High-quality GaSb(111) film on the Si(111)√3×√3-B surface

A.V. Slyshkin[1], L.V. Bondarenko[1], D.V. Gruznev[1], A.Y. Tupchaya[1], A.N. Mihalyuk[1,2], A.V. Zotov[1], A.A. Saranin[1]

[1] *Institute of Automation and Control Processes, RAS, Vladivostok, Russia,*

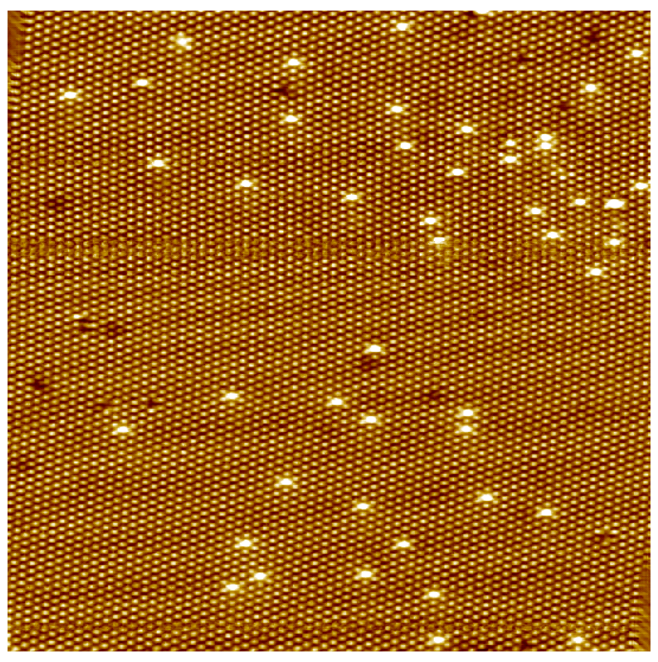
[2] *Far Eastern Federal University, Vladivostok, Russia.*

Introduction

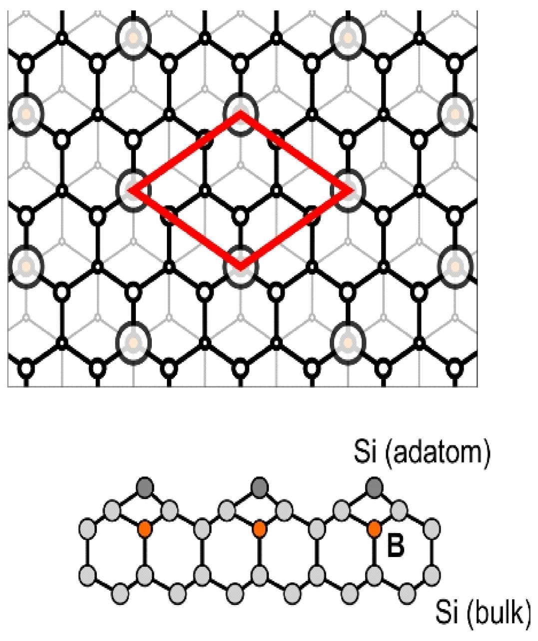
When the Si (111) substrate is heavily doped with B atoms (0.001 Ω cm), the segregation of B atoms during high-temperature annealing leads to the formation of the √3×√3-B reconstruction. This reconstruction has proven to be a stable inert surface suitable for the formation of organic nanostructures and supramolecular ensembles [1]. Due to the absence of unsaturated dangling bonds, such a surface is also suitable for changing the growth mode of some metals [2]. In addition, hole doping of the near-surface layer leads to changes in some physical properties of 2D structures formed on such substrates. For example, an unexpected phase transition in the Sn layer [3] and induced superconductivity in the Si(111)√3×√3-Sn reconstruction [4].

This paper discusses the possibility of using the √3×√3-B reconstruction to form low-dimensional structures, particularly GaSb, whose formation on a "clean" silicon surface is challenging due to the high chemical activity of its constituent elements. The results of experimental studies by scanning tunneling microscopy (STM), low-energy electron diffraction (LEED) are presented.

[1] Y. Makoudi // Surf. Sci. Rep., 72, 316 (2017).
[2] K. Nagase, et all // Appl. Phys. Express, 13, 085506 (2020).
[3] F. Ming, et all // Nat. Comm., 8, 14721 (2017).
[4] X. Wu, et all // Phys. Rev. Lett. 125, 117001 (2020).



45×36 nm^2,
Bright adatoms indicate that the Si atom has not been replaced by the B atom.



