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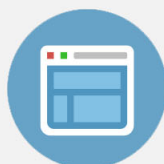
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Formation of an ordered pattern of Bi nanolines on InAs(100) by self-assembly

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Self-assembly of uniform patterns of nanolines over large surface areas has been proven to be difficult. The authors report that bismuth (Bi) adsorbate self-assembles into an ordered pattern of Bi nanolines separated by 4.3 nm on the Bi-stabilized InAs(100)(2×1). The resulted nanoline surface is studied by scanning tunneling microscopy (STM) and low-energy electron diffraction. The plausible atomic models for the Bi nanolines are proposed on the basis of the STM results. The Bi lines are suggested to consist of two chains of adjacent Bi dimers positioned parallel to the chain and parallel to the Bi dimers of the (2×1) substrate. © 2008 American Institute of Physics.

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Low-dimensional structures such as nanolines are being extensively explored due to their potential applications in future electronics and their unique physical properties.^{1–14} Self-assembly is particularly an attractive technique to produce these structures because of its simplicity, but controlled growth of highly ordered single-domain structures over large sample areas has been proven to be difficult. One of the most studied systems is the Si(100)(2×1) surface with Bi nanolines because of its potential use in various applications.^{7–14} For example, recent calculations of the transport properties of the Bi nanolines have shown, that upon passivating the Si(100)(2×1) with hydrogen, they may be used as atom-wire interconnections in molecular electronics.¹⁰ Furthermore, the Bi nanoline structures can be used as templates to grow other one-dimensional structures with tailored electrical, optical, and even magnetic properties.^{11–14}

Compared to the Si or Ge surfaces, the formation of nanolinelike structures on III-V compound-semiconductor surfaces has gained surprisingly little attention despite their technological importance. We show in this letter that by self-organization, on top of the Bi-stabilized InAs(100)(2×1) reconstruction, it is possible to produce a single-domain uniform array of Bi nanolines 4.3 nm apart, which is ten times the lattice parameter ($a_0=4.3$ Å) of the InAs(100)(1×1) surface unit cell. This Bi/InAs(100)(2×10) surface is studied by scanning tunneling microscopy (STM) and low energy electron diffraction (LEED).

The experiments were performed using an omicron surface science ultrahigh vacuum system with a base pressure better than 2×10^{-10} mbar. The STM images were recorded in constant current mode with negative sample bias in order to measure the filled states. Temperature was monitored with an infrared pyrometer. InAs(100) substrates were cut from a S-doped (*n*-type) wafer. The samples were cleaned by cycles

of 1 keV Ar ion sputtering at 380 °C and annealing at 470 °C until a sharp (4×2) LEED pattern was observed. Bi was deposited from a tungsten coil evaporator with the sample held at room temperature. The evaporation rate was estimated with a quartz crystal monitor to be close to 0.5 ML/min, and approximately 1.5 ML of Bi was deposited on the InAs(100)(4×2) surface.

After the Bi deposition, the sample was annealed at 250 °C for an hour, after which a (2×6) [or $c(2 \times 12)$] pattern shown in Fig. 1(a) was observed by LEED. After heating for ~12 h at the same temperature, the pattern changed into a (2×1) with weak *n* times spots in the [011] direction [Fig. 1(b)]. With lower electron energies, the *n* times spots became more pronounced, but still the precise periodicity remained unclear. This, however, is understandable since for large real space unit cells the reciprocal spots are spaced closely, and become unresolvable due to the limitations of the LEED equipment.

Filled-state STM images of the Bi-stabilized InAs(100) surface after heating at 250 °C for an hour and for approximately 12 h are presented in Figs. 2(b) and 2(c), respectively. Figure 2(b) shows a uniform surface with meandering bright

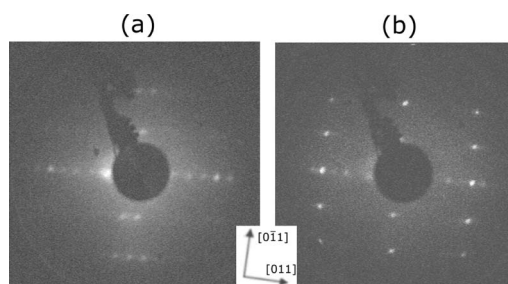


FIG. 1. LEED patterns of the InAs(100) surface after Bi deposition and heating the sample at 250 °C for an hour (a) $E=44$ eV, and approximately for 12 h (b) $E=58$ eV.

