nm. The sample was then annealed at 450 °C in flowing nitrogen at atmospheric pressure for a period of 15 minutes. These contacts are known to form an $m/n^+/i/n^+/m$ system with the semi-insulating GaAs. The contacts are electron injecting, but blocking for holes.

A second sample, fabricated at Epitronics, had heavily doped n- and p-type layers epitaxially grown on opposite sides, forming a $p^+/i/n^+$ system with the same type of SI-GaAs as the bulk material, and the same switch dimensions as the m/i/m switch. This device, shown in Fig. 1, consists of a 19.5 μm wide zinc-doped region, with a shallow acceptor concentration of 7×10^{19} cm^{-3} (zone I). The bulk region (zone II) is 635 μm thick SI-GaAs, followed by a 21.8 μm wide silicon-doped region, with a shallow donor concentration of 3.9×10^{18} cm^{-3} (zone III).

A layer of 100 nm Au was deposited on the Zn-doped region, and a 100 nm Au-Ge layer on the Si-doped region. The metal contacts were annealed at 450 °C.

DARK CURRENT MEASUREMENTS

The steady-state dark current at voltages on the order of 100 volts was measured with a Keithley 617 electrometer. For measurements at higher voltages a pulsed voltage source was used and the current was recorded with a Tektronix 7612 digitizer. The results of these measurements for the m/i/m contact geometry are shown in Fig. 2. The three regions of data correspond to the different voltage sources. The current-voltage characteristic up to 100 V was recorded by using a dc-source. The middle group of data was obtained by using a hard-tube pulser, capable of generating pulses up to 450 ms. The upper group of data was taken using a thyratron switched 25 Ω pulse forming network (PFN) with variable pulse length up to a duration of 35 μs. The transition from ohmic to super-linear behavior occurs at 100 V indicating trap filling at this voltage. The data agree well with previously measured current-voltage characteristics of SI GaAs, where the value of the trap-filled-limit voltage, V_{TFL}, was used to estimate the concentration of EL2 traps to 9.7×10^{15} cm^{-3} [9]. The upper group of data shows a cubic dependence of the dark current on the voltage indicating that double injection of charge carriers due to barrier lowering by trap enhanced space charge fields at the non-injecting contact might play a role in the dark current behavior at higher voltages [18].

The results of dark current measurements on $m/p^+/i/n^+/m$ devices, forward biased and reverse biased, are shown in Fig. 3. The forward biased $m/p^+/i/n^+/m$ system (positive voltage at p^+-side) shows ohmic behavior up to 30 V, a constant dark current from 30 V to 100 V, followed by a transition into a super-linear mode at the trap-filled-limit voltage, similar to semi-insulating GaAs with metal contacts. The resistivity of the forward biased system is also nearly identical to that of the sample with metal contacts. The reverse biased $m/p^+/i/n^+/m$ system displayed a dark current (at low voltages) which was more than one order of magnitude less than for the forward biased system, and varied sublinearly with voltage. The transition into the strongly super-linear current, at the trap-filled-limit voltage, occured at 200 V, compared to 100 V for the forward biased system. This result seems to contradict our assumption that for non-injecting contacts, as is the case with the reversed biased system, the dark resistance should stay constant up to voltages which lead to dielectric breakdown. These are voltages which correspond to electric fields of several hundred kV/cm. As we will show later, however, this low voltage transition can be explained by the development of space charge fields in the contact region.

This hypothesis is supported by the results of measurements of the temporal development of the dark current. A step voltage generator was used which allowed us to apply voltage pulses of up to 3 kV for hundreds of milliseconds to the samples. The results of measurements on the m/i/m system showed that the time required to establish the dc-dark current takes microseconds to milliseconds, depending on the voltage which is applied [9]. For pulse charged systems with pulse durations less than the characteristic dark current development time, the semiconductor switch behaves like a resistor with a resistance determined by the low voltage value. Similar results were obtained on the reverse biased $m/p^+/i/n^+/m$ system (Fig. 4). With a voltage pulse of 35 μs duration no measurable current was recorded up to a voltage of 950 V, corresponding to an average field of 15 kV/cm. Surface flashover prevented further increase in voltage. The forward biased $m/p^+/i/n^+/m$ switch, on the other hand, showed a steep current rise already at 270 V when a 35 μs voltage pulse was applied.

SWITCH RESPONSE TO ELECTRON-BEAM ACTIVATION

The GaAs switches were activated by means of an electron-beam produced by a pulsed thermionic diode [19]. The diode voltage is generated by a pulse forming network (PFN) consisting of an LC chain and stepped up in a ratio 1:11 by a pulse transformer. The pulse duration can be adjusted between 1 μs and 15 μs by varying the number of PFN segments. The rise and fall time of the voltage pulse is 400 ns. The maximum diode voltage is about 200 kV, limited by vacuum breakdown in the diode chamber. The GaAs switch was placed in a vacuum in front of a 1 mil thick titanium foil which serves as the anode of the electron-beam diode. The electron energy distribution of the electron-beam at the position of the switch was calculated by means of a Monte-Carlo code which took the effect of the Ti-foil on the electron energy into account [20]. The electron-beam current density at the switch position, which is dependent on the temperature of the thermionic cathode, and the diode voltage (due to anode foil transmission) was measured by means of a Faraday cup. A typical waveform is shown in figure 5. Maximum obtainable current densities at a diode voltage of 165 kV were measured as 45 mA/cm^2.

