An investigation of the interface and bulk contributions to the magneto-optic activity in Co/Pt multi-layered thin films

Citation for published version (APA):

Demirer, F. E., Koopmans, B., & Lavrijsen, R. (2021). An investigation of the interface and bulk contributions to the magneto-optic activity in Co/Pt multi-layered thin films. *Journal of Applied Physics*, 129(16), [163904]. <https://doi.org/10.1063/5.0047093>

Document license:
TAVERNE

DOI:
[10.1063/5.0047093](https://doi.org/10.1063/5.0047093)

Document status and date:
Published: 27/04/2021

Document Version:
Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
- The final author version and the galley proof are versions of the publication after peer review.
- The final published version features the final layout of the paper including the volume, issue and page numbers.

[Link to publication](#)

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license above, please follow below link for the End User Agreement:

www.tue.nl/taverne

Take down policy

If you believe that this document breaches copyright please contact us at:

openaccess@tue.nl

providing details and we will investigate your claim.

An investigation of the interface and bulk contributions to the magneto-optic activity in Co/Pt multi-layered thin films

Cite as: J. Appl. Phys. 129, 163904 (2021); doi: 10.1063/5.0047093

Submitted: 10 February 2021 · Accepted: 11 April 2021 ·

Published Online: 27 April 2021

Figen Ece Demirer,^{a)} Reinoud Lavrijsen, and Bert Koopmans

AFFILIATIONS

Department of Applied Physics, Eindhoven University of Technology, PO Box 513, 5600 MB Eindhoven, The Netherlands

^{a)}Author to whom correspondence should be addressed: f.e.demirer@tue.nl. URL: <https://www.tue.nl/en/research/research-groups/physics-of-nanostructures/>

ABSTRACT

We report an experimental study that focuses on the magneto-optic interaction between light and perpendicularly magnetized ferromagnetic thin-film multilayers. In this study, samples containing multiple Co/Pt interfaces are measured via the polar magneto-optic Kerr effect. Thanks to a sample set with a continuous Co thickness variation and single and double Co-layered samples, interface and bulk contributions to the magneto-optic activity are separately determined. Kerr rotation and ellipticity signals are recorded as a function of the Co thickness. The results are analyzed via a transfer matrix method that accounts for the standard optical and magneto-optic effects in multi-layered thin-films. Bulk magneto-optic contribution of Co ($Q_{\text{Co,bulk}}$) that is in accordance with the literature is consistently determined despite the use of thin-films. Interfacial Co ($Q_{\text{Co,int.}}$) and magnetized Pt (Q_{Pt}) contributions are presented in terms of two models. Interface phenomena of the large spin-orbit coupling between Co and Pt and the proximity induced magnetization in Pt layer are represented in the models. The strength of interfacial magneto-optic activity is interpreted as an indicator of the relative interface quality among the samples.

Published under an exclusive license by AIP Publishing. <https://doi.org/10.1063/5.0047093>

I. INTRODUCTION

During the 1990s, a vast amount of research was dedicated to study Co/Pt multilayers with perpendicular magnetic anisotropy (PMA) due to their use in magneto-optic (MO) recording media.¹ Recently, upon demonstration of novel spintronic devices that utilize the physical phenomena at heavy metal/ferromagnetic metal interfaces,^{2–7} the research interest has been revived. As evidenced by the commercial product of STT MRAM,⁸ the fabrication processes of the multi-layered thin-films are compatible with large scale semiconductor production. Therefore, it is expected that innovative devices incorporating the multilayers will reach a technological maturity level required for large scale production in a relatively short time. As commonly seen in the family of thin-film multilayers with PMA, Co/Pt multilayers demonstrate high chemical stability,¹ enhanced MO activity,⁹ and tunable magnetic properties via adjustments in the fabrication processes,¹⁰ which are proven to be crucial for device applications. Considering these properties of Co/Pt multilayers and the demand for novel functionalities

provided by integrated photonic devices, Co/Pt thin-film multilayers with PMA were suggested to be implemented on photonic chips for increased functionalities such as integrated photonic memory devices and optical isolators.^{5,11} The suggested functionality relies on the interaction between confined light and a thin-film permanent magnet, which is in the vicinity. This raises an urgency to map the MO properties of Co/Pt thin-film multilayers to simulate, design, and engineer novel functionalities for devices.

Assuming non-local effects¹² are not present, the MO interaction between light and the thin-film stack can be simulated for any device configuration and material stack with inputs of MO Voigt constants (Q) of magnetized layers in a multi-layered thin-film stack. The simulation can quantitatively predict the MO interaction in terms of complex Magneto-Optic Kerr Effect (MOKE), namely, Kerr rotation and ellipticity. There is a large spread in the previously reported Q_{Co} values of thin-film Co. Apart from differences caused by the crystal structure type¹³ and the preferred magnetization orientation, the degree of expression of the interfacial magneto-optic phenomena leads to scattered findings of Q_{Co} .

Earlier works that reported the differences due to different strain states¹⁴ and different fabrication techniques¹⁵ of thin films indicate to this direction (see further in Sec. II). We suggest that highlighting the underlying cause can bring clarity to future findings. In a quest to separate the interface and bulk activity, we unambiguously defined the bulk Q constants and assigned interface Q constants. We developed and used two optical models that account for the MO enhancement at the Co/Pt interface. In these models, the proximity induced magnetization in the Pt layer and the large spin-orbit coupling at the interface were considered separately. The MO contributions from interface-dominated and bulk-dominated Co regions were probed experimentally using a specially designed sample set with a continuous Co thickness variation (wedge) over the samples. A typical sample deposited via DC magnetron sputtering consists of a Ta(4 nm)/Pt(2 nm)/Co(0–2 nm)/Pt(2 nm) stacking, where the Co layer thickness is changed from 0 to 2 nm over a range of 15 mm. Additionally, structural effects at the interface were probed by using single and double Co-layered samples. MO constants of bulk Co ($Q_{\text{Co, bulk}}$) were determined, which agreed well with the literature. Using models, interfacial Co ($Q_{\text{Co, int.}}$) and magnetized Pt (Q_{Pt}) contributions were assigned to the samples. Comparing the differences in the obtained $Q_{\text{Co, int.}}$ and $Q_{\text{Co, bulk}}$ values quantitatively explains the differences in the reported Q_{Co} for thin-films. Additionally, a quantitative comparison of the MO properties of Co and Pt at the interface was shown to have a direct correlation with the interface quality.

