Molecular-beam epitaxial growth and surface characterization of GaAs(311)B

Z. M. Wang,[a] L. Däweritz,[b] and K. H. Ploog
Paul-Drude-Institut für Festkörperelektronik, Hausvogteiplatz 5-7, D-10117 Berlin, Germany

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Reflection high-energy electron diffraction (RHEED) and scanning tunneling microscopy (STM) are used to study the surface and growth of GaAs (311)B. The RHEED pattern reveals a lateral periodicity of 3.2 nm along the $[01\bar{1}]$ direction, which is confirmed in real space by STM images. Pronounced RHEED intensity oscillations during the homoepitaxial growth on GaAs(311)B were observed in a wide substrate temperature range. © *2001 American Institute of Physics.*
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New electronic properties, such as the piezoelectric effect[1] and the amphoteric incorporation of Si dopant,[2,3] have been introduced by the growth of GaAs on substrates with orientations other than [100]. Among them, the (311)B plane located halfway between (100) and (111)B surfaces provides one of the most exciting templates for the growth of low-dimensional nanostructures. Very uniform nanostructures with high lateral confinement have been reported for metal-organic vapor phase epitaxy (MOVPE)[4] and molecular beam epitaxy (MBE)[5–8] of strained (In,Ga)As epilayers on GaAs(311)B substrates, which show considerably improved optical properties compared to that of similar samples grown on (100) surfaces. The high-quality growth of heterostructures suggests that the starting GaAs(311)B surface is smooth and stable. However, the available studies of the (311)B template itself show that the GaAs(311)B surface under MBE conditions is unstable and breaks up into facets.[9,10] In the light of this pronounced discrepancy, we have studied the growth and surface structures of GaAs(311)B using reflection high-energy electron diffraction (RHEED) and scanning tunneling microscopy (STM).

The experiments are carried out in a combined ultrahigh vacuum (UHV) MBE and STM system. The MBE growth chamber equipped with RHEED (operated at 15 kV) is connected to the STM chamber via a gate valve. Epiready *n*-type GaAs substrates with both sides polished were used for comparative studies of (311)A and (311)B surfaces. The (311)A surface shows at appropriate growth conditions the well developed (8×1) reconstruction following the notation for a rectangular surface unit cell.[11,12] In this work, we restrict ourselves to the (311)B surface. Various samples were fabricated at different growth conditions and all showed surface structures with similar characteristics. The samples of approximately 10×10 mm^2 area were indium mounted and outgassed in vacuum at 300 °C, and then transferred to the growth chamber where they were heated to remove the native oxide. The oxide desorption temperature of 580 °C was used as calibration for further temperature measurements. In this study a valved As_4 source is used. The Ga and also As flux were calibrated for growth on a GaAs(100) substrate using RHEED intensity oscillations.[13] Therefore, in our definition an As:Ga ratio of 1:1 means that two Ga atoms arrive for each incident As_4 molecule since the As_4 molecule contributes two As atoms which can be incorporated.[14] The corresponding conventional As_4-to-Ga beam equivalent pressure (BEP) ratio is about 8.4 for the As:Ga ratio of 1:1 in our definition.

Figure 1 shows the RHEED pattern after deposition of the buffer layer of about 100 nm at a substrate temperature of 550°C and an As flux of 6.0×10^{14} atoms cm^{-2} s^{-1} (the As_4 beam equivalent pressure is 6.1×10^{-6} torr) taken in the $[\bar{2}33]$ and $[01\bar{1}]$ azimuths. The patterns clearly evidence a well ordered surface reconstruction and are basically the

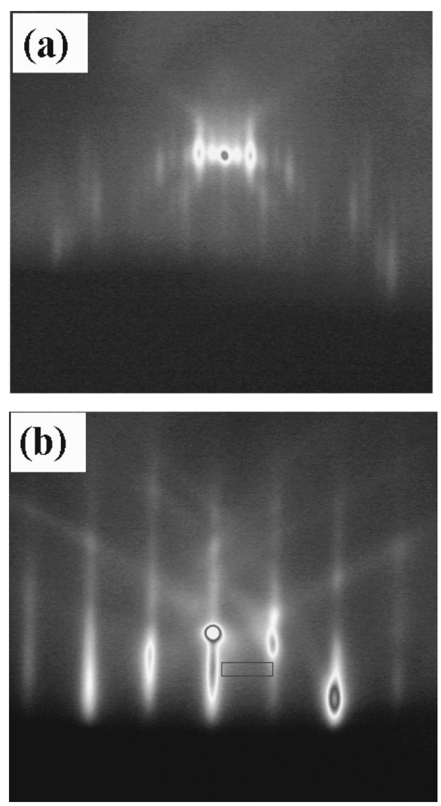

FIG. 1. RHEED patterns of the GaAs(311)B surface recorded (a) along the $[\bar{2}33]$ and (b) along the $[01\bar{1}]$ azimuth.

