Extended Abstracts of the 2005 International Conference on Solid State Devices and Materials, Kobe, 2005, pp.360-361

F-3-1 (Invited)

Quantum Dots, Quantum Dot Molecules, and Quantum Dot Crystals

O. G. Schmidt[1], A. Rastelli[1], S. Kiravittaya[1], L. Wang[1], M. Stoffel[1], G. J. Beirne[2], C. Hermannstaedter[2], and P. Michler[2]

[1]Max-Planck-Institut für Festkörperforschung, Heisenbergstr. 1, D-70569 Stuttgart, Germany; O.Schmidt@fkf.mpg.de
[2]5. Physikalisches Institut, Universität Stuttgart, Pfaffenwaldring 57, D-70569 Stuttgart, Germany

We will present our recent efforts to epitaxially grow and characterize self-assembled quantum dots (QDs). Our investigations reveal new fundamental aspects of self-assembled island growth, and include the fabrication of higher order quantum dot configurations such as lateral quantum dot molecules and 3D quantum dot crystals. The creation of lateral quantum dot molecules combines quantum dot growth and in-situ atomic-layer precise etching The 3D quantum dot crystals are seeded on a lithographically patterned substrate surface. All of the structures reveal novel interesting structural and optical properties.

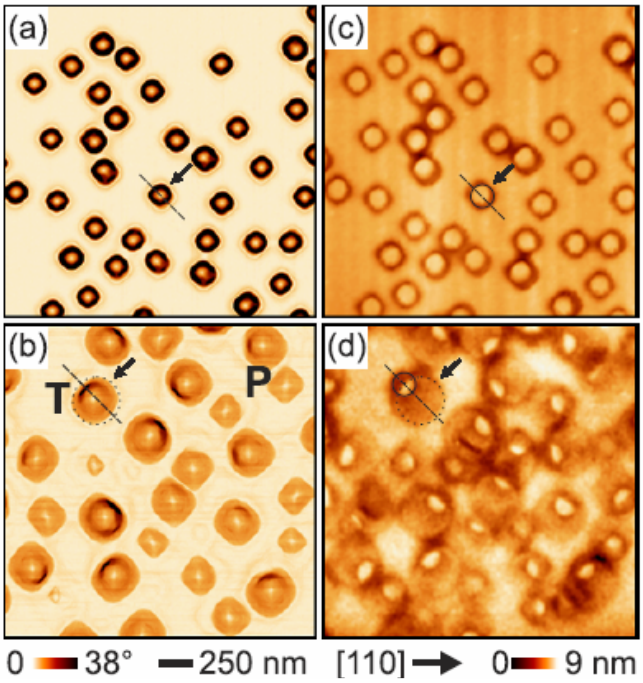

Fig. 1 AFM images of SiGe islands (a),(b) before and (c),(d) after selective etching in BPA solution. The amount of Ge deposited was 10 ML at 740 °C; color scale in left and right panels represents slope and height, respectively. In (a),(c) the sample was cooled to RT immediately after growth while in (b),(d) the sample was annealed for 20 min at 740 °C. Solid circles in (c),(d) indicate representative Si plateaus. The dashed circles in (b),(d) mark island perimeters after annealing (see also [1]).

Figure 1(a) displays an AFM image of SiGe islands obtained by deposition of 10 ML of Ge on Si(001) at 740 °C. A morphology change and size increase occurs in Fig. 1(b), which shows an AFM image of a sample obtained by deposition of 10 ML of Ge and subsequent annealing at 740 °C for 20 min. Most of the islands transform back to pyramids, labeled ''P'' in Fig. 1(b), and to transition structures [''T'' in Fig. 1(b)]. AFM scans obtained after selective wet etching for 2 min in BPA solution are shown in Figs. 1(c) and 1(d) for the same areas shown in Figs. 1(a) and 1(b). Following island removal by the etching, only plateaus remain on the exposed Si surface that was formerly below the islands. These plateaus are circular for the non-annealed sample [Fig. 1(c)] and surrounded by approximately square trenches with sides parallel to the [100] and [010] directions. Etching of the annealed sample [Fig. 1(d)] reveals that the Si plateaus assume a ''half-moon'' shape surrounded by asymmetric trenches. By comparing the half-moons with the original plateaus [see black circle in Fig. 1(c)] and measuring samples annealed for shorter periods (not shown), we find that the half-moon shaped plateaus are remnants of the original circular plateaus. While the apex of the island lies above the center of the plateau for the non-annealed sample, it is significantly displaced from the plateau center after annealing. We can thus conclude that, during annealing, islands not only intermix and change their shape, but also *move* laterally on the surface [1].

