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The growth of high mobility heterostructures on (311)B GaAs

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We demonstrate that the (311)B surface of GaAs can be used for the fabrication of high mobility ($\mu \simeq 2.4 \times 10^6$ cm^2 V^{-1} s^{-1}) two-dimensional electron gases, in which the mobility is found to be anisotropic with $\mu_{[2\bar{3}3]} > \mu_{[01\bar{1}]}$. This paper reviews the magneto-transport properties of the (311)B system and sheds light on the nature of the scattering mechanisms determining the electron mobility. These results are of particular relevance to the current discussion of the nature of the {311} surface.

It is well known that a similar mobility anisotropy exists in hole gases grown on the (311)A surface, although attempts to interpret such results are complicated by the anisotropic and non-parabolic nature of the valence band structure. For electron gases grown on the (311)B surface we demonstrate experimentally (with ballistic focusing) that the Fermi surface is isotropic, leading to the conclusion that the most likely cause of the mobility anisotropy is anisotropic interface roughness scattering. This is also confirmed by measurements of mobility as a function of carrier density, which can be fitted by a simple interface roughness scattering theory.

Further experiments have demonstrated that ballistic quantization can be observed in both $[\bar{2}33]$ and $[01\bar{1}]$ directions, despite the large differences in anisotropic mobility.

1. Introduction

Most high mobility heterostructures grown by molecular beam epitaxy (MBE) have concentrated on the growth of GaAs/AlGaAs on (100) GaAs substrates, using silicon as a donor and beryllium as an acceptor. Recent results have shown that high mobility heterostructures can also be grown on the {311} surfaces of GaAs, in which silicon can act either as a donor or as an acceptor depending on the surface polarity and growth conditions [1, 2]. The mobilities of hole gas structures grown on the (311)A surface of GaAs were shown to be much higher than those obtained using beryllium as a p-type dopant on the (100) surface of GaAs [3]. Following this work, it was proposed by Wang *et al.* [4] that the {311} surface was ideal for the growth of heterostructures for two reasons: of all the surfaces, it had the highest number of step edge atoms which are believed to be less reactive, thus reducing the incorporation of defects; and, secondly, it maintains a step terrace kink growth

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mode, resulting in 2D growth and smooth interfaces. However, the chemical preparation of the {311} surfaces has not been as well characterized as that of the {100} surfaces and the exact nature of the surface structure prior to and during growth is not known.

At present there exists some controversy regarding the nature of the {311} surface structure [5–7]. Nötzel *et al.* [5] report that orientations with high surface energies, such as the {311} surface, break up into facets corresponding to planes with lower surface energy, thus forming distinct ordered surface structures on a nanometre scale. Using this unique reconstruction, they believe that it is possible to synthesize quantum wire structures *in situ* during epitaxial growth. However, other authors [6, 7] have reported that they do not observe this surface reconstruction, and, using TEM analysis, have shown that interfaces between GaAs and AlGaAs grown on the {311} surface are sharp and flat. It has been suggested by Wang *et al.* [6] that arsenic deficiency during growth is the most likely cause of the corrugations reported in the work of Nötzel *et al.* The anisotropy in the mobility of hole gases fabricated on the (311)A surface is, however, generally agreed upon [1, 8]. Attempts to analyse the cause of this anisotropy are convoluted by the complex nature of the valence band structure. It is not clear at this stage if the anisotropy in the mobility arises from the warped Fermi surface [9], corrugations in the {311} surface [5] or from a combination of the two mechanisms.

In this paper we investigate the nature of the {311} surface by looking at the transport properties of a two-dimensional electron gas grown on a (311)B surface. We have studied transport properties in the two orthogonal directions, namely the $[01\bar{1}]$ and $[\bar{2}33]$ directions. We find that there is a marked difference in the mobilities in the two directions at high carrier densities, and a simple theoretical model is introduced to account for this observation. Transverse magnetic focusing experiments confirm the isotropic nature of the conduction band, and measurements on quantum point contacts reveal that ballistic transport is observed in both orientations despite the anisotropy in the scattering times.

