Temperature dependence of the electron mobility in GaAs-GaAlAs heterostructures

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We have studied the temperature dependence of the mobility of two-dimensional electron gases formed at the interface of high-quality GaAs-GaAlAs heterostructures, focusing on the temperature range 4–40 K. The inverse mobility is shown to increase linearly with temperature, with a slope which increases with the electron density and is independent of the zero-temperature mobility. The results are consistent with a theoretical model for the acoustic-phonon mobility that includes screening, indicating that the temperature dependence in high mobility GaAs-GaAlAs structures is dominated by phonons rather than ionized impurities. A good agreement between theory and experiment is found using a value of 13.5 eV for the deformation potential of GaAs.

Selective doping in semiconductor heterostructures has made possible the enhancement of the low-temperature electrom mobility μ in two-dimensional (2D) systems. Values exceeding 10^6 cm^2/Vs at 4 K have been obtained in 2D electron gases formed at a GaAs-GaAlAs heterojunction.[1–3] At very low temperatures, ionized-impurity scattering is believed to be the main mechanism controlling μ, with interface roughness and alloy scattering playing a significant role only at high electron concentrations,[4] and lattice scattering having a small effect.

To date, however, the temperature dependence of μ is not well understood. Some theoretical studies on the scattering of 2D electrons through phonons have been reported.[5–7] At low temperatures[6,7] the lattice scattering is by acoustic-mode phonons through the deformation potential Γ, and by the piezoelectric field. The phonons are taken to be those of bulk GaAs, an assumption supported by the results of magnetophonon experiments in 2D systems.[8] At temperatures low compared to the degeneracy temperature, $T_D = (N_s/1\times10^{12}\ \text{cm}^{-2})\times 416$ K, but above the onset of the Bloch–Gruneisen range, Price[7] finds an effective lattice-scattering rate ($\sim\mu_p^{-1}$) proportional to the temperature T. The proportionality constant depends only on the electron concentration N_s (if small effects of acceptor ions in GaAs are neglected).

On the other hand, no theoretical study of the temperature dependence of the ionized-impurity mobility μ_I, in GaAs-GaAlAs heterostructures, has been published. Both calculations[9] and experiments[10] for Si inversion layers indicate that in this system the effective scattering rate ($\sim\mu_I^{-1}$) increases with increasing temperature. However, a direct application of those results to the GaAs-GaAlAs system seems inappropriate because, in contrast to Si inversion layers, the electron scattering is dominated by small-angle scattering as a result of the small screening parameter and the usually large ionic distance. In fact, preliminary calculations[11] in this system indicate that μ_I^{-1} decreases with increasing T at low temperature and, thus, shows a behavior opposite to Si.

In this letter we present the results of the first systematic study of the temperature dependence of the 2D electron mobility in very high-quality GaAs-GaAlAs heterostructures. Experiments over a large range of electron concentrations N_s and of zero-temperature mobilities μ_0 show that μ^{-1} increases linearly with T, and the slope increases with the carrier concentration, independently of μ_0, and is the same for dark conduction and for photoconduction. This suggests that the temperature dependence of the mobility in very high-quality structures is dominated by acoustic phonons and not by ionized impurities. A good agreement is found with a theory that includes screening, when a value of 13.5 eV is used for the deformation potential of GaAs, and 1.2×10^7 V/cm for the piezoelectric coupling constant h_{14}.

The samples of the present study were heterostructures grown by molecular beam epitaxy. An undoped GaAs layer, 1 μm thick, was first deposited on a semi-insulating, Cr-doped GaAs substrate, followed by an undoped $Ga_{0.7}Al_{0.3}As$ layer (hereafter called spacer), and then a Si-doped $Ga_{0.7}Al_{0.3}As$ layer, typically 400 Å thick. The structures were capped with 100 Å of Si-doped GaAs. Details of the growth conditions have been given elsewhere.[3,12] By using spacer thicknesses of 320 Å (sample A), 180 Å (sample B), and 50 Å (sample C), 2D electron concentrations of 0.9×10^{11} cm^{-2}, 2.25×10^{11} cm^{-2}, and 3.4×10^{11} cm^{-2}, respectively, were obtained. This range was further expanded to 5.7×10^{11} cm^{-2} by shining light onto the samples, while at low temperature, and taking advantage of the persistence of the photoinduced electrons.[13]

