High mobility of a three-dimensional hole gas in parabolic quantum wells grown on GaAs(311)A substrates

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The transport properties of a three-dimensional hole gas were investigated in wide parabolic quantum wells grown by molecular beam epitaxy on top of GaAs(311)A substrates. The *p*-type doping was performed using silicon and the parabolic potential was achieved with the digital-alloy technique. Hall-effect and Shubnikov–de Haas measurements carried out at low temperature revealed that the carrier mobility was more than twice higher than the one usually obtained from similar samples grown on GaAs(100) substrates using beryllium. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1888041]

The growth of $Al_xGa_{1-x}As$–GaAs parabolic quantum wells (PQWs) has already received some attention in the past years due to the possibility to produce a three-dimensional (3D) gas of carriers with a high mobility. When a square well is remotely doped (i.e., the dopant is located in the barrier), the carriers are usually transferred to the well and accumulate at the interface as a result of their Coulombic interactions with the ionized impurities that remained in the barrier, thus yielding the creation of a two-dimensional (2D) electron gas. When a specific concentration of carriers is transferred from the barrier to a parabolic well, the charge potential almost cancels the compositional parabolic potential and the net result is a gas within an approximately flat (square) potential that behaves as a quasithree-dimensional gas with an enhanced mobility. This kind of samples already allowed the investigation of the optical and transport properties of 3D electron gases[1,2] and found applications in the generation of far-infrared electroluminescence.[3] However, until now, only a few works were dedicated to hole gases confined in parabolic potentials because their mobility is generally much lower. The major interest of such a *p*-type system lies in the fact that it is not completely analogous to the electron case: indeed, many-body effects are more pronounced in a hole gas as can be seen by the large dimensionless interelectron spacing (ratio between Coulomb and Fermi energies) which is close to 14 and 2 for the *p*- and *n*-type systems, respectively. In their pioneer work, Hopkins *et al.*[4] described the molecular-beam epitaxy (MBE) growth of a *p*-type PQW and observed Shubnikov–de Haas oscillations and quantized Hall plateaus in magnetotransport measurements. Burnett *et al.*[5] performed photoluminescence excitation spectroscopy experiments on the same kind of sample but did not carry out any detailed transport experiments. The samples analyzed in both works were grown on GaAs(100) substrates using beryllium (Be) as the *p*-type dopant. As is well known, Be has several drawbacks like large diffusion in the host material, low purity and clustering and segregation at high concentrations which can substantially decrease the gas mobility and consequently hide valuable properties of the hole gas in magnetotransport measurements. In order to improve the mobility and overall quality of PQWs containing a hole gas, it is thus essential to avoid the use of Be. A number of works already demonstrated that GaAs(311)A substrates are able to provide *p*-type structures of better quality than on GaAs(100) surfaces. First, it is possible to avoid the use of Be by exploiting the amphoteric behavior of silicon (Si) which acts as an acceptor in AlGaAs and GaAs layers deposited on GaAs(311)A substrates when a low V/III flux ratio is employed.[6] Furthermore, the (311)A surface leads to a reduced incorporation of impurities from the background atmosphere during growth (mainly carbon and sulphur)[7] which contributes to the increase in the mobility of the carriers. Similar crystalline quality can be obtained on both (100) and (311)A surfaces[8] but a better interface (smaller roughness) can be achieved on GaAs(311)A, especially during the growth of AlAs/GaAs superlattices, as a consequence of the presence of steps along the $[\bar{2}33]$ direction that induce a step-flow growth mode.

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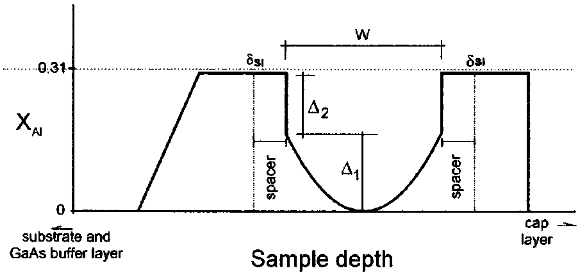

FIG. 1. Al composition (X_{Al}) profile of our samples along the growth direction. W is the well width, Δ_1 is the maximum Al content of the parabolic profile, and Δ_2 was used to increase the barrier height and is equal to 0.11 for the 1000-Å-thick PQW and to 0.04 for the other two samples.

