Very low density two-dimensional hole gas in an inverted GaAs/AlAs interface

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We utilize an inverted heterostructure grown on (311)A GaAs to realize a two-dimensional hole gas (2DHG) with a built-in back gate. The density of the 2DHG is easily and reproducibly varied between 5×10^9 and 5×10^{11} cm^{-2}. The mobility of the 2DHG is highly anisotropic in the (311)A plane. © *1997 American Institute of Physics.* [S0003-6951(97)01311-9]

Two-dimensional electron or hole gas (2DEG and 2DHG, respectively) structures of AlGaAs/GaAs are widely used for the study of physics of low dimensional electronic systems and quantum transport. A particularly versatile realization of 2DEGs is the inverted-semiconductor-insulator-semiconductor (ISIS) structure,[1] where the carriers are accumulated in an undoped GaAs layer on *top* of an undoped AlGaAs barrier (thus ''inverted''), grown over an n^+ conducting layer. In ISIS devices, the sheet carrier concentration can easily be modulated by the underlying conductor layer and by surface Schottky gates, thereby increasing the range of possible measurements and allowing patterned gate structures on the surface while having additional and separate control of n by means of the back gate.

In this work, we study ISIS structures grown on (311)A oriented GaAs substrates where a 2DHG is formed in an analogous fashion. This p-ISIS structure allows us to vary the sheet hole density p over a wide range, and in particular to achieve and to measure extremely low densities.

In conventional modulation doped 2DEGs (2DHGs), placing the donors (acceptors) far from the channel generally leads to improved mobility, particularly at low densities. Indeed, very low density 2DEGs with high mobility have been realized using spacers of order 300 nm.[2] In an ISIS structure, since the carriers are generated by field effect rather than by modulation doping, the spacing between the channel and any intentional doping can be increased at will. Furthermore, increasing the depth of the channel below the surface does not lead to major difficulty in the formation of Ohmic contacts, due to the absence of an AlGaAs barrier between the surface and the channel. For this reason, the ISIS is an attractive device for the realization of high quality, low density 2DHG systems. Given that the carriers are generated by a field effect, one might ask why (311)A substrates are at all necessary for accumulating a 2DHG in a p-ISIS. The answer lies in the pinning of the surface potential and the resulting need for a p-type cap layer which, although depleted by the surface states, has a crucial role in bringing the valence band close to the Fermi level. This point will be elaborated below.

Work on (100) n-type ISIS structures[1,3,4] failed to match the high mobility of conventional heterostructure 2DEGs at the low densities. The inferior mobility was attributed to the relatively poor quality of the interface due to the incorporation of background impurities which tend to ride towards the surface and accumulate at the inverted interface, as well as enhanced interface roughness. However, during molecular beam epitaxy (MBE) growth on the (311)A plane, there is a reduction in background impurity incorporation, particularly carbon,[5] in comparison to growth on the more common (100) plane. Moreover, the height of single monolayer fluctuations in the (311)A direction is smaller due to the tilt angle with respect to the cubic axes (25°). Both effects should give rise to a superior inverted interface and thus to a better quality of the 2DHG in (311)A ISIS devices.

Si is invariably the n-type dopant used to produce high mobility 2DEG in (100) GaAs. Nevertheless, Si is an amphoteric impurity in GaAs, and it is well established that it can be used either as a p- or an n-type dopant on (311)A GaAs substrates, depending on the MBE growth conditions.[6,7] This method has already been successfully utilized in producing various hole devices, such as high mobility 2DHGs[8,9] and p-channel transistors.[10]

Figure 1 shows a schematic layer profile of the p-ISIS structures studied. The samples were MBE grown on semi-insulating (311)A substrates, oriented to within ±0.1 degree, using Si as the p-type dopant. Growth was therefore carried out at a relatively high temperature of $\sim$640 °C and low As_4/Ga flux ratio of $\sim$4. The first layer grown was a 1 micron thick p^+GaAs buffer. As indicated above, this layer serves as a built-in back gate. Next a 300 nm barrier layer, essentially of AlAs, was grown, followed by a 150 nm un-

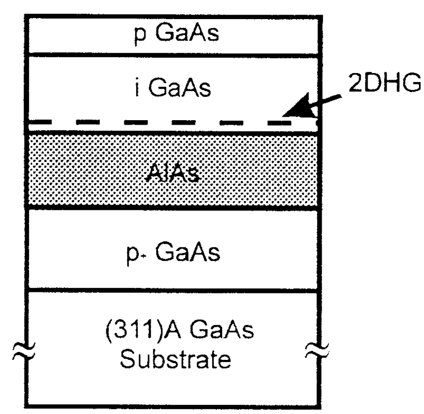

FIG. 1. Schematic presentation of the p-ISIS structure grown on semi-insulating (311)A GaAs substrates, consisting of a thick p^+ buffer, a 300 nm undoped AlAs barrier, a 150 nm undoped GaAs channel layer, and a top 50 nm GaAs layer which is p doped. The 2DHG forms at the lower (inverted) interface of the channel layer upon application of a negative bias to the buffer.

