Site-Controlled and Size-Homogeneous Ge Islands on Prepatterned Si

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We report on a combination of lithography and self-assembly techniques which results in long-range two-dimensionally ordered Ge islands. Island lattices with perpendicular but also with obliquely oriented unit vectors were realized. Quantitative analysis of the island topographies demonstrates that the size dispersion of these islands is much smaller than that found on flat substrates. Furthermore, island formation on the patterned substrates is observed already for a smaller amount of Ge deposition than on unpatterned ones.

Introduction

Semiconductor islands have attracted a lot of interest because of their physical properties and their potential for devices. A simple route to obtain such islands is to exploit the so-called Stranski-Krastanow (SK) growth mode. Beyond a critical thickness of a wetting layer, three-dimensional (3D) islands form spontaneously to reduce the misfit strain. In general, these defect-free islands nucleate at random positions and exhibit rather large size dispersions. In the Ge/Si system for growth temperatures around 600°C, typically a bimodal distribution is found, consisting of pyramid- and dome-shaped islands. However, islands with a narrow size distribution and a site-control are demanded both for fundamental investigations and for applications. Recently, major progress was reported by combining lithography and self-assembly techniques for the positioning of islands. So far two-dimensionally long-range ordered islands were reported for a square lattice, either by using oxide masks or by growing directly on prepatterned substrates, which was demonstrated by our group [1], [2]. However, this is not entirely sufficient to demonstrate the intentional site-control of the islands. Furthermore, no quantitative analysis of the size homogeneity of the islands on patterned substrates has been done so far. In this letter, Ge islands grown on prepatterned Si (001) substrates in a parallelogram lattice, as well as in a square lattice, are shown. A detailed analysis of their surface morphology demonstrates that a breakthrough was achieved as far as the intentional site-control and the size homogeneity of the islands are concerned [3].

Experimental

Sample Preparation

The Si (001) templates were fabricated by holographic lithography via double exposure and reactive ion etching (RIE), which result in 2D periodic pits on the surface. In these 2D lattices of the pits, the length and the orientations of the unit vectors can be intentionally changed. After an ex-situ chemical cleaning and an in-situ thermal desorption of the patterned and flat substrates, a 130 nm Si buffer layer was grown at a rate of 0.5 Å/s ramping the temperature from 500 °C to 650 °C. Subsequently 4 – 10 monolayers (MLs) Ge were deposited at a rate of 0.05 Å/s at 700 °C with 7 s growth interruption after each monolayer. For comparison, islands on patterned and flat substrates were strates were grown simultaneously. In the following, the samples with n MLs Ge deposition on prepatterned and flat substrates are named as Pn and Fn, respectively. Their surface morphologies were investigated in air with a Park Scientific atomic-force microscope (AFM) using the contact mode with an ultra-sharp tip. The AFM images with 512 x 512 points are analyzed in detail.