This work is structured in the following way. Section II describes the state-of-the-art by focusing on the physical phenomena that occur on Co/Pt multilayers with a special interest in the Co/Pt interface and presents a review of the literature about previously reported Q_{Co} values (and in a very few cases, Q_{Pt} values). It includes methodologies used by previous studies to pinpoint the reasons behind the vastly different MO constant findings of thin-film Co. Section III summarizes the methodology used in this work in three subsections. First, Subsection III A describes the specially designed sample set, its preparation, and MOKE measurement setup. Second, Subsection III B depicts the models that describe the magnetization profiles of Co and Pt. Third, Subsection III C elaborates on the transfer matrix method used for multilayered thin-films to separate MO and optical effects. In Sec. IV, the results are presented and discussed. Last, in Sec. V, the conclusions are given.

II. STATE-OF-THE-ART

In the presence of a large spin-orbit interaction, the orbital moment connects the spin moment to the atomic structure of a material. For Co/Pt thin-film multilayers, the hybridization of the Co 3d and Pt 5d orbitals at the interface causes in-plane orbitals to become dominant; thus, the magnetic moment points out-of-plane (oop).²² Structural effects at the interface, such as interfacial roughness, intermixing, alloying, strain, and dislocations,^{10,23–25} are decisive for the strength of the PMA in multilayered thin films. The hybridized orbitals formed at the Co/Pt interface give rise to other physical phenomena as well: a proximity induced magnetization on Pt atoms near the interface^{26,27} and an enhancement of the Co atomic magnetic moment at the interface.²⁸ Similar to PMA, the strength of proximity induced magnetization is also affected by the

structural effects at the Co/Pt interface.^{29–32} Experimental results^{19,33} supported by *ab initio* calculations³⁴ showed that the induced magnetization in Pt rapidly decays away from the interface with a decay length of just a few tenths of a nm.^{35,36} Some works reported asymmetries in Pt layer magnetizations among top and bottom interfaces for samples that contain multiple ferromagnetic metal/Pt interfaces.^{19,31,37} Structural asymmetries between top and bottom interfaces were held responsible for this. In addition, the total thickness of the Pt layer was shown to cause no difference in proximity induced magnetization, provided that there is no structural change at the interface due to the Pt thickness.^{37,38}

MOKE indirectly probes the magnetism in a material by monitoring the allowed orbital transitions governed by the spin-orbit interaction. The preferential absorption of left- over right-handed light causes the observed MOKE signal. The signal is sensitive to changes that occur in a sub-nanometer scale in electronic orbitals. Therefore, MOKE can offer valuable characterization of Co/Pt multilayers, revealing structural effects at the Co/Pt interface, at a sub-nanometer scale. It has been shown that changes in the fabrication method,¹⁵ as well as changes in deposition conditions of a certain method,³⁹ can be probed by using MOKE.

MOKE is a cumulative effect that results from standard optical and magneto-optical phenomena. When standard optical and magneto-optical effects are separately accounted for via use of a transfer matrix method, the MO constant Q of all magnetized layer(s) can be determined. Figure 1 displays the literature reported Q_{Co} obtained by using MO Kerr rotation and ellipticity as inputs in the mentioned method. There is a large scattering in the reported values especially comparing thin-film and bulk Co (shown with filled symbols). As evident in Fig. 1, the Q of Co/Pt bilayers and Co thin-films are larger than that of bulk Co.¹⁸ Previously, the differences in fabrication methods were proposed as the main

FIG. 1. An overview of the literature reported complex Q_{Co} values. The values measured at the He-Ne laser wavelength (632 nm) are presented. Details about each presented data point can be found in Table I.

TABLE I. Details of the literature findings in Fig. 1.

Symb. and ref.	Q_{Co}	t_{Co} (nm)	Crys. lattice	Magn. dir.
⊠ ¹⁶ (Co ₃ Pt alloy)	$0.0174 - 0.0151i$	>50	fcc-hcp	In-plane
● ¹⁵	$0.033 - 0.011i$	50	...	In-plane
⊕ ¹⁵	$0.041 - 0.04i$	0–0.85	fcc	OOP
⊞ ¹⁵	$0.04 - 0.025i$	<0.4	fcc	OOP
⊞ ¹⁷	$0.02 - 0.005i$	<1	...	OOP
⊞ ¹⁸ Co/Pt mult.	$0.027 + 0.007i$	80	...	In-plane
▼ ¹	$0.029 - 0.009i$	>50	fcc	In-plane
⊞ ¹⁹	$0.047 + 0.012i$	0.5	fcc	OOP
⊖ ²⁰ (Co+Pt alloy)	$0.032 - 0.001i$	>50	...	In-plane
○ ²¹	$0.0299 + 0.0122i$	>50	...	In-plane

reason behind the difference.¹⁵ Some works adopted practices to separate the interfacial Co and (sometimes) the magnetized Pt contributions from that of bulk Co. Fiedler *et al.* introduced an excess Kerr rotation and an ellipticity signal for each Co/Pt interface and excluded this amount while calculating Q_{Co} .¹⁵ Some studies assigned a MO constant Q to the Pt layer. The magnetization profile in the Pt differed among these studies. Moog *et al.* assumed the whole Pt layer to be magnetized homogeneously,⁴⁰ while others used a monolayer of a homogeneously magnetized Pt layer with the rest being non-magnetic.^{41,42} An *in situ* MOKE measurement taken during Pt growth on Co showed that the Pt magnetization decays exponentially from the Co/Pt interface.¹⁹ This is found to be in accordance with proximity induced magnetization studies.²⁷ It is the aim of our work to apply different models to the same experimental data on a specially designed set of samples in order to establish a more unambiguous description.

