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HOLE MOBILITY IN MODULATION-DOPED HETEROSTRUCTURES: GaAs-AlGaAs

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Abstract

A comprehensive model for the hole mobility in a two-dimensional hole gas confined at a modulation-doped heterostructure interface is proposed. All the major scattering processes in the two uppermost spin subbands are taken into account. The calculations are substantially simplified by effects of a strong free hole screening. The model explains quantitatively experimental results of the temperature dependence of the hole mobility. It is shown that at large spacer widths, the predicted mobility limit exceeds 2×10^5 cm/Vs and is entirely determined by acoustic phonon deformation potential scattering.

Introduction

Recent years have witnessed an unprecedented growth of interest in two-dimensional electron gas systems. A number of new phenomena such as fractionally quantized Hall effect[1] and extremely high electron mobilities[2,3] have been observed for the electron gas confined at the interface of GaAs-AlGaAs modulation-doped heterostructure (MDH)[4,5]. In this system, the highest reported mobilities exceed $2 \times 10^6 cm^2/Vs$ [2]. At present, the role of different scattering processes limiting the two-dimensional electron gas mobility is quite well understood[6-8].

Considerably much less effort has been directed towards the study of two-dimensional hole systems, although it is believed that such systems are interesting not only from the point of view of fundamental physics, but also because they may have important practical applications[9]. In a number of recently published papers, various aspects of the two-dimensional hole gas in GaAs-AlGaAs have been studied[10-14]. It has been shown that improved modulation doping techniques lead to increased hole mobilities[11,14]. To date the highest reported hole mobility is ~ 9.7×10^4 cm^2/Vs at 4.2 K[14]. Although experimental data on hole mobility is accumulating, there has been no attempt to formulate a theoretical model which could explain the existing data and predict hole mobility limits in p-type MDH's.

In this paper we show for the first time that the present understanding of the electronic structure of p-type GaAs-AlGaAs MDH's allows the formulation of a relatively simple model of the hole mobility. The model assumes that the holes are confined in a triangular quantum well on the GaAs side of the interface. A lack of the inversion symmetry and strong spin-orbit coupling in this system results in splitting of the fourfold degenerate valence band into a series of subbands. The two uppermost heavy hole spin subbands are degenerate for $\vec{k} = 0$ and are well separated from the lower lying subbands so that for typical hole concentrations, only the highest subbands are occupied[13]. Because these two subbands have different spins, there exists no substantial inter-subband scattering for all the important scattering processes. Scattering rates can be calculated separately for each subband. They can be combined according to the well-known formula for the total Hall mobility[16]. Recent theoretical results show that in a limited energy range, these two highest subbands are parabolic[13], and therefore, they can be characterized by effective

masses m_1* and m_2*. Adapting results of Ref. 15, one finds that the z-component of the envelope wave function for the hole gas confined in a triangular well can be written in the form:

$$\chi_h(z) = \frac{z \exp\left(-\frac{b_h z}{2}\right)}{\left(\frac{b_h}{2}\right)^{3/2}} \tag{1}$$

where
$$b_h^3 = b_{1h}^3 + b_{2h}^3 \tag{2}$$

$$b_{ih}^3 = \frac{33\pi\, m_i^*\, e^2}{2\, \varepsilon_s\, \hbar^2}\, p_i \tag{3}$$

p_i $(i = 1,2)$ is the hole concentration in the i-th subband.

Scattering Rates

There are a number of scattering processes which have to be considered for a two-dimensional hole gas in MDH's. In addition to all the scattering mechanisms important for n-type MDH[8], one also has to take into account optical phonon deformation potential scattering. This mechanism plays an important role in limiting high-temperature hole mobility in bulk GaAs[16].

