Mobility Modulation of the Two-Dimensional Electron Gas Via Controlled Deformation of the Electron Wave Function in Selectively Doped AlGaAs-GaAs Heterojunctions

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It is shown for the first time that the controlled deformation of the electron wave function leads to modulation of the two-dimensional electron mobility by as much as 56% even when the electron concentration is kept constant. The deformation is controlled by use of two different gating modes (front gating and back gating) in a novel n-AlGaAs-GaAs heterojunction field-effect-transistor configuration. The observed modulation of electron mobility is in accordance with the theoretical prediction and demonstrates the feasibility of the recently proposed concept of a velocity-modulation transistor.

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In selectively doped n-AlGaAs-GaAs heterojunctions, the donor impurities are placed only in the AlGaAs side of the heterointerface and spatially separated from the two-dimensional electron gas (2DEG) accumulating at the GaAs side of the interface. This modulation-doping scheme reduces the ionized-impurity scattering rate and leads to a dramatic improvement of the mobility μ especially at low temperatures.[1] Such an asymmetry in the spatial distribution of impurities may well bring about another class of effects on μ, since the Coulomb scattering in this system is strongly dependent on the correlation between the impurity location and the shape of the electron wave function.

In this work, we demonstrate both experimentally and theoretically that the low-temperature mobility of such electrons can be substantially modulated by deforming the electron wave function, even when the electron concentration N_s (or Fermi energy) is kept constant. Although similar attempts were made in the substrate-bias (or the back-gate) experiments on Si metal-oxide-semiconductor inversion layers at low temperatures, the measured variation of μ with substrate bias in the low-N_s region was found much smaller than predicted, because of the localization and other complications.[2] On the other hand, μ in the high-N_s region was dominated by the front-gate effect.[3] In either case, clear evidence of mobility modulation (MM) was not quite established. In contrast to these systems, the selectively doped n-AlGaAs-GaAs heterojunction is regarded to be a nearly ideal system for mobility studies, since it is practically free from crystal imperfections and the mobility is primarily dominated by donor impurities whose distribution can be precisely controlled. It should be noted that the MM by the external voltage via controlled deformation of the wave function is a subject of great physical significance and also has a technological importance. This is because MM leads to a change in electrical conductivity along the heterojunction, resulting in a new type of transistor action [velocity-modulation transistor (VMT)].[4] Since the conductivity of the VMT is changed only by varying carrier velocity, and not by varying carrier density, its switching speed is free from the intrinsic transit-time limitation, reaching possibly to the subpicosecond range. In the following we present the first clear evidence of the MM (or VMT) effect and provide a quantitative interpretation based on the theory of the ionized-impurity scattering.

The sample used in this study was grown on Cr-doped semi-insulating GaAs(100) substrate by molecular beam epitaxy. The n-AlGaAs-GaAs heterostructure consists of a 1-μm-thick undoped GaAs buffer layer, a 4.5-nm-thick undoped $Al_{0.3}Ga_{0.7}As$ spacer layer, and a 123-nm-thick Si-doped $Al_{0.3}Ga_{0.7}As$ layer. The doping level N_D in the AlGaAs is 4.6×10^{17} cm^{-3}. Using this wafer, we fabricated a field-effect transistor (FET) with a Hall-bar geometry. The front-gate (FG) electrode was formed by depositing Al on the surface of the Si-doped AlGaAs layer. The substrate was then lapped down to a thickness of 120 μm and Au was deposited on the backside of the specimen to serve as the back-gate (BG) electrode. (See the inset of Fig. 1.)

The concentration of electrons N_s at the heterointerface was measured at 8.9 K by use of the Hall effect as a function of either front-gate voltage (V_{FG}) or back-gate voltage (V_{BG}), as plotted in Fig. 1. When N_s was measured as a function of V_{FG}, the BG electrode was grounded to the source electrode, and vice versa. In each mode, N_s varies linearly with V_{FG} or V_{BG} under reverse-biased conditions, which indicates that the FET operates as an insulated-gate FET in these regions. Under forward-biased conditions, however, N_s shows a drastic saturation in both modes. It is established that this saturation phenomenon in the FG mode results from shielding of the gate electric fields by the undepleted region formed in the AlGaAs.[5] The saturation of N_s in the BG mode for $V_{BG} > 100$ V, on the other hand, suggests that the gate electric field from the back gate is also shielded. This shielding is probably caused by electrons in the undepleted region