2. Experimental

The samples were grown on undoped (311)B oriented GaAs substrates in an Intevac Gen II solid source MBE machine at a growth temperature of 630°C as measured by an optical pyrometer. A GaAs growth rate of 1 μm/h was used and a minimum V/III ratio consistent with good epilayer morphology maintained during growth. Prior to loading in the MBE machine the epiready wafers were etched in a 50/50 HCl/H_2O solution for 1 min to reduce the oxide and were then indium mounted on molybdenum blocks. The growth sequence was as follows: a 1 μm thick undoped GaAs buffer, an undoped $Al_{0.33}Ga_{0.67}As$ spacer layer of thickness d(Å), a 400 Å thick layer of $Al_{0.33}Ga_{0.67}As$ doped at 9×10^{17} cm^{-3} and a 170 Å undoped GaAs cap. A series of samples with spacer thicknesses varying from 200 to 1600 Å were grown in close succession, the sequence chosen to avoid clean-up trends. Hall bars were fabricated using a wet chemical-etched mesa with AuGeNi alloy ohmic contacts annealed at 430°C for 80 s in a 5% H_2/N_2 gas mixture. Magnetotransport measurements were performed in pumped ^{4}He and ^{3}He cryostats using conventional AC lock-in techniques.

3. Results and discussion

Figure 1 shows the variation of the mobility and carrier density with spacer thickness measured at 1.7 K for samples grown at the same time on (100), (311)B and (311)A surfaces. It can be seen that, for all samples, there is a systematic reduction in all the carrier densities as the spacer thickness increases. The mobility of samples grown on the {311} surfaces seems to peak at a spacer thickness of 200 Å, compared to 400 Å for the n-type samples

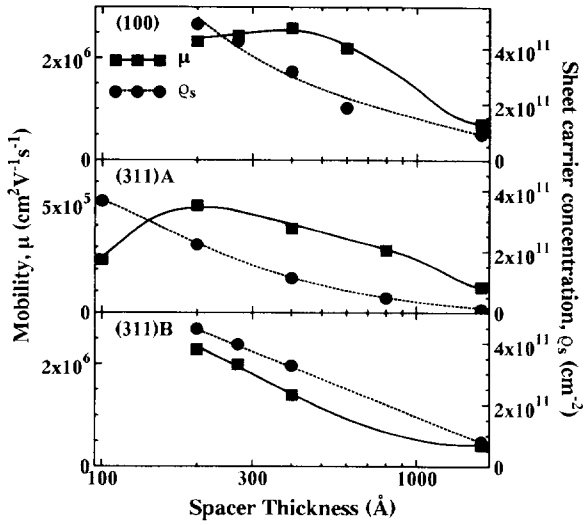

Fig. 1. Mobility and sheet carrier density as a function of spacer thickness for two-dimensional systems grown on the (100) surface of GaAs, the (311)A surface of GaAs and the (311)B surface of GaAs at 1.7 K. Note that the results for (100) and (311)B are after illumination with a red LED.

grown on the {100} surface. The carrier density of the (311)B electron gases was consistently lower than that achieved on the (100) electron gases, suggesting a higher degree of compensation on these surfaces, or indicating a smaller dopant incorporation on the (311)B surfaces.

Initial resistivity measurements indicated a marked anisotropy in the mobility in the two directions. Figure 2 shows a typical result of the magnetoresistance at 1.7 K in the two directions for a 200 Å spacer sample, after illumination with a red LED. It can be seen that, at a carrier density of $4.2 \times 10^{11}\,\mathrm{cm}^{-2}$, the mobility varies from $1.5 \times 10^{6}\,\mathrm{cm}^{-2}\,\mathrm{V}^{-1}\,\mathrm{s}$ in the $[01\bar{1}]$ direction to $2.4 \times 10^{6}\,\mathrm{cm}^{-2}\,\mathrm{V}^{-1}\,\mathrm{s}$ in the $[\bar{2}33]$ direction, a difference of ~40%. At high fields ($B > 0.4\,\mathrm{T}$) Shubnikov–de Haas oscillations are observed and are essentially identical in the two orthogonal directions.