[a] Present address: Department of Physics, University of Arkansas, Fayetteville, AR 72701
[b] Electronic mail: daweritz@pdi-berlin.de

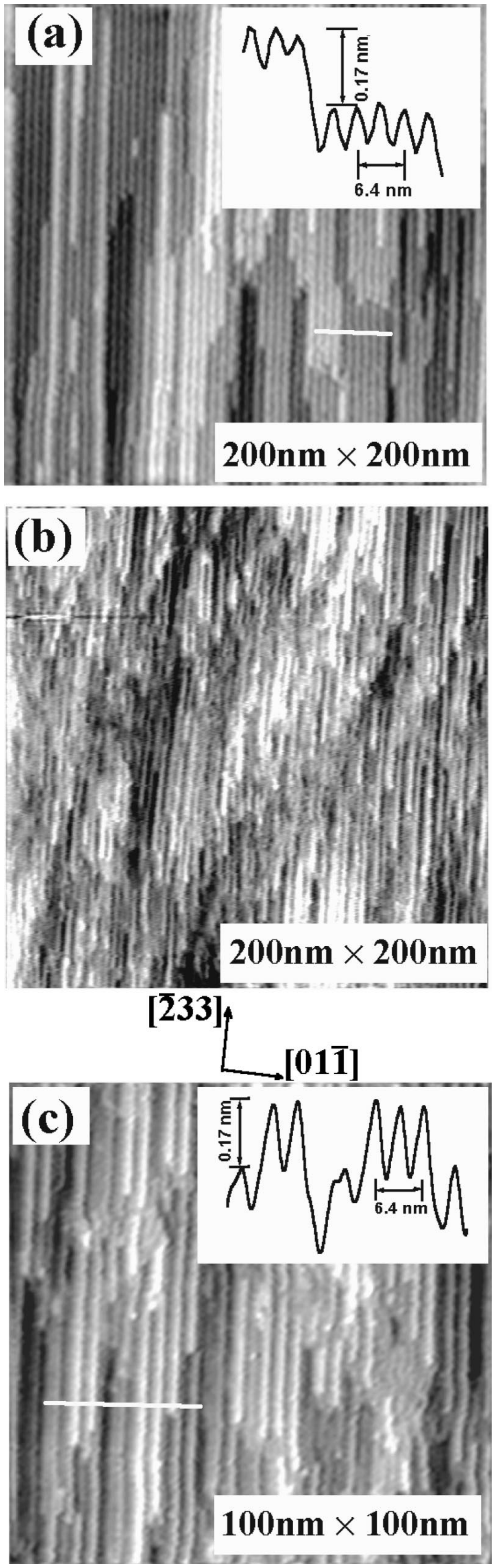

FIG. 2. STM images of the GaAs(311) surface in different magnifications. (a) GaAs(311)A, (b) and (c) GaAs(311)B. The insets (a) and (c) show the height modulation along the marked lines.

same as observed for the GaAs(311)A surface.[11,12] This is the first experimental evidence that the (311)B surface develops a stable (8×1) reconstruction which is analogous to that of the (311)A surface, i.e., the surface phase is characterized by a 3.2 nm periodicity along $[01\bar{1}]$. The observation is in

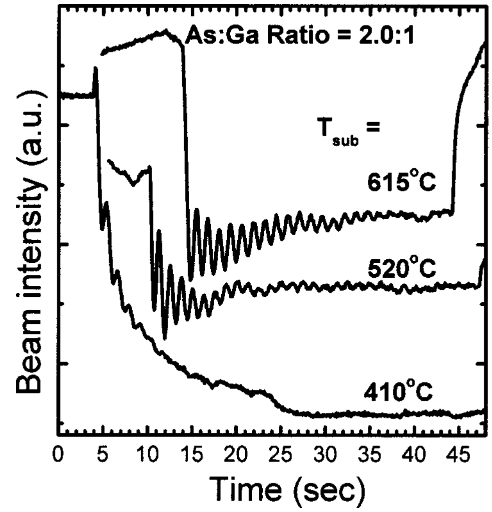

FIG. 3. Temperature dependence of RHEED intensity oscillations of the GaAs (311)B homoepitaxial growth with a Ga flux of 0.78 ML/s.

sharp contradiction to that of other authors from low-energy electron diffraction (LEED) and photoelectron spectroscopy studies resulting in the statement that the GaAs(311)B surface is not stable and does not show any superstructure even after preparation by MBE.[10] Theoretical investigations for GaAs(311)B by Platen *et al.*[15] do not consider a superstructure. Our STM experiments, however, confirm the results obtained by RHEED.

