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Spin reorientation transitions of Fe/Ni/Cu(0 0 1) studied by using the depth-resolved X-ray magnetic circular dichroism technique

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Abstract

The spin reorientation transition (SRT) of Ni/Cu(0 0 1) induced by Fe deposition was investigated using the X-ray magnetic circular dichroism (XMCD) method. In-plane magnetized Ni films ($\leqslant$9 ML) undergo the SRT twice; first, a small amount ($<$1 ML) of Fe deposition causes a transition to perpendicular magnetization. Second, further Fe deposition (1–2 ML in total) causes a return to in-plane magnetization. Perpendicularly magnetized Ni films ($\geqslant$10 ML) also exhibit a transition to in-plane by 1–2 ML Fe deposition. A precise magnetic anisotropy phase diagram was obtained using a combination of wedge-shaped Ni samples and stepwise Fe deposition. Magnetic anisotropy energies in the bulk, surface and interface layers of Ni films were separately determined using the depth-resolved XMCD technique, while values in the 1 ML and 2 ML portions of the Fe films were obtained from the conventional XMCD measurements. The origin of the SRTs is successfully explained with a simple phenomenological layer model using the obtained magnetic anisotropy energies.

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Keywords: Magnetic thin films; Spin reorientation transition; Magnetic anisotropy phase diagram; X-ray magnetic circular dichroism; Magnetic anisotropy energy

1. Introduction

Anomalous spin reorientation transition (SRT) of Ni films on Cu(0 0 1) has been investigated during the last decade. It has been reported that Ni films on Cu(0 0 1) exhibit SRT twice with increasing a Ni film thickness [1–4]. The first sharp transition is from in-plane to perpendicular magnetization at a Ni thickness of 7–10 monolayers (ML). Thicker films exhibit perpendicular magnetization up to ~40 ML. The second SRT takes place gradually from perpendicular to in-plane above ~40 ML [1–4]. The first sharp SRT was generally discussed in terms of the competition between a positive volume anisotropy and a negative surface anisotropy. The former is induced by the lattice strain, favoring perpendicular magnetization and the latter favors in-plane magnetization. Ni grows pseudomorphically on Cu(0 0 1). The in-plane lattice constant of a Ni film increases to match the Cu substrate lattice constant to some extent, while the interlayer spacing is reduced [5]. This tetragonal lattice distortion induces a positive volume magnetic anisotropy energy K_v which favors perpendicular magnetization. The lattice mismatch strain of Ni/Cu(0 0 1) is gradually relaxed above ~11 ML, which is the critical thickness for pseudomorphic growth [5]. This relaxation diminishes the volume part of the magnetic anisotropy energy, which results in the second SRT.

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The magnetic anisotropy is known to be sensitive to surface or interface structures. For instance, H or CO adsorption stabilizes the perpendicular magnetic anisotropy [6–8]. Vollmer et al. [6] reported that H adsorption shifts the critical thickness for the SRT in Ni films to thinner films by 4 ML. They interpreted this effect as a reduction of the surface anisotropy energy which favors in-plane magnetization.

Bulk Fe has an FCC phase only in the temperature range between 1184 and 1665 K, but ultrathin Fe films grown on Cu(0 0 1) exhibit an FCC phase even at room temperature up to 11 ML [9] with an enlarged atomic volume of 12.1 $\mathring{A}^3$ and a perpendicular magnetization. Fe films with a thickness below 4 ML exhibit a ferromagnetic coupling, while those with a thickness between 5 and 11 ML exhibit a unique behavior: The top two layers couple ferromagnetically to each other and the inner layers are either anti-ferromagnetic below 200 K (the Néel temperature) [10], or in a spin-density wave state below 170 K [11]. The phase transition to a BCC state is observed above 11 ML [12], and the magnetization easy axis changes to the in-plane direction.

