LOW FIELD MOBILITY OF 2-D ELECTRON GAS IN MODULATION DOPED Al_xGa_{1-x}As/GaAs LAYERS

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Summary

We derive a simple analytical formula for the low field mobility which uses 2-d degenerate statistics for the 2-d electron gas. It also takes into account the finite width of the depletion layer in (Al,Ga)As (which affects primarily impurity scattering), scattering by the charged interface states and polar optical and acoustic phonon scattering. The maximum mobility for a given structure is determined by scattering by the interface charged states. The ultimate mobility which may be achieved is limited by acoustic phonon scattering at about 8x10^6 cm^2/Vs for a 2-d electron gas density of n_0 = 4x10^11 cm^-2. Our results agree very well with our own and other experimental data.

I. Introduction

In modulation doped structures a two dimensional electron gas is formed in the (Al,Ga)As/GaAs hetero-interface due to the electron affinity difference between two materials. The electrons are separated from the donors in the (Al,Ga)As by a thin spacer layer which decreases the impurity scattering and enhances the electron mobility. Screening of the Coulomb potential by the electrons in the inversion layer also enhances the mobility, thus forming high values of low field mobility which have been observed in modulation doped (Al,Ga)As/GaAs structures. 1-3

In this paper we derive a simple analytical formula for low field mobility. Our approach is an extension of existing theories 1-5 but uses 2-d degenerate statistics for the electron gas. It also takes into account the finite width of the depletion layer in (Al,Ga)As (which affects primarily impurity scattering), scattering by the charged interface states and the polar optical and acoustic phonon scattering.

The mobility limited by the remote donors in the (Al,Ga)As layer is shown to increase with thickness of the undoped spacer layer, d_1, as d_1^5.6. The ultimate value of the mobility which may be achieved is limited by the acoustic scattering at about 8x10^6 cm^2/Vs for a 2-d electron gas density, n_0 = 4x10^11 cm^-2. We also show that the maximum experimental mobilities are limited by scattering by charged interface states. Our results agree very well with experimental data obtained in our laboratory as well as other laboratories. 1, 4, 5

II. Scattering Mechanisms

A. Ionized Impurity Scattering Due to Remote Donors

In a modulation doped structure extremely high electron mobility is obtained by separating the free carriers from the donors in (Al,Ga)As (see Fig. 1). The momentum relaxation time \( \tau_{R1} \) for electrons in the 1-d subband due to the remote donors is:

\[
\frac{1}{\tau_{R1}} = \left( \frac{e}{\hbar M_d} \right) \frac{d_1}{S_0} \left( \exp \left[ - \frac{4d_1}{\hbar \sqrt{2m^*}} \right] \right) \frac{1}{\exp \left[ - \frac{4d_1}{\hbar \sqrt{2m^*}} \right] + \exp \left[ - \frac{4d_1}{\hbar \sqrt{2m^*}} \right]} \frac{1}{\sin^2 \theta + \sin^2 \theta} \]

where \( \theta = \theta_0 \) is the angle between the normal to the interface and the dopant implantation direction. \( \theta_0 \) is the angle between the normal to the interface and the dopant implantation direction.

III. Temperature Dependence

The evaluation of Eq. (3) is very different from that obtained in references [6, 10], because two dimensional degenerate Fermi statistics are used here whereas two dimensional non-degenerate statistics were used previously.

C. Polar Optical Phonon Scattering

An empirical temperature dependent polar optical mobility deduced from bulk GaAs data is used in this work (see Section III).

D. Acoustic Deformation Potential Scattering

We derive the following expressions for the acoustic deformation potential relaxation time:

\[
\frac{1}{\tau_A} = \frac{e^2 k_B T}{M^*_d} \left( \frac{1}{S_0} \right) \left[ 1 \right] \]

