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Superior molecular beam epitaxy (MBE) growth on (*N* 1 1)A GaAs

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Abstract

The (3 1 1)A and (5 1 1)A planes of GaAs were used for the growth of high-quality two-dimensional hole gas (2DHG) and electron gas (2DEG) structures, respectively. A back-gated, inverted interface, AlGaAs/GaAs structure in which a 2DHG or a 2DEG was embedded was studied. This particular structure enabled the two-dimensional carrier concentration to be varied over two orders of magnitude in a single device, as well as the measurement of extremely low carrier densities in the mid 10^9 cm^{-2} range. The remarkably low carrier concentration we were able to achieve in both a 2DHG and a 2DEG opens new frontiers for the study of mesoscopic phenomena governed by Coulomb interactions between carriers, in particular, the possible existence of a Wigner crystal. © 1999 Elsevier Science B.V. All rights reserved.

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1. Introduction

(*N* 1 1) GaAs substrates tilted from the (1 0 0) towards the (1 1 1)A plane, are known to have several significant advantages over (1 0 0) oriented substrates for molecular beam epitaxy (MBE) [1–7]. The stepped nature of the tilted plane enhances a step flow growth mechanism which improves the surface morphology and reduces the number of crystalline defects. This is particularly important in growth of AlGaAs layers and GaAs/AlGaAs interfaces.

A key to the improved quality of layers grown on (*N* 1 1)A GaAs lies in the lower incorporation of impurities, in particular carbon [1,8]. This is due to the lower affinity of these surfaces, which is in turn associated with the less-reactive vacant single dangling bonds situated at the group III atom sites.

Finally, Si is invariably the n-type dopant used to produce 2DEGs on (1 0 0)GaAs. Nevertheless, it is an amphoteric impurity on (*N* 1 1)A GaAs where $N \leqslant 4$ [1]. It is well established that Si can be used

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either as a p-type or as an n-type dopant on (3 1 1)A GaAs [9–13]. The case of (4 1 1)A is more subtle in that Si is more difficult to control either as a p- or an n-type impurity [5], although it has been successfully used in growth of extremely flat hetero-interfaces of quantum wells [6]. Si turns out to be a very well behaved donor on (N 1 1)A where $N \geqslant 5$, and so the (5 1 1)A plane naturally suggests itself as the optimal plane for MBE growth of high-quality n-type GaAs devices [3].

A particularly versatile realization of a two-dimensional gas (2DG) is the inverted-semiconductor–insulator–semiconductor (ISIS) structure [14,15], where the carriers are accumulated in an undoped GaAs layer on *top* of an undoped AlGaAs barrier (thus 'inverted'), grown over a p^+ or n^+ conducting layer. In ISIS devices, the sheet carrier concentration can easily be modulated by the underlying conducting layer as well as by surface Schottky gates, thereby increasing the range of possible measurements.

In this work, we study ISIS structures grown on (3 1 1)A and (5 1 1)A oriented GaAs where a 2DHG and 2DEG is formed at the inverted interface, respectively. 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 establish the superiority of the growth of n-type structures on (5 1 1)A we also studied normal interface 2DEG structures.

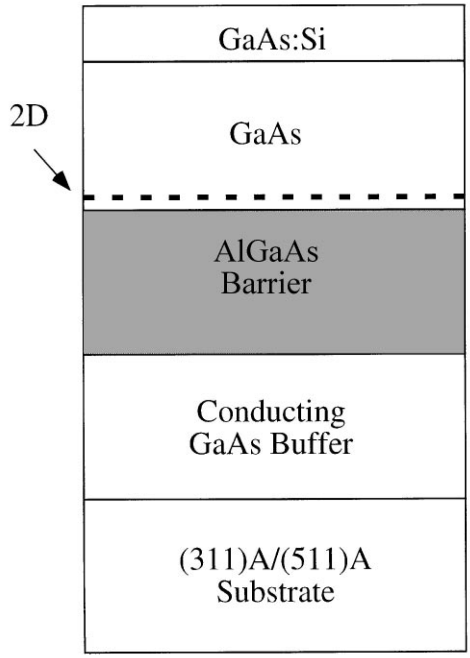

Fig. 1. Schematic representation of an ISIS grown on (N 1 1)A GaAs. The barrier is 300 and 200 nm, and the GaAs channel is 150 and 300 nm, for the p and n ISIS, respectively.

