Spin wave excitations in Fe/Cu multilayers as a function of its parameters

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Correlation of low-temperature magnetic properties with morphology of (Cu(111)/Fe)×36/Cu multilayers prepared by dc-magnetron sputtering with \( t_{\text{Cu}} = 38.5 \pm 0.3 \) Å and \( t_{\text{Fe}} = 7.3 \times 0.3 \) Å found to be discontinuous at \( T_C = 7.3 \) Å, but continuous at \( T_C = 8.5 \) Å. Transition to the continuity of the Fe layers enhances both in-plane and perpendicular surface magnetic anisotropies. This is reflected in the change of the behavior of the temperature dependencies of spontaneous magnetization \( \sigma_s \) measured with external field oriented parallel and perpendicular to the multilayer plane. © 2000 American Institute of Physics.

I. INTRODUCTION

Transition metal superlattices are attractive materials for information storage technologies. The tailoring of specific magnetic properties, such as the orientation and strength of the magnetic anisotropy, may be achieved by choosing appropriate materials and varying the thicknesses of constituent layers. Interfaces, size and relaxation effects (the latter being unfavorable for most applications) often control the magnetic behavior of such artificially structured substances and their influence strongly depends on crystalline structure and morphology. Fe layers in a (Cu(111)/Fe)×36/Cu multilayer prepared by dc-magnetron sputtering with \( t_{\text{Cu}} = 38.5 \pm 0.3 \) Å and \( t_{\text{Fe}} = 7.3 \times 0.3 \) Å were found to consist of iron islands that were ferromagnetic as a result of a tetragonal lattice distortion. The perpendicular magnetic anisotropy was strong enough to prevent superparamagnetic fluctuations of the magnetization and they exhibited a linear temperature dependence of spontaneous magnetization at low temperatures. Here, we present experimental results on changes in the magnetic properties of Cu(111)/Fe multilayers as the Fe layers change from an island to continuous morphology. This shows the role of magnetic anisotropy and interfacial effects on spin-wave excitations.

II. EXPERIMENTAL METHODS

The multilayer film consisting of 36 bilayers with \( t_{\text{Fe}} = 8.5 \pm 1.0 \) Å and much thicker Cu layers of \( t_{\text{Cu}} = 21.0 \pm 1.0 \) Å was prepared by dc-magnetron sputtering onto Si substrates. The deposition sequence and all other conditions were as used previously. The starting layer as well as the oxidation protective capping was Cu. Deposition onto a Si substrate kept at ambient temperature, was performed at an Ar pressure of 10 mTorr with rates of about 2 Å/s and 1 Å/s for Cu and Fe, respectively. The Cu/Fe interface roughness \( \sigma_{\text{Cu/Fe}} \) (Fe on top of Cu) was found to be \( 6 \pm 0.5 \) Å as in the earlier \( t_{\text{Fe}} = 7.3 \) Å multilayer, but that of the Fe/Cu interface \( \sigma_{\text{Fe/Cu}} \) (Cu on top of Fe) was somewhat larger (\( 15 \pm 0.5 \) Å compared with 11 Å for the \( t_{\text{Fe}} = 7.3 \) Å multilayer). The interface roughnesses and thickness calibration were obtained from low-angle x-ray reflectivity data. As before, high-angle x-ray diffraction showed that the multilayer grows coherently with the Cu(111) direction normal to the film surface. Atomic scale properties were obtained using \( ^{57}\text{Fe} \) low-temperature conversion electron Mössbauer spectroscopy (LT-CEMS). A gas-flow He+4% CH₄ proportional counter was used for RT to 90 K, while a newly designed and optimized He-filled proportional counter covered the range down to 50 K. Both counters provided efficient long-term operation with our natural Fe samples, and had an illuminated spot \( \sim 20 \) mm in diameter. Bulk magnetic properties were obtained by extraction magnetometer.

III. RESULTS AND DISCUSSION

The initial susceptibility measured in the plane of the multilayer (excitation field 0.5 mT) exhibits a sharp shoulder at 225 K, slightly higher than the cusp observed for the earlier (Cu 38.5 Å/Fe 7.3 Å)×36 multilayer [Fig. 1(a) of Ref. 2]. This behavior cannot result from a broader distribution of Curie temperatures in the present (Cu 21.0 Å/Fe 8.5 Å)×36 multilayer because no hyperfine magnetic field is detected at temperatures above the shoulder, as illustrated by the RT Mössbauer spectrum shown in Fig. 2. The initial susceptibility measured along the multilayer normal shows no features at all. This is direct evidence for the absence of superparamagnetic relaxation.

