Rotation of uniaxial magnetic anisotropy induced by interface roughness in polycrystalline Co/Ru/Co multilayers

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Uniaxial magnetic anisotropy is a key factor governing the magnetization process in magnetic multilayers. In many thin film systems, the anisotropy axis is determined by crystallographic symmetry or growth-induced effects. In this study, we report a systematic rotation of the uniaxial magnetic anisotropy axis in polycrystalline Co/Ru/Co multilayers as a function of interface roughness. We find the in-plane anisotropy axis rotates by controlling the roughness via buffer layer growth conditions. This behavior is observed in both antiferromagnetically coupled and ferromagnetically coupled Co/Ru/Co multilayers, suggesting that the anisotropy rotation is not limited to a specific coupling state. Control experiments on single-layer Co films show no such rotation, indicating that the phenomenon originates from additional magnetic anisotropy due to the multilayer structure. Our results reveal that an additional parameter plays a vital role for controlling anisotropy in magnetic multilayers.

***Index Terms*— interface roughness, magnetic anisotropy, magnetic multilayers, synthetic antiferromagnet**

I. Introduction

Co/Ru/Co multilayers exhibit interlayer exchange coupling (IEC) that oscillates between ferromagnetic and antiferromagnetic states as a function of the Ru spacer thickness [1]. When the coupling is antiferromagnetic, the structure is referred to as a synthetic antiferromagnet (SAF), which is widely used in spintronic devices due to their reduced stray fields and stable magnetic configuration [2].

Magnetic anisotropy plays a crucial role in determining the magnetization behavior of magnetic multilayers. In epitaxial systems, the anisotropy axis is governed by crystallographic symmetry and/or epitaxial strain, whereas in polycrystalline or amorphous films it is generally attributed to growth-induced effects such as oblique deposition [3] or grain-related shape anisotropy [4]. In these cases, the anisotropy direction is typically regarded as being fixed by the growth conditions.

Interface roughness is known to significantly influence IEC in SAF [5], [6]. However, its impact on magnetic anisotropy, particularly in polycrystalline systems, remains unclear. In this work, we investigate the relationship between interface roughness and magnetic anisotropy in polycrystalline Co/Ru/Co multilayers, showing that the uniaxial anisotropy axis rotates in the film plane as the interface roughness varies.

II. Experiments

Co/Ru/Co multilayers were deposited on thermally oxidized Si(100) substrates using rf magnetron sputtering. The film structure is Nb (3 nm)/Co (4 nm)/Ru (t_{Ru})/Co (3 nm)/Nb (t_{Nb}), where t_{Ru} and t_{Nb} represent the thicknesses of the Ru interlayer and Nb buffer layer thickness, respectively. $t_{\mathrm{Ru}}$was set to 0.7 nm or 1.3 nm, corresponding to the antiferromagnetic and ferromagnetic IEC regions, respectively.

The interface roughness was controlled by varying the thickness and sputtering power for the Nb buffer layer. The surface morphology was evaluated using atomic force microscopy (AFM), and the interface roughness was quantified using the root-mean-square roughness (R_q) of single-layer Nb samples deposited on Si substrates.

Microstructural and compositional characterization was performed using a Spectra Ultra S/TEM (Thermo Fisher Scientific) equipped with a probe aberration corrector and energy-dispersive X-ray spectroscopy (EDX). Magnetic properties were measured at room temperature using the magneto-optical Kerr effect (MOKE). In-plane magnetization curves were recorded for various in-plane magnetic field orientations, and the ratio of the remanent magnetization to the saturation magnetization (M_{r} / M_{s}) was plotted as a function of the in-plane field angle to evaluate the magnetic anisotropy.

III. Results and Discussions

Figure 1(a) shows the in-plane magnetic field orientation dependence of M_{r} / M_{s} for Co/Ru/Co multilayers with t_{Ru} = 0.7 nm, where the two Co layers are antiferromagnetically coupled. For samples with relatively small interface roughness, uniaxial magnetic anisotropy is observed. As the interface roughness increases, the anisotropy axis gradually rotates within the film plane. When the R_q approaches t_{Ru}, that is 0.7

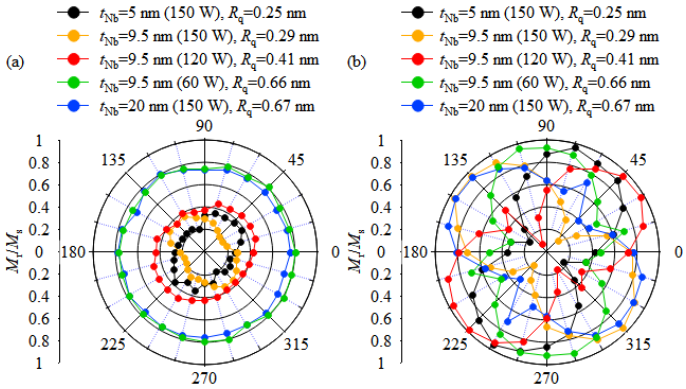


Fig. 1. In-plane field orientation dependence of M_r / M_s for (a) t_{Ru} = 0.7 nm and (b) t_{Ru} = 1.3 nm with different interface roughness.