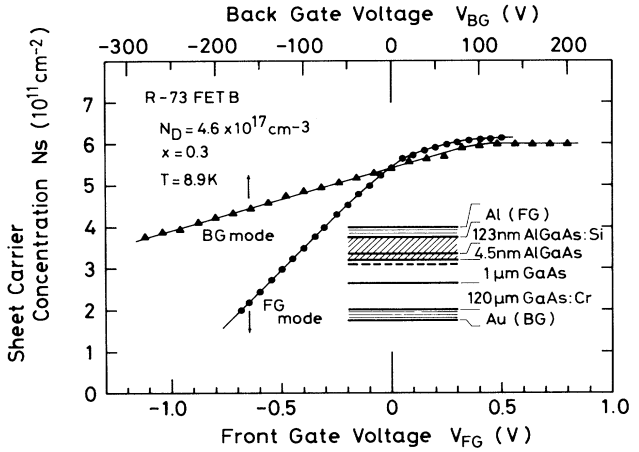

FIG. 1. Measured sheet carrier concentration N_s as a function of either front-gate voltage V_{FG} (circles) or back-gate voltage V_{BG} (triangles).

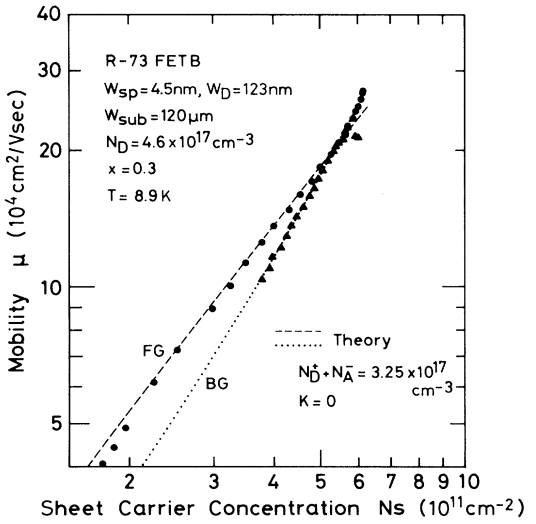

FIG. 2. The electron mobility as a function of electron concentration N_s in two different gating modes. Circles for front-gate (FG) mode; triangles for back-gate (BG) mode.

which is induced in the GaAs buffer layer under forward-biased conditions. Note that in these regions where N_s completely saturates against V_{BG}, the band bending (or the number of space charges) in the GaAs depletion layer is vanishingly small.

Hall mobilities of electrons were measured for both gating modes at 8.9 K, where the mobilities are limited mainly by the ionized-impurity scattering by the donors doped in the AlGaAs. (The contribution of the phonon scattering to the mobility is estimated to be less than 9% at this temperature.[6]) Mobilities in the FG mode (μ_{FG}) and in the BG mode (μ_{BG}) are plotted as functions of electron concentration N_s by use of circles and triangles, respectively, in Fig. 2. In both modes, the mobility shows a monotonic increase with N_s, μ being proportional to N_s^γ with $\gamma > 0$. These tendencies are qualitatively expected since the Fermi energy of the 2DEG is proportional to N_s and electrons with larger kinetic energy are less affected by the ionized-impurity scattering. Note here that μ_{BG} shows a steeper dependence on N_s than μ_{FG} with μ_{FG} proportional to $N_s^{1.4}$ while μ_{BG} is proportional to $N_s^{1.9}$. As a result, μ_{FG} and μ_{BG} deviate from each other when N_s is varied from $N_s = 5.45 \times 10^{11}$ cm^{-2}.

In order to interpret this phenomenon, we consider how the shape of the wave function $\psi(z)$ is affected by the gate electric field in each mode. Figure 3 illustrates the schematic band diagrams of the heterojunction for both modes under reverse-biased conditions and the exact shapes of the electron wave functions calculated by a self-consistent method[7] in the cases where N_s is reduced to 2.0×10^{11} cm^{-2} either by the FG mode [Fig. 3(c), solid line] or by the BG mode [Fig. 3(c), dashed line]. When $V_{FG} < 0$ [Fig. 3(a)], the electric field at the heterointerface becomes weaker and $\psi(z)$ is pushed away from the heterointerface, which reduces the ionized-impurity scattering by the donor impurities in the AlGaAs. When $V_{BG} < 0$ [Fig. 3(b)], on the contrary, the electric field in the GaAs depletion layer becomes stronger and $\psi(z)$ is pushed toward the heterointerface, which increases the ionized-impurity scattering. This electric field F_{depl} in the GaAs depletion layer is often correlated with the effective number of depletion layer charges N_{depl} as $F_{depl} = eN_{depl}/\epsilon_G\epsilon_0$, where $\epsilon_G\epsilon_0$ is the permittivity of

