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GROWTH AND STABILITY OF BI FILMS ON SI(111) STUDIED BY LEEM

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The structural and electronic properties of ultra-thin metal films on semiconductor surfaces have attracted much recent interest primarily due to the dominating dependence of novel device performance on metal contacts. The unique characteristics of devices such as thin film organic transistors and carbon nanotube transistors, suggest exciting applications: cheap, flexible (and perhaps even biodegradable) microelectronics and fast low-power chips, provided that well-functioning contacts can be controllably fabricated. Such control requires an understanding of the factors governing heteroepitaxial growth for example, surface free energies and stress relaxation effects, and *in situ* electron microscopy can play a unique role in increasing our understanding of the processes involved.

Our growth experiments were carried out in the Bi/Si(111) system *in situ* by exposing a clean room-temperature Si(111) 7×7 surface to Bi flux (rate of $2/5$ ML per minute) and recording the film growth process in real time using a low-energy electron microscope (LEEM) constructed at IBM (real space lateral resolution of 5nm) [1]. With the surprisingly large lattice mismatch of 17% between bismuth and silicon, one might expect the growth of Bi/Si(111) to be almost certainly dominated by strain and stress relaxation energy, and therefore three dimensional. Up to about five monolayers, the Bi film grows as expected in Stranski-Krastonov mode with (012) oriented islands on top of a uniform wetting layer [2]. Above five monolayers, the crystal orientation dramatically flips, with a change in the c-axis orientation from (012) to (001), from a two-fold to a three-fold symmetry, into a flat single crystal film (domains are approx. $100\mu m^2$ in size). The transition occurs very quickly and therefore requires large mass transport, with entire grains transitioning as a whole at a rate of about $1\mu m^2 s^{-1}$. After the transition into the (001) structured film, the growth continues in a two-dimensional layer-by-layer mode of bi-layers.

The thermodynamic stability of Bi/Si(111) films was investigated by annealing the films to temperatures of up to 150°C (melting temperature of Bi is 220°C). We found that upon annealing below this temperature the film surface is smoothed and the Bi step edges become modulated with a periodic wavelength of 1µm. Above this temperature, the film undergoes a de-wetting process that begins with the film nucleating vacancy islands (holes) leaving however, a remaining thin Bi layer with $\sqrt{3}\times\sqrt{3}$ structure (observed with LEED) inside, lining the bottom of the holes, and ending with the entire surface covered by the $\sqrt{3}\times\sqrt{3}$ film with large macroscopic droplets of Bi on top. Thus the lowest energy configuration of Bi/Si(111) is actually the $\sqrt{3}\times\sqrt{3}$ film however, the Bi(001)/Si(111) may also be a thermodynamic low-energy configuration.

REFERENCES

[1] R.M. Tromp et al., Surf. Rev. Lett. 5 (1998), 1189.
[2] T. Nagao et al., to be submitted and private discussion.

