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Temperature and thickness dependence of coercivity and magnetization of Co/Cu and Co/Si multilayers

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Co/Cu and Co/Si multilayers of total thickness ~3000 Å were prepared by rf and dc magnetron sputtering. The nominal thicknesses of the individual layers were in the range of 4 to 100 Å. A large coercivity (H_c) at 10 K was observed for very thin layers of Co in Co/Cu samples, and it decreased with increase of the Co layer thickness. For very thin layers of Co in Co/Cu samples, the layer behaved superparamagnetically. Similar behavior was not to be observed in Co/Si samples. With increased substrate temperature (T_s) during deposition, H_c was also observed to increase (decrease) for Co/Cu (Co/Si) samples. Magnetization data were modeled to determine the diffusion layer thicknesses.

INTRODUCTION

Co/Cu and Co/Si multilayers have been prepared by rf and dc magnetron sputtering. It is of interest to study the magnetic properties of magnetic layers separated by different spacer layers. There are several reports on Co/Cu multilayers that showed that the magnetization of the Co layers is approximately the same as that of the Co film.[1] The H_c increased with decrease of Co layer thickness[2] and significant coupling was observed between Co layers through Cu spacer layers.[3] The magnitude of the interlayer magnetic exchange coupling was found to oscillate with the Cr or Ru spacer layer thicknesses.[4] In this paper, we report H_c and magnetization as a function of Co layer thicknesses (X) for different temperatures while keeping the Cu and Si thicknesses constant. Also we report a study of the dependence of H_c on the T_s during deposition.

SAMPLE PREPARATION AND STRUCTURE

Co/Cu and Co/Si multilayers were prepared on Al foils by rf and dc magnetron sputtering. The total thickness of the films was ~3000 Å and the nominal thicknesses of the individual layers were in the range of 4 to 100 Å. For samples Co11.5 Å/Cu11.5 Å and Co11.5 Å/Si11.5 Å, T_s was varied from 20 to 500 °C. The layered structure of the samples was confirmed by small angle x-ray diffraction. It showed that the boundary between Co and Cu was sharper than that for Co and Si. When T_s increased the layered structure became more diffuse. Large angle x-ray diffraction patterns showed the existence of fcc Cu and cubic Si structures. As it is known that the growth of epitaxial Co/Cu superlattices in which the Co atoms are predominantly arranged with cubic, rather than hcp symmetry,[5] we believe that the Co layers in our samples were also predominantly fcc in structure. A SQUID magnetometer was used to investigate the magnetic properties of the films.

RESULTS AND DISCUSSION

Hysteresis loops for Co/Cu and Co/Si samples showed that the in-plane magnetization was higher than that perpendicular to the plane, indicating that the easy magnetization direction was in-plane. This was true for all of our samples. Also the in-plane H_c was observed to be smaller than that perpendicular to the plane for all Co/Cu and Co/Si samples.

The magnetization (σ_{co}) of Co and the diffused layer thicknesses for the Co/Cu and Co/Si samples could be determined using a simple model in which the Co layer is sandwiched between Cu or Si layers. At the interface there would be a diffused layer in which Co loses its magnetization. Let the thickness of this diffused layer at each side be Δd. The spontaneous magnetization (σ_s) per Co mass can be written as

$$\sigma_s = \sigma_{co}\left(1 - \frac{2\Delta d}{X}\right).$$

Figure 1 is the plot of σ_s and $1/X$ for the CoX Å/Cu10 Å and CoX Å/Si11.5 Å samples. From the intercept, the value of σ_{co} obtained are 152 emu/g and 147 emu/g for Co/Cu and Co/Si samples, respectively, which are very close to the Co magnetization 155 emu/g for Co films. From the slope, the diffused layer thicknesses were found to be 1.2 Å in Co/Cu and 2.1 Å in Co/Si samples. At very thin Co layer thickness (4 Å) the layer became discontinuous or islandlike.[6] In this case the magnetic behavior could be different than for a homogeneous film. For the Co4 Å/Cu11.5 Å sample, the Co did not lose its magnetization, in fact the islands became superparamagnetic.

