

SIMULATION OF CURRENT FILAMENTS IN PHOTOCONDUCTIVE SEMICONDUCTOR SWITCHES^{*†}

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Abstract

Photoconductive semiconductor switches (PCSS's), such as optically-triggered GaAs switches, have been developed for a variety of applications. Such switches exhibit unique properties as a consequence of lock-on, a phenomenon associated with the bistable switching of these devices. In this paper, lock-on is explained in terms of collective impact ionization. Furthermore, the effect of defects on the performance of these devices is investigated.

I. INTRODUCTION

Photoconductive semiconductor switches (PCSS's) have been developed for a variety of pulsed power applications in which optical power is used to control electrical power. These switches fall into two main categories: conventional photoconductive switches and optically-triggered bistable switches [1].

The basic operation of a photoconductive switch is schematically indicated in Fig. 1. Each switch consists of a semiconductor between two electrodes. As seen in the figure, the circuit consists of the switch, the power supply, and the load. Prior to illumination, the "off" state current is determined by the resistivity of the semiconductor. For a conventional switch, the "on" state conductivity is proportional to the density of electrons and holes created by the illumination with 1 electron-hole pair created for every photon absorbed [1].

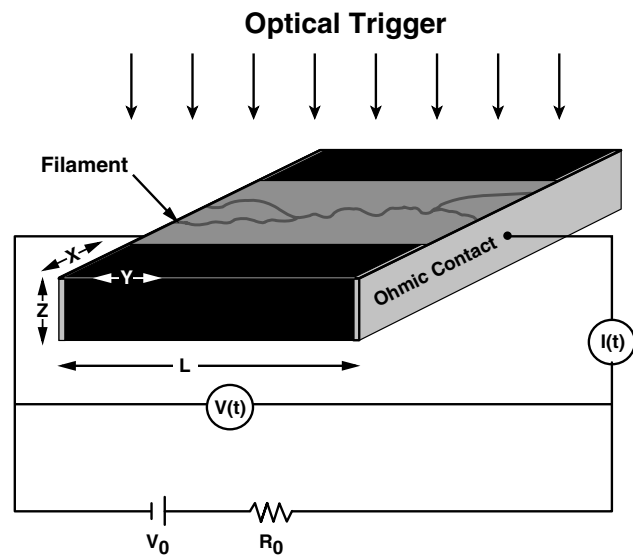


Figure 1: Schematic of a photoconductive semiconductor switch. The photoconductive current flows between two contacts (electrodes). The filamentary current seen during lock-on is also shown. The switch is shown in a circuit consisting of a power source and a resistive load.

The optically-triggered bistable switches rely on a different mechanism of operation that has been named "lock-on" [2,3]. When lock-on occurs, the switch voltage becomes approximately constant, referred to as the lock-

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on voltage, independent of the power supply voltage [2,3]. As many as 10^5 electron-hole pairs are generated per absorbed photon, allowing the use of low power lasers to trigger lock-on (also known as a high gain mode). Furthermore, when the electrode gap is varied, the average lock-on field [2,3] remains constant. Additional studies determined that the current flow is filamentary during lock-on [4,5].

Several theories have been proposed to explain lock-on [6-10]. Most theories have assumed that field enhancements lead to avalanche breakdown at unexpectedly low fields to explain the extra carriers. For example, one class of theories considers the enhancement at the head of a streamer [8,9].

The theory described in this paper is motivated by a set of calculations of the properties of a steady-state theory of electrical breakdown [11,12]. For these calculations, an ensemble Monte Carlo method is used to solve for the carrier distributions. These calculations are motivated by collective impact ionization theory [13,14]. In this theory, the electrical breakdown arises because impact ionization is increased at high carrier densities. This occurs because the carrier-carrier scattering redistributes energy thereby making the carrier distribution function Maxwellian [13,14].

II. THEORY

Collective impact ionization, produces the essential nonlinear phenomenon consistent with the observed S-like current-voltage characteristic [13,14]. The basic idea is that impact ionization is more efficient at high carrier density. One motivation for this approach is the observation of a stable lock-on state maintained by a field smaller than the threshold field for impact ionization [2,3].

Consider the carrier distribution as a function of energy for a given electric field for two cases, the extreme limits of low and high carrier density relative to a cross-over density, approximately $n_c \approx 10^{17} \text{ cm}^{-3}$ [13-15]. For high density such that carrier-carrier scattering dominates carrier-phonon scattering, the distribution function must approach a quasi-equilibrium Maxwellian distribution characterized by a single temperature, the carrier temperature T_c .