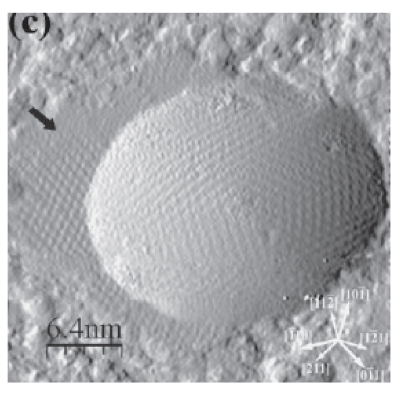
Structual model [5].

[5] R. Headrick, et all // Physical Review Letters 63, 1253 (1989).

Experiment

Our experiments have been performed with a variable-temperature Omicron VT-STM operating in an ultrahigh vacuum (~2.0×10^{-10}, Torr). Si(111)√3×√3-B reconstruction has been prepared from Si (111) substrate, which is heavily doped with B atoms, by annealing to 900°C for one hour. Ga and Sb have been deposited from the Ta tube. Ga and Sb deposition rate has been calibrated using STM.

GaSb(111) on Si(111)

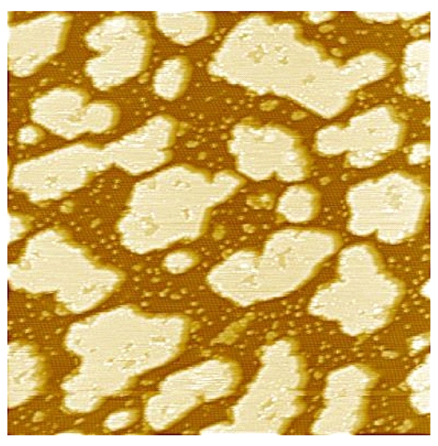


Drop of GaSb [6].

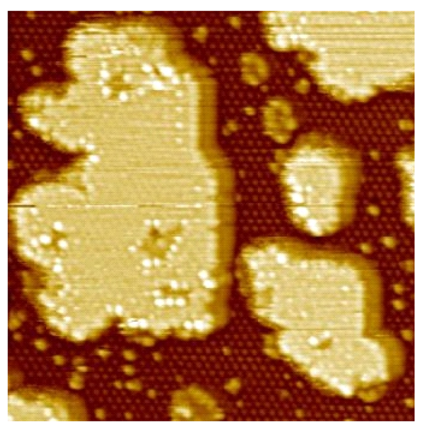
Beside a large lattice mismatch between Si and GaSb (12.2%) and different thermal expansion coefficients, growth of flat GaSb films directly on the Si(111) surface is difficult due to different reaction of Ga and Sb atoms with the Si surface. Sb terminates the surface and further deposition results in formation of huge GaSb dots. [6]

[6] S. Hara, et al // Jap.J.Appl.Phys. 50, 08LB03 (2011).

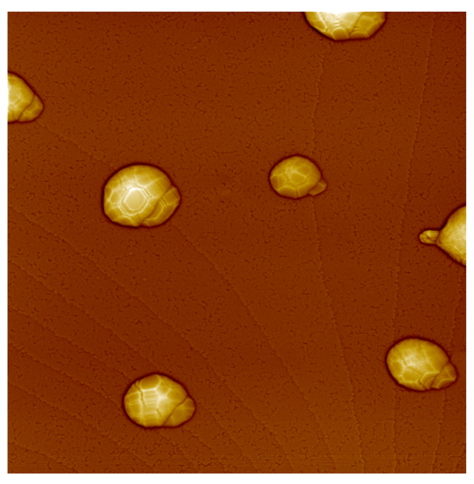
Growth of Ga on Si(111)√3×√3-B surface



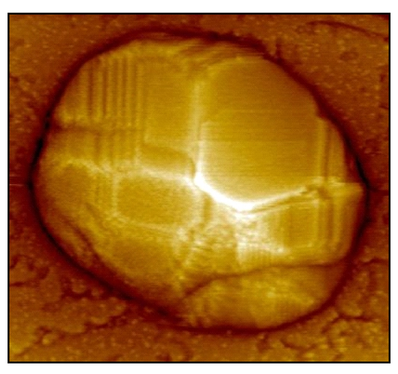
75×75 nm^2,
Growth of Ga on Si(111)√3×√3-B at room temperature.



30×30 nm^2,
Growth of Ga on Si(111)√3×√3-B at room temperature.



