Faraday Effect and X-Ray Birefringence at Cobalt *K*-Absorption Edge with the Tunable X-Ray Polarimeter

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We have measured the Faraday effect of cobalt polycrystalline foil near cobalt *K*-absorption edge with the energy-tunable x-ray polarimeter. The Kramers-Kronig (K-K) relation between spectrum of the Faraday rotation and magnetic circular dichroism (MCD) measured by using the elliptically polarized synchrotron x-radiation has beenconfirmed. Furthermore, we have constructed a new type of x-ray polarimeter with a diamond phase retarder and measured x-ray linear dichroism (LD) and linear birefringence (LB) simultaneously using an *hcp* cobalt single crystal foil. The K-K relation between LD and LB has also been confirmed clearly.

We have constructed an energy-tunable x-ray polarimeter system based on Siddons-Hart's polarimeter.[1,2] Figure 1 shows the experimental arrangement of the x-ray polarimeter. The synchrotron white x-radiation was monochromatized and horizontally polarized by a Hart-Rodrigues[3] type silicon 422 channel-cut offset polarizer. X-rays whose polarization state was modulated by the Faraday effect of a sample were incident on an analyzer crystal, which was similar to the polarizer. The intensities of x-rays reflected by the analyzer were measured with a solid state detector (SSD) by rotating the analyzer around the beam axis in a range of ±2 degree from the crossed Nicol position.

Figure 2 shows spectra of the Faraday rotation together with the absorption spectrum from an *fcc* cobalt polycrystalline sample foil.[4] Magnetic field was applied to the sample in the directions parallel and anti-parallel to the beam axis. The energy scan was performed by changing the Bragg-reflection angles of both the polarizer and the analyzer simultaneously in the vicinity of the cobalt *K*-absorption edge (7709 eV). Figure 3 shows a spectrum of Kramers-Kronig (K-K) transform of the Faraday rotation[4] shown in Fig. 2, which is in good agreement with a spectrum of magnetic circular dichroism measured with the elliptically polarized synchrotron radiation.

Furthermore, we have developed a new x-ray polarimeter system which has introduced Hirano-Ishikawa-Kikuta's phase retarder[5-7] of diamond crystal to produce elliptically polarized x-rays from linearly polarized x-rays. We have attempted to apply this new x-ray optical system to the simultaneous measurement of the x-ray birefringence and dichroism of an *hcp* cobalt single crystal. The experimental arrangement is shown in Fig. 4. The diamond phase retarder which gives 111 reflection of asymmetric Laue geometry was placed downstream of the polarizer. The plane of incidence of the diamond phase retarder was inclined by 45 degree from the horizontal plane. Elliptically polarized x-

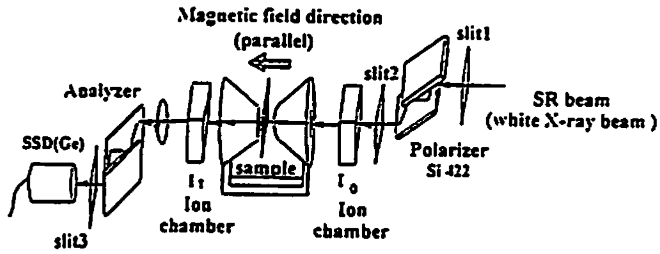

Fig. 1. Schematic drawing of the x-ray energy-tunable polarimeter system for measuring Faraday effect of a sample.

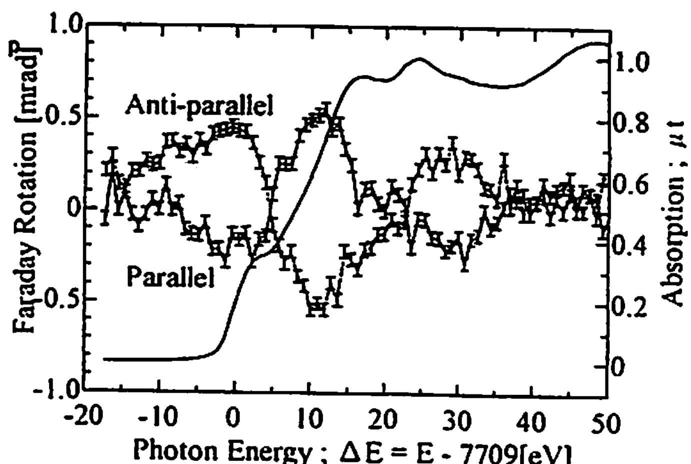

Fig. 2. Faraday rotation spectra of a polycrystalline *fcc* cobalt foil with the spectrum of absorption.

