

Giant Magnetoresistance of Mechanically Alloyed Fe_{7.5}Co_{22.5}Ag₇₀ Mixed with Hard Magnetic Material

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ABSTRACT

Giant magnetoresistive Fe_{7.5}Co_{22.5}Ag₇₀ was alloyed by ball milling for 60 hours. Subsequently, samarium-cobalt (5% by weight) was added to the alloy and the milling continued for another 15 minutes. The inclusion of hard magnetic SmCo₅ was evidently not detriment to giant magnetoresistance (GMR). At room temperature, the bulk mechanical alloy exhibited coercivity of 500 Oe and 1.4 % GMR with modest anisotropic magnetoresistance. GMR increased linearly with decreasing temperature from 300 K to 143 K because the alloy's resistance decreased at low temperature. Significant relaxation time of magnetic moments was observed in magnetoresistance curves as a lag of resistance change behind the field change. **Key words:** spin giant magnetoresistance, mechanical alloy, ball milling, single domain particles, dependent scattering

INTRODUCTION

In the past decade, the interest in giant magnetoresistance (GMR) has rapidly grown because of its applications in magnetic sensing and recording. When subjected to a magnetic field, giant magnetoresistive materials exhibit large decrease in electrical resistance which ranges from a few percent to as much as 80 percent. GMR was discovered in magnetic multilayers consisting of ferromagnetic layers interspersed with non-ferromagnetic layers (Baibich *et al.*, 1988). With non-ferromagnetic partitions, an applied magnetic field is able to modify the relative magnetic orientation of ferromagnetic regions from an anti-parallel configuration to a parallel configuration. This leads to a decrease in electrical resistance in the magnetic field described by a simple resistor model in Figure 1. The origin of GMR is based on

the relationship between the spin dependent scattering and the relative magnetic orientation. The spin dependent scattering is a difference between scattering rates of spin-up and spin-down electrons in ferromagnetic materials. In the parallel configuration (Figure 1b), spin-up electrons have small scattering rates in all cobalt layers. According to Mott's two channel current model, spin-up and spin-down electrons carry electrical currents independently like two resistors connected in parallel. The parallel configuration can then be considered as a short circuit and its resistance is lower than those of the anti-parallel configuration (Figure 1a).

GMR is also observed in magnetic granular structures. Granular GMR structures consist of nanoscale ferromagnetic particles dispersed in a non-ferromagnetic matrix. Examples are granular films (ferromagnetic granules in non-ferromagnetic

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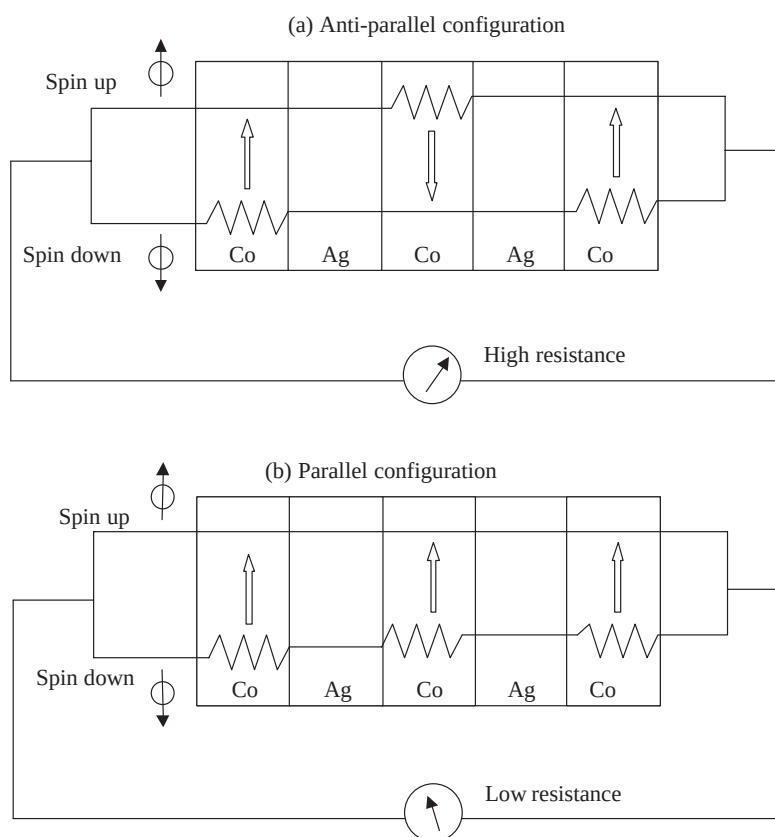


