EVALUATION OF TRANSPORT EFFECTS ON THE PERFORMANCE OF A LASER-CONTROLLED GaAs SWITCH

M.S. Mazzola, R.A. Roush, D.C. Stoudt, and S.F. Griffiths

Pulsed Power Technology Branch (Code F45)
Naval Surface Warfare Center
Dahlgren, Virginia 22448

ABSTRACT

The attempt to use bulk, semiconductor-based photoconductive devices as compact switches in demanding pulsed power applications has been limited by breakdown phenomena variously described as "thermal runaway," "surface flashover," and "lock-on," all forms of non-ohmic conduction. We present a summary of experimental observations related to optically induced non-ohmic current-voltage characteristics in semi-insulating semiconductors and integrate these observations into a revised power scaling criteria for bulk photoconductive semiconductor switches. We pursue an argument that unifies these observations with the physical mechanisms of charge-transport in the bulk and contact related phenomena at the device boundaries.

I. INTRODUCTION

The nature of the problems that have prevented the application of bulk photoconductive switch technology to pulsed power requirements is becoming clear. These problems include voltage hold-off performance low compared to that expected from bulk breakdown electric fields, reduced device lifetime when large currents are switched, and the observation of the so called "lock on" effect which has complicated the application of opening switches based on recombination-dominated photoconductivity decay in semi-insulating GaAs [1].

To account for the difference between expectation and realization of high-power photoconductive switches, we have studied the basic photoconductive device from first principles. We have discovered that boundary conditions imposed by contact physics have a profound effect on the expected device characteristics, and that the scaling rules for photoconductive switches must account for mechanisms that encourage the constriction of current (i.e., the formation of current "filaments") at current densities of interest for pulsed power applications (> 10^2 A/cm^2).

In the following discussion, we will examine the basic premise behind previously published scaling rules, and we will briefly discuss the nature of typical bulk conductivity. We will then show how the solution of the one-dimensional transport equations for bulk transport must be modified to include the boundary conditions imposed by the electrical contacts. It will then be clear how, under ideal circumstances, the choice of contact formulation (say *n-i-n* or forward biased *p-i-n*) can eventually dominate the observed *I-V* characteristics of the switch. We point out that such phenomena as turn-on gain, filamentation, and reduced switch lifetime due to contact damage can be correlated to the transition from ideal boundary conditions to something different, as a result of unintentional thermal and electric field stress at the contacts. Finally, we will postulate new scaling rules for "linear" mode of operation, and offer two different design methodologies to accommodate pulsed power applications.

Because our goal is to scale the Bulk Optically Controlled Semiconductor Switch (BOSS) to the multimegawatt regime [2] by forcing the switch to operate in the ohmic or linear mode, and thus retain control of both the closing and opening phase of the switching cycle [3],[4], we are motivated to this study by the need to understand, and thus avoid, the boundary between ohmic and non-ohmic conduction. As a first step, our analysis treats the device in current-voltage space, specifically investigating the causes of deviation from ohmic conduction. We do so by using a steady-state analytical calculation, realizing that a circuit load-line with sufficient resistance will eventually force the switch to achieve steady state. However, to understand the boundary, we must eventually investigate the transitions, which conceivably may be caused by different mechanisms that all lead to similar steady-state non-ohmic current transport phenomena (i.e., the sustaining mechanism of lock-on). Lacking a self-consistent, time-dependent model that considers drift, recombination, and trapping processes, a thorough analysis of lock-on initiation and formation must come later.

II. CURRENT TRANSPORT

The interest in photoconductive switches for pulsed power applications rests on the premise of scalability: High power photoconductive switches can be realized by increasing the dimensions of the active region of the switch in order to maintain modest average electric fields and current densities. Figure 1 illustrates an idealized photoconductive switch with rectangular-geometry. A widely reported, simple analysis [5],[6] predicts that the photoconductive switch resistance for the geometry of Fig. 1 obeys:

$$R = \frac{L^2}{K P \tau} \quad , \tag{1}$$

where R is the switch resistance, L is the electrode spacing, K is a material constant, P is the peak power of the laser pulse, and τ is the electron-hole pair lifetime.

