自己組織化の自己制御性が生み出す自発的な組織形成への影響
Self-organization of In nanostructures on Si surfaces

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Methods of forming various In nanostructures on Si surfaces are demonstrated. Using a high-index Si(311) surface, isolated nanotriangles and wires were grown by optimizing the deposition rate and substrate temperature. In contrast, nanodots were formed by the deposition of In on a Si(111)–In–311 × 31 surface at room temperature (RT) deposition. On a Si(111)–In–4 × 1/√3 × 1/√3 coexisting surface, nanowires were selectively grown in the Si(111)–In 4 × 1 area by RT deposition through the nucleation promoted by the boundary barrier produced by the surrounding 311 area. Details were studied using scanning tunneling microscopy. © 2009 American Institute of Physics. [DOI: 10.1063/1.3085960]

Nanometer-sized low-dimensional structures, such as nanowires and nanodots, have been attracting growing interest because they provide typical systems for exploring interesting physical phenomena, such as quantized conductance, charge density wave, metal-insulator transition (MIT), and quantum confinement in reduced dimensions. Technologically, they also have great potential for application, for example, in optoelectronic and nanoelectronic devices. Among various methods employed to fabricate nanoscale structures, self-organization or self-assembly processes on material surfaces are used to create large-scale arrays of nanostructures. For example, strain in lattice-mismatch heteroepitaxial growth gives rise to the self-organization of ordered arrays of semiconductor quantum wires and dots with uniform size and shape. Reconstructions, dislocations, steps, and facets also induce selective growth on a substrate surface.

Indium (In) is an attractive material widely used in semiconductor technologies as well as in fundamental studies. The growth of 1.0 ML of In on a Si(111) surface, for example, forms a self-assembled In nanowire array, In–(4 × 1). It is a typical quasi-one-dimensional (quasi-1D) metal system that induces MIT. A recent study has revealed that the MIT of this system can be well controlled by optical doping, making this system a more applicable nanoscale building block that can controllably transport electrical charges. Owning to its anisotropic structure, the In–(4 × 1) surface has been used as a template for the growth of nanostructures. Self-organized Pb islands of uniform width and elongated shape were grown on the surface by taking advantage of substrate-mediated anisotropic strain relaxation. Adsorbed Co atoms showed a self-alignment on the surface by quasi-1D electron-gas-mediated interactions. The epitaxial Ag film on In–(4 × 1) surface formed a well-ordered stripe superstructure. However, only a uniform wire structure has been reported, and the method, for example, of forming isolated In nanowires or In nanodots on a Si surface has not been realized despite the interest of their applications. For more effective applications of the various attractive characteristics of In/Si system, development of the methods that enable the fabrication of In nanostructures in more applicable forms is required. In this letter, we present the methods we found for forming various In nanostructures on Si surfaces.

Experiments were carried out in an ultrahigh vacuum system with a base pressure of 1.5 × 10⁻⁸ Pa. Clean Si(111) and Si(311) surfaces were prepared as substrates by standard procedures. A heat-resistant evaporator was used to deposit In atoms at a flux of 0.3–6.0 ML/min. Scanning tunneling microscopy (STM) images were taken at room temperature (RT).

First, we show the methods of forming isolated nanotriangles and wires. After preparing a clean Si(311) surface with a 3 × 2 structure, the deposition of more than 1 ML of In on the surface at ~300 °C formed a homogeneous Si(311)–In–3 × 2 structure, as shown in Figs. 1(a) and 1(b). On the other hand, for a substrate temperature lower than 50 °C, a nanoscale structure was formed on the surface, but just small clusters [Figs. 1(c) and 1(d)]. Since they do not follow the underlying symmetry, they are considered as amorphous. In contrast, triangular islands were grown on the surface for the substrate temperature at 200–250 °C [Figs. 1(e) and 1(f)], whose atomic structure is similar to that of the Si(311)–In–3 × 2 surface. The distribution of the size of the triangular island measured from the STM image is shown in the inset in Fig. 1(e). Furthermore, when the temperature was kept at 50–150 °C, a single nanowire was formed along the upper edge of the triangular island in the [110] direction [Figs. 1(g) and 1(h)]. The edge of the triangular structure here is considered to function as a barrier that traps In atoms, promoting the formation of In nanowires.

To grow In nanowires, a high In deposition rate (~2.0 ML/min) was needed with the optimization of the substrate temperature. As the inset in Fig. 1(g) shows, the distribution is narrower than that in Fig. 1(e).

