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Hot Electron Transport in Polar Semiconductor at Low Lattice Temperature

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ABSTRACT:

Using electron temperature model and the momentum relaxation time approximation, the dependence of electron temperature upon electric field is studied in polar semiconductor at low lattice temperatures considering the scattering of the non-degenerate electron ensemble with ionized impurity, deformation potential acoustic phonons, piezoelectric acoustic phonons and polar optical phonons. The computed expressions are applied to obtain the dependence of the electron temperature upon the electric field in n-type InSb and InAs. The results thus obtained are compared with available experimental data and other theoretical results.

KEY WORDS: Semiconductor, Hot Electron, Scattering, Phonon, Electron Temperature

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INTRODUCTION:

Different theoretical models were predicted to study the hot electron transport characteristics and the success of these models needs the proper knowledge of the scattering mechanisms of the free electrons. The free electrons are scattered dominantly by optical and intervalley phonons at lattice temperatures above 100K and by impurities at very lower temperatures. Between these two extreme situations the free carriers in compound semiconductors interact rather strongly with deformation potential acoustic phonons and also with piezoelectric acoustic phonons if the bonds in the materials are partly ionic so that the unit cell does not contain a centre of symmetry. The optical phonon scattering can also be important even at low lattice temperature in the presence of a

high electric field when the non-equilibrium electrons can emit high energy phonons [1-6].

The advanced Si technology has motivated most of the studies in semiconductor physics. With these studies a considerable number of works have also been initiated on III-V and II-VI compound semiconductors. Two important III-V-compound semiconductor like Indium Antimonide (InSb) and Indium Arsenide (InAs) have attracted considerable interest for application in semiconductor devices. These find use in infrared detectors, including FLIR systems, thermal imaging cameras, infrared astronomy and in infrared homing missile guidance systems. Thus a good number of theoretical studies on the conductivity characteristics have been reported starting from a rather low temperature to high temperatures both in different bulk III-V semiconductors as well as in two-dimensional electron gas formed in the surface layers of those materials [3, 6-10]. In these analyses, a detailed physical formulation of various scattering mechanisms like ionized impurity scattering, acoustic phonon scattering, piezoelectric phonon scattering, polar optical phonon scatterings, carrier–carrier scattering, and alloy scattering has been made to accurately determine the variation of mobility with free carrier concentration n_0 and lattice temperature T_L.

In this article, we study theoretical results for the mobility of electrons as a function of electron temperature and electric field. Momentum and energy balance equations are used to obtain the theoretical mobility results. The main contributions to momentum and energy loss of electrons are assumed to originate from acoustical and optical phonon scattering processes. Also, the energy band structure of the semiconducting materials is considered to be parabolic. The theoretical calculation carried out by using the model given by Conwell [2], Segeer [11] and Lee *et al* [12] which include the acoustic phonon scattering through deformation potential, piezoelectric coupling and the polar optical phonon scattering. The theoretical results obtained in this article by electron temperature model (ETM) are applied in InSb and InAs samples and the results are compared with available experimental data [13,14] and other theoretical results reported by Ghorai *et al* [6] obtained by Monte Carlo Method.

THEORETICAL MODEL:

In ETM, the electron temperature is calculated as a function of electric field by the simplification of a Maxwell-Boltzmann distribution with an electron temperature $T_{\mathrm{e}}(E)$, by averaging of momentum relaxation time over this distribution. The power supplied to electron system is transferred to the phonon system. When an electric field E is applied, the electron gains energy at the rate of $e\mu E^2$, where e is the electronic charge and μ is the mobility of warm electrons. In steady state, if ϵ be the electron energy, the average rate of energy loss $\langle\frac{d\epsilon}{dt}\rangle$ of the non-equilibrium electron due to phonon scattering is equal to the rate of energy gain from the field and the equation is given as [2]

$$e\mu(T_{\mathrm{e}})E^2 = \langle\frac{d\epsilon}{dt}\rangle. \qquad (1)$$

At low temperature range, the main contributions to energy loss of electrons in polar semiconductors is assumed to be from acoustic phonon scattering due to deformation potential and piezoelectric coupling mechanisms. Moreover, when subjected to high electric field the carriers are

deviated from the state of thermodynamic equilibrium even at low lattice temperature. As such the loss of energy of hot electrons may also occur due to the scattering of electrons by the polar optical phonons [15]. The dominant scattering mechanisms considered here are ionized impurity (im), deformation potential acoustic phonon (dp), piezoelectric acoustic phonon (pz) and polar optical phonon (po). Thus the mobility and power loss terms in Eq.(1) can be given as

$$\frac{1}{\mu} = \sum_i \frac{1}{\mu_i}, \tag{2}$$

and

$$\langle \frac{d\epsilon}{dt} \rangle = \sum_j \langle \frac{d\epsilon}{dt} \rangle_j . \tag{3}$$

