A COLLECTIVE IMPACT IONIZATION THEORY OF LOCK-ON*

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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 associated with lock-on, a phenomenon associated with bistable switching. In this paper lock-on is explained in terms of collective impact ionization.

I. INTRODUCTION

Photoconductive semiconductor switches (PCSS's) have been developed for a variety of 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 conventional switches, the "on" state conductivity is proportional to the optical energy used for illumination.

The optically-triggered bistable switches rely on a very different mechanism of operation which has been named "lock-on" [2,3]. When lock-on occurs, the switch voltage becomes approximately constant, the lock-on voltage, independent of the power supply voltage. Furthermore, when the electrode gap is varied, the average field remains constant. Further studies found that the current flow is filamentary during lock-on.

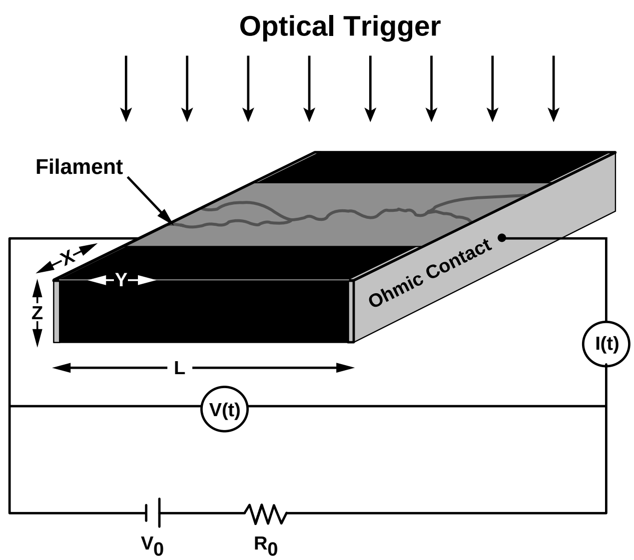

Figure 1: Schematic of a a photoconductive semiconductor switch. The photoconductive current flows between two contacts (electrodes). The filamentary current seen during lock-on is also shown. The switch is shown in a circuit consisting of a power source and a resistive load.

Several theories have been proposed to explain lock-on [4-8]. Most theories have assumed that field enhancements lead to avalanche breakdown at at unexpectedly low fields. For example, one class of theories considers the enhancement at the head of a streamer [6,7].

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The theory to be described in this paper is motivated by the guiding assumption or ansatz that the switch has an S-like current-voltage characteristic as shown in Fig. 2. This principle has guided our theoretical work from the start. In addition to the S-curve, this figure shows the load line corresponding to the power supply and resistive load shown in Fig. 1. The steady state solutions for switch voltage of the circuit shown in Fig. 1 are given by the intersection of the S-like curve and the load line. Of the three solutions, the high-current “on” state and low-current “off” state solutions are the only two which are stable. The working assumption has been that optical triggering drives the system along the load line from the "off" state, through the unstable state, and to the “on” state.

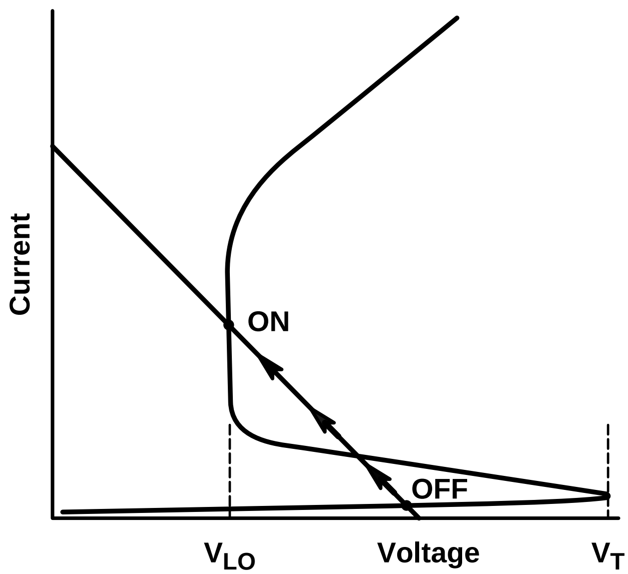

Figure 2: The S-like current-voltage curve which has guided our approach to optically-triggered switches. The steady state solutions are given by the intersections of the load line and the S-like curve. The lowest current solution is the “off” state; the highest current solution is the “on” state. The intermediate solution is an unstable solution. The optical trigger drives the system from the “off” state, through the unstable state, to the “on” state.