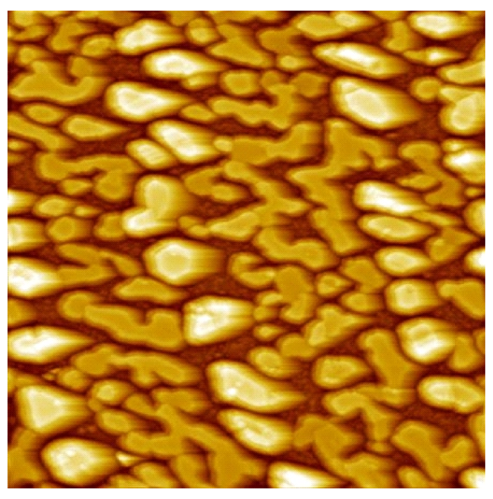
1×1μm^2,
Growth of Ga on Si(111)√3×√3-B at room temperature. STM image was recorded at 115 K.



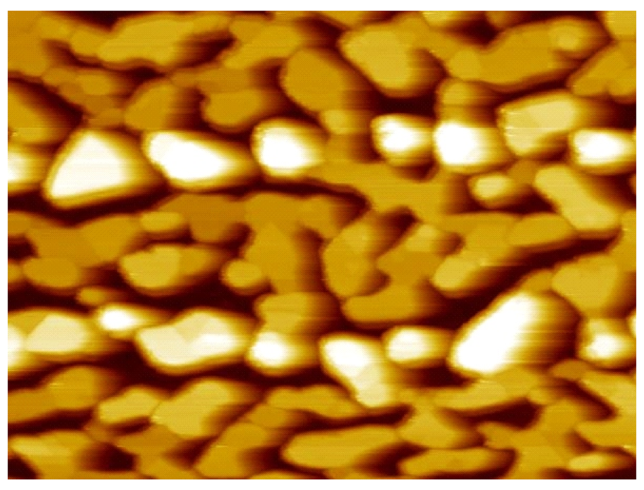
100×100 nm^2
Drop of Ga.

Ga under room temperature shows growth according to the Stransky-Krastanov. First, a metal layer is formed, on which huge faceted islands grow. The diameter of the islands is about 100-150 nm, the height reaches 30 nm. The shape is hemispherical, in fact, these are drops. Their density is not high, the distance between the islands reaches half a micron. This image was recorded at low temperature, about 110 K. In room temperature, these islands are most likely liquid, and STM-image cannot be recorded.

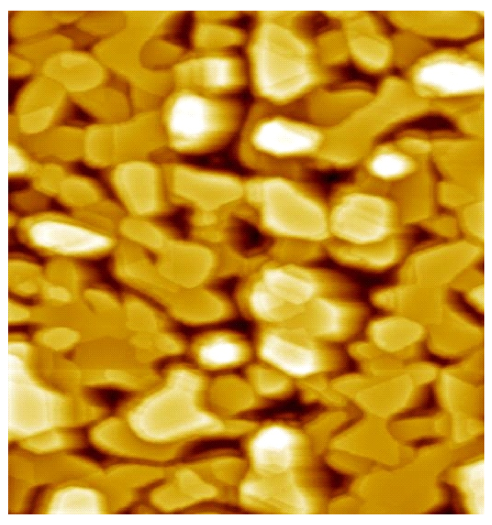
STM images of GaSb(111) on Si(111)√3×√3-B surface



400×400 nm^2,
STM image of 3 BL GaSb on Si(111)√3×√3-B at room temperature. Annealing at ~ 400°C.



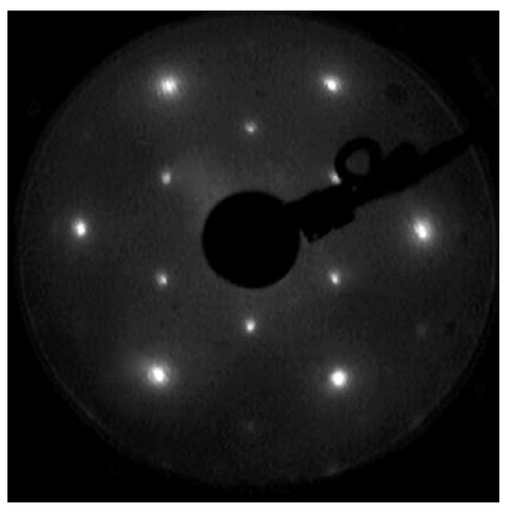
400×300 nm^2,
STM image of 6 BL GaSb on Si(111)√3×√3-B at room temperature. Annealing at ~ 400°C.



