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

Y. Hanein, Hadas Shtrikman, and U. Meirav

Braun Center for Submicron Research, Weizmann Institute of Science, Rehovot 76100, Israel

(Received 4 October 1996; accepted for publication 8 January 1997)

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 $5 \times 10^8$ and $5 \times 10^{11}$ cm$^{-2}$. The mobility of the 2DHG is highly anisotropic in the (311)A plane.

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 be easily 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 GaAs 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 undoped AlAs barrier, a 150 nm undoped GaAs channel layer, and a top $p^+$ GaAs buffer.

![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.](image)

$^a$Electronic mail: hmeirav@wis.weizmann.ac.il
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. However, a 2DHG is readily accumulated by applying a negative voltage \( V_b \) to the interface of the latter. An additional layer of p-doped GaAs channel layer. The 2DHG forms near the lower interface. It is not clear whether the former can account for the anisotropic component in the resistance is only weakly dependent on the hole density. 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 theoretical14 and experimental15 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 [233] 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
mobility along the $\{\overline{233}\}$ direction in comparison to the $[01\overline{1}]$ 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, 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 and hence should increase rapidly with increasing $p$. While at first glance the anisotropy of the mobility $\mu$ does indeed increase with $p$, Fig. 3(b) shows that a significant anisotropic term persists down to rather low $p$ and, in general, $(\mu_2)^{-1} - (\mu_1)^{-1}$ 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 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.

The authors wish to acknowledge useful discussions with M. Heiblum. This work was supported by a grant from the Israeli Ministry of Science and The Arts.