High-temperature anisotropy of the conductivity of superlattices of GaAs quantum wires grown on faceted 311*A* surfaces

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Lateral superlattices of GaAs quantum wires, which have a strongly anisotropic p-type conductivity up to $T \approx 500$ K, can be grown on 311*A* surfaces. The temperature dependence of the conductivity, the Hall mobility, and the hole density in lateral superlattices of this type with a modulated doping have been studied experimentally. © *1994 American Institute of Physics.*

The possibility of fabricating high-quality structures with ultrasmall quantum wires was recently demonstrated.[1–3] The structures were grown by molecular beam epitaxy on 311*A* surfaces of GaAs substrates. The method is based on the capability of a 311*A* surface to split into a highly ordered array of microgrooves 10.2 Å deep with a period of 32 Å (Ref. 1). A faceted surface structure of this sort persists during homoepitaxial growth of GaAs or AlAs. During heteroepitaxial growth, the microgrooves become filled (e.g., an initial AlAs surface becomes filled), and then GaAs facets form. In other words, an array of GaAs wires forms (Fig. 1).

This method for fabricating quantum wires is attractive primarily because of the possibility of producing large-period lateral superlattices of quantum wires with extremely small diameters, ~20 Å , and thus with a pronounced separation of quantum states (>0.2 eV). This circumstance in turn raises the hope that it will become possible to study quantum effects at room temperature and also the hope that it will become possible to use these effects to fabricate quantum devices which work at high temperatures.

There are still many uncertainties regarding the fabrication and study of such complex structures. The uncertainties extend to the assertion that there is actually no splitting of a 311*A* surface into an array of microgrooves.[4] The p-type conductivity in the plane of the layers, in the direction parallel to the wires, $\sigma_{\parallel}$, which was measured in a modulation-doped lateral superlattice in a pioneering study[1] was greater than the conductivity in the perpendicular direction, $\sigma_{\perp}$, by a factor of only 1.3 at 77 K. Such a slight anisotropy of the conductivity at 77 K and the absence of an anisotropy at 300 K make it unclear whether quantum effects can be studied at high temperatures and whether high-temperature quantum devices can be fabricated from this material.

The epitaxial structures studied in the present experiments were grown by molecular beam epitaxy on semi-insulating GaAs substrates with the 311*A* orientation (disorientation $<15'$). The *A* and *B* surfaces were distinguished beforehand by a chemical method. The epitaxial growth was monitored *in situ* by measuring reflection high-energy electron

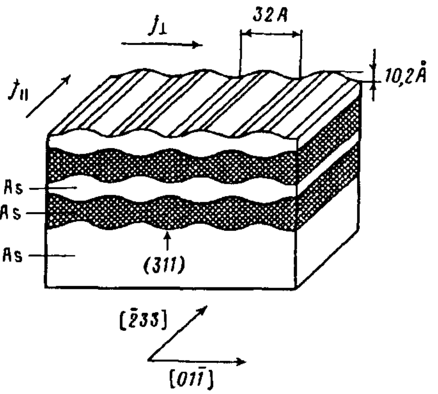

FIG. 1. Schematic cross section of a multilayer lateral 21 Å GaAs/27 Å AlAs superlattice grown on a 311*A* faceted surface.

diffraction patterns with the help of a 20-keV electron beam. A series of Be-modulation-doped multilayer lateral structures containing 75 periods of alternating layers of GaAs quantum wires and AlAs barriers were grown. The structures were grown on identical substrates, with identical thicknesses of the undoped AlAs barriers, and with Be-doped AlAs layers of identical thicknesses, doped under identical conditions. The average thickness of the undoped AlAs layers was 27 Å . The average thickness of the GaAs layers varied systematically from structure to structure in the range 21–8 Å.

In contrast with Ref. 4, we observed some clearly defined features in the evolution of the intensity of the diffraction reflections during the heteroepitaxial growth. This result is evidence of a splitting of the 311*A* surface into an array of microgrooves. It can be seen from Fig. 2 that the change in the intensity after the opening of the Ga slide gate and the subsequent return of the intensity toward the initial state correspond, with allowance for the growth rate, to the deposition on the 311*A* surface of, on the average, six {311} monolayers of material, i.e., 10.2 Å , in confirmation of the results of Ref. 1. The same change in intensity is observed during the opening of the Al slide gate. In our case, in contrast with Ref. 1, we observe a change in the phase of the oscillations during the heteroepitaxial growth of GaAs on AlAs and, vice versa, of AlAs on GaAs. This difference may be due to the choice of diffraction conditions. Cycles associated with a change in the phase of the 311*A* surface during the heteroepitaxial growth were observed in these

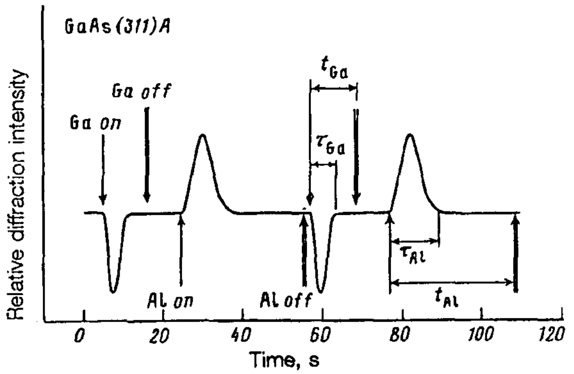

FIG. 2. Intensity evolution of the specular reflection in the high-energy electron diffraction pattern recorded for a direction near the [$\bar{2}$33] azimuthal direction during the growth of a 21 Å GaAs/27 Å AlAs lateral superstructure on a 311*A* substrate. Growth rate: $r_{Ga}=1.0$ μm/h, $r_{Al}=0.315$ μm/h. Average layer thicknesses: $\tau_{Ga}\cdot r_{Ga}=\tau_{Al}\cdot r_{Al}=10.2$ Å, $t_{Ga}r_{Ga}=21$ Å ; $t_{Al}r_{Al}=27$ Å.