where T is the temperature, \( e \) is the electronic charge, \( m^* \) is the effective mass, and \( S_0 \) is the remote ionized impurity density assumed to be uniform (see Fig. 1). \( \gamma \) is the reduced Planck constant, \( \epsilon \) is the dielectric permittivity of GaAs, M is the two dimensional electronic wave vector, \( \xi \) is the screening constant of the 1-d subband (here only intrasubband scattering within a 1-d subband is considered) and \( L_d = d_1 - Z_0 \) where \( d_1 \) is the thickness of the spacer layer and \( Z_0 \) is the average distance of the electronic wavefunction penetration into GaAs. Equation (4) accounts for the finite width of the depletion layer in the AlGaAs through \( L_d = d_1 - Z_L \) where \( d_1 - Z_L \) is the distance from the heterojunction interface for the boundary between the depletion and neutral region (see Fig. 1). For values of \( n_0 > 10^{11} \) cm^-2, the integral in Eq. (1) can be evaluated analytically, because small values of \( \theta \) determine the integral.

The resulting expression for the momentum relaxation time in the zero subband is:

\[
\frac{1}{\tau_{BL}} = \left( \frac{e}{\hbar M_d} \right) \frac{4d_1}{S_0} \frac{1}{\sin^2 \theta + \sin^2 \theta} \]

where \( \theta_0 \) is the 2-d impurity density in the potential well and

\[
L_0(b) = \left[ \frac{1}{2} d_1 \sin^2 \theta \right] \left[ \sin^2 \theta + \sin^2 \theta \right]
\]

where \( S_0 = \frac{S_0}{2\pi r} \).

The evaluation of Eq. (3) is very different from that obtained in references [6, 10], because two dimensional degenerate Fermi statistics are used here whereas two dimensional non-degenerate statistics were used previously.
with extremely high mobility observed at low temperatures (see Fig. 2). According to our calculations, \( \mu_{\text{so}} \) varies as \( d_s^{-3/4} \), where \( d_s \) is large (\( d_s > \text{Z} \)). The mobility \( \mu_1 \) limited by the remote donor scattering varies as \( \mu_{\text{so}} d_s^{-3} \) (see Eq. (2)) at large values of \( d_s \), i.e., \( \mu_1 \) is proportional to \( d_s^{-3/2} \). Thus, in theory, a higher value of \( \mu_1 \) can be obtained by increasing the spacer layer thickness. However, the mobility at large \( d_s \) is dominated by interface state scattering as shown in Fig. 4. As a result the mobility becomes constant at large values of \( d_s \) (see Figs. 3, 4). In other words, the maximum mobility obtained at large \( d_s \) is a measure of the interface state density. The values of \( N_1 \) necessary to explain the experimental reported in reference 5 and our experimental results are 1.6x10^9 cm^-2 and 3x10^9 cm^-2, respectively. Thus, \( N_1 \) depends on the sample preparation. This may explain why these numbers are less than the value of \( N_1 \) estimated in reference 15 from the C-V data (\( N_1 = 6 x 10^9 \) cm^-2).

Also, \( N_1 \) depends not only on the density of the interface states but also on the position of the Fermi level with respect to the neutral level. This may also contribute to the higher value of \( N_1 \) measured in reference 15. Some indication of the dependence of \( N_1 \) on the position of the Fermi level may be inferred from the increase in the low field mobility under illumination. Under illumination on the mobility in the sample with \( d_s = 230 \) \( \AA \) was increased from 3.5x10^6 cm^2/Vs to 1.3x10^6 cm^2/Vs. At the same time the value of \( \mu_{\text{so}} \) changed from 2.2x10^11 cm^-2 to 3.8x10^11 cm^-2. Only part of this increase is due to the increase in screening. Our calculation show that due to the increase in screening the mobility should have increased only to 8x10^6 cm^2/Vs (when the same value of the interface charge \( N_1 \) is used). We interpret this difference as a result of the decrease in \( N_1 \) due to the shift in the Fermi level due to the change in \( N_{\text{so}} \).

\[
\mu_F = \mu_{\text{so}} + \frac{a}{n_{\text{so}}} 
\]

(21)

where \( a = 0.125 \times 10^{-12} \) cm^2 eV and \( \Delta \mu_{\text{so}} = 25 \) meV at low temperature. The energy band diagrams in Eq. (21) is the bottom of the conduction band in GaAs at the heterojunction interface. Hence, the change in \( n_{\text{so}} \) from 2.2x10^11 cm^-2 to 3.8x10^11 cm^-2 leads to a shift of 20 meV. To explain the additional increase of the mobility beyond the increase related to the enhanced screening we have to assume the reduction of \( N_1 \) to be nearly zero (see Fig. 4). The density of the interface states \( N_1 \) may be estimated from

\[
N_1 = \frac{\Delta N}{\Delta \mu} - \frac{2}{e} 
\]

