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Journal of Magnetism and Magnetic Materials 239 (2002) 298–300

www.elsevier.com/locate/jmmm

Anomalous temperature-driven magnetization switching in $\text{Co}_x\text{Ni}_{1-x}/\text{Cu}(1\ 0\ 0)$ binary alloy films

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Abstract

The spin reorientation transition from in-plane to canted phase was found in the $\text{Co}_x\text{Ni}_{1-x}/\text{Cu}(1\ 0\ 0)$ alloy films with $0 \leq x \leq 8\%$. In the critical thickness range the alloy films reveal complicated evolution of magnetization orientation at variation of temperature. These findings may be attributed to the sensitive temperature effect of the higher order term in magnetic anisotropy. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Magnetic thin film; Spin reorientation transition; Alloy

The magnetization switching, the so-called the spin reorientation transition (SRT), is the interesting property which attracts much attention in magnetic ultrathin film systems. It has been shown that SRT changes depending on the measurement temperature [1] and composition variation of the alloy films [2] in addition to coverage [3] and deposition temperature [4]. Different from the SRT found in $\text{Fe}/\text{Cu}(1\ 0\ 0)$ [3], $\text{Fe}/\text{Cu}_3\text{Au}(1\ 0\ 0)$ [5], and $\text{Co}/\text{Cu}(1\ 1\ 1)$ [6], in which the magnetic easy axis is transformed from the out-of-plane into in-plane orientation with increasing film coverage, the $\text{Ni}/\text{Cu}(1\ 0\ 0)$ systems reveal an *inverse* SRT [6,7]. It could be attributed to the large strain-induced volume anisotropy in opposite sign to the other systems [7]. Moreover, the magnetic behaviors for ultrathin films are extremely sensitive to the anisotropies around the range of the critical thickness for the SRT. Unlike the linear thickness dependence of the magnetic anisotropy, the anisotropy reveals more complicated temperature-dependent behavior. To make it clear as to how the magnetic behavior is related to the temperature, conducting a systematic investigation in this system as a function of temperature is of most important. In this work, we report on the anomalous temperature-dependent behaviors of magnetic properties for the ultrathin

$\text{Ni}/\text{Cu}(1\ 0\ 0)$ and $\text{Co}_x\text{Ni}_{1-x}/\text{Cu}(1\ 0\ 0)$ films around the critical thickness range. The temperature-driven spin-reorientation transition as well as the transformation from the multi-domain magnetic structures into stable canted magnetic easy axis were observed by varying measurement temperature. The non-vanishing value of the higher order term of magnetic anisotropy should be taken into account in the anisotropy phase diagram to realize this complicated temperature-dependent behaviors.

All the experiments were carried out in situ in a multi-function ultrahigh vacuum (UHV) chamber [2] with base pressure better than 5×10^{-10} mbar. The alloy composition in our experiments can be controlled within an accuracy of $\pm 0.5\%$ [8]. The study of the magnetic structure evolution was accomplished by means of magneto-optical Kerr effect (MOKE) in polar and longitudinal configurations *quasi-simultaneously* with benefit of the lock-in technique. The temperature dependence of the magnetic behaviors were investigated by varying the measurement temperature for MOKE between 110 and 350 K. It did not exceed 350 K to avoid the interdiffusion between the films and $\text{Cu}(1\ 0\ 0)$ substrate [9]. It is noted that low energy electron diffraction (LEED), LEED $I(E)$, and Auger electron spectroscopy (AES) were taken again after all the magnetic property measurements to ensure that the crystalline and the chemical structures of the films remain invariant under the experimental procedures.

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Fig. 1. MEED intensity oscillations for 7.2 ML Ni/Cu(100) and 12.1 ML $\text{Co}_{0.6}\text{Ni}_{0.94}/\text{Cu}(100)$ films.

