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ABSTRACT

Hole mobilities in the two highest spin-split subbands in a p-type modulation-doped heterostructure are calculated. The light hole mobility is shown to be very low because of efficient scattering by the holes in the heavy mass subband. This finding significantly simplifies calculation of the charge transport, since only the heavy hole contribution has to be considered. It is shown that for the state-of-the-art heterostructures the heavy hole mobility is limited by the deformation potential acoustical and optical phonon scatterings with small contribution from ionized impurities at low temperatures. The valence band deformation potential constant has been determined comparing the theoretical calculations with available experimental data on temperature dependence of the hole mobility.

Identification of the scattering processes limiting carrier mobility is one of the primary goals of studying the charge transport in modulation-doped heterostructures (MDH). In the last few years the mobility of the two dimensional electron gas confined at the heterointerface of two semiconductors has been very extensively investigated[1-4]. Most of the principal features of the electron scattering, as well as their relationship to heterostructure properties, are now quite well understood[5-7]. Accordingly, the extremely high electron mobilities at low temperatures, higher than $2 \times 10^6 \frac{cm^2}{V \cdot s}$ [3], observed in GaAs-AlGaAs MDHs were explained in terms of remote impurity and acoustic phonon scattering[7]. A very profound effect of modulation doping on hole mobility was also observed[8-12]. To date the highest reported hole mobility is $2.35 \times 10^5 \frac{cm^2}{V \cdot s}$ at 2K[12]. It is quite obvious that formulation of a model of hole mobility comprising all the complexity of the valence band is a cumbersome task. However, as has been shown by the author[13], a tractable model of the hole mobility can be devised when a number of simplifying assumptions is introduced. In the previous calculations of the hole mobility[13] the values of the effective masses determined from cyclotron resonance experiments were adopted[8]. The most recent theoretical results indicate that the zero magnetic field effective masses are considerably different from the masses determined at high magnetic field[14,15].

In this letter new theoretical results on the energetic structure of the two-dimensional hole gas[14,15] are used to analyze scattering processes in p-type MDHs. It is shown, for the first time, that the light hole mobility is very low because of efficient heavy hole scattering. Also, the

acoustic phonon scattering rate is calculated using heavy hole subband wavefunctions of proper symmetry rather than adopting a three dimensional deformation potential[13]. We consider p-type MDH in which only the two highest subbands are occupied at low temperatures. The light hole subband is almost parabolic and can be represented by an effective mass $m_2 \simeq 0.19$ m_0[14-15]. Theoretical calculations have shown that the heavy hole mass is strongly dependent upon energy for small hole energies. Further, it has been shown[15] that the heavy hole mass at a given hole energy very weakly depends on the two dimensionsal hole gas density. In this work isotropic, energy dependent density of states[15] heavy hole mass is used. Because of high heavy hole mass free hole screening of electrostatic interactions is much more effective than screening by much lighter electrons[13]. Therefore, the contribution to the scattering from piezoelectric acoustic phonons can be neglected and the efficiency of the ionized impurity scattering is significantly diminished.

In the case of p-type MDH a new scattering process inherently related to the valence band electronic structure has to be considered. For typical p-type AlGaAs-GaAs MDH with the hole density $p > 2 \times 10^{11}$ cm^{-2} the heavy to light hole mass ratio[15] is bigger than 3; therefore, the light holes are very efficiently scattered by the heavy holes. It has been shown[16] for the case of three dimensional electron gas that the electron-hole scattering can be well approximated by ionized impurity scattering for the hole to electron mass ratio larger than 2. Here we adapt this approximation and assume that the heavy holes are evenly distributed within a quantum well of width $8/3b_h$[17]. Here b_h is the variational parameter of the two dimensional hole

gas wave-function[13]. Then the concentration of the scattering centers is given by $N_i^h = 3p_1b_h/8$, where p_1 is the heavy hole density. Under these assumptions the heavy hole scattering rate can be obtained adapting the formula found for the background ionized impurity scattering of the two-dimensional electron gas[18,7]. Since the light hole wavevector k_2 is much smaller than b_h and the screening parameter q_s [13], an approximate expression for the light hole mobility limited by the heavy hole scattering takes the form

$$\frac{1}{\mu_2{}^h} = \frac{15\pi^2 \hbar p_1 m_2^2}{128e(m_1 + m_2)^2} \left(39 - 252 \frac{k_2^2}{b_h}\right) \tag{1}$$

where m_1 and m_2 are the heavy and light hole masses, respectively. In the derivation of expression (1) the effects of the valence band p-type symmetry have been taken into account. For the heavy hole density of 2×10^{11} cm^{-2} one finds from Eq. (1) the low temperature light hole mobility to be lower than $6 \times 10^3 \frac{cm^2}{V \cdot s}$. Since in a good quality MDH the experimentally observed mobilities are much higher, it is evident that the light holes don't contribute to the total mobility. This finding considerably simplifies the overall picture of the hole transport in p-type MDHs, as only the heavy hole subband has to be considered. Also it should be noted that the hole density determined from Hall effect measurements is equal to the heavy hole density rather than to the total hole density.

