Use of superlattices to realize inverted GaAs/AlGaAs heterojunctions with low-temperature mobility of 2×10^6 cm^2/V s

T. Sajoto, M. Santos, J. J. Heremans, and M. Shayegan
Department of Electrical Engineering, Princeton University, Princeton, New Jersey 08544

M. Heiblum, M. V. Weckwerth, and U. Meirav
IBM T. J. Watson Research Center, Yorktown Heights, New York 10598

(Received 7 October 1988; accepted for publication 10 December 1988)

Reproducible realization of high quality inverted interfaces (GaAs on AlGaAs) grown by molecular beam epitaxy is reported. Effective use of thin-layer GaAs/AlAs superlattices in place of an AlGaAs barrier was made to reduce the number of impurities and the roughness at these interfaces. The low-temperature ($\simeq 4$ K) mobility for electrons at these interfaces is as high as 2×10^6 cm^2/V s for an electron density of $\simeq 5\times10^{11}$ cm^{-2}—a factor of four improvement over the highest mobility reported for inverted interfaces.

Recent improvements in growth systems and techniques have led to the realization of two-dimensional electron systems (2DES) at selectively doped GaAs/AlGaAs interfaces with low-temperature mobilities well above 1×10^6 cm^2/V s.[1] These high mobilities have been achieved in *normal* (AlGaAs on GaAs) interfaces; the *inverted* interfaces (GaAs on AlGaAs) in general have been of lower quality. This inferior quality has been attributed to the interface roughness as well as impurity segregation (towards the interface) during the growth of AlGaAs. The inverted interfaces, however, are quite important since they are integral parts of GaAs/AlGaAs quantum wells and superlattices, and have device applications.

Recently, the realization of high-mobility 2DES at inverted GaAs/AlGaAs interfaces was reported.[2–4] This was achieved by studying the kinetics of the growth via reflection high-energy electron diffraction measurements, and by optimizing the growth techniques. The highest low-temperature mobility reported,[3] however, was $\mu\simeq4.6\times10^5$ cm^2/V s, about an order of magnitude lower than the highest mobilities reported for normal interfaces.

We report here the realization of high quality inverted GaAs/AlGaAs interfaces imbedded in an inverted semiconductor-insulator-semiconductor (ISIS) structure (Fig. 1).[2] In this structure, the density of the 2DES at the AlGaAs/GaAs interface can be continuously varied by applying a positive voltage to the gate (the n^+-doped substrate). The low-temperature ($T\simeq4$ K) mobility in our interfaces is as high as 2×10^6 cm^2/V s—a factor of 4 larger than the highest mobility value reported for inverted interfaces.[3] We attribute this significant improvement to our use of thin-layer GaAs/AlAs superlattices in place of AlGaAs barriers [Fig. 1(a)] to trap impurities and to improve the interface smoothness.

The structures were grown in a modular Varian Gen II molecular beam epitaxy (MBE) system consisting of a growth, a buffer, and a load-lock chamber with base pressures of 3×10^{-11}, 7×10^{-11}, and 2×10^{-8} Torr, respectively. We have been able to grow high quality *normal* interfaces with extremely low disorder in the same MBE system.[5–7] Details of the system and wafer preparation were given previously.[5] The structure of a typical high-mobility ISIS structure (M95) is schematically shown in Fig. 1(a). First, we carefully outgassed the substrate [n^+ Si:GaAs (100)] in the buffer and growth chambers.[5] After the removal of the surface oxide, a 200 Å undoped GaAs was grown. We then determined the substrate temperature (T_S) by measuring the congruent sublimation temperature (from the changes in the reflection electron diffraction pattern) and also with the use of an infrared pyrometer. After a 10 min wait at $T_S = 640$ °C, we lowered T_S to 590 °C and started the growth. A 65-period superlattice of GaAs (23 Å)/AlAs (8.5 Å) was first grown. This thin-layer superlattice has an average AlAs mole fraction of 27%. The first 25 periods of this superlattice had 3 s interruptions after each GaAs layer. For the first 15 periods, T_S was 590 °C; T_S was then raised to 620 °C (in 10°/period increments). Finally, a 2700 Å GaAs layer which included a planar sheet (δ layer) of Si was

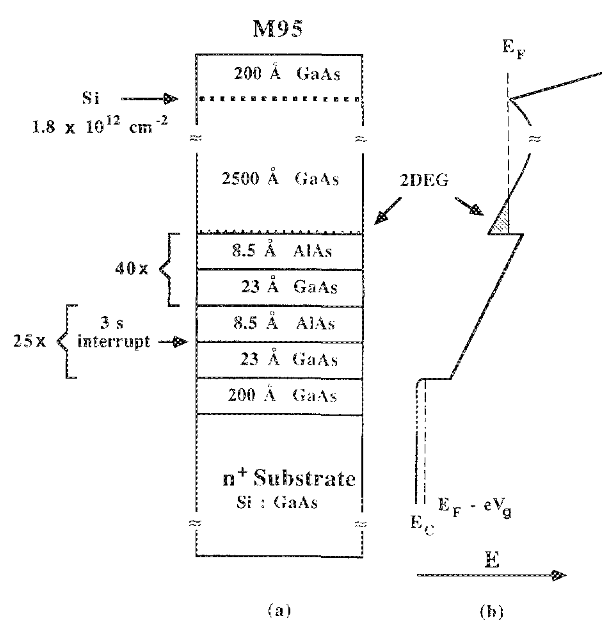

FIG. 1. Schematic description of an ISIS structure. Shown on the right is the potential diagram corresponding to the accumulation mode, achieved by applying a positive gate voltage V_g to the n^+ substrate. On the left, the design structure for sample M95 is schematically shown. Note the use of a thin-layer GaAs/AlAs superlattice in place of AlGaAs barrier.