Equation (1) assumes an electron-hole pair plasma, i.e. $n \approx p$, so that the ambipolar diffusion length can be defined as [7]

$$L_a = \sqrt{\frac{2\,(kT/q)\,\mu_n \tau}{b + 1}} \quad . \tag{2}$$

Rewriting (1) in terms of L_a results in

$$R = (L/L_a)^2 \, \frac{2\,(kT/q)\,\mu_n}{KP(b + 1)} \quad , \tag{3}$$

where μ_n is the electron mobility, and b is the ratio of the electron mobility to the hole mobility. For semi-insulating GaAs, the electron-hole pair lifetime is quite short, and, according to (2) so must be L_a. A typical value is 1 μm [8], which means P must exceed 3 MW per mho of conductance for a 1 cm length photoconductive switch. For those that choose to use a high-

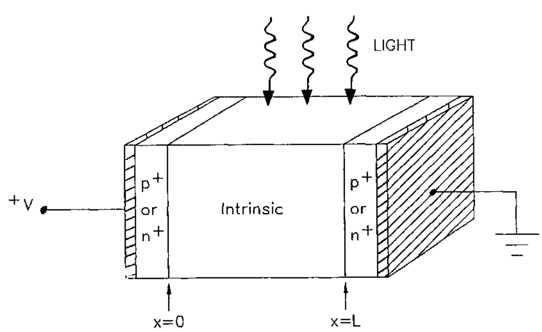

Fig. 1 An idealized model of a photoconductive switch.

Report Documentation Page

Report Documentation Page	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
JUN 1991	**N/A**	**-**

4. TITLE AND SUBTITLE	
Evaluation Of Transport Effects On The Performance Of A Laser-Controlled Gaas Switch	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Pulsed Power Technology Branch (Code F45) Naval Surface Warfare Center Dahlgren, Virginia 22448**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S)
	11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES

See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. Held in San Francisco, CA on 16-21 June 2013. U.S. Government or Federal Purpose Rights License.

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15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**SAR**	**4**	

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peak-power laser to activate the switch a question remains, does Eq. (3) represent a valid power-scaling law? In other words, can ohmic current-voltage characteristics be assumed for photoconductive switches operating at greater than 10 kV and current densities greater than 10^2 A/cm^2?

We have measured representative current-voltage characteristics of both copper-compensated semi-insulating GaAs [2],[9] and native-defect (EL2) compensated semi-insulating GaAs supplied by Sandia National Laboratory. Figure 2 contains the results of the experiment on the Sandia sample, a device consisting of a semi-insulating substrate 5×10^{-2} cm thick in which two 0.25-cm wide Ni:Au:Ge alloyed contacts have been formed on one face leaving a 0.25-cm gap between them. The sample was illuminated from the opposite face with a 1-cm diameter, 30-ns FWHM, 1064-nm Nd:YAG laser pulse containing approximately 100 μJ per pulse; however, a 30% pulse-to-pulse intensity variation is characteristic of the laser. The data points plotted in Fig. 2 were measured at peak photocurrent (i.e., peak illumination) in a 100-Ω system at currents sufficiently below the short-circuit current that the switch voltage could be accurately measured. The data follow two trends: at low current, the *I-V* characteristic is clearly ohmic, with a resistance of 130 Ω; at currents above about 1.1 A the *I-V* characteristic saturates, but significant scatter becomes noticeable. In other words, an ohmic characteristic is observed at this laser intensity until 1.1 A is exceeded (~90 A/cm^2), and then the current no longer increases with switch voltage, subject to an increased sensitivity to laser intensity variation.

A clue to the departure of the data from Ohms law can be derived by expanding (1) into its more general formulation, given by the ratio of a line integral of the electric field to a surface integral of the current density [10]

$$R = \frac{\int \mathbf{E}\cdot d\mathbf{l}}{\int \mathbf{J}\cdot d\mathbf{s}} \qquad (4)$$

Equation (1) results from (4) *only* if the electric field is uniform over L and J remains proportional to **E** through a spatially invariant conductivity σ. Otherwise, R will not remain a constant as the voltage is increased even if the right hand side of (1) does not change.

