



Transport properties of a two-dimensional-hole gas with density varied over a very wide range

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Abstract

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 $5 \times 10^{11} \text{ cm}^{-2}$, thus achieving the lowest density of a 2DHG reported to date. The mobility of the 2DHG is highly anisotropic in the (311)A plane. We observe a cross-over from a metallic behavior at the higher densities to a localized behavior in the lower range. © 1998 Elsevier Science B.V. All rights reserved.

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In this work, we study semiconductor–insulator–semiconductor structure (ISIS) [1] grown on (311)A oriented GaAs substrates where a 2DHG is accumulated in an undoped GaAs layer on *top* of an undoped AlGaAs barrier. This 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 a high quality, low density 2DHG.

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 incorporation of background impurities which tend to move 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

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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.

Fig. 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 $\pm 0.1^\circ$, using Si as the p-type dopant. The details of the growth and the device preparation can be found elsewhere [6].

The 2DHG density can be measured via the Hall effect 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 $\text{cm}^2/\text{V s}$ 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, corresponding to a typical distance between holes of 140 nm, almost two orders of magnitude above the Bohr radius.

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. 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

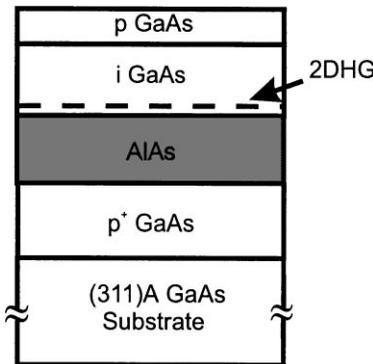


Fig. 1. Schematic presentation of the p-ISIS structure grown on semi-insulating (311)A GaAs substrate. The 2DHG forms at the lower (inverted) interface of the channel layer upon application of a negative bias to the buffer.

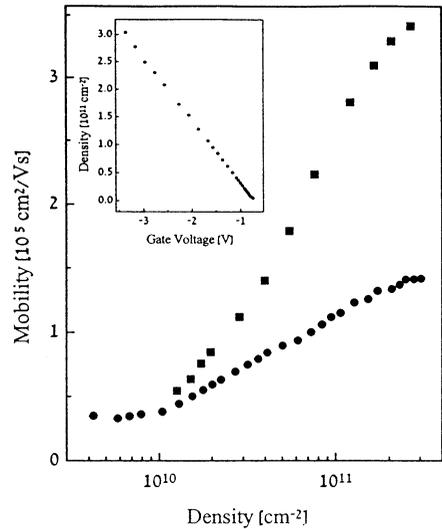


Fig. 2. Mobility of the 2DHG in the $[\bar{2}33]$ direction plotted versus its density p , the latter varied by means of the back gate voltage V_b . The density scale is logarithmic so as to show the wide range involved. Data are shown for 6.2 K (●) and 1.6 K (■). The inset shows, on a linear scale,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

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 mobility 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. Theoretical [7] and experimental [8] works on this question indicate that significant anisotropy in the dispersion of the holes is found only at higher subbands or at relatively high wave vectors. Moreover, we recently investigated samples of normal 2DEG grown on (311)A GaAs and we observed a very similar behavior as seen in the inset of Fig. 3. The explanation one should therefore consider is the morphological anisotropy of the AlAs/GaAs interface [9–11]. Anisotropy in the form of facets could lead to a higher mobility along the $[\bar{2}33]$ direction in comparison to the $[01\bar{1}]$ direction, as we explain below.

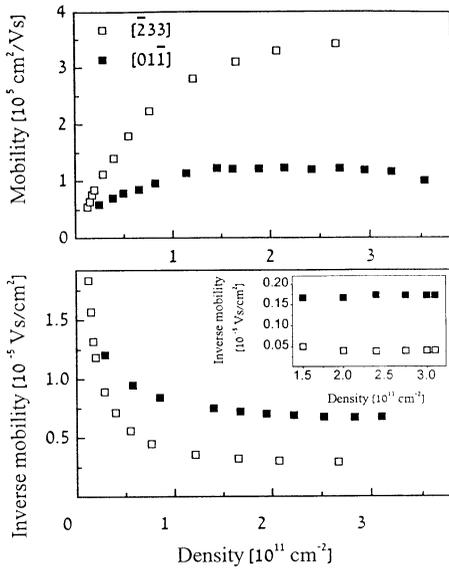


Fig. 3. The anisotropy of the conductance is studied by comparing mobilities μ_1 and μ_2 measured in Hall bars with different orientations [011] and [233], respectively, in the (311)A plane. In the lower panel we show the inverse quantities; note that the difference between the two is not strongly dependent on density. The inset shows the variation of the *electron* mobility with density for normal 2DEG structure, grown on (311)A, measured in Hall bars with different orientations [011] and [233].

