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Growth mode, magnetic and magneto-optical properties of pulsed-laser-deposited Au/Co/Au(1 1 1) trilayers

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ABSTRACT

The growth mode, magnetic and magneto-optical properties of epitaxial Au/Co/Au(1 1 1) ultrathin trilayers grown by pulsed-laser deposition (PLD) under ultra-high vacuum are presented. Sapphire wafers buffered with a single-crystalline Mo(1 1 0) buffer layer were used as substrates. Owing to PLD-induced interfacial intermixing at the lower Co/Au(1 1 1) interface, a close-to layer-by-layer growth mode is promoted. Surprisingly, despite this intermixing, ferromagnetic behavior is found at room temperature for coverings starting at 1 atomic layer (AL). The films display perpendicular magnetization with anisotropy constants reduced by 50% compared to TD-grown or electrodeposited films, and with a coercivity more than one order of magnitude lower ($\lesssim 5$ mT). The magneto-optical (MO) response in the low Co thickness range is dominated by Au/Co interface contributions. For thicknesses starting at 3 AL Co, the MO response has a linear dependence with the Co thickness, indicative of a continuous-film-like MO behavior.

1. Introduction

Owing to its ability to essentially preserve the stoichiometry of targets during evaporation, pulsed-laser deposition (PLD) is often used for the growth of materials with a complex composition, particularly oxides such as high-Tc superconductors, ferroelectrics and manganites [1]. When performed under ultra-high vacuum conditions PLD is also suitable for the epitaxy of metals [2], although it is seldom used for that purpose. There are two main differences between PLD and thermal deposition (TD) concerning the epitaxy of metals. The first difference is the possibility to force layer-by-layer growth in some cases [3], which is a positive aspect. This fact arises from the several orders of magnitude higher instantaneous deposition rate during the laser pulse duration and from the increased kinetic energy of the ejected species (up to several eV) as compared with TD [4]. The second aspect is to potentially induce some intermixing at interfaces [5], which may be a drawback to reach certain physical properties depending on the smoothness of interfaces. Evidence of an increased tendency of intermixing at interfaces in structures grown by PLD versus TD has been given previously by X-ray diffraction [5], and it is generally thought to result from the energy carried by the atoms or ions evaporated from the target and heated upon further interaction with the laser in the plume [4]. Here we report on the growth by PLD and the resulting magnetic and magneto-optical (MO) properties of epitaxial Au/Co/Au trilayers, motivated by the observed perpendicular magnetic anisotropy in TD grown [6] or electrodeposition (ED) [9] Co/Au(1 1 1) films capped with various materials.

In this work the Au surface used as substrate is a thin (1 1 1) film deposited on a buffer layer of refractory metal [Mo(1 1 0)] epitaxially grown on Sapphire ($1\,1\,\bar{2}\,0$). For this particular set and order of elements (i.e., Co deposited on Au) we evidence by scanning tunneling microscopy some intermixing at the Au/Co interface, inducing a close-to layer-by- layer growth for Co as compared to a two-atomic-layer- high-island growth for TD. Interestingly, despite the intermixing ferromagnetic behavior is found at room temperature for coverings starting at 1 atomic layer (AL). An easy axis of magnetization is found perpendicular to the plane for Co coverings between 1 and 5 AL, with magnetic anisotropy constants similar to their TD or ED counterparts, however with a much lower coercivity. The spectroscopic magneto-optical activity of the films has also been measured and modeled.

2. Experimental

The samples were grown by pulsed laser deposition (PLD) under ultrahigh vacuum (UHV) inside a three-chamber setup [10]. The first chamber is devoted to preparation and analysis. It is

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equipped with a heater for sample degassing up to 800 °C, a sputtering gun and an Auger electron analyzer. The base pressure is 2×10^{-10} Torr. The second chamber is the deposition chamber. It is equipped with a 10 keV reflection high-energy electron diffraction (RHEED) setup, a quartz microbalance, and a sample heating similar to that of the first chamber. The base pressure is $2-3 \times 10^{-11}$ Torr and in the 10^{-10} Torr range during laser deposition. A third chamber is dedicated to scanning tunneling microscopy (STM) with a room temperature (RT) Omicron-1 setup (base pressure 5×10^{-11} Torr). A Nd–YAG laser with a 10 ns pulse duration and a 10 Hz frequency was used. The targets are first mechanically polished *exsitu* and then surface-cleaned *insitu* through laser ablation until no gas contaminant is found on the target, as controlled by Auger spectroscopy. The targets are cleaned at the same fluence as that used during the growth (about 1 J/cm^2). This sequence is chosen for each element just above the evaporation threshold, so as both to avoid the formation of droplets [11] and to minimize the energy carried by evaporated individual atoms or ions [4]. Under these conditions the typical growth rate on the sample is 1 Å/s. More details can be found in Ref. [10].

Hysteresis loops were carried out by means of a superconducting quantum interference device (SQUID) magnetometer at low and RT. The magneto-optical (MO) polar response of the samples was studied experimentally in the spectral range from 1.4 to 4.3 eV, using a spectrometer described elsewhere [12]. The sample, placed inside an electromagnet that applies a magnetic field perpendicular to its surface high enough to saturate it, is illuminated at normal incidence by a monochromatic beam coming from a Xe lamp followed by a monochromator. By modulating the beam polarization with a photoelastic modulator, the Kerr rotation and ellipticity for each wavelength are determined.