The field-dependent electron mobility μ can be expressed in terms of electron temperature T_e using relaxation time approximation and a simple model valid for the electron temperature dependent Maxwell-Boltzmann distribution as [2]

$$\mu(T_e) = \frac{e}{m_\mu^*} \frac{\langle \epsilon\tau \rangle}{\langle \epsilon \rangle}, \tag{4}$$

Where m_μ^* is the mobility effective mass of the electron and τ is the relaxation time due to free carrier scattering. The expressions of τ for different scattering mechanisms are available in the literature and using those expressions the corresponding hot electron mobility can be calculated.

Power Loss and Hot Electron Mobility Expressions:

The expressions for various power loss terms and electron mobility expressions as a function of electron temperature T_e are defined considering the corresponding scattering processes. For the prevalent condition of lattice temperature, carrier concentration and applied electric field of interest here the dominant scattering mechanisms are ionized impurity, deformation potential acoustic phonon, piezoelectric acoustic phonon and polar optical phonon.

Ionized Impurity Scattering:

At low lattice temperature the impurities in non-compensated materials may be either neutral or ionized. The neutral impurity scattering usually influence the electrical transport in a rather weak manner and hence it may be neglected in the present investigation. The collision between the electron and the impurity atoms is considered to be elastic and as such there is no power loss of the electron system due to impurity scattering.

For ionized impurity scattering the relaxation time has been calculated with some approximation in the light of Brooks-Herring (BH) and Conwell-Weisskopf (CW) approaches [4]. Ridley [16] showed that the BH formula is appropriate if

$$\frac{Z^2 e^2 m^* n_i b}{24\pi\varepsilon_d \hbar^2 n_0} \ll 1,$$

where Z is the number of charge units of the impurity, m^* is the effective mass of the electron, n_i is the impurity concentration, ε_d the static dielectric constant of the material, $\hbar$ the Dirac constant. When the compensation is low, each ionized impurity contributes one free carrier and n_i can be

used in place of n_0. The mean distance between the impurity centres $b = (3/4\pi n_i)^{1/3}$. The samples for which the experimental data are available for a comparison with our theoretical calculations actually satisfy the above condition. Hence the BH formula [4] for the relaxation time is used to determine the hot electron mobility due to impurity scattering and the result can be given as

$$\mu_{im}(T_e) = \mathcal{C}_1 \frac{\epsilon_\beta^2}{\sqrt{k_B T_e}} \left(1 + \frac{8k_B T_e}{\epsilon_\beta}\right), \tag{5}$$

where $\mathcal{C}_1 = \frac{\varepsilon_d^2}{3\sqrt{2}\pi^{3/2} Z^2 e^3 m^{*1/2} n_i}$, $\epsilon_\beta = \frac{\hbar^2 \beta_s^2}{2m^*}$, $\beta_s^2 = \frac{4\pi e^2 n_0}{\varepsilon_d k_B T_L}$, for non-degenerate ensemble and k_B is the Boltzmann constant.

Deformation Potential Acoustic Phonon Scattering:

The acoustic mode lattice vibration induces changes in lattice spacing, which change the band gap from point to point. Since the crystal is "deformed" at these points, the potential associated is called the deformation potential. The power loss due to the scattering of non-degenerate electron ensemble by deformation potential acoustic phonon is considered here from earlier works [2] and it is given as

$$\langle \tfrac{d\epsilon}{dt} \rangle_{dp} = \frac{8\sqrt{2}\mathcal{E}_a^2 m^{*5/2} k_B^{3/2}}{\pi^{3/2}\hbar^4 \rho} T_e^{3/2} \left(1 - \frac{T_L}{T_e}\right). \tag{6}$$

Here $\mathcal{E}_a$ is the deformation potential constant and ρ is the mass density.

