INVESTIGATION OF A PHOTOCONDUCTIVE CLOSING AND OPENING BULK GaAs SEMICONDUCTOR SWITCH

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ABSTRACT

This paper describes recent results with the Bulk Optically-controlled Semiconductor Switch (BOSS) concept. The BOSS concept involves the excitation of electrons or holes from selected deep centers in the band gap of silicon doped, copper compensated gallium arsenide. The conductivity of the switch can be increased or decreased on command by irradiating the switch with laser light at different wavelengths in the infrared. Recent switch closing results are reported in which current densities as high as 10 kA/cm^2 were switched and fields as high as 20 kV/cm were held off. Lock on was observed at the higher fields (10 kV/cm). Strong optical quenching of the induced photoconductivity has been observed that demonstrates the feasibility of using the BOSS as a nanosecond opening switch.

INTRODUCTION

There are applications in inductive energy storage and pulse forming that require fast opening as well as closing. This can be achieved by exciting direct band gap semiconductors, such as GaAs, with band-gap laser radiation [1-2]. Semi-insulating gallium arsenide can be obtained with dark resistivities greater than 10^8 Ω cm, and since the electron-hole pair lifetime is controlled by fast recombination centers, subnanosecond conductivity decay times can be achieved. However, a short electron-hole pair lifetime represents a large conductivity loss mechanism, which for many applications dictates an unacceptable expenditure of expensive laser photons.

Schoenbach, et al. has proposed an alternative to the direct excitation of free carriers across the band gap of GaAs [3-4]. This concept, which we have called a Bulk Optically Controlled Semiconductor Switch (BOSS), utilizes the excitation of electrons from deep centers, such as provided by copper in coppercompensated silicon-doped semi-insulating GaAs (Cu:Si:GaAs), to induce photoconductivity. The small cross section for electron trapping into a Cu center allows for long conduction times without continuous laser radiation. Just as important, however, BOSS may be interrupted on command by the application of a second laser pulse of longer wavelength. This laser pulse floods the valence band with free holes, thus inducing a rapid quenching of the photoconductivity over a time scale given by the electron-hole pair lifetime of the material, which can be subnanosecond.

Optimization criteria for using Cu:Si:GaAs as a fast closing and opening switch are discussed by Ko, et al. in a companion paper [5]. The purpose of this paper is to present the results of high-power closing experiments with this material as well as the results of a feasibility study that demonstrates strong switch opening by rapid laser-stimulated quenching of the persistent conductivity.

SAMPLE PREPARATION

Low-resistivity, n-type GaAs can be made semi-insulating by the introduction of suitable acceptors into the material through diffusion. One defect, among several formed by copper in GaAs, is a deep acceptor known as Cu$_B$, which is located 0.44 eV above the valence band. The addition of the proper density of Cu$_B$ levels into GaAs grown with a shallow donor (such as Si), will result in a highly resistive, compensated crystal. By thermally diffusing copper into the n-type material, it is possible to achieve resistivities as high as 10^8 Ω cm at room temperature [6].

The crystals used in this investigation were taken from a GaAs wafer grown using the horizontal Bridgman technique [7]. The material was originally doped with silicon to a density of 5×10^{16} cm^{-3}. Silicon is a shallow donor in GaAs with an activation energy of about 5 meV. The crystals were then covered on one side with copper using a vacuum evaporator. The copper layers were approximately 1 μm thick. The samples were placed in a diffusion furnace and annealed in a low-pressure arsenic environment for 2 h. One sample was annealed at 500^{o}C ($\pm$1^{o}C) while another was annealed at 575^{o}C ($\pm$1^{o}C). Both samples were polished and Au-Ge contacts were formed on one side in a planar geometry. Both samples are rectangular in shape and about 5 mm on a side. They are both 0.25 mm thick. The contacts are 3 mm wide and form a 2.5 mm gap across the surface of the crystal.