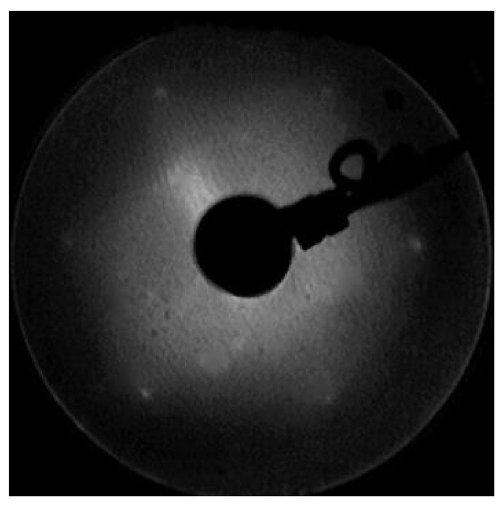
300×300 nm^2,
STM image of 8 BL GaSb on Si(111)√3×√3-B at room temperature. Annealing at ~ 400°C.

Here are the STM images obtained for different film, 3, 6 and 8 bilayers. The film exhibits pseudo-two-dimensional layer-by-layer growth, i.e., 2D islands with a flat surface are formed.

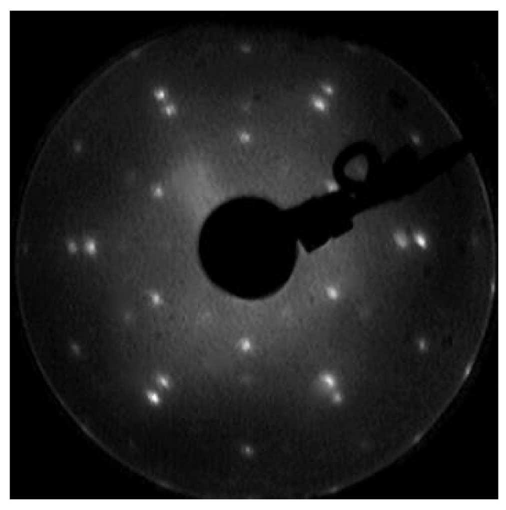
LEED images of GaSb(111) on Si(111)√3×√3-B surface



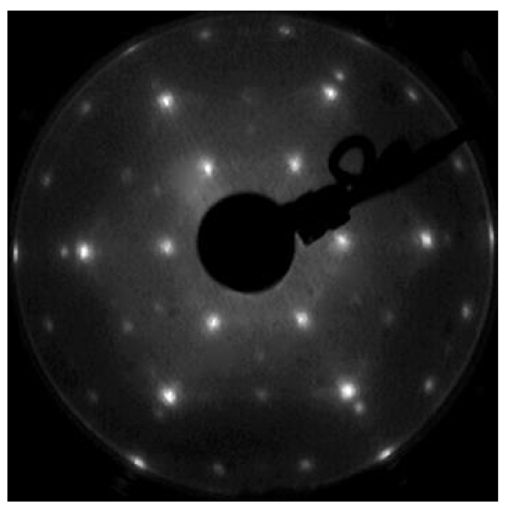
54 eV,
Initial Si(111)√3×√3-B.



54 eV,
3 BL GaSb on Si(111)√3×√3-B at room temperature.

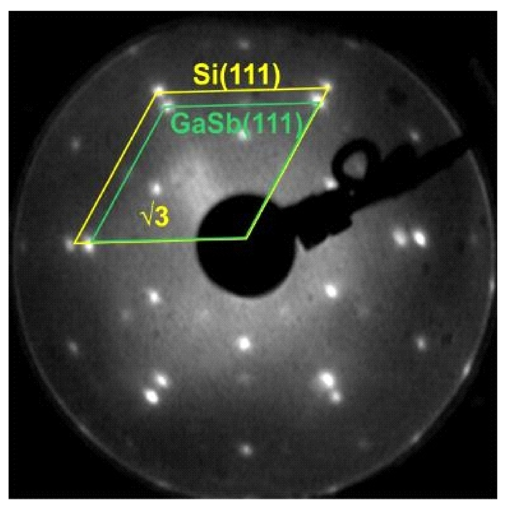


54 eV,
3 BL GaSb on Si(111)√3×√3-B at room temperature.
Annealing at ~ 400°C.



