High-mobility variable-density two-dimensional electron gas in inverted GaAs-AlGaAs heterojunctions

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Inverted heterointerfaces (GaAs on AlGaAs), which are basic constituents of all quantum wells and superlattices, have been significantly improved using electron diffraction and a refined molecular beam epitaxy growth procedure. Utilizing them in a novel structure allowed the variation of the electron density over a wide range, with peak mobilities of 4×10^5 cm^2/V s. The continuously variable electron density allowed comparison to a theoretical analysis of the low-temperature scattering mechanisms, and their relation to the growth process, establishing the importance of interface charges and roughness. High-mobility samples were used to observe the quantum Hall effect with varying carrier concentrations in a single structure.

A high-mobility quasi-two-dimensional electron gas (2DEG) can now be routinely produced in GaAs-AlGaAs normal heterojunctions where a doped AlGaAs alloy is grown on top of a pure GaAs layer.[1] So far, in the inverted heterojunctions, where the pure GaAs is grown on top of the AlGaAs, 2DEG mobilities were relatively low. Inverted heterojunctions are extremely important since half of the interfaces in GaAs-AlGaAs quantum wells and superlattices are inverted. Single inverted interfaces also have some technological advantages.[2] Attempts to improve inverted structures have been reported before,[3-5] but the difficulties were never resolved. Two main reasons were offered to explain the low mobilities in the inverted structures: (a) interface roughness that is inherent to the growth process, and (b) impurity segregation during growth towards the interface and the top GaAs layer.

We report here a study that led to the development, for the first time, of high-mobility inverted interfaces. Moreover, the interface was embedded in a novel structure (an inverted semiconductor-insulator-semiconductor, or ISIS) that enabled the variation of the 2DEG density continuously from the low value of 2×10^{10} to 5×10^{11} cm^{-2} in a single structure, with mobilities approaching those measured in normal heterojunctions. We find strong correlations between the electron mobility and the AlGaAs interface smoothness, as indicated by the intensity of grazing angle reflection high-energy electron diffraction (RHEED) spots.

A variable density 2DEG formed at an interface could facilitate its study, and in particular be useful for inverted structures. Hence, a novel ISIS structure was developed where the 2DEG is formed by the application of an electric field at the GaAs-AlGaAs inverted interface. The structure, grown by molecular beam epitaxy (MBE), is described in Fig. 1. Mesas $\simeq 0.2\ \mu$m deep were etched, and four (or six) lithographically defined AuGe/Nb/Au shallow ohmic contacts were alloyed (to a depth of $\simeq 150$ nm, avoiding shorting to the gate) to form a Van der Pauw (or a Hall bar) pattern. Initially no 2DEG is formed, and current does not flow between the top contacts. As the (positive) gate voltage is increased above a threshold voltage of $\simeq 1$ V, the sheet density n_s of the 2DEG increases proportionally to the electric field at the interface (see Fig. 1).

Our initial attempts to produce inverted structures resulted in a relatively low 4.2 K mobility of 5×10^4 cm^2/V s, as also obtained by other researchers.[4,5] However, normal structures with donors in the AlGaAs and thick AlGaAs spacer layers, grown under the same conditions, had mobilities of some 4×10^5 cm^2/V s. In order to overcome these fundamental differences, which are obviously interface related, we have exploited the RHEED technique,[6] observing the specular reflection pattern of an electron beam in the (110) direction during growth. The diffraction intensity, corresponding to the surface smoothness,[6] exhibits decaying oscillations as GaAs growth proceeds. Each oscillation corresponds to a single monolayer growth time, due to a periodic roughening and smoothing of the surface. The overall decay results from the increased roughness with increasing

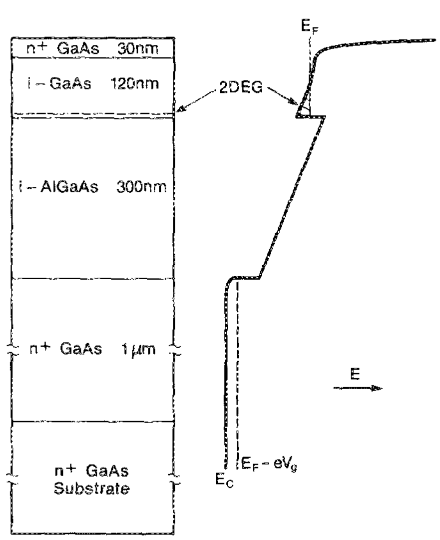

FIG. 1. Description of an ISIS structure. The potential diagram on the right corresponds to the accumulation mode. The top doped GaAs layer is designed to be exactly depleted by the surface potential.

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layer thickness. When growth is interrupted, the smoothness of the surface improves and RHEED intensity increases over a time period determined by the growth conditions. When AlGaAs is grown, surface roughness builds up more rapidly than in the GaAs case, and the recovery is much slower and incomplete. This is due to the low surface mobility of the Al atoms, responsible for the greater roughness of the inverted interface.[7,8]

In order to smooth the top AlGaAs surface the growth was interrupted frequently under excess As flux,[9] and its rate reduced to 4 nm per minute, to allow the Al atoms reach terrace steps and nucleate smoothly.[7] The resultant electron mobility was thus improved, and reached a peak value of 10^5 cm^2/V s for a density $n_s \simeq 6\times10^{11}$ cm^{-2}. However, the mobility dropped very sharply (to a few thousands) when n_s was reduced to 2×10^{11} cm^{-2}.