The contacts were annealed at 450^{o}C for 3 minutes, after which the dark I-V characteristics were measured up to a voltage of 1.3 kV. The contacts were observed to be injecting (ohmic). From the I-V characteristics, the resistivity of the crystal annealed at 550^{o}C was found to be 10^3 Ω cm at 300 K. The resistivity of the crystal annealed at 575^{o}C was found to be 3×10^4 Ω cm, also at 300 K. Based on estimates of the Fermi level determined from these measurements, coupled with known solid solubility curves for copper in GaAs [8], we have concluded that the former crystal is undercompensated (n-type), while the latter crystal is overcompensated (p-type). Further references to the two samples will use these labels.

In order to determine the activation energy of the defect state controlling the dark conductivity of the p-type sample, measurements were made of the dark conductivity as a function of sample temperature. When the sample temperature was reduced from 293 to 241 K, the sample conductivity decreased by almost two orders of magnitude [9]. When the dark conductivity was plotted versus reciprocal temperature, a straight line was observed indicating that a single level controls the dark conductivity over this temperature range. The activation energy calculated from the slope is 0.46 $\pm$ 0.02 eV, which is consistent with the activation energy of Cu$_B$.

EXPERIMENTAL SETUP

Photoconductivity measurements were performed to test the BOSS concept. Two distinct experiments were conducted. The first experiment was designed to understand the closing properties of the compensated crystals at relatively high power. This experiment has already been described in [9]; however, it suffices to say that the p-type sample was optically excited by a Nd:YAG laser (λ = 1.06 μm, FWHM = 7 ns) at various intensities. The crystal switched a 50 Ω PFL charged to a maximum voltage of 5 kV into a 50 Ω load.

The second experiment was designed to test the complete opening and closing performance of both the n-type and the p-type samples at relatively lower power. Figure 1 illustrates the experimental apparatus. Two different lasers were used to allow two consecutive laser pulses to illuminate the crystal, one for closing the switch, and the other to open it. A Nd:YAG laser (λ= 1.06 μm, hν = 1.17 eV) was used to induce the initial conductivity in the crystal (i.e., "turn on" the switch). The laser is Q-switched, which results in a Gaussian shaped temporal response (FWHM = 26 ns) with a peak photon flux of 5×10^{23} cm^{-2} s^{-1} (90 kW/cm^2). The other laser pulse (the "turn-off" pulse) was generated by a tunable laser system. The laser has a center wavelength of 1.62 μm, which can be tuned $\pm$ 0.18 μm (hν = 0.77 $\pm$

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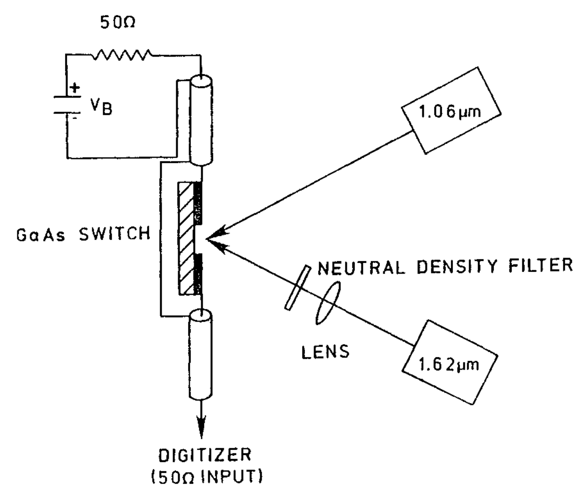

Fig. 1: A diagram illustrating the experimental set up for the opening experiments. Note that the crystal was illuminated on the face containing the contacts.

0.08 eV). This laser has a FWHM of 7 ns, and a peak photon flux of 5 x 10^{25} cm^{-2} s^{-1} (6 MW/cm^2) if the beam is focused onto the active area between the contacts (3 mm x 3 mm).