The low density case is more complicated to analyze because the shape of the distribution function depends on the microscopic details of the carrier-phonon interaction. In particular, at low energies the cooling is due to long wavelength polar optical emission [16]. Above the L-point energy of the GaAs conduction band, the much stronger optical deformation potential scattering between L-valleys becomes dominant [16]. The net result is a non-thermal energy distribution function. At energies below the L-point energy, the temperature appears high. At higher energies, the temperature appears much lower due to the effectiveness of the phonon cooling. The increasing

electron density of states further increases the cooling rate.

Now consider the impact ionization rates for these two different distribution functions. First, recall that carrier generation by electron impact ionization occurs if an electron reaches a threshold energy approximately one band-gap above the conduction band edge (the threshold energy is determined by energy and momentum conservation). Thus the shape of the distribution function in this energy region is critical because it governs the rate of impact ionization. Clearly, the high density distribution function leads to more impact ionization.

At this point the filamentary current flow of lock-on can be understood. A key issue is the coexistence of regions with high and low current density for a given electric field. Inside the filament the carrier density is high which is consistent with a high rate of impact ionization. Outside the filament the carrier density is low which is consistent with a low rate of impact ionization. Given that the electric field is the same on the inside and the outside, the variation in current density is due solely to the variation in carrier density.

III. CALCULATIONS

For the calculations to be described, the theory is formulated in terms of hydrodynamic-kinetic transport equations for electrons and holes optically injected into a semi-insulating GaAs switch biased by an external circuit [13,14,18,19]. The key equations are continuity equations for electron density n and hole density p and energy balance equations for the electron temperature T_n and the hole temperature T_p [18,19].

The carrier densities and temperatures are obtained from kinetic equations. The carrier densities are obtained from the following equations:

$$\begin{aligned} \frac{\partial n}{\partial t} &= \frac{1}{q} \nabla \mathbf{J}_n + R_{iiAn} - k_{2f} T^+ n + k_{2r} T^0 \\ \frac{\partial p}{\partial t} &= -\frac{1}{q} \nabla \mathbf{J}_p + R_{iiAp} - k_{1f} T^0 p + k_{1r} T^+ \end{aligned} \quad (1.1)$$

These equations include contributions from transport (the gradient terms), impact ionization, Auger recombination (these are included in the R_{iiA} terms) and defect recombination (the remaining terms involving reaction rates and defect concentrations). The carrier currents in these equations are obtained from the drift-diffusion approximation:

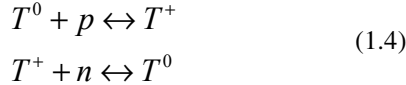
$$\begin{aligned} \mathbf{J}_n &= -q v_n n + D_n \nabla n \\ \mathbf{J}_p &= q v_p p - D_p \nabla p \end{aligned} \quad (1.2)$$

The carrier temperatures are obtained from power balance equations for electron and hole temperatures:

$$\begin{aligned}\frac{3k_B}{2} \frac{\partial T_n}{\partial t} &= -q\mathbf{v}_n \cdot \mathbf{E} - R_n(T_n, T_L) \\ \frac{3k_B}{2} \frac{\partial T_p}{\partial t} &= q\mathbf{v}_p \cdot \mathbf{E} - R_p(T_p, T_L).\end{aligned}\quad (1.3)$$

In each of these equations, the Joule heating term is compensated by an optical phonon cooling term; in this equation T_L is the lattice temperature.

The carriers are assumed to recombine at defects such as deep donor defects, such as the EL2 defects expected in semi-insulating GaAs [17]. These defects exist in neutral and positive charge states, T^0 and T^+ , respectively:



The following kinetic equations govern the defect recombination in terms of forward and reverse rate coefficients for each defect reaction:

$$\begin{aligned}\frac{\partial T^0}{\partial t} &= -k_{1f}T^0p + k_{1r}T^+ + k_{2f}T^+n - k_{2r}T^0 \\ \frac{\partial T^+}{\partial t} &= k_{1f}T^0p - k_{1r}T^+ - k_{2f}T^+n + k_{2r}T^0\end{aligned}\quad (1.5)$$

In accordance with the ensemble Monte Carlo calculations, the electron distribution function is approximated in terms of two temperatures, one for the main portion and the other for the high-energy tail [11,12]. The temperature of the main portion of the distribution governs the phonon cooling rate and the temperatures of the tails govern the rate of impact ionization and Auger recombination:

$$\begin{aligned}R_{iiAn} &= c_n(T_n)(n_i^2(T_m) - np) \\ R_{iiAp} &= c_p(T_p)(n_i^2(T_p) - np)\end{aligned}\quad (1.6)$$