The long range electrostatic potentials are screened by the two-dimensional hole gas. The screening parameter is given by the expression:

$$q_s = \frac{e^2(m_1^* + m_2^*)}{\varepsilon_s \hbar^2}\,(1 - e^{-\alpha}) \tag{4}$$

where $$\alpha = \frac{\pi\hbar^2(p_1 + p_2)}{(m_1^* + m_2^*)\, kT}$$

For a degenerate hole gas at low temperatures, $\alpha \gg 1$ and,

$$q_s = \frac{e^2(m_1^* + m_2^*)}{\epsilon_s h^2} \tag{5}$$

It should be noted that q_s is much larger for holes than for the much lighter electrons. Using the aforementioned approximations, it has been found that the acoustic phonon deformation potential scattering rate for holes has the same form as the one for electrons[17,8] with b_o replaced by b_h and the conduction band deformation potential replaced by $\sqrt{5/8}\, E_{AC}$ where E_{AC} is an effective valence band deformation potential[16]. The factor $\sqrt{5/8}$ accounts for the p-type symmetry of the valence band Bloch functions. The deformation potential relaxation time does not depend on the hole energy. It weakly depends on the hole concentration through the parameter b_h. In contrast to the two-dimensional electron gas[8], the piezoelectric acoustic phonon scattering of holes does not contribute to the total scattering. This is the result of very efficient screening of this electrostatic interaction. Alloy disorder scattering is a process resulting from a finite penetration of the hole gas into the AlGaAs layer. Just as for the electron gas, this scattering process depends on the valence band offset, V_{oh}, and the total free carrier concentration, $p_1 + p_2$ [8].

Although in MDH's the ionized impurity scattering is substantially reduced, it still plays a significant role in limiting the low temperature mobility. Similarly as in the case of a two-dimensional electron gas, the holes in p-type MDH's are scattered by remote, ionized impurities from the highly-doped AlGaAs

region and by background impurities located in GaAs. The remote impurities are separated from the hole gas by the spacer of width "d". The width of the depletion region in highly doped AlGaAs is $(L - d) = (p_1 + p_2)/N_r$ where N_r is the remote ionized acceptor concentration. It can be shown that the remote ionized impurity scattering rate is proportional to $e^{-2qd} - e^{-2qL}$ where q is the wave vector transfer in the scattering process. Therefore the largest contribution to the scattering comes from the terms with $q < 2d$. For the spacer width, $d \gtrsim 100$ Å, one obtains $q_s >> q$ and $b_h >> q$ and the expression for the microscopic mobility has the form:

$$\frac{1}{\mu_r^i} = \frac{\pi\hbar^4 N_r(m_1^* + m_2^*)^{-2} (1 - e^{-\alpha})^{-2} E^{-3/2}}{8\sqrt{2}\sqrt{m_i^*}} \left(\frac{1}{d^2} - \frac{1}{L^2}\right) \qquad (6)$$

In high quality MDH's, the concentration of residual impurities is normally very low ($\lesssim 10^{15}$ cm^{-3}). However, since residual background impurities are located in the immediate vicinity of the hole gas, they can still contribute to the total scattering. There is no simple analytic expression for the background impurity scattering rate[18]. To estimate a contribution from this scattering process at low temperatures, we have used the approach developed for n-type MDH[8] and have adapted it to the subbands with p-type symmetry.

Optical phonon scattering plays a very important role in limiting the high temperature hole mobility. Analogous to the case of a two-dimensional electron gas[8], it can be argued that because hole states in a wide energy range are involved in this scattering, all the features characteristic of a two-dimensional system are smeared out and the optical phonon electron mobility can be approximated by the mobility calculated for three-dimensional hole gas. Here we adopted an approach which utilizes an approximation of partially coupled valence bands[19].

Results and Discussion

The valence band parameters of GaAs are not very well known. Thus, there exists substantial discrepancy between hole effective masses determined from experiments[10] and those obtained from theoretical calculations[13]. The reason for this discrepancy is not clear at present although it has been suggested that it can be related to hole-hole interaction[13]. In the present paper we have adopted experimental values for the effective masses $m_1 = 0.6\ m_o$ and $m_2 = 0.38\ m_o$ [10]. Values of the valence band offsets were adopted after Ref. 14 to be 170 meV and 210 meV for 0.48 and 0.5 Al content, respectively. It has been found that even with the highest reported[20] estimate for the alloy disorder scattering parameter (V_{oh} = 0.7 eV), the alloy disorder scattering contribution to the total scattering does not exceed 10%. Values of all the other parameters are the same as those used in Ref. 8.

