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Magnetoresistance in glass-coated Fe–Ni–Cu microwires

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Glass-coated Fe–Ni–Cu microwires were prepared by Taylor's technique. X-ray diffraction data show patterns corresponding to fcc Cu. Negative magnetoresistance has been observed, which reaches 8.15% at 77 K and 6.35% at 300 K in magnetic field of 9.0 T. There is no significant difference between $I_{\perp H}$ and $I_{\parallel H}$ configurations. Both dc and low frequency ac ($f < 1$ kHz) measurements exhibit essentially the same values of magnetoresistance. The observed magnetoresistance in the Fe–Ni–Cu microwires is of the same origin found in the granular giant magnetoresistance materials and is distinguishable from the giant magnetoimpedance commonly seen in soft magnetic microwires. © 1999 American Institute of Physics.

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I. INTRODUCTION

The discovery of negative giant magnetoresistance (GMR) in Fe–Cr magnetic multilayers by Baibich *et al.*¹ and the subsequent finding that GMR occurs in many other multilayer ultrathin magnetic film systems^{2–5} have attracted much attention. GMR was also found in granular structures where metallic ferromagnetic nanoparticles are dispersed in a nonmagnetic metal matrix.^{6,7} Granular systems exhibiting GMR have been made applying a variety of sample preparation techniques including thin film deposition and mechanical alloying.⁸ In recent years magnetic properties of glass-coated magnetically soft microwires prepared by Taylor's technique have been studied widely.⁹ Most recently, kilometer-long glass-coated Fe–Ni–Cu and Fe–Co–Cr microwires have been prepared and their magnetic properties have been studied.¹⁰ The as-cast Fe–Ni–Cu microwires without further annealing exhibit soft magnetic properties and those annealed at $T > 600$ °C experience significant magnetic hardening. The magnetoresistance in these glass-coated microwires has, however, not been studied. In this article, we report the magnetoresistance in glass-coated soft magnetic Fe–Ni–Cu microwires prepared by Taylor's technique.

II. EXPERIMENTS

The Fe–Ni–Cu alloy (Fe 20%, Ni 20%, and Cu 60%) was prepared by induction melting appropriate amounts of the constituent elements Fe, Ni, Cu (Aldrich). It was then put into a Pyrex glass tube and melted using an induction heating coil. A continuous kilometer-long glass-coated microwires was extracted from the lower end of the glass tube.⁹ The uniformity of the diameter of the wire was checked by a contactless high-frequency technique. Some segments of the wire were examined with a conventional optical microscope (Carl Zeiss). The cross section was about 5 μm in diameter. X-ray diffraction patterns was recorded with a Philips X'Pert diffractometer using $\text{Cu } K\alpha$ radiation. The magnetoresistance was measured at 77 and 300 K with a Physical Property Measurement System (Quantum Design) using four-

probe method. Both dc and ac (frequency up to $f = 975$ Hz) measurements were conducted in applied magnetic fields $0 < H < 9$ T.

III. RESULTS AND DISCUSSION

Figure 1 shows the x-ray diffraction pattern of the as-cast Fe–Ni–Cu (Fe 20%, Ni 20%, and Cu 60%) microwires. The three major peaks are those of the (111), (200), and (220) reflections of fcc Cu lattice. The peaks are slightly shifted to higher degrees, which indicates that Ni and, perhaps, some Fe are dissolved in the Cu lattice leading to smaller lattice parameter. While Ni is completely soluble in Cu, Fe is virtually insoluble in Cu under equilibrium condition. However, the rapid quenching applied in our experiments may extend the solubility of Fe in Cu. The fact that GMR exists in the as-cast samples (see below) suggests that some of the Fe atoms should remain in their elemental form: amorphous and nanocrystalline. This is also seen from the x-ray diffraction pattern in Fig. 1. The microstructure of the

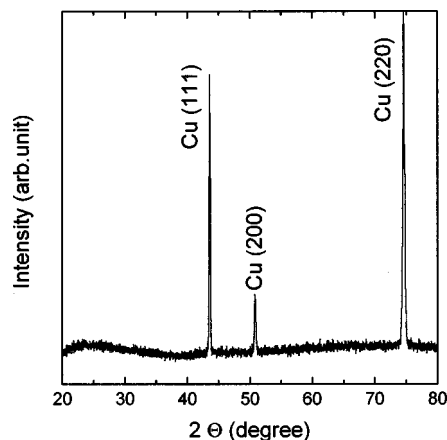


FIG. 1. X-ray diffraction pattern of the as-cast Fe–Ni–Cu (Fe 20%, Ni 20%, and Cu 60%) microwires.