The bias circuit consists of a capacitor charged to a dc voltage, and connected to the crystal by a long 50 Ω cable (two-way transit time = 275 ns). The load is a 50 Ω oscilloscope termination, which acts as a current viewing resistor. The effective system impedance as seen by the crystal is 100 Ω. The current waveform is digitized by a Tektronix 7912 digitizer.

SWITCH CLOSURE

Figure 2 demonstrates a typical switching event for the p-type sample for peak fields less than 10 kV/cm [9]. Upon application of the laser pulse (the beginning of the pulse is indicated by the arrow), the current rapidly rises to 55 A and then decays to a long time constant "tail current," which after 160 ns has settled to 25 A. This represents an approximate tail current density of 3.7 kA/cm^2. The approximate conductivity of the sample on the "tail" of the photoresponse (as the persistent current is called) is 1 $(\Omega\, cm)^{-1}$.

As the peak field is increased above 10 kV/cm, however, a different effect is observed. At these fields the sample typically goes into "lock-on," a state that is typified not by a slowly decaying conductivity, as in the tail current, but by a constant voltage, as in a Zener diode. Our experiments indicate a lock-on voltage of 1.2 kV for this sample, which corresponds to an average field of 4.8 kV/cm [9]. Lock-on has been observed in other semiinsulating GaAs materials and InP at fields comparable to that observed here [2]. Lock-on is believed to be associated with the formation of stable space-charge domains created by the negative differential conductivity observed at high fields in GaAs (the Gunn effect).

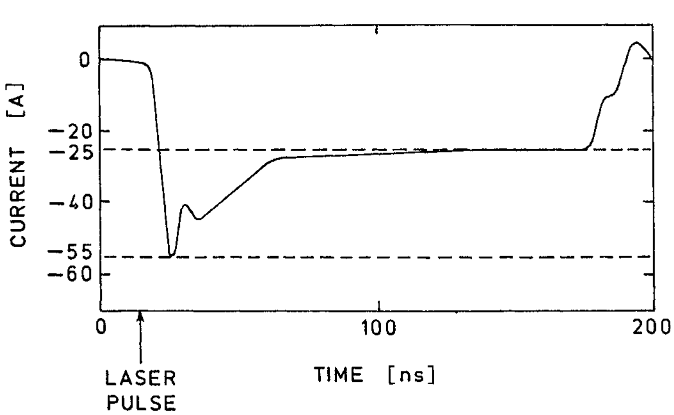

Fig. 2: Sample current vs time (note that the collapse of the current after 160 ns is due to the end of the transmission line voltage pulse).

Figure 3 is a plot of the peak charging voltage of the PFL versus the "steady state" current through the sample after the laser has initiated conductivity. The graph demonstrates that two regimes can be differentiated by their unique voltage-current characteristics. The tail current data are correlated with a straight line of small intercept. This is to be expected as the mechanism involved produces persistent conductivity; therefore, the I-V curve should be a straight line with zero intercept and a slope equal to the total resistance of the circuit. Lock-on represents constant voltage operation [2], thus the I-V curve should break to a new line, at the higher peak voltages, that has an intercept on the voltage axis equal to the lock-on voltage of the sample.

The photoresponses of the p and n-type samples were measured for comparison. Figure 4 demonstrates the response of both samples. Clearly, the n-type sample has a much longer conductivity decay time than the p-type sample (approximately 30 μs and 1 μs respectively). In addition, the ratio of the tail conductivity to the peak conductivity is larger for the n-type sample. Both of these results can be predicted by considering the different occupation probabilities for the CuB level in the two different samples [5].