In the present work, we report on the growth of high-mobility *p*-type PQWs obtained by the digital-alloy technique on GaAs(311)A substrates using Si as the dopant. Magnetotransport measurements carried out at low temperature showed well-resolved plateaus in the Hall resistance and hole mobilities exceeding 4.2×10^4 cm^2/V s for a hole concentration of 3.2×10^{11} cm^{-2} at 1.4 K.

All the samples were grown in a Gen II MBE system on top of epiready semi-insulating (311)A and (100) GaAs substrates mounted side by side on molybdenum blocks. Since Si was used as the dopant, the structures grown on GaAs(100) always yielded an *n*-type character and were used as a reference because the properties of electron gases in PQWs are already well known. In order to achieve a *p*-type doping with Si on GaAs(311)A, we used a substrate temperature of 580 °C and an $As_4/(Ga+Al)$ flux ratio as low as possible (≈ 1.2) but still consistent with a good epilayer morphology. The structure of the AlGaAs PQWs is shown in Fig. 1. Three samples with different well widths (1000, 2000, and 3000 Å) were grown. First, a 1-μm-thick GaAs buffer was grown with a $20\times[(AlAs)_5(GaAs)_{10}]$ superlattice in the middle in order to improve the crystal purity and quality. Then, a 500-Å-thick AlGaAs layer was grown with the Al content varying linearly from 0% to 31% using the digital-alloy technique. The PQW was surrounded by two 500-Å-thick $Al_{0.31}Ga_{0.69}As$ barriers containing a Si spike symmetrically located at 150 Å from the border of the well. The nominal Si concentration was 5×10^{11} cm^{-2} for the 1000- and 2000-Å-wide wells and 1×10^{12} cm^{-2} for the 3000-Å-wide well. Inside the well, the parabolic potential profile was achieved by the digital-alloy technique using, as previously, a 20-Å-period superlattice in which the respective thickness of GaAs and AlAs were varied accordingly. This period is small enough to allow tunneling of the carriers through the thin AlAs layers and is much smaller than their de Broglie wavelength, leading locally to the intended average parabolic potential. The 500-Å-thick GaAs cap layer contained a third Si spike (2×10^{12} cm^{-2}) in the middle to saturate the surface-dangling bonds and to improve the quality of the electrical contacts. The Al and Ga deposition rates were 0.31 and 0.69 monolayer per second, respectively. After the growth, Hall bars were chemically etched and In/Zn or In contacts (for *p*-type or *n*-type samples) were alloyed at 400 °C during 180 s. The bars were oriented along both $[\bar{2}33]$ and $[01\bar{1}]$ directions of the (311)A substrates and along the [011] and $[01\bar{1}]$ directions of the (100) substrates.

Low-temperature transport measurements were carried out at 1.4 K in a superconducting magnet, and the carrier type as well as the values of the carrier concentration and mobility are shown in Table I. As expected, the specific growth conditions used here led to the formation of a hole gas in the samples grown on GaAs(311)A and of an electron gas in the samples simultaneously grown on GaAs(100). The low As flux and high substrate temperature allowed the Si atoms to occupy the As sites in the layers grown on GaAs(311)A, acting as acceptors. On the other hand, on GaAs(100), the Si atoms always incorporate into the Ga sites leading to *n*-type doped layers. In the (311)A case, we found a slight anisotropy between the measured hole mobilities along the $[\bar{2}33]$ and $[01\bar{1}]$ directions. This behavior was already reported in 2D hole gases[9] and is related to the structural corrugations occurring along the $[\bar{2}33]$ direction (direction of the steps on the (311)A surface) which is most probably responsible for the 20% reduction of the mobility along the $[01\bar{1}]$ direction in our samples. The mobility values along the $[\bar{2}33]$ direction (see Table I) range from 4.2×10^4 to 6.2×10^4 cm^2/V s and are at least twice larger than the values already reported in the literature for PQWs of the same thickness grown on GaAs(100) substrates using Be as the *p*-type dopant. Our mobility values for the *n*-type PQWs grown on GaAs(100) range from 1.01 to 1.18×10^5 cm^2/V s and are consistent with the data of the literature, showing no significant anisotropy.

It is worth noting that the ratio of the electron to hole mobility for the same well width (samples grown simultaneously) is always between 2 and 3 for all the PQWs. Considering that the mobility is given by $\mu=e\tau/m$, where τ is the carrier scattering time, m the effective mass, and e the electron charge, one would expect a hole mobility around five times lower than the electron mobility due to the fact that the hole mass is about five times larger than that of the electron. However, since the growth conditions employed here are known to provide good-quality layers on both sub-

TABLE I. Data obtained from the transport measurements carried out at 1.4 K after illumination of the samples. The data for the (311)A samples correspond to the $[\bar{2}33]$ direction.