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 [4,12] and hence should increase rapidly with increasing p . While at first glance the anisotropy of the mobility μ does indeed increase with p , Fig. 3b 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 [12] of IR and thus may require separate theoretical treatment.

As the density of a 2D system is decreased the Coulomb interaction energy dominates the kinetic energy. As a result, at sufficiently low densities the Fermi surface is not well defined, and the electron fluid will ultimately crystallize into an insulating electron lattice structure, known as the Wigner crystal. Usually, however, 2DEG systems undergo a preemptive Anderson metal–insulator (MI) transition due to disorder at densities well above the Wigner crystallization point. The realization of a Wigner crystal at zero magnetic field in a 2DEG in GaAs would require a phenomenally low density. However, due to the heavier mass of holes in GaAs ($0.6m_0$, $0.38m_0$), a 2DHG would undergo Wigner crystallization at more realistic densities of $n \sim 2.5 \times 10^{10}$ and $1 \times 10^{10} \text{ cm}^{-2}$ for the two mass values respectively [13]. In this sense the 2DHG is a good candidate for observing zero magnetic field Wigner crystallization.

To investigate the hole MI transition we mapped the temperature dependence of the resistance of the sample at low temperatures at various densities. We observe a transition from a metallic behavior at high densities to an insulating behavior for densities below $\sim 2.5 \times 10^{10} \text{ cm}^{-2}$ as seen in Fig. 4. The temperature dependence in the insulating limit, seen in Fig. 5, does not agree with hopping conductance of an Anderson insulator nor does it correspond to thermally activated conductance of a pinned Wigner crystal. A possible model is the disordered electron crystal as was suggested recently by Wulf et al. [14], which is also in agreement with the results presented by Goldman et al. for a 2DEG in a high magnetic field [15]. However, we feel that the present data is insufficient to determine the physical mechanisms involved. Nevertheless, by studying the details of the transition, and

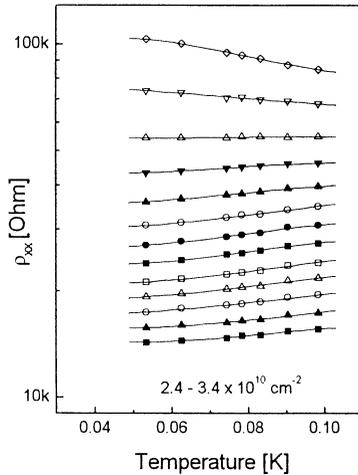


Fig. 4. The sheet resistivity of the sample plotted versus temperature for densities higher than $\sim 2.4 \times 10^{10} \text{ cm}^{-2}$. Symbols correspond to different densities.

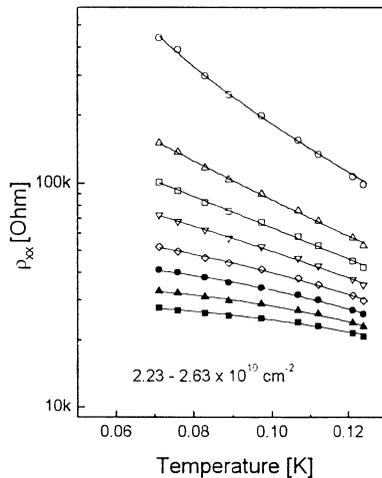


Fig. 5. The sheet resistivity of the sample plotted versus temperature for densities lower than $\sim 2.6 \times 10^{10} \text{ cm}^{-2}$. Symbols correspond to different densities.

comparing among samples with different structure and disorder we hope eventually to be able to determine whether the phenomenon is associated with single particle localization or with a collective behavior of the holes in the system.

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. The transport results show a crossover from metallic to insulating behavior, the details of which are currently under study.

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