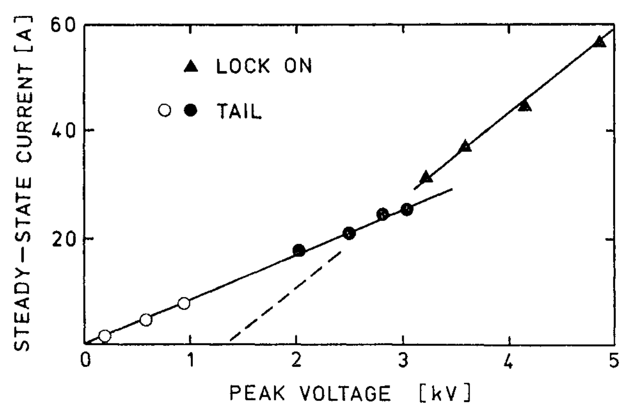

Fig. 3: Peak voltage vs tail/lock-on current. Open circles represent data measured with a low-voltage 50 Ω apparatus, while closed symbols represent data obtained with the higher voltage 50 Ω system.

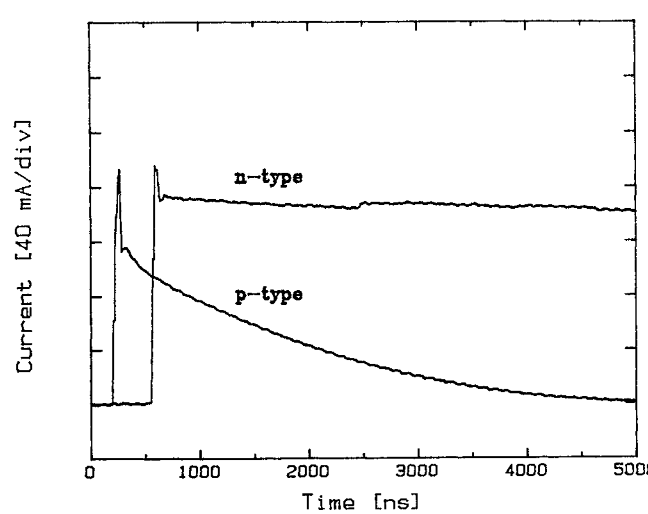

Fig. 4: Comparative turn-on current responses for the p- and n-type samples under similar conditions of voltage and light intensity.

SWITCH OPENING

The complete response of the p-type sample to excitation by both laser pulses is illustrated by a typical current waveform shown in Fig. 5. The crystal has first been excited by the 1.06 µm laser pulse, which causes a current overshoot to a peak of more than 0.6 A. The current then decays to a tail of about 0.4 A. After 200 ns, the 1.62 µm laser pulse is incident (photon flux = 5 x 10^{25} cm^{-2} s^{-1}), which initially creates an increase in current that rapidly gives way to a strong quench. The current decreases below the measurement resolution in under 10 ns.

The response of the current through the p-type crystal when the second laser pulse wavelength was increased to 1.8 µm (hν = 0.69 eV) is shown in Fig. 6. The initial current increase in Fig. 5 associated with the second laser pulse has completely disappeared in Fig. 6, with no apparent reduction in quenching.

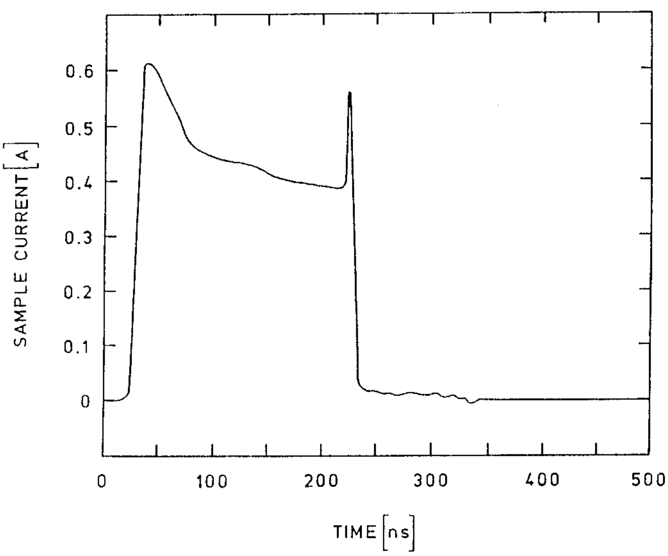

Fig. 5: The current response of the p-type crystal to both laser pulses. Sample conductivity is induced initially by the 1.06 µm laser pulse. The sample conductivity is quenched 200 ns later by the 1.62 µm laser pulse. The initial bias voltage is 67 V.