A deposition of about one monolayer (1 ML) of GaAs on the AlGaAs surface just before growth interruption led to substantially faster and more complete smoothness recovery. Figure 2 compares RHEED intensity oscillations during AlGaAs growth followed by the recovery of both AlGaAs and AlGaAs + 1 ML of GaAs. The shorter interruption time is highly advantageous since the number of incorporated impurities from the surrounding is minimized. Employing this technique in the growth of the AlGaAs ($x\simeq0.26$) improved the peak mobility to 1.5×10^5 cm^2/V s. The mobilities and sheet densities, shown in the lower part in Fig. 3, were measured by the Van der Pauw method, while varying the gate voltage V_g. The maximum achievable n_s was limited by the onset of leakage current into the gate due to tunneling through the resulting triangular potential barrier of the AlGaAs.

A further and crucial step involved the reduction of impurity movement toward the interface. This was accomplished by reducing the substrate temperature to 500 °C during the growth of a thin AlGaAs layer some 5 nm below the inverted interface (thereafter the temperature was quickly raised). This procedure, in conjunction with reducing the AlAs mole fraction to 0.21, produced superior inverted structures with an extremely wide range of electron densities, from n_s as low as 2×10^{10} cm^{-2} up to 5×10^{11} cm^{-2}, and a maximum mobility of 4×10^5 cm^2/V s (upper curve of Fig. 3).[10] The mobility increases sharply as the electron density increases and then levels off. Good ohmic contacts to the 2DEG were maintained even at the extremely low density range.

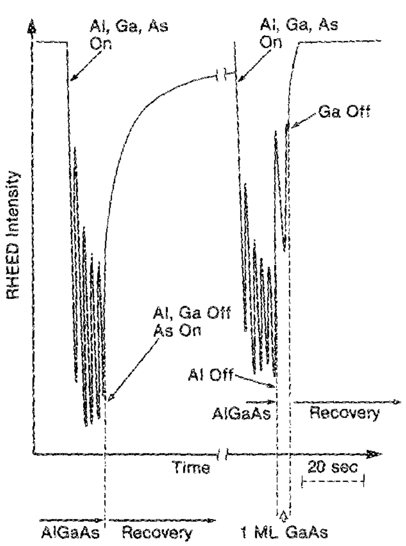

FIG. 2. Description of RHEED intensity oscillations during GaAs and AlGaAs growth followed by surface smoothness recovery facilitated by growth interruption. At left, a relatively long recovery time is required for a bare AlGaAs surface. At right, the faster and more complete recovery of the same AlGaAs surface covered by a monolayer of GaAs (intensity is saturated).

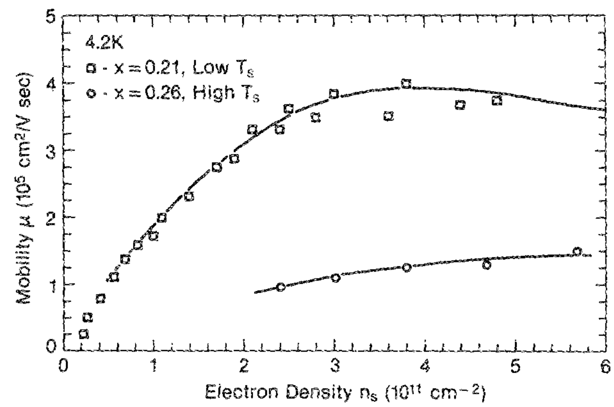

FIG. 3. Mobility vs 2DEG density (controlled by a gate voltage) in two ISIS structures. The results at the bottom (circles) are for an inverted interface with AlAs mole fraction $x\simeq0.26$ grown at a high substrate temperature, thus suffering from high interface charge density and more roughness. The top results (squares) are for $x\simeq0.21$ incorporating a thin AlGaAs region grown at a low temperature. The lines are calculation results from a simple model invoking roughness, interface charges, and bulk impurities.

To understand this dependence and to analyze electron scattering in these inverted structures, we applied an approximate model[11] that includes scattering by background impurities in the GaAs, by interface charges at the GaAs-AlGaAs interface, and by interface roughness. A Fang–Howard envelope wave function (i.e., infinite barrier height approximation) was used, and the calculation made an approximation for the effective depletion field, that does not accurately reflect the more complicated potential profile near the interface (due to the vicinity of the GaAs-vacuum interface). The calculation was otherwise conventional.[12] The interface roughness was characterized by a Gaussian autocorrelation function with rms step height $\Delta = 0.2$ nm corresponding to one monolayer steps (somewhat smaller than the value used by Hirakawa *et al.*[13] in thin quantum wells) and a lateral correlation length $\Lambda = 5.5$ nm. It was necessary to invoke a density of 5×10^9 cm^{-2} interface charges to account for the low mobility at low electron densities. The background acceptor concentration was taken to be 7×10^{14} cm^{-3}, approximately consistent with values found for other samples grown under similar conditions. As shown in Fig. 3, an excellent fit was achieved over the entire range of electron densities for this higher mobility sample (with $x\simeq0.21$). The data measured on the lower quality sample ($x\simeq0.26$) could be accounted for by a rougher interface with about 3×10^{10} cm^{-2} interface charges. While no great significance should be attached to the specific numerical values used in the analysis, it seems clear that both interface charges and interface roughness are required to explain our results. Furthermore, the changes in these quantities resulting from different growth procedures give a direct qualitative correlation between RHEED intensity and interface roughness and also between the growth temperature and the accumulation of charged impurities at the interface, as reflected by Coulombic scattering.

