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Growth of magnetic nanowires on self-organized stripe templates: Fe on Pd–O/W(110)

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ABSTRACT

The structural and magnetic properties of Fe–Pd nanostructures grown on regular alternating Pd and oxygen stripes on the W(110) surface are studied using SPELEEM methods. The self-organized Pd–O stripe template, formed at about 1000 °C and aligned with the [001] direction, has an average period of only few tens nm and is preserved upon quenching the sample temperature to ambient conditions. Fe is shown to preferentially bond to the Pd stripes, forming an Fe–Pd surface alloy within the stripe phase. The magnetic easy axis is found to be aligned perpendicular to the Fe–Pd stripe axis.

1. Introduction

Spontaneously formed ordered structures are commonly observed in nature [1]. Crystalline surfaces provide a rich variety of self-organized periodic patterns [2]. Within the field of surface science, the formation and control of such periodic patterns remains a central goal as a bottom-up fabrication method of low-dimensional magnetic and quantum structures.

Self-organization processes at surfaces are often governed by elastic interactions. The ordering of surface steps or alternating surface phases due to elastic relaxations has been known for two decades [3]. Among other techniques, low-energy electron microscopy (LEEM) has been successfully used to study stress-induced self-organization phenomena for a variety of different systems. In recent years we have demonstrated the existence of periodic Pd monolayer stripes on a W(110) surface with a strongly temperature-dependent period [4]. In further studies, we have shown that the anisotropy and temperature-dependence of the pattern can be drastically altered in a controlled manner by adding oxygen as a second adspecies to the W(110) surface [5]. In particular, the Pd–O stripes, aligned with the [001] direction of the substrate, are highly ordered with a coverage-dependent period down to 16 nm, and are perfectly preserved upon lowering the temperature. In the current work, we demonstrate the exploitation of stress-driven Pd–O stripes as a template for growing magnetic nanowires.

The idea that Pd–O stripes can be used as a template for growing Fe–Pd alloy nanowires stems from the fact that Fe, as well as the other magnetic 3d transition metals, tends to segregate from oxygen on W(110) [6], and that alloying between Fe and Pd is favored according to the Fe–Pd phase diagram [7] and density functional theory calculations [8]. In the following, we will experimentally demonstrate that Fe indeed forms magnetic wires when grown on Pd–O stripes. Moreover, using x-ray magnetic circular dichroism (XMCD) spectro-microscopy we will show that the magnetization is perpendicular to the wire axis.

This work is organized as follows: experimental procedure, growth of Fe on a uniform Pd monolayer on W(110), growth of the Pd–O stripe phase, Fe growth on the resulting patterned surface and its characterization by low-energy electron microscopy (LEEM) and diffraction (LEED), as well as laterally resolved x-ray absorption spectroscopy (XAS), x-ray photoelectron spectroscopy (XPS) and XMCD-PEEM (photoemission electron microscopy).

2. Experiment

The experiments were carried out using the Spectroscopic PhotoEmission and Low Energy Electron Microscope (SPELEEM) at the Nanospectroscopy beamline of Elettra, synchrotron laboratory in Trieste, Italy [9]. The instrument is used either with an LaB_6 electron source for low-energy electron microscopy (LEEM) and diffraction (LEED), or as an x-ray photoelectron emission microscope (XPEEM) using soft x-rays in the range 30–1000 eV as probe. LEEM provides surface structural characterization [10,11], with high lateral resolution and video frame rate image acquisition capability. The microscope at the Nanospectroscopy beamline has a lateral resolution of 12 nm in the LEEM mode.

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XPEEM in combination with the high brightness, tunable photon energy and polarization of the synchrotron provides a variety of different laterally resolved operation modes based on photoemission and x-ray absorption [12]. Along with chemical mapping, the circular polarization makes magnetic imaging possible via the XMCD contrast at the proper absorption thresholds of ferromagnetic materials. In the case of Fe, the magnetic signal is extracted from the L-edge ($2p$–$3d$ transition). When using secondary emission the spatial resolution of our microscope is better than 30 nm. In XMCD–PEEM measurements, the energy resolution is entirely determined by the resolving power of the beamline, which is 3000 at 700 eV corresponding to more than 0.2 eV photon energy spread.

In order to follow the evolution of the film stochiometry during Fe deposition, the microspot x-ray photoemission spectroscopy (μ–XPS) operation mode of the SPELEEM has been employed. In this mode, a micron-sized area of the specimen is selected by means of an aperture placed at the image plane in the middle of the beam separator; then, a magnified image of the energy-analyzer dispersive plane is produced on the imaging detector, its intensity profile giving the photoemission spectrum in a 10-eV wide spectral window [13]. This allows for fast XPS acquisition microspectroscopy capability. The best energy resolution is about 0.2 eV, determined by a convolution of the resolution of the hemispherical energy-analyzer and the photon energy spread.

The W(110) surface was prepared by exposure to oxygen at 1×10^{-6} mbar and 1100 °C to remove carbon, followed by high temperature flashes to about 1900 °C to desorb the oxygen [14]. On the clean surface, molecular oxygen was dosed using a high-precision leak valve at a partial pressure of 5×10^{-9} mbar. The oxygen coverage was calibrated by assigning the maximum in the (1×2) LEED spot intensity to 0.5 monolayers (ML), reached at about 4.5 L [15,16]. Coverages between 0 and 0.5 ML were determined using the oxygen sticking coefficient measured in earlier studies [17].