Well width	1000 Å		2000 Å		3000 Å	
Substrate	(100)	(311)A	(100)	(311)A	(100)	(311)A
Carrier type	electrons	holes	electrons	holes	electrons	holes
Density (cm^{-2})	8.9×10^{11}	4.2×10^{11}	4.1×10^{11}	3.2×10^{11}	2.4×10^{11}	1.7×10^{11}
Mobility (cm^2/V s)	1.14×10^5	6.2×10^4	1.01×10^5	4.2×10^4	1.18×10^5	5.7×10^4

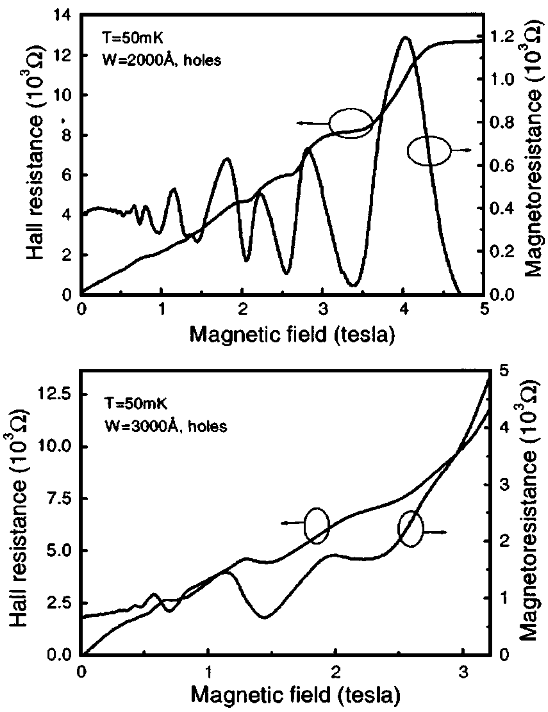

FIG. 2. Magnetoresistance (right axis) and Hall resistance (left axis) measurements carried out at 50 mK in the *p*-type samples containing a 2000-Å-wide (top) and 3000-Å-wide (bottom) PQW. The Hall bar was oriented along the $[\bar{2}33]$ direction and the magnetic field was applied perpendicularly to the sample.

strates, such a behavior is most probably related to the lower incorporation of impurities in the (311)A surface with respect to the (100) surface which contributes to the decrease in the carriers scattering by the background impurities. Indeed, previous works already reported the important role of the background impurities on the carriers scattering that seems to increase dramatically in PQWs when compared with conventional GaAs/AlGaAs heterostructures.[2]

Another interesting point is that the hole sheet density did not vary when the sample was illuminated with a red light-emitting diode, in contrast to what happens with *n*-type PQWs in which the electron density usually increases after illumination. This behavior was already observed in other works on 2D hole systems[10] and can be explained by the reduction of defects or impurities that might act as traps for holes in the epitaxial layers.

In order to gather more information about the quality of these samples, Hall-effect and magnetoresistance measurements were carried out at 50 mK in the mixing chamber of a top-loading dilution refrigerator. Figure 2 shows the results for the 2000- and 3000-Å-wide PQWs which had their hole-mobility values increased to 6.8×10^4 and 9.5×10^4 cm^2/V s, respectively. It is possible to observe well-defined quantized Hall plateaus and a number of Shubnikov–de Haas oscillations even at low magnetic fields. Further measurements on these samples are currently being held and will be published elsewhere. Notwithstanding, it is clear that the improved quality of these samples opens new perspectives in the study of transport properties of quasithree-dimensional hole gases.

As a conclusion, in this work we showed that GaAs(311)A substrates are an excellent choice for the growth of *p*-type GaAs/AlGaAs parabolic quantum wells using silicon as the dopant. The step-flow growth mode and lower impurities incorporation typical of the (311)A surface yielded a good crystalline quality and improved the hole mobility of the quasithree-dimensional hole gas, providing well-defined Hall plateaus and Shubnikov–de Haas oscillations in the magnetotransport measurements. We believe that this type of sample can bring unprecedented results about the transport properties of holes gases in parabolic potentials.

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