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Faraday rotation at the 2*p* edges of Fe, Co, and Ni

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We present resonantly enhanced magneto-optical Faraday rotation data of linearly polarized soft x rays across the 2*p* absorption edges in Fe, Co, and Ni thin films using synchrotron radiation. Rotation angles of up to $\pm 90°$ were measured. These values are more than one order of magnitude larger than so far observed. By linear polarization analysis the dependence of the Faraday rotation on layer thickness, angle of incidence, magnetic field strength, and photon energy was investigated. The dichroism of the dispersion and absorption parts of the refraction index is in agreement with magnetic circular dichroism absorption data of the same films with circularly polarized light.

INTRODUCTION

In recent years the investigation of magneto-optical effects in the soft x-ray range has gained great importance as a tool for the investigation of magnetic materials. Absorption, scattering, and photoemission experiments have been performed using intense, tunable, circularly,[1–4] and linearly[5,6] polarized synchrotron radiation from bending magnets or special insertion devices. Whereas these effects are small in the visible, they are large in the soft x-ray range at the 2*p*- and 4*f*-absorption edges of 3*d*-transition metals and rare-earth compounds, respectively.[7] Presently, the most intensively studied effect is the x-ray magnetic circular dichroism (XMCD) in absorption or photoemission.[1–4] XMCD describes the different response of a magnetized sample to left- and right-handed circularly polarized light. It enables a quantitative determination of spin and orbital magnetic moments,[2] element-specific imaging of magnetic domains[8] or polarization analysis.[9] A less extensively studied MCD phenomenon is the magneto-optical Faraday effect in the x-ray range. The Faraday effect describes the rotation of the polarization plane of linearly polarized light, when transmitting a sample that has a magnetic moment parallel or antiparallel to the light. In the x-ray range at the 1*s* edge of Fe, Co, and Ni rotation angles in the order of 0.1° have been found[10] in accordance with calculations.[11,12] Also Faraday rotation at the 2*p* edge of Pt has been reported.[13] In the soft x-ray range measurements have been performed at the Fe 2*p* edges. On an Fe/Cr transmission multilayer magnetized perpendicular to the sample surface rotation values of up to 5° were found[14] in agreement with theory.[15] An Fe film magnetized in plane yielded up to 15° when operated at grazing incidence.[16] In this paper we present new Faraday rotation data at the 2*p* edges of Fe, Co, and FeNi thin films of various thicknesses. The films were magnetized parallel to the surface. The measurements were taken at different angles of incidence. The results are compared with XMCD data from the same films.

THEORY

The incident linearly polarized light is decomposed into two circularly polarized waves of opposite helicity. The interaction with magnetic material is described by the complex refraction indices $n_\pm$ (+ and − refer to the parallel and antiparallel orientation of the photon helicity and the magnetic moment of the sample):[17]

$$n_\pm = 1-\delta_\pm + i\beta_\pm, \quad \delta_\pm=\delta_0 \pm \Delta\delta, \quad \beta_\pm = \beta_0 \pm \Delta\beta. \tag{1}$$

δ_0 denotes the dispersion and β_0 denotes the absorption of unpolarized light. Circular dichroism is defined as the difference of the optical constants:

$$\Delta n = 1/2(n_+ - n_-) = -\Delta\delta + i\Delta\beta. \tag{2}$$

The dichroism of the absorption determines the XMCD-asymmetry parameter A, defined as

$$A=(T_- - T_+)/(T_- + T_+) \tag{3}$$

via the transmission coefficient $T_\pm = \exp\{-2qd\beta_\pm\}$ (q: wave vector, d: sample thickness). The dichroism of the dispersion, i.e., $\Delta\delta \neq 0$, leads to a phase change between the left- and right-handed polarized waves resulting in a rotation of the polarization pane. Thus, an incident linearly polarized wave ($P_{\text{L-in}}=1$) becomes elliptically polarized after transmission through a magnetized foil. The amount of circular polarization $P_{\text{C-tran}} = (1-P_{\text{L-tran}}^2)^{1/2}$ (assuming fully polarized light) and the rotation angle φ are[17]