III. METHODOLOGY

This section describes the sample set used in this study and the method of fabrication, followed by a description of the MOKE setup used for our experiments. Then, we discuss in more detail the magnetization profiles introduced in Sec. III B. Last, we explain the method we used to fit the Q values for the bulk and the interfacial Co, as well as the proximity induced contribution from the Pt.

A. Sample fabrication and MOKE measurement setup

The sample set used in this work is designed to distinguish the interface and bulk MO contributions. This was achieved by using wedged Co layers varying in thickness from 0 to 2 nm over a lateral extend of 15 mm. Additionally, single and double Co-layered stacks were used for comparison of the interface effects. Names and stack orders of single and double Co-layered samples are reported in Table II. The samples were fabricated via computer-controlled DC magnetron sputtering at room temperature by using high purity (99.99%) metal targets. This fabrication technique is well-established and was previously shown to result in (111) textured face-centered cubic (fcc) Co.⁴⁴ The wedged Co thickness was achieved by a knife-edge shutter, which moves over the substrate and shadows it during deposition. The base pressure of the

TABLE II. Sample names and corresponding material stacks.

Sample name	Stack order ^{ab}
Double Co on 1 nm of Pt (d1)	SiB/Ta1/Pt1/Co0-2/Pt1/Co0-2/Pt2
Double Co on 2 nm of Pt (d2)	SiB/Ta1/Pt2/Co0-2/Pt2/Co0-2/Pt2
Single Co on 2 nm of Pt (s2)	SiB/Ta1/Pt2/Co0-2/Pt2
Single Co on 3 nm of Pt (s3)	SiB/Ta1/Pt3/Co0-2/Pt3

^aNumbers indicate thickness in units of nm.

^bSiB refers to a boron doped silicon substrate with a native oxide layer.

deposition chamber was kept at 10^{-9} mbar to prevent oxidation. During deposition, 10^{-2} mbar argon (99.9999% purity) pressure was used. The samples were grown on boron doped silicon substrates with a native oxide layer. Growth rates of the materials Ta, Pt, and Co were 0.564 Å/s, 0.803 Å/s, and 0.420 Å/s. MOKE measurements were performed using a red laser diode (632 nm wavelength) in a polar MOKE configuration at room temperature. Perpendicular magnetic fields were swept between ± 500 mT, and hysteresis loops were gathered from which the saturation value of the Kerr effect was extracted. To increase sensitivity of Kerr rotation and ellipticity data collection, a photoelastic modulator (PEM) is used together with polarizers. An Si amplified detector detected the light intensity at the fundamental (50 kHz) and the second harmonic (100 kHz) frequency of the PEM, which correspond to Kerr ellipticity and rotation, respectively. Owing to the motor-controlled motion of the sample holder in the setup, wedged samples that have a spatial variation of thickness are measured by incremental steps. The approximate FWHM of the focused laser spot was 0.2 mm, which yields a spread of 0.026 nm thickness per data point.

B. Magnetization profiles in multi-layers

In this section, the two models describing the magnetization profiles of Co and Pt in Co/Pt multi-layered thin-films are presented in more detail. Both models are derived from experimental evidence¹⁹ and theoretical calculations³⁴ reported in the literature. In this work, we attempt to resolve which of the two models better represent the reality based on the experimental evidence. In Fig. 2, the magnetization profiles corresponding to the two models are sketched. Model 1 assumes that the magnetized regions of the multilayers are confined to the Co layers, and the MO activity is enhanced for the first monolayer of Co at the interface with Pt (shown with $Q_{Co,int.}$, while the rest is the bulk value $Q_{Co,bulk}$). Model 2 assumes that the magnetization is homogeneous within the Co layer ($Q_{Co,bulk}$), and the neighboring Pt layers are magnetized symmetrically through proximity induced magnetization, as indicated with Q_{Pt} . As previously reported,¹⁹ the magnetization decay in Pt with respect to Pt thickness d_{Pt} is assumed to be

$$Q_{Pt} = Q_{Pt \max} e^{-\beta(d_{Pt}-0.2)}. \quad (1)$$

Only Pt thicknesses above 0.2 nm are considered since a monolayer coverage is reached at this value.⁴⁶ The exponential decay constant β is 6.36 nm^{-1} , adopted from the findings of Didrichsen *et al.*

FIG. 2. Magnetization profiles of multi-layers according to Models 1 and 2. Co and Pt monolayers are assumed to be 0.22⁴⁵ and 0.27⁴⁶ nm thick, respectively. Proximity induced magnetization in Pt is assumed to decay exponentially (red dashed lines) according to Eq. (1). The models are derived by using experimental and theoretical findings described in Sec. II.

monitoring *in situ* MOKE. It denotes a high magnetization decay within just a few tenths of nm. $Q_{Pt,max}$ corresponds to the Q value of the monolayer of Pt, which is directly adjacent to the Co. Note that as long as the numerical value of the amplitude of β is large, the precise numerical value of it has no significant effect on the resulting $Q_{Pt,max}$ value. Therefore, we have chosen to work with previously obtained results for easier comparison. If the β amplitude is taken as infinite, which would mean that only the first monolayer of Pt is magnetized, the $Q_{Pt,max}$ value would increase approximately by 25%.