The voltage across the switch was applied by using the same pulse forming network as for the pulsed dark current measurements: a thyratron switched 25 Ω PFN with a pulse duration of 35 μs. The electron-beam activates the switch sample about 5 μs after the voltage is applied and lasts for 15 μs. The current through the sample is measured by means of a Pearson coil, the sample voltage is measured using a resistive probe. The signals were recorded with Tektronix 7612 digitizers.

m/i/m system

The current response to electron-beam activation of m/i/m systems was reported and discussed in detail in two previous papers [9], [10]. The observations of electron-beam activated GaAs switches were found to be identical with those of laser activated GaAs switches [21]: At low voltages the photoconductive response is linear, that means that the switch current follows the activation source function. Above a threshold voltage, dependent on the type of semi-insulating GaAs, the switch current locks on. Instead of the switch recovering to the voltage and dark current level before switch activation it continues to carry a high current at a constant forward voltage after the activation source is turned off. The switch forward voltage in this "lock-on" state corresponds, depending on switch material, to average electric fields of several kV/cm to several ten's of kV/cm [21].

forward biased $m/p^+/i/n^+/m$ system

A similar behaviour as in m/i/m devices is observed in forward biased $m/p^+/i/n^+/m$ systems. The switch current response to the electron-beam activation was found to be linear below an applied voltage of 200 V. Above this voltage the switch does not recover fully after electron-beam activation, but continues to carry a current as long as the voltage is applied. A typical voltage and current trace is shown in figure 6a) and 6b) for an applied voltage of 320 V. After the electron-beam is applied to the system, at about 10 μs, the switch voltage decreases to a forward voltage level, which is determined by the electron-beam current (Fig. 5). After the electron-beam current begins to drop off, at about 23 μs, the switch voltage increases again, but not to its initial value. It settles for the remaining pulse duration at 200 V, corresponding to an electric field of 3 kV/cm. The switch current density which rises to values of 8 A/cm^2 (for an electron beam intensity of 20 mA/cm^2) follows the temporal shape of the activation source until the electron-beam is turned off. However, instead of returning to its initial value before electron-beam activation it locks on: A continuous high dark current is measured until the switch voltage returns to zero again.

The electron-beam induced current density, J, for the forward biased $m/p^+/i/n^+/m$ system (Fig. 7) is linearly dependent on voltage up to 170 V, and then increases with voltage, V, following approximately a power law of

$J \alpha V^6$. Lock-on is not observed for voltages in the linear range of the switch. Above 170 V, however, the lock-on current emerges and rises approximately with V^{15}, approaching the value of the switch current at 210 V.

reverse biased $m/p^+/i/n^+/m$ system

Quite different is the switch response to electron-beam irradiation when the $m/p^+/i/n^+/m$ sytem is reverse biased. Figure 8 shows the voltage and current traces of the electron-beam activated switch for an applied voltage of 320 V, which is the same value as used in the experiment with the forward biased system (Fig. 6). After the termination of the electron-beam the switch recovers to its initial hold-off voltage, and no lock-on current is observed up to voltages of 530 V, which is three times as high as the voltage where lock-on was observed in the forward biased system. Above 530 V we have observed electrical breakdown where the forward voltage was about 70 V, corresponding to an average field of 1 kV/cm. The loadline limited current in the breakdown phase indicates that the observed change in the current-voltage characteristics is due to surface flashover at the edges of the sample. In order to test this hypothesis the p^+ and n^+ layers at the edge of the sample were lapped to increase the distance for surface flashover. Before lapping the sample the breakdown occured at 320 V. After lapping, the breakdown potential increased to the previously mentioned 530 V. The current-voltage characteristics of the reverse biased $m/p^+/i/n^+/m$ system is shown in figure 7. It is linear up to the voltage where breakdown was observed. The highest switch current density was 22 A/cm^2, obtained with an electron-beam current density of 22 mA/cm^2 at a diode voltage of 167 kV.

electron-beam induced conductance

More relevant than the current gain for switching is the achieved electron-beam induced conductance. For the m/i/m system irradiated with an electron-beam current density of 28 mA/cm^2 at a diode voltage of 163 kV the switch conductance in the linear current-voltage range is 30 $m\Omega^{-1}cm^{-2}$. For the $m/p^+/i/n^+/m$ systems, with the Zn-doped (p^+) layer facing the electron-beam the measured conductance in the linear range was 85 $m\Omega^{-1}cm^{-2}$ with an electron-beam of 22 mA/cm^2 at a diode voltage of 167 kV. The dimensions of the switch were identical in all cases.

DISCUSSION

The dark current, with its characteristic hold-off voltage, and the temporal response of electron-beam controlled switches were studied using one switch material (SI-GaAs) with different contact configurations. One, the m/i/m configuration, is a symmetric system with metal contacts which serve as electron injecting contacts, but are blocking contacts for holes. The second system, $m/p^+/i/n^+/m$, is non-symmetric. It therefore allows us, depending on the bias, to use it as a system with only injecting contacts, or only blocking contacts. The dc-dark current characteristics for m/i/m and forward biased $m/p^+/i/n^+/m$ switches are almost identical. They show the typical features of semiconductors with large concentrations of traps: an ohmic behaviour at low voltages, and a transition into a breakdown-like current-voltage characteristic above the so-called trap-filled-limited voltage. For the system with injecting contacts we always have the situation of double injection, which at high current levels, can lead to the development of current filaments [17], [22]. In the case of the symmetric m/i/m system, with only electron injection at low voltages, the transition into a double injecting system is enforced due to the development of trap related space charge fields at the anode [18] and consequently Schottky emission of holes at this contact. The dark current then increases cubically with voltage as shown in Fig. 2.

According to these deliberations the dc-dark current in reverse biased $m/p^+/i/n^+/m$ systems should stayohmic (determined by the thermally generated carriers in the bulk) up to voltage values which correspond to the dielectric breakdown field in the material. For GaAs this is several hundred kV/cm, [23] which seems to require applied voltages on the order of 10 kV for our switch. However, strong local electrical fields can develop due to the thermal emission of electrons and holes in the bulk even at low applied voltages. This situation is illustrated in figure 9. When a reverse voltage is applied to the system, the mobile charges in the intrinsic region are swept out, generating a charge density distribution and consequently a field distribution as shown in figure 9a. If the thermal emission rates for electrons and holes from the deep traps are nonidentical, which is very likely, a preferred buildup of one type of charged centers takes place. This thermal emission process leads to a charge density distribution as shown in figure 9b. The developing field distribution is inhomogeneous, with large fields developing at one contact which could provide for the replacement of thermally emitted charges.

Eventually Schottky emission at this contact will lead to the onset of a current flow which just balances the charge carrier loss due to thermal emission from the deep traps. This occurs at current levels of several $\mu A/cm^2$. Small changes in voltage above this point will lead to large variations in the Schottky emission, and thus in the current-voltage characteristics (Fig. 3). Since the charging effect takes a certain time to generate the inhomogeneous electric field, it is possible to increase the hold-off voltage of reversed biased systems by applying a pulsed voltage of duration short compared to the charging time as has been demonstrated experimentally (Fig. 4).