The carrier concentration and the mobility were determined by resistivity and low-field Hall measurements, in the temperature range 4–300 K. A typical result is presented in Fig. 1. The total number of carriers, shown in the upper part of the figure, remains constant from 4 up to 90 K. Above 140 K the carrier concentration increases monotonically with T, probably because of the temperature-induced ionization of impurities (Si) in GaAlAs. In the range 90–140 K a slight decrease of the electron concentration is observed. A similar dependence is apparent in Fig. 3 of Ref. 1, not mentioned explicitly there. A quantitative understanding of that behavior must wait for theoretical calculations of the effect of temperature on carrier concentration in GaAs-GaAlAs heterostructures. The measured mobility shows a monotonic increase with decreasing temperature, down to 4 K. At high temperatures ($\geqslant$80 K) μ is proportional to $T^{-2.4}$ and is dominated by optical-phonon scattering, limiting the 77-K value, for example, to a maximum of $\simeq 2\times10^5$ cm^2/Vs. At lower temperatures, down to 4 K, the mobility keeps increas-

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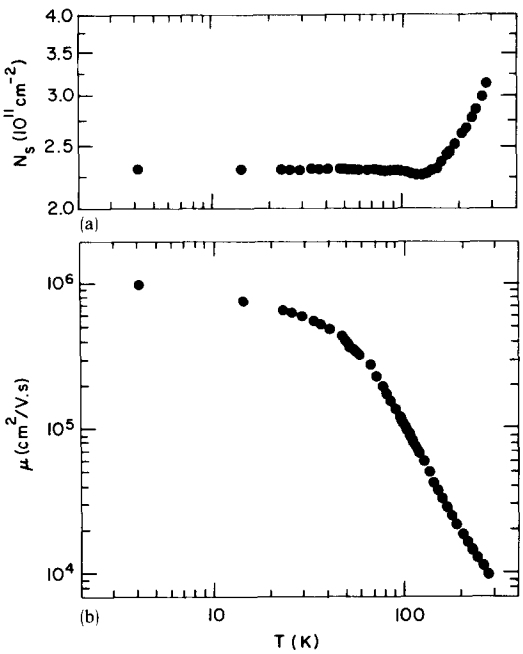

FIG. 1. (a) Electron density, and (b) mobility, as a function of temperature, for a GaAs-$Ga_{0.7}Al_{0.3}As$ heterojunction (sample B), measured under complete darkness.

ing at a much lower rate. In the following we will concentrate on temperatures below 77 K.

Figure 2 shows the inverse mobility μ^{-1} as a function of temperature, for samples A and B. The closed symbols refer to measurements in darkness, whereas the open symbol is for measurements made after the sample was illuminated at low temperature. The linear dependence observed for temperatures in the range 4–40 K is found for all samples both under darkness and after light exposure. A least squares fit of the experimental values to the expression

$$\mu^{-1} = \mu_0^{-1} + \alpha T \tag{1}$$

yields the slope α and the zero-temperature mobility μ_0, plotted in Fig. 3 as a function of N_s. We have made a similar analysis for previously reported measurements[1,2,14] and the results are included in Fig. 3. The slope is seen to increase monotonically with increasing electron concentration. It is remarkable that this behavior is universal and applies to

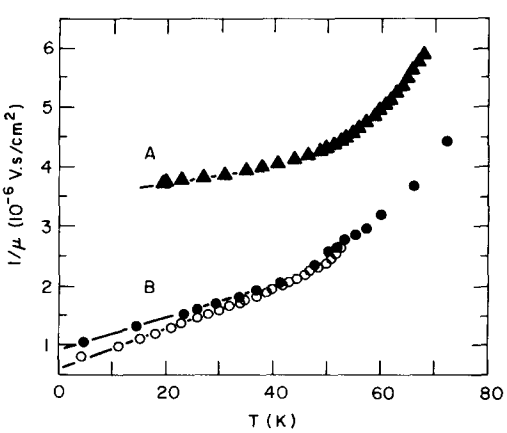

FIG. 2. Inverse mobility vs temperature for samples A and B. Closed (open) symbols indicate measurements under darkness (illumination). The straight lines correspond to least square fits of the experimental data, up to 40 K.

