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Strain Engineering for Control of Self-Organized Quantum Nanostructures

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1. Introduction

Self-organization of nanostructures on semiconductor surfaces is attractive because it is free from the size limitation in optical lithography or the writing-speed limitation in electron lithography. For this approach to be utilized in Si integrated systems, however, fluctuations in size, shape, and position of such nanostructures have to be controlled. We have developed techniques to design atomic structures on Si (111) surfaces that serve as templates for self-assembled Ge nanostructures [1-3] and found that atomic steps and the reconstructed domain boundaries are good templates for fabricating Ge quantum dot networks. In the case of coherently grown Ge nanostructures, on the other hand, the strain field plays a more important role than atomic steps and domain boundaries.

The strain effect has a variety of aspect for self-assembled Ge nanostructures on Si. Its magnitude determines the size and its symmetry the shape. The strain distribution influences the nanostructure nucleation sites. Since the coherently grown Ge nanostructures induce strain on the substrate surface, interaction between the nanostructures are generated through the substrate strain. In this paper, we propose strain engineering on Si substrates as a way to control self-assembled Ge nanostructures.

2. Artificial Control of Strain Distribution

Nucleation sites of the Ge dots on Si(001) are sensitive to the strain field of the substrate. This was shown in a multilayer consisting of the Ge island layers and the Si spacer layers [4]. In this case, Ge island nucleation takes place preferentially just above the embedded Ge islands as shown in Fig. 1(a). Based on this mechanism, we have developed a way to artificially control the strain distribution on Si surfaces [Fig. 1(b)]. Oxygen ion was implanted through an oxide mask formed by the standard Si process. Then the substrates were annealed at 1325°C to form buried oxide inclusions. Through this process, strain field is generated by the volume expansion accompanying the Si oxidation. The SiO_2 inclusions are thermally stable and therefore any subsequent processes can be achieved upon this substrate.

We applied the strain-distribution-controlled substrate to Ge dot positioning. Figure 2 shows an example of Ge island arrangement grown on Si(001). The oxide inclusions are buried along a line as shown in Fig. 2(a) and the Ge islands align along the buried inclusion region as shown in Fig. 2(b). This demonstrates that artificial control of the strain field is effective in forming a regular arrangement of coherently grown Ge quantum dots on Si(001).

3. Effect of Strain Field Symmetry

Since Si(001) and Si(111) surfaces are elastically isotropic, the grown Ge islands are generally dot-shaped. To examine the symmetry effect of strain field, we used Si(113) that is elastically anisotropic [5]. Figure 3 shows an STM image of Ge nanowires grown on a Si(113) surface. The Ge deposition coverage was 6.2 monolayers and the growth temperature 430°C. The nanowires are elongated toward the [33-2] direction and facetted to form (159) and (519) side planes. This result shows that strain symmetry is an important factor in controlling the nanostructure shape, in particular to select quantum dots or quantum wires.

4. Interaction through Strain Field

The strain field generates long-range interaction between Ge nanostructures. This is clearly demonstrated in Fig. 3. All the nanowires are separated by the wetting layer. Since the nanowires are coherent, a large strain is induced on the wetting layer around their edges. This strain is visualized in Fig. 4, where the depressions of the wetting layer are observed around the nanowire edges. The strain on the wetting layer creates a repulsive force between the nanowires. It was found that there are many atomic steps on the (159) and (519) side facets. The nanowires can easily change growth direction by forming atomic steps on the side facets. Consequently, when two nanowires approach each other, they change their growth direction to make the spacing uniform. This suggests that control of the magnitude and distribution of the strain field is a key to controlling the spacing of self-assembled quantum nanostructures.

5. Conclusions

We have demonstrated strain engineering towards control of self-assembled Ge quantum nanostructures. This is of particular importance for coherently grown nanostructures, such as quantum dots on Si(001) and quantum nanowires on Si(113). Control of the strain field will be a key issue in the integration of well-defined and well-arranged quantum nanostructures using a self-assembly process.

