Thickness dependent enhancement of the polar magneto-optic Kerr rotation in Co magnetoplasmonic nanostructures

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We reveal the influence of the thickness of the ferromagnetic layer on the surface plasmon polaritons assisted enhancement of the polar magneto-optic Kerr effect. The thickness of the magnetic layer plays a crucial role in the interaction between plasmonic resonances and magneto-optic response. We show that the feature of the magneto-optic enhancement does not only depend on the in-plane structuring of the sample but also on the out-of-plane geometrical parameter such as the thickness. Specific thicknesses can drive a large, up to nine times higher enhancement of the polar magneto-optical effect.

I. INTRODUCTION

Magnetoplasmonics is an emergent research field that aims to strongly modify the magneto-optic response in the presence of surface plasmons and to control plasmonic resonances with magnetic field[1, 2]. The enhancement of the magneto-optical effects especially of the polar and transversal Kerr effect (PMOKE-TMOKE) due to the presence of surface plasmons has been shown in many different nanostructures. Examples are hybrid nanostructures of noble metal/ferromagnetic metal (or dielectric) like Co/Au, YIG/Au [3], in Au/Co/Au multilayers [4] and multilayers[5], as well as in patterned pure magnetic films [6–12]. The enhancement has been reported for both types of plasmonic excitations for localized (LSPs)- and for propagating (SPPs) surface plasmons. The mechanism for the increased magneto-optical values is the enhancement of the electric field provided by the excitation of either localized plasmons or propagating plasmons as very recently shown by correlating near-and far field optical- and magneto-optical response [13].

Despite the numerous studies on materials combinations and geometrical considerations little attention has been given to the parameter of the thickness of the magnetic layer. In Au/Co/Au multilayers [14] an optimum Co thickness for the redistribution of the electromagnetic field in the magnetic layer has been observed at around 8 nm when plasmon excitation is occurring at the Au/air interface. However, there is no such study for the case of pure magnetic nanostructures. In this paper we use hexagonal arrays of holes perforated in Co films of different thicknesses. We use optical reflectivity and polar magneto-optical Kerr effects together with simulations characterise the thickness dependence of the magnetic layer to magneto-optic enhancement in magnetoplasmonic structures. Our study is focused in relatively thick metal films with the film thickness, t, being smaller than the wavelength of the incident light λ, and larger than the skin depth δ of the metal, i.e. \( \delta \leq t < \lambda \).

We show that the thickness constitute another way to strongly manipulate the enhancement of the PMOKE signal.

Three Co films were patterned by the use of self-organization of colloidal polystyrene beads on Si substrates as shadow masks [7]. The final layout of the samples, is presented in Fig. 1. There is a hexagonal hole structure with a periodicity of \( a_0 = 470(15) \text{nm} \) and with hole sizes of \( d = 260(10) \text{nm} \). A very thin buffer layer of Ti was initially deposited for better adhesion of the Co on the Si and Co layers with different thickness were grown on the seeding layer. To prevent oxidation of the Co surface, a capping layer of 2 nm Au was deposited. The final form of the samples were: Au (2 nm)/Co (X nm)/Ti (2nm)/Si(111), with X being either 20, 60, or 100 nm. Continuous thin films of the same composition were prepared at the same time, as reference samples.

There are two characteristic main directions that are relevant for plasmon excitation and they are the nearest neighbour (ΓK, [10]) and the second nearest neighbour (ΓM, [11]) directions that are aligned parallel to the scattering plane. In our work we have performed measurements aligning the plane of incidence to the ΓK, [10] direction, as shown in Fig. 1.

For the PMOKE measurements a white light source of a mercury lamp is used to obtain a broadband light spectrum. The light is guided into a monochromator with 600 lines/mm gratings. After the monochromator, the light is guided first through a highpass filter to suppress the effects from higher harmonics and thereafter through a set of beam-shaping and focusing lenses to maximise the intensity reaching the sample. To minimise the noise, the light is modulated with either a chopper or Faraday cell. Before being reflected, the light is focused onto the sample with an angle of incidence of 4 degrees through a hole in the magnetic core of the ferromagnetic coils.