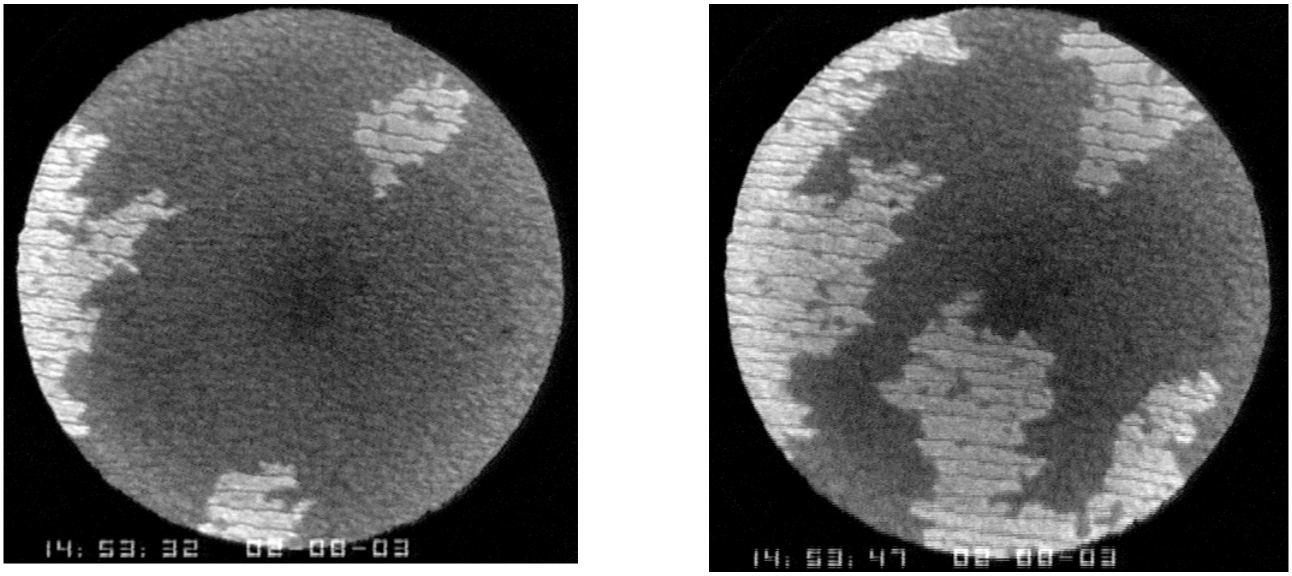

FIGURE 1. Two 5.6 µm field of view LEEM images of Bi/Si(111) film growth undergoing transition from the (012) to the (001) structure near 5 monolayers of coverage. The Bi(001) oriented grains are white and also clearly reflect the horizontal Si(111) step structure at the Bi/Si interface. The notably short time difference of 15 seconds between the two images highlights the speed of this remarkable structural transition.

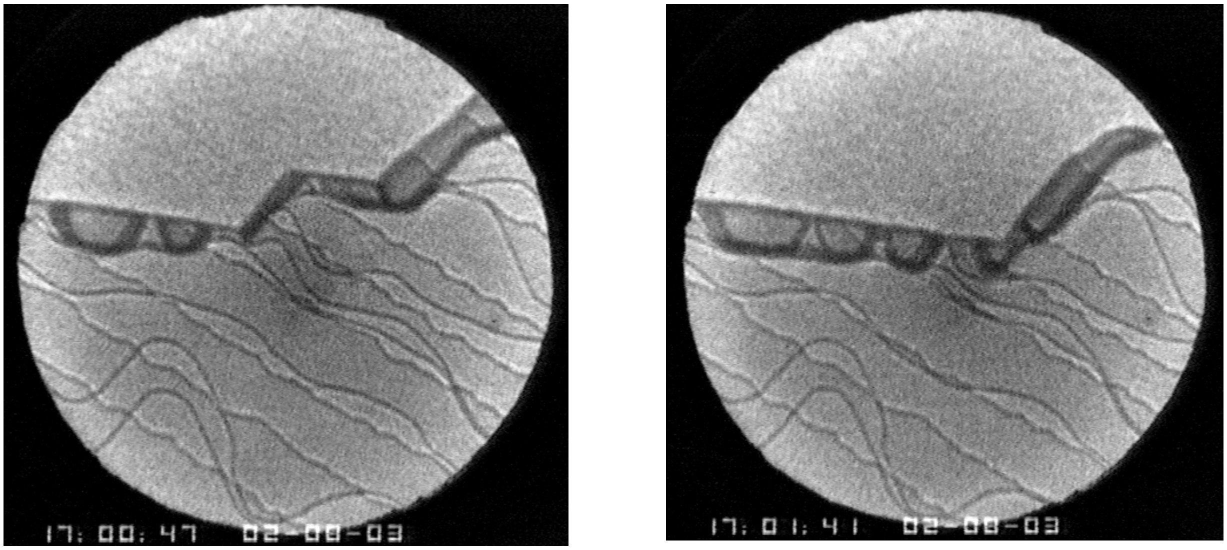

FIGURE 2. Two 2.4 µm field of view LEEM images of an annealed Bi(001)/Si(111) film with hole growing and wavy Bi steps. The light gray speckled region at the top of the images is the bottom of a hole in the Bi(000)/Si(111) film. The hole has grown larger in the image on the right by removing Bi material and piling it near the edge of the hole (dark region running across the field of view). Observe that Bi step edges on the portion of remaining film have surprisingly not changed or grown during the large mass transport de-wetting process occurring between these frames.