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D. Chattopadhyay

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Effect of electron-electron scattering on mobility in GaAs

D. Chattopadhyay
Institute of Radio Physics and Electronics, 92 Acharya Prafulla Chandra Road, Calcutta 700 009, India

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The influence of electron-electron scattering on mobility in GaAs is studied over the temperature range 80–300 K using the variation principle. The mobilities limited by both polar optic and ionized impurity scattering are reduced more significantly due to electron-electron scattering than those limited by deformation potential acoustic and by piezoelectric scattering. For a carrier concentration of 10^{16} cm^{-3}, the overall mobility is reduced by about 10% at 80 K.

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Considerable progress has been made in recent years towards the accurate calculation of electron mobility in polar semiconductors.[1–3] Values of electron mobility calculated by the incorporation of polar optic, deformation potential acoustic, piezoelectric, and ionized impurity scattering processes agree well with experiments for high purity GaAs samples. However, for GaAs films and most of the impure samples, the calculated values of mobility are much larger than those obtained experimentally.[4] To fit the calculated values to the observed values in these cases would require excessively large values of the compensation ratio; such large degrees of compensation are unlikely in view of the photoluminescence experiments[5] and secondary ion mass spectrometric (SIMS) analysis.[6] This discrepancy prompts one to consider the influences of the scattering mechanisms hitherto neglected. The purpose of the present communication is to study the effect of one such scattering mechanism, namely, electron-electron scattering, on the mobility in GaAs. We investigate the effect of electron-electron scattering on the separate mobilities limited by deformation potential acoustic, piezoelectric, polar optic, and ionized impurity modes of scattering together with the effect on the overall mobility when these scattering mechanisms are combined.

Scattering of electrons by each other occurs through the Coulomb interaction between them. The mobility is affected by such scattering characterized by the constraint that the energies and momenta of the electrons are conserved in the scattering. The effect on mobility insignificant in high purity samples where the carrier concentration is low, since electron-electron scattering is infrequent at such concentrations. The effect is also negligible at very large carrier concentrations when the electron distribution is degenerate, since the conservation of energy and momenta near the Fermi surface implies that the electron velocity is practically unaltered upon electron-electron scattering. Electron-electron scattering is thus expected to influence mobility most when the carrier concentration is large in the nondegenerate limit. We choose in this investigation a carrier concentration of 10^{16} cm^{-3} which is high enough for the distribution function to be considered nondegenerate over the temperature range of 80–300 K.

We assume a parabolic band structure; this assumption holds well for a large band-gap material like GaAs. The interaction potentials for electron-electron and electron-ionized impurity scattering are taken to be screened Coulomb potentials scaled by the static permittivity of the material. The spatial dependence of the dielectric function is shown[7] to have a negligible effect, and is not considered here. The Born approximation is valid[8] for the carrier concentration and the temperature range considered, and is used to describe the scattering.

Because electron-electron as well as polar optic scattering cannot be treated by relaxation times,[3,9] the variational method[10] is employed in the present calculations. In this approach, the mobility is given by

$$\mu = \frac{e}{n}\sum_{r=0}^{\infty} C_r \beta_r, \tag{1}$$

where e is the electron charge, n is the carrier concentration, and

$$\beta_r = -\frac{4n}{3(\pi)^{1/2} m^*}\Gamma(r+\tfrac{5}{2}), \tag{2}$$

m^* being the effective mass. The coefficient C_r is obtained by solving the set of equations

$$\sum_s \sum_i (d_{rs})_i C_s - \beta_r = 0, \tag{3}$$

where i denotes the type of scattering mechanism, and

$$(d_{rs})_i = (d_{sr})_i = \frac{2(2m^*)^{1/2}(k_B T)^{5/2}}{3\pi^2 \hbar^3} \times \int_0^\infty x^{r+3/2} \mathscr{L}_i(x^s)\, dx. \tag{4}$$

k_B is Boltzmann's constant, T is temperature, $\hbar$ is Planck's constant divided by 2π, $x = E(k_B T)^{-1}$, and $\mathscr{L}_i(x^s)$ is the collision term. For the different scattering processes we have (in SI units)

$$(d_{rs})_{ac} = \frac{4(2)^{1/2} n E_1^2 m^{*1/2}(k_B T)^{3/2}}{3\pi^{3/2}\hbar^4 \rho u_l^2}\Gamma(r+s+3), \tag{5}$$

$$(d_{rs})_{pz} = \frac{(2)^{1/2} e^2 P_e^2 n (k_B T)^{1/2}}{3\pi^{3/2}\hbar^2 \epsilon_0 K_s m^{*1/2}}\Gamma(r+s+2),$$

$$(d_{rs})_{p0} = \frac{n e^2 k_B \theta_l (K_s - K_\infty) n_l}{6(2)^{1/2}\hbar^2 \pi^{5/2} m^{*1/2}(k_B T)^{1/2} \epsilon_0 K_s K_\infty} \times \int_0^\infty \exp(-x)\left(2\ln\frac{(x+x_0)^{1/2}+(x)^{1/2}}{(x+x_0)^{1/2}-(x)^{1/2}}\right.$$

