Scalable Array of Ordered Si Nano-pillars with Precisely Controlled Ge Quantum Nanostructures at the Pillar Periphery

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Abstract

The scalable array of ordered nano-pillars with precisely controllable quantum nanostructures (QNs) are ideal candidates for the exploration of the fundamental features of cavity quantum electrodynamics. It also has a great potential in the applications of innovative nano-optoelectronic devices for the future quantum communication and integrated photon circuits. Here, we present a synthesis of such hybrid system in combination of the nanosphere lithography and the self-assembly during heteroepitaxy. The precise positioning and controllable evolution of self-assembled Ge QNs, including quantum dot necklace(QDN), QD molecule(QDM) and quantum ring(QR), on Si nano-pillars are readily achieved. Considering the strain relaxation and the non-uniform Ge growth due to the thickness-dependent and anisotropic surface diffusion of adatoms on the pillars, the comprehensive scenario of the Ge growth on Si pillars is discovered. It clarifies the inherent mechanism underlying the controllable growth of the QNs on the pillar. Moreover, it inspires a deliberate two-step growth procedure to engineer the controllable QNs on the pillar. Our results pave a promising avenue to the achievement of desired nano-pillar-QNs system that facilitates the strong light-matter interaction due to both spectra and spatial coupling between the QNs and the cavity modes of a single pillar and the periodic pillars.

Results

- Different Ge nanostructures and their evolutions with the Ge deposition thickness.
- To deliberately tailor the self-assembled nanostructures on the nano-pillar, we develop a two-step procedure for the Ge growth.

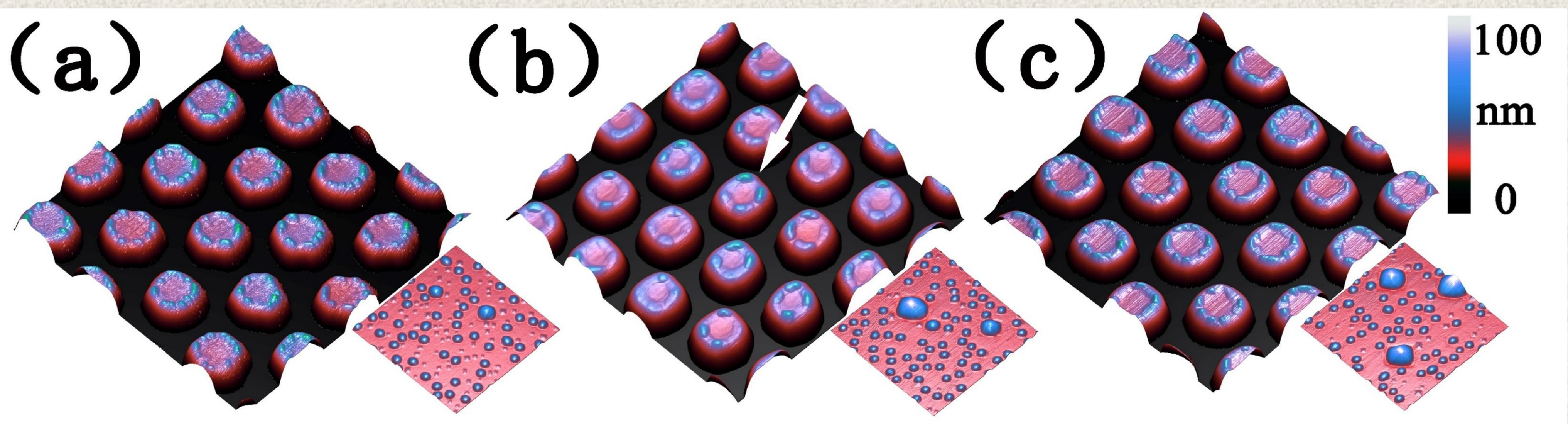

Figure 1. AFM images (2×2 μm²) of self-assembled Ge nanostructures on the ordered Si nano-pillars via the one-step procedure at 520 ºC and a Ge growth rate of 0.025 Å/s with nominal Ge deposition of, a) 1.8 nm, b) 2.0 nm, c) 2.2 nm. The arrow in b) denotes a molecule of four QDs on the pillar. The corresponding AFM images (1×1 μm²) of self-assembled Ge QDs on the reference flat Si (001) substrates are shown in the insets.

