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Surface dynamics during molecular-beam epitaxy of (In,Ga)As on GaAs(331)*B*: Formation of quantum wires with low In content

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$In_{0.2}Ga_{0.8}As$ molecular-beam heteroepitaxial growth on GaAs(331)*B* was investigated by scanning tunneling microscopy. While GaAs(331)*B* homoepitaxial growth always leads to a faceted ridgelike surface, $In_{0.2}Ga_{0.8}As$ growth over this surface can lead to either wirelike corrugations or a flat surface depending on growth parameters. The transition between the phases of wirelike corrugations and a flat surface is reversible, indicating that both phases are thermodynamic favored at different temperatures. Based on this observation, we also demonstrate a novel approach for the fabrication of (In,Ga)As quantum wires in the GaAs matrix with low In contents. The carriers are confined to one-dimensional quantum wires in the $In_{0.2}Ga_{0.8}As$ layer bounded by a lower corrugated $In_{0.2}Ga_{0.8}As$-on-GaAs interface and an upper flat GaAs-on-$In_{0.2}Ga_{0.8}As$ interface.

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To date, strain-driven self-organization has been extensively studied in order to produce coherent semiconductor nanostructures over large areas.[1–4] In principle quantum dots (QDs) and quantum wires (QWRs) are each achievable by this strain-relief mechanism. An interesting question, however, for self-assembled growth, has been whether a QD or a QWR will form. For example, strain driven islanding of mismatched (In,Ga)As on GaAs(100) produces only QDs. The controlled fabrication of QWRs in a GaAs matrix remains a challenge. Several approaches have been pursued, such as the use of a lithographically patterned V groove, ridge, or sidewall substrate for growth[5–7] or by the use of step-bunching on a high index or vicinal low index surface.[7–11] Among these approaches, self-organization based on the instability of a high index surface is a natural and simple process that shows promise for fabrication of QWRs with high uniformity and high density. Utilizing a phase change of the surface corrugation, GaAs/AlAs(311)*A* QWRs are naturally formed at GaAs-thicker regions,[12] as indicated in Fig. 1(a). However, the surface corrugation does not exist at the initial stages of (In,Ga)As strained growth,[13] although the amplitude of the corrugation is still controversially discussed.[14,15] (In,Ga)As QWRs are indeed realized on GaAs(221)*A*,[8] as schematically illustrated in Fig. 1(b). The corrugated GaAs-on-(In,Ga)As upper interface is thermodynamically favored, while the flat (In,Ga)As-on-GaAs lower interface is kinetic limited.[8,16] In order to obtain the surface corrugation, the (In,Ga)As(221)*A* layer needs to be grown at a rather high substrate temperature (⩾570 °C). Such a high temperature introduces significant In-desorption, which makes it very difficult to control the In content. In this letter, we demonstrate a novel approach to fabricate (In,Ga)As QWRs in a GaAs matrix by molecular-beam epitaxy (MBE) as illustrated in Fig. 1(c). While GaAs(331)*B* is unstable to the formation of a faceted ridgelike surface, $In_{0.2}Ga_{0.8}As$ growth over this surface can lead to a smooth surface at the substrate temperature of 540 °C, the highest temperature at which In desorption is negligible.

The present experiments were performed in an MBE growth chamber equipped with reflection high-energy electron diffraction (RHEED) and connected to a scanning tunneling microscopy (STM) chamber via an ultrahigh vacuum transfer module. Epiready *n*-type GaAs(331)*B* substrates were transferred into the growth chamber where the oxide was thermally desorbed at 580 °C under As flux from a valve controlled source. After further annealing at 610 °C for 10 min, a 0.5-μm-thick GaAs buffer layer was grown directly at this temperature with an As beam equivalent pressure of 1×10^{-5} Torr. The resulting surface was quenched by decreasing the substrate temperature and As background pressure in