nm, M_r / M_s increases and the angular dependence becomes isotropic. Figure 1(b) presents the corresponding angular dependence of M_r / M_s for t_{Ru} = 1.3 nm, where the two Co layers are ferromagnetically coupled. In this case, all samples exhibit uniaxial magnetic anisotropy, and a rotation of the uniaxial magnetic anisotropy axis is clearly observed as a function of interface roughness roughness. This is similar to the case of t_{Ru} = 0.7 nm, where R_q is relatively small. The similarity in the behavior of the anisotropy rotation between the antiferromagnetically and ferromagnetically coupled samples suggests that this effect is not directly linked to the sign of IEC.

The increase in the remanent magnetization observed in Fig. 1(a) is likely due to pinholes between the two Co layers [7]. Figure 2 shows cross-sectional EDX measurements for a representative sample (t_{Ru} = 1.3 nm, t_{Nb} = 20 nm, deposited at 150 W). This figure indicates that in samples with a large R_q (i.e., relatively coarse interfaces), the Ru layer becomes locally discontinuous, leading to direct ferromagnetic coupling induced by pinholes (see the arrows in Fig.2). Since the samples with t_{Ru} = 0.7 nm have only about half the Ru film thickness of the sample in Fig. 2, the Co layers are expected to couple more directly, making pinhole coupling dominant.

The rotation of the uniaxial magnetic anisotropy axis (see Figs. 1(a) and (b)) cannot be explained by the generally known origins of uniaxial anisotropy, such as magnetocrystalline anisotropy or shape anisotropy. Magnetocrystalline anisotropy is not expected in the case of polycrystalline and amorphous thin films due to the random orientation of grains [4]. Uniaxial magnetic anisotropy induced by the grain shape [4] is not supported by AFM observations. Effects related to oblique deposition [3] can also be ruled out since the substrates were rotated at 7-8 rpm during film growth.

To further clarify the origin of the anisotropy rotation, control experiments were performed on single-layer Co films without a Ru spacer (t_{Ru} = 0 nm). Figure 3 shows polar plots of M_r / M_s for Nb (3 nm)/Co (7 nm)/Nb (t_{Nb})/Si prepared under various buffer layer conditions. Unlike the Co/Ru/Co multilayers (Figs. 1(a) and (b)), no systematic rotation of the uniaxial magnetic anisotropy axis is observed in the Co single layers. This result indicates that the anisotropy rotation is not an intrinsic property of an individual Co layer.

Taken together, these observations suggest that the rotation of the uniaxial magnetic anisotropy arises from the Co/Ru/Co multilayer structure itself. It is conceivable that the magnetic anisotropy induced by the average crystallographic orientation of the top Co layer or changes in the ratio of pinhole coupling

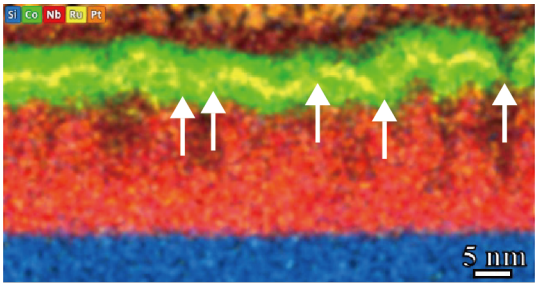


Fig. 2. Cross-sectional EDX elemental mapping of a Co/Ru/Co multilayer with t_{Ru} = 1.3 nm and t_{Nb} = 20 nm deposited at 150 W.

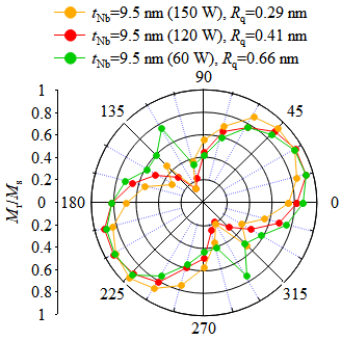


Fig. 3. In-plane field orientation dependence of M_r / M_s for single-layer Co films (t_{Ru} = 0 nm) prepared on various buffer layers.

to IEC may cause the rotation of the net uniaxial anisotropy axis. These combined results demonstrate the importance of interface roughness in determining magnetic anisotropy in polycrystalline Co/Ru/Co multilayers.

IV. SUMMARY

We have demonstrated a systematic in-plane rotation of the uniaxial magnetic anisotropy axis in polycrystalline Co/Ru/Co multilayers by controlling the interface roughness. This rotation likely originates from the average crystallographic orientation of the top Co layer and/or the pinhole coupling ratio. Since no such rotation of the anisotropy axis has been observed in single-layer Co films, this phenomenon arises from the additional magnetic anisotropy associated with the multilayer structure. These findings provide new insights into the control of anisotropy in polycrystalline magnetic multilayers.

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