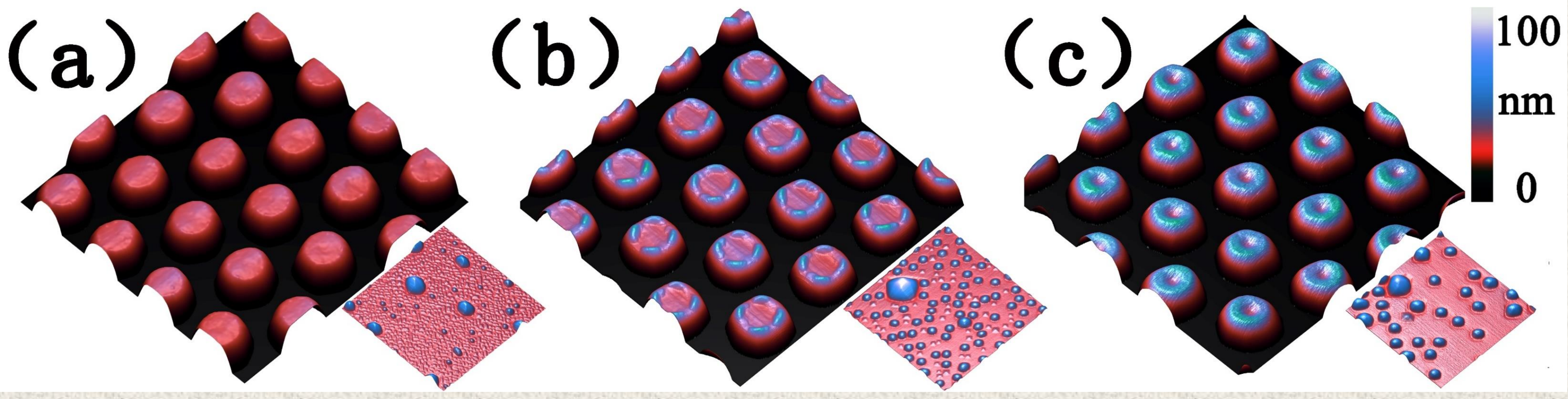

Figure 2. AFM images (2×2 μm2) of self-assembled Ge nanostructures on the ordered Si nano-pillars via the two-step procedure with the Ge deposition of, a) (0.8 nm at 500 ºC and 0.1Å/s) + (1.0 nm at 520 ºC and 0.025Å/s), b) (0.8 nm at 500 ºC and 0.1Å/s) + (1.0 nm at 580 19 ºC and 0.025Å/s), c) (0.8 nm at 580 ºC and 0.025Å/s) + (1.0 nm at 480 ºC and 0.1Å/s). The corresponding AFM images (1×1 μm²) of self-assembled Ge QDs on the reference flat Si (001) substrates are shown in the insets.

- In order to investigate the facet and crystalline, we perform detailed characterization of QDM.

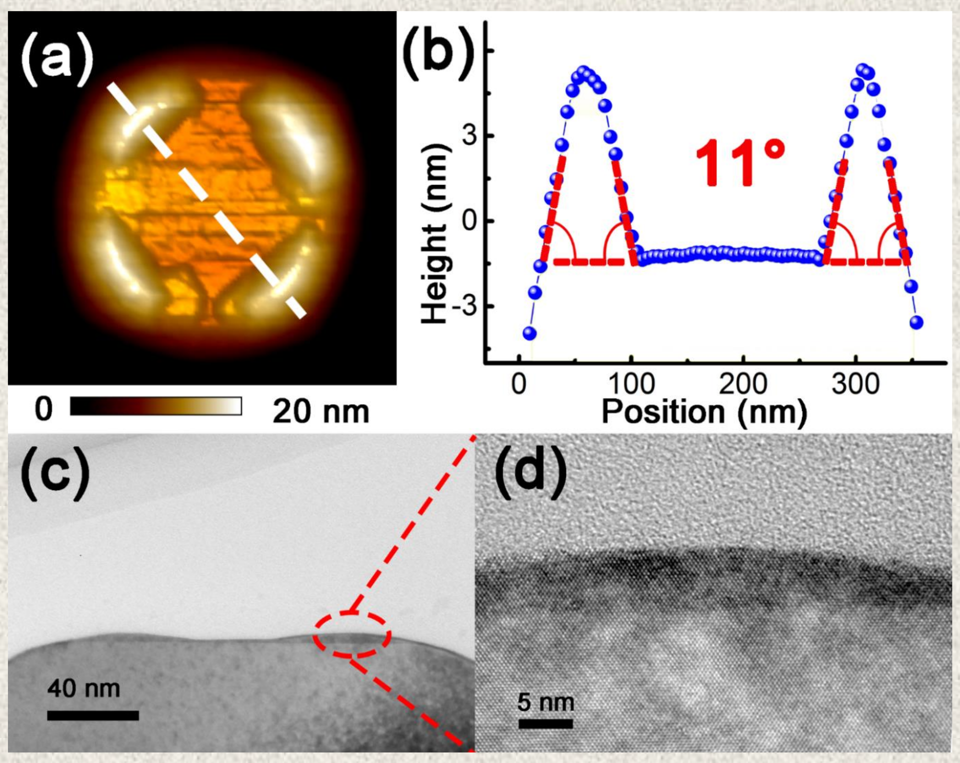

Figure 3. a) 3D AFM image (0.43×0.43 μm²) of single QDM on a pillar, b) the cross-sectional height profile along the dashed line in a), c) TEM image of two dots on the pillar top, d) high-resolution cross-sectional TEM image of the dot denoted by dashed circle in c).

