STEADY STATE PROPERTIES OF LOCK-ON CURRENT FILAMENTS IN GaAs

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Abstract-- **Collective impact ionization has been used to explain lock-on in semi-insulating GaAs under high-voltage bias. We have used this theory to study some of the steady state properties of lock-on current filaments. In steady state, the heat gained from the field is exactly compensated by the cooling due to phonon scattering. In the simplest approximation, the carrier distribution approaches a quasi-equilibrium Maxwell-Boltzmann distribution. In this report, we examine the validity of this approximation. We find that this approximation leads to a filament carrier density which is much lower than the high density needed to achieve a quasi-equilibrium distribution. Further work on this subject is in progress.**

Index terms-- **Photoconductive Switches, PCSS, Lock-on, Collective Impact Ionization**

I. INTRODUCTION

Photoconductive semiconductor switches (PCSS's) usually are operated in the linear mode [1], in which each absorbed photon generates at most one electron-hole pair. Due to recombination, these carriers require continual replenishment. By contrast, certain PCSS's, such as those made from semi-insulating GaAs, can be optically triggered into a sustained "on" state, called "lock-on"; a high gain, nonlinear state [1-4].

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In experiments [2,3] in which a GaAs switch is laser-triggered at several initial biases, it has been found that after laser turn off, the switch goes to a low voltage, high current "on" state ("lock-on") and remains there for hundreds of nanoseconds. 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, laser pulse duration, and geometry. This effect, which has potentially important applications, is always accompanied by current filaments, visible in the infrared [5].

In the present paper, we present preliminary results, obtained using the collective impact ionization theory of Hjalmarson et al. [4,6], of a study of some of the steady state properties of these lock-on current filaments.

II. COLLECTIVE IMPACT IONIZATION

The Hjalmarson et al. theory [4,6] explains the main characteristics of lock-on. It is based on the collective impact ionization of charge carriers by optically injected carriers. This 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, at high carrier densities, the heating of high kinetic energy carriers becomes more effective because carrier-carrier scattering re-distributes the heat from the field. At densities high enough that the carrier-carrier scattering rate dominates the carrier-phonon scattering rate ($n_c \sim 10^{17} \text{cm}^{-3}$) [4,7], the carriers enter a state (lock-on), 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. In the first approximation, the carriers in the current filaments can be described by a distribution function which approaches a quasi-equilibrium Maxwell-Boltzmann distribution function, characterized by a carrier temperature which is much larger than the lattice temperature [4,6,8]. Figure 3 of Ref. [6] schematically illustrates this distribution function. This quasi-equilibrium approximation is similar to the Saha equation describing quasi-equilibrium in plasma physics [9]. In this paper the validity of this quasi-equilibrium approximation will be examined.

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III. PRESENT CALCULATIONS

During lock-on, collective impact ionization theory [4,6] predicts that steady state has been achieved. In this situation, the carrier generation and recombination rates are approximately equal. Also, the Joule heating and phonon cooling rates are approximately equal. Thus the rate that carriers within the filament gain energy from the field must be exactly compensated by the rate of energy loss due to carrier-phonon scattering. As just discussed, an important feature of collective impact ionization theory [4,6] is that carrier-carrier scattering redistributes the energy within a filament, which leads to a distribution function which is thermal or nearly thermal. To achieve these circumstances requires a carrier density high enough that the carrier-carrier scattering rate exceeds the carrier-phonon scattering rate.

In the simplest implementation of collective impact ionization theory, the distribution becomes a quasi-equilibrium distribution characterized by a temperature T_c, which is assumed to exceed the lattice temperature. For this situation, the steady state energy balance condition is

$$|qv_dF| = R(T_c),\qquad(1)$$

where T_c is the carrier temperature, v_d is the drift velocity, F is the electric field, q is the charge, and $R(T_c)$ is the phonon-carrier cooling rate.

