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Fabrication of high-quality one- and two-dimensional electron gases in undoped GaAs/AlGaAs heterostructures

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We have developed a technique for the fabrication of high-mobility electron gases formed in undoped GaAs/AlGaAs heterostructures. The use of an insulated gate allows independent control over the carrier density in the Hall bar and ohmic contact regions of the device. This unique design eliminates difficulties in obtaining reliable ohmic contacts, particularly in the low carrier density regime. In the absence of remote ionized impurity scattering, extremely high transport mobilities are obtained at low carrier densities (1×10^6 $\mathrm{cm^2\,V^{-1}\,s^{-1}}$ at 1×10^{10} $\mathrm{cm^{-2}}$). This design has been adapted to the formation of undoped one-dimensional electron gases that show clean and reproducible conductance plateau at 1.5 K. © *1999 American Institute of Physics.*
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Modulation doping has long been established as a method to reduce the scattering caused by the ionized dopants in GaAs/AlGaAs heterostructures. However, even with the use of a large AlGaAs spacer layer to separate the doped region from the channel, the Coulomb potential caused by the ionized dopants creates a randomly fluctuating background potential.[1–3] The scattering that results from such a nonuniform potential is particularly detrimental at low carrier densities[4] and when the two-dimensional electron gas (2DEG) is confined into lower dimensions.[5] As demonstrated by recent works,[6–8] it is possible to eliminate the need for extrinsic dopants by using an external electric field to electrostatically induce a 2DEG at a GaAs/AlGaAs heterointerface.

In this paper we present a technique for forming electron gases in undoped GaAs/AlGaAs heterostructures which are optimized for the low density, high mobility regime. There are two main advantages associated with this new device design. The first is that the 2DEG is induced by the use of a Schottky gate deposited directly onto the surface of the water. This surface gate can therefore be patterned using electron beam lithography to fabricate mesoscopic devices of varying dimensions. The second advantage is that the use of insulated gates in conjunction with surface Schottky gates allows independent control over the carrier density in the ohmic contact and Hall bar regions of the device. It is therefore possible to vary the Fermi energy in the Hall bar region over one order of magnitude without the possibility of ohmic contact failure. These features, combined with the absence of remote ionized dopant, make this an ideal system for studies of clean, highly correlated systems, such as the Tomanaga–Luttinger liquid.[9]

A schematic diagram of the insulated gate device is shown in Fig. 1. The undoped heterostructure (T227) consists of a 2 μm GaAs buffer, a 300 nm undoped $\mathrm{Al_{0.33}Ga_{0.67}As}$ barrier and a 17 nm GaAs cap grown on an undoped (100)-oriented GaAs substrate. Although a 300 nm AlGaAs barrier is used here, the technique has been successfully applied to devices with the barrier width reduced to 50 nm. The wafer was grown in a 2 in. Varian Gen II molecular beam epitaxy chamber with a low background impurity level of $<5\times10^{13}$ $\mathrm{cm^{-3}}$. The ohmic contacts, optimized for a smooth surface morphology, are composed of 5 nm nickel, approximately 130 nm AuGe eutectic and 10 nm Ni, which are evaporated into pits etched to the GaAs/AlGaAs interface and then annealed at 470 °C for 120 s. A surface Schottky gate is patterned to define the shape and carrier density of the 2DEG in the active region. This device design does not require self-alignment of the ohmic contacts, which are typically positioned in excess of 100 μm away from the Schottky gate. Above this a 500 nm layer of insulating polyimide is deposited and patterned to partially cover the ohmic contacts and the surface Schottky gate and in particular the region between them (see Fig. 1). NiCrAu gates, termed bridging gates, are then deposited over the top of the insulator. Since biases can be applied separately to the bridging gates and the surface Schottky gates, the carrier density in the two regions can be controlled independently.

