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Atomically precise self-organization of perfectly ordered gadolinium–silicide nanomeshes controlled by anisotropic electromigration-induced growth on Si(1 1 0)-16 × 2 surfaces

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ABSTRACT

Detailed scanning tunneling microscopy and spectroscopy (STM and STS) studies for the effects of thermal migration and electromigration on the growth of gadolinium–silicide nanomeshes on double-domain Si(1 1 0)-16 × 2 surfaces are presented to identify the driving force for the self-organization of a perfectly ordered silicide nanomesh on Si(1 1 0). STM results clearly show that the anisotropic electromigration effect is crucial for the control of the spatial uniformity of a self-ordered silicide nanomesh on Si(1 1 0). This two-dimensional self-ordering driven by the anisotropic-electromigration-induced growth allows the sizes and positions of crossed nanowires to be precisely controlled within a variation of ±0.2 nm over a mesoscopic area, and it can be straightforwardly applied to other metals (e.g., Au and Ce) to grow a variety of highly regular silicide nanomeshes for the applications as nanoscale interconnects. Moreover, the STS results show that the anisotropic electromigration-induced growth causes the metallic horizontal nanowires to cross over the semiconducting oblique nanowires, which opens the possibility for the atomically precise bottom-up fabrication of well-defined crossbar nanoarchitectures.

1. Introduction

Currently, tremendous efforts have been devoted to the controlled fabrication of two-dimensional (2D) networks, consisting of two crossed nanowire (NW) arrays [1–6], with the goal to create crossbar nanoarchitectures [2,7,8]. Such nanomeshes have been used as polyvalent building blocks for nanoelectronic and nanophotonic devices, including field-effect transistors, logic gates, light-emitting diodes, demultiplexers, and memory circuits. Crossbar nanomeshes can be fabricated by nanoimprinting or atomic manipulation controlled via a scanning probe microscope. However, nanoimprinting fails to produce NWs below 8 nm in size [2,3]. Scanning probe manipulation is not suitable for industrial manufacturing purposes because it is time-consuming for mass production [9]. Self-organization provides a competitive bottom-up nanofabrication for nanomeshes because of its potential advantages of low cost, simplicity, and high throughput. For practical applications of self-organized nanomeshes in crossbar nanoarchitectures, it is of paramount importance to precisely control where the NWs grow and how the NWs assemble into a well-ordered network on an industrially reliable scale. Because self-assembled rare-earth (RE) silicide NWs with high aspect ratios have potential applications as low-resistance interconnects in nanoelectronic devices and also exhibit highly anisotropic band structures along the NW direction [10], the controlled self-organization of perfectly-ordered RE silicide nanomeshes is one of the most important long-term goals of the bottom-up approach for well-defined crossbar nanocircuits. However, most self-organization processes of silicide nanomeshes are not entirely controllable [4,5,11–13]. Moreover, the large variation in the NW sizes could substantially alter the electronic structures and the charge transport properties along their length [14,15], making these NWs inappropriate as components in large-scale integrated devices for practical applications.

Recently, we developed a template-directed 2D self-organization based on a double-domain Si(1 1 0)-16 × 2 surface [16–18]. A highly-integrated, well-ordered silicide nanomesh can be self-organized over a mesoscopic area by the heteroepitaxial growth of atomically identical silicide NWs on the periodic upper terraces of double domains on the 16 × 2 reconstruction [19,20]. The excellent regularity of such self-ordered nanomeshes is comparable to that of networks produced by lithography. Moreover,

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both the widths and spacings of these self-ordered nanomeshes can be respectively fabricated as small as ~2 nm and ~5 nm, which are much smaller than the minimum size and pitch of crossbar networks (i.e., ~8 and ~16 nm) fabricated by nanoimprinting [2,3]. Moreover, silicide nanomeshes on Si(1 1 0) surfaces are superior to the self-organized nanomeshes on metal or graphite surfaces [21–24] because the silicide nanomeshes on Si(1 1 0) surfaces are compatible with the current Si-based integrated-circuit technology [25–27] and show mesoscopic ordering.

So far, little knowledge concerns about what is crucial for the control of 2D self-organization process on a double-domain Si(1 1 0)-16 × 2 surface. A clear understanding of the growth mechanism of perfectly ordered silicide nanomeshes on Si(1 1 0) is of practical importance for the efficient bottom-up fabrication of such well-defined crossbar nanocircuits in crossbar nanoarchitectures. In this article, we further investigate in detail the template-directed 2D self-organization process based on the double-domain Si(1 1 0)-16 × 2 surface by scanning tunneling microscopy and spectroscopy (STM and STS) studies on two different post-deposition annealing procedures (i.e., at 600 and 850 °C) of Gd-silicide nanomeshes to understand which kinetics (e.g., the thermal migration or electromigration effect) mainly governs the 2D self-organization of perfectly ordered silicide nanomeshes on Si(1 1 0) templates in the resistive heating process. Based on a comprehensive analysis of all STM and STS results, we confirm that the anisotropic electromigration at 850 °C is the driving force governing the spatial uniformity of a self-ordered silicide nanomesh on a double-domain Si(1 1 0)-16 × 2 surface.

