AIP Journal of Applied Physics

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Citation: Journal of Applied Physics **75**, 1231 (1994); doi: 10.1063/1.356463
View online: http://dx.doi.org/10.1063/1.356463
View Table of Contents: http://scitation.aip.org/content/aip/journal/jap/75/2?ver=pdfcov
Published by the AIP Publishing

Effect of alloy scattering on the longitudinal hot electron drift velocity in n-$Hg_{0.8}Cd_{0.2}Te$ in the extreme-quantum-limit magnetic fields at low temperatures

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(Received 22 February 1993; accepted for publication 1 September 1993)

Longitudinal hot electron drift velocity in n-$Hg_{0.8}Cd_{0.2}Te$ in the extreme quantum limit has been investigated at low temperatures using displaced Maxwellian approximation. The model includes various complexities such as band nonparabolicity, quantum screening due to magnetic quantization, and Landau level broadening due to impurity fluctuations. The influence of alloy scattering on the drift velocity has been examined. The field dependences of hot electron drift velocity in n-$Hg_{0.8}Cd_{0.2}Te$ have also been studied.

It has been observed by many investigators[1,2] that the alloy scattering plays an important role in transport properties of n-$Hg_{0.8}Cd_{0.2}Te$. At low electric field and moderate temperature, electron transport is dominated by alloy disorder scattering in addition to usual scattering mechanisms such as phonon scattering as observed in compound semiconductors in the absence of any magnetic field.

The present authors have studied the low field mobility in n-$Hg_{0.8}Cd_{0.2}Te$ in the presence of large quantizing magnetic field, confining the carriers to the lowest Landau subbands, i.e., in the extreme quantum limit (EQL) condition, at low temperatures.[3] The results showed that the mobility in the presence of a magnetic field is also primarily dominated by the alloy scattering. However, the effect of alloy scattering in semiconductors such as HgCdTe under high electric and quantizing magnetic fields have not been reported in the literature.

In the present communication, a theoretical model is proposed to study the drift velocity of electron gas in alloy semiconductors subjected to high electric field in the presence of a quantizing magnetic field where both the fields being parallel to each other, i.e., in the longitudinal configuration. The model has been used to calculate the drift velocity of hot electrons in n-$Hg_{0.8}Cd_{0.2}Te$ in the EQL at low temperatures and to examine the relevance of alloy scattering in high electric field transport. Finally, a relative comparison of the results of the low and high fields have been made.

The essential features of the proposed model is similar to the model used to calculate the low field mobility at low temperature.[3] The inelastic acoustic phonon scattering is used to calculate the energy loss rate while the elastic acoustic phonon, ionized impurity and alloy disorder scatterings contribute to the mobility. Let us consider a nonparabolic band semiconductor subjected to a high magnetic flux density B in the z direction. Assuming that the electric field is applied in the same direction as B and taking a Maxwell–Boltzmann distribution function for carriers characterized by an electron temperature T_e, the average energy loss rate per electron through the emission and the absorption of acoustic phonons is expressed as[4,5]

$$P_{ac}=\frac{(m^*a_0)^{1/2}\hbar\omega_0}{\pi(2\pi k_BT_e)^{1/2}\hbar^2}\exp\left(-\frac{m^*a_0u_{ac}^2}{2k_BT_e}\right)\times\int_0^\infty q_\perp\,dq_\perp\int_0^\infty\frac{dq_z}{q_z}C_i|f_i(q)|^2\times\exp\left(-\frac{1}{2}l^2q_\perp^2-\frac{\hbar^2q_z^2}{8m^*a_0k_BT_e}-\frac{m^*a_0u_{ac}^2}{2k_BT_e}\frac{q_\perp^2}{q_z^2}\right)\times[(N_R+1)\exp(-\gamma_e)-N_R\exp(\gamma_e)], \quad (1)$$

where a_0 measures the band nonparabolicity, m^* is the bandedge effective mass, $\hbar$ is the reduced Planck's constant, $\hbar\omega_0$ is the phonon energy, k_B is the Boltzmann constant, u_{ac} is the acoustic velocity, $q_\perp$ and q_z are the transverse and longitudinal components of the phonon wave vector q, $l=(\hbar/eB)^{1/2}$ is the lowest Landau radius, N_R is the equilibrium phonon occupation number and $\gamma_e=(\hbar\omega_0)/(2k_BT_e)$ and $C_i|f_i(q)|^2$ represents the interaction matrix element for electron-phonon scattering.