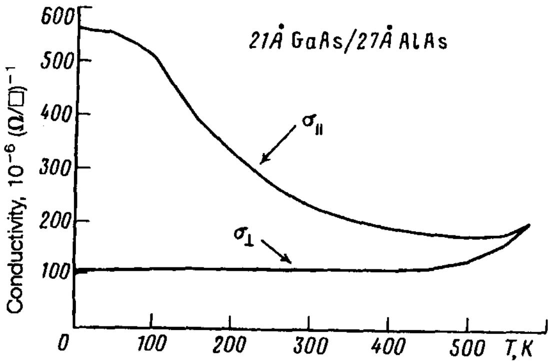

FIG. 3. Temperature dependence of the conductivity of a Be-modulation-doped 21 Å GaAs/27 Å AlAs lateral superlattice measured in directions parallel and perpendicular to the quantum wires.

experiments over the broad temperature range from 350 to 640°C. The results in Fig. 2 thus confirm the data of Ref. 1 and imply the formation of an array of quantum wires or lateral superlattices. We observed a clearer dependence which was seen over a wider temperature range.

Figure 3 shows the results of measurements of the temperature dependence of the p-type conductivity of a multilayer lateral superlattice with an average GaAs-layer thickness of 21 Å and an average AlAs-layer thickness of 27 Å . The structure contains three Be-doped AlAs layers 250 Å thick separated from the lateral superlattice by 50-Å spacers. It can be seen clearly from Fig. 3 that the ratio of the conductivities along the wires and in the direction perpendicular to them changes greatly as the temperature T is raised from 4.2 to 500 K. It is 5.5 at 77 K, 2.3 at 300 K, and 1.3 at 500 K. This is much larger than the conductivity anisotropy observed in Ref. 1. Another interesting fact is that the conductivities differ in temperature dependence. It can be seen from Fig. 1 that the conductivity in the plane of the layers, in the direction parallel to the wires, increases with decreasing temperature, and the conductivity in the direction perpendicular to them is essentially independent of the temperature. To find information on the lateral transport of holes in such a structure we measured the Hall mobility and the hole density over the temperature range 4.2–300 K. These measurements were carried out on samples with a Hall-bridge geometry with separate potential and current leads. In some samples, the current direction was the same as the direction of the wires, while in other samples the current was perpendicular to the wires. The results of the measurements show that there is a strong anisotropy of the Hall mobility: As the temperature is lowered from 300 K to 4.2 K, the mobility of the holes along the wires increases from 150 to 1000 $cm^2/(V\cdot s)$, passing through a maximum at 77 K [1300 $cm^2/(V\cdot s)$], while the mobility in the direction perpendicular to the wires is small [200 $cm^2/(V\cdot s)$ at 4.2 K] and is a weaker function of the temperature. The relatively high mobility along the wires with a diameter ~30 Å is evidence that the GaAs/AlAs heterojunctions are of good quality.[5] At an average GaAs thickness of 21 Å , the wide GaAs regions have a size of 31 Å , and the narrow ones a size of 10 Å . The low mobility of the holes in the transverse direction and the nature of its temperature dependence may be evidence that the hole transport in the transverse direction is governed by either a tunneling of holes [6,7] between wires or a strong scattering of holes by the rough boundaries [5] of the narrow 10-Å GaAs regions connecting the wires. Evidence in favor of the first suggestion comes from results found on lateral superlattices containing thinner GaAs layers (the average thickness of the layers was 14 Å). In these structures, the narrow GaAs regions connecting the wires have a size ~3 Å . The qualitative behavior of the conductivities $\sigma_{\parallel}$ and $\sigma_{\perp}$ in the sample is qualitatively the same as in the preceding sample, but there is an increase in the conductivity anisotropy at room temperature. The concentration of holes found from the Hall measurements is independent of the orientation of the sample and agrees with the layer concentration found from measurements of a $C-V$ profile.

These results reflect the unique nature of this quantum entity: the presence of a fairly strong localization of holes in the case of thin AlAs barrier layers, which, however, create a high potential barrier of 0.55 eV (Ref. 8) and deep quantum levels (thin minibands). At a quantum-well thickness of 20 Å , the energy ground level is only 0.1 eV away from the bottom of the valence band.[8] The probability for tunneling of heavy-mass holes is low.

The measurements of the anisotropy of the p-type conductivity which we have reported here are evidence that structures containing lateral superlattices of quantum wires grown on 311*A* surfaces hold promise for fabricating high-temperature quantum electronic devices. We note in conclusion that producing high-quality quantum wires requires, in addition to a small diameter, without additional layers, a special optimization of the growth conditions. The structures we grew with average GaAs thicknesses of 10 and 8 Å have a much lower anisotropy and a low mobility, indicating a growth of wire-like clusters.[9]

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