II. COLLECTIVE IMPACT IONIZATION

Collective impact ionization, the theory to be described, produces the essential nonlinear phenomenon consistent with the S-like current-voltage characteristic [9,10]. The basic idea is more efficient impact ionization 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.

Figure 3 shows 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. 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. This distribution function becomes a straight line whose slope is determined by the temperature.

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 [11]. Above the L-point energy, optical deformation potential scattering between L-valleys becomes dominant [11]. The net result is a non-thermal energy distribution function, schematically shown in Fig. 3. 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.

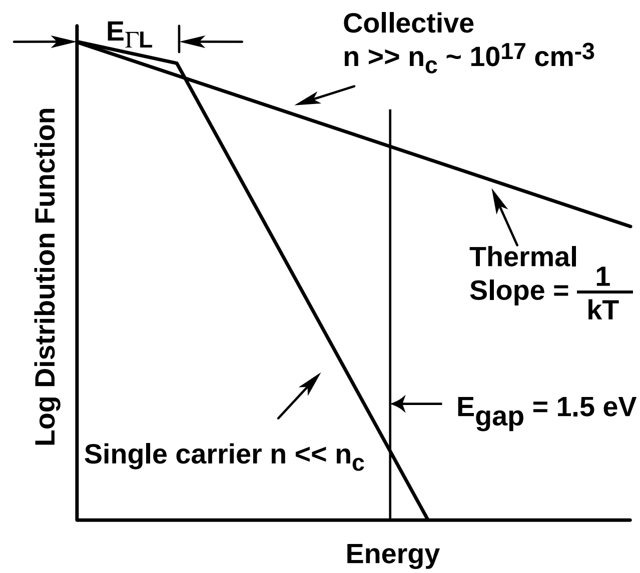

Figure 3: Schematic of the carrier distribution function versus energy for the limiting cases of low and high density. The electric field is the same for both cases.

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 bandgap 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. COMPARISON WITH DATA

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 SI GaAs switch biased by an external circuit [9-10]. The key equations are a continuity equation for electron density *n*, a continuity equation for hole density *p*, and an energy balance equation which governs the energy distribution functions for the carriers, primarily the electron distribution function [9-12].

In accordance with Fig. 3, the electron distribution function is approximated in terms of two temperatures, one for the low-energy portion and the other for the high-energy tail. The temperature of the tail T_{tail} determines the impact ionization rate term

$$R_{ii} \propto (n_i^{\,2}(T_c) - np)$$

by controlling the intrinsic carrier density

$$n_i(T_{tail}) \propto \exp(-E_G / k_B T_{tail}) \ .$$

The temperature T_{tail} is obtained from a power balance equation

$$\tfrac{3k_B}{2}\partial T_{tail} / \partial t = \mathbf{E} \cdot \mathbf{J} - nR(n, T_{tail}, T_L)$$

in which the Joule heating term is compensated by an optical phonon cooling term R; in this equation T_L is the lattice temperature.

A power balance approach becomes problematical at low carrier density because of the two-temperature nature of the distribution function. Given this power balance approximation, the density dependence is obtained by approximating the term as a linear combination:

$$R(n, T_{tail}, T_L) = \frac{nR_L + n_c R_H}{n + n_c} \ .$$

The high density cooling rate R_H is the rate due to polar optical and intervalley scattering for a Maxwellian distribution [11]. The low density rate R_L is solely determined by intervalley scattering [10]. An important feature included in these approximations is that $R_H << R_L$ for temperatures such that the high-density distribution resides below the threshold for intervalley scattering [10]. At higher temperatures both cooling rates become comparable and controlled by intervalley scattering [10].

