Research Article

Thickness and Interface-Dependent Structural, Magnetic, and Transport Properties of Cu/Co Thin Film and Multilayer Structures

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Received 27 May 2014; Revised 2 August 2014; Accepted 3 August 2014; Published 19 August 2014

Academic Editor: Robert Sang

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Structural, magnetic, and transport properties of electron beam evaporated Co/Cu thin films and multilayer structures (MLS) having different layer thicknesses have been characterized utilizing X-ray diffraction (XRD), magnetooptical Kerr effect (MOKE), and resistivity techniques. The structural studies show distinctive crystal structures for different sublayer thicknesses. The Co (300 Å) single layer film is amorphous, while Cu (300 Å) film is nanocrystalline in nature. The average particle size is found to decrease as the number of interface increases. The corresponding magnetic and resistivity measurements show an increase in saturation field and resistivity as a result of an enhanced anisotropy. However, coercivity decreases with a reduction in average particle size. The results conclude that these properties are greatly influenced by various microstructural parameters such as layer thickness, number of bilayers, and the quality of interfaces molded under different growth conditions.

1. Introduction

Magnetic thin films, in particular nanometer scale structures, have been the subject of numerous studies by different laboratories [1, 2]. In recent years, magnetic phenomena such as oscillating exchange coupling, giant magnetoresistance, and surface anisotropy have been extensively investigated. In particular, the structure and morphology of magnetic ($M = \text{Fe, Co, Ni, or perm alloy}$)/nonmagnetic ($NM = \text{Cu, Pd, Ag, and Au noble metals}$) multilayers with disordered interfaces has been of growing interest within the last 20 years for both fundamental and technological reasons. Recently, in the growth of sensor and other magnetoelectronic applications, the immiscible system Co/Cu has an appropriate giant magnetoresistance (GMR) effect, which continues to be of special interest [3, 4]. Co/Cu multilayers (MLS) exhibiting appreciable GMR have been studied widely and there are some reports on the dependence of GMR on factors like number of bilayers [5], thickness of individual Cu-layers [6] and Co-layers [7], and interfacial roughness [8]. However, low sensitivity and high saturation fields have been restricting the application potential of these multilayers.

It is reported that the strength of the antiferromagnetic coupling depends on the interfacial structure, which in turn depends on the growth of the material. Magnetic properties of multilayer thin films can be controlled by an appropriate selection of film thickness, film composition, interface roughness, grain size, annealing temperature, and so forth [9, 10]. Among them the effect of the interface has a critical role in the magnetic properties of multilayer as a result of the break in local symmetry, strain issuing from lattice mismatch with adjacent layers, or interface morphology (e.g., surface reconstruction, roughness, or interdiffusion). On the theoretical side, many studies have shown that the spin-dependent scattering at the interface plays an important role in obtaining the new magnetic properties [11, 12]. However, in many cases the commonly encountered problems are interdiffusion between constituent elements, increase in the interfacial roughness, and formation of compounds at the interface during deposition, which critically alters the physical and chemical properties.

Therefore, establishing the relationship of interface magnetic properties to interface morphology not only is of fundamental interest but also is essential for development

FIGURE 1: Schematic diagram of the three types of bilayer samples (BLs) deposited.

of new multilayers. Thus, in the present paper, the author systematically took out the synthesis and characterization of single layer, bilayer, and multilayer (MLS) using X-ray diffraction and magnetooptical Kerr effect (MOKE) method in order to get out a clear correlation between the structural parameters and the observed magnetic behavior in Co/Cu single layer, bilayer, and multilayer films.