Figure 1 Giant magnetoresistive multilayers consist of ferromagnetic layers (e.g. cobalt) interspersed with non-ferromagnetic layers (e.g. silver). In zero magnetic field, successive cobalt layers may have their magnetizations aligned anti-parallel (magnetizations point in the opposite direction). In an applied magnetic field, the relative magnetic orientation is switched from an anti-parallel configuration to a parallel configuration (magnetization of all cobalt layers are in the same orientation).

films) and mechanical alloys (Figure 2). The latter offers an easily implemented alternative to multilayered GMR. Mechanical alloys may be produced by mixing ferromagnetic powder (such as cobalt and iron) with non-ferromagnetic powder (such as silver). The basic requirement is that the magnetic and non-magnetic materials are immiscible. This mixture was spun in a container loaded with grinding balls. The impact of the balls on the elemental powders leads to a mixture of the two materials on the atomic scale. Since these constituent materials are immiscible, they form no

solid solution and the structure can be best described as nanoscale ferromagnetic particles embedded in a non-ferromagnetic matrix. Coey *et al.* (1994) observed 10% GMR in $\text{Co}_{30}\text{Ag}_{70}$ in 22 kOe field at 4.2 K and 5.7% GMR in $\text{Fe}_{30}\text{Ag}_{70}$ in 80 kOe field at 4.2 K was reported by Gomez *et al.* (2001).

In this paper, magnetotransport properties of $\text{Fe}_{7.5}\text{Co}_{22.5}\text{Ag}_{70}$ mechanical alloy with an addition of 5 wt.% SmCo_5 are examined. The inclusion of a hard magnetic SmCo_5 is aimed to study its effect on GMR. The internal field produced by hard magnetic materials could affect the

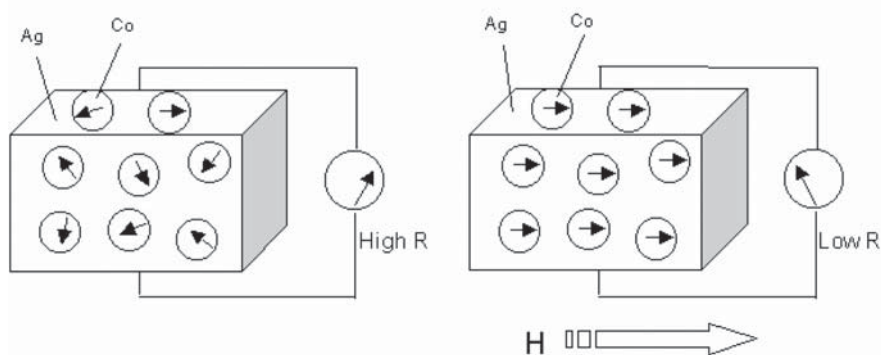


Figure 2 In giant magnetoresistive mechanical alloys, an applied magnetic field may change the relative magnetic orientations from a random configuration in zero field (left) to an aligned configuration (right) and gives rise to GMR.

magnetization rotation of other magnetic particles and hence magnetoresistance characteristics might be modified.

