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Stable nonplanar surface formed on patterned GaAs (311)A substrate by molecular-beam epitaxy

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The evolution of the growth front during molecular-beam epitaxy on patterned GaAs (311)A substrates is investigated by cross-sectional atomic force microscopy. The growth rate on the sidewalls is enhanced due to the preferential atom migration from the mesa top and bottom to the sidewalls. The growth front evolution is terminated by the formation of a stable, corrugated surface which is composed of (311)A terraces and steps toward the [233] and [233] directions. Modulation of island density in strained-layer growth is demonstrated by growing 4 ML InAs on this nonplanar surface. © 2000 American Institute of Physics. [S0003-6951(00)01148-7]

Molecular-beam epitaxy (MBE) growth on patterned GaAs (311)A substrates has been demonstrated as a promising way to fabricate high-quality low-dimensional quantum structures. The formation of GaAs/(Al,Ga)As quantum wires (QWR) and quantum dots (QD) with excellent structural and electronic properties near the bottom of the sidewall towards [2 3 3] relies on the preferential migration of Ga atoms from the mesa top and bottom towards the sidewall, leaving behind a smooth, nonfaceted, convex profile, which is tilted by about 1° to the (311)A plane. To gain a deeper understanding of the unique growth behavior on patterned GaAs (311)A substrates, in this letter we present a detailed study of the evolution of the growth front by cross-sectional atomic force microscopy (XAFM), as well as of the surface morphology by top view AFM for a wide range of GaAs layer thickness. It is found that the growth front evolution consists of two distinct stages, first, the evolution of the fast-growing slope, and second, the formation of a stable nonplanar surface. This stable, nonplanar surface which develops after growth of a thick GaAs layer, provides a novel template for further materials growth. InAs islands grown in the Stranski–Krastanow (SK) mode develop a well-defined modulation of the island distribution.

The patterned GaAs (311)A substrates were prepared by using optical lithography and wet chemical etching in the H2SO4:H2O2:H2O solution. The as-etched substrate pattern is shown schematically in Fig. 1(a). Periodic mesa gratings with 20 nm height (H) and 2 or 4 μm width (W) were patterned along the [011] direction. After etching, the substrate was cleaned in concentrated H2SO4 and rinsed in deionized water before being mounted on the Mo block with indium. The native oxide layer was thermally removed at 580°C. AlAs/GaAs (3 nm/7 nm) multilayers and an 800 nm GaAs cap layer were grown at 620°C with the sample holder rotated at 6 rpm. The growth rates of GaAs and AlAs were 0.39 and 0.19 μm/h, respectively. The V/III flux ratio was kept in the range 5–10. For the InAs samples, 4 monolayers (ML) InAs were deposited at 500°C at the growth rate of 0.08 μm/h. The island formation was monitored by the reflection high-energy electron diffraction (RHEED) pattern changing from streaky to spotty. The XAFM measurements were carried out on the cleaved (011) facet, which is perpendicular to the mesa stripes, after the samples were oxidized in air for three days. The surface morphology was characterized by top view AFM.

In Fig. 1(b) we show the XAFM image of the GaAs/AlAs multilayer structure grown over the 4-μm-periodicity (2 W) pattern. In the XAFM measurements, we selected different...
different scan scales in order to gain high resolution in the Y direction and wide viewing area in the X direction. The bright contrast arises from the oxidized AlAs layers, with 30 periods of the AlAs/GaAs superlattice revealed. The image, thus, covers the evolution of the growth front on both opposite sidewalls. The growth of GaAs on the sidewall towards $\{2\bar{3}\bar{3}\}$ (defined here as I type) is enhanced, due to the atom migration from the mesa top and bottom to the sidewall. The angle between the sidewall and the $\{311\}$A plane decreases drastically within the growth of the first several SL periods, indicating that the as-etched sidewalls are not stable during growth. However, after growing the first several SL periods, the fast-growing slope is relatively stable, changing slowly in size and direction, which is the basis for fabrication of single and stacked quantum wires. It is important to note that the growth selectivity of the sidewall towards $\{2\bar{3}\bar{3}\}$ is much smaller than that of the sidewall towards $\{2\bar{3}\bar{3}\}$ and both sidewalls shift in opposite directions during growth. They meet after the growth of 17 SL periods for the mesas with 4 $\mu$m periodicity. Thereafter, no evidence for growth selectivity, i.e., variation in layer thickness, can be observed by XAFM. According to these observations, we separate the growth into two distinct stages. The first stage includes the evolution of the fast-growing slope at the mesa bottom towards $\{2\bar{3}\bar{3}\}$, resulting in the formation of quantum wires, while the second stage starts after the disappearance of the fast-growing slope, most surprisingly resulting in the formation of a stable nonplanar surface.

In the following, we focus on the evolution of the surface by top view AFM. Figures 2(a) and 2(b) show the surface morphology of two samples with pattern periodicity of 4 and 8 $\mu$m, respectively. A nonplanar stable surface profile is obtained after growth with the same periodicity as the patterned substrate. AFM scan lines perpendicular to the mesa...
stripes are shown in Fig. 3, in which $\alpha_1$ ($\alpha_2$) and $\alpha'_1$ ($\alpha'_2$) stand for the angles measured between the (311)A facet and the I type (II type) sidewalls, for the samples with 4 and 8 $\mu$m periodicity, respectively. It is found that, irrespective of the different periodicity, $\alpha_1 = \alpha'_1$ and $\alpha_2 = \alpha'_2$, indicating that this nonplanar morphology formed on patterned GaAs (311)A substrates is stable. This conclusion is further confirmed by investigating the surface morphology of samples with GaAs buffer layers of different thickness. For samples with 4 $\mu$m periodicity and 20–30 nm mesa height, the nonplanar surface becomes stable after the growth of 200–300 nm GaAs.

The stable nonplanar surface is expected to be potentially useful for studies of the step interaction on GaAs (311)A substrates. The sidewall towards [233], on the atomic scale, is composed of (311)A terraces and I-type steps, since it is tilted to the (311)A plane by only about 1$^\circ$. This is also supported by the fact that the $(8 \times 1)$ RHEED pattern does not change during the growth. Similarly, the sidewall towards [233] consists of II-type steps and (311)A terraces. This interesting surface configuration provides the opportunity to investigate the interactions between I- and II-type steps, as well as interactions between steps towards the same direction, a situation which qualitatively differs from the case of vicinal planes.$^{11}$

Here we apply the stable nonplanar surface as a template in heterostructure materials growth. 4 ML InAs is deposited on a 300 nm thick GaAs layer on the patterned substrate. Figure 4 shows the distribution of the InAs islands formed by the SK growth mode. The average island density on the II-type sidewall is found to be higher than that on the I-type one, evidencing that the island density is modulated by the substrate morphology. The absence of InGaAs islands on the I-type sidewall was reported previously.$^{12}$ Hence, we assume that the steps distributed on the different sidewalls play an important role for this island density modulation, leading to the preferential migration of In atoms from the I-type sidewall to the II-type one.

To summarize, we have studied the evolution of the growth front in molecular-beam epitaxy on patterned GaAs (311)A substrate. The growth selectivity on the sidewalls is clearly revealed by cross-sectional atomic force microscopy. A stable nonplanar surface composed of the I- and II-type sidewalls is formed after the growth of a thick GaAs buffer layer. It is demonstrated that the stable stepped surface has a strong modulation effect on the island density for strained InAs layer growth.

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