2. Experimental procedure

Fig. 1 shows a schematic layer profile of an inverted, back-gated GaAs/AlGaAs structure. A back-gate voltage, V_b, applied to the conductive buffer layer, is used for accumulating a variable density 2DG. The first layer grown is a conductive GaAs buffer. Next, the barrier is grown, 'AlAs' (explained below) and 50% AlGaAs for the p and n ISISs, respectively, followed by an undoped GaAs channel. 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 (3 1 1)A and (5 1 1)A semi-insulating epi-ready GaAs wafers oriented to within $\pm 0.1^{\circ}$ from the nominal respective plane. Si was used either as an acceptor or as a donor. The p-type structures were grown at $\sim 640^{\circ}C$. For the n-type structures the growth temperature was $640^{\circ}C$ and lowered to $530^{\circ}C$ at the final stages of growth. The As_4 to group III ratio was maintained at about 4 and 10 for the p and n-type activation, respectively. The growth rate of GaAs and AlAs was 0.6 and 0.35 μm/h, respectively.

The samples were patterned by standard lithography, wet etching and lift-off techniques to form Hall bars along the two principal, perpendicular directions. Ohmic contacts to the p-type or n-type structures were formed by evaporation of a 2%Zn/Au alloy and a Ni/Au/Ge/Ni/Au film, respectively, and then alloyed by rapid thermal annealing. The ohmic contacts were kept shallow in the ISISs to avoid punch-through into the conductive buffer. The carrier concentration and respective mobility were determined by standard magnetotransport measurements in a pumped helium flow cryostat.

3. 2DHG on (3 1 1)A

We first refer to the p-ISIS structure grown on (3 1 1)A GaAs. When $V_b = 0$, the in-plane conductance vanishes, as expected, since by design no 2DHG forms 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 s) at 1.6 K for the high-density range. The range of densities is quite remarkable, particularly since a stable and reproducible density as low as 5×10^9 could be measured in this structure. 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}.

We now compare the mobilities in the two perpendicular directions $[0\,1\,\bar{1}]$ and $[\bar{2}\,3\,3]$ of the (3 1 1)A plane, which we label μ_1 and μ_2, respectively. Fig. 3a 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. 3b 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. Such anisotropy is not present in the samples grown on (5 1 1)A.

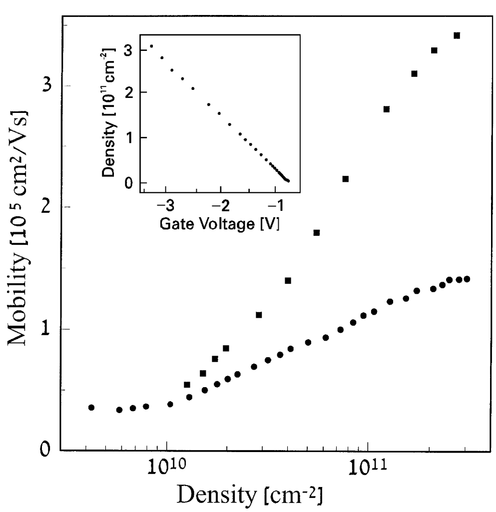

Fig. 2. Mobility of the 2DHG in a p-ISIS, plotted versus its density p. Data are shown for 6.2 (circles) and 1.6 K (squares). The inset shows, the variation of Hall density with V_b.

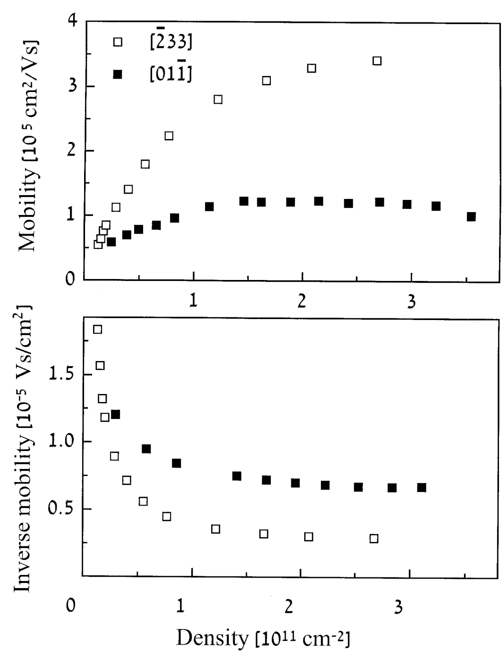

Fig. 3. The mobilities, μ_1 and μ_2 measured in Hall bars in the $[0\,1\,\bar{1}]$ and $[\bar{2}\,3\,3]$, directions of the (3 1 1)A plane, respectively. In the upper panel, μ_1 and μ_2 versus density. In the lower panel, the respective inverse quantities are plotted.

4. 2DEG on (5 1 1)A

In order to establish the superior transport properties of a 2DEG grown on (5 1 1)A GaAs we performed a comparative study of both inverted and normal interface structures grown on (5 1 1)A and (1 0 0) substrates. The mobility in all (5 1 1)A samples was significantly higher than in the analogous (1 0 0) structures. The superiority of the former was particularly pronounced for structures with large spacers and low 2DEG densities.