Since a 2DEG in inverted structures has never been shown to exhibit the quantum Hall effect before, low-temperature (0.5 K), high magnetic field (15 T) measurements were carried out on these structures with Hall bar geometries. The potential of this inverted structure is demonstrated by doing the measurements at different gate voltages thus varying the density over a wide range. We have observed the quantized Hall effect, including magnetoresistance dips at some fractional filling factors as shown in Fig. 4(a). The shift in the positions of the minima in R_{xx} at different carrier densities is clearly demonstrated. Figure 4(b) gives R_{xx} and R_{xy} as a function of the gate voltage (and consequently the carrier density) at 3 T.

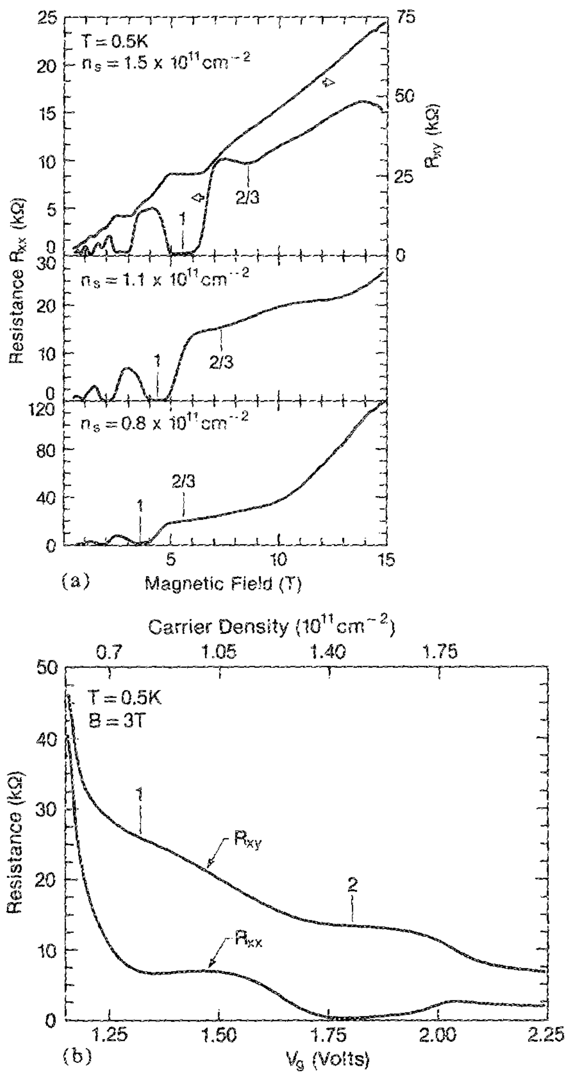

FIG. 4. Quantum Hall effect and magnetoresistance of the 2DEG at the inverted interface. (a) The magnetoresistance as a function of magnetic field for three different gate voltages and 2DEG densities in a single structure. (b) The Hall resistance and the magnetoresistance at 3 T as a function of gate voltage.

In summary, we report the study of inverted heterojunctions with a two-dimensional electron gas (2DEG). We have shown that charges and roughness at the interface are responsible for the generally poor quality of inverted structures. The growth process has been refined with the use of high-energy electron diffraction, leading to peak mobilities at 4.2 K of 4×10^5 cm^2/V s. Moreover, this interface was incorporated in a novel structure (ISIS) which allowed us to vary the electron density continuously, over a wide range, by the application of a gate voltage. A numerical calculation using a simple model allowed the determination of the dominant scattering mechanisms influencing the mobility of the 2DEG, which were clearly related to the different growth procedures. We have demonstrated how the structure could be exploited by measuring the quantum Hall effect over a wide range of carrier densities and mobilities.

Note added in proof. A similar ISIS structure for charged injection purposes was worked on before by A. Kastalsky, J. H. Abeles, R. Bhat, W. K. Chan, and M. A. Koza [Appl. Phys. Lett. **48**, 71 (1986)].

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[10] Employing the same procedure with inverted structures with intentional doping and 20 nm spacer layers in the AlGaAs, produced 2DEG with mobilities of 4.6×10^5 cm^2/V s. See H. Shtrikman, M. Heiblum, K. Seo, D. E. Galbi, and L. Osterling, J. Vac. Sci. Technol. B April/May (1988).

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