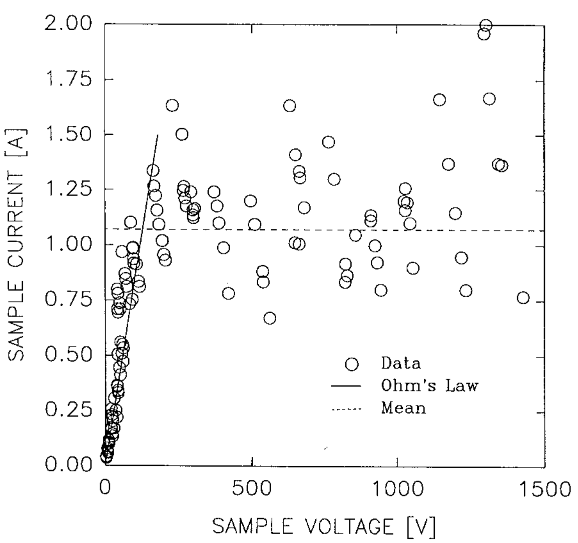

Fig. 2 Current-voltage data on a semi-insulating GaAs switch. The scatter in the data after saturation above 100 V has a mean of 1.1 A and a 27% standard deviation about the mean. This scatter is consistent with the variance in the laser pulse intensity.

What generally known mechanisms cause the conditions set forth above to be violated? Drift velocity saturation is well known to effect σ, causing J to become independent of **E**, but at a field magnitude greater than 2 kV/cm in GaAs [11]. There are other mechanisms, however, that effect the spatial uniformity of **E**, and thus require at least one-dimensional analysis. In this case, boundary conditions, i.e. the region near the electrical contacts, must be considered in *addition* to the bulk conductivity.

A. One-Dimensional Analysis

To illustrate the importance of the boundary conditions, and to introduce the concept of exclusion, which we define as a current-induced depletion region, consider the following simple example. Suppose an intrinsic semiconductor is subjected to strong optical injection of electron-hole pairs throughout the bulk. Assuming that a plasma is created such that $n = p$, and that the electrons and holes have a constant lifetime τ, then the steady state one-dimensional continuity equations are

$$\frac{1}{q}\frac{dJ_p}{dx} = g - p/\tau \qquad (5)$$

$$-\frac{1}{q}\frac{dJ_n}{dx} = g - n/\tau \qquad (6)$$

where g is the electron-hole pair generation rate, and J_n and J_p are the sum of drift and diffusion currents of the electrons and holes, respectively. The total current density is $J_T = J_n + J_p$. Equations (5) and (6) can be combined with the condition $n = p$ to derive an ordinary second-order linear differential equation:

$$\frac{d^2n}{dx^2} - \frac{n}{L_a^2} = -\frac{g\tau}{L_a^2} \qquad (7)$$

for which the solution is readily found to be

$$n(x) = \frac{[n(0) - g\tau]\sinh\left(\frac{L-x}{L_a}\right) + [n(L) - g\tau]\sinh\left(\frac{x}{L_a}\right)}{\sinh(L/L_a)} + g\tau \qquad (8)$$

The boundary conditions are introduced by specifying the electron concentrations at the anode $n(0)$ and cathode $n(L)$, respectively.

B. Boundary Conditions

To specify the boundary conditions, the nature of the interface between the electrical contacts and the bulk must be determined. Fortunately, most photoconductive switches made from GaAs use some form of the well known Ni:Au:Ge alloy for both the anode and the cathode. This is also true of the sample used to obtain Fig. 2. The Ni:Au:Ge metallization forms a thin strongly n-type region in GaAs below the contact during alloying at temperatures exceeding 360 °C [12].

Thompson and Lindholm [13] have treated the case of photoconductors with strongly doped contact regions, and for the case of a *n-i-n* structure, which models the typical Ni:Au:Ge contact geometry described above, the boundary condition of greatest importance is at the anode. This is because an ideal n^+ anode cannot inject holes, thus forcing the solution in the vicinity of the anode to change dramatically from that of the bulk.

To see why, consider the case where the contact regions have a negligible effect on the current-voltage characteristics, which we call the "plasma mode" of conduction. Here, (8) is substituted into the current transport equation ($J_T = J_n + J_p$) and integrated to yield the relationship between sample voltage V and J_T

$$V = \frac{J_T}{q(\mu_n + \mu_p)}\,\frac{L_a \sinh(L/L_a)}{f(J_T)}\,\ln[h(J_T)] \qquad (9)$$

If $e^{L/L_a} >> 1$ and J_T remains modest, then

$$f(J_T) \approx g\tau \sinh(L/L_a) \quad (10)$$

and

$$h(J_T) \approx e^{L/L_a} \quad . \quad (11)$$

In this case, Eq. (9) reduces to an ohmic relationship that satisfies the conditions necessary to validate Eqs. (1) and (3).