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rays were produced from the incident linearly polarized x-rays, owing to difference in refractive index between σ- and π-polarization of x-rays. The elliptically polarized x-rays were incident on an *hcp* cobalt single crystal foil 12 μm thick, whose c-axis lay in the foil surface and was inclined by 45 degree from the horizontal plane. X-rays whose polarization state was modulated by the sample crystal were incident on the analyzer. The polarization analysis was performed in the same way as that for the Faraday rotation. Spectra of both rotation and ellipticity of polarization were analyzed. The energy scan was performed by controlling the reflection angles of the polarizer, analyzer and phase retarder crystals simultaneously. The angular deviation from the Bragg condition of the phase retarder was controlled so that it produced constant ellipticity (-0.04,-0.02, +0.02 and +0.04) during the energy scan, which were calculated from the dynamical diffraction theory.

Figures 5 and 6 show the spectra of ellipticity and rotation with the absorption spectrum. We can obtain from Fig. 5 not only the magnitude but also the sign of difference in refractive index between a-axis and c-axis of the *hcp* cobalt. The helicity of elliptical polarization of x-rays incident on

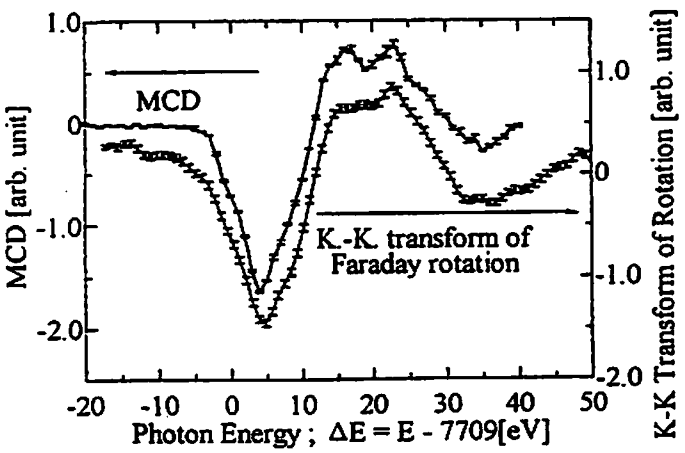

Fig. 3. Spectrum of Kramers-Kronig transform of the Faraday rotation in Fig. 2 is in good agreement with spectrum of magnetic circular dichroism which was measured with the elliptically polarized synchrotron radiation.

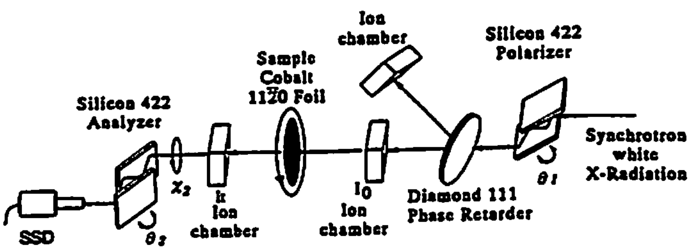

Fig. 4. Experimental arrangement of the x-ray energy-tunable polarimeter with a phase retarder crystal for measuring both linear birefringence and dichroism of a cobalt single crystal.

the sample *hcp* cobalt crystal, is reversed between Figs. 5(a) and 5(d), and between Figs. 5(b) and 5(c), by changing the sign of the phase difference between σ– and π–polarization of the phase retarder. In Fig. 5(b), at +24 eV of photon-energy, the helicity of elliptical polarization of x-rays detected, is reversed from that in the other energy region. A similar reversal of helicity of polarization is found also in Fig. 5(c), at 19 eV.

The phase difference, $\Delta\phi$ between c- and a-axis polarization for the cobalt crystal (σ– and π–polarization for the diamond phase retarder), is given in terms of the ellipticity of polarization, E by the following equations :

$$E = \tan\left(\frac{\Delta\phi}{2}\right) \tag{1}$$

$$\approx \frac{\Delta\phi}{2}. \tag{2}$$

We can observe a slight increase of ellipticity at 3 eV in Figs. 5(a) and 5(b), and a similar decrease in Figs. 5(c) and 5(d).This slight change of ellipticity is about 0.003, which may be considered to be the detection limit of ellipticity in our polarimeter system. Considering the relation of eq. (2), the detection limit for phase difference between σ– and π–polarization in our system which may be regarded as a *polarization interferometer*[8], is estimated to be $0.006 \approx 2\pi/1000$, corresponding to wavefront shift of $\lambda/1000$. This detection limit is one tenth of that of the Bonse-Hart x-ray interferometer,[9-11] ($\lambda/100$).