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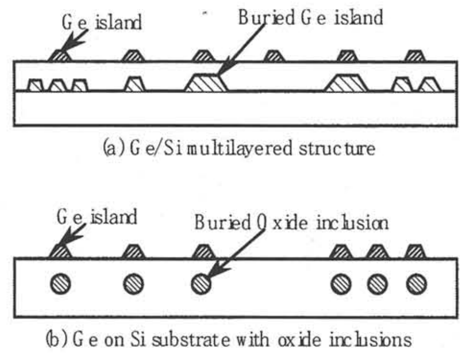

Fig. 1. Positioning of self-assembled Ge nanostructures.

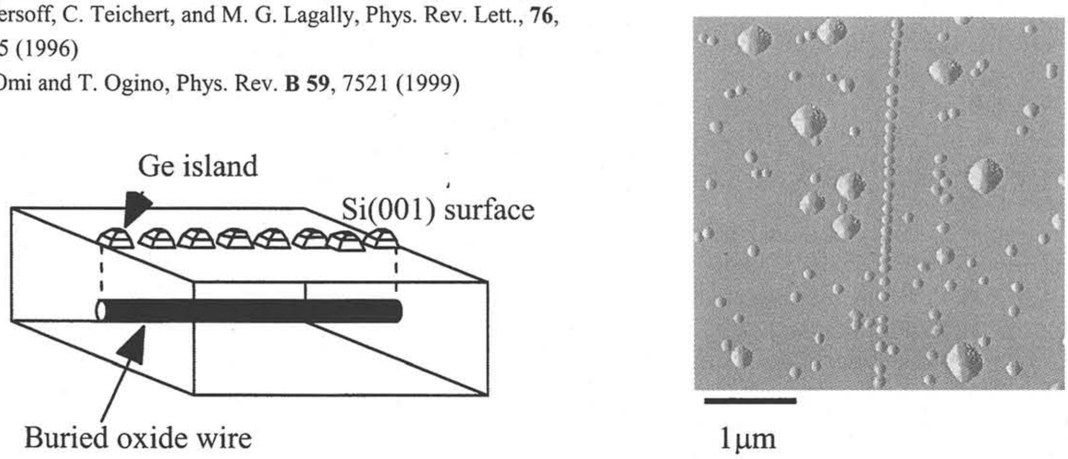

Fig. 2. Ge quantum dots grown on strain-distribution-controlled Si(001) surface. (a) Schematic view of the oxide inclusion and Ge islands, (b) AFM image of the Ge quantum dots arrangement.

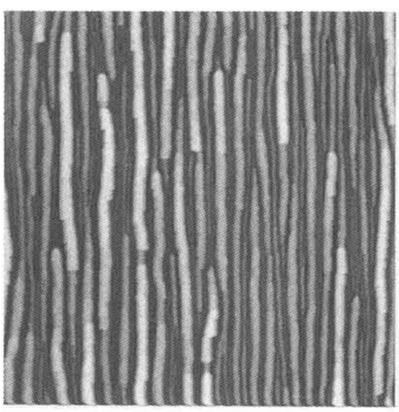

Fig. 3. STM image of Ge nanowires grown on a Si(113) surface. The image area is 500 nm x 500 nm.

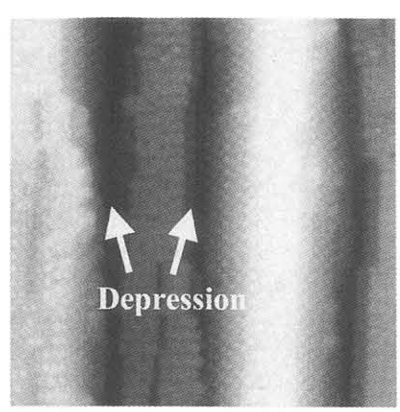

Fig. 4. STM image of the wetting layer between Ge nanowires. The image area is 40 nm x 40 nm.