$$\varphi = qd\Delta\delta, \tag{4a}$$

$$P_{\text{C-tran}} = A \approx 2qd\Delta\beta. \tag{4b}$$

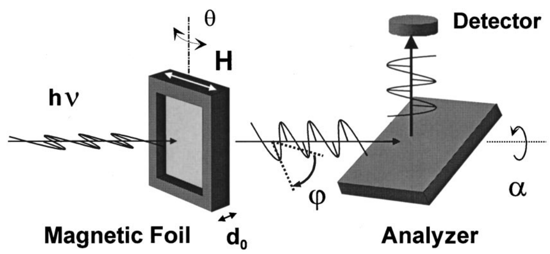

FIG. 1. Schematic setup for Faraday measurements at magnetic films with variable angle of incidence θ and magnetic field H. The rotation angle φ and the degree of linear polarization is detected by an azimuthal rotation of the analyzer and detector around the light beam.

$P_{\text{C-tran}}$ is thus proportional to the XMCD asymmetry parameter A. The origin of the Faraday effect is a circular dichroism in the real part of the refraction index, measured with linearly polarized light. The combined measurements of XMCD [Eq. (3)] and Faraday rotation [Eq. (4a)] allow for the complete investigation of the circular dichroism of optical constants. $\Delta\beta$ can also be deduced via Eq. (4b) by determining the circular polarization induced by the transmission process. Thus, Faraday rotation measurements are an alternative method to the classical XMCD technique with the advantage of using only linearly instead of circularly polarized light.

EXPERIMENT

The present experiment was performed at the Berlin synchrotron radiation source (BESSY I) using the plane grating Petersen-type (SX700) monochromator PM 3.[18] The monochromator delivers in- or off-plane bending magnet synchrotron radiation with adjustable linear or circular polarization in the energy range between 30 and 2000 eV, at a spectral resolving power of approximately $E/\Delta E = 700$. Part of the measurements have been done at the PM 4 monochromator[19] delivering elliptically polarized light. Amorphous Fe, Co, and $Fe_{0.5}Ni_{0.5}$ single layers with thicknesses between 50 and 300 nm have been investigated. Co films were magnetron-sputter deposited on 100 nm Si_3N_4 foils. $Fe_{0.5}Ni_{0.5}$, and Fe were electron-beam evaporated on 1 μm Mylar and Paryllene© (C_8H_8) foils. The experimental setup for the Faraday rotation measurement is schematically shown in Fig. 1. The transmission sample can be set at any angle θ between 0° and 90°. A magnetic coil system supplies variable fields of $-500\ \text{Oe} \leqslant H \leqslant +500$ Oe in the sample plane. All measurements have been performed with magnetically saturated films ($H \geqslant H_{\text{sat}}$) if not indicated otherwise. *In situ* exchange and removal of samples allows for quasisimultaneous polarization analysis of the incident and transmitted light. The linear polarization analysis was performed by rotating a W/B_4C reflection multilayer (300 periods, period 1.2 nm) around the beam by the angle α (analyzer scan) while the reflected intensity is recorded. The analyzer is set at an angle of incidence close to the Brewster angle.[20] The polarizing power R_s/R_p varied between 100 at the Fe 2p edge and 16 at the Ni 2p edge (R_s, R_p: reflectance of the analyzer in s, p geometry, respectively).