For the corresponding studies, the (8×1) reconstructed surface is cooled down by decreasing both the substrate temperature and the As flux while keeping the RHEED pattern unchanged. After closing the valve of the arsenic source at a substrate temperature of 450 °C, the sample is transferred to the STM chamber without breaking the UHV condition. Filled states STM images were collected at sample voltages of 2–4 V and tunneling currents of 0.1–0.4 nA. The surface morphology shown in Fig. 2(b) is comparable with the result obtained from GaAs(311)A shown in Fig. 2(a), but the rows running along $[\bar{2}33]$ are less ordered. The different ordering degree of the (8×1) reconstructions indicates that the kink formation energy for GaAs(311)B is lower than that for GaAs(311)A, but the increased disorder on GaAs(311)B may also partly result from the surface cooling down process. The temperature range in which a stable (8×1) reconstruction observed is more limited for GaAs(311)B than for GaAs(311)A. The line scan in the inset of Fig. 2(c) reveals that the lateral spacing of the rows is about 3.2 nm as calculated from the RHEED pattern. Moreover, the surface step height of the GaAs (311)B surface is determined to be 0.17 nm, similar to the result obtained for GaAs(311)A [Fig. 2(a)]. Therefore, the step height of the GaAs(311)B surface amounts obviously to one monolayer (ML). The line scan of Fig. 2(c) reveals a surface corrugation of one ML height for GaAs(311)B, but this result needs further confirmation by atomically resolved images. The height corrugation observed by STM depends on the tip sharpness and scanning parameters. The corrugation measured for the GaAs(311)A surface in Fig. 2(a) is much smaller than the real value of 0.34 nm demonstrated in former high resolution STM studies.[12]

RHEED intensity oscillations recorded during GaAs growth with an As:Ga ratio of 2:1 and at substrate tempera-

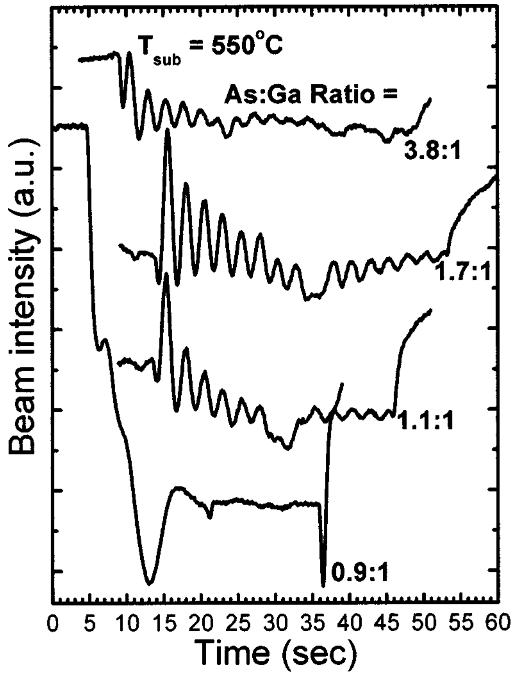

FIG. 4. RHEED intensity oscillations of the GaAs (311)B homoepitaxial growth for several As:Ga flux ratios at a fixed substrate temperature of 550 °C with a Ga flux of 0.40 ML/s.

tures of 615, 520, and 410 °C are shown in Fig. 3. The results presented in this study were obtained with the electron beam incident along the [$\bar{2}33$] azimuth, though oscillations have also been observed in other azimuths. The fractional-order RHEED features due to the surface corrugation disappear above 600 °C and below 450 °C, and the corresponding surfaces will be denoted as Ga(1×1) and As(1×1), respectively, in the following. The growth rate obtained from the oscillation periods is consistent with the results on (100) surfaces when considering the difference in surface atom density. It is important to note that the growth rate is independent on the substrate temperature for the wide range from 350 to 620 °C. A decrease of the growth rate is only observed at temperatures higher than 620 °C where Ga desorption starts, similar as reported for the GaAs(100) surface.[16] The RHEED intensity evolution for GaAs growth on the As (1×1) reconstructed surface in Fig. 3 shows that an intensity overshoot occurs when the Ga shutter is opened. A similar effect has been observed for GaAs(100) when the initial surface is $c(4\times4)$-reconstructed.[17,18] This result indicates that the As(1×1) reconstruction of GaAs(311)B may be an As adsorption structure.

Figure 4 shows the RHEED intensity oscillations for the substrate temperature fixed at 550 °C and a varying As:Ga ratio. While pronounced oscillations are observed at arsenic-rich conditions, a small amount of excess Ga results in three-dimensional growth indicated by the evolution of the RHEED pattern and a very fast damping of the oscillations. Relatively good RHEED intensity oscillations are still observed on GaAs(100) surfaces at similar Ga-rich conditions (this is in fact used to deduce the arsenic flux value). Further studies are needed to understand this difference between (100) and (311)B surfaces.

In summary, a surface characterized by a height modulation along [$\bar{2}33$] with a lateral periodicity of 3.2 nm is observed on GaAs(311)B by RHEED investigations and further confirmed by STM studies. Strong RHEED intensity oscillations during GaAs growth on GaAs(311)B are observed in a wide range of substrate temperatures and As:Ga flux ratios. This high index surface can thus be considered as a good template for further growth of strained nanostructures.

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