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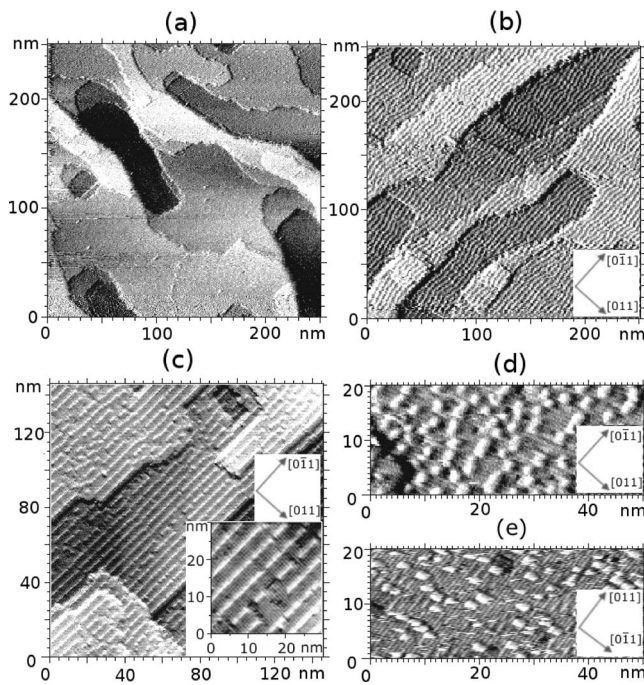


FIG. 2. (a) A STM image of the InAs(100)(4×2) surface before Bi deposition (−2.8 V, 0.21 nA). (b) A large-scale STM image of the surface after Bi deposition and heating for an hour at 250 °C (−3.0 V, 0.21 nA). (c) The surface after prolonged heating for 12 h at the same 250 °C (−2.8 V, 0.28 nA), and after heating at 260 °C (−2.59 V, 0.20 nA) (d) and at 270 °C (−2.89 V, 0.31 nA) (e).

lines in the $[0\bar{1}1]$ direction with the varying local periodicity perpendicular to the lines in the $[011]$ direction. Combining our LEED and STM observations from this surface, we conclude that the (2×6) LEED pattern does not correspond to an ordered reconstruction with six times periodicity in the real space but rather an average over the whole surface. The prolonged heating at 250 °C enhances the ordering by visibly straightening the lines. The inset of Fig. 2(c) shows the orientation of the lines more clearly. Also, the underlying Bi/InAs(100)(2×1) reconstruction, as deduced by LEED, is apparent between the lines. Upon annealing at higher temperatures than 250 °C, the nanolines were found to desorb gradually, revealing the Bi/InAs(100)(2×1) surface, which seemingly stays unperturbed during the desorption process [Figs. 2(d) and 2(e)].

A high resolution STM image from the nanoline surface is presented in Fig. 3(a). The bright lines running in the $[0\bar{1}1]$ direction have a distance of 4.3 nm in the $[011]$ direction which is apparent in the contour plot in Fig. 3(b). The

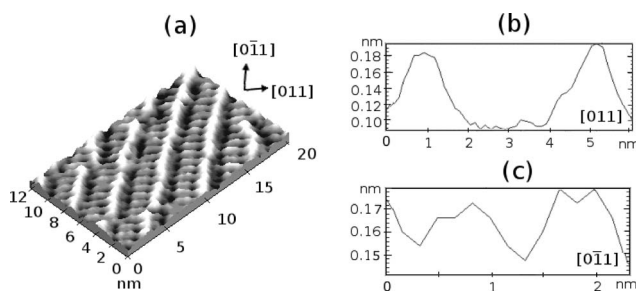


FIG. 3. A filled-state image of the Bi/InAs(100)(2×10) surface taken with −2.83 V and 0.21 nA. (a). The contour plots in $[011]$ (b) and $[0\bar{1}1]$ (c) directions (measured along the lines).

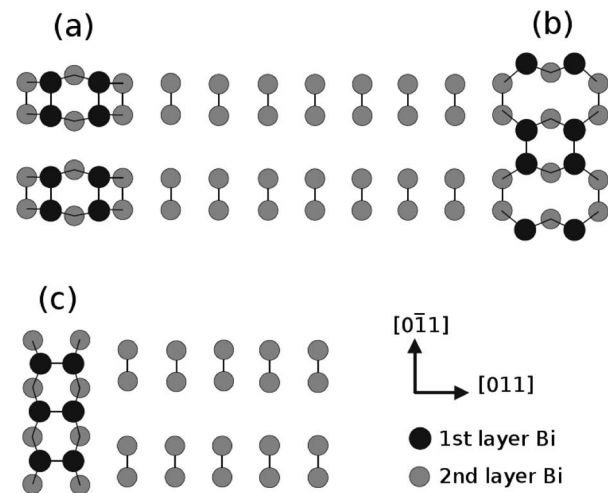


FIG. 4. Possible structures for the Bi nanolines extending in the $[0\bar{1}1]$ direction with Bi dimers parallel (a) and (b) or perpendicular (c) to the Bi dimers of the Bi/InAs(100)(2×1) surface.

distance is ten times a_0 of which length is 4.3 Å. The periodicity along the lines is close to 8.6 Å according to Fig. 3(c) which proposes a two times in the $[0\bar{1}1]$ direction. Thus, Bi assembles a nanolinelike (2×10) reconstruction on top of the Bi-induced InAs(100)(2×1) surface, which is stabilized by annealing at 250 °C.