The cooling rate can be expressed formally as

$$R(T_c) = \sum_k \epsilon_k [\vartheta_-(k) - \vartheta_+(k)]f(k;T_c),\qquad(2)$$

where ϵ_k is the phonon energy and $f(k;T_c)$ is the Maxwell-Boltzmann distribution function. In Eq. (2) and subsequent equations, the sum is over all wave vectors k in the first Brillouin zone. Here, $\vartheta_+(k)$ and $\vartheta_-(k)$ are the quantum mechanical carrier-phonon scattering rates for phonon absorption and emission. They have the form

$$\vartheta_\mp(k)= (1/h) \sum_{k'} |<k|H_{int}|k'>|^2(1-f_{k'})*(E_k - E_{k'} \forall \epsilon_{|k'-k|}),\qquad(3)$$

where h is Planck's constant, $f_{k'}$ is the occupation factor of state k', and $E_{k'}$ and E_k are energy band states for the charge carriers at wave vectors k' and k. In Eq. (3), H_{int} is the carrier-phonon interaction Hamiltonian. Following previous work [8,10], we assume that optical deformation potential scattering is the only process which contributes to H_{int}. Given the quasi-equilibrium approximation, the only unknown in the cooling rate expression, Eq. (2), is the carrier temperature T_c.

The balance of generation and recombination terms for the quasi-equilibrium steady state situation dictates that the electron and hole densities, n and p, are equal and given by the intrinsic carrier density $n_i(T_c)$, corresponding to the carrier temperature [4,6,8]. That is

$$n = p = n_i(T_c).\qquad(4)$$

The carrier densities can be obtained from the relations

$$n(T_c) = \sum_{k_e} f_e(k_e;T_c)\qquad(5)$$

and

$$p(T_c) = \sum_{k_p} f_p(k_p;T_c).\qquad(6)$$

Here, k_e, k_p and f_e, f_p are, respectively the electron and hole wave vectors and the electron and hole distribution functions. The intrinsic carrier density, Eq. (4), is computed using a Maxwell-Boltzmann distribution. The Fermi energy is adjusted to achieve equality between n and p in Eq. (4).

The fact that a critical density is required to achieve collective impact ionization leads to a test of this most simple version of the theory. Given the empirical lock-on field, Eq. (1) can be used to solve for the carrier temperature T_c. Then, the carrier density inside a lock-on current filament is given by the intrinsic carrier density for this carrier temperature, $n_i(T_c)$. This density must exceed the critical density $n_c \sim 10^{17}$cm^{-3} [4,7] at which the carrier-carrier scattering rate dominates the carrier-phonon scattering rate. Whether or not it does so is a consistency test for the present the quasi-equilibrium, steady state implementation of collective impact ionization theory.

IV. RESULTS

For all of the results presented here, we have used an electronic bandstructure for GaAs which was computed in the local pseudopotential approximation [11]. Further, we have kept only the lowest lying conduction band and the highest three valence bands. These four bands are shown in Fig. 1. Other calculations with two conduction and three valence bands [12] have shown that the second conduction band contributes negligibly to the cooling rate.
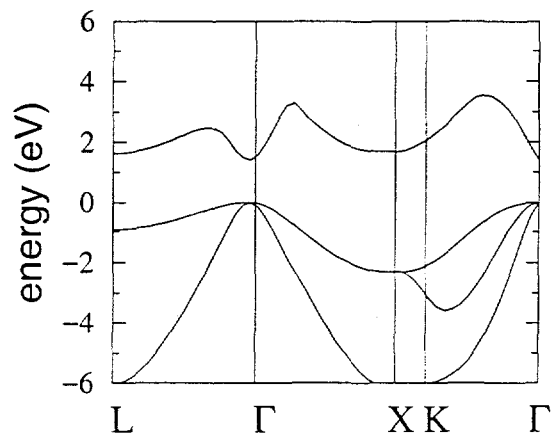

Figure 1. The four bands for GaAs obtained in the local pseudopotential approximation [11] and used in the calculations presented in this paper.

The solid curve in Fig. 2 shows the carrier temperature dependence of the phonon-carrier cooling rate, $R(T_c)$, which we have obtained using Eq. (2) and the local pseudopotential bandstructure of Fig. 1.