(22)

leading to \( N_1 = 7.8 \times 10^9 \) cm^-2 eV^-1. This interpretation is also consistent with the general trend exhibited by the experimental curve \( \mu_1 \) vs. \( d_s \) in the range of \( d_s \) below 200 \( \AA \) in Fig. 4. For these values of \( d_s \) the value of \( n_{\text{so}} \) is large enough to shift the Fermi level closer to the neutral level (just as under illumination). Indeed, from the change in measured value of \( n_{\text{so}} \) and Eq. (21), we estimate the increase in \( n_{\text{so}} \) to be roughly 25 meV when \( d_s \) is decreased from 300 \( \AA \) to 150 \( \AA \). This should increase the low field mobility over the calculated value because the dependence of \( N_1 \) on \( N_{\text{so}} \) is disregarded in our calculation. As can be seen from Fig. 4 this is exactly what is observed experimentally. The temperature dependence of the 2-d electron gas mobility is shown in Fig. 5 where the experimental results agree very well with the calculated mobility which includes contributions from temperature independent ionized impurity scattering and temperature dependent ac phonon and polar optical phonon scattering. An accurate evaluation of the number of the acoustical phonons is very important at low temperature when acoustic scattering limits the ultimate value of mobility, being about 8x10^9 cm^2/Vs for \( n_{\text{so}} = 4x10^9 \) cm^-2. This ultimate value of the low field mobility is inversely proportional to \( n_{\text{so}} \) due to the depen of the Fermi wave vector on \( n_{\text{so}} \).

V. Conclusion

We derived simple analytical formulae for the mobility of the 2-d electron gas formed at the (Al, Ga)As/GaAs heterointerface. Our theory which takes into account the finite width of the depletion region in the (Al, Ga)As layer, the scattering by charged interface states and other factors is in a very good agreement with the experimental results.

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Fig. 1. Energy band diagram of a modulation doped (Al, Ga)As/GaAs heterojunction. Finite thickness of the ionized (Al, Ga)As layer is shown and the two lowest energy levels in the 2-gas are shown.

Fig. 2. Calculated low field mobility vs. undoped (Al, Ga)As thickness for \( n_{\text{so}} = 5x10^{11}/\text{cm}^2 \). Dotted line for \( n_{\text{so}} = 0.125 \times 10^{11} \) (\( \text{cm}^2 \)), solid line for \( n_{\text{so}} = 0.25 \times 10^{11} \) (\( \text{cm}^2 \)), and dashed line for \( n_{\text{so}} = 0.5 \times 10^{11} \) (\( \text{cm}^2 \)). Dots are experimental points (A from [11], B from [2], C from [1], D from [5] and E from [12], the values for B and C are extrapolated at \( n_{\text{so}} = 5 \times 10^{11} \) (\( \text{cm}^2 \)).

Fig. 3. Experimental mobility vs. undoped (Al, Ga)As thickness. Solid line is from [5] and dash line is from our laboratory [18].

Fig. 4. Comparison between theory and experiment for mobility vs. undoped (Al, Ga)As thickness. Two theoretical curves (dotted line for \( N_1 = 0 \) and dashed line for \( N_1 = 1.5 \times 10^9 \text{cm}^{-2} \)) are calculated using measured value of 2-d gas density \( n_{\text{so}} \). Experimental values are from [5]. The increase in mobility under illumination is indicated by an arrow.

Fig. 5. Temperature dependence of 2-d gas mobility. Dots are experimental points from ref. [5] and open circles are obtained in our laboratory. Solid line is calculated from Eq. (22) using temperature independent values of \( a_1 = 0.125 \times 10^{-12} \text{cm}^{-2} \text{eV}^{-1} \) and \( a_2 = 2.5 \times 10^5 \text{cm}^2/\text{Vs} \).
References


