

Surface Plasmon Resonance Effects in the Magneto-Optical Activity of Ag–Co–Ag Trilayers

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A complete magneto-optical characterization of Pt capped Ag–Co–Ag sputtered trilayers with varying Co thickness is presented. Polar Kerr rotation and ellipticity exhibit a gradual increase in signal as the Co layer gets thicker, with a sharp feature around 3.75 eV due to the bulk Ag plasmon resonance. The transverse Kerr signal of such trilayers is strongly affected by the surface plasmon polariton (SPP) resonance excitation when measured in the Kretschmann configuration, with a maximum transverse Kerr effect for around 2 nm Co thickness which corresponds to the optimum SPP excitation. This behavior is in contrast with the monotonous increase in transverse Kerr signal with Co thickness measured when the SPP is not excited. These results are in qualitative agreement with simulations using the transfer matrix formalism, the discrepancies mainly being due to the deviation from 2-D growth of the system and possible Ag and Co oxidation effects.

Index Terms—Cobalt, magnetic thin films, magneto-optic Kerr effect, silver.

I. INTRODUCTION

SURFACE plasmon polaritons (SPPs) are electromagnetic waves localized at the interface between two media with dielectric constants of opposite sign, like a metal and a dielectric. Such modes, with wavelengths ranging between the far infrared and the visible, are strongly dependent on the optical properties of both media, which makes them useful in different applications such as biological sensors [1], optical switching [2], light guiding at the subwavelength scale [3]–[5] or far-field optical microscopy [6]. Typical plasmonic materials are noble metals, especially gold and silver, characterized by low absorption losses in the optical range. To excite SPPs optically, both the frequency and the component parallel to the surface of the wavevector of the light must equal those of the SPP. While the first condition is readily achievable, the second one requires the use of a coupler (for instance a prism in the so-called Kretschmann configuration) since, due to the SPP dispersion relation, its wavevector is always larger than that of the light for each photon energy [7].

When a plasmonic material is combined with a magneto-optically active one (for instance a ferromagnet) both the plasmonic and the magneto-optical (MO) properties of the resulting magnetoplasmonic system become interrelated. For example, the wavevector of the SPP in Au/Co/Au trilayers can be modified by an external magnetic field [8]. On the other hand, also in the Au/Co/Au system, the MO activity can be greatly enhanced when the SPP resonance is excited [8]–[10]: in this situation the light absorption is maximum and, for specific layer thickness, the electromagnetic field of the light is greatly enhanced at the MO active layer (Co in this case). This leads respectively to a

reduction in the system reflectivity and to an enhancement in the magnetic component of the MO activity [8] which altogether is responsible of the enhanced global MO response.

Compared to gold, silver exhibits narrower and more intense plasmon resonances due to its longer relaxation times and lower absorption losses in the visible range [11], [12], which makes it an even better material candidate for the implementation of magnetoplasmonic materials for example in sensing and telecom applications. However the long term chemical instability of silver represents a serious drawback against the actual realization of these devices. The fabrication of magnetoplasmonic structures with Ag as the plasmonic material, protected with a capping layer, would allow comparing with equivalent systems made with Au, and therefore a deeper understanding of the magnetoplasmonic properties of noble metal/ferromagnetic structures as a function of the plasmonic material.

Having this in mind, in this work we present a systematic study on the influence of SPP excitation in the MO activity of Pt capped Ag–Co–Ag trilayers grown by magnetron sputtering. Pt and Ag layers thicknesses are maintained constant, while the Co layer thickness is varied between 0 and 7 nm. Once the samples are grown, the morphology is studied by AFM and SEM, the magnetization reversal by Kerr-effect hysteresis loops, and the MO activity is thoroughly characterized by measuring polar Kerr rotation and ellipticity spectra. The influence of SPP excitation is studied by measuring the transverse Kerr signal with and without plasmon excitation for all the samples. All MO experimental data are compared with theoretical calculations.