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$$\times [x^{r+s+1} + (x+x_0)^{r+s+1}]$$

$$+ \left[2[x(x+x_0)]^{1/2} - (2x+x_0)\ln\frac{(x+x_0)^{1/2}+(x)^{1/2}}{(x+x_0)^{1/2}-(x)^{1/2}}\right] \quad (6)$$

$$[x^r(x+x_0)^s + x^s(x+x_0)^r]\Big) dx, \quad (7)$$

$$(d_{rs})_{\text{imp}} = \frac{nN_i e^4}{12(2)^{1/2}(\pi m^* k_B T)^{3/2}\epsilon_0^2 K_s^2} \times \int_0^\infty x^{r+s}\exp(-x)\left[\ln(1+b) - \frac{b}{1+b}\right]dx, \quad (8)$$

where the subscripts ac, pz, po, and imp stand for deformation potential acoustic, piezoelectric, polar optic, and ionized impurity modes of scattering. In the above expressions $x_0 = \theta_l/T$, $b = 4k^2/\lambda_s^2$, k is the Bloch wave vector λ_s is the inverse Debye screening length, P_e is the piezoelectric coefficient, and the other symbols have the same significance as in Ref. 3.

In the present case convergence is achieved by keeping terms up to $r = 2$ in Eq. (1). For electron-electron scattering, the expressions for d_{rs} up to this order have been developed by Appel.[9] These are[11] (in SI units)

$$(d_{rs})_{ee} = \frac{n^2 e^4}{24(m^*\pi k_B T)^{3/2}(\epsilon_0 K_s)^2} P_{rs}(\delta^2), \quad (9)$$

where

$$\delta^2 = \frac{\hbar^2 \lambda_s^2}{2m^* k_B T}, \quad (10)$$

$$P_{ro} = P_{os} = 0, \quad (11)$$

$$P_{11} = L_1(\delta^2), \quad (12)$$

$$P_{12} = P_{21} = (7/2)L_1(\delta^2) + L_2(\delta^2), \quad (13)$$

$$P_{22} = (77/4)L_1(\delta^2) + 7L_2(\delta^2) + L_3(\delta^2), \quad (14)$$

and $L_n(\delta^2)$ is the integral defined in Ref. 9. Equation (9) shows that $(d_{rs})_{ee}$ depends on n^2; electron-electron scattering thus assumes importance at large carrier concentrations. Also, in view of Eq. (11), which is a consequence of the conservation of momentum in electron-electron collisions, the mobility would be infinite if there were no other scattering mechanism besides electron-electron scattering. Thus electron-electron scattering has to be jointly considered with lattice or impurity scattering processes.

Numerical results are obtained by assuming an effective mass of 0.07 m_0, m_0 being the free mass of the electron. The values of the other relevant material parameters are taken from Ref. 3. The ratio between the mobility obtained with particular scattering mechanisms together with electron-electron scattering (μ_{x+ee}), and that obtained with those mechanisms only (μ_x) is plotted in Fig. 1 as a function of temperature. Absolute values of μ_{x+ee} are shown in Fig. 2.

Electron-electron scattering is found to reduce the mobility. Being Coulombic in nature, its influence on lattice scattering mechanisms increases with decreasing temperature. The opposite is the case for ionized impurity scattering; electron-electron scattering affects the ionized-impurity-scattering mobility more at higher temperatures. This is a consequence of the fact that ionized impurity scattering is also Coulombic. We treat the ionized impurity scattering here for uncompensated material. The factor by which the mobility limited by this scattering is reduced through electron-electron scattering is a minimum in the limit $\delta^2 = 0$. Appel[9] estimates this minimum to be 0.58. In the present case this factor is larger, and decreases from 0.82 to 0.72 as the temperature rises from 80 to 300 K (curve 5, Fig. 1). This is a reflection of the fact that δ^2 is not sufficiently small, but decreases steadily from 0.16 to 0.011 with the increase of temperature over the range concerned.

Our calculations show that electron-electron scattering affects the mobilities due to polar optic and ionized impurity scattering more significantly than those due to deformation potential acoustic and piezoelectric scattering. Electron-electron scattering tends to randomize energy. Such scattering is therefore more effective for those processes in which the scattering rates strongly depend on electron energy. Dependence of the scattering rates on electron energy is stronger for polar optic and ionized impurity scattering than for the other scattering mechanisms considered.[1-3]