The hole Hall mobility for different scattering processes is shown in Fig. 1. The inherent mobility limit is defined as a mobility determined by the intrinsic scattering processes which are always present for a specific MDH and by remote ionized impurity scattering[8]. We find that the inherent mobility is dominated by the optical phonons at high temperatures > 150 K. In the intermediate temperature range 20 - 100 K, the largest contribution to the mobility comes from the acoustic deformation potential scattering. We have found that the best agreement with experimental data is obtained when the value 6.7 eV for the deformation potential is used. This value is slightly higher than the effective deformation potential E_{AC} = 5 eV as given in Ref. 16 but agrees very well with the value E_{AC} = 7 eV as determined in Ref. 20. At the lowest temperatures T < 10 K, remote ionized impurity scattering sets the

inherent mobility limit. The alloy disorder and piezoelectric acoustic phonon scattering do not contribute importantly to the total scattering. The piezo-acoustic mobility is ~ 10^7 cm^2/Vs for the case presented in Fig. 1. The triangles in Fig. 1 represent experimental data of Ref. 11. At high temperatures T > 100 K when the inherent mobility limit is set by phonon scattering, the experiment agrees very well with the calculated mobility. However, at lower temperatures the experimental mobility falls below the inherent limit which is determined mostly by remote impurity scattering indicating the existence of yet another scattering mechanism. The scattering process which most likely would contribute to the scattering at low temperatures is background impurity scattering. The calculations have shown that the background impurities of concentration 4 x 10^{15} cm^{-3} resulting in a temperature independent hole mobility of ~ 9 x 10^4 cm^2/Vs account very well for the difference between the inherent limit and the experimental data.

Spacer width dependence of the hole mobility for GaAs-$Al_{0.5}Ga_{0.5}As$ MDH with remote acceptor concentration 1.5 x 10^{18} cm^{-3} which corresponds to the case analyzed in Ref. 14 is given in Fig. 2. As can be seen, only at the lowest spacer width ~ 100 Å is the inherent mobility limit affected by remote impurity scattering. At higher spacer widths the limit is entirely determined by acoustic deformation potential scattering. The highest experimental mobility 9.7 x 10^4 cm^2/Vs was observed for d = 443 Å[14]. The corresponding inherent mobility limit is 2.1 x 10^5 cm^2/Vs indicating a significant contribution of background scattering. The difference between the experimental and calculated mobilities can be accounted for by background impurities of concentrations ~ 10^{15} cm^{-3}. It can thus be concluded that a further increase of two-dimensional hole gas mobility is expected upon a decrease in background doping. Our calculations

show that at large spacer widths, the acoustic deformation potential is the dominant scattering process at very low temperatures. Therefore the two-dimensional hole gas is an ideal system to study the effect of hole gas heating at low electric fields. This effect was predicted to occur in the electron gas at very low temperatures[21]. However, it cannot be easily detected in the two-dimensional electron gas where, unlike for holes, remote impurity scattering is always an important process limiting the low temperature electron mobility[8].

In Fig. 2 the total hole concentration $p_1 + p_2$, and the Hall hole concentration $P_H = 1/eR_H$ are given. In general, $p_1 + p_2 \neq P_H$ and the difference between these two concentrations depends on the effective mass and the mobility ratio. We have found that the difference is quite significant for acoustic phonon limited mobilities and is becoming smaller when ionized impurity scattering is a dominant scattering process.

In conclusion, we have presented the first quantitative model to calculate the two-dimensional hole gas mobility in p-type MDH. The model accounts very well for the temperature dependence of the hole mobility in GaAs-AlGaAs MDH. It has been found that the acoustic phonon deformation potential is the dominant scattering process responsible for mobility limits at low temperatures. The model gives a value of ~ 2×10^5 cm^2/Vs for the mobility limit in p-type GaAs-AlGaAs MDH at 4.2 K for the hole density ~ 2.5×10^{11} cm^{-2}. This result is about two times higher than the highest reported experimental values.