In the case of the m/i/m and forward biased $m/p^+/i/n^+/m$ systems, a transition into a permanent dark current after the termination of the electron-beam is observed in the form of the so-called lock-on effect. For the forward biased $m/p^+/i/n^+/m$ system it is the unlimited injection of carriers at both contacts which allows trap-filling and therefore, at voltages above the trap-filled-limited voltage, a continuous flow of high level dark current. For the m/i/m system, where the anode contact is a blocking contact for holes, it requires the buildup of large trap related space charge fields to enforce hole emission. But when this condition is reached the m/i/m system behaves identical to the forward biased system with injecting contacts. The lock-on effect is a threshold effect with respect to voltage. The minimum voltage in the case of injecting contacts is the trap-filled-limited voltage, which for systems with negative differential conductivity can far exceed the lock-on voltage [17]. Because reaching the threshold voltage requires the filling of traps, the lock-on effect is also dependent on the intensity and duration of the activation pulse. Because of the accelerated filling of traps due to electron-beam (or laser) generated charge carriers, the transition into the permanent dark current regime is reduced from microseconds or milliseconds (with no external ionization source) to times on the order of the electron-beam (or laser) pulse, causing an immediate lock-on of the dark current to the externally controlled current.

Another characteristic of the the lock-on effect is the occurrence of current filaments, [6], [7], [8] an effect similar to a glow-to-arc transition in diffuse gas discharges. This effect can be explained by the presence of a negative differential conductivity regime in most trap dominated semiconductors with double injecting contacts [16], [3]. In such a system, the transition from the low current to the high current region of the current-voltage characteristic is always connected to the development of filaments [24].

In light of these considerations, the results obtained with the reverse biased $m/p^+/i/n^+/m$ system are not surprising. Understanding the lock-on current as a permanent dark current in a trap-filled semiconductor, allows us to expect that preventing the refill of thermally emptied traps after the activation pulse by restricting the injection of carriers through the contacts, leads to the re-establishment of the conditions before the activation. In other words, because the trap-filled state cannot be sustained after activation in a system with non-injecting contacts the lock-on effect is supressed. This is exactly what we have observed with reverse biased junctions as contacts.

Another positive side effect of using heavily doped contacts is the increased electron-beam induced conductance over systems with metal contacts. The observed increase was from 30 $m\Omega^{-1}cm^{-2}$ to 85 $m\Omega^{-1}cm^{-2}$ with slightly different electron-beam parameters. By taking these differences into account the gain in conductance when using heavily doped contacts is 3.5. The reason for this effect is the increased rate of radiative recombination in Zn-doped GaAs compared to undoped GaAs [25]. The electron-beam generated photons are able to ionize the bulk of the semiconductor beyond the electron-range and therefore enhance the overall conductance.

An additional advantage of using Zn as acceptor material is the experimentally observed increase in the wavelength of the emitted radiation, [25] which allows us to ionize the bulk of the switch radiatively over a distance of mm from the cathodoluminescent layer. The wavelength of the emitted radiation and consequently the absorption depth can be adjusted by varying the Zn-concentration. Optimization of the thickness and the concentration of the Zn-layer should allow us to increase the gain from 3.5 to a gain of about 30 [20]. In addition, by using a heavily doped n-type contact layer as the cathode contact, we have shown that we are able to extend the threshold voltage for the lock-on effect by at least a factor of three, enhancing the potential of these switches in high voltage systems.

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FIGURE CAPTIONS

Figure 1. Schematic representation of the device.

Figure 2. Dark current-voltage characteristics of the m/i/m system.

Figure 3. DC dark current-voltage characteristics of the forward and reverse biased GaAs $m/p^+/i/n^+/m$ system.

Figure 4. Pulsed dark current-voltage characteristics of the forward and reverse biased GaAs $m/p^+/i/n^+/m$ system. The pulse width of the applied voltage was 35 μs.

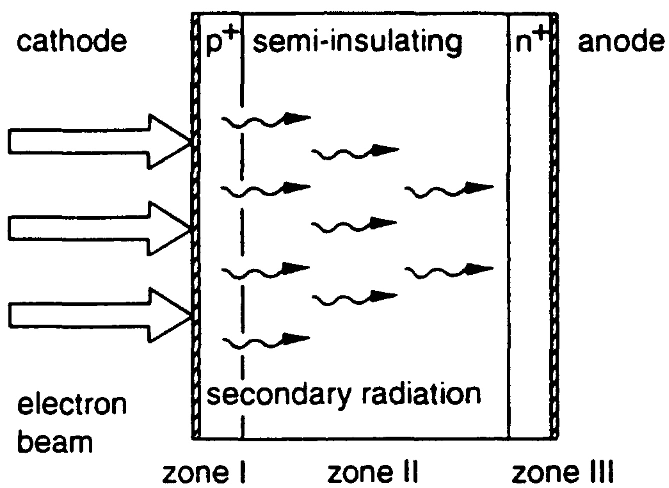
Figure 5. Plots of the temporal pulse shape of the electron-beam current density as measured by the faraday cup.

Figure 6. The temporal development of switch voltage and current density of the forward biased GaAs $m/p^+/i/n^+/m$ system.

Figure 7. Electron-beam-induced conductivity (EBIC) of the forward biased (FB) and reverse biased (RB) GaAs $m/p^+/i/n^+/m$ system, and lock-on (LO) values for the forward biased system.