Figure 1 shows that, for a carrier concentration of 10^{16}

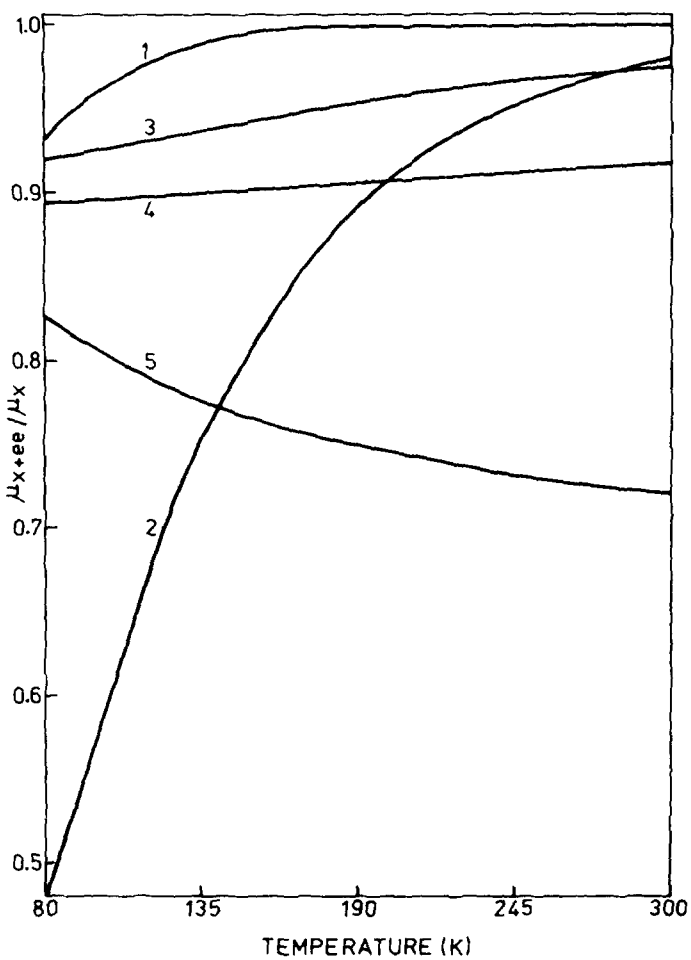

FIG. 1. Variation with temperature of factors by which mobilities due to various scattering mechanisms are reduced by electron-electron scattering. Curves 2 through 5 are for polar optic, deformation potential acoustic, piezoelectric, and ionized impurity scattering respectively. Curve 1 is for all the lattice and impurity modes of scattering treated jointly.

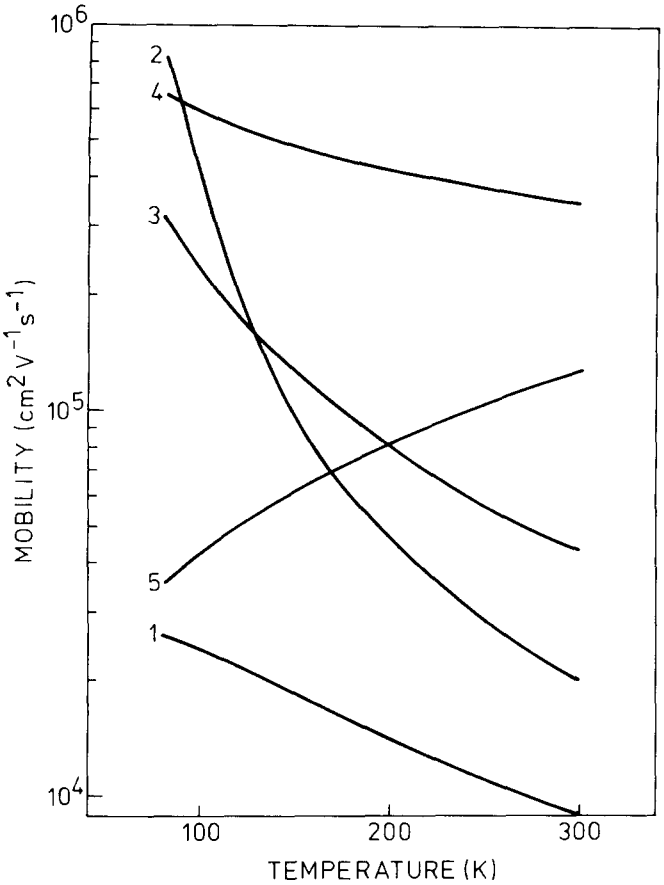

FIG 2. Mobility of n-GaAs considering electron-electron scattering. Curves 2 through 5 give the calculated mobilities when electron-electron scattering is included together with any of the following scattering mechanisms: polar optic (curve 2), deformation potential acoustic (curve 3), piezoelectric (curve 4), and ionized impurity scattering (curve 5). Curve 1 gives the overall mobility taking all scattering processes into account.

cm^{-3}, electron-electron scattering reduces the overall mobility (considering all types of lattice and ionized impurity scattering) by about 10% at 80 K, but the effect may be neglected above 150 K. Curve 1 in Fig. 2 shows that for this concentration the theoretical mobility, calculated with lattice, ionized impurity, and electron-electron scattering, is 2.6×10^4 $cm^2 V^{-1} s^{-1}$ at 80 K. The corresponding experimental value[4] is about 1.4×10^4 $cm^2 V^{-1} s^{-1}$. Incorporation of electron-electron scattering cannot thus completely resolve the discrepancy between theory and experiment, and one must resort to other plausible scattering processes. Some processes such as scattering by space charges,[12] or by local potentials,[13] have been proposed in the literature.

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