However, as the current density is increased, the ohmic relationship gradually begins to fail because of the formation of an anode exclusion zone. Since the anode does not inject holes, J_p must be identically equal to zero at the interface between the heavily doped region and optically excited bulk. This boundary condition is achieved by balancing hole drift toward the cathode with hole diffusion toward the anode. The diffusion current is achieved by a monotonic reduction in the hole population as the anode is approached from the bulk. To maintain quasi-neutrality n remains nearly equal to p throughout the exclusion region; a condition virtually assured by the very small Debye length at free carrier densities on the order of 10^{16} cm^{-3}. The boundary condition at the anode can be approximated by

$$n(0) = g\tau - \frac{L_a J_T}{2kT\mu_n} \quad (12)$$

for the conditions that satisfy (10) and (11).

As the density of electrons and holes in the exclusion zone becomes much less than that in the bulk region the applied potential becomes disproportionally distributed across the exclusion zone. Because increases in switch voltage are not proportionally distributed across the bulk plasma, then the current density increases at a slower rate than the voltage such that saturation of the overall I-V relationship is observed. Because the exclusion zone extends only a few ambipolar diffusion lengths, the electric field near the anode can build to quite large magnitudes in semiconductors with very small values of L_a, such as semi-insulating GaAs or InP. Thompson and Lindholm [13] have calculated anode field enhancements of as much as 40 or more, which in photoconductive switches used in pulsed power applications can clearly cause intense thermal and electric field stress at the anode. Not surprisingly, device failure often occurs at the anode in photoconductive switches with an *n-i-n* structure [2],[14]

C. Other Non-Linear Mechanisms

There are other mechanisms, such as drift-velocity saturation and field-sensitive trapping kinetics, which require us to justify the association of exclusion with the data of Fig. 2. In the first instance, our observation of saturation inevitably occurs in *n-i-n* structures at average electric fields well below the known saturation fields (> 2 kV/cm in GaAs [11]). In Fig. 2, saturation begins at less than 200 V or 800 V/cm, average. However, drift velocity saturation can influence the I-V characteristic *after* saturation, and indeed may explain why the sample in Fig. 2 appears to remain saturated at average fields that would easily result in avalanching in the exclusion zone (see Ref. [15] for details).

As to field-dependent trapping, we comment that changes in the temporal shape of the current waveform did occur at the higher bias voltages, but it is not known if this is attributable to field-sensitive trapping kinetics, or just changes in the transport solution. Indeed, there is some debate in the literature over the relative importance of field-dependent trapping over exclusion (see Ref. [16] for this point of view), but we point out that exclusion is a natural consequence of the transport problem in photoconductive switches, while field dependent trapping is generally not directly observable, and remains a form of phenomenology.

III. POWER SCALING ISSUES

Given that the ability to power scale a linear-mode device, such as the BOSS device, requires the uniform distribution of electric field and current density, we have to consider mechanisms that work against this ideal. Ridley [17] has shown using thermodynamic arguments that any form of current-controlled negative differential conductivity (NDC) is unstable against the formation of current filaments. There are many mechanisms that can be classified as leading to or initiating current-controlled NDC, including double injection [18], thermal runaway [19], and magnetic constriction [20]. All of these processes represent different ways of initiating filamentation and lock-on, but do not change the final steady-state conduction parameters of the filament (assuming melting does not occur), which is the formation of a constricted dense electron-hole plasma with current-voltage characteristics determined by double-injection transport physics, and whose radial dimensions are limited by diffusion [8]. The question remains, how to avoid the initiating mechanisms?

Exclusion can play an initiating role when the current density exceeds a limit, estimated by rearranging (12) for the condition $n(0) << g\tau$

$$J_T/g\tau < \frac{2kT\mu_n}{L_a} \quad , \quad (13)$$

because the resulting high fields near the anode can lead to thermal runaway or the initiation of avalanche injection at defect sites in the exclusion zone. In other words, the region near the anode can be converted by breakdown or heating into a reservoir of holes and thus defeat the anode blocking conditions. While the creation of holes would appear to reduce the fields in the exclusion zone by relaxing the boundary condition, it is also likely that hole injection would occur at localized defect centers first (the "weak links") which would enhance the formation of filaments. There would appear only two satisfactory ways to prevent the onset of instabilities due to exclusion: either satisfy (13) under all operating conditions, or utilize a contact formulation that prevents the formation of the exclusion zone, e.g., a forward-biased *p-i-n* structure. We have begun preliminary experiments to test the suitability of forward-biased *p-i-n* structures for avoiding saturation, but conclusive results are not yet available, so we will concentrate on satisfying (13) in the following discussion.