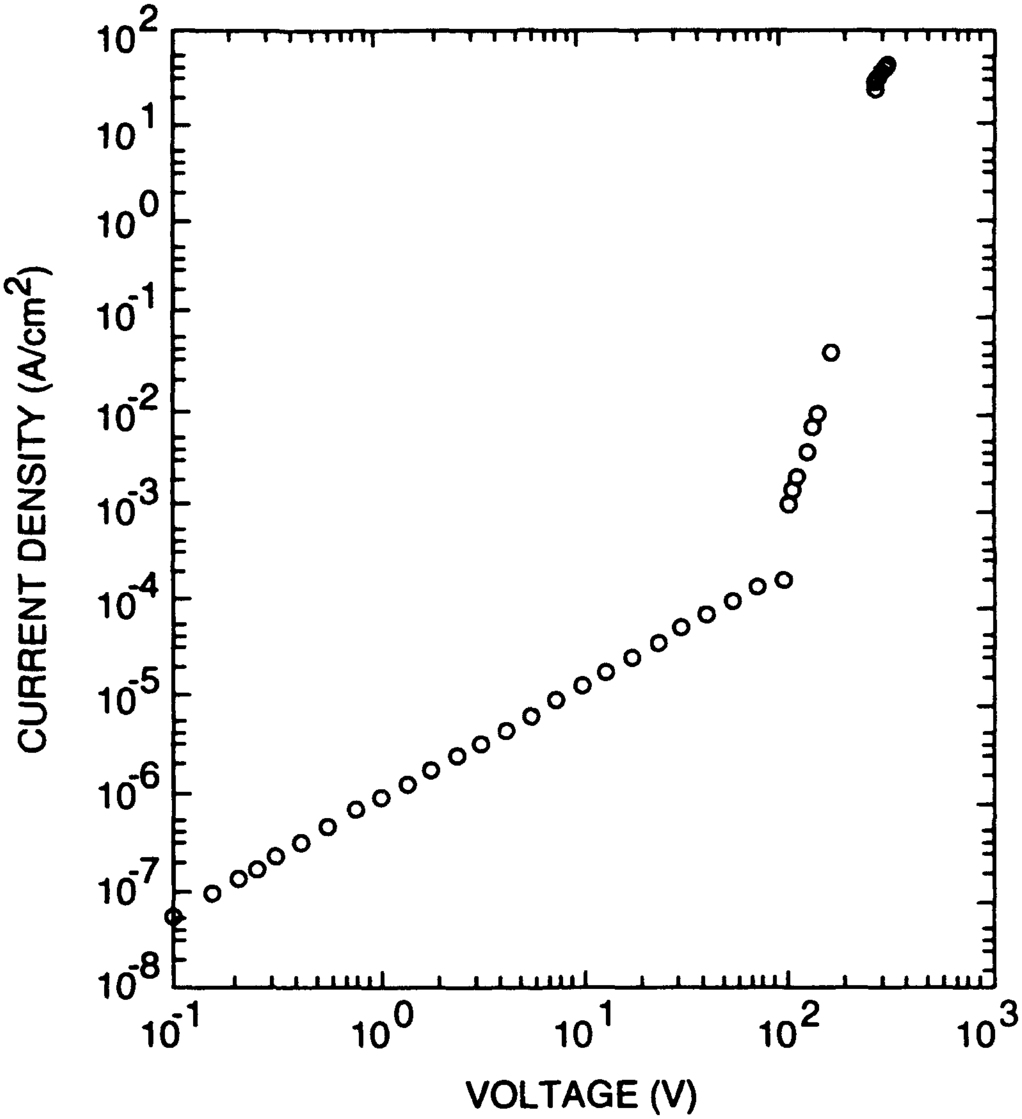
Figure 8. The temporal development of switch voltage and current density of the reverse biased GaAs $m/p^+/i/n^+/m$ system.

Figure 9. Charge density $\rho(x)$ and electric field $E(x)$ profile for a reverse biased GaAs $m/p^+/i/n^+/m$ system at a) time of charge sweep out and b) time after charge sweep out.



cathode
p+
semi-insulating
n+
anode
secondary radiation
electron
beam
zone I
zone II
zone III

Fig. 1



CURRENT DENSITY (A/cm^2)
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-1}
10^0
10^1
10^2
10^3
VOLTAGE (V)