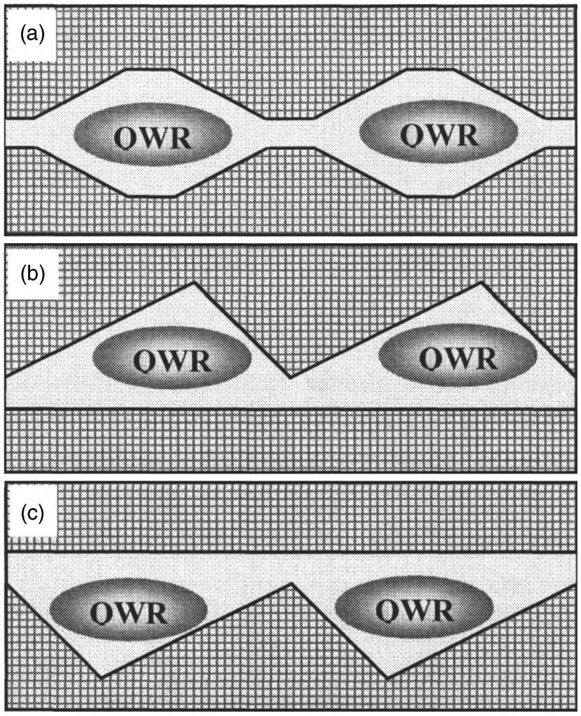

FIG. 1. Schematic illustration of the QWR structures on GaAs high index surfaces. (a) QWRs with a phase change of interface corrugations as proposed in Ref. 12. (b) QWRs with a top interface corrugation as investigated in Ref. 8. (c) QWRs with a lower interface corrugation as demonstrated in this work.

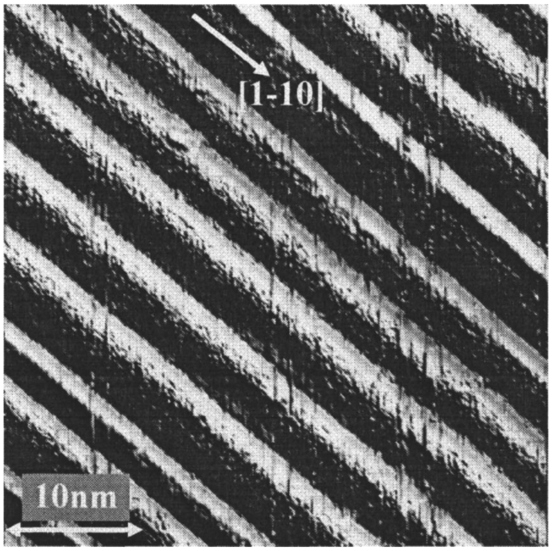

FIG. 2. STM image of the bare GaAs(331)*B* surface with straight ridges bounded by (110) and (111)*B* facets.

order to maintain the as-grown surface morphology. After the valve of the As source is completely closed at a substrate temperature of about 300 °C, the sample was transferred into the STM chamber for imaging. STM images of filled states were taken at room temperature in the constant current mode with negative sample biases of 2–4 V and tunneling currents of 0.1 nA.

A typical STM image of the resulting GaAs(331)*B* surface is shown in Fig. 2. Straight ridgelike corrugations with a lateral periodicity of 5.3 nm are present running along [1-10]. The amplitude of the corrugation is 1.0 nm. As in our previous report,[11] the surface ridges are bounded by (110) and (111)*B* facets. The physics origin of the corrugation is the thermodynamic instability of GaAs(331)*B* to (110) and (111)*B* faceting on a nanometer scale. By depositing GaAs at 610 °C instead of 500 °C or 580 °C as in our previous work,[11] the uniformity and straightness of the surface ridges were enhanced.