2. Experimental Details

The samples Co (300 Å), Cu (300 Å) single layers as well as [Co (300 Å)/Cu (300 Å)] bilayer, [Co (60 Å)/Cu (60 Å)]_{X5}, and [Co (30 Å)/Cu (30 Å)]_{X10} MLS used in the present study were synthesized using the electron beam evaporation method under the ultrahigh vacuum (UHV) conditions [13]. Prior to the deposition, *ex situ* cleaning of the substrates was done. The glass substrates were initially washed with soap solution and rinsed with distilled water. Before loading to a UHV chamber, they were ultrasonically cleaned and dried using infrared lamp. The base pressure inside the evaporation system was $\sim 2 \times 10^{-9}$ Torr, while during deposition, it dropped to $\sim 3 \times 10^{-8}$ Torr. The deposition rate of 0.1 Å/s for both Cu and Co was maintained by using quartz crystal thickness monitor. The first deposited layer on the substrate was of Cu. The X-ray diffraction measurements were done using Rigaku RINT-2000 diffractometer equipped with a rotating Cu anode as the source of X-rays at $\lambda = 1.542$ Å. The associated changes in magnetic properties were characterized by means of magnetooptical Kerr effect (MOKE) method with a laser source (He-Ne) of wavelength 632.8 nm and transport properties with the help of four-probe method. All the measurements reported were carried out at room temperature. From here onwards for ease the author has denoted Co (300 Å) single layer film by sample A, Cu (300 Å) single layer film by sample B, [Co (300 Å)/Cu (300 Å)] bilayer film by sample C, [Co (60 Å)/Cu (60 Å)]_{X5} MLS by sample D, and [Co (30 Å)/Cu (30 Å)]_{X10} MLS by sample E. Figure 1 shows the schematic diagram of the three types of MLS deposited.

3. Result and Discussion

3.1. XRD Measurement. Figure 2 shows the XRD patterns of single, bilayer, and multilayer films. The XRD pattern of Co (300 Å) shows a broad hump at around $2\theta = 44.56^\circ$ due to the reflection from hcp (002) planes, indicating an amorphous nature of the deposited Co thin film as presented

FIGURE 2: XRD patterns of (a) Co (300 Å) and (b) Cu (300 Å) single layer thin films along with (c) [Co (300 Å)/Cu (300 Å)] bilayer sample, (d) [Co (60 Å)/Cu (60 Å)]_{X5} MLS, and (e) [Co (30 Å)/Cu (30 Å)]_{X10} MLS.

in Figure 2(a) [14]. The broad hump clearly indicates the formation of nanosized crystallites in this case. The average particle size obtained from Scherrer formalism is found to be ~ 39 Å. However, the layer structure for Cu (300 Å) film is crystalline in nature [15]. The XRD pattern, corresponding to Cu (300 Å) in Figure 2(b), shows a sharp crystalline peak due to reflection from Cu (111) planes at $2\theta = 43.38^\circ$ and matches well with the reported value. In this case the average

FIGURE 3: Hysteresis loops of (a) Co (300 Å) single layer thin film along with (b) [Co (300 Å)/Cu (300 Å)] bilayer sample, (c) [Co (60 Å)/Cu (60 Å)]_{x5} MLS, and (d) [Co (30 Å)/Cu (30 Å)]_{x10} MLS.

particle size is found to be ~ 152 Å (see Table 1). Table 1 shows the values of average particle size, saturation field, and coercivity for different samples obtained from XRD and MOKE measurements. Likewise, the XRD pattern of Co (300 Å)/Cu (300 Å) bilayer film also presents a single crystalline peak at a 2θ value of 43.52° and is due to the combination of both Co and Cu layers [15]. However, the peak is shifted towards higher 2θ value as compared to the above case. The shift in the peak position is caused by the elongation of the (111) interplanar distance “ d ” due to internal stress in Cu layer induced by an adjacent Co layer because of different lattice constants of Co and Cu. Since 2θ values of both Co and Cu elements are closely overlapping, they cannot be resolved in the present measurement. However, it is clear from the above XRD patterns that the layer structure of Cu (300 Å) film is crystalline, whereas Co (300 Å) film is amorphous in nature. Thus, the author concludes that the crystalline nature of the peak is primarily ascribable due to the reflection from Cu (111) planes. The average particle size in this case decreases

to ~ 112 Å (see Table 1). The peak becomes further broader and shifted towards higher 2θ values as the number of bilayers increases to 5 and 10 (i.e., for multilayer cases) as shown in Figures 2(a) and 2(b). The observed broadness and reduction in peak intensity are due to the reduction of average particle size and increase in intermixing of Co and Cu layer at the interfaces produces disorders in the crystal structure induced by increasing the number of interfaces.

3.2. MOKE Measurement. The MOKE measurements carried out on the corresponding single, bilayer, and multilayer films are shown in Figure 3. For all the measurements, magnetic field was applied parallel to the surface of the films and the hysteresis loops were recorded up to saturation magnetization. It can be seen that M-H loop corresponding to the as-deposited Co (300 Å) film is square in shape indicating that the distribution of anisotropy is rather sharp (180° type, domain walls), which makes the domain magnetization switching beyond certain applied magnetic field [16]. It

TABLE 1: Particle size, saturation field, and coercivity values obtained from XRD and MOKE measurements.