MATERIALS AND METHODS

The mechanically alloyed $\text{Fe}_{7.5}\text{Co}_{22.5}\text{Ag}_{70}$ with 5 wt.% samarium-cobalt (SmCo_5) was prepared by a ball milling technique at University College, London. Fine iron, cobalt and silver powders were mixed together with the atomic ratio 7.5:22.5:70 in a syalon vial containing grinding steel balls. The vial was sealed and then spun for 60 hours. SmCo_5 (5% by weight) was then added to the vial and the milling continued for 15 minutes. After the milling, the alloy powder was compressed in a mold under a high pressure of 230 MPa to produce disk-shaped bulk samples. No heat treatment was given to modify the structure of alloy. In the magnetoresistance measurements performed at Clarendon Laboratory in Oxford, the holder whose 4 spring-loaded pins made contacts with the sample (Figure 3) was connected to the end of a measurement probe. The probe was then inserted in a cryostat between the poles of electromagnet. The four-point resistance measurement was performed with a microohmmeter using a test dc current of 10 mA. The magnetic field was applied in a plane of the

sample, perpendicular or parallel to the current. The sample resistance may therefore be plotted as a function of the magnetic field. A diagram of the measurement set-up is shown in Figure 4.

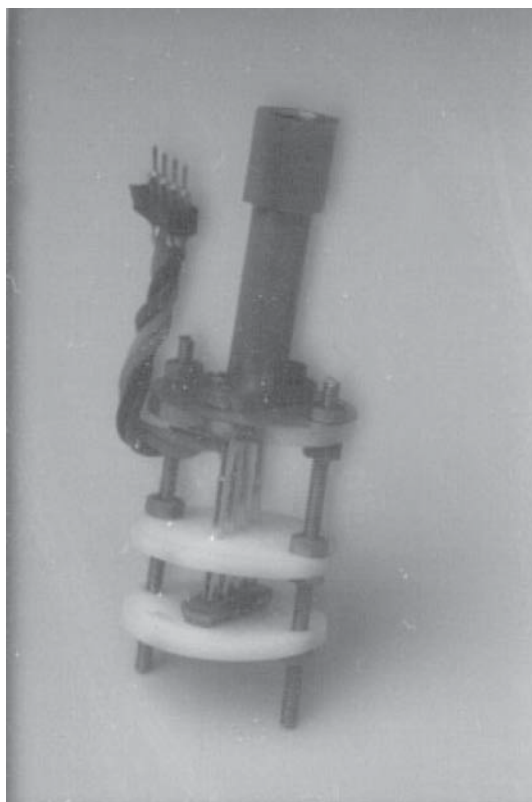


Figure 3 The mechanical alloy in a sample holder.

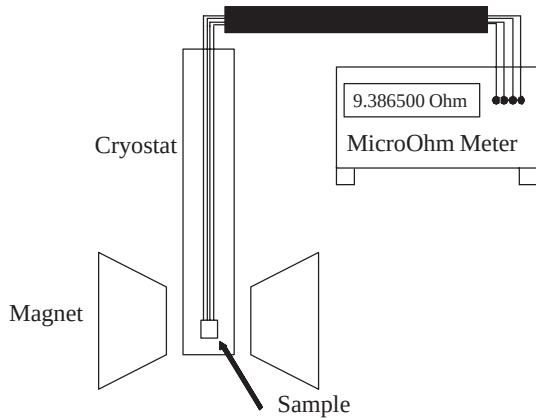


Figure 4 Magnetoresistance measurement set-up.