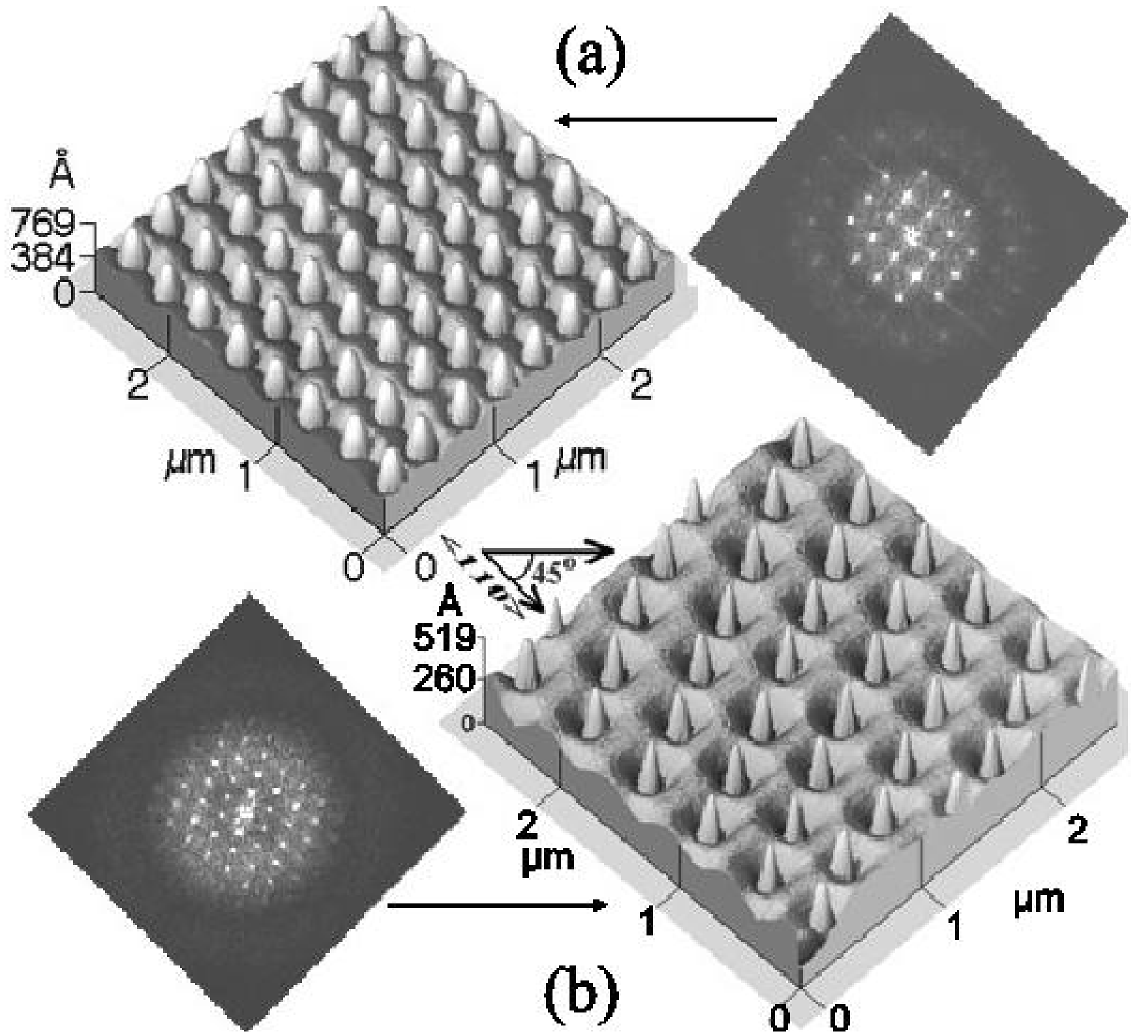

Fig. 1: 3D topography of the islands in (a) sample P10 (period: 370 x 370 nm, along <110> directions), (b) sample P6 (period: 400 x 400 nm, along [110] and [100] directions). The Fourier transforms (FT) of the topographies are also shown at the left in (a) and right in (b), their sizes are 0.034 nm^{-1}, after Ref. [3].

Measurements

The 3D topographies and their 2D Fourier transforms (FT) of samples P10 and P6 are shown in Figs.1 (a) and (b), respectively. Evidently, the islands on these patterned substrates are perfectly two-dimensionally arranged. In the FT images, a number of narrow satellite peaks in 2D plane are clearly visible. Higher-order satellite peaks are damped, primarily due to the envelope function that is determined mainly by the size and the shape of the islands. These FT images explicitly demonstrate the 2D long-range ordering (LRO) of the islands, in a square lattice along two <110> directions in Fig. 1 (a), and in a parallelogram lattice along [110] and [100] directions in Fig. 1 (b). It also implies that the regular arrangement of the islands can be intentionally determined on the prepatterned substrates. For comparison, the 3D topographies of the islands grown on flat substrates (samples F10 and F6) were investigated as well, for which the islands are randomly distributed. Another important result of the islands grown on patterned substrates is that they are mono-modal. From the aspect ratios and the morphologies of the island, it can be seen that only dome-shaped islands grow in these samples. Our surface orientation analyses of the islands in samples P6 and P10 show that the dominant facets of these islands are {15 3 23} and {1 1 3}, like for the growth on unpatterned substrates. On the other hand, in sample F10, some superdome-shaped islands (4.5% out of 16/μm^2) appear.

The 2D periodic pits after Si buffer layer growth look like inverted truncated-pyramids, in general with sidewall slopes in the range of about 4.5° ~ 15° and depths smaller than 20 nm. The sidewalls of the pits are composed of steps. In analogy to the growth of Ge on stripe-patterned substrates, Ge (or Ge-Si) ad-dimers on the terraces between the pits readily migrate to the edges and tend to diffuse to the sidewalls. Those at the sidewalls prefer to migrate downwards. As a result, Ge atoms tend to accumulate at the bottom, i.e. at the intersections of the sidewalls, facilitating there the nucleation of Ge-rich islands. Given the small pit bottom area, only one island per pit can be grown. This qualitative model for the growth process is confirmed by the island ($\langle H \rangle$ = 95 Å) formation in sample P4 with only 4 MLs Ge depositions, as shown in Fig. 1 (b). In sample F4 grown on a flat substrate, however, no islands are observed. The islands in sample P4 are all lens-shaped without particular facets. During growth, the Si-Ge intermixing impact on the size and/or shape of the islands, but it essentially does not affect the positioning of the islands. The photoluminescence data of capped islands on patterned and on flat substrates16 indicate that the amount of SiGe intermixing is similar. From preliminary x-ray data we obtained for the growth temperature of 700°C an average Ge content of about 45% for the dome-shaped islands on both patterned and flat substrates.

The excellent size homogeneity of the islands in samples P_n (n > 6) is mainly attributed to the periodic structure on patterned substrates. The surface on patterned substrates is composed of 'unit cells'. Based on the above discussion, it is reasonable to assume that only Ge atoms deposited within these unit cells can take part in the islanding in the corresponding pits. Consequently, the number of Ge atoms that can contribute to each island is about the same. In addition, the island average size in samples P_{10}, P_6 and P_6(A1) is larger than that in the corresponding samples F_{10} and F_6, respectively, Therefore, with same amount of Ge deposition, larger islands are formed in samples P_n than in samples F_n (n > 6). To some extent we can adjust the size of the coherent islands to the desired value with excellent homogeneity, only via changing the amount of the deposited Ge.

Conclusion

In summary, we realized both two-dimensional long-range ordering and size homogeneity of Ge-rich islands via depositing Ge on the prepatterned Si (001) substrates. The main features of the island growth on the patterned substrates are explained qualitatively. Our results demonstrate that the regular island arrangement and their homogeneous size can be adjusted within certain limits to the desired ones by combining the lithographic and the self-assembly techniques. These achievements on the site-control and the homogeneity of the islands will stimulate both fundamental investigations and device applications.

Acknowledgements

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References

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