The scattering processes limiting the heavy hole mobility in MDHs are[13]: ionized impurity, acoustic phonon deformation potential and

optical phonons. The remote ionized impurity scattering is treated, here, using the approximate model valid for MDHs with spacer width larger than ~100Å[13]. It is well known that for a subband with p-type symmetry both longitudinal and transverse acoustic phonons contribute to the acoustic phonon scattering[19,20]. Applying the deformation potential theory developed for p-type symmetry bands to the two dimensional case[19] one obtains the following expression for the acoustic phonon limited mobility:

$$\mu_{def} = \frac{16\hbar^3 \rho v_\ell^2 e}{3k_o T m_2^2 b_h E_{dp}^2} \tag{2}$$

$$\text{where} \quad E_{dp}^2 = \left(\frac{\ell + m}{2}\right)^2 + \frac{v_\ell^2}{v_t^2}\left(\frac{n - m}{2}\right)^2 \tag{3}$$

and l, m and n are parameters related to the valence band deformation potentials a, b and d, as $l = 2b + a$, $m = a - b$, $n = \sqrt{3}\, d/2$. v_ℓ and v_t are the longitudinal and transverse sound velocities respectively, and ρ is the specific density of the crystal. For temperatures T > 80K the optical phonon scattering becomes a dominant scattering process. This scattering is included using the mobility calculated for the three dimensional hole gas[13,21].

In Fig. 1 the temperature dependences of the heavy hole mobilities for various scattering mechanisms are shown. The mobilities were calculated adopting results of theoretical calculations for the energy dependence of

the heavy hole mass for GaAs-AlGaAs MDH[15], and assuming the value $p_1 = 2 \times 10^{11}$ cm^{-2} for the heavy hole density and $N_i^r = 1.5 \times 10^{18}$ cm^{-3} for the remote ionized impurity concentration[11]. This corresponds to experimental data of Ref. 12 shown along with the theoretical results in Fig. 1. The temperature dependence of the experimental mobility indicates that the acoustic phonon deformation potential scattering is a dominant scattering process over a broad temperature range, 4 K < T < 60 K. One can thus determine the the value of the parameter $b_h \cdot E_{dp}^2$ by comparing the theoretical results with the experiment. For the present case we have found $b_h E_{dp}^2 = 8.4 \times 10^7$ eV^2/cm. Using a simple approximation for the value of the variational parameter b_h [13], one obtains $E_{dp} = 4.2$ eV. Since the deformation potentials b and d are quite well known from uniaxial stress experiments[22] (b = -1.7 eV, d = -4.4 eV), one obtains from Eq. (3) the value of the third deformation potential a $\cong$ -1.0 eV. Although this value is substantially lower than a = 2.7 eV found in Ref. 22, we note that using our present value of a, we obtain $\Xi_{eff} = 6.1$ eV for the effective three dimensional deformation potential which favourably compares with $\Xi_{eff} = 6.6$ eV determined from hole mobility analysis in p-type GaAs[22,23]. It is, however, much different from $\Xi_{eff} = 9.5$ eV calculated with the deformation potentials proposed in Ref. 24. The largest uncertainty in determination of the deformation potential comes from the approximation used to calculate b_h [13]. In order to estimate the accuracy of this approximation we have calculated b_h using the MDH parameters of Ref. 14. The value of $2/b_h \simeq 24$ Å agrees very well with $Z_{max} = 27$ Å obtained for the position of the maximum of the hole density distribution determined from a self consistent Hartree approximation[14], thus justifying the simple approximation for b_h [13].

The present analysis of the phonon scattering sheds some new light on recent discussions[25,26] on whether the acoustic phonon scattering should be screened by free carriers in the same way as long range electrostatic interactions. Assuming, as was done in Ref. 17, that the acoustic phonon deformation potential is screened by free carriers one gets an unreasonably large value of the deformation potential[12] which cannot be reconciled with the mobility data for high purity p-type GaAs[27].

Phonon mobility limits for two-dimensional (2D) and three-dimensional (3D) hole gases are compared in Fig. 2. At room temperature the mobility is limited by optical phonon scattering and is practically the same in both cases. At lower temperatures the deformation potential scattering dominates the mobility. Because of different energy dependences of the scattering rates, the hole mobilities for 2D and 3D gases show different temperature dependences. Also the 2D gas mobility is considerably lower in the whole temperature range. This explains why at 77K the highest 2D mobility reported in MDHs is lower than the 3D hole mobility in high purity p-type GaAs[12,27]. At temperatures lower than ~40K the 3D hole mobility is limited by ionized impurity scattering even for the purest p-type GaAs[27], whereas, as shown in Fig. 1, the 2D hole gas mobility follows the phonon mobility limit down to ~4 K.

