Soft X-ray Resonant Magnetic Reflectivity Study on Induced Magnetism in [Fe\(_{70}\)Co\(_{30}\)/Pd\(_n\) Super-Lattice Films

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Abstract. We performed soft x-ray resonant magnetic reflectivity experiments on [FeCo/Pd\(_n\)] super-lattice films to study the depth profile of magnetization near the interface. From the analysis of the reflectivity measured at the Fe-L\(_{III}\) absorption edge, we obtained the magnetization profiles for the samples with different FeCo layer thicknesses. The profiles can be divided into three different zones: (A) Mixed region at the Pd interface where the magnetization decreased due to the structural randomness, (B) Enhanced region where the magnetization increased, and (C) Non-enhanced region. We estimated the thickness where the FeCo magnetization is enhanced by the adjacent Pd layer is about 4 atomic monolayers.

1. Introduction
In recent years, the density of magnetic recording is continuously increasing by introducing new device structures and new materials. Recently, we developed the [Fe\(_{70}\)Co\(_{30}\)/Pd\(_n\)] super-lattice films for the main pole material in a writing head that shows the saturation magnetization (\(B_S\)) of 2.6T, which is higher than the standard FeCo alloy of 2.4T, and suitable for the high density recording [1]. In the proceeding investigation [2], we studied the magnetization with different FeCo thicknesses by using Soft X-ray Magnetic Circular Dichroism (SXMCD) in the transmission geometry [3]. SXMCD can provide the spin and orbital moments separately for Fe and Co atoms based upon the sum rule analysis. As a result, we observed that the orbital moments of Fe and Co atoms were independent of the FeCo layer thickness but the spin moments of Fe and Co atoms increases as the FeCo thickness decreased. The result can be explained if the magnetic moments of Fe and Co are increased around the interface with the Pd layer. Soft X-ray Resonant Magnetic Reflectivity (SXRMR) can provide a depth profile of the magnetization by analyzing the reflected x-ray profile measured at the resonance energy where the contributions of the magnetic scattering are increased. We applied the method using the circularly polarized soft x-ray with an energy at the Fe-L\(_{III}\) absorption edge.

2. Non-resonant reflectivity
The super-lattice samples were deposited in a magnetron sputtering at room temperature. For the SXRMR measurement, the [FeCo/Pd\(_n\)] super-lattice was formed on a Si wafer with a Cr(50Å) buffer...
layer. On top of the layers, a Ru(35Å) layer was formed to prevent the oxidation of the internal multilayers. The composition of the FeCo layer is Fe 70% and Co 30%. To compare the depth profile of magnetization, the following three samples with different FeCo thicknesses, (I):[FeCo(9Å)/Pd(1.4Å)]36, (II):[FeCo(18Å)/Pd(1.4Å)]18, and (III):[FeCo(42Å)/Pd(1.4Å)]10 were prepared. The number after the angle bracket indicates the total number of the layers. The total thicknesses of the samples were around 400 Å. On the other hand, samples with the same structure were deposited on a SiN (1000Å) membrane for the SXMCD measurement in the transmission geometry. From the diffraction study, FeCo is body center cubic (bcc) with (110) orientation whose perpendicular layer spacing is 2.0 Å.

The soft x-ray experiments were carried out at the beamline BL25SU in the SPring-8 facility (Japan) where the twin helical undulators system with five kicker magnets switches the beam on and off-axis, that provides a circularly polarized x-ray with a helicity +1 and -1. The grating monochromator provides the monochromatic soft x-rays in the energy range between 0.22 to 2 keV [4]. We placed the versatile polarization apparatus [5] in the beamline as a reflectometer. For this experiment, we prepared a special sample holder made of two permanent magnets, which produces a magnetic field of 1kG parallel to the sample surface. For the detection of the x-rays, a micro channel plate (MCP) was used. The incident photon intensity was monitored by the photo-electron yield from an Au coated refocusing mirror placed upstream of the apparatus.

