STRUCTURAL, MAGNETISATION AND MAGNETORESISTANCE STUDIES OF {Fe(1 nm)/Cr(2 nm)} MULTILAYERS

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Abstract. The sputtered $\{Fe(1\ nm)/Cr(2\ nm)\}_{70}$ multilayers have been investigated by means of the X-ray diffraction, magnetisation and magnetoresistance. The multilayer structure of the as-deposited film is evidenced by the existence of two separate *bcc*-Fe and *bcc*-Cr Bragg peaks. This multilayer structure remains in heat treatments up to T_A = 425°C and is destroyed to form the heterogeneous ones at T_A = 500°C. Room temperature magnetoresistance $\Delta R/R\{= (R(H) - R(0))/R(0)\}$ equals to 0.8 %. $\Delta R/R$ increases with increasing T_A and reaches a maximum value of about 3.5 % at T_A = 425°C. Similar tendency is observed when fixing T_A = 350°C and increasing the annealing time. This enhancement of the magnetoresistance is associated to the broadening of the interfaces, leading to the reinforcement of the antiferromagnetic coupling between the Fe layers. This is in good agreement with the magnetisation data. At 77 K, a $\Delta R/R$ value as large as 10 % was obtained. Low temperature $\Delta R/R$ data is attributed to the temperature dependence of Fe-layer magnetisation, but not to that of antiferromagnetic coupling.
Keyword: Multilayers, Giant Magnetoresistance, Magnetic coupling.

1. Introduction

Magnetoresistance (MR) is the change in electrical resistance (or resistivity) of a conductor in an applied magnetic field. In non-magnetic conductors the MR is associated to the Lorentz force exerted on the moving electrons and it is named as Ordinary Magnetoresistance (OMR). In ferromagnetic conductors, because of the spin-orbit coupling, the resistance depends on the angle between the magnetisation and the electrical current. This leads to the so-called Anisotropic Magnetoresistance (AMR). Giant Magnetoresistance (GMR) was discovered in 1988 in Fe/Cr multilayers [1], which was preceded by the discovery of the oscillating exchange coupling between the magnetic layers across a nonmagnetic layer. Antiferromagnetically coupled multilayers exhibit a high resistance, whereas ferromagnetically coupled ones show a smaller resistance. Nowadays, the mechanism of GMR has been clearly attributed to the spin-dependent scattering process. In this context, it is worth to mention following models of GMR: the Two Currents Model, the Model of Camley and Barnas, Other Semi-classical Models, Quantum Models and Theoretical Models of the Spin Dependent Scattering [2]. On the basis of the GMR effect, various types of devices, such as sensors, read heads, high-density magnetic random access memories etc. have been developed (see e.g [3]).

It is well known that the origin of GMR is the spin-dependent scattering of conduction electrons. However, there is a controversy on the exact location of the scattering centers. They can occur at the interfaces and/or in the bulk of the ferromagnetic layers. In addition, together with applications, there arises the question to what extent is the GMR at elevated temperatures. Recently, the answers for these questions were partly given by Duc et al. [4]. They showed that in Fe/Cr multilayers, scattering centers seems to locate at the interfaces. The aim of this paper is not only to confirm the above-mentioned answer but also to discuss the role of the antiferromagnetic coupling on the thermal variation of GMR.

2. Experimental

$\{Fe(1\ nm)/Cr(2\ nm)\}_{70}$ mutilayers was prepared by using a triode rf-magnetron sputtering system in the University of Brest (France). The substrates were glass laminae with a nominal thickness of 1.0 mm. Both target and sample holders were water-cooled during the sputtering process. The samples were annealed at temperatures $T_A = 350, 425$ and 500°C for 1 hour in vacuum of 10^{-4} mbar. The annealing at 350°C was also carried out for different annealing times of 1 and 3 hours, respectively.

The multilayer structure of the films was investigated by X-ray diffraction using Cu-K_α radiation (Siemens D5000 diffractometer).The magnetoresistance was measured by a four-point technique in a current-in-plane configuration and in a longitudinal geometry at various temperatures from 77 to 300 K. The magnetisation measurements were performed in fields up to 1.3 T using a vibrating sample magnetometer (VSM).

3. Experimental results and discussions

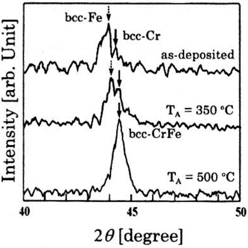

Fig. 1: X-ray diffraction spectra of as-deposited and 350, 500 °C annealed-Fe/Cr multilayers.

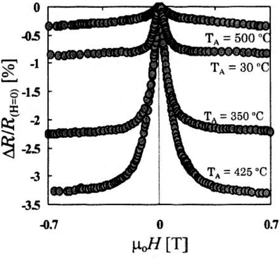

Fig. 2: Room temperature GMR data for Fe/Cr multilayers at different annealing temperatures.

The X-ray diffraction parttens of both the as-deposited and annealed samples are shown in figure 1. The obtained results show evidence that the Fe and Cr individual layers are formed in a multilayer-type structure in the as-deposited sample. This structure remains at annealing temperatures up to T_A= 425°C. The X-ray diffraction patrons of the sample annealed at T_A = 500°C, however, exhibits only a broad peak. This indicates that the layer structure was destroyed and a heterogeneous structure was formed.

Presented in figure 2 is the room temperature GMR ratio $\Delta R/R(= (R(H) - R(0))/R(0)$, where $R(0)$ and $R(H)$ are the resistance of the sample in zero field and in the applied field $\mu_o H$, respectively) for the as-deposited and one-hour annealed Fe/Cr multilayers. The results show that the saturation GMR increases with increasing annealing temperature up to T_A = 425°C.