Difference in absorption coefficient between a-axis and c-axis polarization results in the rotation spectrum in Fig. 6.

This is the first simultaneous measurement of both birefringence and dichroism in the x-ray frequency region, while the measurement of only dichroism was pioneered by Templeton and Templeton.[12-14]

Refractive index and absorption coefficient correspond to the real and imaginary parts of the dielectric constant, respectively. Fig. 7 shows the K-K transform of $\Delta\varepsilon''$ together with $\Delta\varepsilon'$ and Fig. 8 shows the K-K transform of $\Delta\varepsilon'$ together with $\Delta\varepsilon''$,where $\Delta\varepsilon'$ and $\Delta\varepsilon''$ are the real and imaginary parts of $\Delta\varepsilon$. $\Delta\varepsilon$ is $\varepsilon_c - \varepsilon_a$, where ε_c and ε_a are relative dielectric constants for c-axis and a-axis polarization. Kramers-Kronig relations in the x-ray frequency region have been clearly confirmed. Numbers of scales of left and right axes in Figs. 7 and 8 are drawn in the absolute scale.

Furthermore, we could distinguish random polarization from elliptical polarization. Figure 9(a) shows the spectrum of 'ellipticity' measured using a polycrystalline *hcp* cobalt foil and linearly polarized incident x-rays. If in Fig. 9(a), the