We have studied the mobility anisotropy as a function of carrier density, utilizing a semi-transparent NiCr/Au surface Schottky gate. From this we were able to determine the transport lifetime as a function of carrier density, as shown in Fig. 3(a). It can be seen that at low carrier densities the transport lifetimes are independent of direction, but as the carrier density is increased above $3 \times 10^{11}\,\mathrm{cm}^{-2}$ anisotropy in the scattering times develops. Similar anisotropic scattering, increasing with carrier density, has been observed in 2DEGs grown on vicinal (100) GaAs surfaces, where a lateral superlattice is formed with 0.5 monolayers of AlAs placed at the edges of the terraces [10, 11].

In order to try and explain this observed anisotropy in our samples, a simple calculation similar to that performed by Noda *et al.* [11] was carried out to obtain the scattering time in orthogonal directions. A Fang–Howard wavefunction was assumed [12], the lifetimes being calculated at $T = 0\,\mathrm{K}$ assuming contributions from (i) remote ionized impurities and (ii) interface roughness. The interface roughness was defined by three

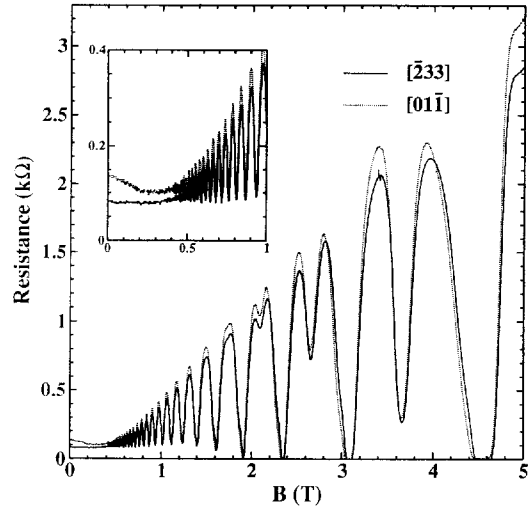

Fig. 2. Longitudinal resistance of a two-dimensional electron has grown on the (311)B surface of GaAs as a function of magnetic field in the $[01\bar{1}]$ and $[\bar{2}33]$ directions, at 1.7 K. Note the large anisotropy in the resistance, and hence the mobility, at zero magnetic field.

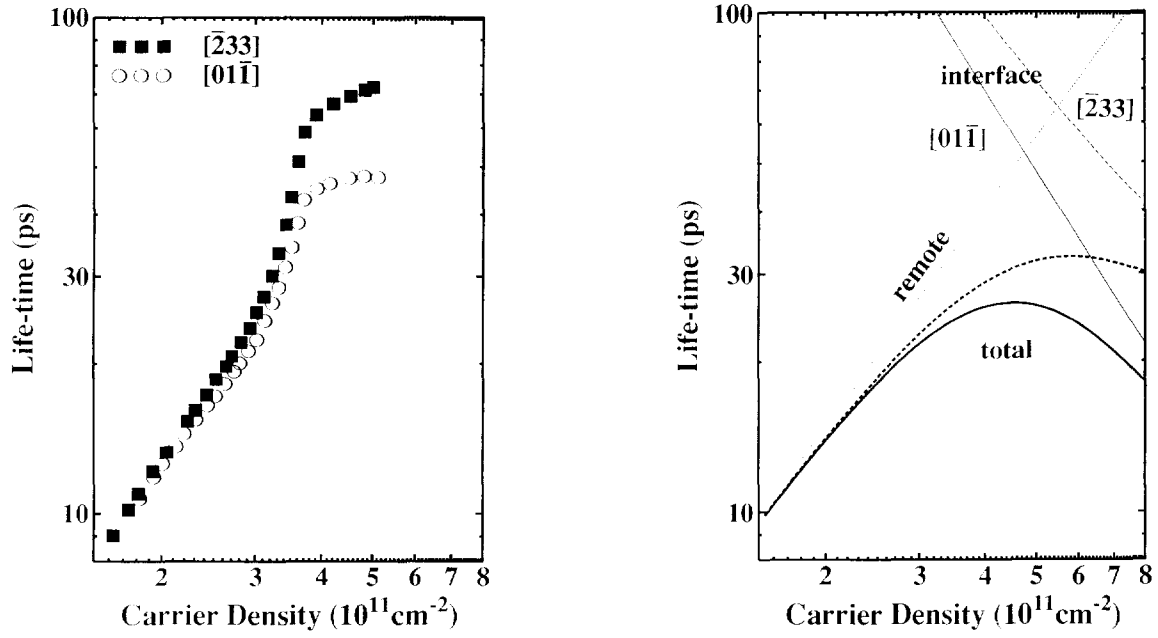

Fig. 3. (a) Transport lifetime for a (311)B 2DEG with a Schottky barrier surface gate for a range of carrier densities. The lifetimes were derived from zero magnetic field mobility values. (b) Calculated values of transport lifetimes as a function of carrier density.