- Ge QD is crystalline and defect-free.
- Such hybrid pillar-QN system is the potential candidates for the innovative optoelectronic devices due to the compatibility with sophisticated Si integration technology.

Discussion

- The diffusion of Ge adatoms is controlled by the surface chemical potential (SCP), which is related to the curvature and the strain field on the surface. We systematically analyze the actual distribution of deposited Ge around the pillar based on the SCP and its variation with the Ge deposition thickness Z.

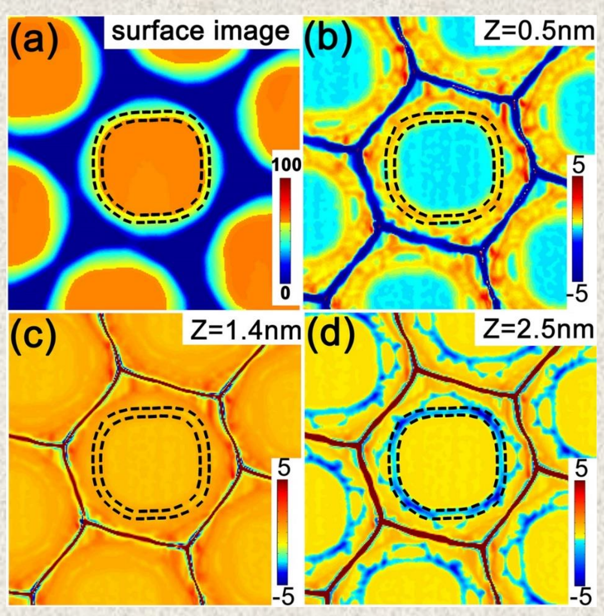

Figure 4. a) Typical AFM images (1×1 μm²) of the ordered Si nano-pillars before Ge growth, b), c) and d) the corresponding SCP around the pillars with the parameter Z of 0.5 nm, 1.4 nm, and 2.5 nm, respectively. The two black dashed circles denote the top edge of the pillar.

- Ge adatoms migrate from local maximum to local minimum of SCP. We calculate the difference ($\Delta\mu=\mu_{center}-\mu_{edge}$) of the SCP at the top center (μ_{center}) and edge (μ_{edge}) of the pillar as a function of the parameter Z. Our results clearly disclose the inherent mechanism of the Ge growth on the Si pillar.

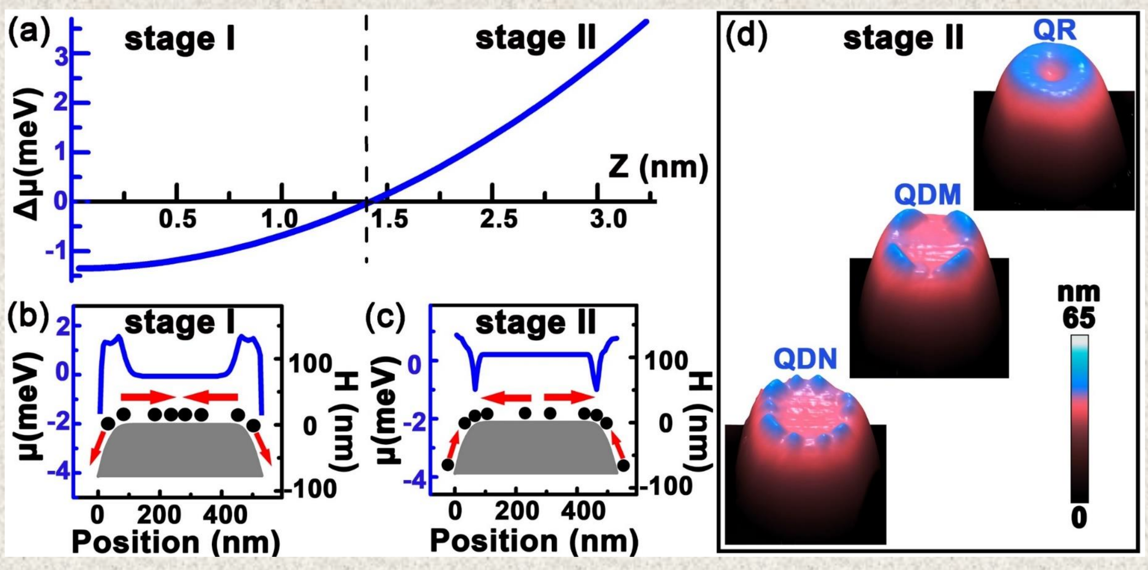

Figure 5. a) The difference ($\Delta\mu=\mu_{center}-\mu_{edge}$) of the SCP at the top center and edge of the pillar as a function of the parameter Z, b) and c) the typical SCP (blue line) and the height profile (gray region) across the center of a pillar in the growth stage I and II, respectively, d) the AFM images of three typical QNs, the QDN, the QDM and the QR, on the pillar.