The theory is compared with measurements of the current and voltage following optical triggering of a GaAs switch [9-10]. The calculations are examined for a particular case with an applied voltage V_0 = 7400 V and a load resistance R_0 = 74 Ohm. Figure 4 shows the switch voltage V(t) as a function of time following a 1 ps optical pulse. During the pulse, the voltage drops as carriers are injected; following the pulse, the carrier density remains nearly constant for approximately 10 ps. Also, during this time, the carrier temperature in the center of the illuminated volume is increasing as can be seen in Fig. 4.

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 risen 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.

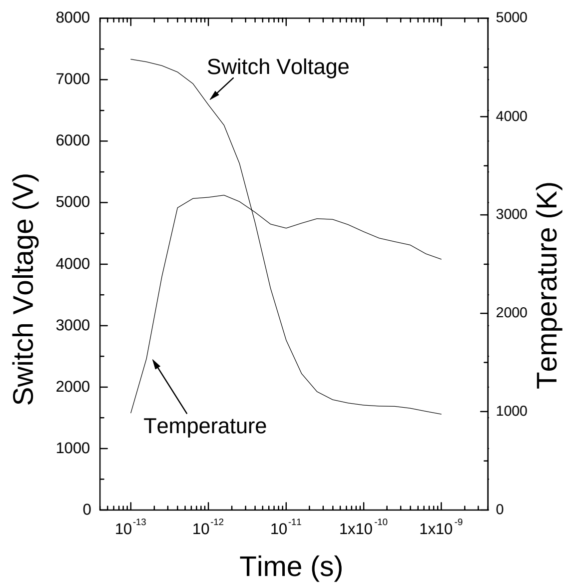

Figure 4: The computed switch voltage and temperature as function of time after triggering. The temperature rises following triggering as the carrier density increases. At the same time the switch voltage drops. At long times these quantities reach steady state values.

The rapid rise in carrier density drops the switch voltage dramatically to the lock-on voltage as can be seen in Fig. 4. This drop is caused by the additional loading of the power supply due to the increased current following impact ionization.

The nearly constant switch voltage beyond the switching time demonstrates that this model can successfully reproduce the experimentally observed constant lock-on field. For this particular sample with electrode spacing L = 0.25 cm, the lock-on field of approximately 5 kV/cm compares well with the empirical value of 4-6 kV/cm [1].

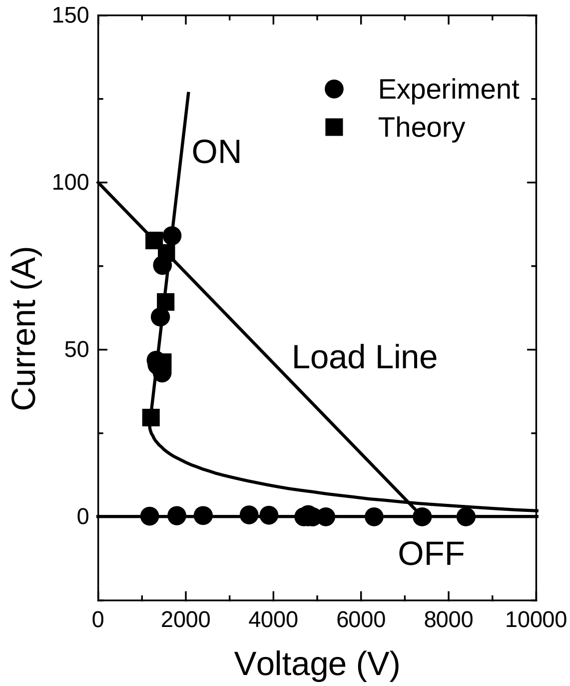

Figure 5: The calculated steady state current as function of voltage. The load-line corresponds to the experimental conditions of the calculation shown in Fig. 4. Furthermore, the shape of the figure corresponds to the S-like characteristic shown in Fig. 2.

The calculations agree well with the steady-state measurements taken approximately 30 ns after triggering and shown in Fig. 5. This figure shows a series of different experiments and calculations in which only the initial voltage has been varied. The load-line shown corresponds to the particular case shown in Fig. 4. The overall comparison of theoretical and experimental current-voltage strongly suggests that these devices behave as bistable switches (stable “on” and “off” states).

IV. SUMMARY

In summary, our theory contains 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, and (4) bistable switching. The quantitative results are in good agreement with the experimental data.

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