C. An optical transfer matrix method for MOKE in multi-layered thin-films

An optical transfer matrix method for determination of MOKE in multi-layered thin-films containing magnetic and non-magnetic layers has been developed by Zak *et al.*⁴⁷ Using this method, the Kerr rotation and ellipticity from a multilayered thin-film with magnetic and non-magnetic layers can be simulated given the inputs of layer thicknesses, refractive indices, MO constant(s) of the magnetized layer(s), and angle of incidence of the incoming light. In this work, the method is used in reverse order, and the MO constant(s) of the magnetized layer(s) in multi-layered samples are determined by using the experimental data (Kerr rotation and ellipticity). Assuming Co is the only magnetized layer with homogeneous magnetization resulted in $Q_{Co,eff.}$ vs Co thickness behavior where the magneto-optic activity is enhanced at the Co/Pt interface. Therefore, the magnetization profiles described in

TABLE III. Complex refractive indices of materials.

Material	Refractive index
Si with native oxide (subst.) ⁴³	$3.84 + 0.02i$
Ta ^a	$4.31 + 4.26i$
Pt ¹⁵	$2.35 + 4.82i$
Co ¹⁵	$2.57 + 4.14i$

^aObtained from ellipsometry measurements of thin film Ta (10 nm).

Sec. III B are employed and the MO constants for bulk and interfacial Co, and the magnetized Pt are determined separately. Refractive indices of each layer are given in Table III. Note that the bulk Co and Pt refractive indices⁴³ differ slightly from the thin-film values that are used in this study.

IV. RESULTS AND DISCUSSION

In order to separate bulk and interface contributions in Co/Pt multilayers, we performed MOKE experiments on our specially designed structures. We analyzed them by a transfer matrix method⁴⁷ using two different models to extract bulk and interface values for the respective complex Q -values.

A sample set of thin-film multilayers designed to probe the interface and bulk effects separately was used. Measuring them in a polar MOKE setup, complex MOKE signals were obtained as a function of Co thicknesses. A magnetization state that is saturated and stable is assured for each data point in the indicated PMA window. Figure 3 shows full hysteresis loops of applied H-field vs

FIG. 3. Applied magnetic field dependence of the magneto-optic signal obtained from various Co thicknesses of the sample s2. Thicknesses of 1.5 nm, 1.2 nm, 0.8 nm, and 0.4 nm of Co are shown where the PMA range of the sample is from 0.4 nm to 1.42 nm. Perpendicular to in-plane transition is seen at 1.5 nm Co. The magneto-optic signals are normalized to the maximum value measured for each Co thickness.

normalized magneto-optical signals for varying Co thicknesses of sample s2. The saturation ranges shown in Fig. 3 were used in our quantitative analysis.

In Fig. 4, the evolution of the Kerr signal vs total Co thickness for the sample set with single (s2, s3) and double (d2) Co layers is shown. In the left column, real and imaginary parts correspond to Kerr rotation and ellipticity, respectively. The regions where samples demonstrate PMA are framed with color-coded vertical dashed lines. The first line indicates the completion of a closed, ferromagnet film, while the second line marks the point where the Co layer becomes too thick to sustain PMA, and the in-plane shape anisotropy takes over. It was seen that, upon reaching

approximately 0.3–0.5 nm of a single-layer Co thickness, i.e., 0.8–1.0 nm total Co thickness for the double-layer structure (d2), the sample has developed an OOP magnetization. This thickness corresponds well to the thickness of two monolayers of fcc Co oriented (111), which is 0.44 nm.⁴⁵ It was observed that upon exceeding ~1.5 nm individual Co layer thicknesses (~3.0 nm total thickness for the double layer), the magnetization turned in-plane. Expectedly, the Kerr rotation and ellipticity, thus the modulus, increase with increasing Co thickness in the PMA region, the region framed between the dashed lines.

The MOKE data shown in Fig. 4 were first analyzed with a simplified optical model that does not explicitly account for the

FIG. 4. Complex polar magneto-optic Kerr effect vs total Co thickness (nm) behavior of the samples. (a) and (c) depict Kerr rotation (θ_K) (real) and ellipticity (ϵ_K) (imaginary), while (b) and (d) depict the modulus. The color-coded dashed lines frame the regions where samples show PMA. A sample color-code legend is given in the plot (d). The detailed stack compositions can be found in Table II.

Co/Pt interface phenomena. This optical model assumes that only the Co layers are magnetized and their Q values are homogeneous throughout these layers, denoted by $Q_{\text{Co,eff}}$. The resulting values of $Q_{\text{Co,eff}}$ are depicted as a function of an individual Co layer thickness in Fig. 5. For all structures, a maximum is found near the thickness where a ferromagnetic OOP layer has developed at around 0.44 nm and a decrease is observed upon a further increase in Co thickness. The strong dependence of the observed $Q_{\text{Co,eff}}$ as a function of thickness strongly suggests that at least one of the assumptions in the simplified optical model is not valid.

In Fig. 5, the thickness at which the maximum $Q_{\text{Co,eff}}$ is observed corresponds well with two monolayers of fcc (111) oriented Co. Hence, we conjecture that the Co/Pt interface is responsible for the increased MO activity when reducing the Co layer thickness. In order to account for the Co/Pt interface effects and

map the MO activity with respect to thickness, the two optical models described in Sec. III B were used (see also Fig. 2). Model 1 assumed that the Co is the only layer that contributes to the MO activity, and its activity is enhanced at the Co/Pt interface due to large spin-orbit coupling, whereas Model 2 assumed that Pt contributes to the MO activity as well via its induced magnetization due to proximity to the Co layer. As indicated via color-coded regions in Fig. 2, Model 1 accounts for $Q_{\text{Co,int}}$ and $Q_{\text{Co,bulk}}$ values separately, whereas Model 2 distinguishes Q_{Pt} and $Q_{\text{Co,bulk}}$ values. We assume the respective Q values being independent of the layer thickness and the same for each sub-layer/interface.