The expression for P_{ac}, on simplification, becomes

$$P_{ac}=W_{ac}\int_0^\infty\frac{dv}{v}\exp(-v)f_{ac}(v), \quad (2)$$

where

$$W_{ac}=\frac{(m^*a_0)^{1/2}E_1^2\hbar\omega_0N_R}{8\pi(k_BT_e)^{1/2}l^3\rho\hbar u_{ac}}\left[\exp\left(\frac{\hbar\omega_0}{k_BT_L}\right)-\exp\left(\frac{\hbar\omega_0}{k_BT_e}\right)\right]\exp\left(-\frac{-\hbar\omega_0+m^*a_0u_{ac}^2}{2k_BT_e}\right) \quad (3)$$

and E_1 is the acoustic phonon deformation potential constant.

In deriving Eq. (2), we have made some assumptions as well as used the expressions for $C_i|f_i(q)|^2$ and $\hbar\omega_0$ from

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the low field mobility calculations.[3] The function, $f_{ac}(v)$, in Eq. (2) is a slowly varying function of v and to a good approximation $f_{ac}(v)$ can be taken outside the integral over v by evaluating its value at the optimum value of v, which is unity.[6] The Eq. (2) for P_{ac} shows a divergence at $v=0$, i.e., $q_z=0$. This has been eliminated by considering the broadening of the Landau level due to electron-impurity interactions. This corresponds to taking the lower limits of the integrals in Eq. (2) as $E_c/4k_BT_e$ where E_c is the cutoff energy[7] which varies on B as $B^{2/3}$.

Finally we can write

$$P_{ac}=W_{ac}f_{ac}(v)\ln\left[\exp(-C)\frac{4k_BT_e}{E_c}\right], \tag{4}$$

where C is the Euler's constant and f_{ac} is $f_{ac}(v)$ at $v=1$.

The electric field is given by the relation

$$\mathscr{E}=(P_{ac}/e\mu)^{1/2}, \tag{5}$$

where μ is the mobility and its value is calculated from the momentum relaxation times of carriers.[3]

The drift velocity of carriers in the high electric field region is assumed to be proportional to the applied electric field with the electron mobility being the constant of proportionality. This assumption is justified in high electric field condition where the electron temperature model is considered. The electron temperature model is used in electron gas in the EQL due to strong electron–electron interaction caused by magnetic confinement as observed in the low dimensional electron system.[8] The high electric field affects the mobility through the relaxation time τ or the effective mass m^* (for nonparabolic band semiconductors), both being the function of electron temperature.[9]

In calculating the energy loss rate and the relaxation time for acoustic phonon scattering via deformation potential, the phonon occupation number is assumed to be independent of electric field and it is given by Bose–Einstein statistics. The effect of phonon disturbance on the drift velocity due to lattice heating have been neglected because of large wavevector acoustic phonon ($q\cong 1/l$, $l=\hbar/eB$) in the EQL.[10]

Using the model, the electron temperature dependence of the drift velocity of electrons at $B=4$ and 6 T has been calculated using the material parameters of n-$Hg_{0.8}Cd_{0.2}Te$.[11] The electron temperature range used for the calculation is 2.5–5 K at a lattice temperature 1.5 K. It is observed from the experimental data on specific heat of n-$Hg_{0.8}Cd_{0.2}Te$ that the electron gas behaves as a nondegenerate electron gas for the above temperature range.[12] The cutoff energy E_c is taken to be 0.1 meV.[7]