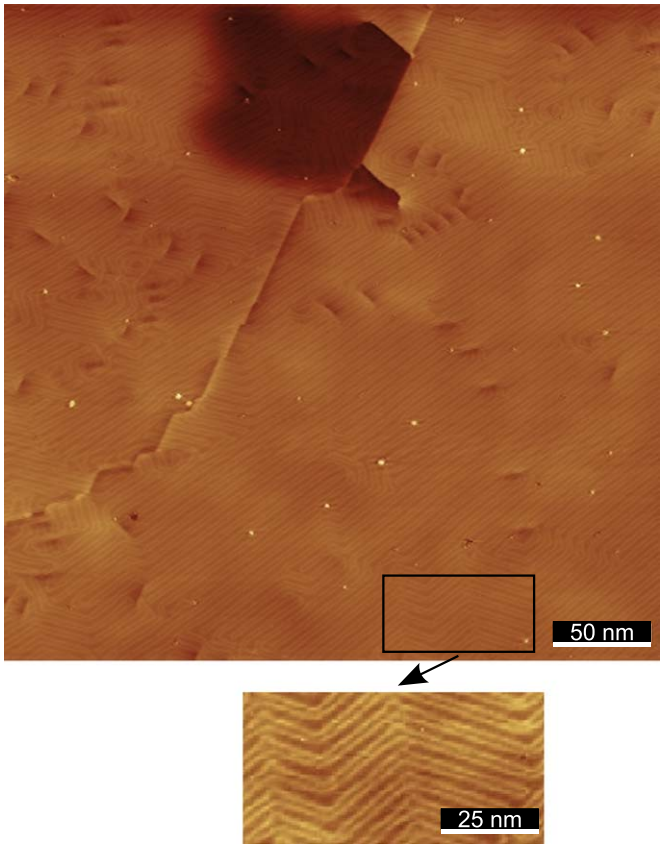

Fig. 1. (Color online) 375 × 375 nm STM image of Au(1 1 1) grown on Mo(1 1 0) (sample voltage 1 V, current 0.25 nA). The gray scale has been adjusted between zero and the maximum height $Z_{max} = 1.5$ Å. A zoom of a selected area is show in the lower part, displaying the Au(1 1 1) herringbone reconstruction with $Z_{max} = 0.54$ Å.

3. Au(1 1 1) surface preparation

We used commercial sapphire (1 1 $\bar{2}$ 0) wafers with a miscut angle smaller than 0.1°. A 10 nm-thick buffer layer of Mo(1 1 0) was first deposited following an optimized procedure [10,13]. Its surface is single-crystalline and displays ≈200 nm- wide terraces separated by monoatomic steps. The steps separation and orientation are determined by the miscut of sapphire, which is uniform on a 2-in wafer, however varies from one wafer to another. This residual miscut, on the average smaller than that typically found on metal single-crystals, does not influence the growth mode and thus presumably neither the magnetic properties.

Next a 5 nm-thick Au film was deposited at RT on top of the Mo buffer layer. The Au surface was then sputtered with 1 kV Ar^+ ions to remove a few AL, then annealed at 550 °C during 30 min. The resulting Au surface was studied by STM. It is atomically-flat with the usual $22 \times \sqrt{3}$ reconstruction of Au [14–16]. However the presence of micro-grain-boundaries and dislocation loops prevent the occurrence of a perfect long range herringbone superstructure as for Au single crystals Fig. 1, its appearance being limited to restricted areas as shown in the zoom to Fig. 1.

4. Co growth on Au(1 1 1)

Fig. 2 shows STM pictures of various amounts of Co deposited at RT on the Au surfaces described above. In the sub-atomic-layer range Co growth proceeds through the more-or-less random nucleation of 1 AL-high islands. The distribution of island lateral size is quickly bimodal (Fig. 2(b) and (c)) owing to the combination of homogeneous nucleation by adatom aggregation and heterogeneous nucleation on the Au(1 1 1) defects [17–20]. The growth in this sub-atomic-layer range dramatically differs from the case of TD, for which the islands are 2 AL-high and nucleate almost solely at the elbows of the Au herringbone reconstruction [21], with a random 0.02 nm corrugation on the top of the islands owing to the large mismatch between Co and Au [22,23]. Here, stripe-like areas of two different heights are observed on the top of the 1 AL-high Co islands, as the zoom of a selected area in Fig. 2(b) shows (note that the vertical scale in this 25 × 25 nm area has been optimized to better display the top part of the islands). This feature points to some degree of intermixing between Co and Au as previously observed in PLD deposited systems [5]. As above mentioned, the interfacial intermixing in PLD is a result of the energy carried by the atoms or ions evaporated from the target and heated upon further interaction with the laser in the plume [4,5]. Although we set the laser fluence just above the evaporation threshold, tails in the energy distribution or hot spots in the laser beam may create a small fraction of atoms or ions carrying a few eV or more. Notice that interfacial intermixing is not a systematic feature of PLD, as we did not observe such inhomogeneities in other systems, e.g. Fe [24] or Co deposited on W or Mo(1 1 0). The higher bonding energy of the latter with respect to Au may prevent the intermixing. The growth mode of further Co layers proceeds close-to a layer-by-layer fashion, with a morphology and inter-island distances at 4 AL of approximately 20 nm, very similar to those obtained with TD [25]. Thus the topography of PLD-grown