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Dysprosium-induced nanowires on Ge(001)

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ABSTRACT

Dysprosium-induced, self-assembled nanowires on Ge(001) were studied by scanning tunneling microscopy (STM) and low energy electron diffraction (LEED). For this, submonolayers of dysprosium were deposited on Ge(001). After subsequent annealing, the surface shows a variety of structures as different kinds of wires with varying thickness, larger islands and surface defects like missing dimers and vacancy rows perpendicular to the Ge(001)-dimer rows. The structures are forming on all intact Ge(001)-terraces. In contrast to dysprosium on Si(001), on Ge(001) no wetting layer is found. In this work we focus on the thinnest nanowires, which have a width of four times the Ge(001)-lattice constant. STM topographies of the unoccupied states show a two-fold superstructure on the wires. In contrast, topographies of the occupied states show that the structure of the wires is less regular. They exhibit elevations with distances, which are multiples higher than two of the Ge(001)-surface lattice constant. Density of states mapping reveals a cell structure of the nanowires. Possible explanations for this behaviour are discussed.

1. Introduction

Quasi one-dimensional (1D) structures on semiconductor surfaces are in the scope of scientific research for more than a decade. They exhibit exotic quantum phenomena like Luttinger-Liquids [1,2], Charge-Density-Waves [3] or magnetic ordering in 1D or quasi-1D [4].

Due to the magnetic properties of rare earth (RE) metals and their alloys with silicon or germanium as well as due to their limited dimensionality, rare earth induced nanowires on Si or Ge surfaces promise interesting quantum effects. As a consequence much attention has been focussed on self-organized nano-structures of rare earth metals on silicon surfaces. It has been found that rare earth silicides form different nanowire structures on Si(001) [5–10], Si(110) [11] and Si(557) [12].

ARPES studies of the electronic structures of RE-silicede systems like Gd- and Er-silicide nanowires on Si(001) have revealed one-dimensional metallic band structures [13,14]. In YSi_2-nanowires on Si(001) short-range charge-ordering was found [15] and with $GdSi_2$-nanowires on Si(001) nanotransport measurements were performed [16].

Dy-induced structures on Si(001) are of particular interest in relation to Dy-induced structures on Ge(001), because the bare surfaces have a similar atomic structure. On Si(001) Dy-induced structures grow in the Stransky–Krastanow mode, i.e. a two-dimensional (2D) wetting layer [8,17] coexists with Dy-silicide nanowires. Detailed structure models of Dy-silicide nanowires are proposed [9,18,19,13], and their electronic structure has been investigated on vicinal Si(001), where the nanowires grow unidirectional in direction of the surface steps [6, 20,10,13,21]. The measurements show metallic behaviour for the so-called broad dysprosium silicide nanowires and nonmetallic behaviour for the so-called thin dysprosium silicide nanowires.

It is interesting to compare the rare earth induced structures on silicon to rare earth induced structures on germanium surfaces. However, less work than on rare earth silicides has been done on rare earth induced nano-structures on germanium surfaces. Dysprosium on Ge(111) yields a two-dimensional dysprosium germanide [22], while holmium forms nanowires [23] on that substrate.

On Ge(001) holmium induces structures as nanowires, small islands and defect structures [24]. In contrast ytterbium on Ge(001) leads to a two dimensional (4×2)-reconstruction [25]. Properties of 50 Å thick Dy films on Ge(001) were investigated by Bhuiyan et al. [26]. However, to our knowledge experimental data of rare earth metals on germanium surfaces are quite limited and to improve our understanding it is necessary to gain further insight into growth processes as well as structural, morphological and electronic features of rare earth metals on Ge(001).

In this paper we provide experimental data of dysprosium induced self-organized nano-structures on the Ge(001)-surface studied by scanning tunneling microscopy (STM) and low energy electron diffraction (LEED).