In Fig. 6, a simplified picture of the fitting procedure is shown, indicating the asymptotes of $Q_{\text{Co,bulk}}$ for Models 1 and 2 and $Q_{\text{Co,int}}$ for Model 1. The results obtained by the exemplified fitting procedure are depicted in Fig. 7. Each data point is tagged

FIG. 5. Effective Co MO constant ($Q_{\text{Co,eff}}$) vs Co layer thickness (nm) for different samples. $Q_{\text{Co,eff}}$ values are found by assuming that the Co is the only magnetized layer and is magnetized homogeneously. (a) and (c) show real and imaginary parts of $Q_{\text{Co,eff}}$, while (b) and (d) depict the modulus. The color-coded dashed lines frame the regions where samples show PMA. The legend for the samples is given in (d). The detailed stack compositions can be found in Table II.

FIG. 6. The expected behavior of $Q_{\text{Co,eff.}}$ according to Models 1 and 2 depicted in red (dashed) and blue lines, respectively. An experimentally obtained $Q_{\text{Co,eff.}}$ value is shown in half filled light blue circles. The sample chosen for this demonstration is s2 (see Table II for details). The yellow shaded area indicates the region of PMA. Horizontal black dashed lines indicate the interface and bulk contributions from the Co layer named as $Q_{\text{Co,int.}}$ and $Q_{\text{Co,bulk}}$.

with the sample name and the model (see Table II). The error margins of the fitting procedure are included in the graph, albeit only visible at the blue-shaded zoom-in section. The two models yield slightly different $Q_{\text{Co,bulk}}$ values. The extracted Q_{Pt} and $Q_{\text{Co,int}}$ values were found to be grouped in two clusters of data-points, corresponding to single and double Co-layered samples. These clusters were speculated to be due to the difference in the Co/Pt interface quality. Since addition of each layer contributed to the roughness, the single Co-layered samples were expected to have smaller interface roughness than the double ones. Consequently, the single Co-layered samples showed greater amplitudes of $Q_{\text{Co,int}}$ and $Q_{\text{Pt,max}}$. Works presented in the state-of-the-art section support this conclusion as they mentioned that the microscopic ordering at the interface affects the spin-orbit coupling strength and the degree of proximity induced magnetization in the Pt layer.^{30,31} Additionally, an interface asymmetry between top and bottom Co/Pt interfaces, which causes only the bottom Pt layer to be magnetized, should be considered as it was previously observed.³⁷ In this respect, it can be argued that the Co layers grown on rougher Pt layers (double-layered Co samples) show more disorder that prevents the induced magnetization in the Pt layer. One can argue that the quantitative comparison of the obtained Q_{Pt} and $Q_{\text{Co,int}}$ values between samples s2 and s3 (as well as d1 and d2) suggests that the thicker Pt layers (in the range of 1–3 nm) contribute to smoother and well-defined Co/Pt interfaces and increases the amplitude of Q_{Pt} and $Q_{\text{Co,int}}$ for sample s3 (as well as d2). As seen in Figs. 5(b) and 5(d), the earlier PMA onset and the broader thickness window of PMA in sample s3 with respect to s2 support the argument that sample s3

FIG. 7. Summary of the values obtained by using the models (see Sec. III B). A zoom-in section is added in a blue-shaded region to show the error bars obtained from the fitting procedure. Model 1 yields $Q_{\text{Co,bulk}}$ and $Q_{\text{Co,int.}}$, while Model 2 yields $Q_{\text{Co,bulk}}$ and $Q_{\text{Pt,max}}$. Each data point is labeled with the corresponding sample (s2, s3, d1, d2) and the model (m1, m2). Detailed stack orders of the samples are given in Table II.

has a sharper interface. However, further studies on Pt thickness vs roughness are required before concluding.

Comparing quantitatively, the average bulk Co MO constant $Q_{\text{Co,bulk}}$ of $0.033 - 0.030i$ is found to be in good agreement with the literature values,^{15,16} albeit with a larger amplitude of the imaginary component. This difference was inferred to be due to structural differences between used samples. In literature reported cases, annealed bulk samples (thickness larger than 50 nm) of fcc (111) oriented epitaxial Co with in-plane magnetization were used. Continuing the quantitative comparison with the Pt MO constant, the average $Q_{\text{Pt,max}}$ value of $0.0102 - 0.0333i$ reported in our work is smaller than what has been reported in literature.^{19,40–42} It should be stressed that a quantitative comparison for Q_{Pt} was not straightforward. To our knowledge, the amount of studies reporting Q_{Pt} values is limited to a few. Additionally, the profile of the induced magnetization in the Pt, decaying away from the interface, differed among the reports. To exemplify, Didrichsen *et al.* used a decaying magnetization in Pt, supported by *in situ* MOKE. Lee *et al.*⁴² and Train *et al.*⁴¹ assumed a homogenous magnetization in Pt that is only present at the first monolayer at the Co/Pt interface. Since thicknesses of the magnetized Pt layers differed among studies, we based the comparison on the integral MO effect. As a result, the Pt layer contribution in our samples are found to be smaller than the literature reports.