Using the results of the cooling rate calculation just described, the empirical lock-on field can be used to estimate the carrier temperature in a lock-on current filament. This field controls the Joule heating term, which also depends on the carrier drift velocity v_d. We assume that the drift velocity is given by the saturation drift velocity, v_s. For GaAs, this velocity is $v_s \sim 10^7$ cm/s [13]. In addition, we assume a nominal value for the lock-on field of $F_{lo} \sim 5$ kV/cm. Given this field and the estimated drift velocity, the resulting heating rate from the left hand side of Eq. (1) is 5 $\times 10^{10}$ eV/s. This is shown as the horizontal line in Fig. 2. By inspection of Fig. 2, the estimated filament carrier temperature is approximately 500K. This is much lower than previous estimates [8].
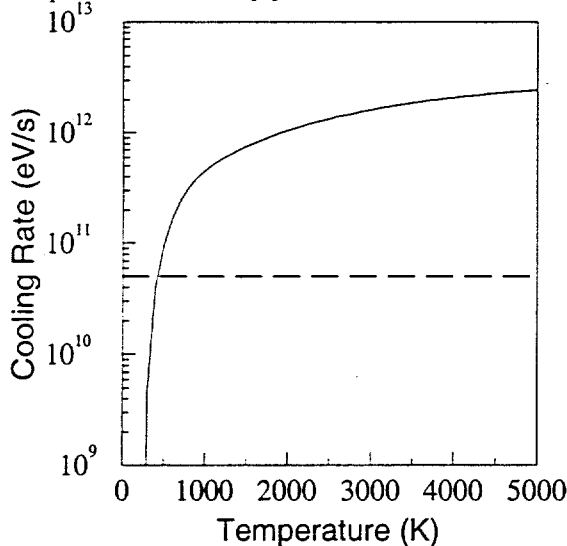

Figure 2. The cooling rate $R(T_c)$ for GaAs, obtained from Eq. (2) using the bandstructure of Fig. 1.

Figure 3 shows the carrier temperature dependence of the intrinsic carrier density, $n_i(T_c)$, which we have obtained using Eqs. (4)-(6), along with the bandstructure of Fig. 1.

The quasi-equilibrium carrier density at the lock-on field can be obtained by using the filament carrier temperature obtained above, along with the results for the carrier density shown in Fig. 3. For $T_c = 500K$ the carrier density from Fig. 3 is approximately 2.0×10^{11} cm^{-3}. This is orders of magnitude lower than the critical density $n_c \sim 10^{17}$ cm^{-3} needed to achieve quasi-equilibrium [4,6-8]. This preliminary result therefore suggests that collective impact ionization does not lead to a quasi-equilibrium carrier distribution within the filaments.
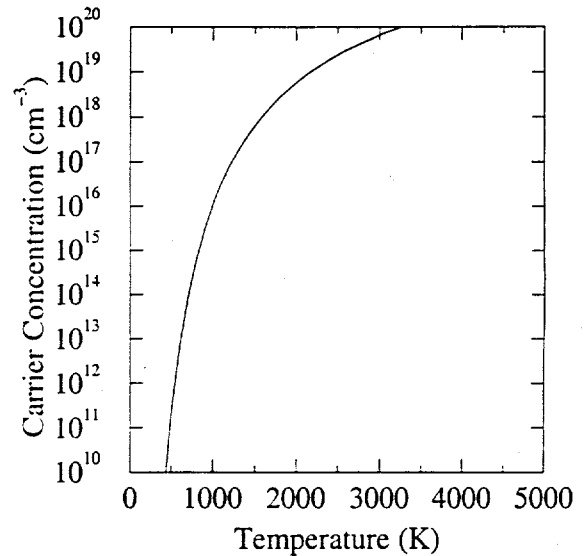

Figure 3. The intrinsic carrier density as a function of carrier temperature for GaAs.

V. SUMMARY CONCLUSIONS

We have used the collective impact ionization theory of Hjalmarson et al. [4,6] to study some of the steady state properties of lock-on current filaments. In particular, we have examined whether using a quasi-equilibrium, Maxwell-Boltzmann approximation for the carrier distribution function in the filaments results in filament properties which are consistent with the collective impact idea [4,6]. The preliminary results presented here suggest that the carrier density obtained using this approximation is much too low to be consistent with collective impact ionization. We thus conclude that the quasi-equilibrium approximation for the filament carrier distribution at steady state may be too crude. We emphasize that these results do not affect the basic collective impact ionization idea [4,6], which we believe to be sound; they only call into question the quasi-equilibrium, steady state implementation of it.

Further cooling rate calculations are planned which will use more sophisticated bandstructures for GaAs.

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