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Giant magnetoresistance effect in Co/Cu/Co nanostructures

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Abstract

The giant magnetoresistance effect (GMR) in Co/Cu/Co nanostructures is investigated in association with different sets of experimental conditions. GMR shows an up–down variation with increasing Co film thickness, with a peak for 6 nm thickness. A rather similar trend was observed in annealed samples with maximum annealing temperature of 400 °C. There is also a tendency of GMR to change with the number of Co/Cu bilayers and argon gas pressure introduced during the deposition, as indicated by the unstable wavy like curves.

Keywords: Giant magnetoresistance; Nanostructures; Annealing; Ferromagnetic; Co/Cu bilayer

1. Introduction

GMR refers to the considerable drop in the resistance (%) of coupled magnetic/non-magnetic layers when a sufficiently high magnetic field is applied to the sample, a phenomenon which was first observed by Baibich et al. [1]. Since then, extensive research studies on GMR have been done over a wide range of materials prepared by various fabrication methods. Recent works on metal/non-metal structures indicated the possibility of obtaining higher GMR up to 50%, and these are generally applied to ultra thin metallic layers of Cu or Ag of approximately 10 nm sandwiched between two ferromagnetic metals, such as cobalt and iron.

The main interest of this study is to observe the variation of GMR (%) in Co/Cu/Co samples when subjected to changes in the film thickness, annealing temperature, number of Co/Cu bilayers and argon gas pressure. Less report has been given on these effects for Co/Cu/Co sputtered samples except those prepared using different deposition techniques [2–4]. Cobalt was chosen as the ferromagnetic material because it is one of the very few elements with ferromagnetic behavior at room temperature [3]. In addition, the Curie temperature, T_C, of Co is higher than those of the other ferromagnetic materials (e.g. Ni and Fe) that capable of stabilizing the GMR properties at elevated temperatures and avoiding the ferromagnetic–paramagnetic shift at T_C when GMR starts to degrade gradually. Meanwhile copper, the most common good conducting material, is chosen as the non-magnetic material.

2. Experimental

Cobalt and copper disks of 99.99% purity were used as starting materials to prepare Co/Cu nanostructure layers by means of RF sputtering method. The samples were deposited at room temperature onto corning glass substrates using a PENTA high vacuum coater system under different experimental conditions. Film thicknesses were monitored using a FTM5 quartz crystal during the deposition and were later confirmed using a Dektak^3 Surface Profiler. The GMR measurements have been carried out using a four-point van der Pauw method in magnetic fields of ±2500 Gs. Post-deposition annealing was carried out in an evacuated quartz tube at temperatures between 30 and 500 °C up to 180 min. The basic 6.0/2.5/6.0 nm Co/Cu/Co sample was chosen throughout the experiment. For GMR measurements a constant current of 15.6 mA was applied to the samples previously set into four-point terminals, where the output voltage was measured to give the corresponding sample's resistance. GMR (%) is determined from the expression $((R_1 - R_2)/R_2) \times 100\%$ where R_2 and R_1 are the resistivities of the samples in the presence and absence of the magnetic field, respectively.

3. Results and discussion

3.1. Effect of film thickness

The effect of Co layer thickness, t_{Co}, in Co/Cu/Co nanostructured layers was investigated. The curve in Fig. 1 shows that GMR attains almost 10% when the Co layer thickness increases from 2 to 6 nm with a further drop and gradual decrease along the layer thickness increase up to 20 nm. The results are comparable with those calculated using a theoretical approach on similar

