A COLLECTIVE THEORY OF LOCK-ON IN PHOTOCONDUCTIVE SEMICONDUCTOR SWITCHES

K. Kambour[a], Harold P. Hjalmarson[*,+,b], and Charles W. Myles[++,a]
[a] *Department of Physics, Texas Tech University*
Lubbock, Texas, 79409-1051 USA
[b] *Sandia National Laboratories*
Albuquerque, NM, 87185-0316 USA

Abstract

Collective impact ionization has been developed to explain lock-on, an optically-triggered, electrical breakdown that occurs in GaAs photoconductive semiconductor switches (PCSS's). The basic principle of collective impact ionization is that, at high carrier density, carrier-carrier interactions increase the impact ionization probability by increasing the number of carriers with energies above the impact ionization threshold. In this paper, we describe a rate equation approach, based on collective impact ionization, that leads to new insights about electrical breakdown in insulating and semiconducting materials. In this approach, the competition between carrier generation through impact ionization and Auger recombination leads to steady state solutions for the carrier generation rate, and it is the accessibility of these steady state solutions, for a given electrical field, that governs whether breakdown does or does not occur. This approach leads to theoretical definitions for not only the lock-on field but also the intrinsic breakdown field. Results obtained for GaAs, InP, and Si using a carrier distribution function calculated by both a Maxwellian approximation and an ensemble Monte Carlo method will be discussed.

I. INTRODUCTION

A photoconductive semiconductor switch (PCSS) is a type of solid state switch which enters a photoconductive "on" state when the surface is illuminated, see Figure 1. These switches are fabricated by attaching electrical contacts to a bulk semiconductor, usually GaAs or Si. There are two major switching regimes for a PCSS, the linear or normal mode and the non-linear or "lock-on" mode.

In the linear mode [1] each absorbed photon generates at most a single electron-hole pair. Carriers in the linear mode require continual replenishment by optically injected carriers in order to keep the switch in the "on" state due to carrier recombination.

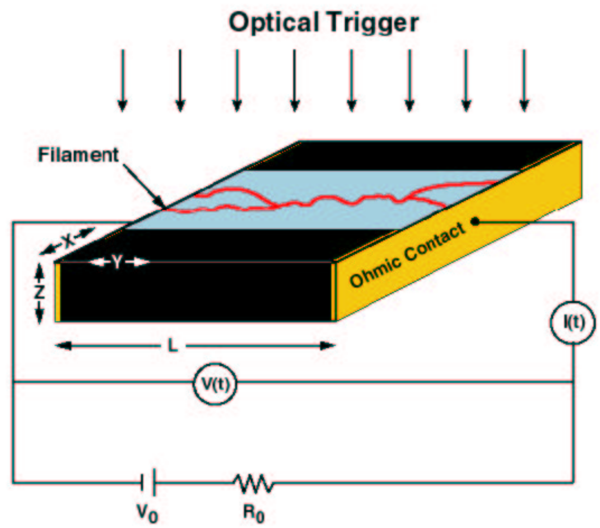

Figure1. A PCSS with its application circuit.

By contrast, certain PCSS's, such as those made from semi-insulating GaAs or InP, can be optically triggered into a self-sustained on state, called lock-on; a high gain, nonlinear state [1,2,3,4]. Carriers in the lock-on mode do not require optical replenishment.

In experiments [2,3] on a GaAs switch that is optically-triggered at several initial biases, it has been found that the switch enters the lock-on state, which is characterized by a low voltage and a high current. In this state the device is locked-on to a field in the range [1] of 3.5 to 9.5 kV/cm, which is independent of initial bias, optical pulse duration, and switch geometry. This effect, which has important applications, is always accompanied by current filaments, visible in the infrared [5].

Collective impact ionization (CII) theory [4,6] explains the main experimental characteristics of lock-on. It is based on the collective impact ionization of charge carriers, which have been optically injected into the switch. This process leads to a stable, filamentary current, sustained by a reduced field [4] and to a bistable, S-like current-voltage characteristic for the switch [6].

The essential physical mechanism in this theory is that,

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* email: hphjalm@sandia.gov

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at high carrier densities, the heating of high kinetic energy carriers becomes more effective because carrier-carrier (cc-) scattering redistributes the heat from the field. At densities high enough that the cc-scattering rate dominates the carrier-phonon scattering rate (~10^{17}cm^3) [4,7] the carriers enter the lock-on state, characterized by a much lower field than normally required to sustain impact ionization [4].