Following a decrease of the substrate temperature from 610 °C to 540 °C, $In_{0.2}Ga_{0.8}As$ was deposited on the top of faceted GaAs surface. The surface evolution during deposition was *in situ* monitored by RHEED. The tilted streaky pattern of the bare GaAs(331)*B* surface which is the signature of nanofaceting of GaAs(331)*B* gradually disappears during the growth of the first 3.0 nm of $In_{0.2}Ga_{0.8}As$. Figures 3(a) and 3(b) show the RHEED patterns of the 3.0 nm $In_{0.2}Ga_{0.8}As$ surface taken along [1-10] and [11-6] substrate directions respectively. The diffracted spots lie on a well-defined Laue circle, indicating that the surface is atomically flat on the nanometer scale. RHEED patterns also give access to the surface periodicity along the direction perpendicular to the electron beam. The deduced surface periodicity along [11-6] is 0.9 nm, half of the smallest periodicity reported on GaAs(331)*B*, suggesting a new surface phase.

The new surface phase is confirmed in real space by STM, as shown in Fig. 4. The flat terraces are characterized with atomic rows running along [1-10] with a lateral periodicity of 0.9 nm. The measured height corrugation within the atomically flat terraces is less than 0.13 nm, the height of one-monolayer steps on GaAs(331)*B*. The most frequently observed surface defects are one-dimensional trenches or islands along [1-10] with one monolayer modulation from the flat terraces.

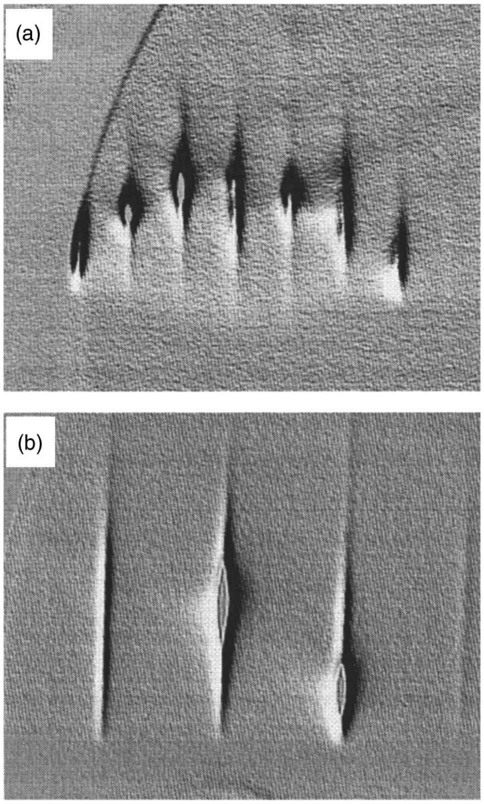

FIG. 3. RHEED patterns from the flat surface of a 3.0 nm $In_{0.2}Ga_{0.8}As$ layer grown at 540 °C on GaAs(331)*B*. (a) and (b) are taken along [1-10] and [11-6] substrate directions, respectively.

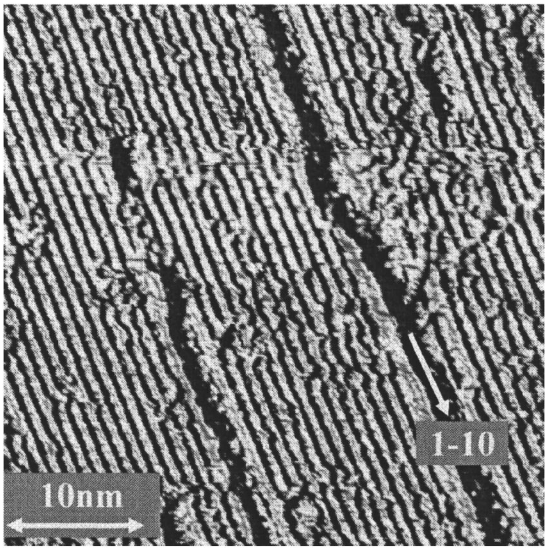

FIG. 4. STM image of the flat surface of a 3.0 nm $In_{0.2}Ga_{0.8}As$ layer grown at 540 °C on GaAs(331)*B*.