The scattering intensity of x-rays from the atoms in the samples is given from the atomic scattering factor, \( I = f_{\text{chg}} + f_{\text{mag}} \). In the expression, \( f_{\text{chg}} \) is the charge scattering factor which can be written as \( f_{\text{chg}} = f_0 + f_{\text{a}} \langle \text{ch} \rangle \), where \( f_0 \approx Z \) is the Thomson charge scattering factor with the number of electrons \( Z \), and \( f_{\text{a}} \langle \text{ch} \rangle \) is the anomalous scattering term. On the other hand, \( f_{\text{mag}} \) is the magnetic scattering factor, which also can be written as \( f_{\text{mag}} = f_{\text{a}} \langle \text{mag} \rangle \). A reason to use resonant energy is due to the fact that at far from resonance, a pure magnetic contribution in \( f_{\text{mag}} \) is fairly small and difficult to do the depth analysis. In comparison at resonance, charge-magnetic interference effects give rise to a sizable contribution of magnetic amplitude to the total scattering amplitude, that is suitable to estimate the depth profile of the magnetization.

Prior to determination of the magnetic parameters of the samples, it is important to determine the charge parameters. For this reason, we measured the non-resonant reflectivity at energy of (a) 8856 eV and (b) 692.5 eV, respectively. The former hard x-ray measurements were done at the “SUNBEAM” BL16XU in the SPring-8. Figures 1 (a) and (b) show the measured profiles for sample (I) at the above two energies where the 1st order Bragg peak from the super-lattice is clearly seen. In these figures, the

![Figure 1](https://example.com/figure1.png)

**Figure 1.** Measured (dot) and calculated (line) non-resonant x-ray reflection at energy of (a) 8856 eV and (b) 692.5 eV.
solid line indicate the simulated results from a layered model where the reflected intensity is calculated from the layer thickness, mass density and interface roughness. The non-resonant charge scattering factor is obtained from the table of Henke [6]. In the analysis, these layer parameters are optimized to reproduce the hard x-ray data for the wide intensity range of reflectivity. Next, these parameters are used as the initial values to optimize the soft x-ray data. We used these soft x-ray charge parameters as the starting value for the resonant reflectivity analysis in the following section.

3. Resonant reflectivity

SXRMR was measured at the Fe-L\textsubscript{III} edge at 708.6 eV. Figure 2 shows the resonant x-ray reflection for the all samples in which the upper and lower profiles correspond to that measured with the circularly polarized soft x-ray with +1 and -1 helicity. Compared to the non-resonant reflectivity, the interference oscillation around the small angle is not clear in the resonant reflectivity. The difference comes from the strong absorption of soft x-ray at resonance that decreases the reflected intensity from the deep region and the oscillation corresponding to the total thickness was reduced. Figure 3 shows the x-ray intensity in the sample with mass density profile. We assumed the charge and magnetic parameters are same for all layers except for the top layer where the effect of capping layer gives a slightly large roughness, as confirmed by the analysis of non-resonant data.

Figure 2. Measured (dot) and calculated (line) resonant x-ray reflection at energy of 708.6 eV (Fe-L\textsubscript{III} absorption edge) for samples (I)-(III). $I^+$ and $I^-$ indicate the intensity observed with the circularly polarized x-ray with helicity +1 and -1. For clarity, each data set has been displaced vertically.

Figure 3. Calculated x-ray intensity inside the sample (I) at $\theta=15^\circ$ for on-resonance (708.6 eV) and off-resonance (692.5 eV) with mass density profile.
The amplitude for resonant magnetic scattering of x-rays has been derived by Hannon et al [7]. For the L-edge resonance of the transition metals, a dipole transition predominates. To determine the magnetic scattering factor $f_{mag}$ experimentally, SXMCD was measured on the corresponding samples, prior to this experiment. The imaginary part can be obtained from the absorption profile, and the real part was obtained by applying the Kramers-Kronig relation to the imaginary part. The obtained resonant scattering factor for Fe is shown in Figure 4. The charge and magnetic scattering factors of FeCo were finally calculated from the weighted average of the factors for Fe and Co by using their atom numbers, where the non-resonant scattering factor of Co was obtained from the table of Henke. The scattering factors of FeCo used in the following analysis were $(f'_c, f''_c) = (-9.90, 54.28)$ and $(f'_m, f''_m) = (1.33, -15.06)$ in the unit of classical electron radius.