RESULTS AND DISCUSSION

A magnetization measurement by a vibrating sample magnetometer (VSM) revealed that the alloy had a coercive field of about 500 Oe and the magnetization saturated in a field of 5 kOe (Figure 5). In magnetoresistance measurements at 143, 199, 255 and 300 K, the alloy exhibited a decrease in electrical resistance when the magnetic field increased from zero to 16 kOe. The results confirmed that heat treatment after the ball milling was not compulsory. A typical magnetoresistance (MR) curve is shown in Figure 6. The peak resistance occurred at 2 kOe and -2 kOe corresponding to a random configuration in which the coercive field randomized all magnetic moments. However, this value did not coincide with the coercive field observed in the magnetization curve. This discrepancy is attributable to a relaxation time of the magnetic moments and this effect will be discussed later in this section. When the field increased beyond the coercivity, the magnetic moments gradually aligned in the field direction resulting in a decrease in resistance. A rapid reduction occurred at low field between 2-5 kOe and this should be a regime that most moments re-oriented in the field. When the field was higher than 5 kOe, the resistance decreased slightly indicating

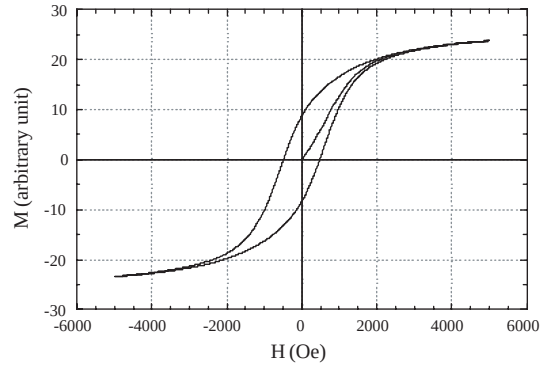


Figure 5 Room temperature magnetisation curve of the mechanical alloy.

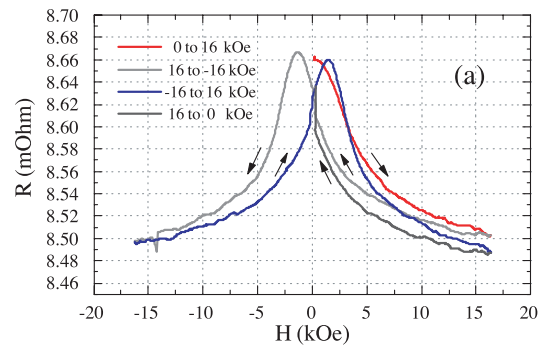
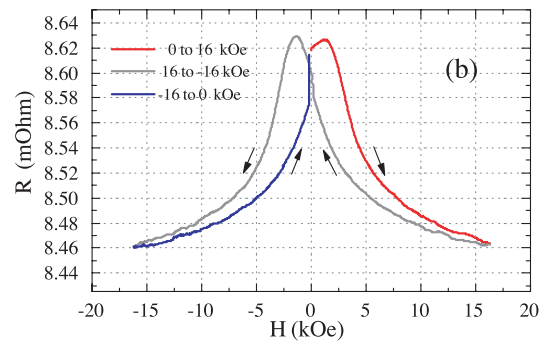


Figure 6 Giant magnetoresistance at 199 K is (a) 1.92% when a 10 mA current is parallel to the field and (b) 1.95% when the current is perpendicular to the field. A sweep rate is 16 kOe in 20 minutes.

that most moments had already lined up. This result agreed with the magnetization curve in which the alloy approached the saturation in 5 kOe field. The further decrease at higher field was possibly due to a disorder that froze some magnetic moments and only the large magnetic field was able to align them.

From MR results, it was evident that the inclusion of 5% by weight hard magnetic materials was not detriment to GMR. Furthermore, since the MR curve clearly reflects magnetic behaviors of the alloy's structure, one may expect to modify MR characteristics by varying percentage of hard magnetic materials. For example, an increase coercive field by the inclusion of hard magnetic materials should shift the most sensitive regime in MR curves to a higher field. In this way, characteristics of GMR devices may be tuned.

Repeat sweeps of magnetic field up and down gave rise to hysteresis in MR curves. Hysteresis behaviors observed in both magnetization and magnetoresistance curves indicated the existence of non-superparamagnetic single-domain particles. This corresponds to magnetic particle sizes of the order hundreds angstrom (Coey *et al.*, 1994). Multi-domain particles do not lead to GMR because conduction electrons may flip its spin during their transport between domains and as a result, the spin dependent scattering diminishes.

