Temperature and carrier density dependence of mobility in a heavily doped quantum well

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Interest in heterostructure field-effect transistors (HFETs) utilizing narrow, heavily doped channels motivates a study of mobility in heavily doped quantum wells. We have measured electron mobility as a function of carrier concentration and temperature in an $In_{0.15}Ga_{0.85}As$ quantum well with a doping of $N_D=6\times10^{12}$ cm^{-2}. Mobility is found to rise significantly as the ratio of electron to impurity concentration increases. Even at $T=300$ K, μ climbs by nearly a factor of 2 as carrier concentration in the well is increased from 1×10^{12} to 5×10^{12} cm^{-2}. The results agree qualitatively with recently published theoretical predictions, and suggest that device models utilizing constant mobility are not appropriate for HFETs using doped two-dimensional channels.

Doped quantum wells have recently demonstrated significant promise for high-power, high-frequency heterostructure field-effect transistors (HFETs).[1,2] Improving the design of such transistors will require understanding of low-field transport in doped two-dimensional (2D) systems. Unfortunately, while transport experiments in undoped 2D systems are numerous,[3–8] studies of the physics of low-field transport in doped quantum wells have been rare and limited in scope. A few groups have performed extractions of mobility from measured device characteristics, and have established that a mobility dependence on sheet carrier concentration may be present in these devices.[9,10] Masselink has discussed the temperature and doping-distribution dependence of mobility in doped wells, but this study did not examine the impact of varying the sheet carrier concentration.[11]

In a heavily doped well, it is expected that mobility will rise as the ratio of sheet carrier concentration to sheet dopant concentration is increased. Intuitively, this is easy to understand—increasing the electron concentration should both enhance screening and increase k_F, the Fermi wave vector, leading to suppression of ionized impurity scattering.[9] This effect has been proposed[9] and indirectly observed.[9,10] In this letter, we present a detailed study of mobility as a function of sheet carrier concentration and temperature in a doped quantum well system. These measurements offer experimental confirmation of the mobility's enhancement with sheet carrier concentration, and demonstrate that the dependence is very strong at low temperatures and is also significant at typical device operating temperatures.

To investigate this effect, we performed measurements using an $Al_{0.38}Ga_{0.62}As/n^+$-$In_{0.15}Ga_{0.85}As$ HFET that has been well characterized from a device perspective.[12] The heterostructure was grown by molecular beam epitaxy on top of a semi-insulating GaAs substrate, and consists of 1000 Å of $Al_{0.38}Ga_{0.62}As$, a 100 Å GaAs undoped smoothing layer, a 150 Å $In_{0.15}Ga_{0.85}As$ channel uniformly doped with a total sheet Si donor concentration of approximately $N_D=6\times10^{12}$ cm^{-2}, a 300 Å undoped $Al_{0.38}Ga_{0.62}As$ insulator layer, and a 50 Å GaAs undoped cap. The region of interest is the very narrow, heavily doped $In_{0.15}Ga_{0.85}As$ channel. Self-consistent Poisson–Schrödinger calculations indicate that throughout the range of gate bias we consider, there is very little parallel conduction in the $Al_{0.38}Ga_{0.62}As$ insulator and in the GaAs smoothing layer.

A gated Hall-bar structure, sketched in the inset of Fig. 1, with an active area measuring 180 μm×20 μm was used to measure mobility and sheet carrier concentration; the channel taps measured 4 μm across, and were placed sufficiently far from the drain and source to suppress experimental deviations from the theoretical Hall voltage.[13] Due to degeneracy, the Hall factor is not expected to differ significantly from unity.[13] Lock-in techniques were to measure the Hall voltage and current. Carrier concentration was modulated by applying a bias to the gate of the structure.

In Fig. 1, we plot measured charge control and mobility characteristics of the gated Hall bar at $T=300$ K. The n_s vs V_{GS} curve is nearly linear, reflecting the almost constant capacitance of the narrow channel. Figure 1 shows that since the well is doped, it is possible to induce a substantially higher carrier concentration than is generally observed in modulation-doped structures. Indeed, even at room temperature, n_s reaches nearly 6×10^{12} cm^{-12} before gate leakage becomes significant. Figure 1 also demonstrates that the mobility rises strongly with increasing gate voltage.