grown. Just prior to the doping with Si, T_S was lowered to 580 °C.

Mesas $\simeq 0.3$ μm deep were etched, and four (or six) lithographically defined AuGe/Nb/Au shallow ohmic contacts were alloyed (to a depth of $\simeq 0.25$ μm, avoiding shorting to the gate) to form Van der Pauw (or a Hall bar) pattern. The transport coefficients were measured at low temperatures ($T \lesssim 4.2$ K) and in magnetic fields up to 0.5 T. The measured Hall mobilities for several structures (M95, M98, and M99) are shown in Fig. 2 as a function of the electron areal density (n_s) which was varied by applying a positive gate voltage to the n^+ substrate. The dependence of n_s on the gate voltage for the structure M98 is also shown in Fig. 2. The mobilities plotted in Fig. 2 are the highest ever reported for any inverted GaAs/AlGaAs interface.

We attribute the significant improvement in the mobility to the use of the GaAs/AlAs superlattice instead of an AlGaAs barrier. The effectiveness of the GaAs/AlAs interfaces and superlattices in impurity trapping, surface smoothing, and defect reduction has been already established.[8–10] Other aspects of our structure design and growth procedure that may be partly contributing to the realization of high mobility are the following. To reduce the possibility of any Si atoms reaching the 2DES, we did not grow any n^+-GaAs buffer layer (note that no Si was deposited except for the δ layer near the surface). In fact, after outgassing the Si furnace (prior to growth), it was kept at 150 °C below its operating temperature during the growth of the AlAs/GaAs superlattice and the first 850 Å of GaAs layer (to reduce possible outgassing from this furnace at the 2DES interface). The lower T_S at the beginning of the growth of the superlattice was used to reduce the migration of Si and other impurities with the growth front.

The average composition of the barrier (determined by the thickness of the AlAs and GaAs thin layers in the superlattice) and its total thickness for M98 and M99 were different than those for M95 (shown in Fig. 1). We do not have an explanation for the differences in the mobilities for these structures at this point but the data in Fig. 2 show that these structures all have very high mobilities. Similar structures grown in a different MBE system (a Riber 1000-1) also had mobilities well in excess of the values achieved for inverted interfaces that were grown in the same machine but which had not employed superlattices.[2,3]

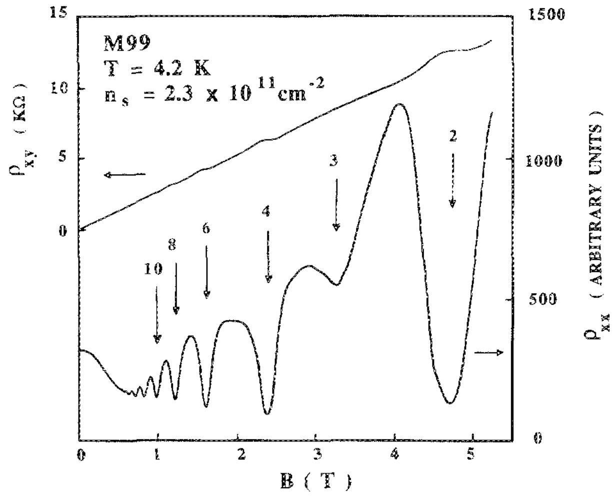

FIG. 3. Transport coefficients ρ_{xx} and ρ_{xy} for sample M99 are shown as a function of magnetic field at a fixed gate voltage. The vertical arrows indicate some of the Landau-level filling factors at which the integral quantum Hall effect is observed.

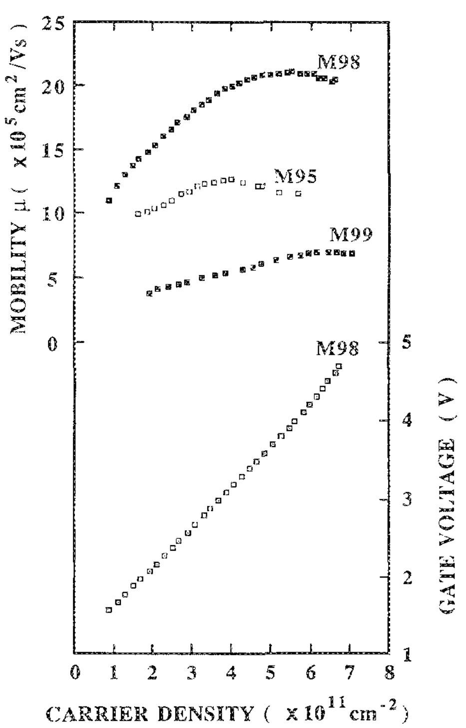

FIG. 2. Dependence of mobility on 2DES density in several ISIS structures is shown. The variation of the 2DES density with the gate voltage is also shown for structure M98.