The percentage of MR may be defined as $100 \times (R_H - R_0) / R_H$ where R_0 and R_H are the resistance in zero field and the resistance in a magnetic field respectively. As seen in Figure 7, the magnitude of GMR increased linearly with decreasing temperature from 300 K to 143 K. This result could be very well explained by the linear increase in the resistance of alloy with temperature whereas the magnitude of $R_H - R_0$ remained fairly constant. To investigate the anisotropic magnetoresistance (AMR) contribution, the measurements at 199 K were performed with the current parallel and perpendicular to the in-plane magnetic field. About 1.9% MR was observed in both configurations proving that AMR contribution was insignificant.

Finally, measurements were performed with three different magnetic field sweep rates. In Figure 8, the sweep rate as fast as 16 kOe in 5 minute caused the largest deviation of the peak from zero magnetic field and the lowest GMR. This was a relaxation time effect in which the magnetic moments took a substantial time to response to the applied magnetic field. This slow response time

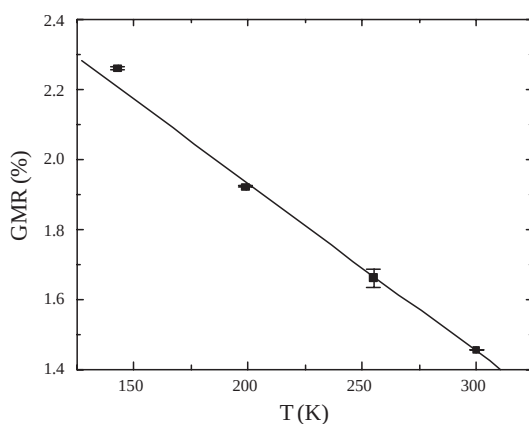


Figure 7 Giant magnetoresistance increases linearly with decreasing temperature. Measurements were performed with 10 mA current parallel to the field and a sweep rate of 16 kOe in 20 minutes.

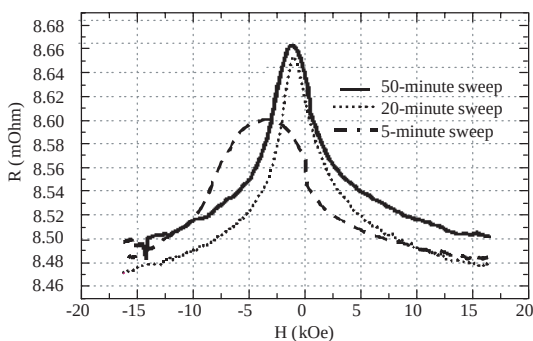


Figure 8 Giant magnetoresistance curves at 199 K with three different magnetic field sweep rates (16 kOe in 5, 20 and 50 minutes). The relaxation time of the magnetic moments results in different characteristics for different sweep rates.

resulted in a lag of the resistance change behind the field change in MR curves and prevented such alloys from being implemented as fast switching devices.

CONCLUSION

Giant magnetoresistance (GMR) is a new frontier of studying and implementing magnetism and magnetic materials because it combines interesting theoretical aspects with wide range of applications. In this paper we demonstrated that giant magnetoresistive materials could be fabricated with a relatively simple process and hard magnetic materials might be added to the alloy. The mechanically alloyed $\text{Fe}_{7.5}\text{Co}_{22.5}\text{Ag}_{70}$ with SmCo_5 exhibited temperature dependent GMR. GMR of 1.4-2.2% was observed between room temperature and 143K with modest AMR contribution. The relaxation time of magnetic moments was observed. The results suggest possible applications as magnetic sensors and magnetic read heads. In the implementation, the substantial effect at room temperature is its major advantage but the slow switching time remains a drawback.

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