It is also interesting to compare the obtained Q_{Co} with Q_{Pt} values and the theoretical (*ab initio*) predictions by Reichl *et al.*,³⁴ although the structural differences between the analyzed Co/Pt multilayers of the two works should be kept in mind. More specifically, the *ab initio* work simulated Co/Pt layers where Co is

epitaxially grown on (111) oriented fcc Pt, while the samples used in our study are polycrystalline, textured in the (111) direction. Nevertheless, the strong first-monolayer Q_{Pt} contribution at the Co/Pt interface predicted by the *ab initio* work signaled the importance of a sharp interface for high Q_{Pt} . This is in line with our findings of a larger Q_{Pt} contribution in single Co-layered samples where interface roughness is smaller.

Last, a discussion on which one of the two models better describe the physical picture at the Co/Pt interface is presented. As seen in Fig. 6, the predictions of the two models differ greatly at the region framed between the minimum thickness for exhibiting PMA and the two monolayer thickness of Co. We refer to this region as the indicator region. Note that in case the minimum Co thickness required for PMA is thicker than two monolayers of fcc (111) Co (0.44 nm), the indicator region lies outside of the extend of PMA, and thus, an evaluation becomes unreliable. This is the case for samples with double Co layers (d2 and d3) as the increased interface roughness pushed the PMA onset to a greater thickness in these samples. Focusing on a single Co layer sample s2 as seen in Fig. 6, at the indicator region (0.37–0.44 nm), Model 1 seems to describe the experimental observation slightly better than Model 2. However, the following points should be considered before concluding. As described in Sec. II, the proximity induced magnetization in the Pt layer requires a certain interface magnetization threshold to be induced as previously shown by Inyang *et al.*³¹ Therefore, prior to the formation of two complete Co monolayers (0.44 nm), an induced magnetization in the Pt layer may remain absent, which yields the observed behavior in Fig. 6. Additionally, in the indicator region, the ferromagnetic order is being established; thus, the thickness dependent electronic effects and thermal activation effects are convoluted. Therefore, we argue that the actual physical picture at the interface is a combination of both models.

V. CONCLUSIONS

We demonstrated enhancement of the MO activity at the Co/Pt interface by using a sample set that is designed to probe the interface effects. We discussed that the vast scattering of Q_{Co} values reported in the literature for thin-film Co samples are due to inclusion of interfacial Co and Pt contributions. We assigned interfacial Co ($Q_{\text{Co, int.}}$) and magnetized Pt (Q_{Pt}) magneto-optic constants by using models and consistently determined bulk Co ($Q_{\text{Co, bulk}}$) values. Via the methodology described in this work, we showed that even when Co thin-films (2 nm) are used, bulk Co MO constant ($Q_{\text{Co, bulk}}$) values that are in good agreement with the literature can be obtained. Additionally, we presented a discussion that a quantitative comparison of the resulting $Q_{\text{Co, int.}}$ and Q_{Pt} from different stacks can be used to deduce information regarding the relative interface qualities of these samples. More specifically, this might be of particular interest where more conventional methods such as X-Ray Reflectivity (XRR) fail to differentiate samples in terms of interface quality due to lack of contrast. However, it would be worthwhile to conduct studies where XRR and MOKE are quantitatively compared and calibrated before relying on MOKE for interface characterization.

ACKNOWLEDGMENTS

This work is part of the Gravitation program “Research Centre for Integrated Nanophotonics,” which is financed by the Netherlands Organization for Scientific Research (NWO).

The authors acknowledge the assistance from Professor Dr. P. Vavassori on MOKE set-up calibration.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

REFERENCES

- 1D. Weller, H. Brändle, G. Gorman, C. J. Lin, and H. Notarys, “Magnetic and magneto-optical properties of cobalt-platinum alloys with perpendicular magnetic anisotropy,” *Appl. Phys. Lett.* **61**, 2726–2728 (1992).
- 2J. Sinova, D. Culcer, Q. Niu, N. Sinitsyn, T. Jungwirth, and A. H. MacDonald, “Universal intrinsic spin Hall effect,” *Phys. Rev. Lett.* **92**, 126603 (2004).
- 3J. Sinova, S. O. Valenzuela, J. Wunderlich, C. Back, and T. Jungwirth, “Spin Hall effects,” *Rev. Mod. Phys.* **87**, 1213 (2015).
- 4A. D. Kent and D. C. Worledge, “A new spin on magnetic memories,” *Nat. Nanotechnol.* **10**, 187–191 (2015).
- 5M. L. Laliou, R. Lavrijsen, and B. Koopmans, “Integrating all-optical switching with spintronics,” *Nat. Commun.* **10**, 110 (2019).
- 6S. Mangin, D. Ravelosona, J. A. Katine, M. J. Carey, B. D. Terris, and E. E. Fullerton, “Current-induced magnetization reversal in nanopillars with perpendicular anisotropy,” *Nat. Mater.* **5**, 210–215 (2006).
- 7F. Hellman, A. Hoffmann, Y. Tserkovnyak, G. S. Beach, E. E. Fullerton, C. Leighton, A. H. MacDonald, D. C. Ralph, D. A. Arena, H. A. Dürr *et al.*, “Interface-induced phenomena in magnetism,” *Rev. Mod. Phys.* **89**, 025006 (2017).
- 8D. Apalkov, A. Khvalkovskiy, S. Watts, V. Nikitin, X. Tang, D. Lottis, K. Moon, X. Luo, E. Chen, A. Ong *et al.*, “Spin-transfer torque magnetic random access memory (STT-MRAM),” *ACM J. Emerging Technol. Comput. Syst.* **9**, 13 (2013).
- 9E. Lišková, M. Veis, Š. Višňovský, J. Ferré, A. Mougin, P. Mazalski, A. Maziewski, M. O. Liedke, and J. Fassbender, “Effect of Ga⁺ irradiation on the magneto-optic spectra of Pt/Co/Pt sandwiches,” *Thin Solid Films* **520**, 7169–7172 (2012).
- 10R. Lavrijsen, D. M. Hartmann, A. Van Den Brink, Y. Yin, B. Barcones, R. A. Duine, M. A. Verheijen, H. J. Swagten, and B. Koopmans, “Asymmetric magnetic bubble expansion under in-plane field in Pt/Co/Pt: Effect of interface engineering,” *Phys. Rev. B* **91**, 104414 (2015).
- 11F. E. Demirel, C. van den Bomen, R. Lavrijsen, J. J. G. M. van der Tol, and B. Koopmans, “Design and modelling of a novel integrated photonic device for nano-scale magnetic memory reading,” *Appl. Sci.* **10**, 8267 (2020).
- 12R. Weber, C. M. Valderrama, L. Fallarino, and A. Berger, “Dependence of the magneto-optical signal on the Co layer thickness asymmetry in Co/Pt/Co films,” *Phys. Rev. B* **102**, 214434 (2020).
- 13R. Osgood, K. Riggs, A. E. Johnson, J. Mattson, C. Sowers, and S. Bader, “Magneto-optic constants of hcp and fcc Co films,” *Phys. Rev. B* **56**, 2627–2634 (1997).
- 14J. Arregi, J. González-Díaz, O. Idigoras, and A. Berger, “Strain-induced magneto-optical anisotropy in epitaxial hcp Co films,” *Phys. Rev. B* **92**, 184405 (2015).
- 15S. Fiedler, H. Stillrich, and H. P. Oepen, “Magneto-optic properties of electron cyclotron resonance ion beam sputtered and magnetron sputtered Co/Pt multilayers,” *J. Appl. Phys.* **102**, 083906 (2007).
- 16G. R. Harp, D. Weller, T. A. Rabedeau, R. F. Farrow, and M. F. Toney, “Magneto-optical Kerr spectroscopy of a new chemically ordered alloy: Co₃Pt,” *Phys. Rev. Lett.* **71**, 2493–2496 (1993).