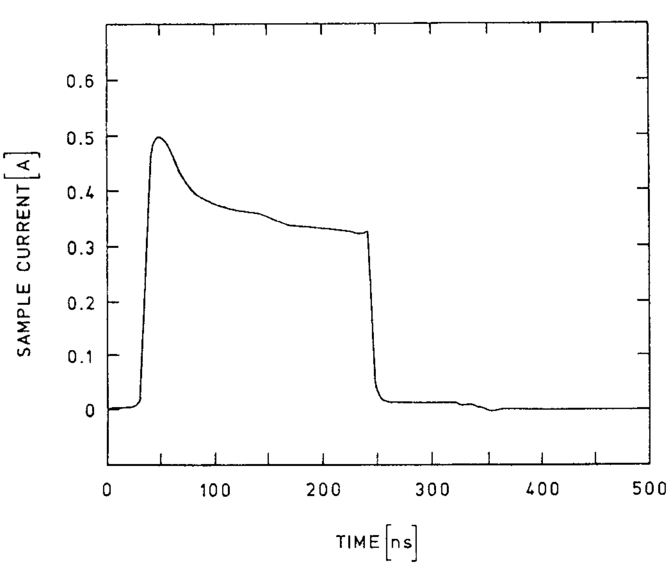

Fig. 6: The current response of the p-type crystal to both laser pulses. Sample conductivity is induced initially by the 1.06 µm laser pulse. The sample conductivity is quenched 200 ns later by the 1.8 µm laser pulse. The initial bias voltage is 55 V.

The intensity of the second laser pulse was varied from 5 x 10^{25} to 5 x 10^{22} cm^{-2} s^{-1} with neutral density filters. Figure 7 shows the intensity dependence of the quenching factor Q, which is defined as:

$$Q \equiv \frac{\Delta\sigma}{\sigma_T}$$

where $\Delta\sigma$ is the difference between the initial tail conductivity and the final quenched conductivity, and σ_T is the initial tail conductivity. The maximum value of Q that could be resolved was about 98%. Figure 7 indicates that Q decreases below 98% at a photon flux of 3 x 10^{24} cm^{-2} s^{-1}. As the laser intensity decreases, the initial increase in conductivity just prior to the fast quench rapidly diminishes. The initial peak virtually disappears at a photon flux of 5 x 10^{24} cm^{-2} s^{-1}.

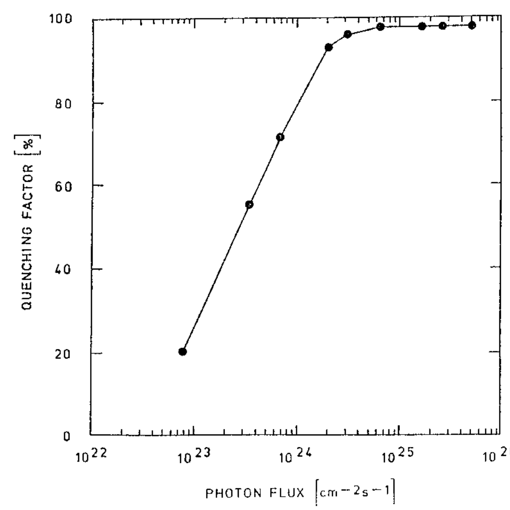

Fig. 7: Quenching factor as a function of the 1.62 µm laser pulse peak intensity. The maximum quenching factor that could be resolved was 98%.