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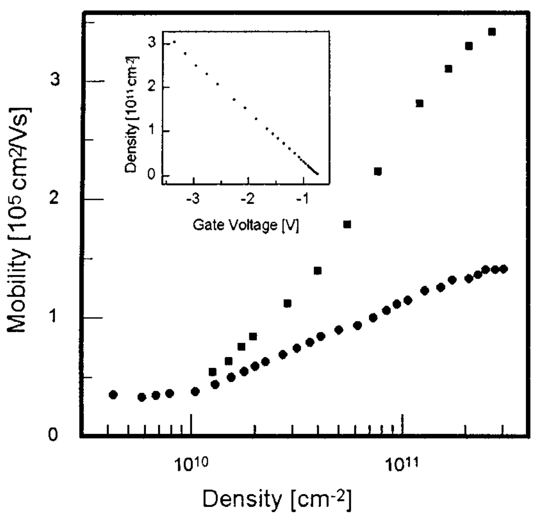

FIG. 2. Mobility of the 2DHG plotted vs its density p, the latter varied by means of the back gate voltage V_b. The scales are logarithmic so as to show the wide ranges involved. Data are shown for 6.2 (●) and 1.6 K (■). The inset shows, on a linear scale, the variation of the density with V_b. The measurements were performed on a Hall bar with current flowing in the $[\bar{2}33]$ direction.

doped GaAs channel layer. The 2DHG forms near the lower interface of the latter. An additional layer of p-type GaAs was grown on top, to provide carriers to the surface states and bring the Fermi level close to the valence band. The cap layer is designed to be depleted by the surface states. Nonetheless, the doping level of this cap layer was limited to $\sim 5\times 10^{17}$ cm^{-3} so that even if the depletion is incomplete, its residual carriers will freeze at low temperatures, thus avoiding the possibility of a parallel conducting channel.

Special care was taken to maintain the smoothness of the interface where the 2DHG resides. This was done by introducing two monolayers of GaAs and a 12 s growth interruption after every 10 nm of AlAs, to allow repeated recovery of the surface smoothness and improve the ultimate interface morphology.[11] Thus the barrier was not entirely composed of AlAs but rather included these GaAs layers.

The samples were patterned by standard lithography, wet etching, and lift-off techniques to form Hall bars along the two perpendicular directions $[01\bar{1}]$ and $[\bar{2}33]$ in the 2DHG plane. An evaporated alloy of Au with 2 percent Zn was used to form shallow Ohmic contacts; the latter had to be carefully alloyed to avoid penetration into the conductive buffer layer. Samples were cooled in the dark in a pumped helium flow cryostat. A back-gate voltage V_b was applied to the p^+ buffer layer, and the 2DHG carrier density p and Hall mobility μ were determined by standard magnetotransport measurements.

With $V_b=0$ the in-plane conductance vanishes, as expected, since by design no 2DHG is formed in the sample in equilibrium. However, a 2DHG is readily accumulated by applying a negative voltage V_b below a certain threshold, where p varies approximately linearly with V_b and can be measured in the range between 5×10^{9} and 5×10^{11} cm^{-2}. The mobility μ increases with p, as seen in Fig. 2, and exceeds 3×10^{5} cm^2/Vs at 1.6 K for the higher density range. The range of densities is quite remarkable, especially the fact that a stable and reproducible density as low as 5×10^{9} could be measured in this structure. This is the lowest reported 2DHG density we are aware of in a heterostructure, corresponding to a typical distance between holes of 140 nm, almost two orders of magnitude above the Bohr radius. We note that the lower limit of the density appears to depend on the sample temperature, and at 1.6 K we could not measure densities below 1×10^{10} cm^{-2}.

In trying to understand why such improvement has been achieved in the low density regime, we point out that in this structure the 2DHG forms at a rather large distance from any intentional doping, substantially larger than in typical modulation doped structures. Indeed, a similar approach was used by Kane *et al.*[12] to achieve very low densities and excellent mobilities in 2DEGs and in 2DHGs with normal (i.e., non-inverted) field-effect heterostructures on (100) substrates; unfortunately, however, their structures require a rather delicate contacting scheme and do not support the option of additional patterned surface gates. Interestingly, the n-ISIS on (100) substrates failed to achieve superior low density performance, despite having large spacers. This shortcoming has long been understood in terms of the accumulation of unintentional impurities at the inverted interface[13] offsetting the advantage of the large spacer. However, as pointed out above, this detrimental effect is much weaker in (311)A growth, thus allowing the advantage of the large spacers to fully express itself.

We have also compared mobilities in the two perpendicular directions $[01\bar{1}]$ and $[\bar{2}33]$, which we label μ_1 and μ_2, respectively. Figure 3(a) shows μ_i versus p for these two orientations. We find that μ_2 exceeds μ_1 by as much as a factor of three at the higher p, and a large difference is maintained even at low densities. This fact is further underlined in Fig. 3(b) where, motivated by Mathiessen's rule, we plot $(\mu_1)^{-1}$ and $(\mu_2)^{-1}$ vs p. The observation that the difference between the two curves is almost constant implies that the anisotropic component in the resistance is only weakly dependent on the hole density.

