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(N11)A GaAs: a preferable platform for high quality GaAs/AlGaAs structures

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Abstract

We have successfully used (311)A and (511)A GaAs for the realization of high quality two-dimensional hole gas (2DHG) and electrons gas (2DEG) structures, respectively. This study was performed mostly on a back-gated, inverted interface, GaAs/AlGaAs structure, in which a 2DHG or 2DEG is embedded. This particular structure enabled the variation of the 2D carrier concentration over two orders of magnitude in a single device, as well as measurement of extremely low carrier densities in the mid $10^9\ \mathrm{cm}^{-2}$ range. This remarkably low carrier concentration achieved both in a 2DHG and in a 2DEG opens new frontiers for the study of mesoscopic phenomena governed by Coulomb interactions between carriers and, in particular, the possible existence of a Wigner crystal.

Keywords: Electron gas structures; Hole gas structures; (N11)A GaAs

1. Introduction

The motivation for MBE (molecular beam epitaxy) growth of GaAs on non-(100) planes belonging to the (N11)A family, is threefold. (a) The highly stepped surface of these substrates enhances a step flow growth mode which is important for producing sharp growth surfaces and interfaces. (b) The high concentration of non-reactive, empty single dangling bonds reduces the overall background of impurities, particularly carbon, which ensures a relatively low background of impurities. (c) Finally, thanks to the amphoteric nature of Si on (N11)A surfaces (where $N < 5$), high quality *p*-type, *n*-type or mixed structures can be grown, depending on N and the growth conditions. Indeed, the MBE growth on various (N11)A surfaces has attracted considerable attention [1–10].

It is well established that Si, which is invariably the *n*-type dopant on (100)GaAs, can be used either as a *p*-type or as an *n*-type dopant on (311)A GaAs [9]. The case of (411)A is more subtle in that Si is more difficult to control either as an *n*-type or as a *p*-type impurity [5], although it has been successfully used, particularly for the growth of extremely flat hetero-interfaces of quantum well structures [6]. Si turns out to be a very well behaved donor on (N11)A where $N \geq 5$, and so the (511)A plane, naturally suggests itself as the optimal plane for MBE growth of high quality *n*-type GaAs devices and structures [3].

The (N11)A surfaces have a mixed nature which is determined by the existence of both single and double dangling bond sites. The tilt towards the (111)A plane forms (100) plane terraces terminated by (111)A step edges. The tilt angle, which is 25° and 16° for (311)A and (511)A, respectively, determines the density and size of these terraces. The typical width of the terraces is 6 Å for the (311) plane and 10 Å for the (511) plane.

In this work, we used (311)A and (511)A GaAs for growth of 2DHG and 2DEG structures, respectively. We utilized the so-called ISIS device [11,12] which is an inverted semiconductor–insulator–semiconductor where the carriers are accumulated in an undoped GaAs layer on *top* of an undoped AlGaAs *barrier* (thus ''inverted''), grown over a conducting layer. The sheet carrier concentration can easily be modulated by the underlying conducting layer, thereby increasing the range of possible measurements, by allowing for patterned Schottky gate structures to be applied to the surface. The ISIS structure allows us to vary the sheet carrier density of either holes or electrons over a wide range, and in particular to achieve and measure extremely low densities. In order to further establish the superiority of the growth of *n*-type structures grown on (511)A, we also studied normal interface 2DEG structures.

Work on (100) *n*-type ISIS structures [11,12] failed to

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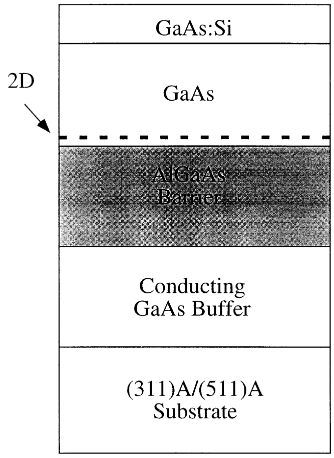

Fig. 1. Schematic representation of an ISIS grown on (*N*11)A GaAs. The barrier is 300 and 200 nm and the GaAs channel is 150 and 300 nm, for the *p*- and *n*-ISIS, respectively.

match the high mobility of conventional heterostructure 2DEGs at the low densities. The inferior mobility was attributed to the relatively poor quality of the inverted 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 MBE growth on the (*N*11)A planes, there is a reduction in background impurity incorporation. Moreover, the height of the single monolayer fluctuations in the (311)A and (511)A directions is smaller due to the tilt angle, with respect to the cubic axes. Both effects should give rise to a superior inverted interface and thus to a better quality 2DHG on (311)A or 2DEG on (511)A in ISIS devices.

