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Growth of Au thin film on Cu-modified Si(1 1 1) surface

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ABSTRACT

Miniaturizing of electronic devices requires that conductive elements maintain advanced electrical characteristics upon reducing their geometrical sizes. For gold, which is valued for its high electrical conductivity and stability against ambient conditions, creation of extra-thin films on silicon is hampered by formation of the quite complex Au/Si interface. In the present work, by forming a Si(1 1 1)5.55 × 5.55-Cu surface reconstruction prior to Au deposition we formed Au films with smoother surface morphology and higher surface conductivity compared to Au film grown on a pristine Si(1 1 1)7 × 7 surface. Scanning tunnelling microscopy and four-point probe measurements were used to characterize the growth mode of the Au film on a Si(1 1 1)5.55 × 5.55-Cu reconstruction at room temperature.

1. Introduction

Growth of conductive structures on Si substrates attracts considerable interest due to a constant demand for wiring tracks, contacts in integrated circuit devices, etc. Since in modern electronics there is an evident trend towards miniaturization, conductive films are required to become thinner yet maintain high electrical conductivity. In this instance, achieving a high degree of structural perfection in thin films is believed to be a prime route to attaining this goal.

Studies of Au/Si(1 1 1) interface formation have quite a long history [1,2]. It was intensively studied by means of virtually every characterization technique developed in surface science (see [3] and references therein). The commonly accepted model for room-temperature (RT) Au/Si(1 1 1) interface formation involves the growth of a silicide-like layer (Au_3Si) during Au deposition up to coverage of about 4 ML. (A monolayer (ML) is defined as 7.8×10^{14} cm^{-2} corresponding to the top-Si atom density at the unreconstructed Si(1 1 1)1 × 1 surface. Note that one atomic layer of Au(1 1 1) contains 6.9×10^{14} cm^{-2} of Au atoms, which is equal to 0.9 ML.) When deposition proceeds above 4 ML, metallic Au nucleates between the segregating Au_3Si layer and Si(1 1 1) substrate, thus forming a sandwich-like structure [4]. Scanning tunnelling microscopy (STM) studies of the initial stages of Au adsorption onto Si(1 1 1)7 × 7 [3] have revealed the formation of small Au clusters of about 0.1 ML and no intermixing of Au atoms with Si below this coverage, thus favouring a "screening" model [5,6], according to which intermixing starts only at some critical coverage.

To prevent formation of the silicide-like compound and to thus obtain better structural and electrical properties in the Au film, modification of the substrate surface with a suitable surface reconstruction may be a possible solution. In the present paper, we report on STM and four-probe electrical measurement results on Au film growth on a Cu-modified Si(1 1 1) surface. To enhance the quality of the Au thin film, we have incorporated onto the Au/Si(1 1 1) interface a quasi-periodical Si(1 1 1)5.55 × 5.55-Cu surface reconstruction (denoted as 5.55 × 5.55-Cu hereinafter), which has recently been proven to be an efficient surface modifier [7].

2. Experimental

STM experiments were carried out in an ultra-high vacuum chamber STM-VT25 supplied by Omicron Nanotechnology GmbH. Electrical measurements were performed *in situ* in a separate RIBER DEL-300 UHV chamber. Base pressure in both chambers was less than 2×10^{-10} Torr. P-doped Si(1 1 1) samples (45 Ω cm) were used as substrates. Atomically clean Si(1 1 1)7 × 7 surfaces were prepared *in situ* by flash annealing at 1280 °C after the samples were first outgassed at 600 °C for several hours. Initial 5.55 × 5.55-Cu surface reconstruction was prepared by adsorption of about 2 ML of Cu on the atomically clean Si(1 1 1) substrate at room temperature followed by direct-current heating to about 550 °C. STM measurements revealed total compliance of the resulting 5.55 × 5.55-Cu surface as previously reported [8,9]. High purity