Moreover, the anisotropic electromigration-induced growth of nanomeshes causes the crossed NWs to intersect at two different vertical levels and exhibit different electronic properties, i.e., the metallic horizontal NWs cover across the semiconducting oblique NWs. The differences in both electronic properties and geometries of these crossed NWs open the possibility for their utilization in crossbar nanoarchitectures. This work also demonstrates that such a template-directed 2D self-organization can be employed as a simple and versatile method to realize the optimal bottom-up nanofabrication of well-ordered 2D silicide nanomeshes for a broad range of metals.

2. Materials and methods

2.1. Preparation of atomically clean single-domain Si(1 1 0)-16 × 2 surface

All experiments were performed in a commercial ultra-high-vacuum, variable-temperature STM system (Omicron Nano-Technology GmbH) at a base pressure of ~4×10^{-11} mbar. Device-quality flat Si(1 1 0) substrates (n-type, ~10 Ω cm) with rectangular shapes of 12×2 mm^2 were initially degassed at 600 °C for 12 h and cleaned by repeatedly flashing to 1250 °C for 5 s to remove the oxide layer and SiC; the system pressure was maintained below 1×10^{-9} mbar. Sample heating was achieved by passing a DC current through the substrate (hereafter called "direct heating") along the [1$\bar{1}$2] direction of Si(1 1 0) (i.e., the horizontal direction of the sample). Sample temperatures were monitored by an infrared pyrometer with an uncertainty of ±50 °C. Atomically clean Si(1 1 0)-16 × 2 surfaces were confirmed by the STM observation of the mesoscopically ordered 16 × 2 superstructure as shown in Fig. 1.

2.2. Preparation of coplanar double-domain Si(1 1 0)-16 × 2 surface

After an atomically clean single-domain Si(1 1 0)-16 × 2 surface was obtained, we prepared a coplanar double-domain Si(1 1 0)-16 × 2 surface (i.e., the 16 × 2 and 2 × 16 domains are coplanar) to act as a nanopatterned template for the 2D self-organization

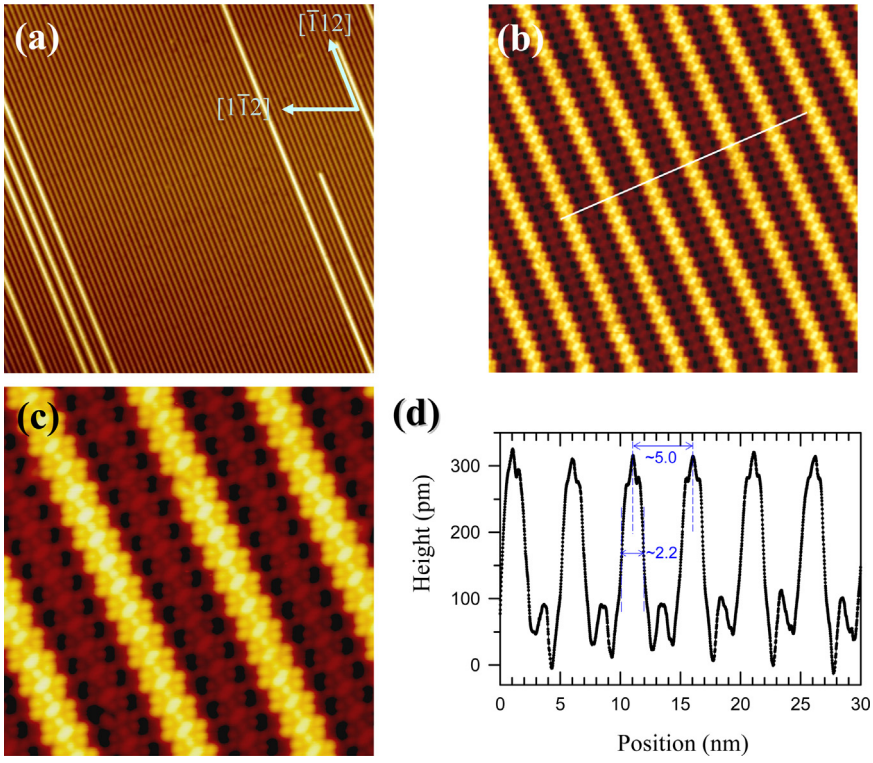

Fig. 1. STM images and topography profile of a single-domain Si(1 1 0)-16 × 2 surface: (a–c) A set of different magnified STM topographic images of the single-domain Si(1 1 0)-16 × 2 surface; (a) 450 × 450 nm^2 (bias voltage V_b = 1.5 V, tunneling current I_t = 0.25 nA), (b) 45 × 45 nm^2 (V_b = 1.5 V, I_t = 20 pA), and (c) 15 × 15 nm^2 (V_b = 1.0 V, I_t = 10 pA). (d) Topography profile across the up-and-down terraces of the 16 × 2 reconstruction along a white line marked in (b).