2. Experimental methodology

Fig. 1 shows a schematic layer profile of an inverted, back-gated GaAs/AlGaAs structure. It is grown on a p^+ or n^+ GaAs buffer for the *p*-ISIS and *n*-ISIS, respectively. The back-gate voltage, V_b, is used for accumulating a variable density two-dimensional gas (2DG). The first layer grown is

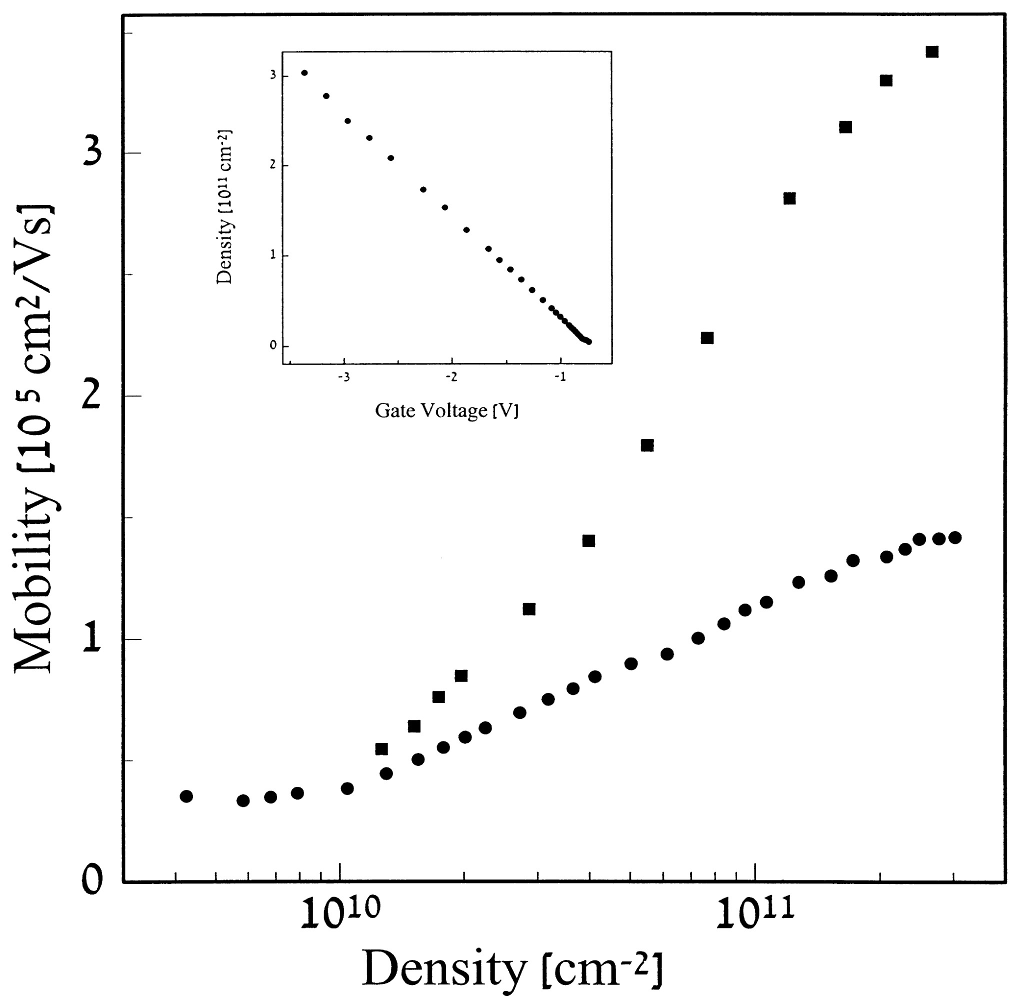

Fig. 2. Mobility of the 2DHG in a *p*-ISIS, plotted versus its density *p*. Data are shown for 6.2 (circles) and 1.6 K (squares). The inset shows, the Hall variation of density with V_b.