![Figure 4. Charge and Magnetic scattering factors of Fe around the L_{III} absorption edge for sample (II), obtained from SXMCD measurement.](image)

The optimization program was developed to analyse the resonant magnetic reflectivity data. For the calculation of scattering intensity, we used the method of [8] and [9] where the scattering intensity is calculated by generalizing the distorted wave Born approximation for the tensor susceptibility with the charge and magnetic roughness at the interface. To take into account the distribution of magnetization at the depth $z$ in the FeCo layer, we parameterized the magnetic scattering factor as $f_{mag}(z) = M(z) \cdot f_{mag}^{av}$, where $M(z)$ is the normalized magnetic profile, and $f_{mag}^{av}$ is the averaged magnetic scattering factor obtained from SXMCD data for sample (II). In the layered model, FeCo layer was subdivided into layers with a different $M(z)$. The optimization of parameters was done by minimizing the chi square defined in the following equation in log form.

$$
\chi^2 = \frac{1}{2N} \sum \sum \frac{(\log I_{obs}^{\pm} (\theta) - \log I_{cal}^{\pm} (\theta))^2}{\sigma_i^2}
$$

In the equation, $I_{obs}^{\pm}$ and $I_{cal}^{\pm}$ are the observed and calculated scattering intensities for +1 and -1 polarized circular x-ray, $\sigma_i$ is the standard deviation of the data. The results of the optimization were shown in the solid line in Figure 2. The obtained charge roughness $\sigma_c$ and magnetic roughness $\sigma_m$ were $4 \pm 1 \text{ Å}$ and $5 \pm 1 \text{ Å}$, respectively. To reproduce the measured reflectivity profile, we needed to introduce a depth dependent magnetization profile as shown in Figure 5. The solid line in the figures shows the magnetization profile including the smearing effect with Gaussian form due to the magnetic roughness.
Figure 5. Normalized magnetic profiles for FeCo layer of samples (I)-(III) as a function of the distance to the Pd interface determined from SXMRM. The solid line indicates the profile including a smearing effect due to the roughness at the interface. The profile can be divided into three regions A, B, and C.

To see the effect of magnetization profile on reflectivity, we plotted the asymmetry of the reflectivity, 
\[
\frac{I^+ - I^-}{I^+ + I^-},
\]
which is sensitive to the profile, around the 2nd peak for sample (III) in Figure 6 where the three different shapes of magnetic profiles, shown in the inset figures, are assumed.

Figure 6. Asymmetry of the reflectivity around the 2nd peak of sample (III) assuming different magnetic profiles; (a) corresponds to our results, (b) magnetization is maximum at interface, and (c) constant profile, as shown in the inset figure. The solid line is the simulation and dot is the data.

4. Discussion

Based upon the obtained magnetization profile as shown in Figure 5, we can divide the FeCo layer into three regions, (A) Mixed region whose thickness is around 4 Å, (B) Enhanced region with a thickness of 5 Å, and (C) Non-enhanced region. In region C, the magnetization is the same as that of thick FeCo layer. In region B, magnetization is higher than that of region C, that may be attributed to the induced magnetism where the 3d electron of Fe/Co atoms and 4d electron of adjacent Pd atoms are hybridized which increases the unpaired electron that contributes to the magnetization [10,11]. In region A, the induced effect still exists since the magnetic moment measured by SXMCD is increased in sample (I). However the random disorder at the interface of Pd causes fluctuation in the spin and the chemical mixing of FeCo with Pd suppresses the total magnetization. The thickness of region A coincides well with the chemical roughness at the Pd interface. This interpretation can explain why the
Bs is saturated in sample (I), because the structural randomness suppresses the induced magnetization effect. Since the induced effect exists in region A and region B, the effect possibly extends about four monolayers, which coincides to the depth of induced magnetic moments for Pd at the interface with Fe [12, 13].

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