Usually for the reconstructed III-V(100) surfaces, the major building blocks are dimers as the dimerized atoms reduce the surface dangling bonds and hence the free energy of the surface.¹⁵ Therefore, we can expect the atomic structure of the Bi/InAs(100)(2×10) surface to consist of chains of Bi dimers, which appear as bright lines in the STM images on top of the Bi/InAs(100)(2×1) reconstruction, which appears similar to the Bi/GaInAs(100)(2×1) surface.¹⁶ The dimer formation also agrees with the two times found above. Three possible structural models for the Bi nanolines are presented in Fig. 4. The Bi dimers adsorbed on the first layer are assumed to break the bonds of the second layer Bi dimers below the lines due to the tetrahedral bonding geometry. We have ruled out the model consisting of a single dimer line with dimers parallel to the substrate Bi dimers, based on the full width of half maximum (FWHM) of 11 Å for the peaks in the line profile in Fig. 3(b). This value is more than twice the FWHM of the Bi single-dimer line profile which is reported to be 5 Å.¹⁷ In contrast, corresponding line scans from a previously measured parallel Bi double-dimer line structure on Si(100)(2×1) is close to our value.⁹

Solely from the STM images, it is difficult to say whether the first layer Bi dimers sit on the surface parallel or perpendicular to the second layer Bi dimers, since the geometric structure cannot be directly extracted from the STM images which are based on the electron density. However, when comparing the models in Fig. 4, the periodicity along the lines in the $[0\bar{1}1]$ direction is two times the models with parallel dimers [Figs. 4(a) and 4(b)] and one times for the structure with perpendicular dimers [Fig. 4(c)]. As found above, the periodicity along the nanolines in the $[0\bar{1}1]$ direction is two times [Fig. 3(c)], which is in favor of the parallel-dimer line structure. Also, the Bi dimer bond length is close to 3 Å, which agrees with the distance of the double-peaked

structure of the peaks, which could arise from the dangling bonds of a dimer when probed along it in the $[0\bar{1}1]$ direction. Thus, according to the STM results, we suggest the Bi nanolines to construct two chains of dimers positioned parallel to the chain and parallel to the Bi-dimers of the Bi/InAs(100)(2×1) substrate as described in Figs. 4(a) and 4(b).

When compared to previously studied wirelike structures on Si(100) (for example, Ga, In, Al, and Bi wires^{5,7,18,19}), the atomic lines were also found to be constructed by chains of dimers. In each case, the dimers were found to sit parallel to the Si(100)(2×1) substrate dimers,^{5,7,18,20} which is an energetically stable configuration for the group III elements.²¹ In contrast, the formation of perpendicular dimers to the substrate dimers is found to lead to a two-dimensional growth of the surface layer.²¹ One of these examples is the Bi/Si(100)($2 \times n$) structure.²² However, long chains of Bi dimers positioned parallel to the chain and parallel to the underlying Si dimers are found for Bi nanolines on Si(100)(2×1).^{7,8}

Similar factors that prefer the formation of parallel Bi dimers to the substrate dimers on Si(100) may also be applicable here. We also note that we observed the (2×6) LEED pattern when a small amount of additional Bi was deposited on the Bi/InAs(100)(2×1) surface held at room temperature even before annealing, which suggests that the surface polymerization reaction also plays a part in the formation of the Bi/InAs(100)(2×10) reconstruction.^{5,20} According to this, once a dimer is formed, the third adatom prefers to bind adjacent to the dimer since this orientation does not perturb the substrate too much, and this sets up a chain reaction because the atoms have a strong preference to form dimers. The surface polymerization reaction would result in a structure similar to that of Fig. 4(b),^{5,20} in which case this would be the preferred model for the Bi lines. However, we cannot distinguish the models [Figs. 4(a) and 4(b)] from the STM images. Also, the straightening of the lines by additional heating gives evidence to the substrate mediated interaction of repulsive force between the lines which stabilizes them at ten times the lattice parameter a_0 apart.²³ Future investigations are required in order to understand the detailed formation mechanism behind the Bi/InAs(100)(2×10) reconstruction.

In conclusion, we have observed a self-assembled pattern of Bi nanolines on the Bi/InAs(001)(2×1) substrate leading to a Bi/InAs(100)(2×10) reconstruction, of which plausible atomic structures are presented based on the STM results. The suggested atomic model consists of a double-dimer line structure with dimers parallel to the Bi dimers of

the underlying (2×1) reconstruction and parallel to the lines. Based on the literature, the surface polymerization reaction and substrate mediated interaction may be the formation mechanisms behind this structure. We emphasize that the Bi/InAs(100)(2×10) could be a potential template for the growth of other ordered nanoscale systems. Furthermore, the presented results are important for the understanding and controlling of Bi-surfactant growth of III-V device materials.^{24,25}

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