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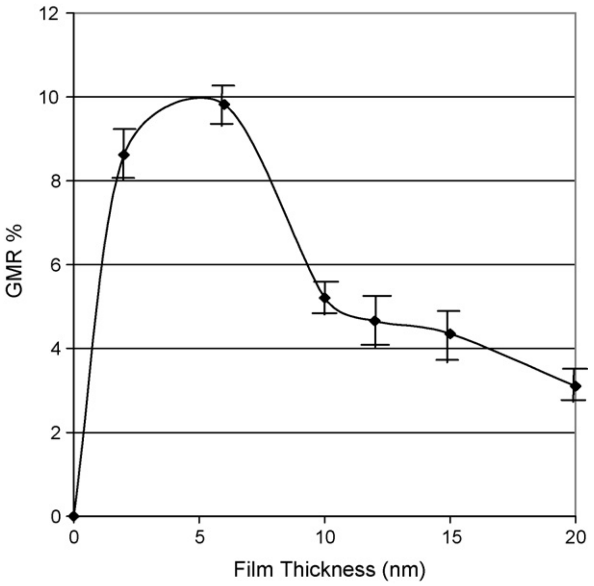

Fig. 1. GMR% vs. cobalt film thickness.

Co/Cu/Co samples [3]. This initial change ($t_{Co} \leq 6$ nm) is due to an increase of the amount of ferromagnetic spins in the ferromagnetic layers caused by the ferromagnetic exchange interactions associated with the increase of ferromagnetic Co layer thickness [4]. The average dimension of Co particles and magnetic field efficiency are also increasing as a consequence of increasing t_{Co}. Further observation at higher thicknesses ($t_{Co} > 6$ nm) shows a decrease in GMR due to the decrease in the antiferromagnetic interactions existing between the two Co layers near the Cu layer [4]. An increase of Co thickness contributes to a different saturation state and its resistance, thus, enhancing GMR [3].

3.2. *Effect of annealing*

The effect of annealing temperatures was studied and the result is shown in Fig. 2 for the temperature range 200–450 °C and a fixed duration of 2 h. It seems that GMR increases almost steadily from 9.8% to 23.7% over the range of 27–400 °C, followed by a rapid falls beyond this point and toward 450 °C. This can be attributed to the recrystallization of Co and Cu occurred during the early state of annealing, and both species become soluble to each other as they reach 400 °C. In doing so, the Co atoms gradually precipitate from the Cu matrix and form Co clusters. When the annealing temperature exceeds 400 °C, Co particles become larger and result in the appearance of ferromagnetic interactions between larger Co particles. The results obtained in this study are similar to those predicted using Monte-Carlo simulation, where an optimum GMR occurred at around 400 °C [5,6].

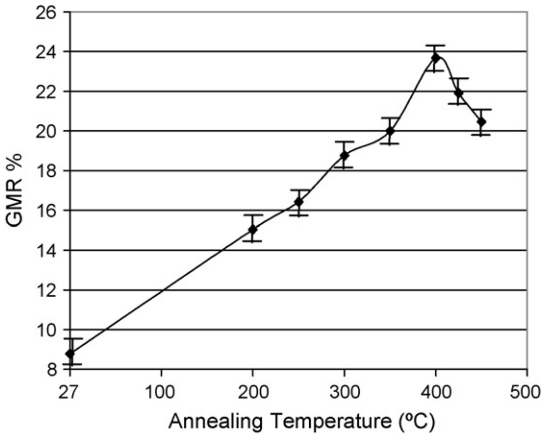

Fig. 2. GMR% vs. annealing temperature.

3.3. *Effect of Co/Cu bilayer*

The dependence of GMR on the number of bilayers, n, for samples with (Co/Cu) × n structures was also investigated. The thicknesses of Co/Cu layers were set at 6.0/2.5 nm and the deposition rate was fixed at 0.06 nm/s. Seven sets of samples, with $n = 3$, 5, 7, 8, 9, 10, and 15 have been prepared and tested for this experiment. In case of non-annealed samples (Fig. 3a) the GMR increases for $n < 5$, followed by a further decrease within the range $5 < n < 9$, and another increase up to 12.5% at $n = 15$. According to Smadar and Nathan [7], when the magnetic fields are applied in plane to the sample, the total resistance is not equal to the sum of resistances of all segments, but it is a rather increase in resistivity with increasing number of bilayers, i.e. $R_{total} = R_1 + R_2 + R_3$. For annealed samples (400 °C) shown in Fig. 3b the mode remains unchanged, but it appears to be more pronounced and shifted upward with GMR exceeding 30%. This result suggests that GMR can be further improved with a combined number of bilayers and annealing.