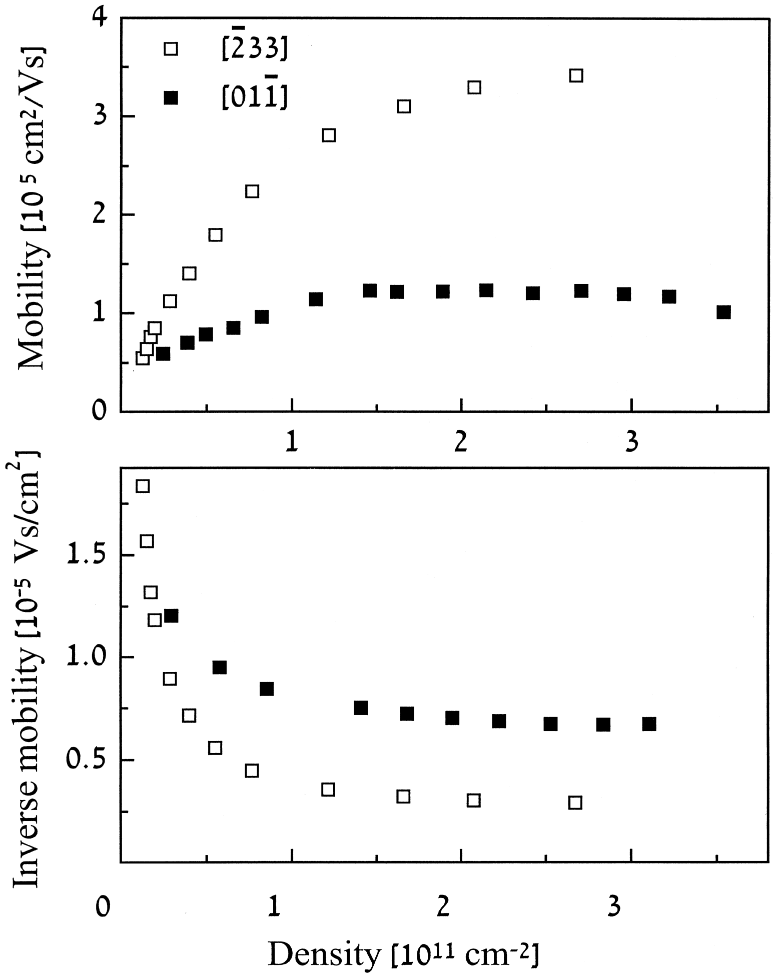

Fig. 3. The mobilities, μ_1 and μ_2, measured in Hall bars in the [01$\bar{1}$] and [$\bar{2}$33], directions, respectively. In the upper panel, μ_1 and μ_2 versus density. In the lower panel, the inverse quantities are plotted.

thus a conductive GaAs buffer. Next, the barrier layer is grown, ‘‘AlAs’’ (explained later) and 50% AlGaAs for the *p*- and *n*-ISISs, respectively, followed by an undoped GaAs channel layer. The 2DG forms near the lower interface of the latter. An additional layer of doped GaAs is grown on top, to provide carriers to the surface states and bring the Fermi level close to the valence or conduction band for the *p*- and *n*-ISISs, respectively. The cap layer is designed to be depleted by the surface states.

Special care was taken to maintain the smoothness of the interface where the 2DG resides. Therefore, the barriers were actually composed of an AlAs/GaAs superlattice (SL) where a growth interruption of 12 s was introduced at each period, after the growth of GaAs. The ‘‘AlAs’’ and AlGaAs barriers for the *p*- and *n*-ISISs were composed of an AlAs/GaAs SL of 35/2 and 7/7 monolayers, respectively. Thus, the ‘‘AlAs’’ barrier was not entirely composed of AlAs but rather included very thin GaAs layers.

The samples were grown by MBE on (311)A and (511)A semi-insulating epi-ready GaAs wafers oriented to within $\pm 0.1°$ from the nominal respective plane. Si was used either as the *p*-type or as the *n*-type dopant. The *p*-type structures were grown at a relatively high temperature of $\sim 640°C$ in order to enhance a maximum *p*-type activation of the Si and ensure a high crystalline quality. For the *n*-type structures, the temperature was kept at about 640°C in order to enhance high quality growth, but was lowered at the final stages of growth to 530°C to reduce Si segregation and diffusion. The As_4 to group III ratio was maintained at about 4 and 10 for the *p*- and *n*-type activations, respectively. The growth rate of GaAs and AlAs was 0.6 and 0.35 $\mu m\ h^{-1}$, respectively.

