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Unusual temperature dependence of polar Kerr rotation in ultrathin Co films grown on Pd(1 1 0)

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Abstract

For Co films on Pd(1 1 0) covered with Au, the polar hystersis loops measured at 120 K are reversed below 2.7 ML with respect to those of thicker Co films, which is due to the negative contribution to polar Kerr rotation from the Co/Pd interface dominating in this thickness range over the positive polar Kerr rotation from the non-interface part of the Co film. Near the film thickness where the Kerr rotation changes sign a remarkable combination of two loops (normal and reversed) of two slightly different coercivities is observed regarded as a superposition of two different magneto-optical contributions corresponding to thinner and thicker parts of the Co film. The thin and thick film areas could have different temperature dependence of magnetization (the negative contribution could depend stronger on temperature since it is related to the thinner part of the film), leading to the increasing total polar Kerr rotation with increasing temperature.

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Keywords: Magneto-optical effect; Surface magnetism; Perpendicular magnetic anisotropy

1. Introduction

Artificial multilayers and ultrathin magnetic films are a subject of a large research effort, particularly due to their special magnetic properties such as perpendicular magnetic anisotropy (PMA) and enhanced magnetic moment at surfaces and interfaces [1]. These properties are correlated to geometric and electronic structures near surfaces or interfaces [2,3]. Since the PMA has been considered as a basis for developing magnetic data storage devices, systems like thin films and multilayers of Co/Pd have been intensively studied [4–6]. However, the microscopic origin of the PMA and the correlation between Co/Pd interface structure and magnetic properties of the system have not been understood completely yet. Contradictory to what is commonly expected, we have recently shown that the Co films grown at room temperature on Pd substrates exhibit spontaneous in-plane magnetization independent of the film thickness and change to perpendicular to the surface only after a special treatment like gas adsorption, covering with Au, Pd or annealing [7]. Since the magnetic properties are often probed with magneto-optical Kerr effect (MOKE), it is worth to mention that the magneto-optical response for ultrathin Co films grown on different low-index surfaces of Pd is topology dependent [8].

In this contribution, we report on the unusual magnetic properties of ultrathin Co films grown on Pd(1 1 0) substrate. The temperature dependence of magnetization of the Co films covered with Au is probed by MOKE. In particular, a comparison between low-temperature and room temperature values of the polar Kerr rotation measured in saturation is made and discussed. A model which correlates magnetic (and magneto-optical) properties with a peculiar change of sign of the polar Kerr rotation observed for the thinnest Co films is proposed.

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The temperature dependence of magnetization for the Co/Pd system is discussed in view of the film thickness inhomogeneity and its influence on the overall magneto-optical properties.

2. Experimental

The experiments were carried out in a multichamber ultrahigh vacuum (UHV) system with base pressure $<5\times10^{-11}$ and $<2\times10^{-10}$ mbar during deposition. Prior to deposition the Pd substrates were cleaned by cycles of Ar^+ sputtering followed by annealing at 950 K until only Pd peaks were detected in the Auger electron spectra, and sharp low-energy electron diffraction (LEED) patterns and atomically flat terraces under the scanning tunneling microscope (STM) were observed. The magnetic properties were studied by longitudinal and polar MOKE where a p-polarized laser beam with a wavelength of 675 nm was used. For the polar MOKE, the laser beam incidence angle was approximately 5° (near normal incidence). The MOKE setup and measurement details are described elsewhere [9].

3. Results and discussion

It was recently reported for Co films on Pd(0 0 1) substrate [7] that the magnetization changes from in-plane to out-of-plane covering the film with Au. The out-of-plane magnetization persists up to 1.2 ML and then rotates toward the film plane due to the shape anisotropy, which favors the in-plane magnetization. The measured polar Kerr p-rotation loops of Co/Pd(0 0 1) are reversed compared to the loops for thicker Co films when they could be magnetized out-of-plane (i.e. after annealing) [7]. This is attributed to the negative magneto-optical component to the Kerr rotation taking origin at the Co/Pd interface. For Co/Pd(1 1 1) system covered with Au, the positive polar Kerr rotation is measured even at lowest coverage due to initially three-dimensional growth of Co on Pd(1 1 1) at room temperature [8]. Only in the case of Au/Co/Pd(1 1 0) system, the negative polar Kerr rotation detected below a certain thickness t_c evolves into a positive one above t_c and occurs up to the thickness t_m up to which the perpendicular magnetization is kept (about 5 ML). This phenomenon is due to the positive polar Kerr rotation from the Co film which dominates over the negative polar Kerr rotation from the Co/Pd interface above the Co film thickness of t_c [8]. Fig. 1 shows the polar Kerr rotation loops measured at room temperature for Co films grown on Pd(1 1 0) and covered with Au. The loops are rectangular indicating that the Kerr signals in remanence and in saturation are exactly the same. The loops change sign at a thickness of 2.2 ML showing a little strange shape suggesting a superposition of two loops, normal and reversed, around this thickness. The reversed loop (i.e. negative Kerr rotation due to dominating contribution from the Co/Pd interface) corresponds to the thinner part of the film whereas the normal loop (i.e. positive polar Kerr rotation) corresponds to the thicker Co. This is very similar to what we recently observed for 2.5 ML of Co on Pd(1 1 0) at 270 K [8]. The most striking result is that the contributing loops exhibit slightly different coercivity that produces characteristic "features" when the loops balance to zero around 2.2 ML (when measured at room temperature). Such behavior also suggests that the loops correspond to two different film thicknesses exhibiting not exactly the same coercivity at room temperature.