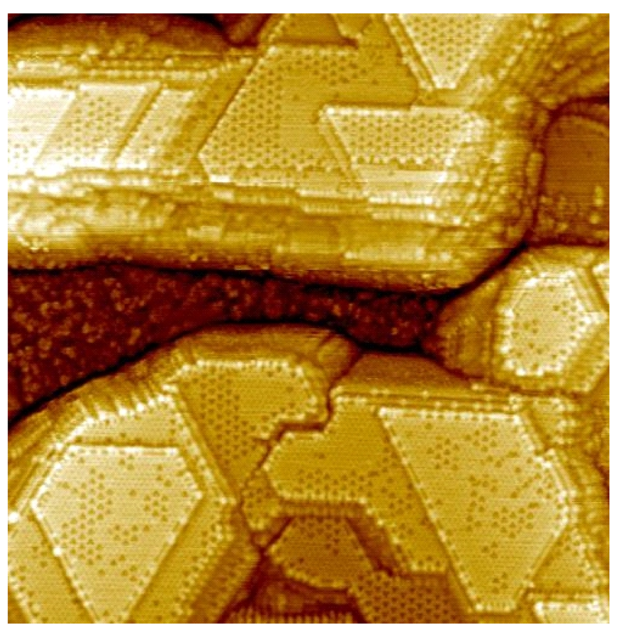
54 eV,
10 BL GaSb on Si(111)√3×√3-B at room temperature.
Annealing at ~ 400°C.

The LEED images of the GaSb(111) on Si(111)√3×√3-B system and evolution upon annealing are presented. After deposition of 3 bilayers, i.e. 3 ML Ga + 3 ML Sb. As can be seen, even the main reflections of Si are seen very weakly, the surface is simply with some kind of disordered layer. However, up at about 400°C changes everything. Si 1x1, √3-B return, and in addition, quite bright and clear pointy new reflections appear. By comparison with Si 1x1, it became clear that these reflections belong to gallium antimonide, the lattice period of which is slightly larger. That is, judging by the diffraction, some flat GaSb structures with good crystalline quality are formed. For thicker films, about 10 bilayers, everything is even better - silicon decays, the antimonide becomes even brighter with additional spots of 1/2-order. All A3B5 are known to have 2x2 reconstructions, including GaSb.

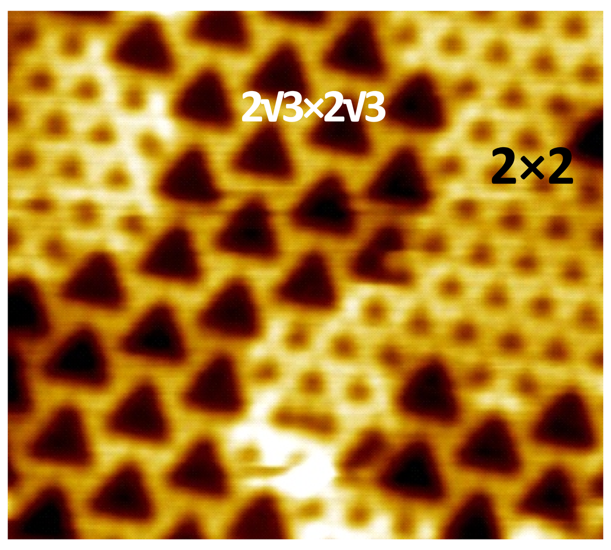


aSi = 0.384 nm
aGaSb = 0.431nm

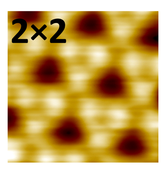
High resolution STM images of GaSb(111) on Si(111)√3×√3-B surface

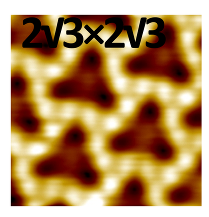


80×80 nm^2,
STM image of 6 BL GaSb on Si(111)√3×√3-B at room temperature. Annealing at ~ 500°C.



10×9 nm^2,
STM image of 6 BL GaSb on Si(111)√3×√3-B at room temperature. Annealing at ~ 500°C.





High resolution STM images are presented here. It can be seen that although the islands have an irregular shape and the flat surfaces of the islands are reconstructed. There are two reconstructions, for the most part a 2x2 structure, it is also visible on diffraction. This is a typical reconstruction of all A3B5. Another reconstruction has a period of 2√3. It is rarely seen.

Conclusion

The growth mode of the GaSb(111) film changes from Stranski–Krastanov to pseudo-two-dimensional layer-by-layer. The film is aligned along the main crystallographic directions of the substrate. The surface of the film is revealed to be Ga-terminated one by STM observations of 2×2 and 2√3×2√3 reconstructions. Si adatoms from initial √3×√3-B reconstruction migrate into growing film and act as a p-type doping.