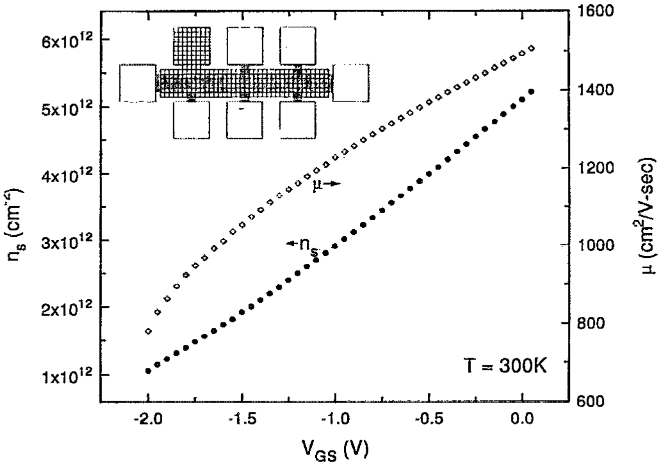

FIG. 1. Measured sheet carrier concentration and mobility at $T=300$ K as a function of gate bias. Inset shows schematic representation of gated Hall bar.

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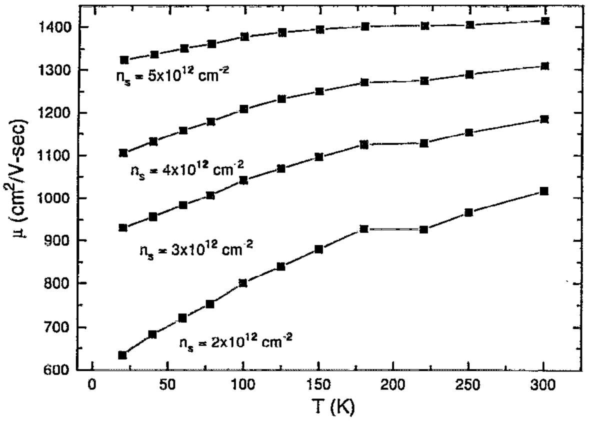

FIG. 2. Measured mobility as a function of temperature at various carrier concentrations. The carrier concentration was changed by varying the gate voltage.

Figures 2 and 3 present the results of mobility measurements as a function of temperature and carrier concentration. In Fig. 2, we see that mobility exhibits a positive temperature dependence throughout the range of temperatures and carrier concentrations considered. As carrier concentration is increased, the temperature dependence becomes weaker. The increase of mobility with increasing temperature is a key signature of the dominance of impurity scattering in a 2D system.[14] This result is consistent with phonon scattering rates in this system, which we have calculated using the approximate approach advocated by Lee *et al.*[15] Using appropriate material parameters, we find that even at room temperature, the phonon-limited mobility is more than five times our maximum measured mobility.[16]

The reduced temperature dependence of the mobility at higher carrier concentrations can be attributed to the increased degeneracy of the system. Because the temperature dependence of ionized impurity scattering arises almost entirely from thermal smearing, the increasing magnitude of the Fermi wave vector, k_F, reduces the relative effect of thermal smearing on the scattering rate.

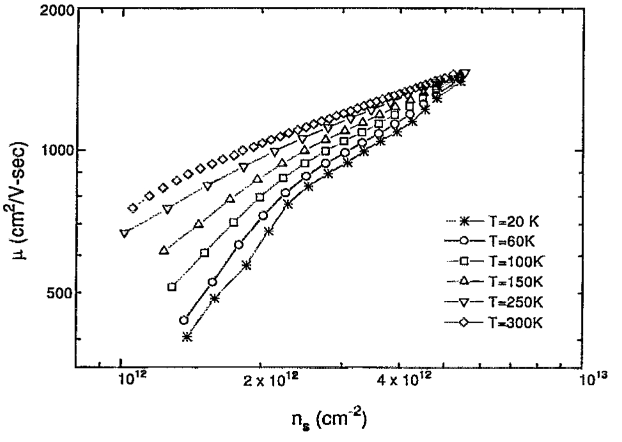

FIG. 3. Measured mobility as a function of carrier concentration at various temperatures.

In Fig. 3 we see that for all temperatures considered, the mobility rises as carrier concentration increases. The effect is greatest at low temperatures. Two regions in the $\mu(n_s)$ behavior are apparent: for $n_s<2\times10^{12}$ cm^{-2}, the mobility rises strongly with increasing carrier concentration, while for $n_s>2\times10^{12}$ cm^{-2}, the dependence is weaker. These two regions are more clearly defined at low temperatures.

Qualitatively, the positive $\mu(n_s)$ relation agrees with theoretical predictions made by a number of groups.[14,15] It is tempting to attribute this mobility enhancement to improved screening—as carrier concentration increases, the potentials of ionized impurities are shielded more effectively by the electron gas. While that is indeed the case for nondegenerate systems, screening cannot explain the significant rise in the mobility in a heavily doped, degenerate 2D system. Our calculations indicate that the characteristic 2D screening length changes less than ten percent over the range of carrier concentrations considered in this work;[16] indeed, for a highly degenerate 2D system, screening is predicted to be independent of carrier concentration.[17]

