A theory of low-field, high-carrier-density breakdown in semiconductors

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Abstract. Collective impact ionization has been used to explain lock-on, an optically-triggered electrical breakdown occurring in some photoconductive semiconductor switches (PCSS's). Lock-on is observed in GaAs and InP but not in Si or GaP. Here, a rate equation implementation of collective impact ionization is discussed, and it leads to new insights both about intrinsic electrical breakdown in insulating materials in general and about lock-on specifically. In this approach, lock-on and electrical breakdown are steady state processes controlled by competition between carrier generation and recombination. This leads to theoretical definitions for both the lock-on field and the breakdown field. Our results show that lock-on is a carrier-density dependent form of electrical breakdown which exists in principle in all semiconductors. Results for GaAs, InP, Si, and GaP are discussed.

INTRODUCTION

A photoconductive semiconductor switch (PCSS) is a solid state switch fabricated by attaching electrical contacts to a bulk semiconductor. It is activated into a conductive state when the surface is illuminated. All of these switches exhibit conventional photoconductivity whereby they become conductive while illuminated [1]. In this case, each absorbed photon generates at most a single electron-hole pair, and it is necessary to continually replenish the carriers by photogeneration in order to maintain the photoconductivity.

Some PCSS's, such as those made from semi-insulating GaAs or InP, can also be triggered into a self-sustaining "on" state, called "lock-on" [1, 2, 3]. In the lock-on mode the field across the switch is "locked-on" to an almost constant field [1] and the current flows in filaments, visible in the infrared [1]. The lock-on mode of operation has the advantage that once the initial trigger is applied, the current continues without the need for optical replenishment.

Collective impact ionization (CII) theory [4] explains the main characteristics of lock-on. The physical mechanism of CII theory is that, for high carrier densities, the heating of high kinetic energy carriers becomes more effective because carrier-carrier (cc-) scattering redistributes the energy of the carriers.

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THEORY

Our approach is to write an expression for the time evolution of carrier density after the trigger is discontinued. We include impact ionization, Auger recombination, and recombination at defect centers, with corresponding quantum mechanical rates of r_{ii}, r_{Auger} and $r_{defects}$. We obtain

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

in which the integral spans the first Brillouin zone and f_k is the carrier distribution function.

Qualitative Solution

The approximate carrier density dependence for each term in Eq. (1) [5, 6] is known. Substituting these approximate dependences into Eq. (1) gives:

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

where F is the electric field and $C(F,n)$, a, and r are the impact ionization, Auger, and defect recombination rates. We seek the non-trivial steady state solutions which correspond to the cases when $R(F,n) = 0$.

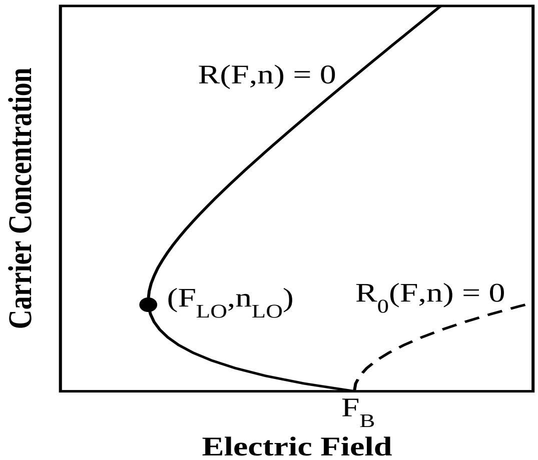

FIGURE 1. Schematic plot of the steady state carrier density n as a function of electric field F. The dashed curve is the low carrier density result and the solid curve is the result for high carrier density.

In the case of no cc-scattering, the impact ionization rate $C(F,n)$ is independent of the carrier density ($C(F,n) = C(F)$). Assuming $C(F) = \alpha e^{-\beta/F}$ [7, 8], the steady state carrier density n can be obtained as a function of field, and it is plotted schematically as the dashed curve in Fig. 1 with the breakdown field, F_B, defined as the minimum field for which a non-trivial solution exists.

In the case of significant cc-scattering (e.g., at high carrier density), then the carrier density dependence of the impact ionization rate must also be included. For this qualitative discussion, we assume a linear dependence of the form $C(F,n) = C(F)(1+n/n_0)$, where n_0 is a constant. The resulting $n(F)$ is shown schematically as the solid curve in Fig. 1. Clearly, including the effects of cc-scattering changes the solution for $n(F)$ both qualitatively and quantitatively. At the breakdown field, F_B, there is now a sudden jump in the carrier density conforming to our expectations about a catastrophic breakdown event. Furthermore, the solutions can be characterized by a new minimum field for which a non-zero steady state carrier density is possible. We define this field to be the lock-on field, F_{LO} (see Fig. 1).

Quantitative Calculations

Three types of calculations were undertaken. First, collective impact ionization (CII) theory [4] was implemented by using an ensemble Monte Carlo (EMC) to solve the Boltzmann equation. Second, the effects of cc-scattering are minimal at low carrier densities, and for this case we use an EMC simulation without including the effects of cc-scattering. Third, for high carrier densities, CII theory [4] predicts that a quasi-equilibrium steady state will be achieved. In these calculations, the carrier distribution function is approximated as a Maxwellian distribution function.

RESULTS

We did extensive calculations for GaAs and InP, two materials in which lock-on has been observed. The predicted intrinsic breakdown fields are 177 kV/cm and 173 kV/cm, respectively, and the predicted lock-on fields are ≈ 90 and 40 kV/cm, both of which are larger then the experimental lock-on fields of ≈ 5 and 14.4 kV/cm.

We did similar calculations for Si and GaP, two materials in which lock-on has not been observed. Our predicted breakdown fields are 104 and 192 kV/cm, and our predicted lock-on fields are 77 and 176 kV/cm. For these materials, the predicted breakdown and lock-on fields are close to each other. This means that an observation of lock-on would require that the switch be triggered near the breakdown field, and we suggest this makes lock-on difficult to distinguish from breakdown.

SUMMARY/CONCLUSIONS

We have used CII theory to develop a both a theory of lock-on in PCSS's and a new approach to the classic problem of steady state electrical breakdown in insulators. We suggest that our theory predicts the correct qualitative lock-on behavior. We also suggest that the lock-on effect is common to all semiconductors. In our opinion, however, we suggest that lock-on may be difficult to observe if the lock-on and breakdown fields are similar.

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