Figure 2 shows the $H_{c\perp}$ and $H_{c\parallel}$ of CoX Å/Cu11.5 Å and CoX Å/Si11.5 Å samples measured at 300 and 10 K as a function of X. It shows that at room temperature Co/Cu has low H_c (<50 Oe). But at 10 K, for very thin layers of Co, H_c was much higher. For $X = 4$ Å, $H_{c\perp} \cong 800$ Oe, and $H_{c\parallel} \cong 375$ Oe. Figure 3 shows the H_c as a function of T_s for Co11.5 Å/Cu11.5 Å and Co11.5 Å/Si11.5 Å samples. For Co/Si samples H_c decreases with the increase of T_s. Above

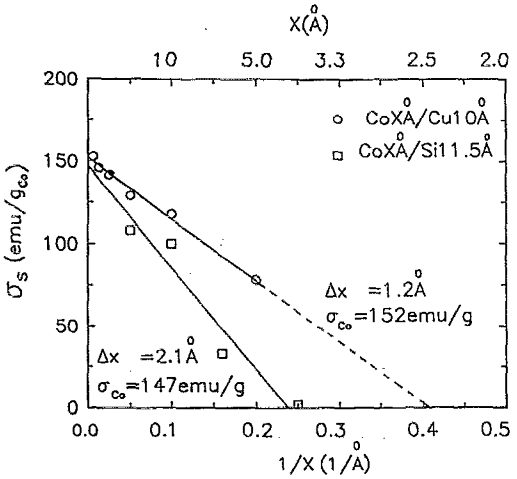

FIG. 1. Spontaneous magnetization (σ_s) per Co mass as a function of $1/X$ for CoX Å/Cu10 Å and CoX Å/Si11.5 Å samples.

$T_s = 200$ °C, the H_c stayed constant with further increase of T_s. For the Co/Cu samples, H_c increases with the increase of T_s, and reaches $H_{c\perp} = 570$ Oe at 10 K.

The sharp drop of H_c with temperature (Fig. 2) suggests a superparamagnetic behavior.[7] H_c of single-domain particles can be expressed by[8]

$$H_c = \frac{2K}{M_s}\{1 - (25k_BT/KV)^{1/2}\},$$

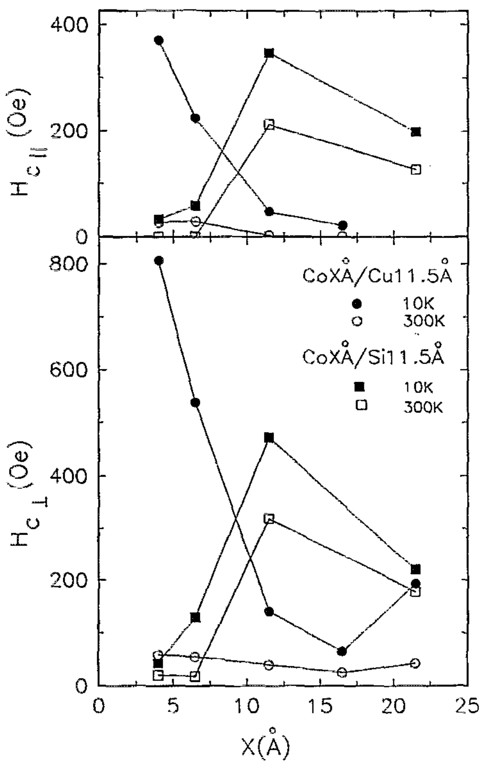

FIG. 2. $H_{c\parallel}$ and $H_{c\perp}$ as a function of X for CoX Å/Cu11.5 Å and CoX Å/Si11.5 Å samples.

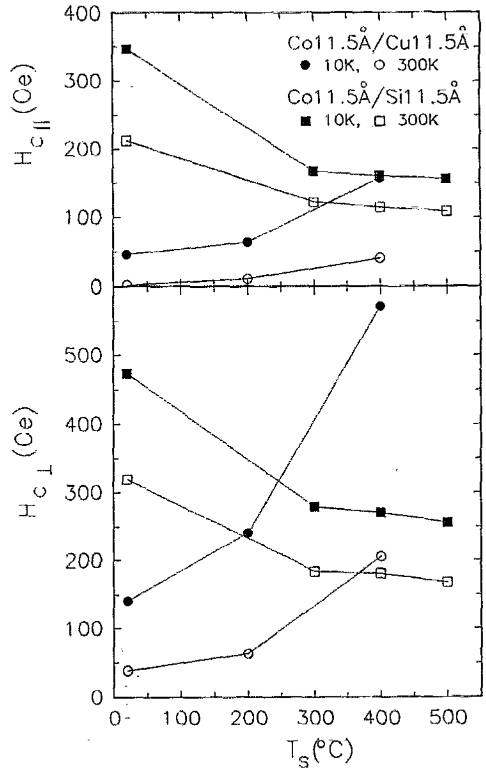

FIG. 3. $H_{c\parallel}$ and $H_{c\perp}$ as a function of substrate temperature for Co11.5 Å/Cu11.5 Å and Co11.5 Å/Si11.5 Å samples.