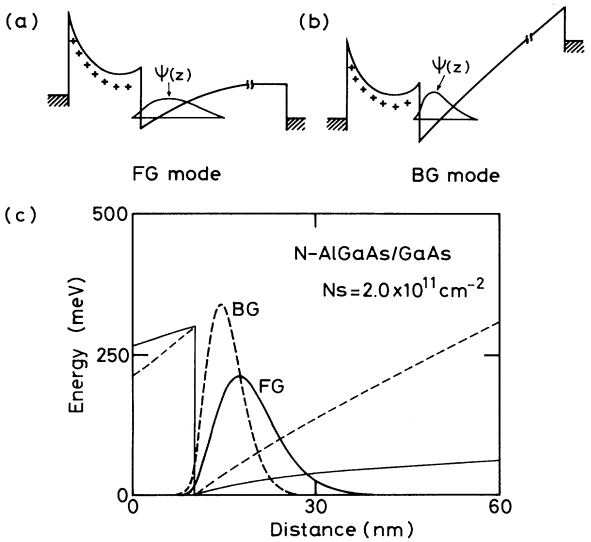

FIG. 3. Schematic illustrations of the band diagram under reverse-biased conditions: (a) front-gate (FG) mode, and (b) back-gate (BG) mode. (c) Exact shapes of the electron wave function are shown in the FG mode (solid line) and in the BG mode (broken line) calculated at $N_s = 2.0 \times 10^{11}$ cm^{-2}.

GaAs. From this simple consideration, μ_{FG} is expected to be higher than μ_{BG} when they are compared with each other at the same electron concentration N_s. Under forward-biased conditions, all the situations are reversed. Thus the mobility is expected to be modulated by varying the shape of the wave function.

To provide a theoretical basis to this sample consideration, we have performed theoretical calculations of the mobility limited by the ionized-impurity scattering, following the method developed by Ando.[8] In the calculation, the extended Stern-Howard variational wave function was used, in which the penetration of the wave function into the AlGaAs is taken into account. It was assumed that electrons populate only the lowest quantum subband (electric quantum limit) and that the spacer layer and the GaAs buffer layer are free from residual impurities. Moreover, the number of ionized impurities in the AlGaAs layer was assumed to be constant when $V_{FG} < 0$, because the linear dependence of N_s on V_{FG} indicates that the AlGaAs layer works as a simple insulator. The calculation was done mainly for $V_{FG} < 0$. The single fitting parameter used in the calculation is the net ionized-impurity concentration $(N_D^+ + N_A^-)$ in the doped AlGaAs layer and is chosen to be 3.25×10^{17} cm^{-3} so that the calculated mobility coincides with the measured mobility at one point where $V_{FG} = V_{BG} = 0$. This value of $N_D^+ + N_A^-$ is about 30% smaller than the nominal doping level N_D $(=4.6\times10^{17}$ cm$^{-3})$ of Si donors in the AlGaAs. The origin of this slight discrepancy is not clear; it may be due to Si segregation during the growth, which reduces the effective scattering rate.[9] In any case, we have calculated mobility for a variety of bias conditions and the results are plotted as dashed and dotted lines in Fig. 2. The calculated results agree quite well with the experiments in the studied region of N_s. This proves clearly that the mobility variation observed here is caused mainly by the kinetic energy dependence of the Coulomb scattering but, at the same time, it is strongly influenced by the shape of the electron wave function with respect to the spatial distribution of the donors in the AlGaAs. Note that μ_{FG} at $N_s = 3.7\times10^{11}$ cm^{-2} is 21% greater than μ_{BG} at the same electron concentration. This demonstrates clearly that the mobility can be modulated by varying the shape of the wave function using two different gating modes (FG,BG) in accordance with the theoretical prediction.

