Reversible Nanofacetting and 1D Ripple Formation of Ge on High-Indexed Si (11 10) Substrate

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Silicon-germanium has been an intensely studied model system for the growth of self-assembled quantum dots by the Stranski-Krastanow mode. A prominent feature of these dots is their highly facetted pyramidal or dome-like shape [1] that is governed by the formation of energetically favored side facets. The formation of the different dot shapes not only depends on the Ge coverage and growth condition, but also on the substrate orientation [2]. The (11 10) Si substrate orientation is special because of its particular relationship to the low energy {105} facets of compressively strained Ge pyramids, in which case the intersections of these facets are parallel to the (1110) surface. In addition, local (1 1 10) Si substrate facets also play a major role in site-controlled growth of Ge islands on pit-patterned or stripe-patterned Si substrate templates [3], [4].

In the present work, Ge growth on high-indexed (11 10) substrates was studied systematically using *in situ* variable temperature scanning tunneling microscopy. The experiments were performed in a multi-chamber MBE/STM system, allowing sequential growth and imaging of the epitaxial surface structure formed after each growth step [4]. The results demonstrate that the (1110) growth properties radically differ from those on the usual (001) Si substrates. At certain critical coverage of ~4 monolayers (ML), a highly stable quasi-periodic 1D ripple structure is formed perpendicular to the dimer direction. As demonstrated by Fig. 1 (1) well defined {105} facetted ripples completely cover the whole (1110) substrate surface, in contrast to the usual isolated Ge islands formed by the Stranski-Krastanow growth mode on (001) surface.

A quantitative analysis shows that in the ripple formation process, the initial 2D Ge wetting layer is completely consumed, i.e., no wetting layer remains underneath the ripples. Thus, the ripples represent a novel pathway for lowering the free energy of the system. Moreover, the ripples show a well defined and unique width and height with a lateral periodicity of ~20 nm with a rather narrow size dispersion. Most strikingly, during thermal cycling of the Ge layers on Si (1110), a reversible transition from the rippled surface to a flat surface is found to occur when the annealing temperature is raised above a critical temperature of 600 °C. This process is reversed when the temperature is lowered again. This was demonstrated by the variable temperature STM image in Fig. 1 (2), where the rippled surface was heated from 500 °C to 590 °C and then cooled down again to 500 °C. Moreover thermal cycling was monitored using RHEED, that the intensity evolution of the ripple spot present hysteresis behavior during multiple heating and cooling cycles. Both factors clearly demonstrate that the ripples represent an equilibrium structure and their formation closely resembles a thermodynamic phase transition.

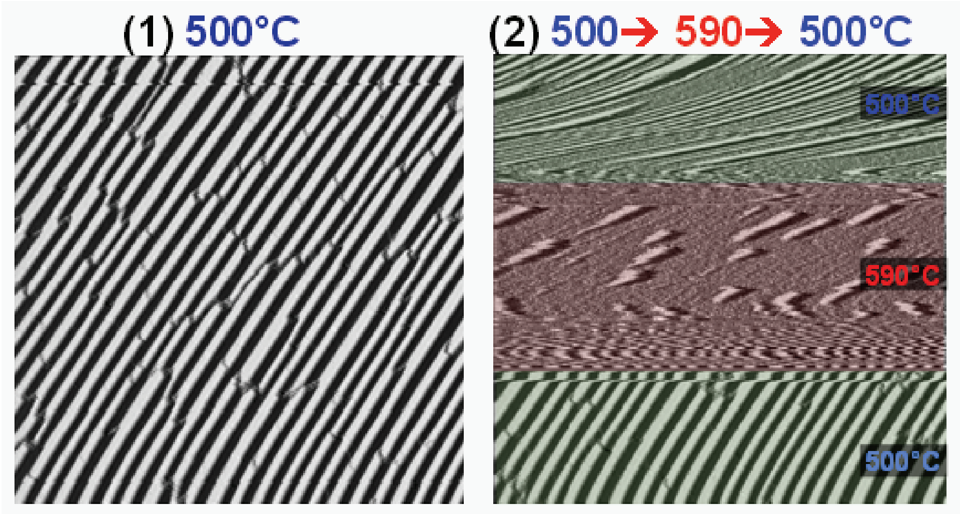

Fig. 1: Reversible ripple formation is demonstrated via variable temperature STM images. (1) {105} facetted ripple covered surface at 500 °C, corresponding Ge coverage is 4.5ML. Right: the sample was annealed from 500 °C to 590 °C using DC current. Ripple structure almost disappears at 590 °C and then reappears at 500 °C within few seconds.

References

[1] *see* M. Brehm, et al., Nanoscale Research Letters (in print) and references therein.

[2] J.T. Robinson, A. Rastelli, O. Schmidt and O.D. Dubon, Nanotechnology **20**, 085708 (2009).