Figure 2 shows the operating characteristics of an induced two-dimensional electron gas. Initially a positive volt-

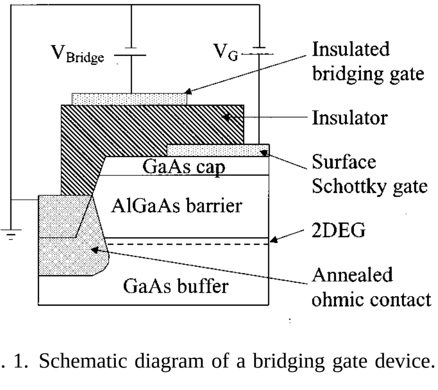

FIG. 1. Schematic diagram of a bridging gate device.

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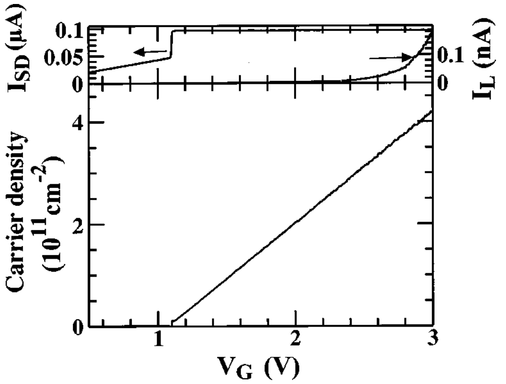

FIG. 2. Operating characteristics of an induced 2DEG device, showing dependence of the carrier density on the surface gate voltage, V_G. The source-drain (I_{SD}) and leakage (I_1) currents are shown in the upper graph.

age of approximately +12 V, with leakage current <0.1 nA, is applied to the bridging gates to induce a 2DEG with a carrier density of $4\times10^{11}\ \mathrm{cm}^{-2}$ in the ohmic contact regions. A voltage of $V_G\sim+1.1$ V is then applied to the surface Schottky gate in order to induce a 2DEG with a carrier density of approximately $1\times10^{10}\ \mathrm{cm}^{-2}$ in the Hall bar region. This is accompanied by a sharp increase in the source-drain current, I_{SD}, which, due to the external circuitry, subsequently remains constant at 0.1 μA. After this, the change in carrier density with applied voltage is linear and reproducible, and agrees within a few percent with the expected capacitance calculated from the growth thickness parameters. At carrier densities of up to $3\times10^{11}\ \mathrm{cm}^{-2}$, leakage currents ($I_L$) are below 10 pA (for gate dimensions of $1250\times50\ \mu\mathrm{m}^2$), rising to 0.1 nA as the density is increased to $4\times10^{11}\ \mathrm{cm}^{-2}$.

The relationship between the carrier density and mobility for this undoped heterostructure is shown in Fig. 3. For comparison, the mobility versus carrier density relationship of a doped 2DEG (T139), grown in the same chamber and with a similar background impurity concentration, is also presented. The doped device contains a 17 nm GaAs cap and 200 nm of AlGaAs, doped with Si at $1.2\times10^{17}\ \mathrm{cm}^{-3}$, which is separated from the interface by 80 nm of undoped AlGaAs. At high carrier densities, where the scattering is dominated by the unintentional background impurities and interface roughness, the mobility of the two devices is similar. However, as the carrier density (and hence screening) is reduced the mobility of the doped device drops sharply, due to increased scattering from the rough background potential. Markedly different behavior is observed when the scattering due to remote ionized dopant is eliminated. At carrier densities between $7\times10^{10}\ \mathrm{cm}^{-2}$ and $2\times10^{11}\ \mathrm{cm}^{-2}$ the mobility of the undoped device follows the relationship $\mu\propto n^{\alpha}$, where $\alpha=0.55$. At carrier densities below $5\times10^{10}\ \mathrm{cm}^{-2}$ this value of α reduces to 0.33, much lower than that typically obtained in high mobility doped heterostructures where $\alpha\sim0.6$–0.7.[10] The ability to obtain high mobility at low density is an inherent advantage of induced systems (similar data has been observed by Kane *et al.*[6]), since scattering is limited mainly by the cleanliness of the growth chamber. This device design enables this quality to be exploited since the minimum density obtained is limited only by the quality of the 2DEG and not by the possibility of ohmic contact failure, allowing future investigation of the low density regime.