For the case of Fig. 5, approximately 1 mJ of laser energy was expended to induce a tail conductivity of at least 0.5 $(\Omega\ cm)^{-1}$ in the crystal; however, because of the long absorption length for light at wavelengths exceeding the cutoff imposed by the band gap, only a fraction of the incident radiation was absorbed (estimated at 1%). Approximately 5 mJ of laser energy at 1.62 µm was expended to quench the conductivity to a final value less than 0.002 $(\Omega\ cm)^{-1}$. While the absorption at this wavelength is expected to be stronger, it is still estimated to be only 10%. Therefore, if the radiation were contained in the sample rather than allowed to pass through (e.g., by side pumping to increase the optical path length), then increased efficiency would be expected.

When the n-type sample was irradiated with an identical 1.62 µm laser pulse the quenching factor was approximately 20%, as opposed to at least 98% for the p-type sample. Therefore, the n-type sample demonstrated inferior opening with respect to the p-type sample, but produced a superior closing effect.

DISCUSSION OF RESULTS

The current response of the Cu:Si:GaAs switch to the two incident laser pulses can be understood by considering the electron gain and loss processes in the semiconductor. The initial overshoot of the photocurrent (Fig. 5 and Fig. 6) is due to electron-hole generation by a two step process through deep levels. After the first laser pulse is gone a portion of the electrons recombine rapidly with excess holes, either by direct recombination or through fast recombination centers. In addition, electrons may be captured in fast traps, such as EL2. However, the bulk of the conduction electrons decay slowly, because further decay is controlled by the slow capture processes associated with Cu_B.

However, if the valence band is suddenly flooded with photoexcited holes, then the lifetime of the tail electrons is reduced to the nanosecond regime or less. This is accomplished in our experiment by irradiating the crystal with a second laser pulse of photon energy less than 1 eV (thus avoiding Cu_B to conduction band transitions) but greater than 0.44 eV, which will excite stored holes from Cu_B into the valence band. Provided that the recombination rate for electron-hole pairs is substantially greater than the hole loss rate due to other mechanisms (e.g., hole trapping at Cu_B), the conductivity of the crystal is significantly reduced over a time scale of nanoseconds or less. This effect, called infrared photoquenching, is strong enough in Cu:Si:GaAs to be used as an opening switch, as observed in Figs. 5 and 6.

The short duration of the quenching process (less than 10 ns) indicates that the lifetime of the electron-hole pairs is shorter than the duration of the laser pulse. This fact points, in our opinion, to the presence of recombination centers in the Cu:Si:GaAs crystal, which could have been introduced either during the Cu diffusion or during crystal growth. A rate equation model of the switching process [5] predicts that recombination center concentrations as small as 10^{14} cm^{-3} can explain the observed rapid quenching of the photocurrent.

The second laser pulse applied after about 200 ns quenches the photocurrent. However, for laser wavelengths below 1.75 μm, the photoconductance shows a spike just before the on set of quenching (see Fig. 5). This initial increase in photocurrent is thought to be a two photon process. Based on published values of the two-photon absorption coefficient [10] we estimate that for our experiment two-photon excitation must be considered when the photon flux exceeds 10^{25} cm^{-2} s^{-1}. A two-photon process will not occur for photon energies less than half the band gap. The fact that the current spike became insignificant when the wavelength was increased to a value above 1.75 μm or the intensity was decreased to a value below 10^{25} cm^{-2} s^{-1} supports the two-photon interpretation of the switch response.

CONCLUSIONS

The feasibility of the BOSS concept has been successfully demonstrated with p-type Cu:Si:GaAs. Optically controlled closing and opening can be achieved on a nanosecond time scale. According to a rate equation model of the switch, currents on the order of kiloamperes should be controllable with reasonable laser power, thus making the material suitable for pulsed power applications. Furthermore, since the concept is not restricted to one particular material, as has been demonstrated with CdS [11], the shift of the controlling radiation into the visible range should be possible with wider band gap semiconductors.

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