The effect of two components to the overall Kerr rotation is observed around the t_c thickness, however, in

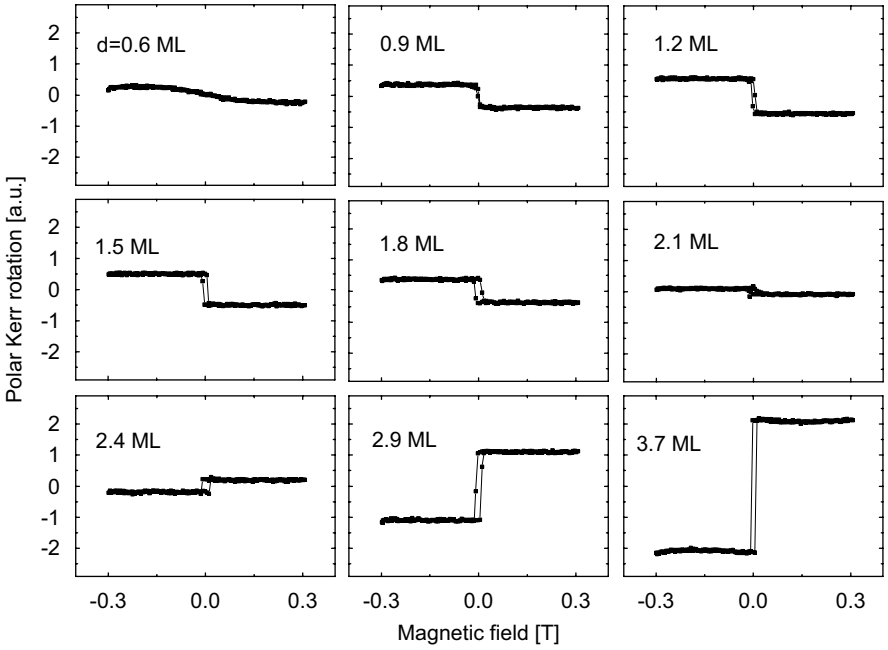

Fig. 1. Polar MOKE rotation loops measured at room temperature for Co films of different d grown on Pd(1 1 0) and covered with Au.

the thickness range which depends strongly on the film topology (and on the number of atomic layers up to which the polar Kerr rotation remains negative). In other words, the average coverage of 2.5 ML could mean a half of the substrate covered with two and a half with 3 MLs of Co, or a half with 1 ML and a half with 4 ML. For 1 and 4 ML thick Co films on Pd(1 1 0), the polar Kerr rotation is expected to be clearly of opposite sign, whereas in the case of 2 and 3 ML thick films the corresponding polar Kerr rotation would not differ too much. The above consideration helps to understand that, actually, the initially negative polar Kerr rotation changes sign not with the increasing number of completed atomic layers but rather when the negative Kerr rotation from thinner areas is overridden by the positive Kerr rotation from the increasing population of the thicker areas of the Co film. This has been confirmed from the STM images of the Co films with different thickness. It is very clear that the growth is three-dimensional one and the film thickness differs locally quite remarkably [7].

The mode of growth and resulting film topology could significantly influence temperature variations of magnetization, in particular, for films consisting of a few atomic layers only. This is quite important whether the film consists of the integer number of (completed) atomic layers or whether the number of atomic layers varies locally. In the latter case, the temperature dependence of magnetization could differ between the film areas of different thickness. In Fig. 2, we show temperature dependences of polar Kerr rotation in saturation for the 2, 2.5 and 4 ML thick Co films grown on Pd(1 1 0) at room temperature covered with Au. Surprisingly, for the 4 ML thick Co film the polar Kerr rotation in saturation increases with increasing temperature. This kind of behavior cannot be expected at any case for magnetization, and could result only from superimposed negative and positive contributions to the magneto-optical response from the sample. Crucial is that with increasing temperature the negative contribution must contribute less to the overall polar Kerr rotation than the positive one. Only then the sum of both contributions can be more positive or less negative, i.e. could result in the increased Kerr signal with increasing temperature. Such different temperature dependencies are not surprising since it is well known that for thin magnetic film magnetization depends strongly on temperature compare to the thicker one. The results of superimpostion of two such dependencies depend strongly on the population of two respective areas over the total sample area. In the case of Co/Pd(1 1 0) system, the thinner and thicker areas of the Co film coexist due to three-dimensional growth. In the temperature range in which polar Kerr loops for the Co films on Pd(1 1 0) are measured, the change of sign of the overall Kerr rotation is approached with decreasing film thickness down to 2.5 ML (Fig. 2). This is a result of the negative component to the Kerr signal disappearing due to its stronger dependence on temperature in comparison to the positive component related to the thicker film area. With further reduction of Co thickness, when the positive component disappears, only the negative total Kerr rotation would be detected independent of temperature at which the MOKE experiment had been performed, in agreement with the experimental results of Fig. 2. It is known from the conversion electron Mossbauer experiments performed on the 1.2 ML thick Fe film on W(1 1 0) that the temperature decrease of magnetization could not be uniform over the whole sample area [10]. At least two different contributions were distinguished in that case and clearly related to the monolayer "sea" and double-layer patches, the latter is visible at temperature the former had disappeared [10].