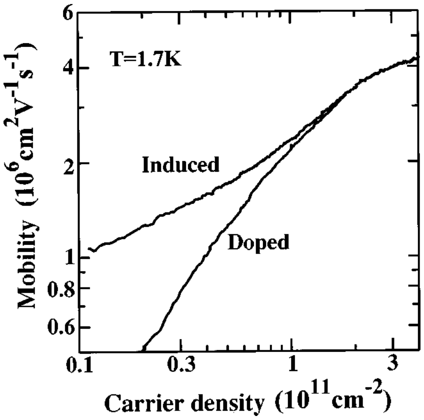

FIG. 3. Comparison of transport mobilities over a range of carrier densities of an induced 2DEG with a modulation doped 2DEG (T=1.7 K).

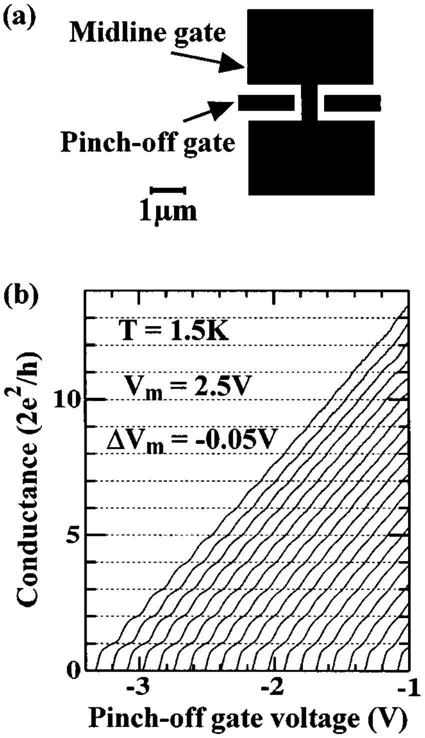

FIG. 4. (a) A schematic diagram of an induced one-dimensional constriction showing electron beam patterned surface gates, and (b) conductance quantization at 1.5 K as a function of the pinch-off gate voltage, for midline gate biases of 1.3–2.5 V in increments of 0.05 V.

By further patterning of the surface Schottky gate the induced 2DEG can be confined to form a one-dimensional wire, as shown in Fig. 4(a). The midline gate is patterned by electron beam lithography, and when a positive bias is applied to the gate an electron gas is formed in the region beneath the gate. Two pinch-off gates are patterned to the sides of the channel, which are used to deplete the electron gas in the constriction. Figure 4(b) shows the conductance of such a one-dimensional wire at 1.5 K as it is depleted, measured in a four-terminal configuration with an excitation voltage of 10 μV at 77 Hz. Successive sweeps demonstrate the ability to change the Fermi energy of the channel by adjusting the midline gate voltage, V_m. Up to ten plateau are clearly observed at integer values of $2e^2/h$. The pinch-off characteristics of the devices have been found to be extremely reproducible, even on successive cooldowns. No evidence of random telegraph signals has been observed, as may be expected since the elimination of intentional dopants will reduce the density of electron traps.[11]

To conclude, the formation of 2DEGs of variable density in undoped GaAs/AlGaAs heterojunctions has been demonstrated using an insulated gate technology, which allows the low density regime to be investigated without the possibility of ohmic contact failure. In the absence of remote ionized impurity scattering, extremely high transport mobilities of 1×10^{6} $\mathrm{cm^{2}\,V^{-1}\,s^{-1}}$ have been obtained at carrier densities of 1×10^{10} $\mathrm{cm^{-2}}$. The fabrication process has been adapted for the formation of one-dimensional structures, which demonstrate clean reproducible plateau at 1.5 K. This device design offers great potential for the future study of low density, highly correlated low dimensional systems.

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