The samples were patterned by standard lithography, wet etching and lift-off techniques to form Hall bars along the two principal, perpendicular directions. The two directions were required in order to study the anisotropy in the conductivity. Ohmic contacts to the *p*-type or *n*-type structures were formed by evaporation of a 2% Zn/Au alloy and an Ni/Au/Ge/Ni/Au film, respectively, and then alloyed by rapid thermal annealing. Special care was taken to ensure that the ohmic contact was kept shallow in the ISIS structures, in order to avoid punch-through 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 conductive buffer layer and the 2DG carrier density

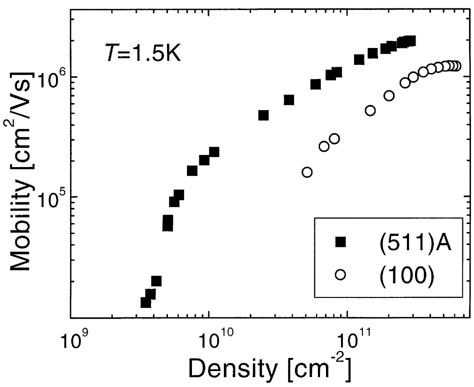

Fig. 4. Mobility of the 2DEG in *n*-ISIS structures grown on (511)A and (100), plotted versus density. The density is varied by means of a back-gate voltage.

and Hall mobility were determined by standard magneto-transport measurements.

3. Results and discussion

We will now refer to the *p*-ISIS structure. When $V_b = 0$, the in-plane conductance vanishes, as expected, since by design, no 2DHG is formed in the sample at 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} at 6.2 K. The mobility, μ, increases with p, as seen in Fig. 2, and exceeds 3×10^5 cm^2 V^{-1} s^{-1} 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

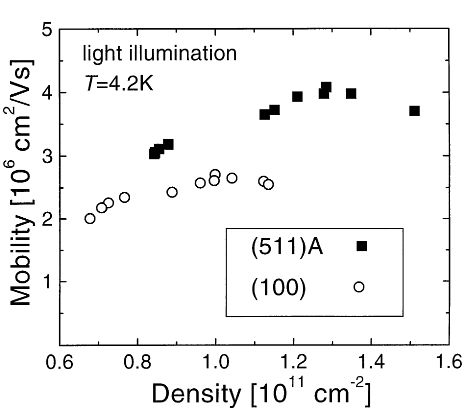

Fig. 5. Mobility of a normal 2DEG structure grown on (511)A and (100) plotted versus density. The density is varied by short pulses of illumination.

to depend on the sample temperature, and at 1.6 K we could not measure densities below 1×10^{10} cm^{-2}.

We now compare the mobilities in the two perpendicular directions $[01\bar{1}]$ and $[\bar{2}33]$, which we label μ_1 and μ_2, respectively. Fig. 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 $(\mu_2)^{-1}$ versus 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.

In order to establish the superior transport properties of a 2DEG grown on (511)A GaAs, we performed a comparative study of both inverted and normal interface structures grown on (511)A and (100) substrates. By growing *identical* structures on both types of lattice planes, we can quite clearly associate the significant improvement in 2DEG qualities with the MBE growth dynamics on (511)A. The mobility in all of the (511)A samples was significantly higher than in the analogous (100) structures. The superiority of the former was particularly pronounced for structures with large spacers and low 2DEG densities. Moreover, it is noteworthy that in back-gated structures grown on (511)A we were able to achieve and measure extremely low electron densities, comparable with the values we achieved for holes in the analogous *p*-ISIS structures grown on (311)A GaAs.

First we discuss the *n*-ISIS structure, on (511)A and on (100), where the built-in back-gate allows us to easily control *n*. The structure of these samples has been described earlier. We note that the thickness of the AlGaAs barrier layer is 200 nm and the 2DEG is located at the bottom of the 300 nm thick undoped GaAs layer, namely quite far removed from any intentional doping in the structure. Fig. 4 shows mobility versus density for two such ISIS samples on a log–log scale. One can readily see the superiority of the (511)A sample, not only in that the mobility is substantially higher—easily by a factor of two and more—but also in that much lower densities are experimentally accessible and measurable. This we attribute to the lower disorder and higher homogeneity of the (511)A layers, in particular the interface between the AlGaAs barrier and the undoped GaAs where the 2DEG resides. This in turn can be related to the step flow growth mode on the highly stepped (511)A surface. It is interesting to note that the lowest density shown here is about 4×10^9 cm^{-2}, which is comparable to the lowest density reported in a normal interface AlGaAs/GaAs structure [13], as well as the lowest densities of holes which we achieved on (311)A substrates.