The problem with satisfying (13) under all operating conditions is probably not severe for linear closing switches based on pure silicon; however, opening switches that operate in the ohmic regime at peak current will probably violate (13) at some point in the opening cycle, where the voltage is increasing and the current density is decreasing along a path dictated by the load-line, which may not be along the optimum path imposed by the decay of $g\tau$. A simple power scaling criteria for linear-mode opening switches is now derived from (13).

First, we assume that saturation occurs when the inequality given by (13) becomes an equality

$$(J_T/g\tau)_c = \frac{2kT\mu_n}{L_a} \approx 4.2\times10^{-13}\ A{\cdot}cm \quad , \quad (14)$$

which is a constant. The indicated value is calculated when $L_a = 1 \times 10^{-4}$ cm, $kT = 0.026$ eV, and $\mu_n = 5000$ cm^2/V-s (i.e, GaAs). We can then bound the regime of ohmic conduction by combining (14) with Ohms law

$$V \le \frac{L}{q(\mu_n + \mu_p)} (J_T/g\tau)_c \approx 118\ V \quad . \quad (15)$$

Here, the saturation voltage is calculated for $L = 0.25$ cm. Thus, the I-V characteristic for this sample, assuming L_a is a constant, will saturate at 118 V regardless of the laser intensity. If a load line is imposed on the sample, and the open circuit voltage is greater than 118 V, then there will always be some point during the opening cycle that saturation will occur.

That is not to say that an exclusion zone will form in the off-state *prior* to illumination, because transport in this case is likely to be dominated by majority carriers, and if the majority carriers are electrons, then ohmic *I-V* characteristics are expected. However, during the turn-off cycle following peak illumination, the electron-hole plasma should recombine at more or less the same rate over several orders-of-magnitude of $g\tau$. For a 100-Ω load line and a 1-kV open circuit voltage, Fig. 3 illustrates that a sample with sufficient $g\tau$ at peak illumination ($g\tau = 10^{16}$ cm^{-3} in this example) to operate in the linear mode, will inevitably saturate as $g\tau$ decays (through 10^{13} cm^{-3} in the example). During the time the sample is saturated, the conditions for anode exclusion zone breakdown and initiation of filamentation exist. Therefore, for *n-i-n* contacts either the sample voltage must remain below the critical value at all times, meaning values of L much larger than Eq. (1) would make desirable, or the switch must be returned to dark equilibrium conditions fast enough that the probability of nucleating filaments is small. Anything else risks the onset of lock-on.

IV. CONCLUSIONS

We have demonstrated the importance of boundary conditions in understanding current transport in photoconductive switches designed for pulsed power applications. For the most common switch formulation, that of an *n-i-n* device, we have developed a power scaling criteria that imposes a minimum switch conductivity in order to achieve sufficient uniformity of the electric field such that instabilities in current transport are avoided. This minimum conductivity has not been included heretofore in the power scaling criteria for photoconductive switches.

For linear mode closing switches with long carrier lifetimes, such as silicon, power scaling can be achieved if careful attention is given to creating a large enough value of $g\tau$. However, for opening switches based on *n-i-n* structures a clearer understanding of the time development of breakdown effects that lead to filamentation are necessary if "lock-on" or "gain" mode is to be avoided at all times during the opening cycle.

The authors thank Dr. Guillermo Loubriel of Sandia National Laboratories for kindly supplying the semi-insulating GaAs switch used in this investigation. This work was partially supported by the Independent Research and the Independent Exploratory Development programs at the Naval Surface Warfare Center.

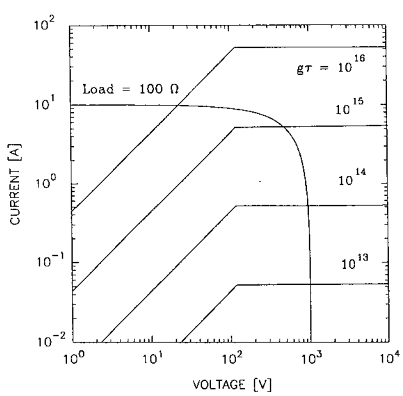

Fig. 3 An example of transport effects on an idealized GaAs switch during the opening cycle as the laser intensity decays. The operating point at any time is given by the intersection of the switch *I-V* characteristic with the load line. $g\tau$ in the figure has units of cm^{-3}.

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