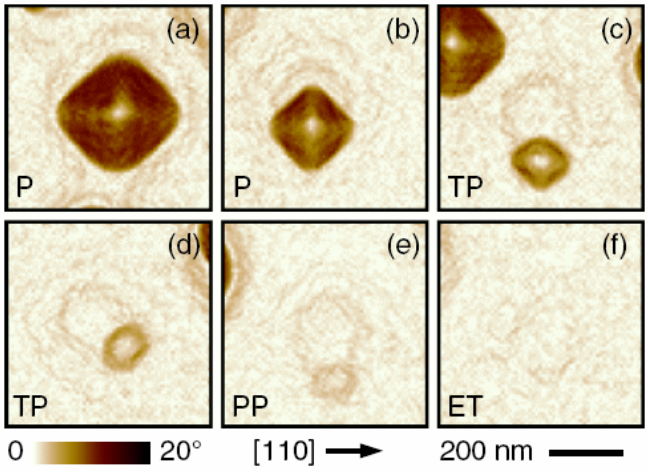

Fig. 2 Sequence of AFM magnifications illustrating shrinking SiGe pyramids and the pyramid-to-prepyramid transition. Images have color scale according to local surface slope with respect to the (001) plane (see also [2]).

The trenches left behind by the islands also allow us to discriminate shrinking from growing islands [2]. While shrinking, pyramid islands transform back into unfaceted mounds (see Fig. 2 (a)-(f)), which is the reverse process observed during island growth. This indicates that island shape and facet formation are thermodynamically determined.

Recently, we have introduced a technique to create laterally closely spaced QDs [3]. The technique comprises capped InAs/GaAs quantum dots, which are subsequently in-situ etched by AsBr3.

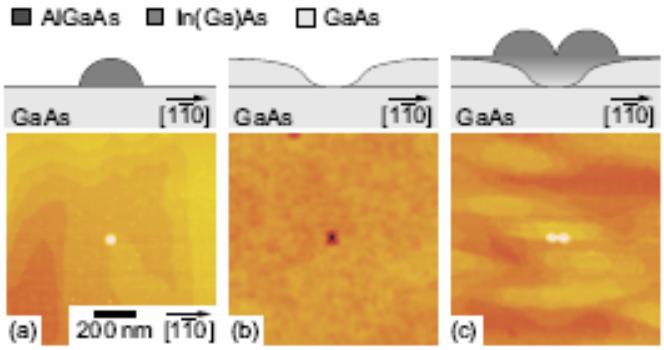

Fig. 3 AFM images and schematic representations of the structures discussed here. An InAs QD (a), a nanohole on GaAs (b) and a QD-bimolecule (c).

This procedure leads to the formation of nanometer sized holes since the etchant preferably etches those regions of the surface, which are distorted by the strain fields of the buried QDs. The surface is then again decorated with InAs QDs, which now form into closely spaced QDs around the nanoholes. Figure 3 displays representative AFM images of low density structures (bottom panels) together with cross-sectional sketches (top panels). Figure 3(a) shows a typical InAs island used to produce nanoholes [Fig. 3(b)]. If the nanoholes are overgrown with InAs at a substrate temperature of 500 °C, closely spaced InAs quantum dot molecules are obtained [Fig. 3(c)]. We will show by single micro-photoluminescence and photon correlation measurements that charge carriers confined to the lateral quantum dot molecules indeed couple electronically.