Pd and Fe were evaporated from target rods heated by electron-beam bombardment. The deposition rates ranged from about 0.05 ML/min to 0.2 ML/min. The rate calibrations were obtained with an error of about 1% by measuring the time needed to complete defect free Fe or Pd pseudomorphic monolayers on W(110). All coverages are referenced to the density of a W(110) monolayer. Therefore, unless otherwise stated, ML units correspond to pseudomorphic layers, and need to be scaled in order to get the actual number of atomic layers for films thicker than a single monolayer. In particular, we emphasize that the layer density of Fe(110) is about 20% larger than that of the W(110) surface.

3. Fe growth on Pd/W(110)

We first examine the growth of Fe on the W(110) surface uniformly covered by a Pd monolayer. Fe deposition on (1 ML)-Pd/W(110) at 240 °C was monitored using time-resolved μ–XPS measurements. The temperature was optimized to favor smooth Fe growth on the Pd–O stripes (see below).

The photoemission data are displayed in Fig. 1. The tungsten signal, seen in Fig. 1a, decreases continuously for increasing Fe coverage consistent with a layer-by-layer growth. Interestingly, the Pd core-level signal, shown in Fig. 1b, linearly decays only up to about 0.5 ML Fe coverage. From 0.5 ML to about 1.0 ML, it is nearly constant. At 1.0 ML Fe, the Pd signal slightly increases, and for coverages higher than 1.1 ML it remains constant. The initial linear decrease in both Pd and W signals indicates a 2-dimensional Fe overlayer growth. The sharp decrease of the Pd signal at low Fe coverage would require an inelastic mean free path (IMFP) value of

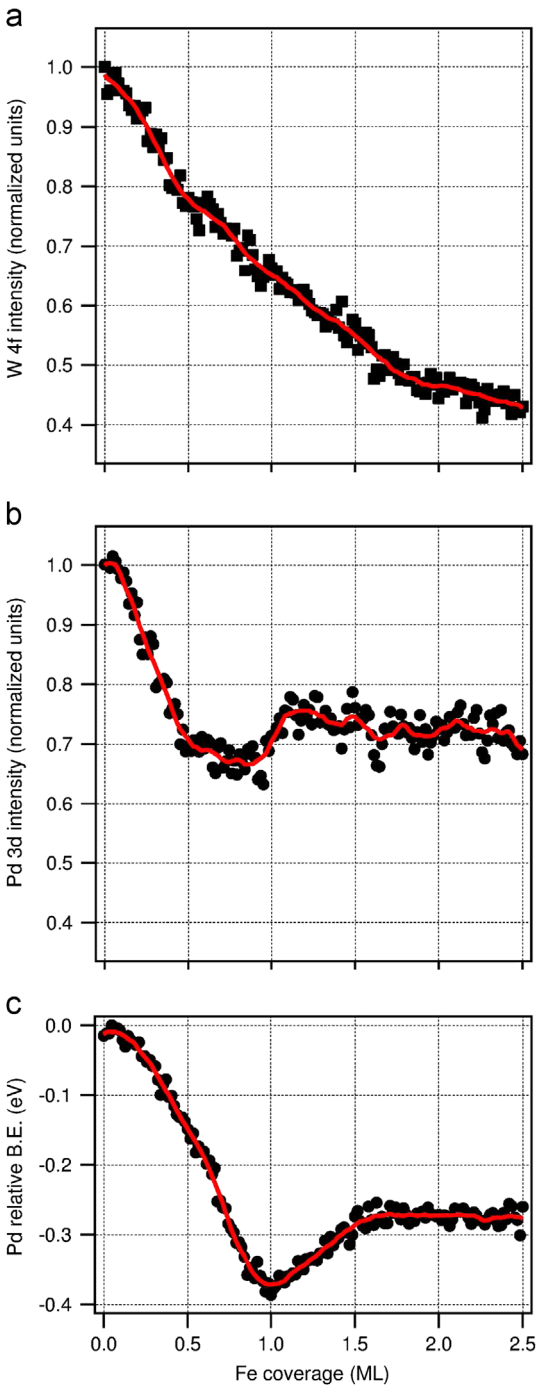

Fig. 1. Fe deposition at 240 °C on a Pd monolayer on W(110). (a) W 4*f*, (b) Pd 3*d* core-level photoemission signals versus Fe coverage. The solid lines are obtained by smoothening the data in order to emphasize the kinks. (c) Pd 3*d* binding energy as a function of Fe coverage. Photon energy is 450 eV.

2.5 Å (at a kinetic energy of 117 eV), which is considerably smaller than the value expected from bulk Fe, about 4.8 Å [18]. For the same coverage range, the IMFP calculated from the decrease of W 4f photoelectrons at 415 eV kinetic energy is 4.3 Å, which is again smaller by the same factor from the reported value of about 8 Å at the given energy [18]. The discrepancy with the bulk data may derive from the fact that the electronic structure of ultrathin films, in particular Pd films [19], differs strongly from that of the bulk, and consequently causing also differences in the electronic energy losses. The saturation of the Pd signal above 1.1 ML instead shows that at higher coverages Fe diffuses below Pd.