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Acoustic phonon scattering in modulation-doped heterostructures

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We use recently determined values of conduction and valence band edge deformation potentials to analyze two dimensional electron and hole mobilities in GaAs/AlGaAs modulation-doped heterostructures. Contrary to the commonly accepted view, it is shown that a consistent description of low temperature mobility can be given only if the short range deformation potential scattering is not screened by free carriers.

Scattering by lattice vibrations plays a major role in limiting carrier mobility in pure semiconductors. In ionic semiconductors polar optical phonon scattering is the major scattering process at room temperature whereas at lower temperatures, acoustic phonon scattering dominates¹. In such semiconductors, free carriers interact with acoustic phonons through a short range deformation potential as well as through a long range electrostatic potential resulting from the piezoelectric effect. The parameters determining strengths of the polar optical and the piezoelectric interactions are known from independent experiments unrelated to charge transport. On the other hand, until recently the band edge deformation potentials could not be measured separately. Only the difference between the conduction band and the valence band deformation potentials was known from the hydrostatic pressure dependence of the energy gap². In the absence of directly measured values, the conduction or valence band deformation potentials were determined by fitting of theoretical calculations to the existing free carrier mobility and/or free carrier absorption data. In many instances, this led to a situation where deficiencies of theoretical models and/or poor quality of experimental data were accommodated by fitting the value of the deformation potential. Therefore, it is not surprising that the deformation potentials obtained from such procedures varied substantially. In the case of GaAs, the conduction band deformation potentials ranged from -7 eV^3 to -16 eV^4 .

The introduction of modulation-doped heterostructures (MDH)^{5,6} led to a large reduction of ionized impurity scattering, dramatically enhancing sensitivity of the low temperature carrier mobility to the acoustic phonon scattering. Most recently, n-⁷ and p-type⁸ GaAs/AlGaAs MDHs were fabricated with extremely high mobilities exhibiting linear temperature

dependence of the inverse low temperature mobility. This indicated that acoustic phonon scattering dominates in these MDHs. Also a new method for a direct measurement of the values of the band edge deformation potential has been proposed⁹. The method based on the existence of universal reference energy levels given by the transition metal impurities has been used to measure absolute conduction and valence band deformation potentials in GaAs and InP. These new determinations completed the set of parameters necessary for full description of the carrier transport in these materials. In this paper, we use this set of parameters to analyze the effects of acoustic phonon scattering on the mobilities of two-dimensional electron and hole gases in GaAs/AlGaAs MDHs. We show that an internal consistency for the set of GaAs parameters is obtained only if the long range piezoelectric scattering is screened by free carriers and the short range deformation potential is not. The commonly used free carrier screening of the deformation potential leads to values of the deformation potential constants which are much larger than those measured directly.

A detailed analysis of the acoustic phonon scattering of the two-dimensional electron gas in the triangular well was given by Price¹⁰. For the screened deformation potential scattering the inverse relaxation time is:

$$\frac{1}{\tau_{dp}} = \frac{3m_e^* a_c^2 k_B T b_e}{16\pi C_{\ell} \hbar^3} \int_0^{\pi} s^2 (1 - \cos \theta) d\theta \quad (1)$$

where $s = Q^2 / (Q + q_s \hbar)^2$,

$Q = 2k \sin \frac{1}{2}\theta$,

k is the electron wavevector,

$$H = \frac{1 + \frac{9}{8}r + \frac{3}{8}r^2}{(1 + r)^3},$$

$$r = \frac{Q}{b_e},$$

$$b_e = \left(\frac{33\pi m_e e^2 N_s}{\epsilon_s \hbar^2} \right)^{\frac{1}{3}},$$

$$q_s = \frac{2e^2}{\epsilon_s \hbar^2} (1 - e^{-\alpha}) \text{ is the temperature-dependent screening parameter}$$

$$\alpha = \frac{\pi \hbar^2}{m_e kT}$$

N_s is the electron gas density, a_c is the deformation potential constant, and ϵ_s is the dielectric constant. In the absence of the free carrier screening, $q_s = 0$ and Eq. 1 reduces to:

$$\frac{1}{\tau_{dp}} = \frac{3m_e^* a_c^2 k_B T b_e}{16C_\ell \hbar^3} \quad (2)$$

where C_ℓ is the longitudinal elastic constant.