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(6N) elemental Au was deposited onto the 5.55 × 5.55-Cu surface from a gold-covered tungsten filament. Prior to deposition, the Au deposition rate was calibrated with the STM by measuring the area fraction occupied by the Si(1 1 1)5 × 2-Au reconstruction at different Au coverages. Since this reconstruction has a well-defined composition (0.4 ML of Au [2,10]), the deposition rate could be estimated and it appears to be about 0.8 ML/min in the present experiment. In the second chamber, the Au deposition rate was calibrated by monitoring low-energy electron diffraction (LEED) spot intensities of the 5 × 2-Au reconstruction. For STM observations, electrochemically etched tungsten tips cleaned by *in situ* heating were employed. All STM images were acquired in a constant-current mode at room temperature. Electrical conductivity was measured by a four-point probe method at room temperature with probes making a square of about 0.6 × 0.6 mm^2. For the probes, electrochemically sharpened 0.6 mm thick tungsten wires were used.

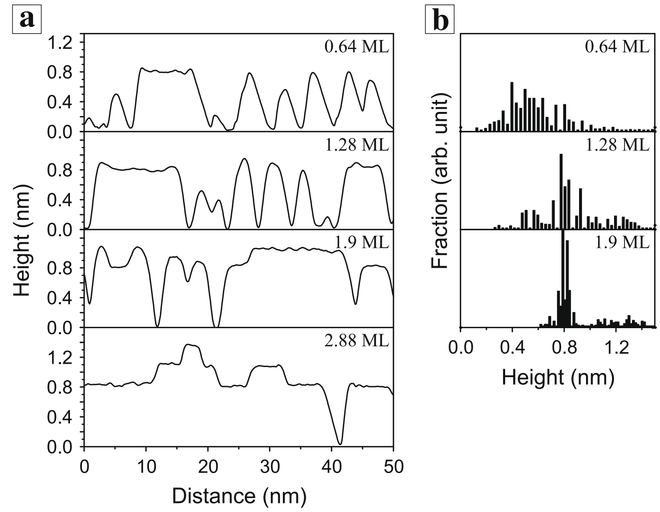

Fig. 2. (a) STM profiles along green lines in the corresponding STM images (Fig. 1). (b) Histogram for island height distributions. (For interpretation of the references to colour in figures, the reader is referred to the web version of this article.)

3. Results and discussion

Sequential stages of Au growth on the 5.55 × 5.55-Cu reconstructed surface are illustrated in the STM images shown in Fig. 1. At low Au coverage, small islands nucleate over the initial 5.55 × 5.55-Cu reconstruction. Reaching a height of about 0.8 nm, the islands stop growing vertically and with increasing Au coverage they grow only laterally and when they touch each other they start to coalesce, thus forming larger islands (Fig. 1c). In addition, the next layer starts to grow. At Au coverage close to 3 ML, percolation takes place with the formation of a continuous film with small punctures as shown in Fig. 1d. Recall that, under similar conditions of Au film grown on pristine Si(1 1 1)7 × 7 surface, a Au_3Si layer is formed and nucleation of metallic Au film at this coverage is not even initiated [4].

Fig. 2a shows surface linear profiles obtained for the cases of 0.64 ML, 1.28 ML, 1.9 ML and 2.88 ML. The height distribution histograms for surfaces covered with separate Au islands (up to about 2 ML) are shown in Fig. 2b. The profile analysis reveals that there is a minimal height of about 0.8 nm for the flat Au islands grown on the 5.55 × 5.55-Cu reconstruction. That is also the height of the Au film after percolation and corresponds to the height of 3 atomic layers of Au(1 1 1). After the three-layer film is completed, growth continues in a layer-by-layer fashion with each layer having a thickness of 0.26 nm, which is close to the thickness of a single layer of Au(1 1 1) (0.29 nm). This behaviour is known as electronic growth and is controlled by quantum confinement, when the quantized energy spectrum of the film induces the stability of the film at certain numbers of layers [11]. This kind of growth has recently been demonstrated for the Pb/Si(1 1 1)7 × 7 system at growth temperatures below RT [12–14].