where K is the anisotropy energy associated with the islands, M_s is the saturation magnetization, V is its volume of the islands, k_B is the Boltzmann constant, and T is the measuring temperature. Figure 4 is the plot of $H_{c\perp}$ vs $T^{1/2}$ for Co4 Å/Cu11.5 Å. Most of the islands were superparamagnetic with a blocking temperature around 178 K. Figure 5 is a plot of magnetization for the same sample as a function of H/T where H is the applied magnetic field.

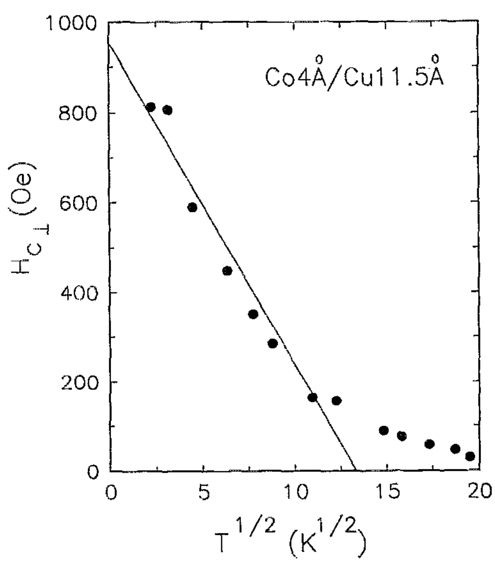

FIG. 4. $H_{c\perp}$ as a function of $T^{1/2}$ for Co4 Å/Cu11.5 Å.

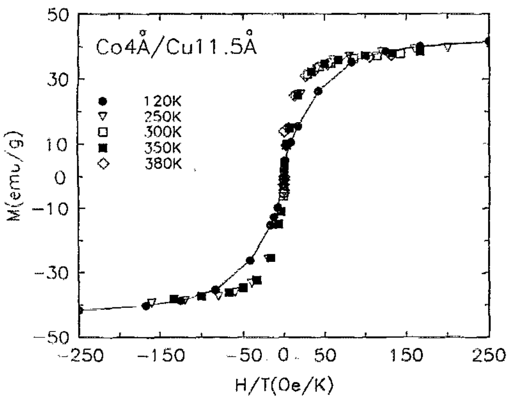

FIG. 5. Magnetization for Co4 Å/Cu11.5 Å as a function of H/T. The solid line is an eye guide for the data taken at 120 K.

All the data points taken at 250, 300, 350, and 380 K superimposed on one line which is expected for superparamagnetic particles. When the magnetization data taken at 120 K were plotted against H/T, the data were found to distinctly deviate from the original line. These islands were not paramagnetic, rather superparamagnetic because we could saturate them with less then 20 kOe field. Films with Co6.5 Å/Cu11.5 Å also showed superparamagnetic behavior with blocking temperature around 250 K. The anisotropy energy and the volume of the islands were determined for Co4 Å/Cu11.5 Å and Co6.5 Å/Cu11.5 Å as 6.44×10^5 erg/cm^3, 9.52×10^5 Å^3 (equivalent to a spherical particle of 122 Å diam) and 4.1×10^5 erg/cm^3, 1.9×10^6 Å^3, respectively. It was noticed that the anisotropy energies associated with these islands were about one order of magnitude smaller than the magnetocrystalline anisotropy for hcp Co. For larger Co layer thicknesses, the layer became continuous, and H_c initially decreased and then increased. For Co/Si samples and very thin layers of Co, H_c was very low, apparently forming a magnetically soft alloy with Si. For Co11.5 Å/Si11.5 Å, the sample had a layered structure (as verified by small angle x-ray diffraction), and had a higher $H_{c\perp}$ (445 Oe) unlike the Co11.5 Å/Cu11.5 Å sample. With further increase of the Co layer thickness, H_c decreased. Superparamagnetic behavior could not be observed for any of the Co/Si samples.

In summary, we have shown that for very thin layers of Co in Co/Cu multilayers, Co layer behaves superparamagnetically. Similar behavior was not observed in Co/Si samples. H_c increased (decreased) with T_s for Co/Cu (Co/Si) samples. The magnetization of Co in Co/Cu samples was found to be very close to that for Co in a thin film.

ACKNOWLEDGMENTS

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