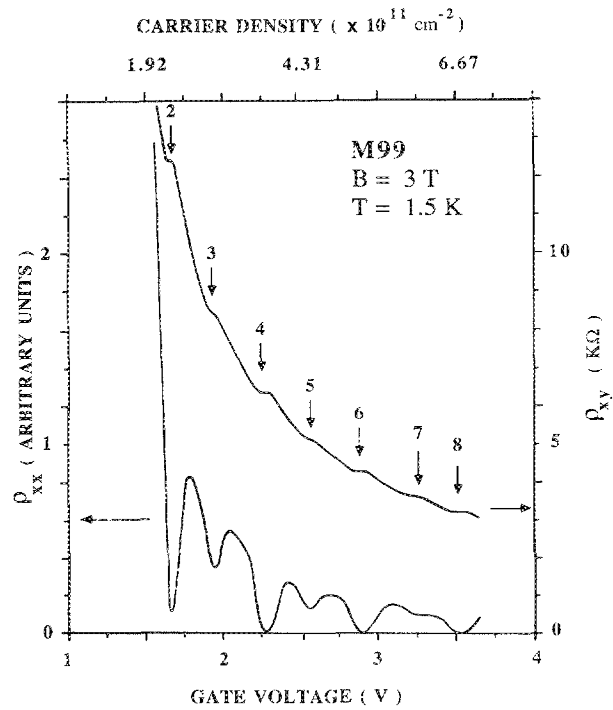

FIG. 4. Transport coefficients ρ_{xx} and ρ_{xy} for sample M99 are shown at a fixed magnetic field and as a function of the gate voltage. The vertical arrows indicate the filling factors at which the integral quantum Hall effect is observed.

We have also performed transport measurements at higher magnetic fields ($B \lesssim 6$ T) and low temperatures ($1.5 \leqslant T \leqslant 4.2$ K). Representative data for structure M99 are shown in Figs. 3 and 4. In Fig. 3, the diagonal resistivity (ρ_{xx}) and the Hall resistivity (ρ_{xy}) are plotted as a function of magnetic field at a fixed gate voltage ($n_s = 2.3 \times 10^{11}$ cm^{-2}). In Fig. 4, the magnetic field is kept constant and ρ_{xx} and ρ_{xy} are shown as a function of the applied gate voltage. In both figures, well-resolved Shubnikov–de Haas oscillations in ρ_{xx} and quantum Hall plateaus in ρ_{xy} are observed. The data in Fig. 4 are especially noteworthy—the realization of such a high quality 2DES with variable density has seldom been achieved before.

In summary, effective use of thin layer GaAs/AlAs superlattices to grow very high-mobility inverted GaAs/AlGaAs interfaces is reported.

We thank V. J. Goldman, S. A. Lyon, and D. C. Tsui for advice. Support of this work by National Science Foundation grants No. ECS-8553110 and DMR-8705002, Department of Defense University Research Instrumentation Program grant No. DAAL03-87-G-0105, and a grant by the New Jersey Commission on Science and Technology is acknowledged.

[1]See, e.g., J. H. English, A. C. Gossard, H. L. Störmer, and K. W. Baldwin, Appl. Phys. Lett. **50**, 1825 (1987).
[2]U. Meirav, M. Heiblum, and F. Stern, Appl. Phys. Lett. **52**, 1268 (1988).
[3]H. Shtrikman, M. Heiblum, K. Seo, D. E. Galbi, and L. Osterling, J. Vac. Sci. Technol. B **6**, 670 (1988).
[4]N. M. Cho, D. J. Kim, A. Madhukar, P. G. Newman, D. D. Smith, T. Aucoin, and G. J. Iafrate, Appl. Phys. Lett. **52**, 2037 (1988).
[5]M. Shayegan, V. J. Goldman, C. Jiang, T. Sajoto, and M. Santos, Appl. Phys. Lett. **52**, 1086 (1988).
[6]M. Shayegan, V. J. Goldman, T. Sajoto, M. Santos, C. Jiang, and H. Ito, J. Cryst. Growth (in press).
[7]M. Shayegan, V. J. Goldman, M. Santos, T. Sajoto, L. Engel, and D. C. Tsui, Appl. Phys. Lett. **53**, 2080 (1988).
[8]P. M. Petroff, R. C. Miller, A. C. Gossard, and W. Wiegmann, Appl. Phys. Lett. **44**, 216 (1984).
[9]T. J. Drummond, J. Klem, D. Arnold, R. Fischer, R. E. Thorne, W. G. Lyons, and H. Morkoç, Appl. Phys. Lett. **42**, 615 (1983).
[10]M. Shinohara, T. Ito, and Y. Imamura, J. Appl. Phys. **58**, 3449 (1985).