In these expressions,

$$n_i(T) = \sqrt{N_c(T)N_v(T)} \exp(-E_G/k_B T). \quad (1.7)$$

The effects of carrier-carrier scattering on impact ionization are included by letting the tail temperature depend on the carrier density. This is done by using the following functional form for the tail temperatures:

$$\begin{aligned}T_{in} &= \alpha_n T_n \\ T_{ip} &= \alpha_p T_p\end{aligned}\quad (1.8)$$

with

$$\begin{aligned}\alpha_n &= \frac{n\beta_n + n_c}{n + n_c} \\ \alpha_p &= \frac{p\beta_p + p_c}{p + p_c}\end{aligned}\quad (1.9)$$

In these calculations $\beta_n = 0.2$ and $n_c = 10^{17} \text{ cm}^{-3}$. Furthermore, the hole distribution is assumed to be Maxwellian with $\alpha_p = 1.0$.

The phonon cooling rates for electrons R_n and holes R_p are due to polar optical and intervalley scattering for a Maxwellian distribution [16]. These rates also include acoustic phonon scattering. This cooling rate is computed analytically and also from a table obtained from the actual density of states used in the Monte Carlo transport calculations.

The results of these calculations are in approximate agreement with the Monte Carlo predictions for lock-on.

At this point we consider the effects of defect recombination on the lock-on field and other characteristics. These results are shown in Table I.

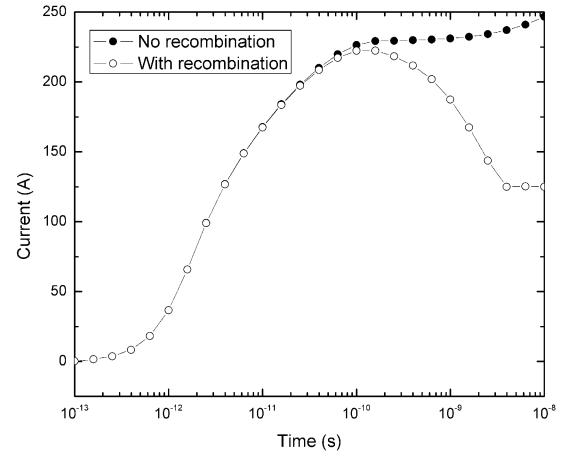


Figure 2: The computed switch current as function of time after triggering. The current rises as the carrier density increases. For the case that includes defect recombination, the current drops to a lower steady state value at long times after trigger. The lock-on voltage is increased for this case.

The time-dependence of the switch current following optical triggering of a GaAs switch is shown in Fig. 2. The calculations are examined for a particular case with an applied voltage $V_0 = 50 \text{ KV}$ and a load resistance $R_0 = 74 \text{ Ohm}$. Figure 4 shows the switch current as a function of time following a 1 ps optical pulse. During the pulse, the current rises and reaches a steady state value at long times.

Due to the reduced optical phonon cooling, the carrier temperature is highest near the center of the illuminated stripe. During this time the lattice temperature remains

constant. After approximately 10 ps, the carrier temperature has become large enough to produce band-to-band impact ionization whose rate is highest in the high carrier density region in the center of the stripe. This creates a growing filament (a runaway instability) whose growth is finally halted by the limitations of the external circuit.

This figure also shows the effects of defect recombination. For this case, the defect recombination rate $R = 10^9 \text{ sec}^{-1}$. In this case, the lock-on voltage is increased to approximately 40 KV corresponding to a field 160 KV/cm. Further increasing the defect recombination rate to 10^{10} sec^{-1} suppresses lock-on.

The rapid rise in carrier density drops the switch voltage dramatically to the lock-on voltage. This drop is caused by the additional loading of the power supply due to the increased current following impact ionization.

Table I.

| V_n (KV) | R_i (sec^{-1}) | V_{lo} (KV) |
|------------|-----------------------------|---------------|
| 50 | 0 | 30 |
| 50 | 10^9 | 40 |
| 50 | 10^{10} | no lock-on |
| 50 | 10^{11} | no lock-on |
| 200 | 0 | 40 |
| 200 | 10^{11} | 60 |

IV. SUMMARY

In summary, our theory describes some of the most important features of optically triggered SI GaAs switches: (1) a lock-on field that is independent of power supply voltage and time following switching, (2) filamentary current flow, (3) a rapid rise-time, (4) bistable switching, and (5) lock-on field that increases with defect density.

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