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continuous reference films exhibit a typical metallic be-

thickness, however can be estimated around

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sample and at

Figure 2 (b) shows that below 3 eV the main feature

is the trough in reflectivity at \( \approx 2.81 \) eV for the 60 nm

sample and at \( \approx 2.69 \) for the 100 nm. The trough is

present but hardly visible for the sample with 20 nm Co

thickness, however can be estimated around \( \approx 2.9 \). The

continuous reference films exhibit a typical metallic be-

haviour. A second broad and intense dip is appearing

for energies \( \approx 3.75 \) eV and \( \approx 4.0 \) eV for the 100 nm

and 60 nm respectively. Figure 2 (a) presents the calculated

reflectivity curves for the three samples. Apart from the

20 nm sample where the reflectivity of the Si substrate

dominate, the calculation captures well the reflectivity

behaviour of the samples. The observed minima in ref-

lectivity for all the Co samples are the result of the res-

onant coupling of light to SPPs excitations at the Co / air

patterned interfaces as it can numerically calculated

by using the scattering matrix approach\[15\] and shown

in Fig. 2 (a). The simulation is close to the experiment

as indicative shown with the vertical lines, showing re-
duced reflectivity where SPPs are excited. An additional

feature is appearing in the calculation at \( \approx 3.1 \) eV that

originates from the splitting of the plasmonic excitation

in different directions as we move away from the normal

incidence. Experimentally we hardly see these dips in

the reflectivity curves due to their lower relative inten-
sity in combination with the smaller resolving power of

our reflectivity setup.

From Fig. 2 we see that the reflectance minima exhibit

a red shift in energies as we change the thickness from 20

to 100 nm. For example, the three minima of reflectivity

for the sample of 60 nm are located at \( \approx 2.81, \approx 3.2 \) (cal-

culation) and \( \approx 4.0 \). On the contrary the three minima

of reflectivity for the sample of 100 nm are at \( \approx 2.69 \), at

\( \approx 3.1 \) and \( \approx 3.75 \) all of them red shifted compared to the

thinner 60 nm sample. By holding constant the size of

the holes at 260 nm the critical parameter here becomes

the ratio of the thickness with respect to the period of

the pattern \( h/a \) \[16\]. By increasing the thickness from

to 60 nm to 100 nm sample and the corresponding ratio

from \( h/a = 0.13 \) to \( h/a = 0.21 \), we cause a redshift of

the reflectivity minima. Similar redshift of transmission

maxima with the thickness in the presence of plasmonic

excitations has been observed in antidot structures com-
poved of Ag, and Au \[16\]. The presence of an absorbing

magnetic metal does not alter this behaviour revealing

that the driving force of the reflection minima or trans-
mision maxima are the excitation of surface plasmons

polaritons.

The experimental Kerr rotation spectra of the three

patterned and the three reference Co samples, with dif-

ferent thicknesses, are presented in Fig. 2 (d). The

magneto-optic response depends on the minima of re-

lectivity. The thinnest sample of 20 nm that presents

a very small signature of SPPs signature in its reflec-
tivity curve, does not exhibit a significant difference in

the Kerr spectrum with respect to its continuous coun-

terpart. However, the other two patterned samples show

strong changes as compared to the continuous films, with

extraordinary enhancement of the Kerr rotation. At the

energies where SPP modes are involved the Kerr rotation

\( \theta_K \) is enhanced. \( \theta_K \) is maximized at \( \approx 2.69 \), and at \( \approx 2.81 \)

for the 100 and 60 nm respectively. A second important

feature appears at energies \( \approx 3.1 - 3.2 \) eV where another

enhancement maximum is noticeable for both thick sam-

FIG. 1. A SEM image of a typical sample to show the overall

uniformity of the structure. The inset that shows the hexago-
nal hole arrangement in better detail as well as the two main

excitations that are available in this type of lattice.

The maximum magnetic field strength is 2.2 T. Finally

the light goes through the automated polariser before be-
ing focused onto the photo-detector or photo-multiplier tube.

The modulated signal is measured through either a

photo-detector or a photo-multiplier tube connected to

a lock-in amplifier. For the spectral reflectivity the same

setup like the PMOKE measurements is used adjusted for

reflectivity measurements by guiding the reflected light

through a lens into a photo-multiplier tube (PMT) or

photo detector. The configuration of the setup allows for

measuring low light intensities, although as all light will

not be collected the reflectivity has arbitrary units. The polar

Kerr rotation is measured in absolute values (de-

grees), as it is measured through magnetically saturating

the sample in the two polar directions and comparing the

polarisation rotation difference, by scanning the polariser

for the point of light extinction.