parameters, the amplitude of the roughness and the two correlation lengths in the [01$\bar{1}$] and [$\bar{2}$33] directions. The results of these calculations (detailed in Ref. [2]) are presented in Fig. 3(b). At low carrier densities the lifetime is determined by the number of remote ionized impurities in the AlGaAs region. As the carrier density is increased, λ_{Fermi} decreases, and the scattering from remote ionized impurities becomes less important. At high carrier densities, the electrons are pressed against the heterointerface by the increased electric field, leading to an increase in the interface roughness scattering and a corresponding decrease in the scattering time.

In comparing the experimental and theoretical results we note that there is a slight discrepancy for carrier densities in the region of 3–4×10^{11} cm^{-2}. We think that this may be due to some of the remote ionized donors becoming neutralized as the gate voltage is varied; thus the experimental lifetime increases in this region more rapidly than the theory predicts. The parameters required to fit the data suggest that the surface roughness has a smaller period than that observed by Nötzel *et al.* [5]. However, whilst all samples grown on the (311)B surface did exhibit anisotropy in the mobility, there was no correlation between the magnitude of the anisotropy between similar samples grown at different points in the growth run. This indicates that the anisotropic interface roughness scattering is dependent on the precise growth parameters.

Heremans *et al.* [8] have observed similar anisotropic mobilities in hole gases on the (311)A orientation, as well as measuring the anisotropy of the Fermi surface [9]. Both of these observations they attribute to the corrugations along the

[$\bar{2}33$] direction of the {311} surface. In order to clarify the cause of the mobility anisotropy on (311)B surfaces, we have conducted focusing experiments similar to those of Heremans *et al.* [9]. A schematic of the device is shown in the insert of Fig. 4. The lithographic pattern (the solid parts in the figure) was defined with an electron beam in PMMA and subsequently etched with an H_2SO_4:H_2O_2:H_2O mixture to a depth of about 700 Å, thus defining a number of narrow constrictions of about 0.8 μm in width and 1 μm in separation. Using this design, the path of the electron orbit can be analysed as a function of the angle between adjacent constrictions. A ballistic cone of electrons is emitted from one of the constrictions and on application of a magnetic field this cone is bent round towards another constriction denoted the detector. The design of this particular device allows us to measure the diameter of the cyclotron orbit at five different cross-sections [13]. Typically, a current of 100 nA was passed from contacts A to G through a constriction (the emitter), and a voltage was detected across an adjacent constriction (the collector) at contacts B to H. All other voltage probes were grounded to prevent stray charging effects. A magnetic field was then applied to obtain the transverse magnetic focusing spectrum. As the field is increased, a series of oscillations across the voltage probes is observed. The first peak corresponds to a situation when the electron wavevector satisfies $\mathbf{k} = n\pi Be\mathbf{L}/h$, where $\mathbf{L}$ is the distance between the two adjacent constrictions. At higher fields, further peaks are observed, decaying in amplitude and corresponding to multiple skipping orbits along the length of the lithographically defined regions between the constriction, where $n = 2, 3, 4 \ldots$ etc. Finally, at higher fields, Shubnikov–de Haas oscillations are observed, which are used to calculate the carrier density of the sample (4.5×10^{11} cm^{-1}).