The variations of drift velocity with electron temperature are shown in Fig. 1. The lower two curves and upper two curves, respectively, represent the variations of drift velocity with and without alloy scattering contributions. It is seen that the inclusion of alloy scattering reduces the magnitude of drift velocity quite significantly. The drift velocity without alloy scattering contribution appears to increase steadily with electron temperature. However, the lower curves show a tendency for saturation. It is also observed from the figure that the drift velocity of hot electrons in the EQL increases with the increasing magnetic field as observed by other investigators.[13]

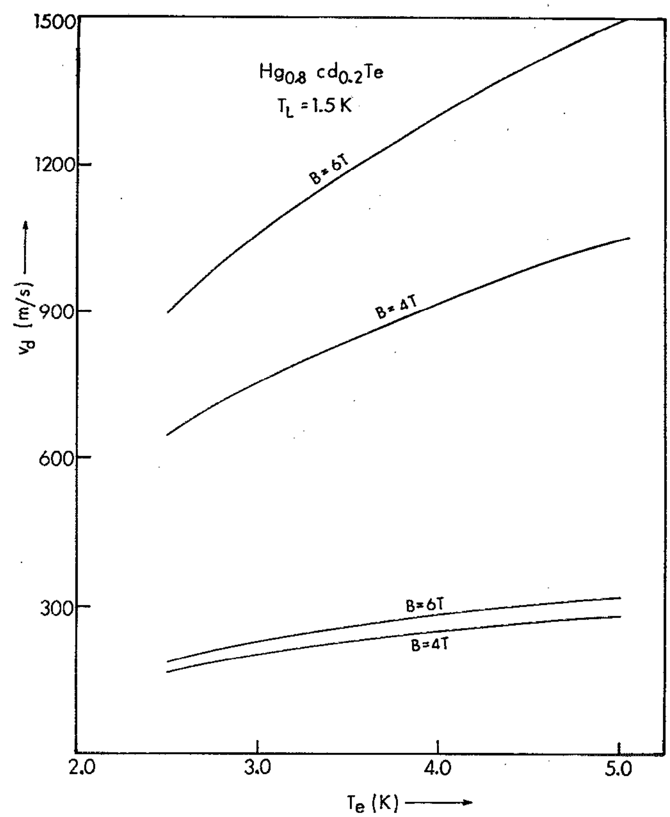

FIG. 1. Variation of the drift velocity of hot electrons in n-$Hg_{0.8}Cd_{0.2}Te$ in the extreme quantum limit as a function of electron temperature at a lattice temperature of 1.5 K for magnetic fields of 4 and 6 T. The lower two curves and upper two curves, respectively, represent the variations with and without alloy scattering contributions.

The energy loss rate at low temperature due to acoustic phonon increases with electron temperature and the drift mobility also increases with electron temperature. The effect of ionized impurity scattering decreases with increasing electron temperature because it is of electrostatic nature.[9] As the effect of Coulomb scattering decreases with increasing electron temperature, the drift velocity increases steadily. But when the alloy scattering is considered, the drift velocity decreases because of the enhancement in scattering rate. However, the energy loss rate due to hot electron in the extreme quantum limit is found to show a weak magnetic field dependence and it increases slowly with the magnetic field. This gives rise to electron drift velocity as an increasing function of magnetic field.

The effect of alloy scattering is found to dominant for both the low and high field mobility in the EQL at low temperatures. The low temperature high field mobility is primarily determined by the momentum relaxation time of nonphonon type of scatterings such as ionized impurity and alloy disorder since the effect of electron temperature (energy relaxation time) on the mobility is not so significant due to small energy loss rate when acoustic phonon scattering is considered. In the present analysis, the effect of ionized impurity scattering on the high field mobility is diminished due to low impurity concentration (10^{20} m^{-3}) as well as due to high electric field[9] and leaving the effect of alloy scattering to be most dominant.

One of the authors (P.B.) acknowledges the financial support, in the form of a Senior Research Fellowship, provided by the Council of Scientific and Industrial Research, New Delhi.

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