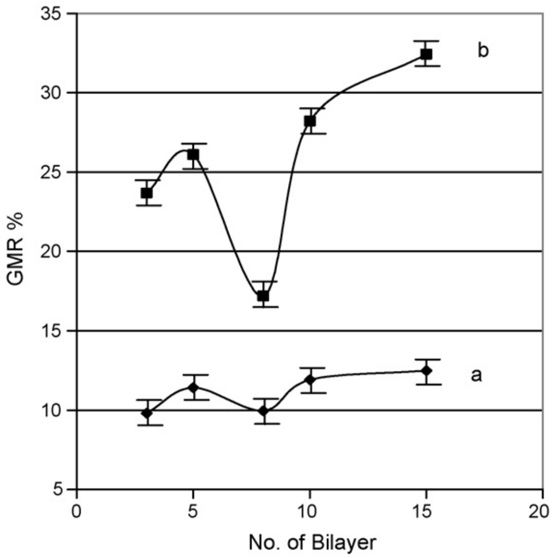

Fig. 3. GMR% vs. number of Co/Cu bilayer for (a) as-prepared and (b) annealed samples.

3.4. *Effect of argon working pressure*

The effect of argon gas pressure introduced during the sputtering process reveals an interesting feature, mainly for the range between 4.8 and 2.3 mTorr, when the chamber pressure and deposition rates were fixed at 9×10^{-7} Torr and between 0.03

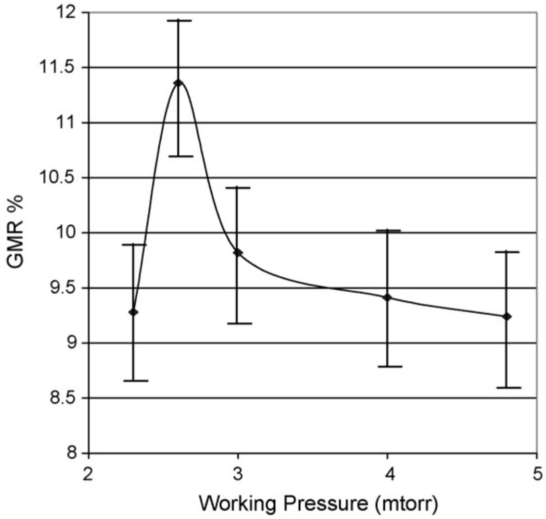

Fig. 4. GMR% vs. argon gas pressure.

and 0.1 nm/s, respectively. The curve in Fig. 4 shows a rapid increase in GMR from 9.3% to a maximum of 11.4% when the working pressure is increased from 2.3 to 2.6 mTorr. After this turning point the curve is observed to decrease rapidly down to 9.6% followed by a further steady drop to 9.2% at 4.8 mTorr. Following earlier studies on similar samples [5], such a change in GMR may be attributed to structural changes set by the argon pressure which responsible for the formation of different grain sizes of target materials deposited on the substrate. It is possible that a large amount of Co crystal is formed during the deposition at high argon pressures and creating a very small superparamagnetic grains that may not contributing to GMR due to magnetization of the sample [8], this causes reduction in GMR.

4. Conclusions

It was observed that the GMR effect in Co/Cu/Co nanostructures was found to be dependent of experimental conditions. The Co layer thickness plays a significant role in increasing the GMR response, but essentially restricted to 6 nm due to changes in magnetic behaviour. Annealing up to 400 °C was another key factor for improving GMR. Significant effects of Co/Cu bilayer and argon pressure were also observed; the former suggested $n > 10$ whilst the latter recommended an argon pressure of 2.6 mTorr for optimum GMR%.

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