II. PROCESS AND RESULTS

A. Fabrication and Morphology

Two series of 2 nm Pt/7 nm Ag–Co X nm/16 nm Ag structures have been grown simultaneously by magnetron sputtering at RT, one over glass substrates and another one over polycrystalline quartz. Samples grown on glass are used in transverse Kerr experiments with SPP excitation, and samples grown on

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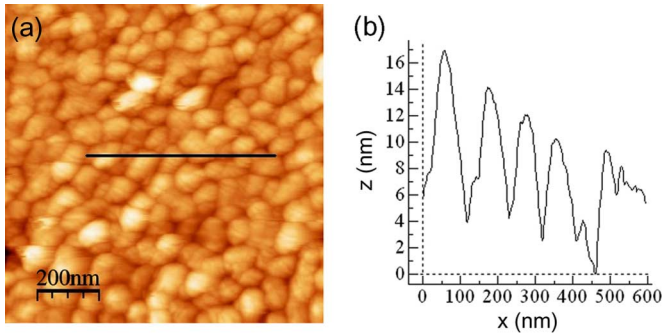


Fig. 1. (a) AFM image of the 3.5 nm Co thick sample. (b) Line profile taken along the mark indicated on (a). In both images the big roughness of the surface can be appreciated.

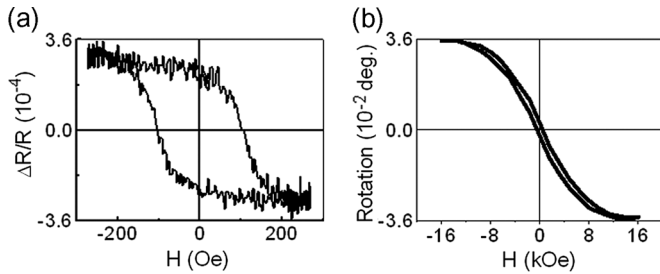


Fig. 2. Kerr loops of a representative sample (4.5 nm Co thickness) measured in (a) Transversal configuration; (b) polar configuration.

quartz are used in the rest of experiments. The morphology of the fabricated structures is investigated both by SEM and AFM measurements. In Fig. 1 we show both an AFM image and a topographic profile of the 3.5 nm Co thick sample, that is representative of the series. As it can be seen, the surface presents a characteristic roughness that indicates a deviation from 2-D growth.

Mounds of 50 nm diameter and 10 nm depth cover the surface. Since the total thickness of the fabricated structures ranges between 25 and 32 nm, we can conclude that this morphology is due to the first Ag layer, with a characteristic roughness that propagates upon deposition of successive Co, Ag and Pt layers.

B. Magnetic Characterization

Both transverse and polar Kerr rotation hysteresis loops (sensitive to in-plane and out-of-plane magnetization, respectively) are measured for all the samples to determine magnetic anisotropy and reversal process. The low saturation field and the high remanent magnetization observed for the transverse loops, compared with the polar ones, evidence an in-plane magnetic anisotropy for all the samples (loops of a representative sample are given in Fig. 2). We have verified that the loops are similar in all in-plane directions, as expected from the isotropic mounds observed by AFM. Taking into account such morphology and the polycrystalline structure of the samples, it can be stated that shape anisotropy dominates.

C. Magneto-Optical Characterization

The MO response has been studied using the Kerr effect in polar configuration, i.e. applying a 1.6 T magnetic field perpendicular to the sample surface and measuring the light reflected

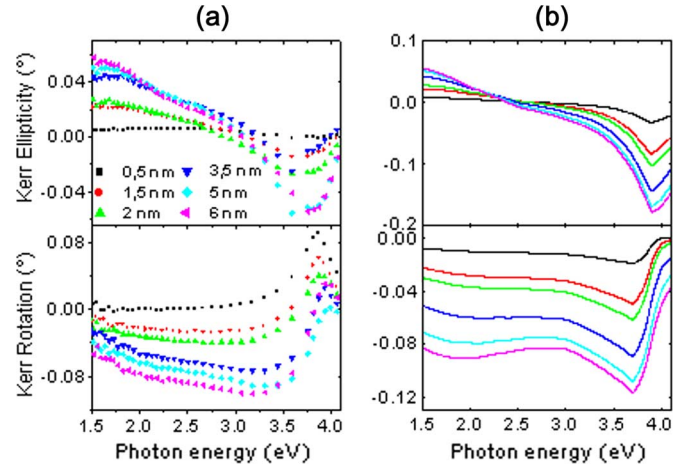


Fig. 3. Experimental (a) and theoretical (b) ellipticity and rotation spectra (upper and lower panels, respectively) of the samples. Displacement and enhancement of the peaks can be observed when the Co amount is increased.

by the magnetized sample, in particular the rotation of the polarization plane and the change in the ellipticity state with respect to the incident linearly polarized light.