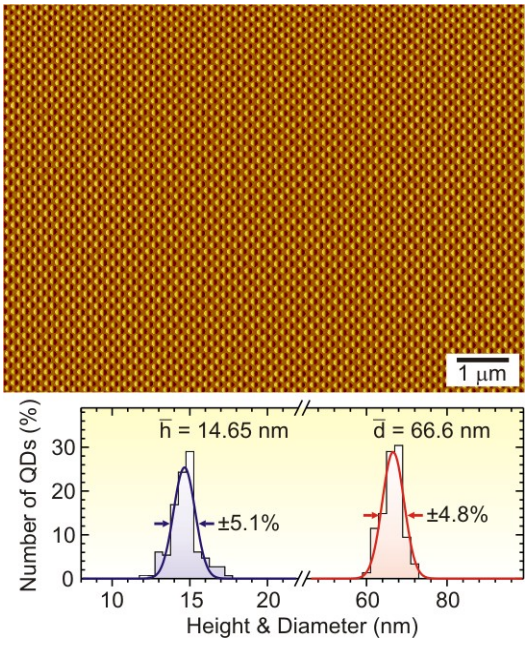

Fig. 4 Strictly ordered InAs QD array on patterned GaAs (001).

Highly ordered quantum dot arrays are achieved by the growth of quantum dots on patterned substrates [4]. The atomic force microscopy image in Fig. 4 for example shows a strictly periodic array of InAs/GaAs quantum dots grown on a shallow modulated GaAs(001) substrate. Under optimized growth conditions the quantum dot array experiences a size dispersion of only about 5 %.

The surface in Fig. 4 can be used as a template to stack several QD layers, thus resulting in a three-dimensional QD crystal [5]. The surface of different QD layers of such a QD crystal are given in Fig. 5.

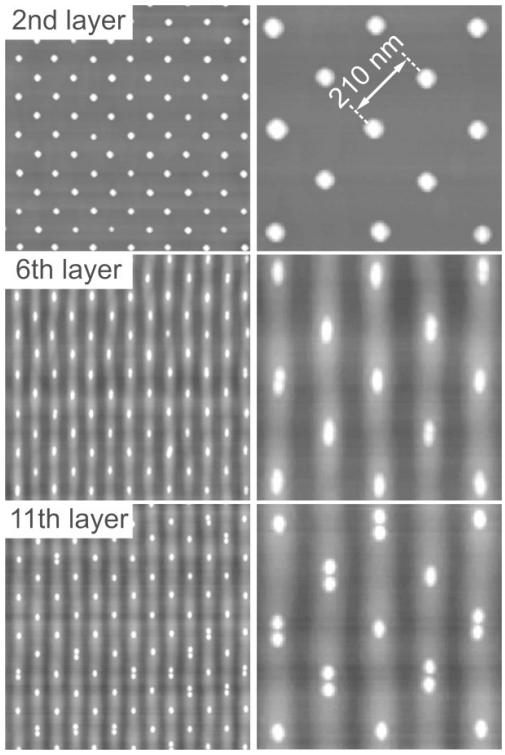

Fig. 5 AFM scans of ordered InAs/GaAs QD arrays after the 2nd, 6th, and 11th layer.

The AFM images reveal that single QDs replicate into pairs of QDs (along the [1-10] direction) with increasing separation distance during the growth of a three-dimensional QD crystal [5]. Kinetic Monte Carlo simulations – that rely on strain profiles deduced from experiment – can describe this lateral replication process, which is triggered by a distinct ridge structure that evolves during the overgrowth of two-dimensional periodic QD arrays. The ability to laterally replicate QDs could open a path to create well-designed lateral QD molecules with tuneable separation distance.

[1] U. Denker et al., Phys. Rev. Lett. 94 (2005) 216103.
[2] A. Rastelli et al., Phys. Rev. Lett. 95 (2005) 026103.
[3] R. Songmuang, S. Kiravittaya, and O. G. Schmidt, Appl. Phys. Lett. 82 (2003) 2892.
[4] S. Kiravittaya and O. G. Schmidt, Appl. Phys. Lett. 86 (2005) 206101.
[5] S. Kiravittaya, H. Heidemeyer, and O. G. Schmidt, Appl. Phys. Lett. 86 (2005) 263113.