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Figure Captions

Fig. 1. Temperature dependence of the hole mobility in GaAs-AlGaAs heterostructure. Points represent experimental data of Ref. 10 for the hole Hall concentration of 4.57×10^{11} cm^{-2} and remote acceptor concentration of 2×10^{18} cm^{-3}.

Fig. 2. Hole mobility and concentration as functions of the spacer width for the case considered in Ref. 14 with a remote acceptor concentration of 1.5×10^{18} cm^{-3}.

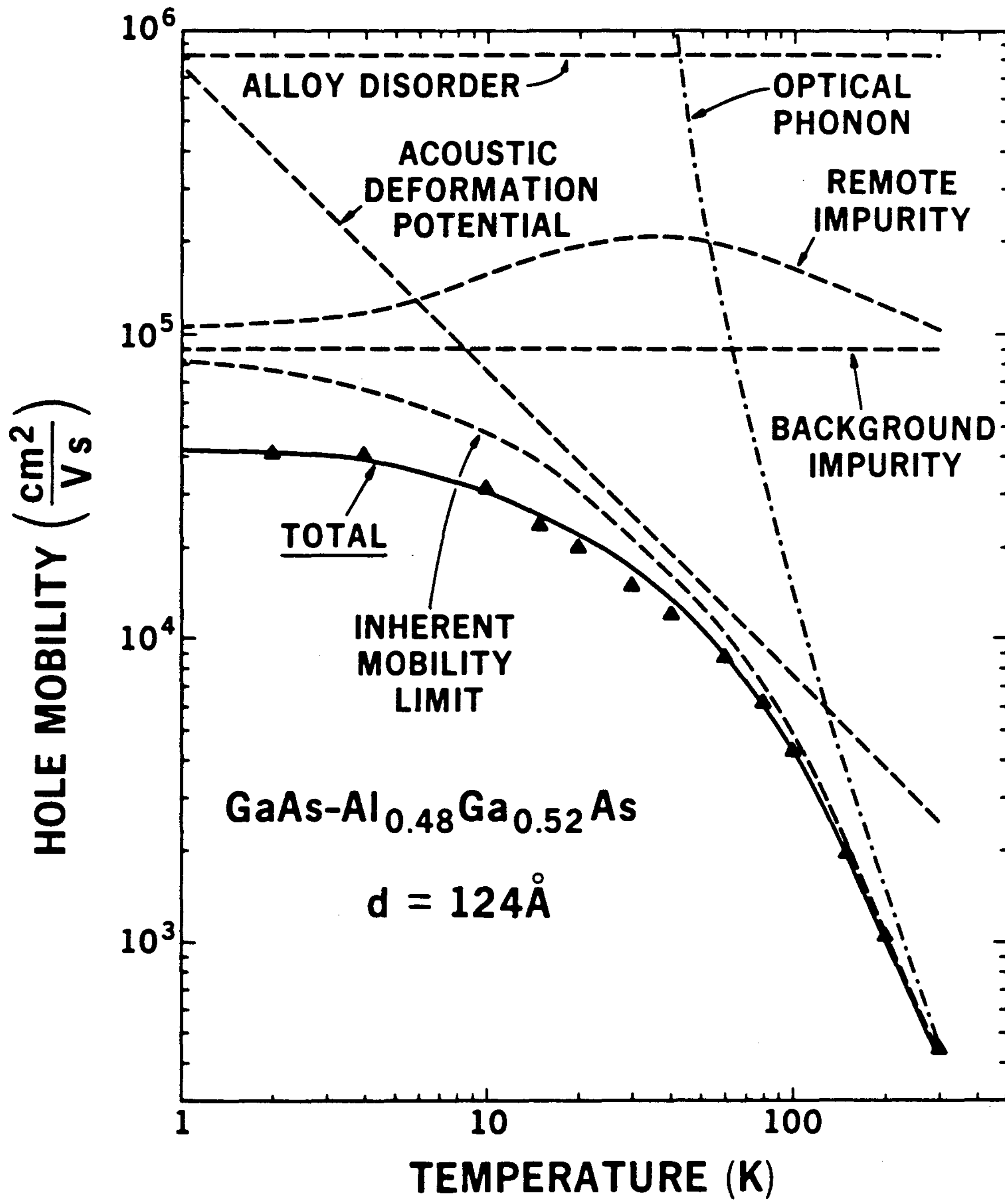

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Figure 1.