In this state, the carrier heating is in steady state with the carrier-phonon cooling, and the carriers inside the current filaments can be described by a distribution function that approaches a Maxwell-Boltzmann distribution, characterized by a carrier temperature that is much larger than the lattice temperature [4,6]. This quasi-equilibrium approximation is similar to the Saha equation describing quasi-equilibrium in plasma physics [8].

In this paper, we implement the CII theory by solving the steady state Boltzmann transport equation with cc-scattering included. We do this by using an ensemble Monte Carlo (EMC) method. We discuss the breakdown and lock-on fields, and show that CII theory predicts that the current will flow in stable filaments sustained by the lock-on field.

II. THEORY

Our approach is to write an expression for the rate of change of carrier density in terms of the difference between the carrier generation and recombination processes. The only significant carrier generation process is impact ionization, which has a quantum mechanical rate, r_{ii}. If we include impact ionization, we must include its reverse process, Auger recombination, with a corresponding rate, r_{Auger}. We also include recombination at defect centers, with a rate, $r_{defects}$.

The rate of change of carrier density, n, for these three processes can be written as an integral over the first Brillioun zone as

$$\frac{dn}{dt}=\int f_k[r_{ii}-r_{Auger}-r_{defects}]d^3k \qquad (1)$$

where f_k is the carrier distribution function.

A. Qualitative Solution

Since we know the forms for each term in Eq. (1), we can do a theoretical analysis to gain physical insight before we do the EMC calculations. This allows us to write [10]

$$\frac{dn}{dt}=C(F,n)n-an^3-rn\equiv Rn \qquad (2)$$

where F is the electric field and $C(F,n)$, a, and r are the the impact ionization, Auger, and defect recombination rates. We are interested in non-trivial steady state solutions to Eq. (2), so we consider the case

$$R=C(F,n)-an^2-r=0. \qquad (3)$$

If there is no cc-scattering, then $C(F,n)$ = C(F) and Eq. (3) can be solved for the carrier density, $n(F)$, which results in zero net carrier growth, giving

$$n(F)=\sqrt{\frac{C(F)-r}{a}}. \qquad (4)$$

Using the common approximation that C(F) = $\alpha e^{-\beta/F}$ (α and β are parameters), $n(F)$ is plotted schematically as the dashed curve in Figure 2. In that figure, the intrinsic breakdown field, F_B, is defined as the field for which $n(F_B)$ = 0.

If there is significant cc-scattering (i.e., high carrier density) then the carrier density dependence of the impact ionization rate must also be included. For this qualitative analysis we assume a linear dependence, $C(F,n)$ = $C(F)(1+n/n_0)$, where n_0 is a constant. In this case it is possible to solve Eq. (3) numerically, and the results are shown schematically as the solid curve in Figure 2.

Including the effects of cc-scattering changes the solution in a qualitative way. It introduces a new minimum field that we define to be the lock-on field, F_{LO} (see Figure 2).

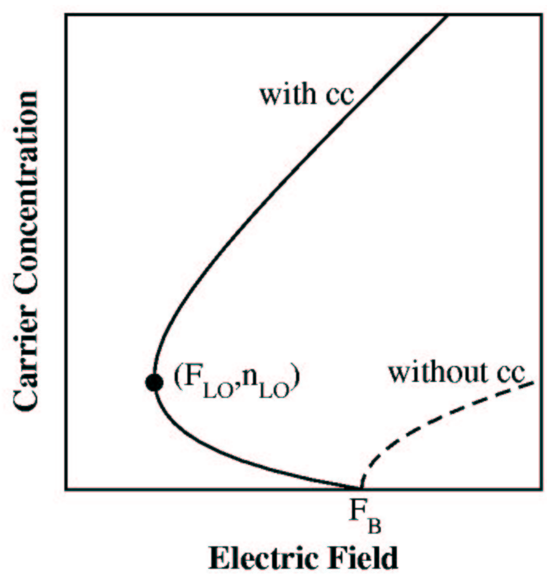

Figure2. Schematic breakdown plot.

B. Quantitative Calculations

In addition to the computationally intensive EMC calculations to implement CII theory, we do two other major classes of calculations designed to represent the low and high carrier density extremes. For low carrier densities, the effects of cc-scattering are minimal and a standard Monte Carlo (MC) simulation without cc-scattering is used to evaluate the right hand side of Eq. (1).

The second class of calculations is based on CII theory [4,6], which predicts that a quasi-equilibrium steady state will be achieved at high densities. In this state the carrier generation and recombination rates must be approximately equal and the Joule heating and phonon cooling rates must also be approximately equal. Thus, in a high density implementation of CII theory, the distribution becomes a quasi-equilibrium Maxwellian distribution characterized by a carrier temperature T_c.