In summary, it has been shown that in p-type MDH the mobility of the light holes is dominated by heavy hole scattering and is much lower than the mobility of the heavy holes. Therefore, the temperature dependence of the hole mobility can be explained in terms of a single subband transport. In a

wide temperature range the heavy hole mobility is determined by deformation potential acoustic phonon scattering. The value of the deformation potential found from comparison of the present calculations with experimental results is consistent with the hole mobility data in p-type GaAs.

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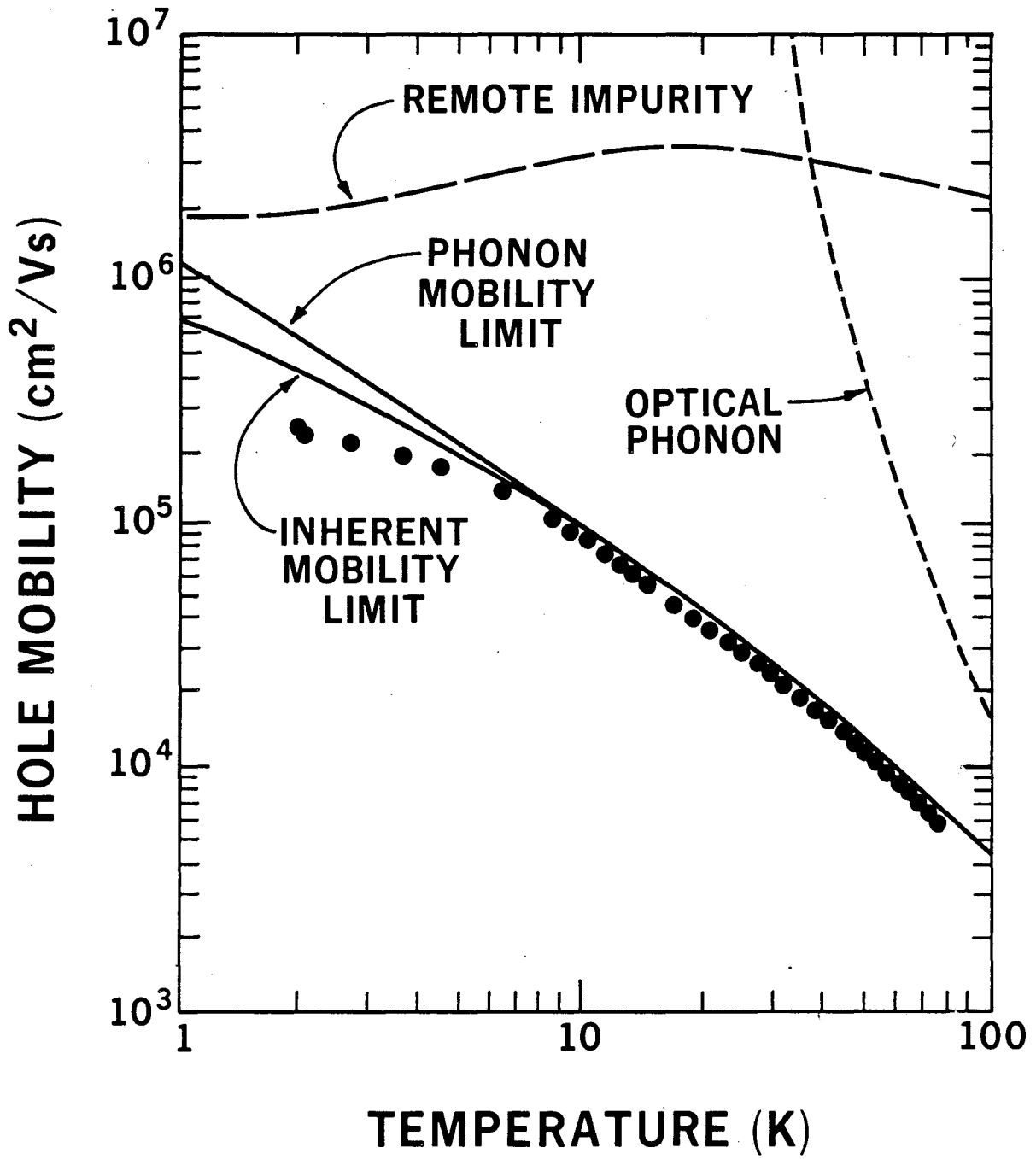
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FIGURE CAPTIONS