In addition, the magnetoresistive susceptibility of these samples is almost constant with increasing $T_A : \xi_R (= (\Delta R/R)/\mu_o H) \approx 13\% T^{-1}$. Thus, the saturation field increases. A maximal magnetoresistance ratio $\Delta R/R$ of 3.5 % is reached in the sample annealed at T_A = 425 °C. This tendency does not remain with further increasing T_A: for the sample annealed at 500 °C, the GMR ratio drops to 0.4 % only.

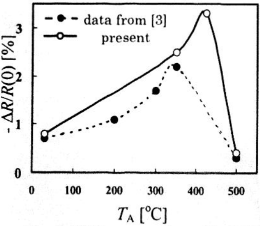

Fig. 3: GMR measured at $\mu_o H$ = 0.3 T vs. T_A for Fe/Cr multilayers.

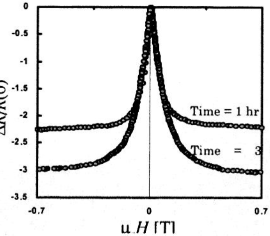

Fig. 4: Room temperature GMR curves for sample annealed at 350 °C with different annealing times.

Figure 3 + 4

A similar behavior was recently report by Duc et al. [4]. For a comparison in more details, the plot of $\Delta R/R$ versus T_A is presented in figure 3. It is worthwide to mention here that data obtained from different samples are strongly support to each other. Our data, however, show that the optimum annealing temperature for GMR is of T_A = 425°C. The enhancement of GMR with increasing T_A can be understood as follows. The annealing at $T_A \leq 425°$ C is usually thought to make a break-up of the layers due to the interdiffusion and to broaden of the interfaces [5]. This leads to an increasing interface/volume fraction. The enhancement of the GMR with increasing T_A, thus, is associated to the interface expansion. This finding suggests that the scattering centers locate at interfaces.

The annealing at 500°C, however, is attributed to a further break-up of the layers, leading to the formation of heterogeneous structures of small particles. This was already proposed by Flores et al. [6]. X-ray diffraction results of the sample annealed at T_A = 500°C strongly support above arguments. At $T_A \leq$ 425°C, the stability of individual Fe- and Cr-layers is well evidenced by the existence of the separated (110) *bcc*-Fe and (110) *bcc*-Cr reflections. At T_A = 500 °C, however, a broadened Bragg peak is observed, indicating the formation of fine particles of the *bcc*-CrFe phases (see fig. 1). In this state, the antiferromagnetic coupling breaks down and the ferromagnetic one is established. The system, thus, can no longer switch between an antiparallel (ground state) and parallel (applied field) aligned state.

The GMR of the samples annealed with different annealing times of 1 and 3 hours at 350°C is presented in figure 4. The figure shows that the GMR ratio increases slightly with increasing the annealing times. This finding indicates that not the duration but the temperature of the annealing is effective to the interdiffusion.

Figure 5 presents the GMR ratio measured at low temperatures and in an applied field up to 0.3 T for the sample annealed at T_A = 425°C. It is clearly seen that the GMR ratio increases linearly with decreasing temperature and reaches a value as large as 10 % at 77 K. This GMR ratio is about three times larger than that measured at room temperature. This enhancement of the GMR is usually thought to relate to the strength of the antiferromagnetic coupling at low temperatures. The corresponding hysteresis loops presented in figure 6, however, show an almost similar antiferromagnetic behaviour. This means that the antiferromagnetic coupling is temperature independent. The enhancement of GMR at low temperatures, thus, may be attributed to the thermal variation of magnetisation.

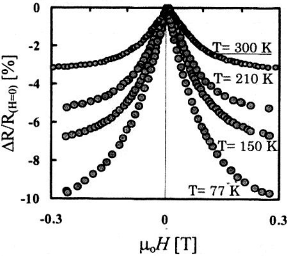

Fig. 5: GMR ratio of sample annealed at 425 °C measured at low temperatures.

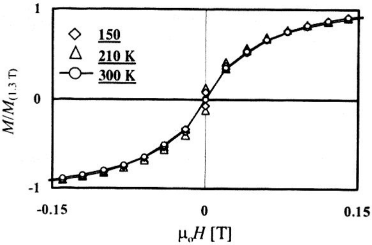

Fig 6: Hysteresis loops of the Fe/Cr multilayer samples at low temperatures.

4. Conclusions

Our GMR investigations of Fe/Cr multilayers confirm that the scattering centers are located at the interfaces. The annealing plays an important role in enhancing the antiparallel coupling between the Fe layers leading to the increase of the GMR ratio. The enhancement of the low-temperature GMR, however, is attributed to the thermal variation of the magnetisation.

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References

1. A. Barthlmy, A. Fert and F. Petroff, in: Handbook of Magnetic Materials, Ed. K.H.J. Buschow, *Elsevier Science,* vol. **12**(1999), 1-96.
2. A. Fert and P. Bruno, *Ultrathin Magnetic Structures,* Eds. J.A.C Bland and B. Heinrich, Springer-Verlag Berlin Heidelberg, vol. II(1994), 83-117.
3. K.Y. Kim and J.E. Evetts, *J. Magn. Magn. Mater.*, **92**(1999), 198-199.
4. N.H. Duc, N.A. Tuan, N.T. Nam, N.H. Sinh, J. Teillet, A. Fnidiki, *Physica B,* 2003, in press.
5. M. Hecker, D. Tietjen, D. Elefant and C.M. Schneider, *J. Appl. Phys.*, **89**(2001), 7113.
6. W.H. Flores, S.R. Teixeira, J.B.M. da Cunha, M.C.M. Alves, H. Tolentino, A. Traverse, *J. Magn. Magn. Mater.*, **233**(2001), 100.