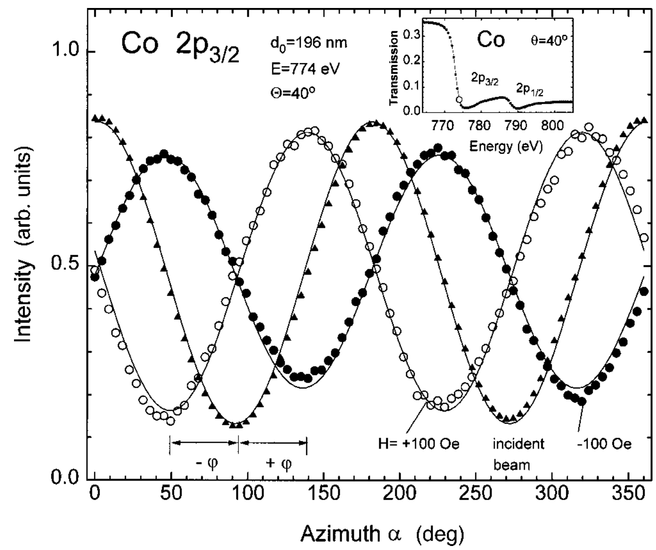

FIG. 2. Faraday rotation measurement on a Co sample at the Co 2p absorption edge: polarization measurement without (triangles) and with sample having magnetic moments parallel (open circles) and antiparallel (solid circles) to the light. The rotation angle φ is indicated, curves are fitted according to Eq. (5). Inset: transmission curve.

RESULTS

Figure 2 shows the polarization measurement for Co. The photon energy was set at 774 eV within the Co $2p_{3/2}$ absorption edge (see inset). The normalized angular distribution of the incident beam (triangles) as a function of the analyzer angle α shows maximum intensity at $\alpha = 0°$ and 180° corresponding to a horizontal polarization plane. After inserting a Co film at an angle of 40° grazing incidence, the polarization plane is rotated symmetrically by $\varphi = \pm 45°$ depending on the direction of the magnetic field applied (solid and open circles). In propagation direction right-handed Faraday rotation ($\varphi > 0°$) is found for antiparallel orientation of the magnetic field and light direction. The rotation angle φ and the degree of linear polarization $P_{\text{L-tran}}$ of the transmitted light are obtained by a least-squares fit to the intensity (full curves):

$$I(\alpha) = I_0[1 + P_{\text{L-tran}}(R_s - R_p)/(R_s + R_p)\cos 2(\alpha + \varphi)] \tag{5}$$

with fitting parameters I_0, $P_{\text{L-tran}}$, and φ. We obtain an incident polarization $P_{\text{L-in}} = 0.76$ and $P_{\text{C-in}} = 0.65$. After transmission the circular polarization increases to $P_{\text{C-tran}} = 0.81$. This allows for the determination of $\Delta\beta$ according to Eq. (4b) as discussed later.

The dependence of the Faraday rotation on the angle of incidence of the sample is shown in Fig. 3. The data are obtained at an energy within the Co $2p_{3/2}$ edge where the rotation is maximum (cf. below Fig. 4). In normal incidence ($\theta = 90°$) the magnetic field is perpendicular to the direction of light propagation and no rotation is observed. With decreasing angle of incidence the rotation angle φ increases due to the increasing effective layer thickness $d_0/\sin(\theta)$ and the increasing magnetic field component $B\cos(\theta)$ parallel (antiparallel) to the light

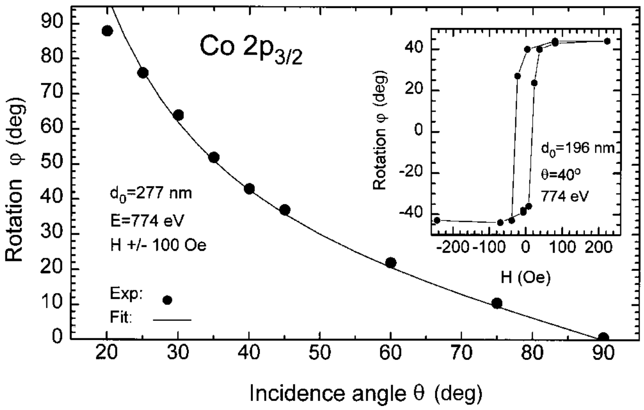

FIG. 3. Dependence of Faraday rotation on the angle of incidence for a Co sample. Symbols: experimental data. Curve: fit according to Eq. (6). Inset: hysteresis curve for the Faraday rotation.

$$\varphi = Bkd_0/\tan(\theta). \tag{6}$$

This geometrical dependence (Fig. 3, full curve) of the Faraday rotation is known from the visible spectral range. Near grazing incidence at $\theta=20°$ we find maximum Faraday rotation close to $\varphi=90°$. By varying the angle of incidence we can establish a continuous variation of the linear polarization between horizontal, diagonal, and vertical orientation.