First we discuss the n-ISIS structure, on (5 1 1)A and on (1 0 0). Fig. 4 shows mobility versus density for two such ISIS samples. One can readily see the superiority of the (5 1 1)A sample, not only in that the mobility is substantially higher, but also in that much lower densities are experimentally accessible and measurable. It is interesting to note that the lowest electron density measured is about $4\times 10^9\ cm^{-2}$, which is comparable to the lowest density reported in a normal interface AlGaAs/GaAs structure [16], as well as the lowest densities of holes which we have achieved on (3 1 1)A substrates.

Next we turn to the normal 2DEG grown on (5 1 1)A and (1 0 0). Fig. 5 shows the evolution of mobility with increasing density for a conventional, normal 2DEG with a spacer of 100 nm for both orientations. The (5 1 1)A sample starts out with a higher density (before illumination), which is probably due to the lower concentration of unintentional acceptors. Furthermore, the mobility at $T = 1.5$ K is significantly higher at any given density, and the peak mobility of the (5 1 1)A structure exceeds $4\times 10^6\ cm^2/(V\ s)$. Note, that the maximum value ever obtained on (1 0 0) substrates in this particular MBE machine is only $3\times 10^6\ cm^2/(V\ s)$. Indeed, the peak mobility of the (1 0 0) sample, under illumination, is 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.

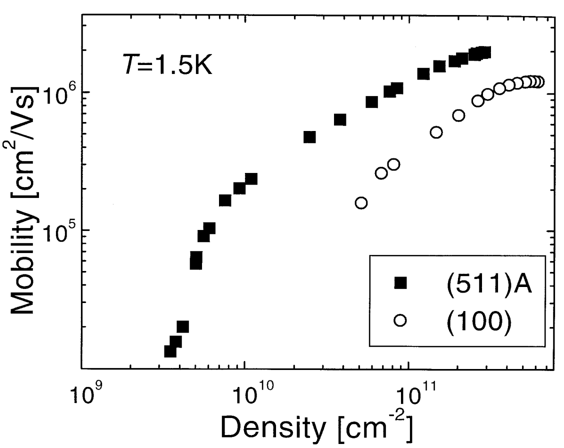

Fig. 4. Mobility of the 2DEG in n-ISIS structures grown on (5 1 1)A and (1 0 0), plotted versus density. The density is varied by means of a back-gate voltage.

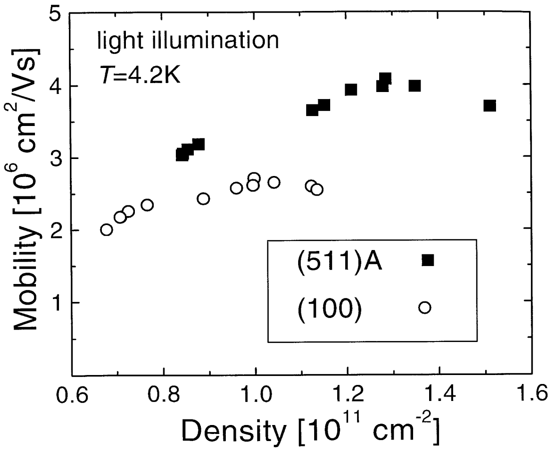

Fig. 5. Mobility of a normal 2DEG structure grown on (5 1 1)A and (1 0 0) plotted versus density. The density is varied by short pulses of illumination.

We associate these improved results with the fact that the 2DG forms at a rather large distance from any intentional doping, substantially larger than in typical modulation doped structures. Indeed, very low-density 2DEGs with high mobility have been realized using spacers of order 300 nm [16]. Moreover, a similar approach (to the ISIS) was used by Kane et al. [17] to achieve very low densities and excellent mobilities in 2DGs with normal (i.e. noninverted) field-effect heterostructures on (1 0 0) GaAs. Unfortunately, however, their structures required a rather delicate contacting scheme and did not support the option of additional patterned surface gates. The failure of the n-ISIS [grown on (1 0 0) 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 [18]. However, this detrimental effect is much weaker in (*N* 1 1)A growth, thus allowing the advantage of the large spacers to fully express itself. Furthermore, the stepflow growth mode typical of the (*N* 1 1)A surfaces is likely to enhance a smooth, high quality GaAs/AlGaAs interface, particularly in inverted structures.

5. Conclusions

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, low background impurities as well as smooth interfaces. The comparative study of normal and inverted 2DEG structures grown on (5 1 1)A and (1 0 0) GaAs demonstrates the high potential of (5 1 1)A GaAs as an alternative platform for realizing high quality 2DEGs.

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