Fig 2

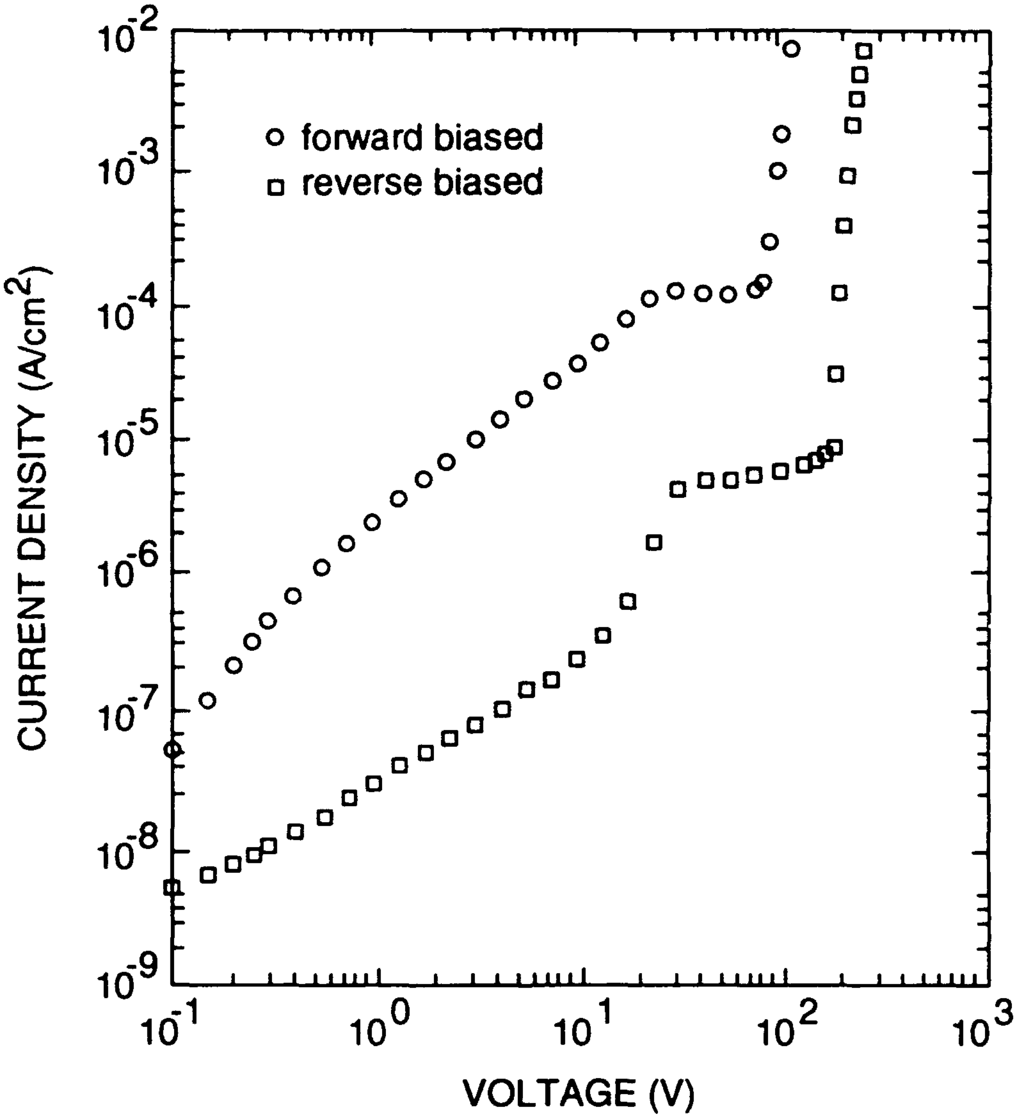

CURRENT DENSITY (A/cm²)
VOLTAGE (V)
forward biased
reverse biased
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
10⁻⁸
10⁻⁹
10⁻¹
10⁰
10¹
10²
10³

Fig 3

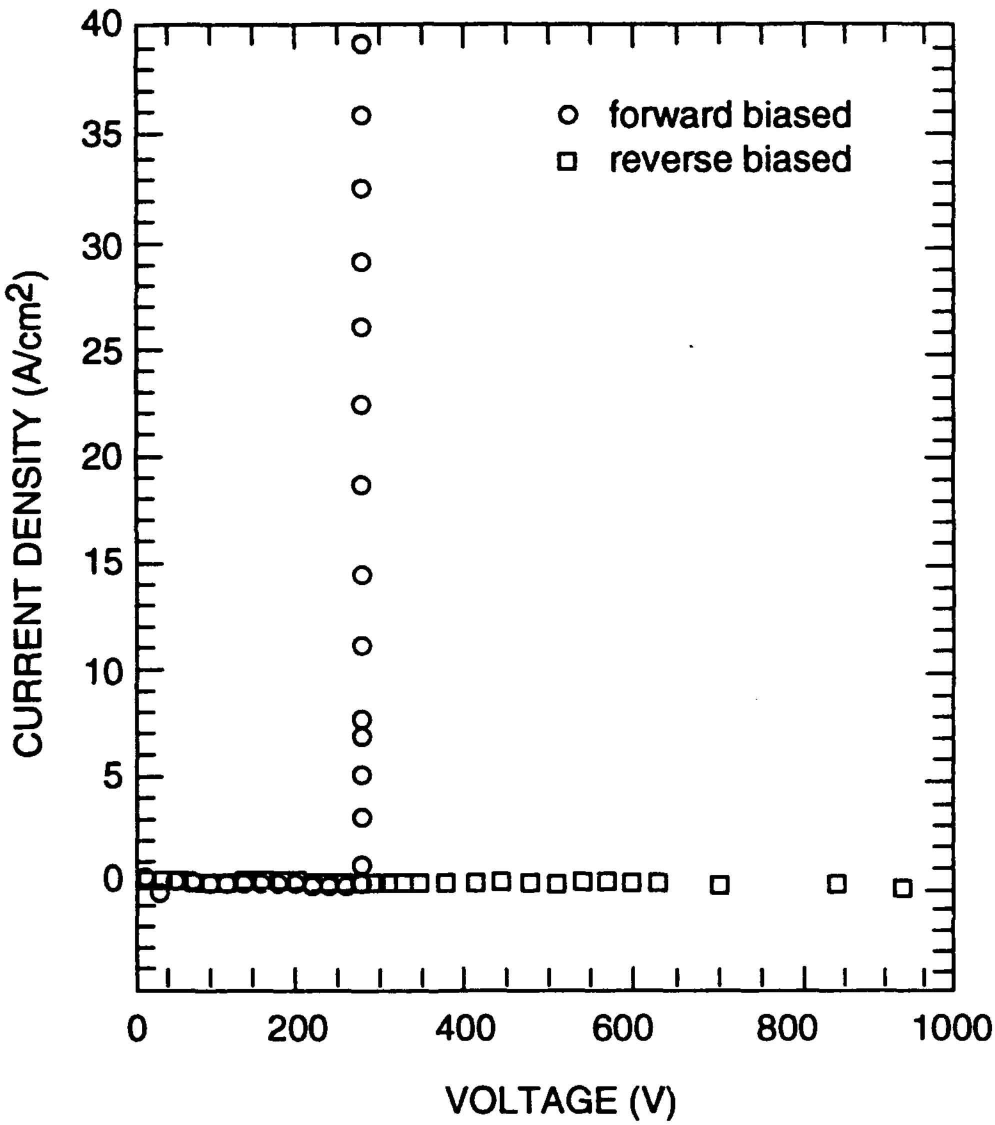

40
35
30
25
20
15
10
5
0
CURRENT DENSITY (A/cm2)
forward biased
reverse biased
0
200
400
600
800
1000
VOLTAGE (V)