For this situation, the steady state energy balance condition is

$$qv_d F = B(T_c) \tag{5}$$

where v_d is the drift velocity, q is the charge, and $B(T_c)$ is the phonon-carrier cooling rate. The calculation of $B(T_c)$ for a Maxwellian distribution is discussed in [9]. Using the requirement that the net carrier generation rate is zero, it is possible to find T_c for a given value of n. Then using Eq. (5), T_c can be used to calculate F.

III. RESULTS

A. Model Material

In order to test the theory, we first applied it to a model material with single parabolic conduction and valence bands and a band gap of 1.5 eV. Both bands had effective mass 0.5 m_e. To simplify the calculation for this model material we also allowed only acoustic deformation potential scattering.

A breakdown plot such as Figure 3 contains considerable information. Using Figure 3 as an example, it and each subsequent plot can be interpreted as follows. By inspection, it has a lock-on field, $F_{LO} \cong 15$ kV/cm, the lowest field for which there is a non-trivial steady state solution. If $F < F_{LO}$, any injected charge will decay to zero. If $F > F_{LO}$, then the injected charge can grow. For example if $F = 20$ kV/cm, then it either decays until $n = 0$ or grows until $n = 4 \times 10^{19}$ cm^{-3}.

Figure 3 shows numerical results for the steady state carrier density of the model material as a function of field. The hollow circles represent the results obtained using MC without cc-scattering. The squares are the results of the Maxwellian approximation. The solid circles are the EMC results which include cc-scattering explicitly.

Figure 3 also shows the intrinsic breakdown field, the field where the Monte Carlo results without cc-scattering first have a non-zero solution, approximately 28 kV/cm. Once this field is reached, an arbitrarily small carrier density will produce more carriers until the system reaches a steady state, and the carrier density reaches a maximum value given by the upper curve. Earlier breakdown theories implicitly assume that at the breakdown field the carrier density will increase to infinity [11]. By contrast, our theory predicts that the carrier density at breakdown will be large, but limited by Auger recombination.

Figure 3 shows that for a simple model material it is possible to produce a lock-on effect. Also it is worth noting that this result confirms that CII will produce an S-like current-voltage characteristic as predicted, resulting in a bistable switch [6].

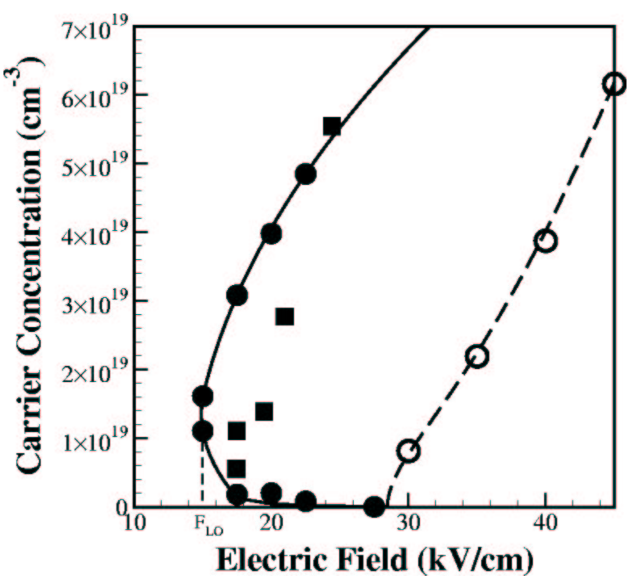

Figure 3. Breakdown plot for the model material. The hollow circles are MC results without cc-scattering. The solid circles are EMC results with cc-scattering. The squares are Maxwellian results. The solid and dashed curves are included to guide the eye.

B. GaAs, InP, and Si

We have done similar calculations for GaAs, InP, and Si. The results are shown in Figures 4, 5, and 6. For these materials we have used electronic bandstructures computed in the local pseudopotential approximation [12]. For Si we used the improved form factors of Kunikiyo [13].

