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Structure and magnetism of ultrathin Co and Fe films epitaxially grown on Pd/Cu(0 0 1)

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Abstract

A contribution originating from the Co/Pd and Fe/Pd interfaces to the magneto-optical Kerr effect (MOKE) rotation is analyzed for Co and/or Fe films grown on a Pd-buffer-monolayer on Cu(0 0 1). A clear increase of the MOKE signal in comparison to the Co(Fe) films grown directly on Cu(0 0 1) is detected. An interpretation is supported by similar observations for Co films grown on Pd(1 1 0) and Pd(0 0 1). In particular, the sign reversal of the Kerr loops with increasing thickness of the Co(Fe) films is discussed. Magneto-optical effects are separated from the real magnetization and its dependence on the film thickness.

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Keywords: Co and Fe ultrathin films; Pd substrate; Magneto-optical Kerr effect

Magnetic properties of the ultrathin structures are reflected in a way which may depend on the experimental technique that is applied. This is important, in particular, in the case of the magneto-optical Kerr effect (MOKE) which gives information on the combined magnetic and optical properties of the investigated system. The MOKE at magnetic saturation generally increases with the thickness of ferromagnetic material (like Co or Fe), being dependent on the magnetic moment of the films. However, sometimes the magneto-optical response produces effects which cannot be directly related to the varying magnetic moment. This concerns e.g. Co and Fe films epitaxially grown on Pd substrates [1–3].

It has been found for Co films grown on Pd(1 1 1) that the Kerr rotation varies linearly

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with thickness above ~2 ML, however, the linear extrapolation has non-zero negative offset at zero thickness [1]. This negative offset has been interpreted as a result of opposite sign of the Kerr rotation for Co and polarized Pd. The observation is completed by a reversed hysteresis Kerr rotation loop measured for the same system at a Co thickness just below 2.5 ML by Lee et al. [2]. The polarity change of the Kerr rotation and the negative offset in Co/Pd(1 1 1) is suggested to be evidence of an opposite direction of the polarized Pd moments with respect to Co moments [2]. Very similar properties are found for the Co films grown on Pd(1 1 0) [4]. In both cases, the loops change sign at the Co thickness of around 2 ML.

In order to verify the concept of the Pd/Co interface contribution to the total magneto-optical response from the Co films, a monolayer of Pd is grown by pulsed laser deposition (PLD) on Cu(0 0 1) as a template for further growth of Co films. Due to similarity in the structure of Co films on Cu(0 0 1) and Pd/Cu(0 0 1), any difference in magneto-optical response of both systems could be interpreted as a result of Pd polarization. A comparison of these Co films on Pd/Cu(0 0 1) and Cu(0 0 1) is made to the Fe films grown on the same templates.

The experiments were carried out in a multichamber ultrahigh vacuum system with base pressures of $<5\times10^{-11}$ and $<2\times10^{-10}$ mbar during deposition. Prior to deposition, the copper substrate was cleaned by cycles of Ar^+ sputtering followed by annealing at 900 K until only Cu lines were seen in the Auger electron spectra, sharp low-energy electron diffraction (LEED) pattern, and atomically flat terraces under scanning tunneling microscopy (STM) were observed. In most cases, the substrate was kept at room temperature (RT) of 300 K during deposition. During PLD, the substrate was placed about 100–130 mm away from the targets. The pulse laser energy was set to 325 mJ. The whole growth process of films was monitored by a reflection high-energy electron diffraction system. The magnetic properties were recorded by polar and longitudinal MOKE.

Ultrathin Pd films have been grown by PLD on Cu(0 0 1) substrate at RT. Up to Pd coverage of about 4 ML an ideal layer-by-layer growth mode is observed in topography STM images. Previous results have indicated that the PLD method could greatly retard surface alloying and the occurrence of strain relaxation, and significantly improves morphology in this highly mismatched system, whereas the mismatch strain can relax via formation of misfit dislocations for thicker films [5]. As a template for a further thermal deposition of Co or PLD of Fe films, we have grown at RT only a monolayer of Pd which is pseudomorphic to the Cu(0 0 1) substrate. The Pd monolayer wets perfectly the Cu(0 0 1) surface showing only very few small islands of 1 ML height [5]. No evidence of the Cu–Pd surface alloying was detected, in particular a $c(2\times2)$ reconstruction was not observed by LEED. On such a perfect monolayer of Pd, the Co growth proceeds in a layer-by-layer mode (Fig. 1) up to at least 11 ML, in comparison to the layer-by-layer growth only up to 3 ML when the Co is grown on Pd(0 0 1). This is due to a reduced lattice mismatch between Co and strained Pd layer on Cu(0 0 1) with respect to the Co/Pd(0 0 1) system. Actually, the structure of Co on