Anisotropy in the conductance of 2DHGs grown on (311)A surface has been reported and discussed by several groups in recent years. The two general lines of reasoning put forward are (a) an intrinsic anisotropy of the hole dispersion in a 2DHG, and (b) morphological anisotropy at the interfaces. It is not clear whether the former can account for the conductance anisotropy we observe, since the theoretical[14] and experimental[15] works on this question indicate that significant anisotropy in the dispersion is found only at higher subbands or at relatively high wavevectors. We do note, however, that these works focused on quantum-well confined 2DHGs rather than the single-heterojunction system. The alternative one should consider is the structural anisotropy of the AlAs/GaAs interface. Various studies have been carried out to investigate the morphology of the (311)A surface.[16–18] There are conflicting reports regarding the systematic formation of nanometer scale features, on two sets of facets oriented along the $[\bar{2}33]$ direction. Different values, between 3.4 and 10.2 Å, have been reported for the height of these corrugations,[19,20] and some works report no such features at all.[18] These facets, if present, could lead to a higher

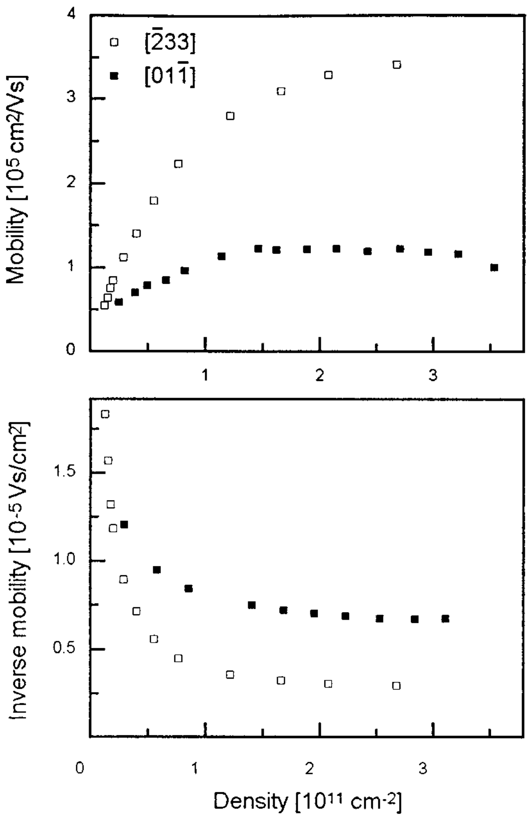

FIG. 3. The anisotropy of the conductance is studied by comparing mobilities μ_1 and μ_2 measured in Hall bars with different orientations [01$\bar{1}$] and [$\bar{2}$33], respectively, in the (311)A plane. In the upper panel, we plot μ_1 and $\mu_2$vs the density, where we find as much as a factor of three difference in favor of μ_2. In the lower panel, we show the inverse quantities; note that the difference between the two is not strongly dependent on density.

mobility along the [$\bar{2}$33] direction in comparison to the [01$\bar{1}$] direction, as we explain below.

Anisotropic interface roughness has quite clearly been shown to account for the observed anisotropy of 2DEG (electrons) mobility in the (100) plane,[4] in terms of interface roughness (IR) scattering. Such scattering, by terrace steps in the interface, scales approximately with the cube of the roughness correlation length, so that even a small level of orientation in the interface topography can give rise to significant conductance anisotropy. While this mechanism seems highly plausible in the present case as well, we note that IR scattering in a single-interface 2DEG or 2DHG is quadratic in the perpendicular electric field[4,21] and hence should increase rapidly with increasing p. While at first glance the anisotropy of the mobility μ does indeed increase with p, Fig. 3(b) shows that a significant anisotropic term persists down to rather low p and, in general $(\mu_1)^{-1} - (\mu_2)^{-1}$ is only weakly dependent on p. Thus the data suggest that there is an anisotropic scattering mechanism which is not strongly density dependent, and therefore does not show the characteristic behavior of IR scattering. The misleading observation that the relative anisotropy increases with p is primarily due to the decrease in Coulomb scattering. At present, we do not know how to reconcile this observation with the notion that IR scattering is the origin of the observed anisotropy. We note, however, that the suggested morphology of the faceted interface is quite different from the conventional picture[21] of IR and thus may require separate theoretical treatment.

In conclusion, we have investigated the behavior of a 2DHG embedded in an inverted interface of GaAs/AlAs which is remotely spaced from any intentionally doped layers. The high mobility and the extremely low densities achieved suggest the presence of a high quality interface, and have allowed us to measure remarkably low 2DHG densities. The large anisotropy of the conductance, although probably related to the morphology of the interface, is not well understood at present.

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