Fig 4

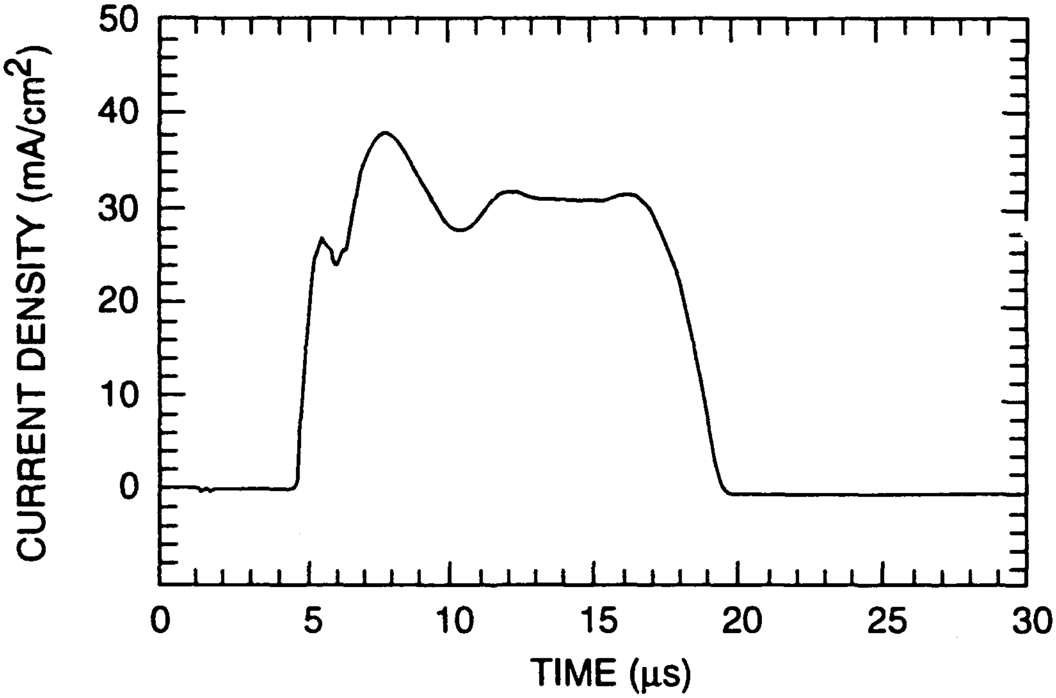
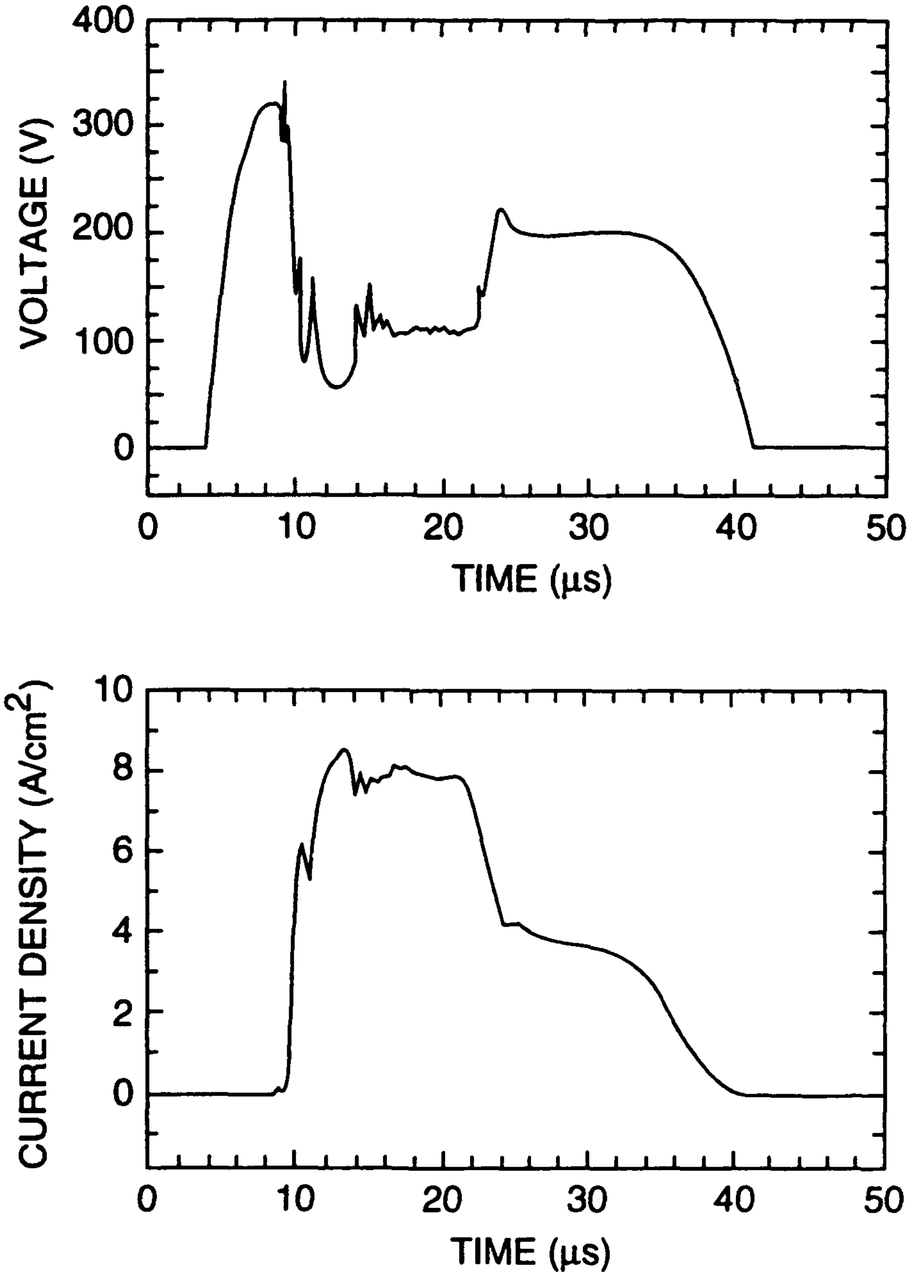
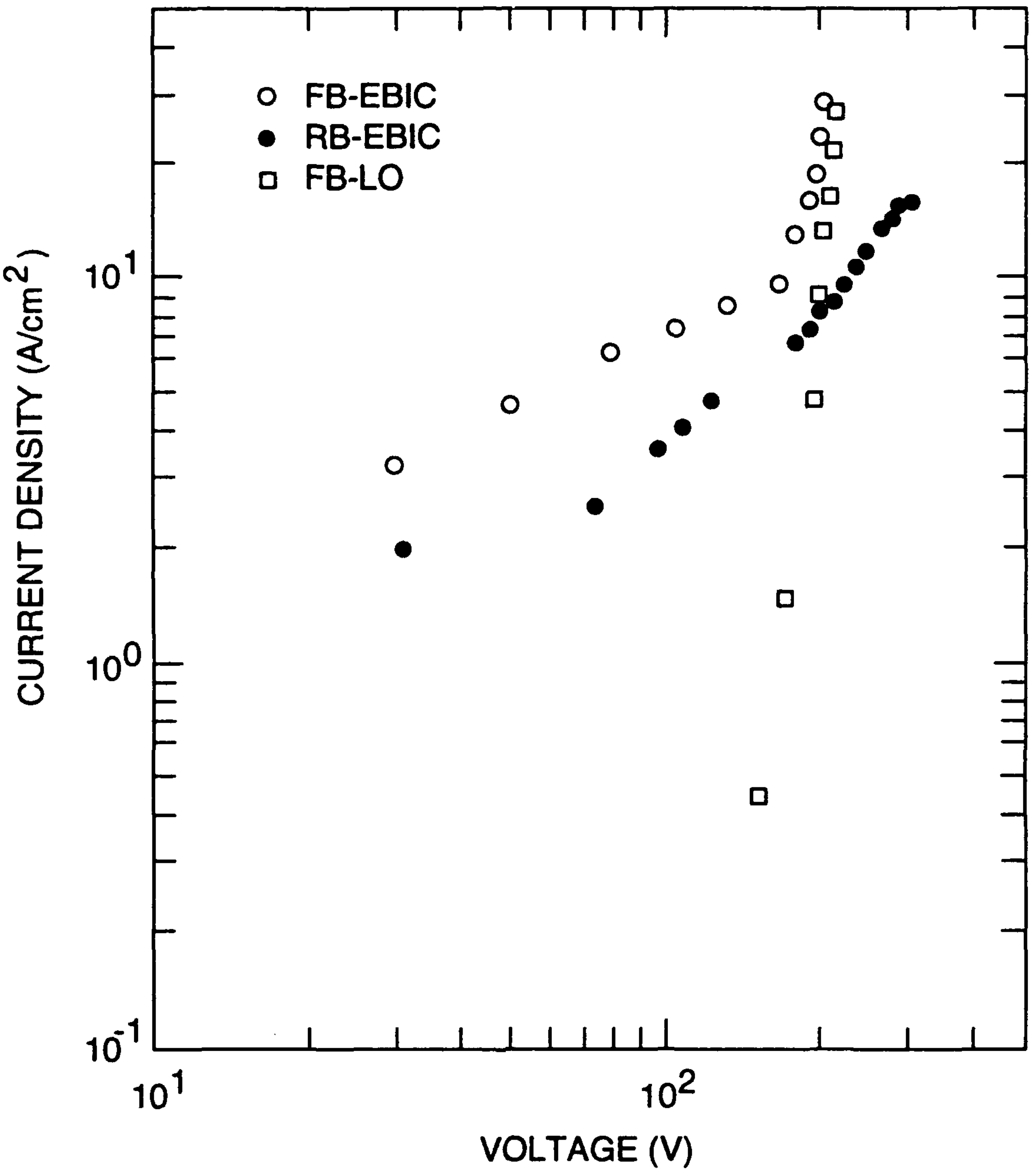