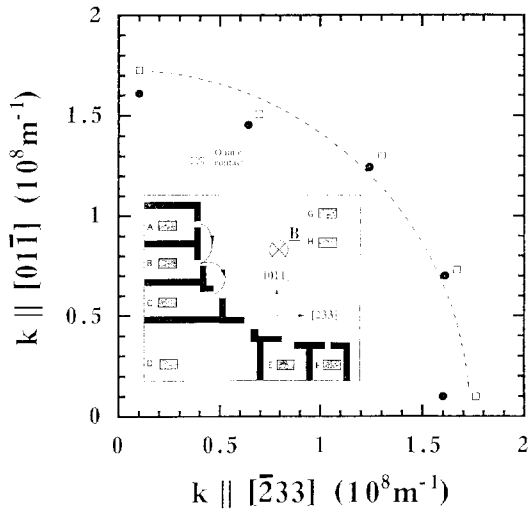

Fig. 4. Values of the electron wavevector are plotted as a function of different measurement angles for two different samples. A circle is plotted to indicate that the Fermi surface is isotropic. The insert shows a schematic representation of the device, showing the lithographically defined constrictions (the solid regions).

A plot of the wavevector $\mathbf{k}$ as a function of angle for two different samples from the same wafer is given in Fig. 4. Knowing the carrier density and assuming an isotropic effective mass, we calculate the Fermi wavevector to be $\mathbf{k} = 1.70 \times 10^8$ m^{-1}, as indicated by the dashed line on the figure. It can be seen that, to within experimental error, the electron wavevector lies on a circle, in contrast to the result obtained by Heremans *et al.* [9]. These results indicate that, whilst we observe anisotropy in the mobility, the wavevector, and therefore the electron effective mass, is isotropic. The anisotropic mobility is therefore purely due to an empirical scattering time and does not result from any anisotropy in the effective mass. The discrepancy between this work and that of Heremans *et al.* is not yet understood, although it should be noted that the (311)A valence band structure is expected to have some intrinsic anisotropy independently of any surface roughness effects [14].

Finally, quantum point contacts have been fabricated on both the [$\bar{2}$33] and the [01$\bar{1}$] directions of a 200 Å spacer sample grown on the (311)B surface of GaAs. E-beam lithography was

used to define a channel of length 0.2 μm and width 0.4 μm. Using a current of 10 nA and applying a negative voltage on the split gate, we defined a quasi-one-dimensional channel in both directions which showed up to 12 quantized conductance steps (Fig. 5). The sub-band energies at definition were found to be 2.9 ± 0.2 meV. The flatness of the quantized steps is an indication of the quality of the sample, whilst the absence of any resonant structures on the plateau indicates that the anisotropy in the scattering is not affecting the ballistic behaviour of these electrons.

In summary, we have demonstrated that the (311)B surface of GaAs can be used to fabricate high mobility heterostructure devices. We observe anisotropy in the mobility of 2D electron gases, similar to that observed in hole gases fabricated on (311)A GaAs. Transverse magnetic focusing experiments have proved that this anisotropy does not arise from any anisotropy in the Fermi surface, which was found to be isotropic. The anisotropy in the scattering times has been fitted by a simple theoretical model, in which interface roughness scattering was proved to be important at high carrier densities. Ballistic quantization has been shown to be unaffected by the anisotropy in the scattering, further clarifying the use of the {311} surface for high quality heterostructures.

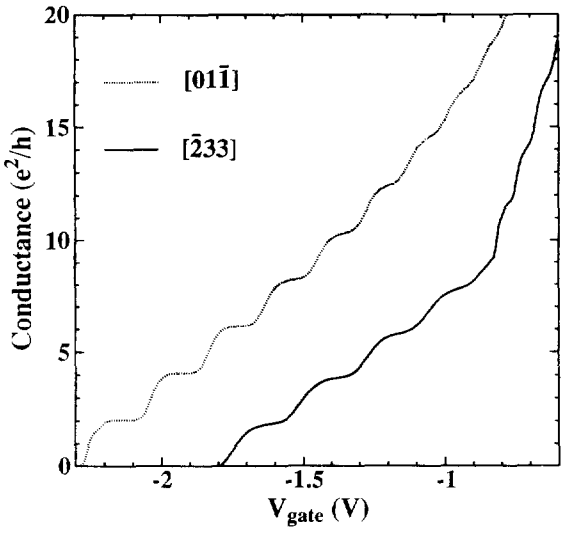

Fig. 5. The conductance of quantum point contacts fabricated on the [$\bar{2}$33] and [01$\bar{1}$] directions of a two-dimensional electron gas grown on the (311)B surface of GaAs, as a function of gate voltage.

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