The relaxation time for piezoelectric scattering is given by¹⁰,

$$\frac{1}{\tau_{pe}} = \frac{1}{\tau_L} + \frac{2}{\tau_T} \quad (3)$$

where

$$\frac{1}{\tau_{L,T}} = \frac{\hbar a_{L,T}}{k_B T k^2} \int Q s^2 f_{L,T}(Q) dQ \quad (4)$$

For GaAs

$$\alpha_T = 3.21 \times 10^4 \left(\frac{m}{m_0} \right)^* \text{ (cm}^{-1}\text{)}$$

$$\alpha_L = 1.66 \times 10^4 \left(\frac{m}{m_0} \right)^* \text{ (cm}^{-1}\text{)}$$

The function of f_L and f_T are given in Ref. 10.

The degeneracy of the GaAs valence band leads to substantial complications of the energy level structure of the two-dimensional hole gas. It has been shown, however, that the energy separating the two uppermost subbands from lower lying levels is large enough so that only these two subbands have to be considered.^{11,12} Also, it has been argued¹³ that since the light holes located in the spin-down subband are very efficiently scattered by the heavy holes from the spin-up subband, one can neglect light hole contribution to the hole transport. In the present calculations we assume that an isotropic cyclotron effective mass calculated in Ref. 12 provides a proper description of the heavy hole spin-up subband in GaAs. With these assumptions, Eq. 1 and 4 for the acoustic phonon scattering can be modified to account for p-type symmetry of the valence band. In the case of piezoelectric scattering, the integral function in eq. 4 has to be multiplied by the overlap function $1/4 (1+3\cos^2\theta)$. For the short range deformation potential both longitudinal and transverse phonons contribute to the scattering. Also, the interaction of the holes with the transverse phonons can lead to spin-flip transitions between heavy and light hole subbands. The effective deformation potential for holes can be divided into two parts representing intra- and intersubband contributions to the scattering:¹⁴

$$E_{dp}^2 = E_{intra}^2 + E_{inter}^2 \quad (5)$$

where:

$$E_{intra}^2 = \frac{C_l + C_t}{4C_t} \left[(1+m)^2 + n^2 \right] + \frac{C_l}{4C_t} m^2 \quad (6)$$

$$E_{inter}^2 = \frac{m_2^* C_l}{3m_1^* C_t} n^2 \quad (7)$$

m_1^* and m_2^* are heavy and light hole effective masses, respectively, C_l and C_t are longitudinal and transverse elastic constants, l , m and n

are parameters related to the valence band deformation potentials a_v , b_v and d_v ; ¹⁵ $l = 2b_v + a_v$, $m = a_v - b_v$, $n = \sqrt{3} d_v / 2$.

The macroscopic mobility can be expressed in terms of the average relaxation time:

$$\mu = \frac{e \langle \tau \rangle}{m} \quad (8)$$

$$\langle \tau \rangle = \frac{\int x \frac{\partial f_0}{\partial x} \tau(x) dx}{\int x \frac{\partial f_0}{\partial x} dx} \quad (9)$$

and f_0 is the Fermi-Dirac distribution function. The GaAs parameters used in the calculations are listed in Table I. In Fig. 1 the inverse electron and hole mobilities in GaAs/AlGaAs MDHs are shown. The solid lines represent the mobilities calculated without free carrier screening of the deformation potential scattering. Excellent agreement with a recent experiment for an n-type MDH with highest ever reported low temperature mobility was obtained. The contribution of the screened piezoelectric scattering to the total electron mobility represented by the solid line is about 30 percent. It has to be emphasized that no fitting parameters are used in these calculations. If the deformation potential is screened by free carriers, then the resulting total scattering shown by the upper dashed curve in Fig. 1 is too low. To account for this discrepancy, a value of -13.5 eV for a_c had to be adopted in previously reported calculations.¹⁷ This value is, however, in obvious disagreement with directly measured $a_c = -9.3 \pm 1$ eV (9) and recently calculated values of -8.8 eV¹⁸ and -7.3 eV.¹⁹ Also, such a high value of a_c could not be reconciled with an existing mobility data on high purity GaAs.^{20,21}