It is clearly seen in Fig. 3 that the overall polar Kerr rotation from the Co/Pd(1 1 0) structure is influenced by

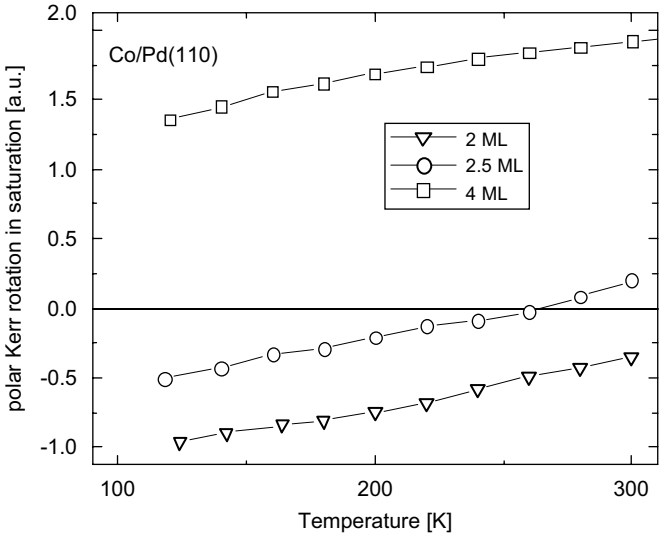

Fig. 2. Temperature dependence of polar Kerr rotation in remanence for 2, 2.5 and 4 ML thick Co films grown on Pd(1 1 0) and covered with Au.

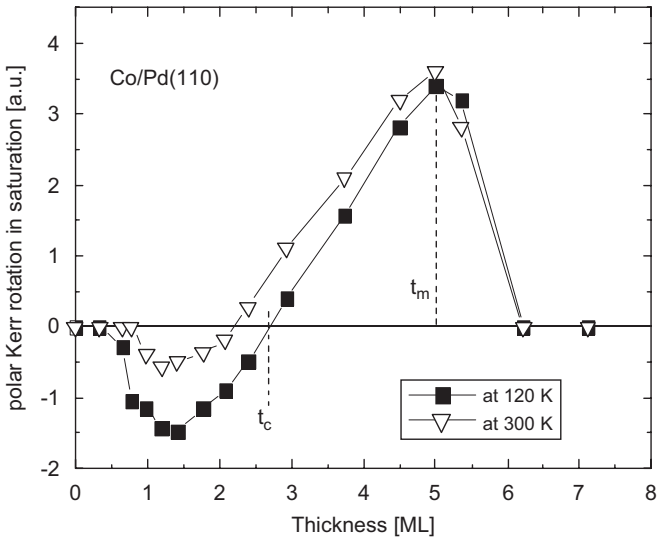

Fig. 3. Polar Kerr rotation in remanence at 120 K and at room temperature versus film thickness for Co/Pd(1 1 0) covered with Au.

the negative Co/Pd interface component which is balanced to zero by a positive component from the Co film only at the t_c thickness of about 2.7 ML when measured at 120 K and 2.2 ML at 300 K. The positive total Kerr rotation in saturation starts to decrease at the thickness t_m of about 5 ML. Above this thickness, the shape anisotropy favors the magnetization to lie in the film plane. Note that this kind of complex behavior could be observed only for Co films grown on Pd(1 1 0), because only in this case the maximum thickness t_m, at which perpendicular magnetization still persists, exceeds the thickness t_c at which the polar Kerr rotation changes sign, i.e. $t_m > t_c$ (note that for Co on Pd(0 0 1) $t_m < t_c$, whereas for Co on Pd(1 1 1) $t_c = 0$ [8]). The polar Kerr rotation in saturation measured at room temperature is less negative (below t_c) or more positive (above t_c) than that measured at 120 K, independent of the film thickness, which is consistent with the results and explanation of Fig. 2.

4. Conclusion

In conclusion, Co films grow on the Pd(1 1 0) substrate in a three-dimensional mode, which results in a coexistence of film areas of clearly varying thickness. The measured overall polar Kerr rotation is a combination of negative polar Kerr rotation from the thinner part of the Co-film and positive polar Kerr rotation from the thicker part of the Co film. Both contributions depend on temperature differently, thus leading to the increased polar Kerr rotation with increasing temperature.

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