Liu and Wuttig have studied the magnetic behavior of the Fe/Ni bilayers on Cu(0 0 1) [13]. According to their report, Fe(9 ML)/Ni(10 ML)/Cu(0 0 1) and Fe(9 ML)/Ni(15 ML)/Cu(0 0 1) exhibit in-plane and perpendicular magnetization, respectively, and Fe deposition shifts the Ni thickness for the SRT from in-plane to perpendicular to the thicker films. Thus, they claimed that the Fe–Ni interface favors an in-plane anisotropy, which was also confirmed in a recent study [14]. Very recently, it was revealed that in-plane magnetized Ni films undergo the SRT to perpendicular magnetization with a small amount (<1 ML) of Fe, while the films exhibit in-plane magnetization at further Fe mild deposition [15]. However, an essential question still remains; how Fe deposition affects the magnetic moment of Ni films, and how strong the magnetic anisotropies of the Fe and Ni layers are at the interface.

To clarify these problems, we have studied the magnetism with different Ni and Fe coverages by the XMCD technique, which has the advantage that element-specific orbital magnetic moments can be quantitatively determined [17]. Recently, we have developed a depth-resolved XMCD technique [16], which provides depth-resolved magnetic moments by collecting XMCD signals with different probing depths. In the present study, we have applied this technique to study the depth-resolved magnetism of Ni/Cu(0 0 1) and Fe/Ni/Cu(0 0 1) magnetic films, in which the Fe film is below 4 ML and the Ni film is in the range of 6–16 ML. The magnetic anisotropies of Fe and Ni at the interface have been extracted by an analysis of the experimental data.

2. Experiments

All the experiments were performed at BL-7A of the Photon Factory at the Institute of Materials Structure Science, High Energy Accelerator Research Organization (KEK-PF), equipped with an ultrahigh vacuum XMCD chamber (base pressure of 5×10^{-8} Pa) at room temperature. A Cu(0 0 1) single crystal was cleaned by repeated cycles of Ar^+ sputtering with an ion energy of 1.5 kV and annealing at 900 K. Fe and Ni films were deposited by an electron-beam evaporation, and the film thickness was monitored with in situ RHEED observations. To obtain the magnetic anisotropy phase diagram of Fe/Ni/Cu(0 0 1) precisely, wedge-shaped Ni samples were prepared (see Fig. 1b), in which the slope of the wedge was either 1 ML/mm or 2 ML/mm. Synchrotron radiation emitted downwards from the electron orbit of the storage ring by 0.4 mrad is about 80% circularly polarized. It was incident on the sample via a grazing incidence monochromator with a varied-line-spacing plane grating. The beam spot size was about 2.5 mm (horizontal) $\times 0.3$ mm (vertical) at the sample position. The sample was magnetized using pulsed current through a coil (about 700 Gauss) oriented along the X-ray propagation direction. The coil was retracted out during the measurement. Fe *L*-edge and Ni *L*-edge X-ray absorption spectra (XAS) were measured with the field parallel and antiparallel to the fixed photon helicity and XMCD spectra were obtained from

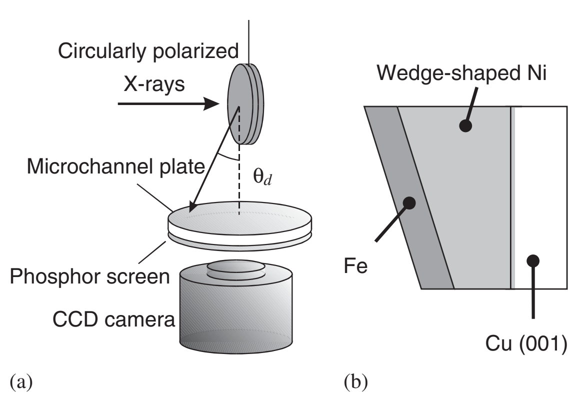

Fig. 1. A schematic illustration of the experimental setup for: (a) depth-resolved XMCD and (b) a wedge-shaped Ni sample. θ_d denotes the electron detection angle.