As is seen from eqs. (5-7), the determination of the effective deformation potential for holes requires the knowledge of both light m_2^* and heavy

hole m_1^* effective masses. Recent calculations¹² have shown that $m_2^* = 0.19 m_0$ and is independent of the carrier concentration. Therefore the only parameter necessary for the description of the hole mobility is the heavy hole effective mass. As is shown in Fig. 1, a good agreement between theory and experiment is obtained for the screened piezoelectric and unscreened deformation potential scatterings with the heavy hole effective mass of $m_1^* = 0.68 m_0$. This value is only slightly below the range of m_1^* calculated for a p-type MDH¹² with the total hole concentration of $\sim 2.7 \times 10^{11} \text{ cm}^{-2}$ corresponding to the experimental data of ref. 8. Also we find that with this value of m_1^* the intersubband contribution to the total deformation potential scattering given by eq. (7) does not exceed 15 percent and the piezoelectric contribution is less than 10 percent. Isotropic heavy hole mass m_1^* has been employed in the above calculations. In order to estimate the accuracy of this approximation, we assume that the angular dependence of the effective mass can be written in the form,¹² $m_1^*(\theta) = A + B \sin^2 2\theta$, where A and B are constants. The anisotropy of the heavy hole effective mass measured by the ratio B/A does not exceed 0.5.¹² To account for the anisotropy in the case of unscreened deformation potential scattering one has to compare the integrals:

$$m_1^{*2} \int_0^\pi (1 - \cos \theta) d\theta$$

and

$$\int_0^\pi (A + B \sin^2 2\theta) (1 - \cos \theta) d\theta$$

where $m_1^* = (A + 1/2B)$ is the average cyclotron mass. It can be shown that the relative difference between those two integrals is $0.13B^2/(A+B/2)^2$. Thus, for $B/A < 0.5$ an error introduced by the isotropic mass approximation does not exceed 2 percent.

The lower broken curve in Fig. 1 represents hole mobility for the case where both piezoelectric and deformation potential scatterings are screened by free holes. The resulting acoustic phonon mobility is not only more than two times higher than the experimental mobility but also shows much different temperature dependence for the temperatures lower than 30K. Therefore the agreement between the theory and experiment cannot be improved by adjusting heavy hole effective mass and/or the effective deformation potential. We may conclude from the above analysis that for both two dimensional electrons and holes a good agreement with the experiment is obtained only when the deformation potential is not screened by free carriers.

The problem of whether the short range deformation potential scattering should be screened has been analyzed for the case of 3D electrons.²² It has been found that although the arguments used to introduce free carrier screening of long-range potentials are not applicable in the case of deformation potential, however, the effective matrix element obtained by an inversion of the full dielectric matrix has the same form as for the potential screened by free carriers. This finding could not be tested previously since for a 3D electron gas the screening effects are significant only at high electron densities at which ionized impurity scattering is a dominant scattering mechanism. The present analysis shows that a simple Thomas-Fermi screening of the deformation potential cannot be used in the case of 2D electron and hole gases and that reconsideration of the screening of short range interactions is needed.

In summary, acoustic phonon electron and hole mobilities were calculated using recently determined GaAs conduction and valence band edge deformation potentials. A consistent description of the temperature dependence of the mobilities in GaAs/AlGaAs MDHs can be given only if the short range deformation potentials are not screened by free carriers.