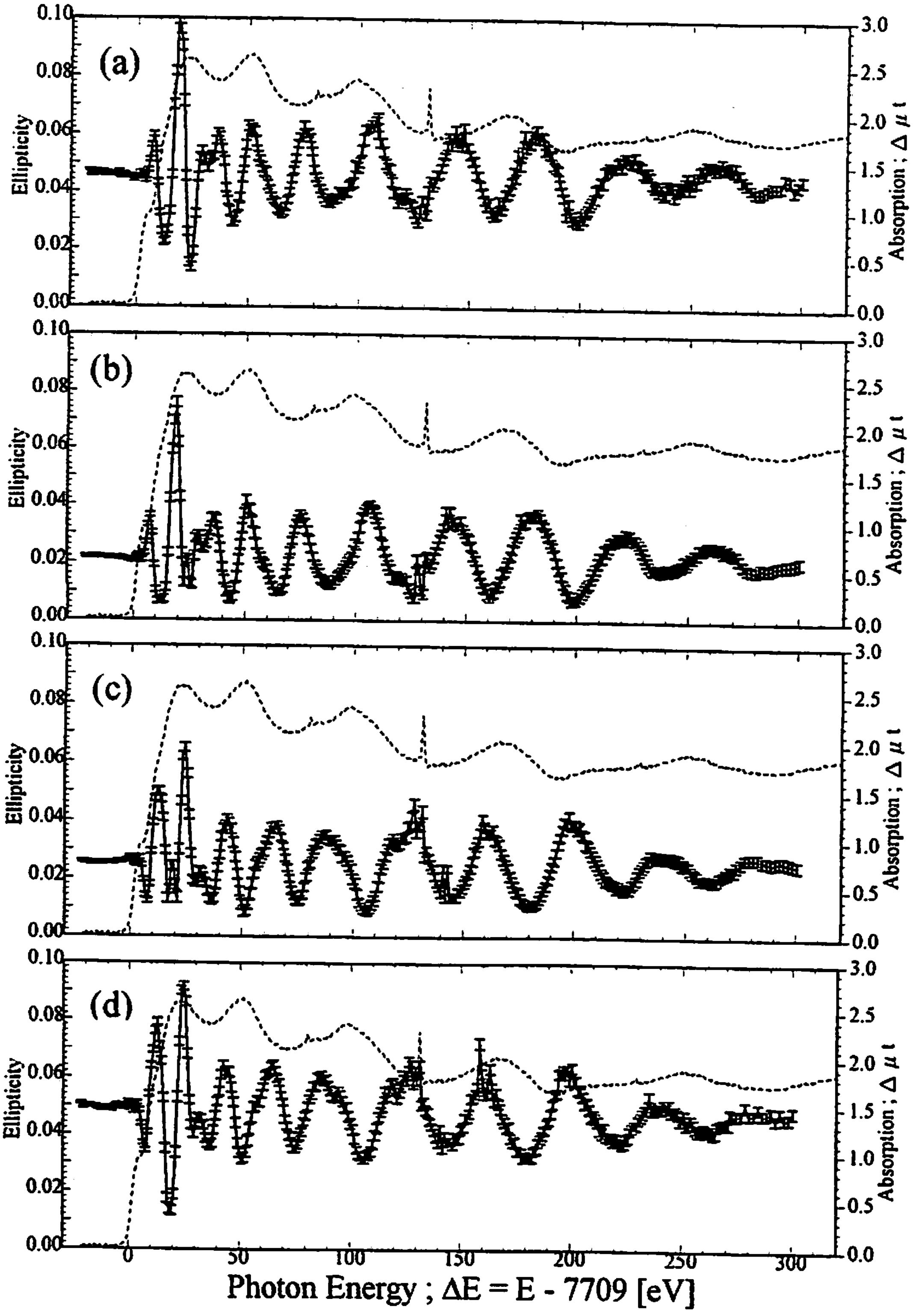

Fig. 5. Spectra of ellipticity for an *hcp* cobalt single crystal in the vicinity of cobalt *K*-absorption edge (7709 eV) measured with elliptically polarized incident x-rays. The ellipticity of the incident beam which were calculated from the dynamical theory were (a) -0.04, (b) -0.02, (c) +0.02 and (d) +0.04.

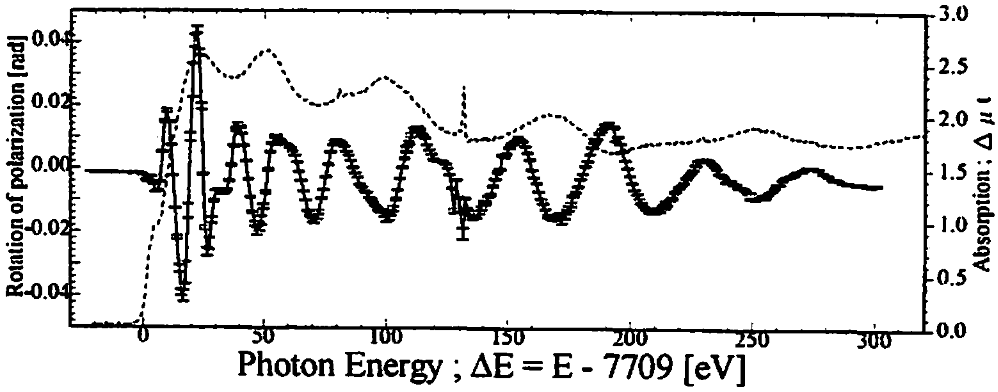

Fig. 6. Spectrum of rotation of polarization in the vicinity of cobalt *K*-absorption edge for an *hcp* cobalt single crystal sample. The rotation spectra measured with the incident elliptical polarization with ellipticity of ± 0.02 and ± 0.04 were identical.

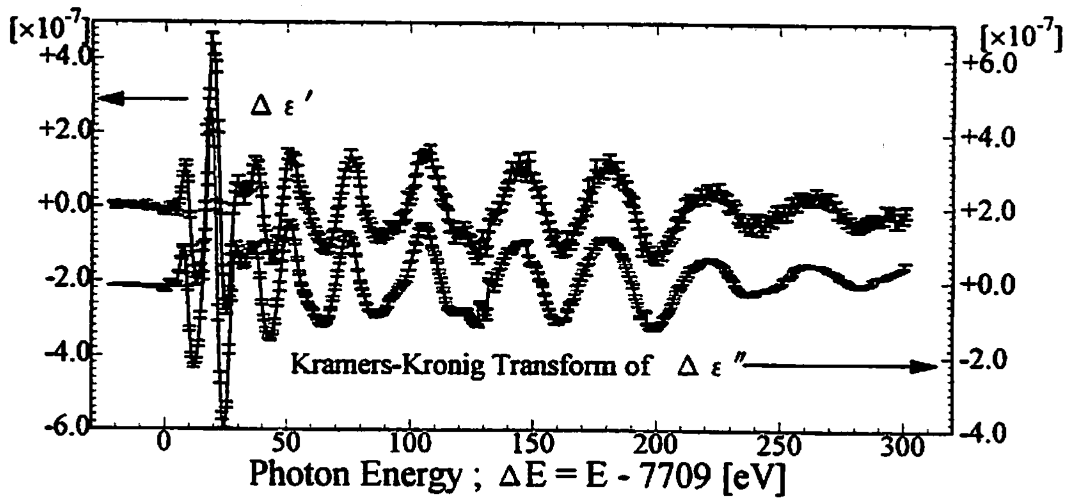

Fig. 7. The upper spectrum is $\Delta\varepsilon'$, the real part of $\Delta\varepsilon$. The lower is Kramers-Kronig transform of $\Delta\varepsilon''$, the imaginary part of $\Delta\varepsilon$. The ordinates are drawn in absolute scales. The right and left axes are shifted for clarity.