Fig 5

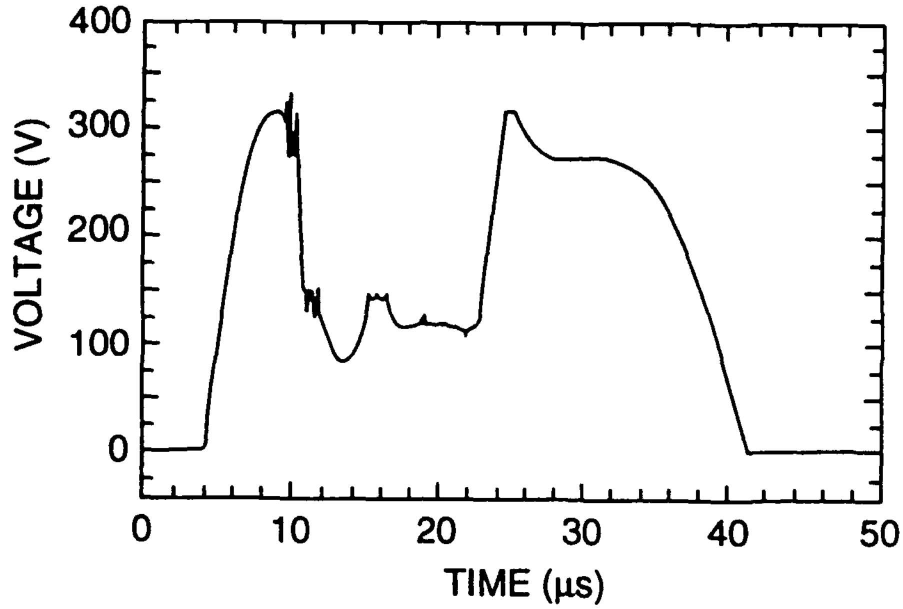


VOLTAGE (V)
400
300
200
100
0
0
10
20
30
40
50
TIME (µs)
CURRENT DENSITY (A/cm2)
10
8
6
4
2
0
0
10
20
30
40
50
TIME (µs)