Fig. 3 shows the rotation and ellipticity spectra for all the samples. The ellipticity spectra (Fig. 3(a), upper panel) show a characteristic negative peak around 3.75 eV that can be attributed to the bulk plasmon resonance of Ag [13]. Kerr rotation spectra (Fig. 3(a), lower panel) also varies gradually with increasing amount of Co, with a broad minimum around 3.4 eV only clearly observed for 6 nm Co, and a well defined maximum at around 3.9 eV. Such gradual variation of the MO ellipticity and rotation spectra with Co thickness has been qualitatively reproduced using simulations made with the Transfer Matrix method [14], even though some differences are observed. Regarding the theoretical ellipticity spectra, the zero crossing occurs at lower photon energies and the position of the minimum around 3.75 eV is basically independent of the amount of Co, while in the experiments the zero crossing occurs at higher energies and the position of the minimum shifts with Co thickness to higher energies.

On the other hand, the calculated Kerr rotation spectra show a sharp minimum at 3.75 eV together with a maximum above 4 eV, while the minimum is hardly observed experimentally and the maximum occurs at somehow lower energies. In addition, both calculated ellipticity and rotation values are systematically larger than the corresponding experimental ones. All these discrepancies are very likely due to the rough morphology of the structures that implies a deviation from the flat interface structures used in the calculations. Moreover, a possible Ag and Co oxidation induced by a poor Pt protection of the structure can also contribute to the observed differences. However, qualitatively both the spectral behaviour and their overall trend with the amount of Co are reproduced.

D. Magnetoplasmonic Analysis

Measurements of the transverse Kerr effect (magnetic field in the film plane and perpendicular to the light plane of incidence) using a *p* polarized 633 nm laser are carried out with and without SPP excitation in the same setup. To excite the SPP,

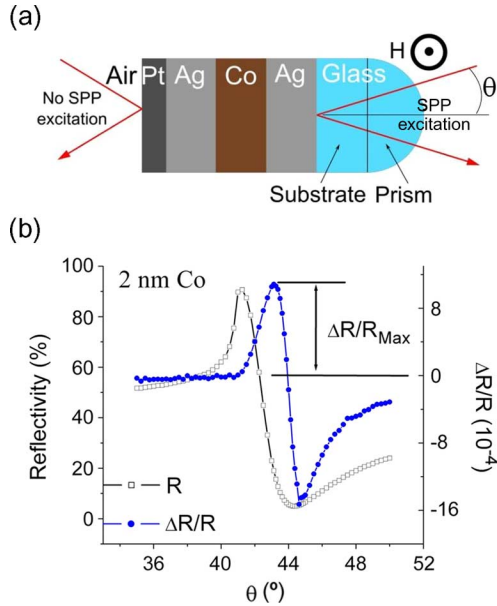


Fig. 4. (a) Schematic view of the sample configuration. If the light is incident from the left, no SPP excitation occurs; if light is incident from the right the prism allows SPP excitation (Kretschmann configuration). (b) Measurements of the reflectivity and MO signal for the 2 nm Co thickness sample. A big enhancement on the MO signal when the SPP is excited (absorption peak of reflectivity) can be appreciated.

we have used the Kretschmann configuration [15], [16] (see Fig. 4(a) with the light coming from the right side) where the beam lights the metal-dielectric interface through a semi-cylindrical glass prism that allows the matching between the in-plane component of the wave vector of the light and that of the SPP. The SPP excitation manifests itself as a reduction on the reflectivity at a specific angle of incidence above the critical angle for total internal reflection. In order to perform the measurements without SPP excitation, the beam lights the air-metal side of the samples and no matching occurs (see Fig. 4(a) with the light coming from the left).

Fig. 4(b) shows the angular dependence of the reflectivity (R), and the magnetic field induced variation of the reflectivity related to total reflectivity ($\Delta R/R$), for the 2 nm Co sample with SPP excitation. The angular variation of the reflectivity shows firstly the total internal reflection at around 41° and then the SPP excitation with the clearly observed minimum around 44° .

On the other hand, the variation of reflectivity for opposite magnetic fields applied (ΔR) also exhibits a maximum in this angular region. As a consequence, the transverse Kerr effect defined as $\Delta R/R$ is characterized by a sharp resonance like angular behaviour at around 44° , i.e. when the SPP is excited. When the SPP is not excited, both R and $\Delta R/R$ are basically constant in the same angular range (not shown).