In order to get further insight on the mobility-modulation effect, we next study the substrate bias effect on the mobility at 8.9 K. N_s was varied by the FG voltage while the BG voltage was maintained at various values. The measured Hall mobilities are plotted in Fig. 4 as functions of N_s with the BG voltage as a parameter. For simplicity we have indicated the value of V_{BG} in parentheses; so, for example, $\mu(-200$ V) denotes the mobility at $V_{BG} = -200$ V. From Fig. 1,

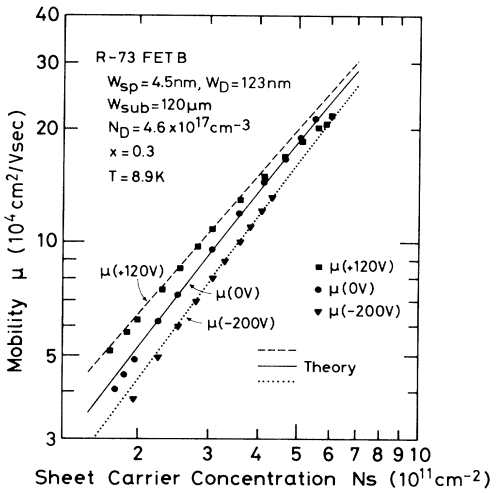

FIG. 4. The electron mobility as a function of electron concentration N_s under different back-bias conditions. Squares for back-gate voltage $V_{BG} = +120$ V, circles for $V_{BG} = 0$ V, and triangles for $V_{BG} = -200$ V. N_s was varied by the front-gate voltage.

one can see that the conditions of $V_{BG} = +120$, 0, and -200 V correspond, respectively, to small, medium, and large degree of band bending in the GaAs depletion layer where the effective numbers of depletion layer charges N_{depl} are 0, 0.57×10^{11}, and 1.76×10^{11} cm^{-2}. One sees immediately from Fig. 4 that $\mu(+120\text{ V}) > \mu(0\text{ V}) > \mu(-200\text{ V})$ when compared at the same N_s in the region of $N_s < 4.5\times10^{11}$ cm^{-2}. Note in particular that the mobility-modulation ratio, $[\mu(+120\text{ V}) - \mu(-200\text{ V})]/\mu(-200\text{ V})$, is as high as 56% at $N_s = 2\times10^{11}$ cm^{-2}. This dependence is qualitatively expected, since the positive (negative) substrate bias causes the wave function of electrons to be pulled away (pushed toward) the heterointerface side where scatterers are mainly distributed, leading to the suppression (enhancement) of the Coulomb scattering. One notices also that the mobilities vary as $\mu(+120\text{ V}) \propto N_s^{1.25}$, $\mu(0\text{ V}) \propto N_s^{1.39}$, and $\mu(-200\text{ V}) \propto N_s^{1.47}$; larger N_{depl} leads to steeper dependences in the $\mu - N_s$ characteristics. For comparison, theoretical calculations of mobilities were performed by the method described before and are shown by the dashed, solid, and dotted lines in Fig. 4. Except for a narrow range of N_s, to be mentioned later, the theoretical curves show excellent agreement with the experimental results. This indicates that the substrate-bias dependence of the mobilities is well ascribed to the enhancement or suppression of the electron interaction with the scattering potential of the ionized donors via the deformation of the wave functions. A small discrepancy between the theory and the experiment which is observed when $V_{BG} = +120$ V ($N_{depl} \simeq 0$) and $N_s > 3\times10^{11}$ cm^{-2} can be mostly ascribed to the

onset of intersubband scattering, which is neglected in our theoretical model. Note that the self-consistent calculation of the energy-band diagram for this experimental condition ($N_{depl} \simeq 0$) has shown that the first excited subband becomes occupied already at $N_s = 3 \times 10^{11}$ cm^{-2} when N_{depl} is nearly zero,[10] in accordance with our experimental finding.

In conclusion, we have shown for the first time that the controlled enhancement or suppression of the electron interaction with the asymmetrically distributed donor impurities in a modulation-doped n–AlGaAs-GaAs heterojunction leads to a new phenomenon of mobility modulation. It is demonstrated that the electron mobilities and conductivities can be varied as much as 56% by varying only the shape of the electron wave function even when the electron concentration N_s is kept constant. The observed variation of the mobility is in excellent agreement with the theory, suggesting that the further optimization of impurity distribution may lead to a much greater modulation of mobilities.[4] Our present work demonstrates the feasibility of the physical principle of the newly proposed VMT.

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