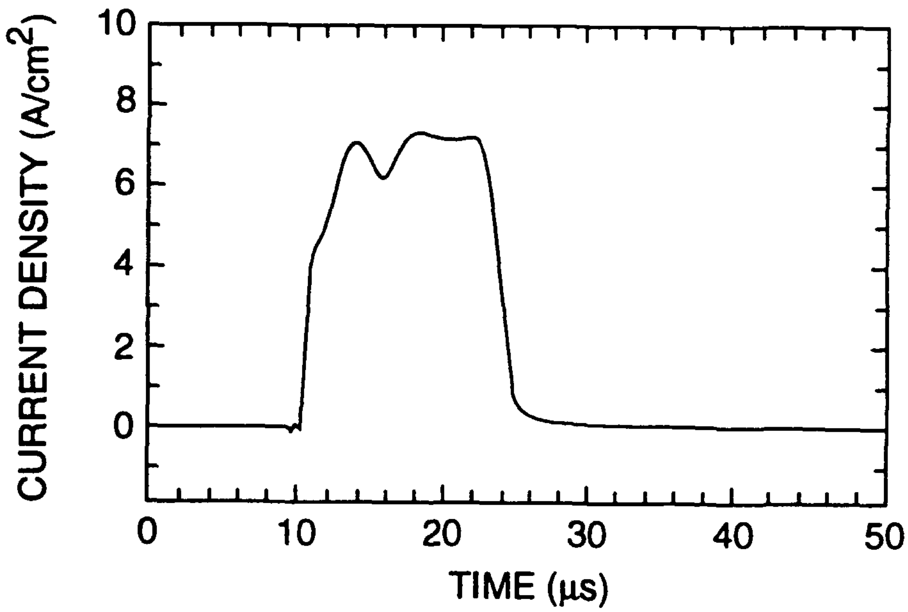
Fig 1.



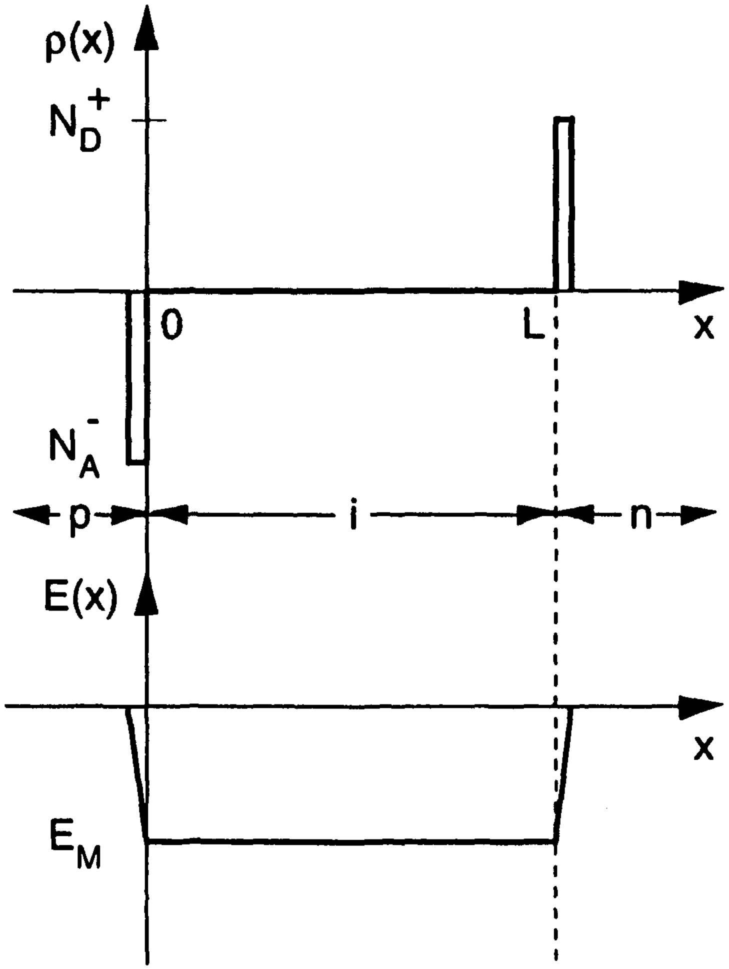
FB-EBIC
RB-EBIC
FB-LO
CURRENT DENSITY (A/cm^2)
10^1
10^0
10^{-1}
10^1
10^2
VOLTAGE (V)



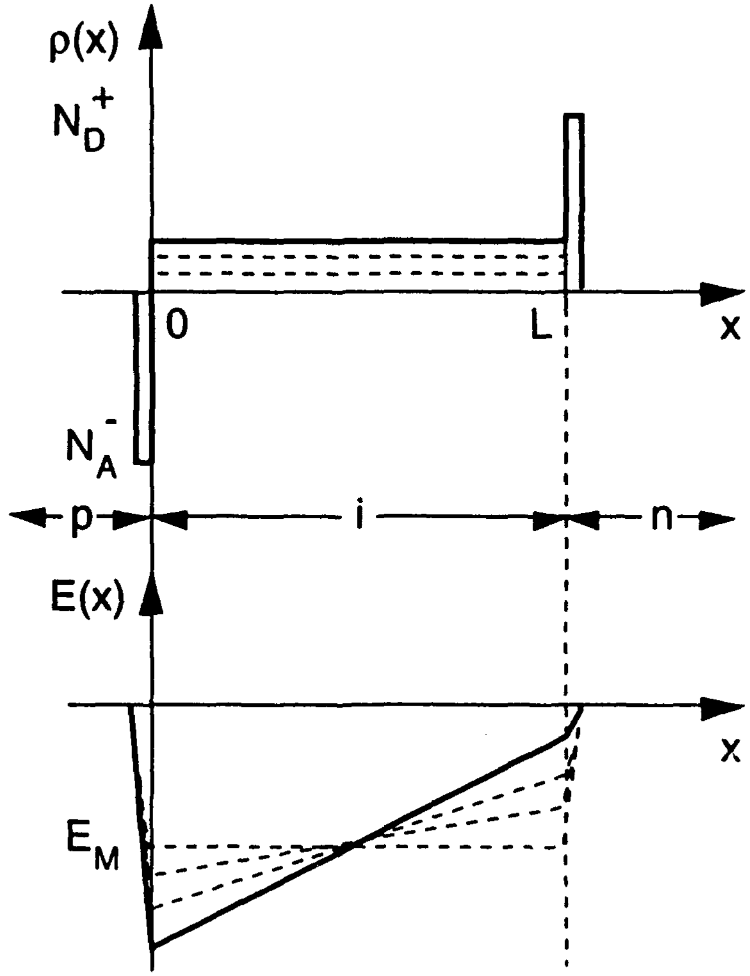
400
300
200
100
0
VOLTAGE (V)
0
10
20
30
40
50
TIME (μs)



10
8
6
4
2
0
CURRENT DENSITY (A/cm2)
0
10
20
30
40
50
TIME (μs)



(a)



(b)