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Scanning tunneling microscopy study of Fe, Co and Cr growth on Re(0001)

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ABSTRACT

Atomically flat terraces of the Re(0001) surface with a contaminant density below 0.5% have been obtained by oxygen annealing followed by a flash to higher temperature. This Re(0001) single crystal has been used as a substrate for the deposition of Fe, Co and Cr atoms. Scanning Tunneling Microscopy experiments characterize the growth mode for the submonolayer coverage regime. Co, Cr and Fe atoms self-assemble to form monolayer high islands. Despite a large lattice mismatch between film and substrate, Co and Fe grow pseudomorphically up to half a monolayer. Cr islands are pseudomorphic only for a size below 10 nm. Higher coverage leads to reconstructed islands with an element-dependent reconstruction pattern. Scanning Tunneling Spectroscopy measurements at 8 K reveal the electronic properties of Fe and Re. Differential conductance measurements on the Re(0001) show the presence of standing waves, possibly due to a rhenium surface state. Atomic resolution images of Fe attached to a Re step edge lead to the conclusion that the Fe atoms occupy hcp hollow sites. A Néel magnetic ordered state of the Fe hcp monolayer is revealed with Spin-Polarized Scanning Tunneling Microscopy and Magnetic Atom Manipulation Imaging.

1. Introduction

The number of publications with Scanning Tunneling Microscopy (STM) experiments performed on a rhenium substrate appears very low as compared to tungsten or ruthenium substrates. However, technological interest of rhenium-based alloys has been reported for the catalysis industry [1,2], or as a high melting refractory materials for gas turbine applications [3]. Beside these applications, the last 30 years allowed to create thinner and thinner magnetic films and consequently the role of the substrate on the magnetic properties became more and more important. By determining the positions of the atoms and their hybridization, the substrate governs the value of magnetic moments and the nature and strength of their interaction to quite some extent. According to a previous theoretical investigation [4], in the case of an Fe monolayer (ML), various substrates can even result in various complex magnetic order. The dominant coupling between neighboring Fe magnetic moments on Re(0001) is antiferromagnetic. This antiferromagnetic coupling combined with the geometrical frustration of the (0001) surface is expected to lead to a Néel ordered state.

The preparation of a clean rhenium surface and the study of Co, Cr and Fe growth onto it are major steps before the investigation of their electronic and magnetic properties. The present paper offers a comprehensive STM investigation of the submonolayer coverage regime for the three elements. In the case of Fe, for which we obtained large pseudomorphic areas, we investigate the electronic and magnetic properties at low-temperature with spin-polarized Scanning Tunneling Spectroscopy (SP-STS) [5] and high lateral resolution experiments.

2. Preparation of a clean Re(0001) surface

This section details the preparation of a clean Re(0001) surface with atomically flat terraces, sub-percent level of contaminants and without surface reconstruction. This step is a prerequisite for epitaxial thin film growth.

The experiments were performed in a home-built ultra-high vacuum (UHV) system including e-beam heating for preparation, molecular beam epitaxy (MBE), standard surface analysis LEED and Auger, a variable temperature STM (see [6]) and a low-temperature STM with out-of-plane magnetic field (see [7]). We used bulk W and bulk Cr STM tips whose preparation procedure is described in [8,9]. The base pressure was in the low 10^{-10} mbar regime. We used a single crystal from Mateck, size $6.3 \times 3 \times 1$ mm. This crystal has been sputtered with Ar-ions for the initial preparation for one hour, see the result in Fig. 1a. In the following, we refrained from sputtering the sample, as suggested by some reports in the literature [10–12]. Our cleaning procedure consists first in annealing at $T = 1400$ K with partial oxygen pressure of $3 \cdot 10^{-8}$ mbar, for 10 minutes. This O_2-annealing is followed by a flash at $T = 1800 - 1850$ K. This flash causes the desorption of oxygen and sulfur (see [2] for S-desorption temperature). After the preparation, the sample is transferred to the LEED and/or AES stages. We repeated such a cleaning cycle until AES revealed no sulfur, carbon, and oxygen

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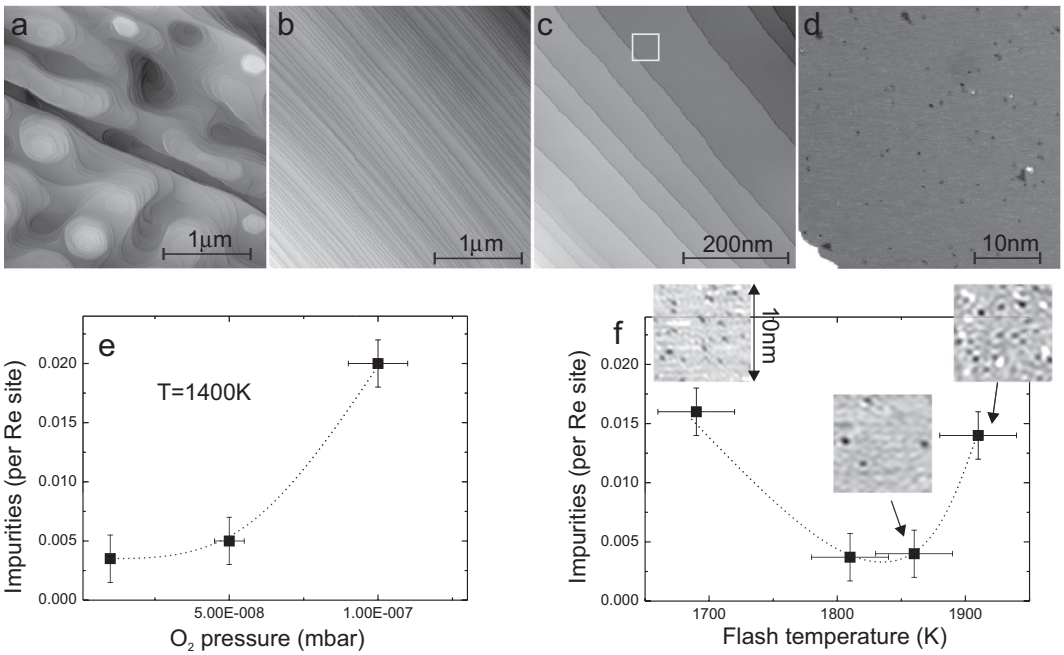