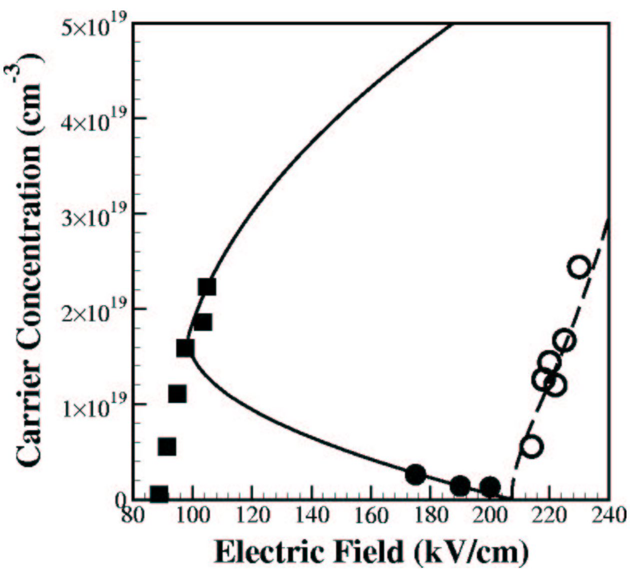

Figure 4. Breakdown plot for GaAs. The interpretation is the same as in Figure 3.

From the results in Figures 4 and 5, the following predictions can be made. The intrinsic breakdown fields, F_B, for GaAs and InP are 207 and 175 kV/cm, respectively. For the same materials, the lock-on fields, F_{LO}, are 100 kV/cm and 20 kV/cm, respectively. The experimental values for the lock-on fields are 5 to 10 kV/cm for GaAs and 14.4 kV/cm [14] for InP.

From Figure 6, the predicted breakdown field in Si is 100 kV/cm. This theory also predicts that lock-on will not be experimentally observed in Si. The reason can be seen in Figure 6. The low and high carrier density extremes result in minimum fields which are so close together that experiments would be unlikely to distinguish between them.

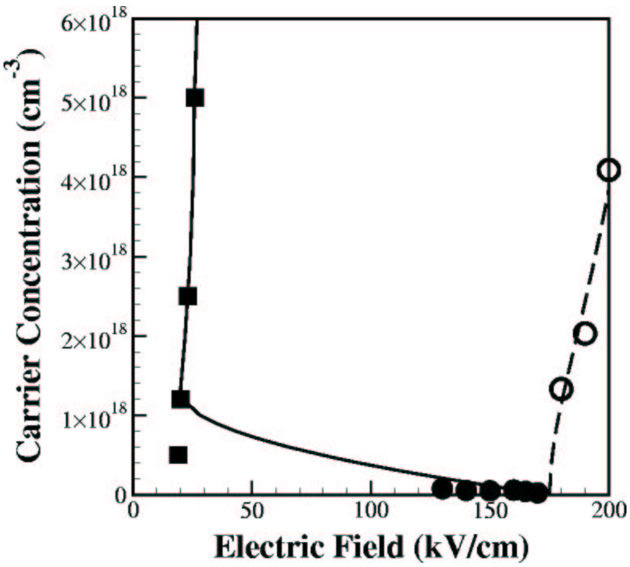

Figure 5. Breakdown plot for InP. The interpretation is the same as in Figure 3.

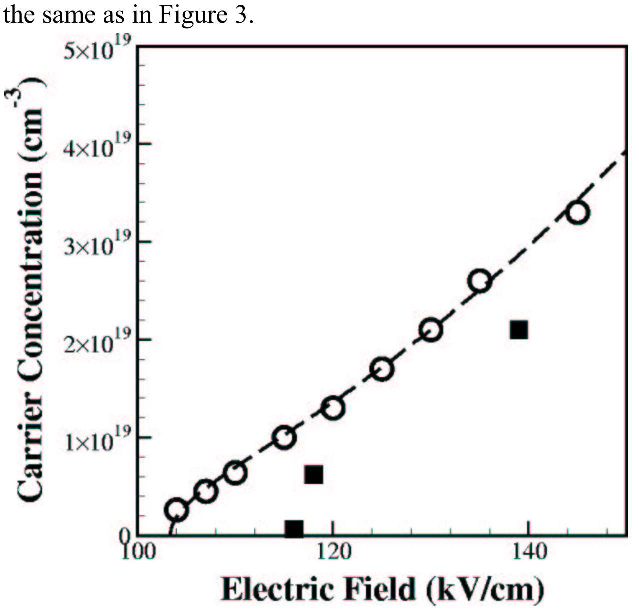

Figure 6. Breakdown plot for Si. The interpretation is the same as in Figure 3.

IV. SUMMARY/CONCLUSIONS

We have used CII theory to study some of the properties of lock-on current filaments and of breakdown in different materials. We predict that lock-on will occur in both GaAs and InP, in qualitative agreement with experiment. The predicted InP lock-on field is in reasonable quantitative agreement with experiment. We also correctly predict that lock-on in Si will be experimentally difficult to observe.

V. REFERENCES

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