The paper is organized as follows: In Section 2 we briefly introduce experimental details. This is followed by the results and discussions in Section 3. The measurements reveal the formation of a variety of different Dy-induced structures on Ge(001) as quasi one-dimensional (1D) nanowires, two-dimensional islands and several kinds of vacancy defects. This is described in detail in Section 3.1. Particularly interesting are the thinnest nanowires, which have a width of four lattice constants

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and varying lengths up to 50 nm. Their discussion starts in Section 3.2. They grow perpendicular to the dimer rows of the substrate. These nanowires exhibit different structures depending on the bias voltage. Topographies of unoccupied states clearly show a twofold superstructure on the wires, while topographies of the occupied states exhibit overall less regular ordering which partially reveals higher multiples of the lattice constant. This is shown in Section 3.3. Density of states (DOS) mapping reveals a deeper insight into the atomic structure of the nanowires as shown in Section 3.4. Several effects and explanations of the atomic structure are discussed in the context of experimental findings in Section 3.5. Our conclusions are drawn in Section 4.

2. Experimental procedure

For the experiments, antimony doped germanium substrates were used with a specific resistivity of 0.01 to 0.1 Ωcm. They were chemically etched using the recipe of Blumenstein et al. [27], in situ flashed at temperatures above 900 °C, Ar^+-sputtered at 0.5 keV and annealed at about 700 °C. During the deposition of dysprosium, the surface was held at a temperature of about 500 °C. The evaporation was performed with an electron beam evaporator out of a tantalum crucible. For the data presented here, about 0.15 monolayers of dysprosium were deposited on the Ge(001)-surface. After the deposition, the samples were annealed for three minutes at 500 °C. Longer annealing-durations lead to increased growth of islands and broader nanowires. The STM-measurements were performed with a commercial Omicron low-temperature STM, where sample and tip are located inside a cryostat. Electrochemically etched tungsten tips were used after calibration measurements on an Ag(111)-crystal. For dI/dV-mapping a lock-in-amplifier was used. The modulation frequency was about (840 ± 5) Hz and the modulation voltage was $V_{pp} = 30$ mV (peak to peak). The dI/dV-maps show the local density of states (LDOS) in a range of ± 15 mV around the bias-voltage.

3. Results and discussion

3.1. Arrangement of the nanowires on the Ge(001)-surface

With a coverage of about 0.15 monolayers (ML) of Dy on the Ge(001)-surface and annealing for three minutes, all intact Ge-terraces are covered with several nanowires of different widths as well as with almost rectangular islands as shown in Fig. 1a. The nanowires grow in two domains rotated to each other by 90°. Partly rectangular islands form, which are higher than the nanowires. The nanowires lengths reach up to 50 nm and are limited by the terrace width in most cases. In some cases however, terraces grow along nanowires and the terrace gets a bulge at that place (marked by rectangles in Fig. 1a). This effect also appears for holmium-induced nanowires on the Ge(001)-surface [24]. At the same coverage of 0.15 ML but with a longer annealing-time, significantly more Dy-induced islands and larger wire-structures appear on the surface and the number of narrow structures decreases. This observation can be explained by Ostwald-ripening and indicates, that the structures are not in thermal equilibrium but yield insight into early stages of the growth process.

Results obtained from LEED measurements of the pristine Ge(001)-surface are displayed in Fig. 1b. The discrete LEED-spots are due to the p(2 × 1)-reconstruction of the Ge(001)-surface and the crossed streaks are caused by flipping dimers of the c(4 × 2)-reconstruction of the Ge(001)-surface. All reconstructions have two domains on the Ge(001)-surface, which are rotated by 90° to each other. Detailed studies of the pristine Ge(001)-surface can be found in [28] and [29].