Reflectivity and polar Kerr-rotation measurements

were performed at an energy range from 1 to 4.2 eV. Polar

Kerr-rotation spectra were measured at samples’ satura-

tion state (maximum applied magnetic field \( B = 1.1 \) T),

while the samples were oriented with the \( \Gamma K \)-direction of

the hexagonal array parallel to the plane of incidence.

Figure 2 (a) shows the calculated reflectivity, (c) the

experimental reflectivity, (b) the calculated magneto-
optical spectra for the three antidot samples, and (d) the

MOKE spectra of the patterned samples in comparison

with their corresponding continuous films. The reflect-
vity curves were obtained with p-polarized light and

measured relative to the intensity of the direct beam.

Figure 2 (b) shows that below 3 eV the main feature

is the trough in reflectivity at \( \approx 2.81 \) eV for the 60 nm

sample and at \( \approx 2.69 \) for the 100 nm. The trough is

present but hardly visible for the sample with 20 nm Co

thickness, however can be estimated around \( \approx 2.9 \). The

continuous reference films exhibit a typical metallic be-
The excited SPPs are correlated to the thickness through their field penetration depth. As it has been shown the penetration depth of SPPs, \( \delta_{kin} \), in a metal is usually of the order of 10 nm in the visible and infrared [17]. Furthermore, in our case the absorbing ferromagnetic materials introduces significant losses (large intrinsic absorption). The role of overlapping SPPs field in the magnetic layer has been previously observed in symmetric structures of Au/Co/Au [14, 18] and in Pt-capped Ag/Co/Ag structures [19]. They have revealed an optimum enhancement of the MO activity for specific Co thickness being around 7-10 nm where the excitation of the SPP in the Au layer maximises the electromagnetic field distribution in the MO Co layer for that thickness. So one would expect that our samples with much higher thickness should have higher optical absorption and dominant damping preventing an optimal SPP excitation, and therefore a reduction in the observed MO signal. Instead, the experiment shows a maximum enhancement for the 100 nm sample. Here, we must mention that the aforementioned SP penetration depth is referred to continuous trilayers and they are not to be compared and confused with our antidot structures. The antidot structure and the presence of holes render the thickness parameter a very important factor for the behaviour of SPPs. As we have shown in Ref. [13] the excitations of surface plasmon polaritons in thick magnetic films leads to remarkable electric field intensity patterns.

FIG. 2. Calculated reflectivity (a), experimental reflectivity (c), calculated PMOKE spectra (b), and experimental PMOKE spectra (d) for three different thicknesses of 20 nm, 60 nm and 100 nm. Black symbols refer to the patterned samples, while white symbols show the behaviour of the continuous films of the same composition. Extraordinary troughs are observed in the reflectivity. The patterned samples show clear changes in the Kerr spectra at different thicknesses. Strong enhancement of the Kerr rotation is obtained from the 60 nm and 100 nm samples at energies where SPPs are excited.
that are responsible for the magneto-optic enhancement. The enhancement of electric field of the excited SPPs that is sufficiently strong in order to interact within the magnetic Co layer together with the multiplicity of the excited plasmonic modes leads the large enhancement of the Kerr rotation at energies above \( \approx 3.5 \) eV. Although the calculation in Fig. 2 (b) captures well the size and the shape of magneto-optic enhancement in the whole spectral region it can not reproduce the very big enhancement above \( \approx 3.75 \). The experiment shows an impressive enhancement. The reason for this is the almost zero reflectivity that is experimentally measured while in the theory the samples obtain a significant percentage of reflectivity. Accordingly, the experimentally measured \( \theta_K \) depends not only in the polarization conversion due the SPPs excitations but also on the reflectivity [13]. When the reflectivity goes to zero the Kerr rotation is diverging since the optical reflection coefficient is in the denominator [13]. The very low measured reflectivity that strongly depends on the thickness of the antidot samples significantly contributes to the very large enhancement of Kerr rotation.

In conclusion we have shown a new way to manipulate the magneto-optic response of magnetoplasmonic structures by taking advantage of the thickness of the magnetic layer. We have used patterned Co hexagonal antidot lattices with different thickness to generate a large enhancement of P-MOKE signal close to SPP resonances. We have revealed that not only the in-plane structural parameter that defined the excitation condition for SPPs is important for the PMOKE enhancement but also the out of plane direction represented by the thickness of the magnetic layer is crucial. We have shown that the thickness can control the magneto-optic Kerr enhancement by SPPs excitation and very low reflectivity values. Consequently, new routes for tailoring the functionality of patterned structures can emerge, when the influence of the thickness on the magneto-optic activity is taken into account.

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