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References

1. See for example, D.L. Rode in Semiconductors and Semimetals, edited by R.K. Willardson and A.C. Beer (Academic, New York, 1975), Vol. 10, Chap. 1.
2. M. Chandrasekhar and F.H. Pollak, Phys. Rev. B15, 2177 (1977).
3. E.M. Wolfe, G.E. Stillman and W.T. Lindley, J. Appl. Phys. 41, 3088 (1970).
4. P. Pfeffer, I. Gorczyca and W. Zawadzki, Solid State Comm. 51, 175 (1984).
5. R. Dingle, H.L. Störmer, A.C. Gossard and W. Wiegmann, Appl. Phys. Lett. 33, 665 (1978).
6. L.C. Witkowsky, T.J. Drummond, C.M. Stanchok and H. Morkoc, Appl. Phys. Lett. 37, 1033 (1980).
7. J.H. English, A.C. Gossard, H.L. Stormer and K.W. Baldwin, Appl. Phys. Lett. 50, 1826 (1987).
8. E.E. Mendez and W.I. Wang, Appl. Phys. Lett. 46, 1159 (1985).
9. D.D. Nolte, W. Walukiewicz and E.E. Haller, Phys. Rev. Lett. 59, 501 (1987).
10. P.J. Price, Surf. Sci. 143, 145 (1984).
11. M. Altarelli and U. Ekenberg, Phys. Rev. B32, 5138 (1985).
12. T. Ando, Jour. Phys. Soc. Japan 54, 1528 (1985).
13. W. Walukiewicz, J. Appl. Phys. 59, 3577 (1986).
14. The difference between the present expression for the intrasubband deformation potential and that obtained in ref. 13 is a consequence of the incorrect form of the valence band wave functions used in ref. 13. It has to be emphasized however that the numerical values for E_{intra} are very similar in both cases.
15. G.E. Pikus and G.L. Bir, Sov. Phys. Solid State 1, 1502 (1958).

16. D. Wiley, in Semiconductors and Semimetals, edited by R.K. Willardson and A.C. Beer (Academic, New York, 1975). Vol. 10, Chap. 2.
17. E.E. Mendez, P.J. Price and M. Heiblum, Appl. Phys. Lett. 45, 294 (1984).
18. M. Cardona and N.E. Christensen, Phys. Rev. B35, 6182 (1987).
19. C.G. Van de Walle and R.M. Martin, to be published.
20. P.J. Price, Phys. Rev. B32, 2643 (1985).
21. W. Walukiewicz, H.E. Ruda, J. Lagowski and H.C. Gatos, Phys. Rev. B32, 2645 (1985).
22. P. Boguslawski and J. Mycielski, J. Phys. C: Solid State Phys. 10, 2413 (1977).

Table I. Parameters Employed in Present Calculations

MDH	n-type	p-type
Parameter		
Effective mass	$m_e^* = 0.066m_0$ (a)	$m_1^* = 0.68m_0$ $m_2^* = 0.19m_0$ (b)
Deformation Potential	$a_c = -9.3\text{eV}$ (c)	$a_v = -0.7\text{eV}$ (c) $b_v = -1.7\text{eV}$ (d) $d_v = -4.4\text{eV}$ (d)
Carrier concentration	$N_e = 1.6 \times 10^{11} \text{cm}^{-2}$ (e)	$N_h = 2.7 \times 10^{11} \text{cm}^{-2}$ (f)
Static dielectric constant	$\epsilon_s = 12.9$ (a)	
Elastic constants	$C_\ell = 1.4 \times 10^{12} \text{ dyn/cm}^2$ (d) $C_t = 0.49 \times 10^{12} \text{ dyn/cm}^2$ (d)	
Piezoelectric coupling parameter	$h_{14} = 1.2 \times 10^7 \text{ V/cm}$ (d)	

a Ref. 1

e Ref. 7

b Ref. 12

f Ref. 8

c Ref. 9

d Ref. 18

Figure caption

Fig 1. Inverse electron and hole mobilities. The experimental points are the data of ref. 7 (●) and 8 (o). The solid lines and broken lines represent the mobilities calculated for unscreened and screened deformation potentials, respectively. The parameters used in the calculations are listed in Table I.

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Figure 1.

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