- ¹⁷G. S. Krinchik and V. A. Artemjev, "Magneto-optic properties of nickel, iron, and cobalt," *J. Appl. Phys.* **39**, 1276 (2010).
- ¹⁸R. Atkinson, S. Pahirathan, I. W. Salter, P. J. Grundy *et al.*, "Fundamental optical and magneto-optical constants of CoPt and CoNiPt multilayered films," *J. Magn. Magn. Mater.* **162**, 131–138 (1996).
- ¹⁹G. Didrichsen, W. R. Hendren, R. Atkinson, R. J. Pollard, and I. W. Salter, "Dynamic, in situ, magneto-optical studies of non-reciprocal polarisation of Pt, At Co–Pt and Pt–Co interfaces," *J. Magn. Magn. Mater.* **198**, 558–560 (1999).
- ²⁰G. Prinz, J. Krebs, D. Forester, and W. Maisch, "Magneto-optical characterization of Fe and Co-based alloy films," *J. Magn. Magn. Mater.* **15**, 779–781 (1980).
- ²¹M. R. Pufall and A. Berger, "Studying the reversal mode of the magnetization vector versus applied field angle using generalized magneto-optical ellipsometry," *J. Appl. Phys.* **87**, 5834–5836 (2000).
- ²²H. Ouyang, Y. H. Han, S. C. Lo, C. H. Su, Y. R. Shiu, K. W. Lin, R. D. Desautels, and J. Van Lierop, "Tailoring perpendicular magnetic anisotropy in ultrathin Co/Pt multilayers coupled to NiO," *Phys. Rev. B* **81**, 224412 (2010).
- ²³D. C. Worledge, G. Hu, D. W. Abraham, J. Z. Sun, P. L. Trouilloud, J. Nowak, S. Brown, M. C. Gaidis, E. J. O'Sullivan, and R. P. Robertazzi, "Spin torque switching of perpendicular Ta/CoFeB/MgO-based magnetic tunnel junctions," *Appl. Phys. Lett.* **98**, 022501 (2011).
- ²⁴G. A. Bertero and R. Sinclair, "Structure-property correlations in Pt/Co multilayers for magneto-optic recording," *J. Magn. Magn. Mater.* **134**, 173–184 (1994).
- ²⁵S. Peng, W. Zhao, J. Qiao, L. Su, J. Zhou, H. Yang, Q. Zhang, Y. Zhang, C. Grezes, P. K. Amiri, and K. L. Wang, "Giant interfacial perpendicular magnetic anisotropy in MgO/CoFe/capping layer structures," *Appl. Phys. Lett.* **110**, 072403 (2017).
- ²⁶N. Nakajima, T. Koide, T. Shidara, H. Miyauchi, H. Fukutani, A. Fujimori, K. Iio, T. Katayama, M. Nývlt, and Y. Suzuki, "Perpendicular magnetic anisotropy caused by interfacial hybridization via enhanced orbital moment in Co/Pt multilayers: Magnetic circular x-ray dichroism study," *Phys. Rev. Lett.* **81**, 5229 (1998).
- ²⁷R. M. Rowan-Robinson, A. A. Stashkevich, Y. Roussigné, M. Belmeguenai, S. M. Chérif, A. Thiaville, T. P. Hase, A. T. Hindmarch, and D. Atkinson, "The interfacial nature of proximity-induced magnetism and the Dzyaloshinskii-Moriya interaction at the Pt/Co interface," *Sci. Rep.* **7**, 645 (2017).
- ²⁸C. Clavero, L. Martínez, A. García-Martín, J. M. García-Martín, Y. Hüttel, N. D. Telling, G. Van Der Laan, A. Cebollada, and G. Armelles, "Morphology and capping effects in the magnetic and magneto-optical properties of nanoparticulate Co films," *Phys. Rev. B* **77**, 094417 (2008).
- ²⁹W. L. Lim, N. Ebrahim-Zadeh, J. C. Owens, H. G. Hentschel, and S. Urazhdin, "Temperature-dependent proximity magnetism in Pt," *Appl. Phys. Lett.* **102**, 162404 (2013).
- ³⁰T. P. Hase, M. S. Brewer, U. B. Arnalds, M. Ahlberg, V. Kapaklis, M. Björck, L. Bouchenoire, P. Thompson, D. Haskel, Y. Choi, J. Lang, C. Sánchez-Hanke, and B. Hjörvarsson, "Proximity effects on dimensionality and magnetic ordering in Pd/Fe/Pd trilayers," *Phys. Rev. B* **90**, 104403 (2014).
- ³¹O. Inyang, L. Bouchenoire, B. Nicholson, M. Tokac, R. M. Rowan-Robinson, C. J. Kinane, and A. T. Hindmarch, "Threshold interface magnetization required to induce magnetic proximity effect," *Phys. Rev. B* **100**, 174418 (2019).