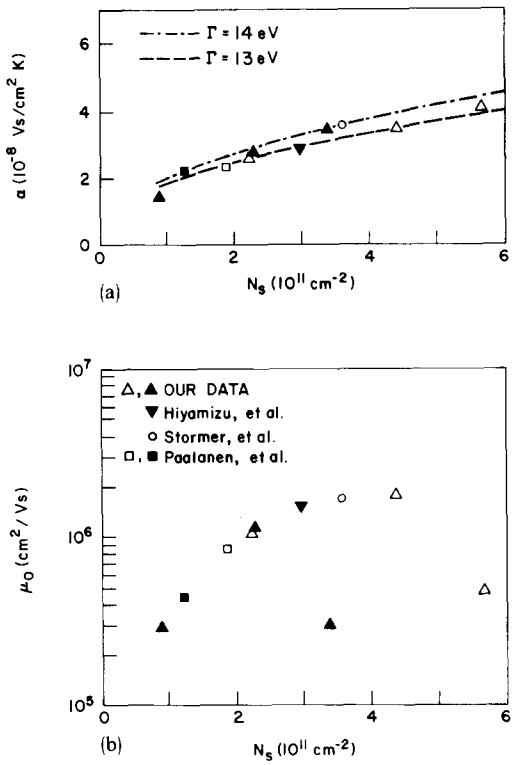

FIG. 3. (a) Temperature coefficient α and (b) zero-temperature mobility μ_0, for samples A, B, C, as a function of the electron density. Closed (open) symbols refer to measurements under darkness (illumination). Also included are the results of an analysis of previously reported data (see Refs. 1, 2, 14). The dotted lines correspond to the calculated phonon-scattering parameter α_p for two values of the deformation potential.

samples grown in different laboratories under different conditions. The only common characteristic of all the structures is their high mobility, represented by μ_0. For most of the structures shown, a higher N_s corresponds to a higher μ_0. A value of μ_0 as high as 1.7×10^6 cm^2/Vs is obtained for a carrier concentration of 4.4×10^{11} cm^{-2}. (The highest value reported,[1] after illumination, is 2.12×10^6 cm^2/Vs, at 5 K, for a carrier concentration of 5×10^{11} cm^{-2}.) The value of α is found to be a function of N_s and not correlated with μ_0, as the results for $N_s = 3.4\times10^{11}$ cm^{-2} and 5.4×10^{11} cm^{-2} show (sample C, before and after illumination). Although the values for the relatively low mobility sample deviate from the general dependence on N_s, nevertheless, the corresponding values of α fall on the curve defined by the other structures. Thus, α is independent of μ_0, at least in this range, and apparently depends only on the heterolayer itself and on intrinsic material parameters.

We attribute the observed temperature dependence to acoustic-mode phonon scattering. A recent calculation[7] for this system, below the degeneracy temperature, gives a phonon scattering rate proportional to T, as observed here. Included in Fig. 3(a) is the calculated phonon-scattering parameter α_p vs N_s for two values of the deformation potential, which shows the same functional dependence as the experimental data. The latter is enclosed between the two curves, except for the lowest N_s, leading to an optimum value of about 13.5 eV for Γ. The other parameters that enter in the calculation, such as the elastic constants, are well known for GaAs. The value of the deformation potential obtained falls

in the range 7–16 eV, of previous determinations.[15,16]

The overall dependence of μ^{-1} on T should include contributions from both phonon scattering and ionic scattering. Preliminary calculations[11] indicate that the latter is such that $\mu_I^{-1} \simeq \mu_{I0}^{-1}(1+\beta T^2)$, with $\beta < 0$, at very low temperatures. The fact that the observed μ^{-1} increases linearly with T, and that the slope can be accounted for by a value of Γ consistent with independent determinations, suggests that the contribution of ionized-impurity scattering to the temperature dependence of μ is small. Simple considerations based on thermal broadening of the Fermi distribution suggest[11] that the decrease of μ_I^{-1} with T is stronger for low N_s, which could explain the small value of α found for $N_s = 0.9 \times 10^{11}\ \mathrm{cm}^{-2}$.

The zero-temperature mobility is, on the other hand, limited in practice by ionic scattering, even in samples of the quality of those shown in this work. The origin of this scattering may be the distant ions in GaAlAs, or even unknown centers closer to the interface. For structures of lower quality, in which these centers are supposedly more abundant, not only μ_0 should be smaller, but also the temperature dependence of ionic scattering would be expected to dominate that of phonon scattering, leading to an increase of the overall mobility with increasing temperature. Such a behavior has been observed experimentally in low mobility samples in GaAs-GaAlAs[14,17] as well as in InAs-GaSb[18] heterostructures.

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