Using the expression for the relaxation time due to deformation potential acoustic phonon scattering given by Conwell [2] we may calculate the corresponding hot electron mobility as

$$\mu_{dp}(T_e) = \mathcal{A}_1 T_e^{-1/2}, \tag{7}$$

Where $\mathcal{A}_1 = \frac{2\sqrt{2\pi} e \hbar^4 \rho v_s^2}{3\varepsilon_a^2 m^{*5/2} k_B^{3/2} T_L}$, v_s is the average sound velocity through the crystal.

Piezoelectric Acoustic Phonon Scattering:

In polar semiconductors, the bonds are partly ionic and the unit cell does not contain a center of symmetry and electrons interact with acoustic phonons due to piezoelectric coupling at low lattice temperature. In such materials the power loss of the non-degenerate electron system due to interaction with piezoelectric coupling may be calculated in the light of Conwell's prescription and then we get

$$\langle \tfrac{d\epsilon}{dt} \rangle_{pz} = \frac{(e k_m \hbar v_s)^2}{32\sqrt{2}\pi^{9/2} \varepsilon_d m^{*1/2} k_B^{3/2}} T_e^{-3/2} I_{pz}(T_e), \tag{8}$$

Where

$$I_{pz}(T_e) = \int_0^\infty x^3 \Gamma\left(0, \frac{\hbar^2 x^2}{8m^* k_B T_e}\right) Exp\left[-\frac{\hbar v_s}{k_B T_e}\right] dx. \tag{9}$$

Here k_m is the piezoelectric coupling constant of the material. $\Gamma(a,b)$ is the incomplete Gamma function. From Eq.(9) it is obvious that the integration is not amenable to analytical evaluation and as such one has to take recourse to some numerical technique [17] for their evaluation.

The electron temperature dependent electron mobility due to piezoelectric phonon scattering can be calculated using the relaxation time expression given by Conwell [2] as

$$\mu_{pz}(T_e) = B_1 T_e^{-1/2}, \qquad (10)$$

where $B_1 = \frac{16\sqrt{2\pi}\hbar^2\varepsilon_d}{3ek_m^2 m^{*3/2}k_B^{1/2}}$.

Polar Optical Phonon Scattering:

The power loss due to the scattering of non-degenerate electron ensemble by polar optical phonon is taken into account here and it is given as [2]

$$\langle\frac{d\epsilon}{dt}\rangle_{po} = \frac{\sqrt{2}ek_B^{1/2}\theta_D^{1/2}E_0}{\pi^{1/2}m^{*1/2}}\frac{e^{(x_L-x_e)}-1}{e^{x_L}-1}x_e^{1/2}e^{x_e/2}K_0\left(\frac{x_e}{2}\right), \qquad (11)$$

Where

$$E_0 = \frac{em^*k_B\theta_D}{\hbar^2}\left(\frac{1}{\varepsilon_\infty}-\frac{1}{\varepsilon_d}\right), \quad x_L = \frac{\theta_D}{T_L}, \quad x_e = \frac{\theta_D}{T_e}.$$

Here θ_D is the Debye temperature and ε_∞ is the high-frequency dielectric constant of the material. K_0 is the modified Bessel function of the second kind.

The hot electron mobility due to polar optical phonon scattering has already been calculated [2] and it is given as

$$\mu_{po}(T_e) = \frac{3\sqrt{\pi}k_B^{1/2}\theta_D^{1/2}}{\sqrt{2}m^{*1/2}E_0}\frac{e^{x_L}-1}{x_e^{3/2}e^{x_e/2}}\frac{1}{(e^{(x_L-x_e)}-1)K_0\left(\frac{x_e}{2}\right)+(e^{(x_L-x_e)}+1)K_1\left(\frac{x_e}{2}\right)} \qquad (12)$$

Where K_1 is the modified Bessel function of the second kind.

RESULT AND DISCUSSION:

To observe the efficacy of ETM to study the hot electron transport we consider the most important III-V semiconductors InSb and InAs for which experimental data are available at low lattice temperatures. For the calculation of the above formulation we use the material parameters of these materials listed in Table-1.

From Fig.1 and Fig.2 it is seen that the results obtained here by ETM show moderate agreement with the experimental data both qualitatively as well as quantitatively. In the present study we have considered a simple model and have not taken into account many factors which are rather predominant at low lattice temperature and at the application of high electric field. Much of the disagreement may be ascribed to the fact that at low lattice temperature and carrier concentration of interest here, the effect of screening of the electron ensemble and degeneracy of electron system must be considered in developing the theory of electron transport. Moreover, the effects of non-parabolicity [4] of the conduction band and the finite phonon energy in the energy balance equation have to be

taken into account in the process of electron-phonon collision. Besides these, the perturbation of the phonon system should also be given due consideration under the prevalent condition of low lattice temperatures [2]. Thus the remaining disagreement is likely to be reduced if we consider these factors.