Fig. 1. Micrometer scale constant-current STM images of the Re(0001) single crystal (a) before and (b) after cleaning. Smaller scale images of the clean sample are presented in (c) and (d). The selected area with the white square in (c) is zoomed in (d), showing the typical impurity density. The role of parameters for cleaning is illustrated in (e) and (f), for the partial O_2 pressure during annealing to T = 1400 K and the flash temperature, respectively. The insets in (f) illustrate that the impurities appear as indentations. The corresponding height reduction is 25 ± 5 pm. For all images, the measurement parameters are the same ($I = 1$ nA, $U = 1$ V, bulk W tip at room temperature).

impurities. Our LEED patterns were hexagonal without any trace of reconstruction, as confirmed by the high resolution images of Section 5. We performed 20–30 of these cycles to obtain a satisfactorily clean substrate.

The result for clean Re(0001) is shown in Fig. 1b, with smaller scale in Fig. 1c and d. The step edges are regularly spaced and straight with an apparent height corresponding to the distance between adjacent (0001) planes for bulk rhenium. The terraces are 40 nm wide in average. The total height change corresponds to a crystal miscut angle of 0.3°. The residual amount of contaminants is about 0.3% of a monolayer. These contaminants appear as point depletions, that we attribute to oxygen atoms.

To develop this standard cleaning procedure, we carefully adjusted the O_2 pressure as well as the flash temperature to minimize the impurity density. Fig. 1e and f illustrate the role of these two parameters. Such an influence of O_2 had been mentioned in [13]). These trends should be helpful for future experiments since they are expected in any other experimental setup.

3. Co, Cr and Fe growth

The clean Re(0001) surface is used as a substrate for the growth of different magnetic materials. The atoms have been evaporated from an electron-beam heated high purity rod at a rate of about one pseudomorphic atomic layer per minute. The pressure during the deposition was always in the low 10^{-10} mbar range. The samples have been transferred into the STM after the deposition. The Co, Cr and Fe films can be removed by flashing the sample up to 1600 K, before the standard cleaning procedure described in the previous section.

The substrate temperature for deposition is chosen close to room temperature, in order to avoid intermixing or alloying. This precaution is justified in the case of Co, for which dominant intermixing has been reported for a substrate temperature larger than 400 K [12], as well as for Cr, because bulk Re-Cr alloy can be synthesized [14]. On the contrary, Fe and Re are immiscible and sharp interfaces are therefore expected. We increased the substrate temperature for Fe deposition until the step-flow growth mode occurs, yielding large Fe areas attached to the Re step edges.

Fig. 2 summarizes the coverage and element dependence of the growth, discussed separately in Subsections 3.1, 3.2 and 3.3. We want to obtain large pseudomorphic monolayer areas and avoid the formation of structural defects. The role of the substrate temperature for the Fe growth is qualitatively presented in Subsection 3.4. We then focus on the electronic and magnetic properties of pseudomorphic Fe on Re(0001) in Sections 4 and 5, respectively.

3.1. Co growth

Fig. 2a presents different Co coverages. At 0.2 ML, we see that the Co atoms self-assembled to nucleate into monolayer islands. Analysis of the line profile gives their apparent height of 215 ± 10 pm. Increasing the coverage to 0.4 ML results in a larger number of islands with a larger size. At 0.8 ML, these islands have coalesced and the second layer starts to form. The shape of the Co islands depends on the coverage. At 0.2 ML, the islands have a dendritic shape, as reported by [12]. Increasing the coverage, the islands are getting more compact and their shape tends to be triangular.

The formation of a structural relaxation is expected since the lattice mismatch between hcp Co and Re amounts to 9.1%. However, we could not identify the trigger mechanism for their formation since we observed defects on islands without clear relation to their size or location with respect to the Re step edges, starting from 0.6 ML. At 0.8 ML, more than half of the Co film is reconstructed. The pattern consists of lines of higher apparent height closing up. Their shape evolves from triangular to circular indicating an isotropic relaxation. Similar triangular dislocations have been reported for the system Co/Pt(111) [15] whose lattice mismatch is 9.4%.

3.2. Cr growth

Fig. 2b shows the result of Cr growth under the same conditions. The Cr atoms also diffused to nucleate into monolayer islands but the island density is clearly higher as in the case of Co for a similar coverage. Either