The LEED-pattern of the Dy-covered Ge(001)-surface is shown in Fig. 1c. It differs only slightly from the LEED-pattern of the pristine Ge(001)-surface, showing two additional diffraction-streaks on the main axis, which vanish at higher electron energies. This indicates that there is no wetting layer reconstruction as on Si(001) [8]. Even though

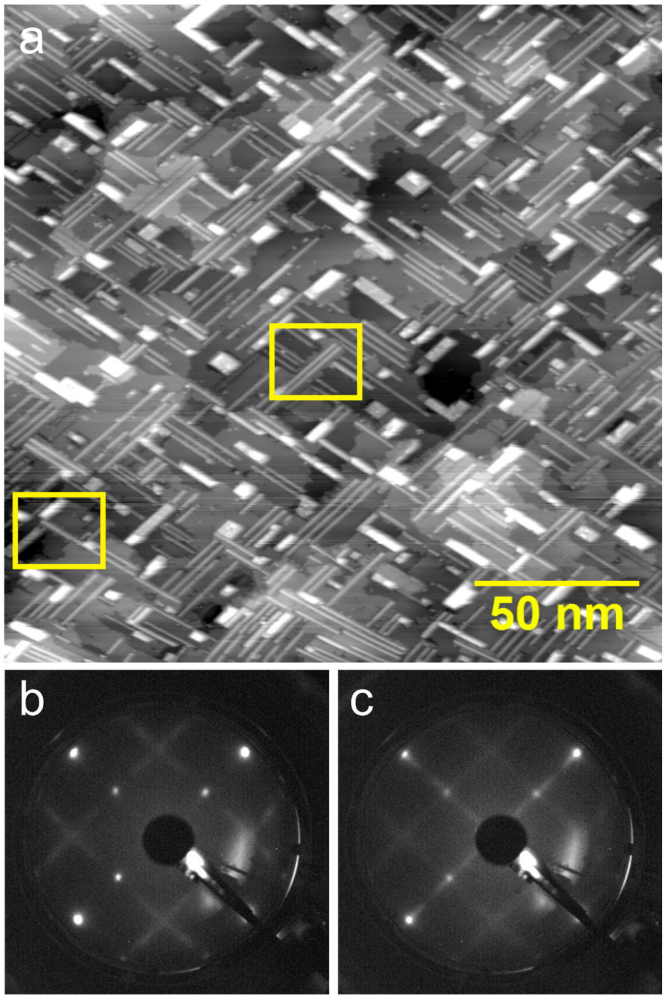

Fig. 1. a) Overview scan of a Ge(001)-surface covered with 0.15 monolayers of Dy. $V_{Bias} = +2.09$ V; $I = 0.3$ nA; $T = 78$ K. All Ge(001)-terraces are covered by nanowires. Terraces with bulges along nanowires are marked by rectangles. In the lower third of the image creep of the STM is visible. The image is background corrected. b) LEED-pattern of a plain Ge(001)-surface. The discrete spots are caused by the p(2 × 1)-reconstruction, the crossed streaks are caused by the c(4 × 2)-reconstruction. c) LEED-pattern of a Ge(001)-surface covered with 0.15 monolayers of Dy. There are two additional streaks on the main axis. The electron energy in b) and c) is $E = 20.4$ eV, respectively. LEED-measurements were performed at room temperature.

a (2 × 1) reconstructed wetting layer cannot be excluded from the LEED-measurements, high resolved STM-images (Fig. 2) show the dimer row structure of the bare Ge(001) surface between the Dy-induced structures, and exclude the presence of a wetting layer. It cannot be excluded that there are some kind of flipping atoms or dimers on the Dy-induced nanowires, which lead to the additional diffraction streaks. However, it is more likely that they are produced by non-periodic structures. The distances between the nanowires differ and can be every multiple of the Ge(001)-surface lattice constant of 3.99 Å. It is also possible, that the streaks are due to defects in the Ge(001)-(2 × 1) reconstruction along the nanowires, which are seen in STM in Fig. 2.

3.2. Structure of the nanowires

Fig. 2a shows parts of neighbouring Ge(001)-terraces with typical Dy-induced structures in detail. In contrast to the adsorption of Dy on Si(001) [8], the Ge(001)-surface is not fully covered and no wetting layer is found after deposition of Dy. The Ge(001)-dimer rows are marked with an A in Fig. 2b. They are visible between the Dy-induced nano-structures. Vacancies in the dimer rows appear often alongside