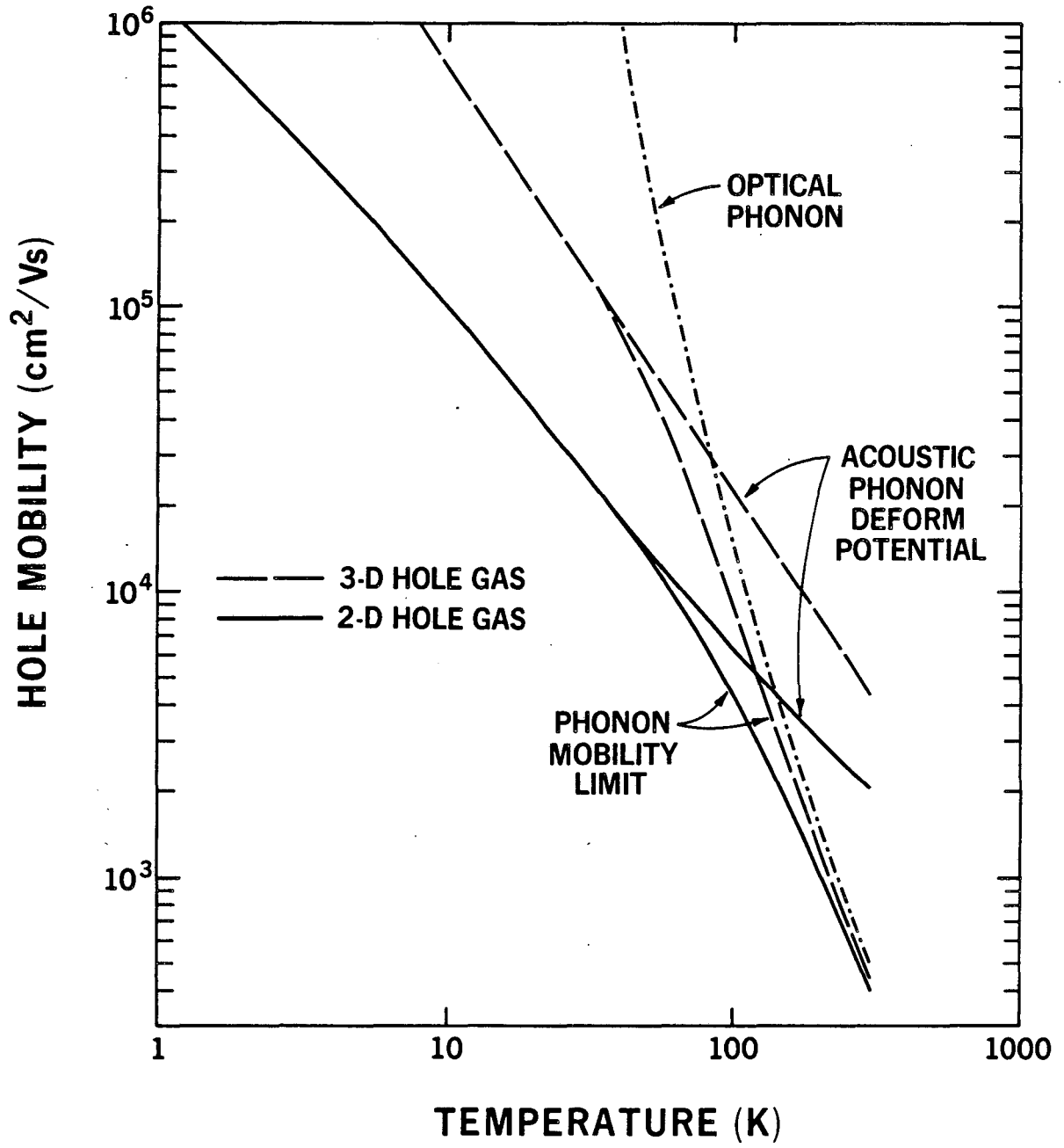Fig. 1   Temperature dependence of the hole mobility in a GaAs—AlGaAs MDH.
Points represent experimental data of Ref. 12 for the hole
concentration 2×10^{11} cm^{-2}.

Fig. 2   Temperature dependence of the phonon mobility limits for 2D and 3D
hole gases.   The MDH parameters are the same as in Fig. 1.

Figure 1.

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The plot shows HOLE MOBILITY (cm^2/Vs) on the vertical axis versus TEMPERATURE (K) on the horizontal axis, with labeled curves: OPTICAL PHONON, ACOUSTIC PHONON DEFORM POTENTIAL, PHONON MOBILITY LIMIT, 3-D HOLE GAS, and 2-D HOLE GAS.

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Figure 2.