Mössbauer spectra of the present multilayer measured at 93 K, i.e., below \( T_C \) (also shown in Fig. 2), are close to low-temperature spectra observed previously from similarly nanostructured Cu/Fe multilayers, which indicated perpendicular magnetic surface anisotropy. A satisfactory fit to the spectra is only possible by applying the same structural model used for the earlier 7.3 Å sample. Distorted interior regions in paramagnetic (PM) state were modeled by a quad-

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A moderate external field of 0.1 T increases the freezing of the moments. The freezing of the moments would also lead to a widening of the hyperfine field distribution which is not the case—standard deviation $\sigma_{B_{hf}} = 9 \pm 1$ T also remains unchanged. The freezing of the moments would also lead to a widening of the hyperfine field distribution which is not the case—standard deviation $\sigma_{B_{hf}} = 9 \pm 1$ T also remains unchanged. The values of $\langle B_{hf} \rangle$ and $B_{int}$ are practically the same as for the earlier 7.3 Å sample. This points to the unchanged structure of the inner regions of Fe layers. At the same time the interfaces in the present 8.5 Å sample are less alloyed as can be inferred from a slightly higher most probable field for the alloyed interfaces $B_{int} = 17 \pm 3$ T (compared with 12 \pm 3 T for the earlier 7.3 Å sample). Less alloying of the interfaces is expected to lead to more continuous layers and stronger perpendicular surface anisotropy.

An external field of 0.1 T applied in the sample plane leads to essentially no redistribution of spectral intensity, indicating that the magnetic moments of the sample do not rotate towards the field, in contrast with the case of the earlier 7.3 Å sample. For the present 8.5 Å sample, the angle between the average moment direction and the γ beam ($\langle \Theta \rangle$) is the same without and with the applied field, being 27\(\pm\)7° and 28\(\pm\)13°, respectively. By contrast, for the earlier 7.3 Å film, $\langle \Theta \rangle$ changes from 19\(\pm\)19° to 66\(\pm\)11° in the same field. This shows that the present 8.5 Å sample possesses much stronger perpendicular anisotropy.

The slightly larger initial tilting of the average moment suggests a larger role of the in-plane shape anisotropy especially for the moments in a thicker alloyed interfaces where exchange is weaker. This points to a more continuous morphology of the Fe layers. The in-field data also support this conclusion. A moderate external field of 0.1 T increases $T_c$ by 100 K. The shoulderlike shape of susceptibility curve may be explained then by the action of in-plane shape anisotropy associated with the 2D character of the FM layers induced by external field. The change in dimensionality is also confirmed by bulk magnetization data. Temperature dependence of hysteresis loops measured with in-plane applied field is very different for the present multilayer. For the earlier 7.3 Å sample, temperature dependence of the coercivity resembles the behavior for single domain particles, collapsing rapidly on warming from 5 to 90 K to a very small value ($\sim$5 mT). While for the present 8.5 Å sample the coercivity remains constant at $\sim$15 mT from 25 K to 150 K. It de-
The change of ropy upon transition to continuous Fe layers is reflected in small Fe islands in the case when the external field acts along the anisotropy direction, i.e., for the out-of-plane shape or perpendicular surface anisotropy. The transition of \( \sigma_r^s(T) \) from Bloch-like \((T^{3/2})\) to \(T^1\) dependence correlates with the change to discontinuous morphology of Fe layers. The shape of \( \sigma_r^s \) depends on the interplay between perpendicular surface anisotropy and the weakening of pinning of spins in the alloyed interface regions together with in-plane shape anisotropy.

**IV. CONCLUSIONS**

Our results show that the curvature in the temperature dependence of spontaneous magnetization \( \sigma_r \) of Fe/Cu multilayers is associated with strong magnetic anisotropy either in-plane shape or perpendicular surface anisotropy. The transition of \( \sigma_r^s \) from Bloch-like \((T^{3/2})\) to \(T^1\) dependence correlates with the change to discontinuous morphology of Fe layers. The shape of \( \sigma_r^s \) depends on the interplay between perpendicular surface anisotropy and the weakening of pinning of spins in the alloyed interface regions together with in-plane shape anisotropy.