Fig. 1 shows the medium energy electron diffraction (MEED) intensity oscillations for 7.2 ML Ni/Cu(100) as well as 12.1 ML $\text{Co}_{0.6}\text{Ni}_{0.94}/\text{Cu}(100)$. One can see that both films have the similar MEED oscillations implying that there is no significant deviation between their morphology. As mentioned, the ultrathin films reveal a complicated temperature dependence of the magnetic behaviors in the range around the critical thickness. In particular, the temperature-driven SRT are different between the Ni/Cu(100) and $\text{Co}_x\text{Ni}_{1-x}/\text{Cu}(100)$ alloy films. As shown in Fig. 2, for Ni/Cu(100), there exists a temperature-driven SRT from in-plane to canted [8] orientation for the film coverage around d_c by thermal heating process after the films have been grown. The 7.2 ML Ni/Cu(100) film grown at room temperature reveals the in-plane magnetization only, as shown in the 110 K-taken Kerr signals (top of the Fig. 2). The polar Kerr signal develops while increasing the measurement temperature. It becomes significant at the temperature above 200 K and the remanent signal of the longitudinal MOKE exhibits an abrupt increase in the same temperature range. Both the longitudinal and polar Kerr signals vanish for the same temperature at about 260 K, indicating that there is a single canted-phase domain which is responsible for the hysteresis loops under these two geometries. This is compatible with our previous study [8].

The $\text{Co}_{0.6}\text{Ni}_{0.94}/\text{Cu}(100)$ alloy film shows the very fascinating temperature dependence of the magnetic behaviors. It also reveals a temperature-driven SRT, as shown in Fig. 3. Similar to Ni/Cu(100), only longitudinal hysteresis loop is observed at 110 K. The polar hysteresis loop dramatically appears at about 160 K and increasing with the measurement temperature. Different from the Ni/Cu(100) films, the remanent signal of the longitudinal loop decreases while the polar Kerr signal develops, as depicted in Fig. 3 (a)(180 K). Besides, the longitudinal loops look slanted like the hard-axis loops. For the measurement temperature higher than 200 K, the polar hysteresis loop vanishes and the longitudinal loop recovers to the original shape, that is, the magnetization reoriented to the in-plane direction, as shown in Fig. 3(a)(210 K). During the cooling process,

Fig. 2. Magnetic hysteresis loops for 7.2 ML Ni/Cu(100) at various measurement temperatures under polar and longitudinal geometries.

Fig. 3. Magnetic hysteresis loops for 12.1 ML $\text{Co}_{0.6}\text{Ni}_{0.94}/\text{Cu}(100)$ alloy films at longitudinal and polar configurations under (a) heating and (b) cooling processes.

both the polar and longitudinal hysteresis loops enlarge at the measurement temperature below 250 K. The remanent signals for both configurations increase with the decrease of the measurement temperature, as shown in Fig. 3. In addition, they are much larger than the values before heating. Unlike the heating process, the films always reveal stable canted magnetization for the cooling process, which are similar to the behaviors for Ni/Cu(100) films.

By applying the magnetic anisotropy flow concept [10], we can interpret the anomalous temperature-driven spin reorientation transition for Ni/Cu(100) as well as $\text{Co}_x\text{Ni}_{1-x}/\text{Cu}(100)$ films with qualitative success. By introducing the higher order contribution in magnetic

anisotropy, we could explain the possibility of the canted single-domain phase or multi-domain which is composed of in-plane and out-of-plane phases [10]. During the heating process, the magnetization can be driven by temperature from in-plane phase to canted phase [Ni/Cu(100)] or multi-domain phase [Co_xNi_{1-x}/Cu(100)] due to the different temperature dependence of first-order and higher-order anisotropy. It should be noted that the anisotropy flow follows a different path during the cooling process, causing the canted magnetization phase as mentioned above. This may be referred to the variation of morphology which influences the anisotropy during the whole annealing process.

This work was supported by National Science of Council under Grant No. NSC 89-2112-M-002-067 and by Outstanding Project of Education Ministry of Taiwan.

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