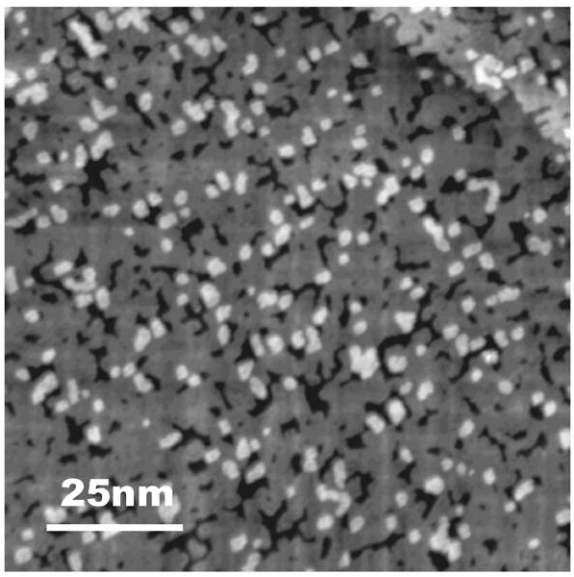

Fig. 1. STM image of 1 ML Co on 1 ML Pd/Cu(0 0 1). The Co layer was grown by thermal deposition at RT. Only a few small islands of 1 ML height are seen confirming almost perfect layer-by-layer growth.

Pd/Cu(0 0 1) does not differ from the structure of the Co film grown on Cu(0 0 1).

Compared to Co films grown on Pd(0 0 1), a strongly enhanced magneto-optical response is found in Co films grown on Pd/Cu(0 0 1) [5]. For the Co on Pd(0 0 1) above 2 ML, the Co structure develops into an unstrained FCC, however with a large number of structural defects [5]. For the Co on Pd/Cu(0 0 1), the Co adlayers have a strained FCC structure like in the case of the Co/Cu(0 0 1) system. In fact, both Co/Pd/Cu(0 0 1) and Co/Cu(0 0 1) systems prepared under identical conditions have the same slope in the thickness dependence of Kerr rotation (Fig. 2). However, the rotation measured for Co/Pd/Cu(0 0 1) is enlarged with respect to that measured for Co/Cu(0 0 1) by roughly the signal that corresponds to 0.6 ML of Co independently of the Co film thickness. This has been proven by the Kerr rotation measured for 3 ML thick film of Co deposited on the Pd wedge of the thickness varying from 0 to 1.5 ML. Up to a wedge thickness of 1 ML, the Kerr signal increases linearly, reflecting the increasing contribution of the Co/Pd/Cu(0 0 1) system characterized by larger Kerr rotation. When the Pd-wedge is thicker than 1 ML, the Kerr rotation from 3 ML of Co remains constant suggesting that the second Pd layer does not contribute significantly to the magneto-optical response of the system. All together, this means that the Co/Pd interface introduces a contribution to the total Kerr signal, which is independent both of Pd and Co thickness (Fig. 2). We interpret the offset as an indirect evidence of the polarization of the Pd near the Co interfaces. The polarization effect is rather large. It is too large to be a result of an enhanced moment of the Co, unless the optical constants of interface Co are also changed. The observed effect could be possible with a small polarization of the Pd due to the large spin–orbit coupling, which directly influences the Kerr rotation. Most likely, the effect reflects a property of the Pd/Co interface comprising both the polarization of Pd and the enhanced moment of Co. Magneto-optical response from ultrathin Co films grown on Pd substrates behaves even more confusingly. An interesting observation comes from the MOKE analysis of the Co/Pd(1 1 0) system which has been performed at low temperature, and reported elsewhere [4]. The longitudinal signal taken along the [1 0 0] direction increases linearly with film thickness only above a thickness of Co at which the polar signal is no more detected. Below this thickness, an anomalous peak exists where the signals are larger than those of the thicker films. Moreover, the reversed loops (a negative rotation at positive fields) have been detected over the thickness range where the MOKE signal is anomalously large [4].

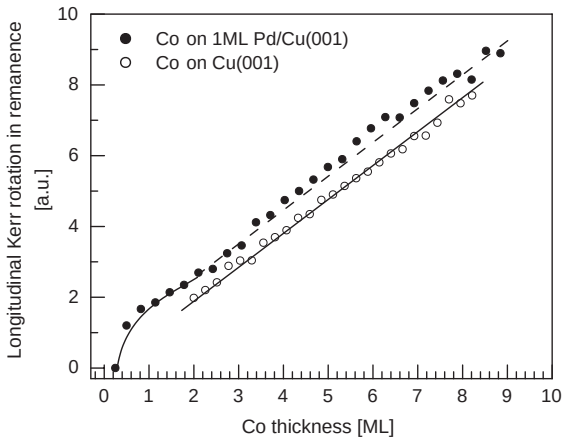

Fig. 2. Thickness dependence of remanent MOKE rotation measured along the [1 0 0] direction at 70 K for Co films grown on Pd/Cu(0 0 1) (full dots) and Cu(0 0 1) (open circles). The slope of both linear dependencies is almost the same. The positive offset in the case of Co/Pd/Cu(0 0 1) system corresponds to the signal from about 0.6 ML of Co.