Based on the above observation, the growth of an $In_{0.2}Ga_{0.8}As$ layer at 540 °C in a GaAs matrix results in a cross configuration as shown in Fig. 1(c). Carriers are confined in the wirelike $In_{0.2}Ga_{0.8}As$-thicker regions. Indeed the QWR confinement, depending on the In content and the thickness of the (In,Ga)As layer, is demonstrated by polarization photoluminescence spectra.[17] It is important to note that the fabrication of QWRs with this approach relies on the thermodynamic instability of the GaAs(331)*B* surface, different from the strain-relief mechanism in the Stranski-Krastanov (S-K) mode. Therefore, using this approach it is possible to access a spectra range that is hard to achieve for the popular S-K growth approach.

While the growth of $In_{0.2}Ga_{0.8}As$ at 540 °C leads to a flat phase, growth of $In_{0.2}Ga_{0.8}As$ at 450 °C gives a ridgelike corrugation, again bounded by (110) and (111)*B* facets. The STM image in Fig. 5 shows the surface morphology after the growth of 3.0 nm $In_{0.2}Ga_{0.8}As$ at 450 °C. The lateral periodicity of the $In_{0.2}Ga_{0.8}As$ ridges is close to 8.0 nm, nearly double the periodicity of the buried GaAs corrugation. In addition, the transition between the flat phase and the corrugated phase of the $In_{0.2}Ga_{0.8}As$ surface was monitored by the evolution of RHEED patterns during annealing. The flat phase of the $In_{0.2}Ga_{0.8}As$ surface grown at 540 °C will transfer into the corrugated phase by annealing at 450 °C, while the corrugated phase turns into the flat phase by annealing at 540 °C. The transition between these two phases is reversible, indicating that both phases are thermodynamic favored at different temperatures.[18] The dramatic variation of (In,Ga)As morphologies on GaAs(331)*B* as a function of the substrate temperature highlights the infinite capability to engineer nanostructures on high index surfaces. A huge amount of mass transport is necessary to accommodate the phase transition. Some atomic processes with high energetic barriers such as atomic jumps could play a role in this case. This is consistent with several recent reports that suggest MBE growth may proceed under conditions much closer to thermodynamic equilibrium than more traditionally believed.[19–21] While the (In,Ga)As surface morphologies depend on the substrate temperatures as reported above, it is necessary to note that the phase transition is not sensitive to the As background pressure.

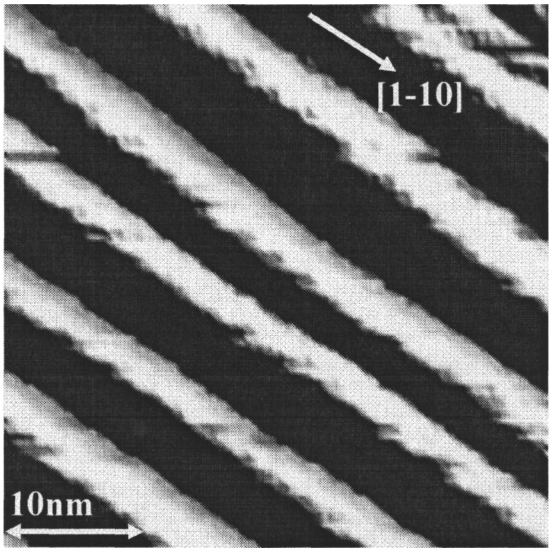

FIG. 5. STM image of the corrugated surface of a 3.0 nm $In_{0.2}Ga_{0.8}As$ layer grown at 450 °C on GaAs(331)*B*.

In summary, employing the faceted GaAs(331)*B* surface as a highly anisotropic template, we demonstrate a novel approach for the fabrication of (In,Ga)As QWRs in the GaAs matrix with low In content. This approach is based on the evolution of the (In,Ga)As surface morphology on GaAs(331)*B*. After the growth of an $In_{0.2}Ga_{0.8}As$ layer, wirelike corrugations are observed at a substrate temperature of 450 °C and a smooth surface is obtained for a substrate temperature of 540 °C.

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