Second, we represent the method of forming In nanodots on a Si surface. With the deposition of 0.6 ML of In atoms on a clean Si(111)–7 × 7 surface at 300 °C, a uniform Si(111)–In–√31 × √31 structure is formed, which was used as the substrate. When In atoms were deposited with the substrate temperature being kept at RT, In nanodots were grown on the surface, as shown in Fig. 2. Figures 2(a)–2(c) show the STM images obtained for the nanodots grown by depositions of about 0.1, 0.2, and 0.3 ML of In, respectively. From the diameter distributions of the nanodots shown in the insets, the size of the nanodots increases with deposition ra-

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FIG. 1. STM images obtained for the large and small areas of (a) and (b) Si(311)–In–3×2 (substrate temperature $T_s \sim 300$ °C, 1–15 ML; large islands are also formed at high coverage, $V_e=-2.0$ V, $I_e=0.2$ nA). [c] and [d] small In clusters ($T_s=\sim 50$ °C, 1 ML, $V_e=2.0$ V, $I_e=0.2$ nA), and (c) triangular structures ($T_s=200–250$ °C, 1 ML, $V_e=2.0$ V, $I_e=0.2$ nA), and (g) triangular structures with nanowires ($T_s=50–150$ °C, 1 ML, $V_e=-2.0$ V, $I_e=0.2$ nA). The insets in (e) and (g) show the distributions of the triangular size (length of side without wire) and the wire length reduced by the averaged lengths of $L_a$ (16 and 8.1 nm), respectively.

FIG. 2. STM images of In nanodots grown at RT with In coverages of (a) 0.1 ML ($V_e=-1.0$ V, $I_e=0.2$ nA), (b) 0.2 ML, ($V_e=-2.0$ V, $I_e=0.5$ nA), and (c) 0.3 ML ($V_e=-1.0$ V, $I_e=0.2$ nA). The diameter (d) distribution of In dots is shown in the inset, the average value of which is shown in (d) as a function of coverage.

structure, it is still a challenging issue to experimentally grow In wire arrays on a homogeneous In-4×1 surface because of the fast diffusion of In adatoms on the surface even at RT. Here, we realized the formation of In nanowires on the In-4×1 surface with the combination of the RT growth and use of an In/Si(111)-4×1/$\sqrt{3}$×$\sqrt{3}$ coexisting phase as the substrate. Figure 3(a) shows an STM image of the template surface grown by the deposition of ~0.7 ML of In on a Si(111)-(7×7) surface at ~400 °C. As shown in Fig. 3(a), the surface consists of two phases with the 4×1 and $\sqrt{3}$×$\sqrt{3}$ structures. The In coverage of the $\sqrt{3}$×$\sqrt{3}$ phase is about 0.6 ML,14 while that of the 4×1 phase is 1 ML.14 Therefore, the density and size of the 4×1 and $\sqrt{3}$×$\sqrt{3}$ phase areas can be controlled by adjusting the substrate temperature and In coverage from 0.6 to 1.0 ML. After the structure with the two phases at a certain ratio was formed, the sample was cooled to RT, and In atoms were deposited.

Figure 3(b) shows an STM image obtained after the deposition of ~0.2 ML of In on the template surface shown in Fig. 1(a). As was observed in Fig. 2, In nanodots are formed on the $\sqrt{3}$×$\sqrt{3}$ phase that surrounds the 4×1 phase area. However, In nanowires are selectively formed in the In-(4×1) area. Since no wires but large islands were formed on a homogeneous 4×1 surface without the $\sqrt{3}$×$\sqrt{3}$ phase at RT, the boundary barrier may play an important role in the nucleation and growth of the In wires on a Si(111)–In-4×1/$\sqrt{3}$×$\sqrt{3}$ surface. Similar boundary effect may work in part in the case shown in Figs. 1(g) and 1(h). To clarify the detailed mechanism, further study is necessary.

Figures 3(c)–3(f) show the STM images of the nanowire arrays obtained for three different In coverages and their cross sections. The wire array of 0.1 ML In coverage shows a wide spacing. With increasing In coverage to 0.2 ML, the space becomes uniform with an eight times periodicity in the
In future semiconductor technologies as well as to fundamental findings are expected to make the system more applicable to controlling nanoscale electronic and optical devices. The elements will enable further development in designing and controlling nanoscale electronic and optical devices. The findings are expected to make the system more applicable to future semiconductor technologies as well as to fundamental research studies. Studies on the detailed atomic structures and electronic properties of the nanostructures are in progress.

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