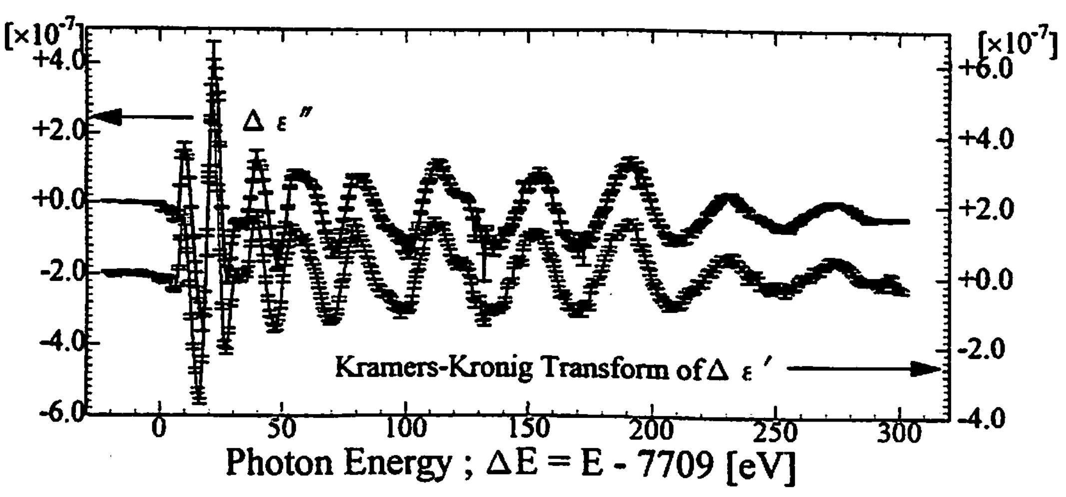

Fig. 8. The upper spectrum is $\Delta\varepsilon''$, the imaginary part of $\Delta\varepsilon$. The lower is Kramers-Kronig transform of $\Delta\varepsilon'$, the real part of $\Delta\varepsilon$.

broad peak of 'ellipticity' found near +20 eV is really elliptical polarization, decrease of ellipticity should be observed near +20 eV with the incidence of elliptical polarization of either plus or minus ellipticity. However, such decrease of 'ellipticity' was not observed as shown in Figs. 5(b) and 5(c) with the incidence of ellipticity of ± 0.01. Therefore, it is concluded that the peak of 'ellipticity' in Fig. 5.(a) is not elliptical but random state of polarization. The present work is the first x-ray experiment for analyzing polarization state of x-rays completely.

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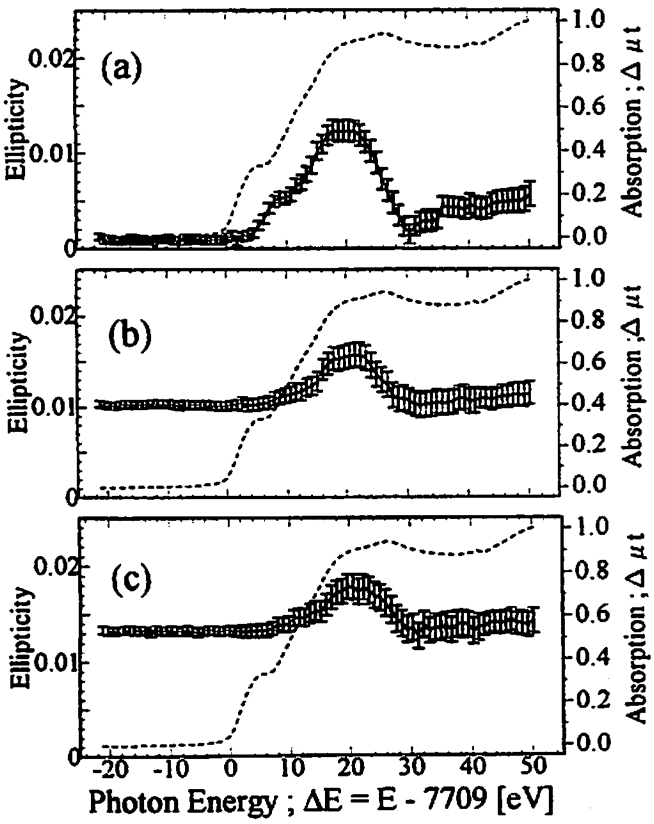

Fig. 9. Spectra of ellipticity for a polycrystalline *hcp* cobalt sample measured using (a)linearly polarized incident x-rays and eliptically polarized incident x-rays with ellipticity of (b)-0.01 and (c) +0.01.

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