The strong increase of Kerr rotation is observed also for ultrathin Fe films grown by PLD on the Pd-monolayer on Cu(0 0 1) [5]. The magnetization behavior in this case can be described as two regions of a linear dependence on thickness (Fig. 3). At the thinner Fe films (below 1.6 ML), the Fe/Pd/Cu(0 0 1) system indicates a larger slope than in the thicker films. The slope above 2 ML remains unchanged up to 8–9 ML. The larger slope at low coverage could be interpreted by an enhanced magnetic moment of Fe. However, no evidence is found of any structural transformation that could explain the rapid decrease of the moment just above the thickness of 1.6 ML [5]. Taking into account that the MOKE loops measured below the

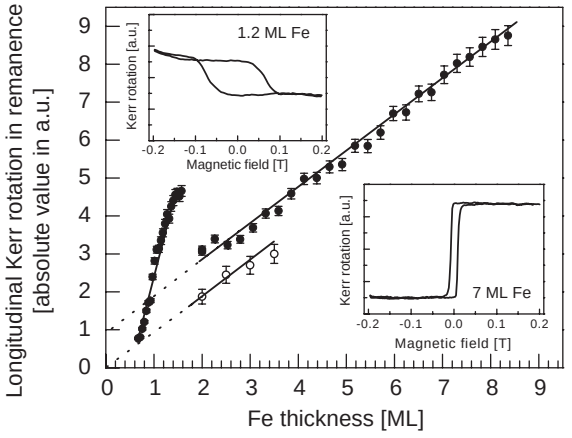

Fig. 3. Thickness dependence of remanent Kerr rotation measured along the [1 0 0] direction at 60 K for Fe films grown on Pd/Cu(0 0 1) (full dots) and Cu(0 0 1) (open circles). The data for Fe grown on Cu(0 0 1) is shown only in the thickness range the films are magnetized in plane and do not experience any structural transformation (2–4 ML). The slope of both linear dependencies is the same. The positive offset in the case of Fe/Pd/Cu(0 0 1) system corresponds to about 1 ML of Fe.

thickness of 1.6 ML are reversed, one also has to take into account a possible magneto-optical origin of the effect, i.e. a property similar to what we have observed for the Co film grown on Pd(1 1 0) [4]. It is worth noting that for the Fe/Pd/Cu(0 0 1) films of the thickness of 2–4 ML, the slope of the curve of Kerr signal vs. thickness is the same as for the Fe films deposited by PLD directly on Cu(0 0 1). Nevertheless, the structurally identical Fe films, grown on Pd/Cu(0 0 1) and Cu(0 0 1), magnetically behave differently. Above 4 ML, the Fe films on Cu(0 0 1) experience a structural transformation, and the Kerr signal loses its linear dependence on thickness [6]. Below 1.6 ML, an increased in-plane signal with the reversed MOKE loops is detected when the film is grown on Fe/Pd/Cu(0 0 1) (Fig. 3), whereas the Fe/Cu(0 0 1) system displays out-of-plane magnetization in this thickness regime [6]. This supports our expectation that the larger MOKE signal does not necessarily mean enhanced magnetic moment at the interface layers of Fe on Pd/Cu(0 0 1) or the interface contribution to the longitudinal Kerr effect. As in the case of the Co films grown on Pd, it can manifest other contributions to the Kerr rotation, e.g. polar contribution due to the possible out-of-plane anisotropy of the Fe/Pd/Cu(0 0 1) system in the low Fe thickness limit. In the case of Co films grown on Pd(1 1 0) or Pd(0 0 1), we see a clear correspondence between the anomalously increased longitudinal signal and appearance of the polar one [4]. In the case of Fe on Pd/Cu(0 0 1), below 1.6 ML of Fe, no clear relation of the increased signal (and reversed loops) to the polar signal is found. However, it requires further investigations to explain this behavior more precisely.

Besides the anomalous MOKE response below 1.6 ML of Fe on Pd/Cu(0 0 1), the signal increases linearly showing positive offset exactly as for Co grown on Pd/Cu(0 0 1). The rotation measured for Fe/Pd/Cu(0 0 1) is enlarged with respect to that measured for Fe/Cu(0 0 1) by roughly the signal that corresponds to 1 ML of Fe. Consequently, we believe that Fe/Pd interface introduces a significant contribution to the total Kerr signal, which is independent of the Fe thickness. We interpret the offset as an indirect evidence of the polarization of Pd near the Pd/Fe interface comprising both an induced magnetic moment of Pd and enhanced moment of Fe. It is worth noting that the magneto-optical response of the Fe/Pd interface (Fe/1 ML of Pd), equivalent to the signal from 1 ML of Fe, is much larger in comparison to the Co/Pd interface which produces the response equivalent to the signal from 0.6 ML of Co.

In conclusion, we confirm with our experiments that the Pd interlayer strongly influences magnetic properties of the Co and Fe films deposited on top of it. In particular, the magneto-optical response from both Co/Pd/Cu(0 0 1) and Fe/Pd/Cu(0 0 1) structures is increased in comparison to that from Co/Cu(0 0 1) and Fe/Cu(0 0 1) structures, respectively. This suggests a strong polarization effect of Pd due to the interfacing Fe(Co) films.

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