Next we turn to the normal structure 2DEG grown on (511)A. Fig. 5 shows the evolution of mobility with increasing density for normal 2DEG structures with a spacer of 100 nm for both types of substrates. The increase in density in this case is achieved by short pulses of illumination which induce the well known persistent photoconductivity effect.

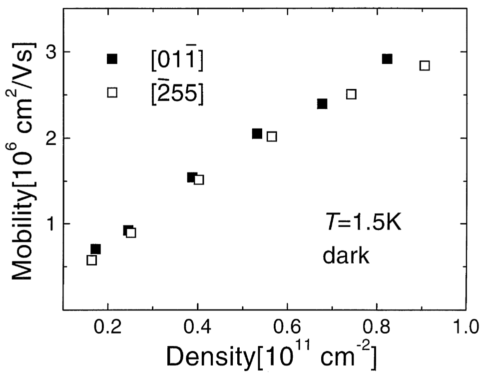

Fig. 6. Mobility of the normal 2DEG on (511)A versus density, in the lower density range. The density is controlled by a Schottky gate.

The (511)A sample starts out with a higher density (before illumination), which is probably due to the lower concentration of unintentional acceptors, as explained above. Moreover, the mobility at $T = 1.5$ K is significantly higher at any given density level, and the peak mobility of the (511)A structure exceeds $4 \times 10^6\ \mathrm{cm^2\,V^{-1}\,s^{-1}}$. Note that the maximum value ever obtained on (100) substrates in this particular MBE machine is only $3 \times 10^6\ \mathrm{cm^2\,V^{-1}\,s^{-1}}$. Indeed, the peak mobility of the (100) sample, under illumination, is quite close to this upper limit. We expect that this difference between the mobility of 2DEGs grown on the two substrate orientations will diminish, as the background purity of the system is increased.

In order to further study the normal interface (511)A sample, we used a gated Hall bar, as described earlier, where we deplete the 2DEG and measure mobility versus density in the low density limit. This is shown in Fig. 6, where the approximately linear dependence of μ on n is typical of Coulomb scattering. Note that a density as low as $1 \times 10^{10}\ \mathrm{cm^{-2}}$ is obtained while preserving a reasonably high mobility of $5 \times 10^5\ \mathrm{cm^{-2}\,V^{-1}\,s^{-1}}$. The plot shows data corresponding to current flow in the two principal orientations. The mobility is quite isotropic for most of the density range shown, but some anisotropy is found at the higher densities. This anisotropy has been associated in the past quite conclusively with anisotropic interface roughness topography [12].

We note, however, that the anisotropy in the (511)A sample is rather small; not only in comparison with the (100) sample in this study, but also with previous studies of (100) ISIS structures and, perhaps most interestingly, it is very small in comparison with the anisotropy measured on similar (311)A structures. This suggests that the growth of AlGaAs on the (511)A plane is qualitatively distinct from the (311)A plane, in that it does not exhibit the dramatic faceting and the anisotropic topography characteristic of (311)A growth [14].

In conventional 2DGs, placing the doping layer far from the channel generally leads to an improved mobility, particularly at low densities. Indeed, very low density 2DEGs with high mobility have been realized using spacers of order 300 nm in a normal interface structure [13]. 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*. Moreover, increasing the depth of the channel below the surface does not lead to any difficulty in the formation of Ohmic contacts, due to the absence of an AlGaAs barrier. A similar approach was used by Kane et al. [15] to achieve very low densities and excellent mobilities in 2DEGs and 2DHGs with normal (i.e. non-inverted) field-effect heterostructures grown on (100)GaAs; unfortunately, however, their structures require a rather delicate contacting scheme and do not support the option of additional patterned surface gates. The failure of the *n*-ISIS [grown on (100)GaAs] to achieve superior low density performance, despite having large spacers, has long been understood in terms of accumulation of unintentional impurities at the inverted interface [16]. However, as pointed out earlier, this detrimental effect is much weaker in (*N*11)A growth, thus allowing the advantage of the large spacers to fully express itself. Moreover, the high concentration of steps on the (*N*11)A surfaces ensures a high crystalline quality, particularly at the inverted interface.

4. Conclusion

In conclusion, we have investigated the behavior of a 2DHG and a 2DEG embedded in an inverted interface of GaAs/AlGaAs which is remotely spaced from any intentionally doped layer. The high mobility and extremely low densities achieved are probably associated with superior material properties as well as smooth interfaces. The study of normal interface 2DEG structures provides a further demonstration of the high potential of (511)A GaAs as an alternative platform for realizing high quality 2DEGs.

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