By defining the maximum of the reflectivity variation, $\Delta R/R_{\text{Max}}$, as its maximum positive value (see Fig 4(b)) we can study the Co thickness dependence of this magnitude and compare it with its counterpart obtained without plasmon resonance excitation. In Fig. 5(a) we show the experimentally determined transverse Kerr signals, both with and without SPP excitation, as a function of Co thickness. As it can be

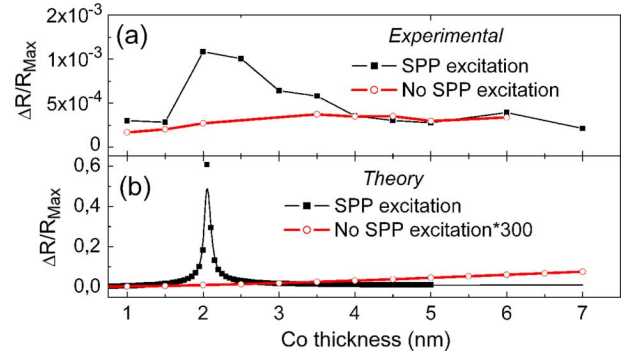


Fig. 5. Co thickness dependence of the transversal MO signal with and without SPP excitation. (a) Experimental curve for 633 nm light. (b) Simulation using transfer matrix formalism. We can see a strong Co dependence peak around 2 nm when SPP is excited, contrary to the non excitation case, where the MO signal gradually increases with Co thickness.

observed, when no SPP excitation is present, the MO signal exhibits the expected behaviour and monotonously increases with Co amount. However, when the SPP resonance is excited, a maximum is observed at around 2 nm Co thickness, gradually decreasing for thicker Co layers. This is due to the optimum excitation of the SPP at this specific Co thickness and to the subsequent maximization of the electromagnetic field at the MO active (Co) layer. For thicker Co thickness, the higher optical absorption of the system makes the SPP excitation not optimal anymore. It is worth mentioning that this behaviour is similar to that obtained in Au/Co/Au trilayers [8] where the maximum was obtained for about 6 nm Co thickness. This different Co thickness for optimal SPP excitation and therefore maximum MO transverse Kerr signal is due to the different optical constants of Au and Ag.

The transverse Kerr signal, with and without SPP excitation for such structures, has been calculated via Transfer Matrix method simulations using bulk values for the optical constants of the materials, and is presented in Fig. 5(b). As it can be seen, in the absence of SPP excitation $\Delta R/R$ gradually increases with the amount of Co, while it exhibits a maximum for 2 nm of Co when SPP is excited, in excellent agreement with the experimental results. However, both the magnitude of the effect and the sharpness of the curve are much larger in the calculations than in the experiment. This is probably due to the deviation from the ideal structures that the theory is treating. The growth mode is far from 2-D, yielding a rough morphology and the absence of sharp interfaces in lateral areas of hundreds of nm. As a consequence, a good protection of the layers by the Pt cap is not easily guaranteed and partial oxidation of Ag, Co or both cannot be excluded. Taking this into account, the actual optical and magneto-optical constants of the layers may differ from the bulk ones used in the calculations.

In this sense, further experiments need to be performed, on one hand, carrying out chemical analysis of the fabricated structures to determine the actual oxidation state of the different layer constituents, and on the other hand a systematic study varying deposition conditions in order to promote 2-D growth and improve films planarity.

III. CONCLUSION

We have fabricated Pt capped Ag–Co–Ag structures to study the influence of SPP excitation in the MO activity. The magnetic characterization indicates that shape anisotropy dominates, giving rise to in-plane anisotropy. The MO response has been studied, and a gradual variation of the polar Kerr rotation and ellipticity with Co thickness has been found, qualitatively in agreement with theoretical calculations. On the other hand, an enhanced transverse Kerr signal when the SPP is excited has been observed in contrast to the results obtained when no SPP is excited. The transverse signal dependence with Co thickness agrees qualitatively with theoretical simulations, obtaining a signal maximum around 2 nm Co thickness. The differences appearing between the experimental results and the calculations are probably due to the absence of sharp interfaces as well as to Ag and Co deterioration due to the poor Pt coverage.

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