	Average particle size (Å)	Saturation field (Oe)	Coercivity (Oe)
Sample A	~39	19	16
Sample B	~152	—	—
Sample C	~110	126	67
Sample D	~69	146	49
Sample E	~52	260	38

can also be explained by the weak crystalline magnetic anisotropy due to the existence of small crystal grains and negligible magnetostriction. In the recorded M-H loop, it is also seen that the magnetization reversal from saturation in one direction to saturation in the other direction occurs almost entirely by motion of these walls in the form of large Barkhausen jump occurring in a field equal to the coercive field (H_c). The magnetization corresponding to H_c depends on the extent to which sample imperfections impede the wall motion. The large vertical jumps with retentivity almost equal the saturation magnetization and the lower coercivity value indicating the soft magnetic nature of the deposited sample. Further, the sample does not show saturation with a magnetic field applied perpendicular to the plane of the film, also indicating that the sample has an easy in-plane magnetization direction. However, the author observed drastic changes in the hysteresis loop of sample C, that is, in [Co (300 Å)/Cu (300 Å)] bilayer sample (see Figure 3(b)). One can see that the shape of the square loop (as in a case of as-deposited Co (300 Å) film) changes to a smoother one indicating the different type of interaction of domains and their wall motion with respect to the applied magnetic field. Large increase in saturation (126 Oe) and coercive field (67 Oe) has been observed in this case as shown in Table 1. The observed increase in coercivity and saturation field value is mainly due to the introduction of adjacent Cu layer, causing the different type of interaction with domain and their wall motion with respect to the applied magnetic field. Similarly, M-H loop behavior, but with further increase in saturation field (146 Oe) and reduction in coercivity (49 Oe) value, is obtained for sample D as shown in Figure 3(c). These changes in the M-H loop behaviour are due to increase in the number of interfaces that may alter the response of applied magnetic field showing gradual variation of domains with increase H_s and decrease H_c values and also due to a subsequent reduction in average particle size. Alike is the case for sample E. Moreover, XRD measurement in this case also shows modifications in the layer structure after the formation of the MLS.

3.3. Resistivity Measurement. The electrical resistivity measurement of the corresponding single, bilayer, and multilayer samples is shown in Figure 4. The resistivity values of as-deposited Co (300 Å) and Cu (300 Å) thin films are 14.81 and 6.12 $\mu\Omega\text{cm}$, which are much higher than those of both of their elements. The reported resistivity values for pure bulk Co and Cu are 5.81 $\mu\Omega\text{cm}$ and 1.68 $\mu\Omega\text{cm}$, respectively.

FIGURE 4: Resistivity behaviour of (a) Co (300 Å) and (b) Cu (300 Å) single layer thin films along with (c) [Co (300 Å)/Cu (300 Å)] bilayer sample, (d) [Co (60 Å)/Cu (60 Å)]_{X5} MLS, and (e) [Co (30 Å)/Cu (30 Å)]_{X10} MLS.

The higher resistivity values obtained in each case are because of various factors such as point defects and structural disorders generally present in the as-deposited layers. From Figure 4, further one can see that resistivity increases with a number of bilayers and shows a maximum (84.93 $\mu\Omega\text{cm}$) for sample E. The obtained resistivity behavior in different cases can be understood as follows (a) different growth morphology of Co and Cu single layers, whereas (b) in case of the bilayer and multilayer samples (i) formation and growth of intermixed layers of Co-Cu at the interface as the number of bilayer increases and individual layer thickness decreases and (ii) subsequent reduction in particle size.

4. Conclusions

The properties of electron beam evaporated Co/Cu thin film and MLS having a different bilayer thickness (keeping the total layer thickness same) have been characterised. The structural studies show modification in the crystal structures for different sublayer thicknesses. The intensity of the peak as well as average particle size decreases due to increase in intermixing of Co and Cu layer at the interfaces and its further growth as the number of interfaces increases. The corresponding magnetic and transport properties additionally vary with transmutation in interface parameters. The results conclude that these properties greatly depend on various microstructural ML parameters such as layer thickness, number of bilayers, and the quality of interfaces formed under different growth conditions. In the near future, the author has planned to investigate the temperature-dependent structural and magnetic properties of Co/Cu interface.

Conflict of Interests

The author declares that there is no conflict of interests regarding the publication of this paper.

Acknowledgment

The author is grateful to UGC-DAE-CSR, Indore, India, for providing experimental facilities.

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