An explanation of the mobility enhancement requires considering the effect of changing the carrier concentration on the Fermi wave vector. As k_F increases with n_s, the effectiveness of ionized impurity scattering drops, because the average scattering angle becomes smaller, so that the forward momentum component is affected less. Although exact computation of impurity-limited mobility in a 2D system requires extensive calculations and accurate wavefunction modeling, the $T=0$, single subband case has been shown to reduce approximately to $\mu\propto n_s^{3/2}$.[17] A similar power-law relationship has been consistently observed in modulation-doped field effet transitions (MODFETs), with the exponent ranging between 1 and 2.[3]

Our experimental data appears to obey such a simple exponential law in the low n_s region. The softening of the temperature dependence is due to thermal smearing, and can be easily calculated, as shown below. However, it is obvious that at $n_s\approx2\times10^{12}$ cm^{-2}, this simple theory and our experimental data diverge markedly, regardless of temperature. Poisson–Schrödinger calculations indicate that a second subband becomes occupied in this structure at approximately this carrier concentration.[16]

Unfortunately the multiple subband problem does not lend itself to easy analytical treatment, primarily because of intersubband scattering. To first order, though, it should be possible to model the total mobility by considering the $\mu(n_s)$ behavior of each subband independently, and treating the system using the simple two-carrier Hall expressions.[18] In this case, we obtain the following expression for the $T=0$ Hall mobility:[16]

$$\mu_{\text{Hall}}=\frac{A(n_{1s}^{5/2}+n_{2s}^{5/2})}{n_{\text{Hall}}}. \tag{1}$$

Here A is a fitting constant, which depends on doping level, well width, and material parameters; n_{1s} and n_{2s} are the calculated populations of the first and second subbands; and n_{Hall} is the measured Hall carrier concentration. To perform the calculation, we select a single value of A using low tem-

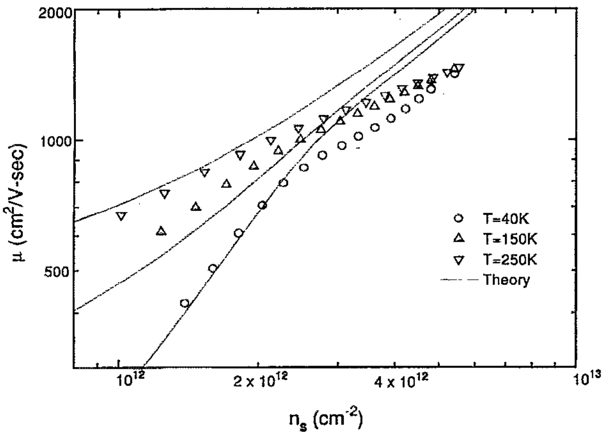

FIG. 4. Comparison of data and two-subband analytical model. The divergence at high carrier concentrations is likely due to the omission of intersubband scattering in the analytical model.

perature $\mu(n_s)$ data, and then perform appropriate thermal averaging of the $T=0$ mobility to obtain higher temperature $\mu(n_s)$ curves.

Figure 4 compares the results of this simple two-subband model with experimental results. In the single subband regime ($n_s<2\times10^{12}$ cm^{-2}), the data and theory are in excellent agreement. In the two-subband regime, experiment and theory show qualitative agreement; however, the theory consistently overestimates the mobility. This is probably because intersubband scattering effects are not included in Eq. (1).

The onset of the second subband does not appear to cause a drop in mobility as observed in MODFETS.[19] This is due to two effects: first, since the system is heavily doped, we expect intersubband scattering events to be infrequent relative to intrasubband scattering events, because the impurity scattering mechanism favors small values of Δk. Furthermore, thermal smearing of the onset of the second subband is likely to mask any drop in mobility—even in MODFETs measured at 4 K, the mobility drop is substantially smeared.[19]

With the occupation of the second subband, the system begins to make the transition from 2D to 3D. Examination of the predictions made by our simple theory of two equivalent, noninteracting subbands reveals that the dependence of the mobility on carrier concentration is somewhat weakened as the second subband becomes occupied, even if intersubband scattering is not present. Physically, this is because half of the newly added carriers reside in the second subband, and therefore have small k values in the plane of the well. This makes carriers in the second subband more susceptible to impurity scattering and therefore have a lower mobility than those in the first subband.

From a device perspective, the dependence of mobility on carrier concentration can clearly have both detrimental and beneficial effects. Near the threshold voltage of a doped-channel HFET, we expect the mobility to be very low; thus the turn-on characteristics of the device will be softer than those of an equivalent device with constant mobility. On the other hand, when the device operates in accumulation mode, the mobility is expected to be significantly higher, as some experiments have suggested.[9]

In conclusion, we have measured the dependence on carrier concentration in a heavily doped quantum well. The mobility is found to rise both as carrier concentration increases, and as temperature increases. Both effects are attributed to the reduced effectiveness of impurity scattering at large Fermi velocities. The effects are found to be strongest at low temperatures and when only one subband is occupied.

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