Fig. 3 shows STM images of the thicker (about 15 ML) Au film grown on the 5.55 × 5.55-Cu reconstruction (Fig. 3a) in comparison to that grown on the pristine Si(1 1 1)7 × 7 surface (Fig. 3b).

Comparison of Figs. 3a and 1d clearly shows that film growth on the 5.55 × 5.55-Cu reconstruction proceeds as classic layer-by-layer growth with the previous layer being almost completed before the next layer is initiated. Third layer patches and 3D formations are scarce. In contrast, for the Au/Si(1 1 1)7 × 7 system (Fig. 3b), the surface appears multi-level. At least seven incomplete layers can be distinguished. Thus, Au film grown on the Cu-modified 5.55 × 5.55 surface at RT is much more uniform in thickness compared to that grown on the bare Si(1 1 1)7 × 7 surface. We attribute the improvement of surface morphology to the absence of segregative Au_3Si silicide, the formation of which is blocked by the presence of the 5.55 × 5.55-Cu reconstruction between Au film and Si substrate (recall that the 5.55 × 5.55-Cu reconstruction is actually a Cu_2Si monolayer incorporating ~1.7 ML of Cu [8,9]).

However, the difference in the interfacial reconstructions, while leading to different film morphologies, does not affect their crystallinity. In both cases, LEED displays a pattern without any spots,

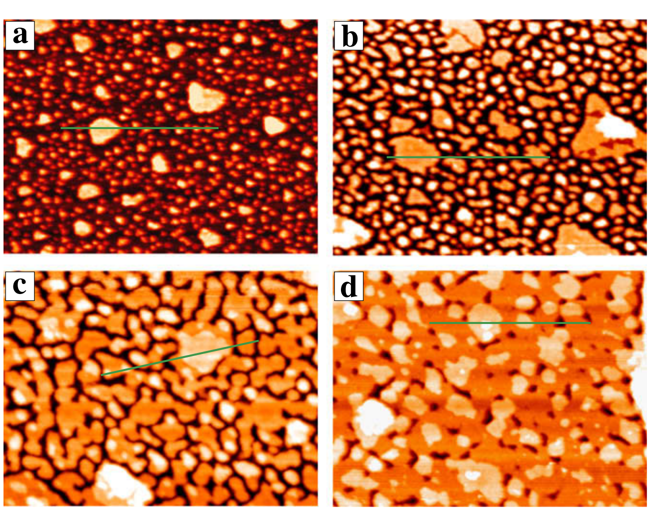

Fig. 1. 100 × 75 nm^2 filled state STM images of the Si(1 1 1)5.55 × 5.55-Cu surface after RT deposition of (a) 0.64 ML, (b) 1.28 ML, (c) 1.9 ML and (d) 2.88 ML of Au.

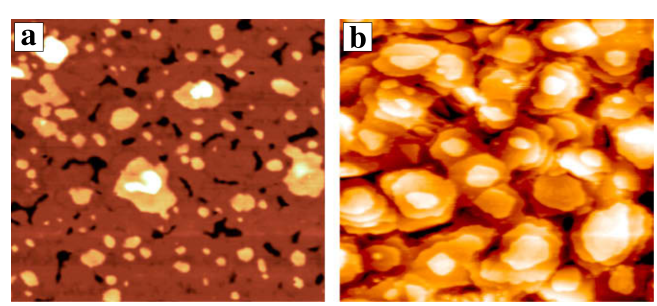

Fig. 3. 100 × 90 nm^2 filled state STM images of 15 ML Au film grown at RT on (a) Si(1 1 1)5.55 × 5.55-Cu reconstruction and (b) bare Si(1 1 1)7 × 7 surface.