The dependence of the rotation angle on the magnetic field is plotted in Fig. 3 (inset) for one Co film. The rotation shows a hysteresis loop with saturation for $H \geqslant H_{sat} \approx 50$ Oe. For this Co film the rotation constant varies as $7.4 \pm 0.7 \times 10^3$ [deg/mm Oe] at the coercive field of $H_{coe} = 25 \pm 2$ Oe. For magnetically saturated films, maximum rotation constants of up to 2×10^5 deg/mm for Co and Fe and 0.25×10^5 deg/mm for Ni were found. These constants are one order of magnitude larger than observed in Fe films in the visible (3.5×10^4 deg/mm, at $\lambda = 546$ nm).[21] Our results are also five orders of magnitude larger than previously observed in the x-ray range.[10]

The energy dependence of the investigated magneto-optical effects across the Fe $2p$ edge is shown in Fig. 4 for a 50 nm FeNi foil. The upper part shows the well-known XMCD transmission spectra T_+ and T_- obtained with circularly polarized light. The Faraday rotation data, obtained with linearly polarized light, are shown in the middle part. Each data point was obtained by an analyzer scan according to Fig. 2. Maximum rotation of $\varphi = \pm 12°$ is found immediately below and above the $2p_{3/2}$ transmission minimum. The Faraday rotation is smaller at the Fe $2p_{1/2}$ edge and it fades out going to off resonance. Inverting the magnetic field changes only the sign which reflects the homogeneity of the sample magnetization.

The dichroism $\Delta\delta$ of the dispersion part was calculated according to Eq. (4a) (Fig. 4, middle, right ordinate scale) for the two magnetic field directions with maximum values of $\pm 1.4 \times 10^{-3}$ on the left and right side of the $2p_{3/2}$ transmission minimum, respectively. In principle the absolute value of δ_0 for unpolarized light could be extracted by a Kramers-Kronig transformation of the corresponding absorption spectra. However, the energy dependence of oscillator strengths within and far away from the resonance is not known. Data taken from the Henke table[22] predict $\delta_0 = +1 \times 10^{-3}$ at ± 20

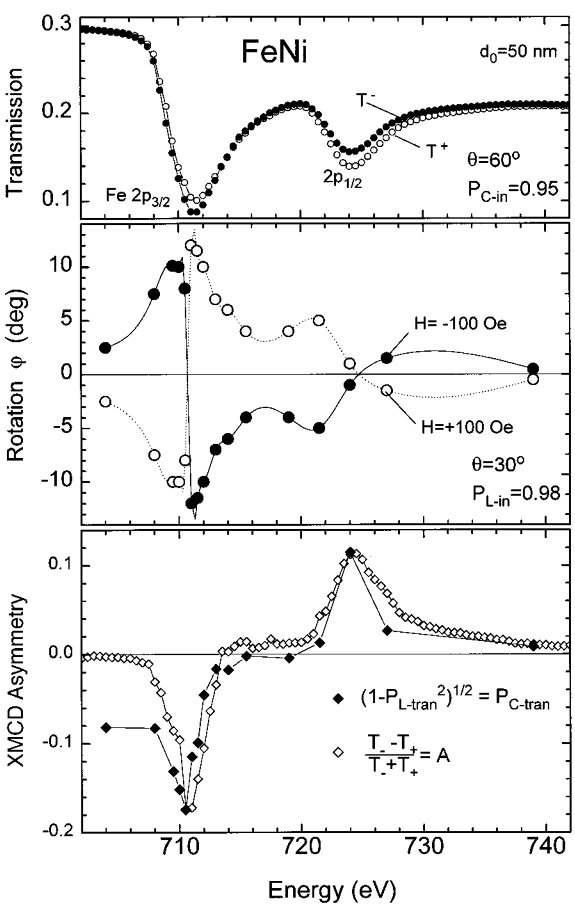

FIG. 4. Magneto-optical effects on a FeNi sample at the $2p$ absorption edge. Top: XMCD transmission spectra T_+, T_- obtained with circularly polarized incident light. Center: Faraday rotation data obtained with linearly polarized incident light. Bottom: XMCD asymmetry obtained from top (open symbols) and from middle part (full symbols), respectively.