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Table-1

Material parameters of InSb and InAs [3, 6]

Physical constants	InSb	InAs
Deformation potential, ε_a (eV)	30.0	5.8
Effective mass ratio(m^*/m_0)	0.0145	0.023
Acoustic velocity, v_s ($10^5 cms^{-1}$)	3.7	4.2
Density, ρ (gcm^{-3})	5.78	5.67
Piezoelectric coupling constant, k_m	0.027	0.0168
Static dielectric constant, ε_d	17.9	14.6
High-frequency dielectric constant, ε_∞	15.7	11.8
Debye temperature, θ_D (K)	284	350

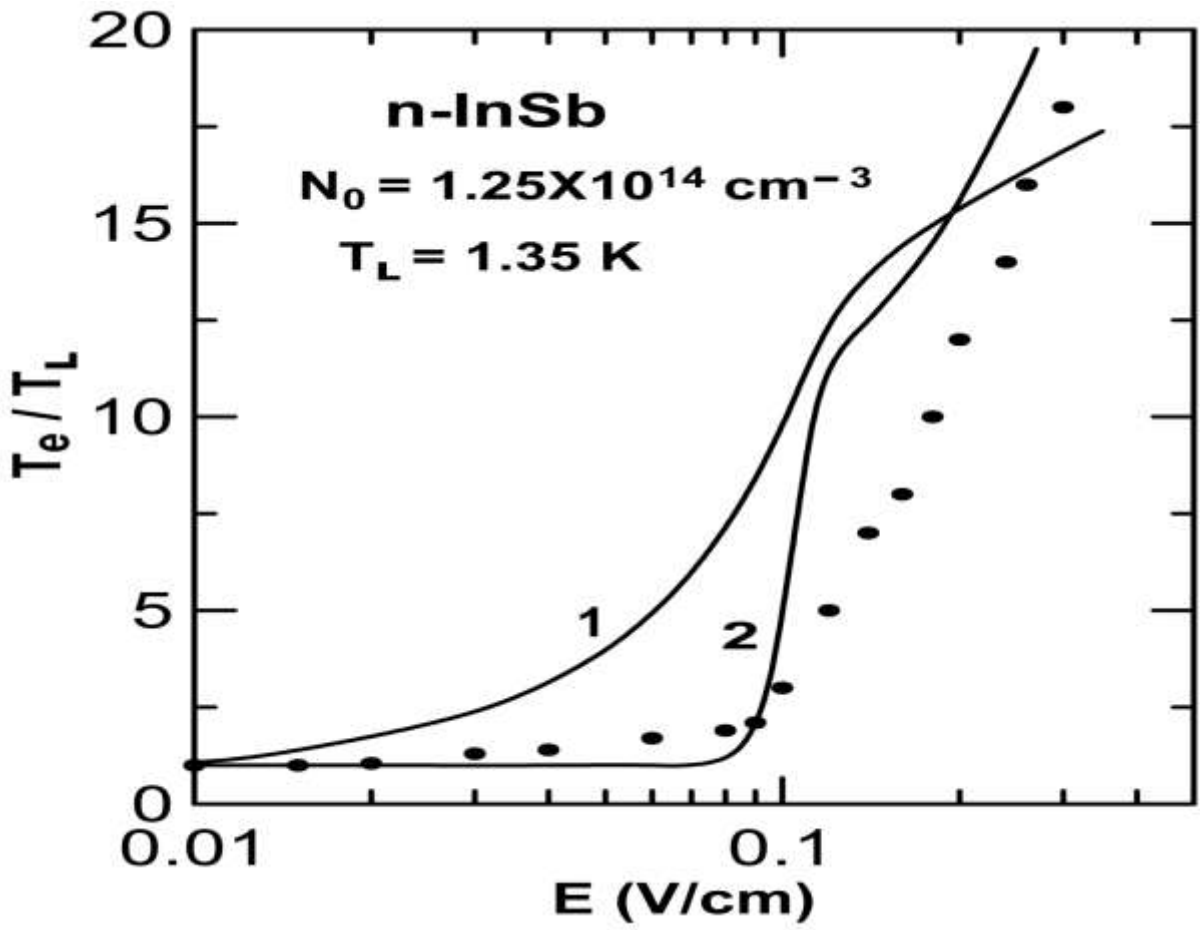

Fig.1 Dependence of electron temperature upon electric field in n-InSb. Curve marked 1 is the result from the present theory and that marked 2 is the result obtained by Monte Carlo Method considering all the prevalent scattering mechanisms [6]. Symbols (•) represent the experimental data [13].