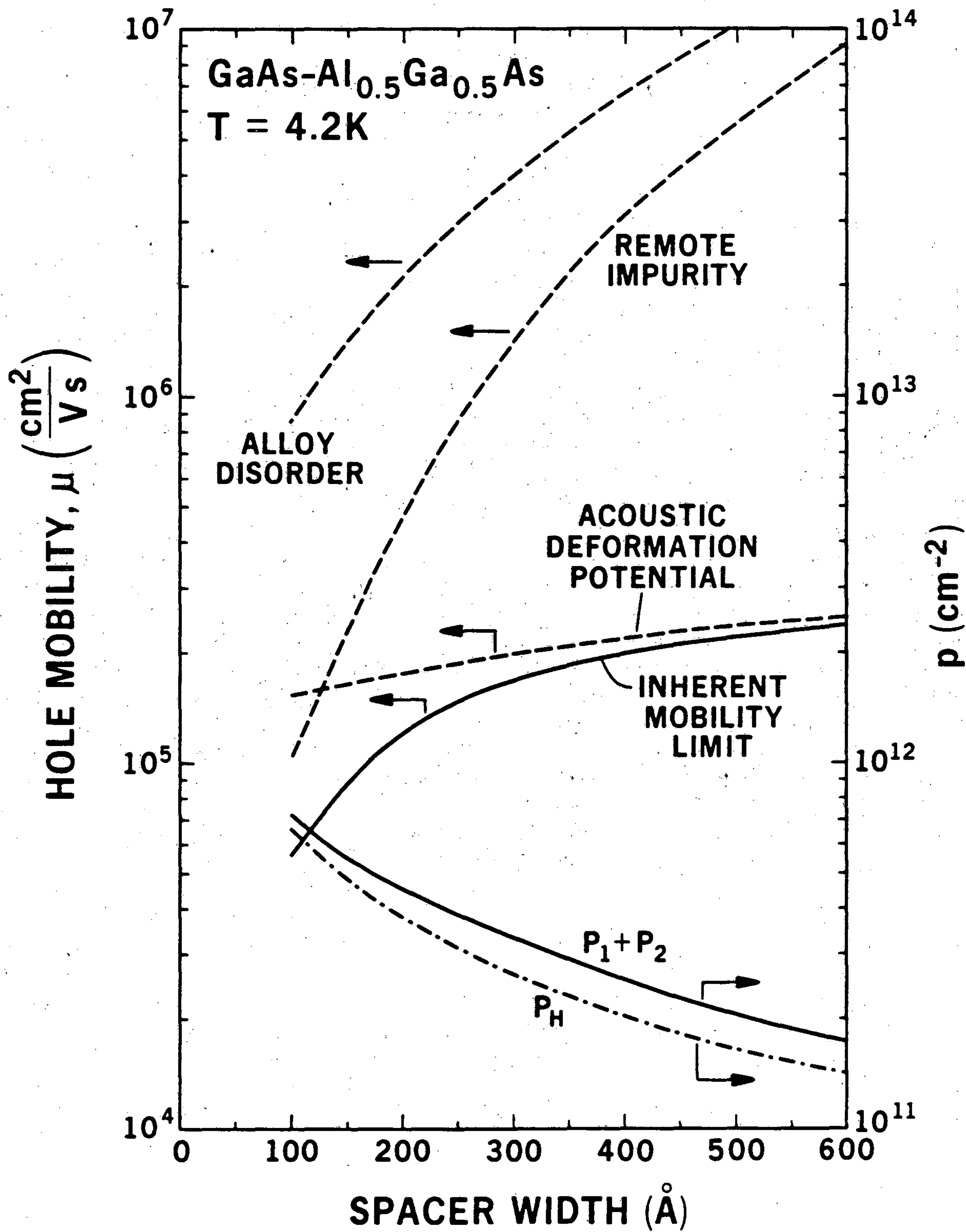

Figure 2.

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