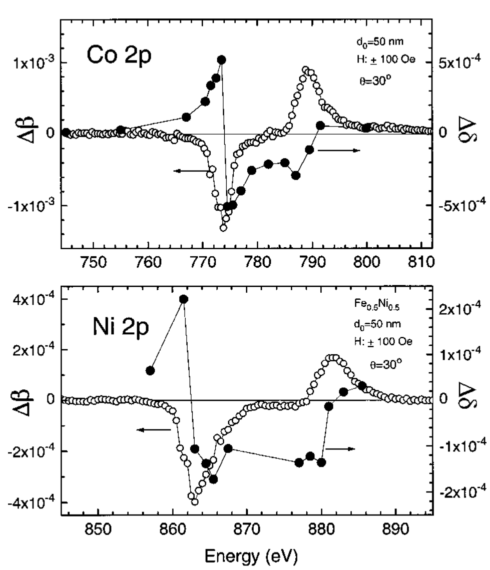

FIG. 5. Dichroism of the optical constants for Co $2p$- (top) and Ni $2p$-absorption edges (bottom): $\Delta\delta$ obtained from rotation data (filled symbols) and $\Delta\beta$ obtained from XMCD data (open symbols).

eV away from the 2p edge and $\delta_0 = -2\times10^{-3}$ at the edge. This would correspond to an asymmetry $\Delta\delta/\delta_0$ on the order of 100%.

The lower part of Fig. 4 shows the XMCD asymmetry A (open symbols) obtained according to Eq. (3) from the transmission spectra $T_\pm$ (Fig. 4, upper part). Alternatively, this asymmetry can be obtained from Faraday measurements by polarization analysis of the transmitted light [Eq. (4b)]. These values correspond to the circular polarization induced by the transmission process (filled symbols). They coincide well with the XMCD asymmetry data and confirm therefore the equivalence of $P_{\text{C-tran}}$ and A [Eq. (4b)]. Thus, both the Faraday and XMCD data of magneto-optical materials can be obtained from one experiment using only linearly polarized radiation.

These data can be further evaluated according to Eq. (4) to yield the dichroism of the optical constants $\Delta\beta$ and $\Delta\delta$. This is shown for the case of Co and Ni, in Fig. 5. Maxima in $\Delta\beta$ are found at the transmission minima, where $\Delta\delta$ changes sign. This behavior of $\Delta\delta$ and $\Delta\beta$ reflects the relation between the real and imaginary parts of the optical constants which is described by the Kramers-Kronig transformation.[17] For Co and Ni the peak values of both quantities are smaller than those of Fe which is partly due to the lower magnetic moments of Co and Ni. The peak relation $\Delta\beta(2p_{3/2})/\Delta\beta(2p_{1/2})$ in our films is smaller than the ratios obtained with thinner films.[2] This is possible due to microhole formation and saturation effects in our transmission films. No attempt was made, however, to correct our data for this.

CONCLUSION

We have measured resonantly enhanced magneto-optical Faraday rotation of Fe, Co, and Ni in the soft x-ray range by means of linear polarization analysis of the transmitted light. Large rotation values up to ±90° have been found, one order of magnitude larger than observed so far in the visible and five orders of magnitude larger than observed so far in the x-ray range. The dichroism of the dispersion part of the refraction index n was determined directly from this experiment. It shows strong resonant behavior at the $2p_{3/2}$ absorption edges. The dichroism of the absorption part of n was determined by the analysis of the circular polarization, induced by the transmission process, as well as by XMCD transmission spectra. Comparison shows that Faraday measurements provide an experimental pathway to obtain element-specific information on the circular dichroism of magnetic materials even with linearly polarized light.

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