- ³²Y. Zhang, X. Yang, P. Li, and M. Wu, "Strain engineering of magnetic proximity effect and spin-orbit torque in heavy metal/ferromagnet heterostructures," *J. Magn. Magn. Mater.* **498**, 166112 (2020).
- ³³Y. An, L. Duan, T. Liu, Z. Wu, and J. Liu, "Structural and magnetic properties of Pt in Co/Pt multilayers," *Appl. Surf. Sci.* **257**, 7427–7431 (2011).
- ³⁴I. Reichl, J. Zabloudil, R. Hammerling, A. Vernes, L. Szunyogh, and P. Weinberger, "Magneto-optical Kerr effect in perpendicularly magnetized (Co₂Pt₆) in Pt (111) superstructures," *Phys. Rev. B* **73**, 054402 (2006).
- ³⁵F. Wilhelm, P. Pouloupoulos, G. Ceballos, H. Wende, K. Baberschke, P. Srivastava, D. Benea, H. Ebert, M. Angelakeris, N. K. Flevaris, D. Niarchos, A. Rogalev, and N. B. Brookes, "Layer-resolved magnetic moments in Ni/Pt multilayers," *Phys. Rev. Lett.* **85**, 413–416 (2000).
- ³⁶J. Geissler, E. Goering, M. Justen, F. Weigand, G. Schütz, J. Langer, D. Schmitz, H. Maletta, and R. Mattheis, "Pt magnetization profile in a Pt/Co bilayer studied by resonant magnetic x-ray reflectometry," *Phys. Rev. B* **65**, 020405 (2001).
- ³⁷A. Mukhopadhyay, S. K. Vayalil, D. Graulich, I. Ahamed, S. Francoal, A. Kashyap, T. Kuschel, and P. A. Kumar, "Asymmetric modification of the magnetic proximity effect in Pt/Co/Pt trilayers by the insertion of a Ta buffer layer," *Phys. Rev. B* **102**, 144435 (2020).
- ³⁸T. Kuschel, C. Klewe, J. M. Schmalhorst, F. Bertram, O. Kuschel, T. Schemme, J. Wollschläger, S. Francoal, J. Stempfer, A. Gupta, M. Meinert, G. Götz, D. Meier, and G. Reiss, "Static magnetic proximity effect in Pt/NiFe₂O₄ and Pt/Fe bilayers investigated by x-ray resonant magnetic reflectivity," *Phys. Rev. Lett.* **115**, 097401 (2015).
- ³⁹B. Rellinghaus, D. Weller, M. Q. Tran, and F. Hellman, "Growth-induced magnetic anisotropy and clustering in vapor-deposited Co-Pt alloy films," *Phys. Rev. B* **60**, 12826–12836 (1999).
- ⁴⁰E. R. Moog, J. Zak, and S. D. Bader, "Kerr effect from Pt/Co superlattices and the role of the magneto-optic activity of Pt," *J. Appl. Phys.* **69**, 880–885 (1991).
- ⁴¹C. Train, P. Beauvillain, V. Mathet, G. Pénissard, and P. Veillet, "Spectroscopic polar magneto-optical Kerr rotation on Co/Pt interface," *J. Appl. Phys.* **86**, 3165–3170 (1999).
- ⁴²Y. P. Lee, K. W. Kim, R. Gontarz, and V. Y. Kudryavtsev, "Magneto-optical properties of spin-polarized Pt in Co/Pt multilayered films," *IEEE Trans. Magn.* **35**, 3088–3090 (1999).
- ⁴³D. R. Lide, *CRC Handbook of Chemistry and Physics: A Ready-Reference Book of Chemical and Physical Data* (CRC Press, 1995).
- ⁴⁴J. Lucassen, C. F. Schippers, M. A. Verheijen, P. Fritsch, E. J. Geluk, B. Barcones, R. A. Duine, S. Wurmehl, H. J. M. Swagten, B. Koopmans, and R. Lavrijsen, "Extraction of Dzyaloshinskii-Moriya interaction from propagating spin waves," *Phys. Rev. B* **101**, 064432 (2020).
- ⁴⁵E. Lundgren, B. Stanka, M. Schmid, and P. Varga, "Thin films of Co on Pt (111): Strain relaxation and growth," *Phys. Rev. B* **62**, 2843–2851 (2000).
- ⁴⁶W. Ranke, M. Ritter, and W. Weiss, "Crystal structures and growth mechanism for ultrathin films of ionic compound materials: FeO(111) on Pt(111)," *Phys. Rev. B* **60**, 1527–1530 (1999).
- ⁴⁷J. Zak, E. Moog, C. Liu, and S. Bader, "Universal approach to magneto-optics," *J. Magn. Magn. Mater.* **89**, 107–123 (1990).