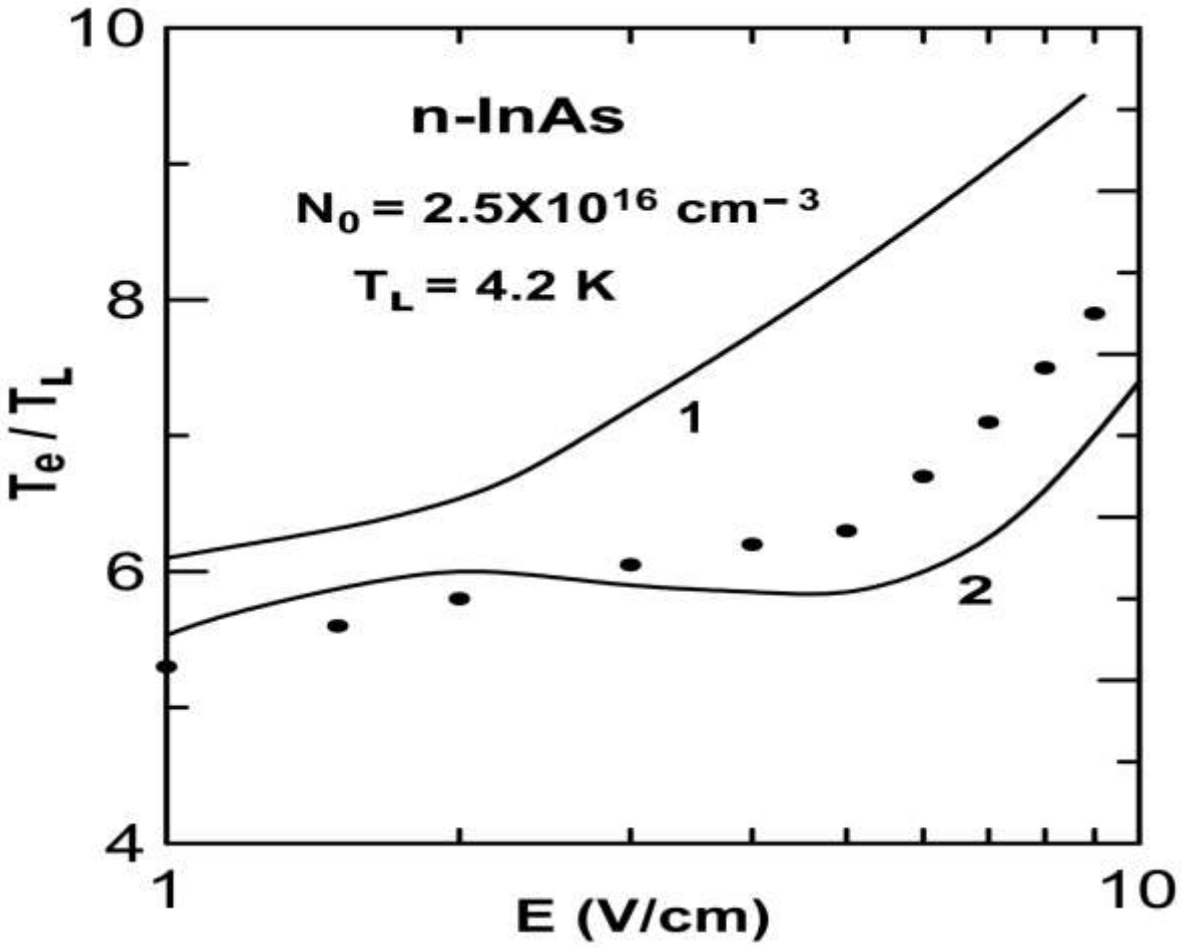

Fig.1 Dependence of electron temperature upon electric field in n-InAs. Curve marked 1 is the result from the present theory and that marked 2 is the result obtained by Monte Carlo Method considering all the prevalent scattering mechanisms [6]. Symbols (•) represent the experimental data [14].

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