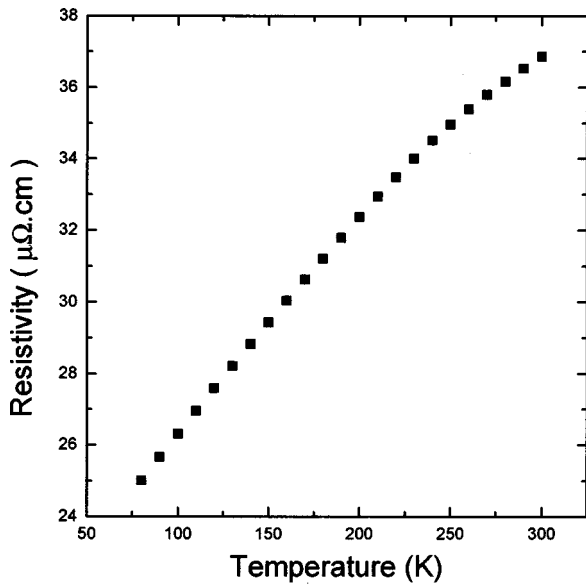


FIG. 2. Resistivity of as-cast Fe-Ni-Cu microwires as a function of temperature from 77 to 300 K.

Fe-Ni-Cu resembles those of GMR granular materials in which magnetic Fe nanoparticles are imbedded in predominantly nonmagnetic Cu matrix.⁸

The Fe-Ni-Cu microwires are magnetically soft. Both as-cast microwires and those heat treated at 500 °C for an hour have typical coercivity of a few Oersted. Samples heat treated above 600 °C have much higher coercivity. Our magnetotransport study concentrates on the soft Fe-Ni-Cu microwires both as-cast and subsequently heat treated.

Figure 2 shows the resistivity of as-cast Fe-Ni-Cu microwires as a function of temperature from 77 to 300 K. Metallic resistivity is evident. DC magnetoresistance was first measured at room temperature using an electromagnet which can reach a maximum field of 1.1 T. Figure 3 shows

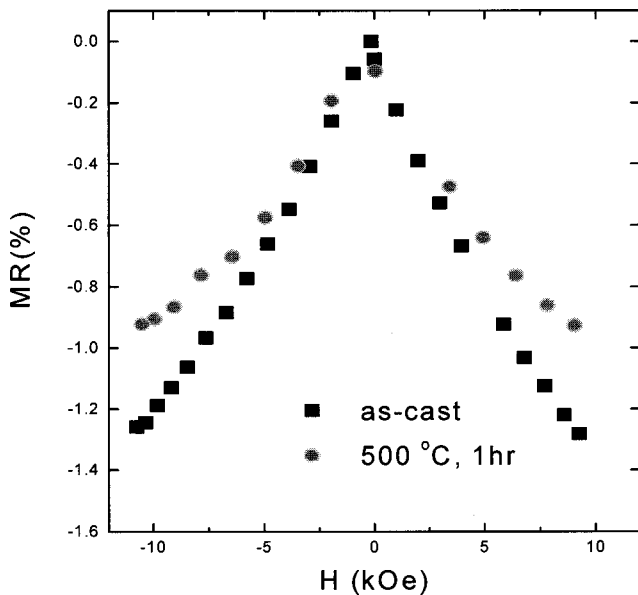


FIG. 3. Room temperature magnetoresistance vs applied field for both as-cast and subsequently annealed Fe-Ni-Cu microwires.

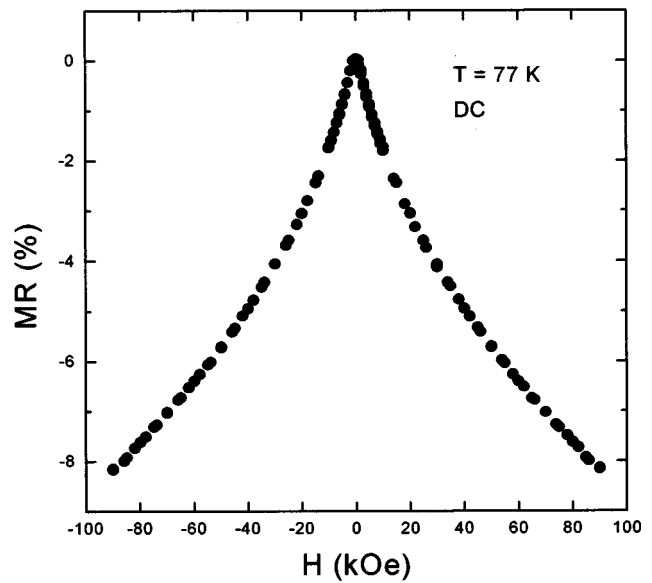


FIG. 4. Magnetoresistance of the as-cast microwires taken at 77 K from -9 to 9 T. Magnetoresistance reaches 8.15% in magnetic field $H=9$ T.

the magnetoresistance, defined as $MR = [\rho(H) - \rho(0)] / \rho(0)$, versus applied field for both as-cast and subsequently annealed Fe-Ni-Cu microwires. The magnetoresistance is about 1.3% at 300 K in a field of 1 T for the as-cast sample. Measurements have been carried out with the current both parallel to the applied field and perpendicular to the field. Both orientations show negative magnetoresistance of the same magnitude. This is characteristic of GMR and it can be ruled out that the observed magnetoresistance arises from anisotropic magnetoresistance (AMR). The as-cast sample was subsequently annealed for 1 h at 500 °C. At this temperature Fe particles, which is responsible for the spin-dependent scattering, grow significantly in size effectively

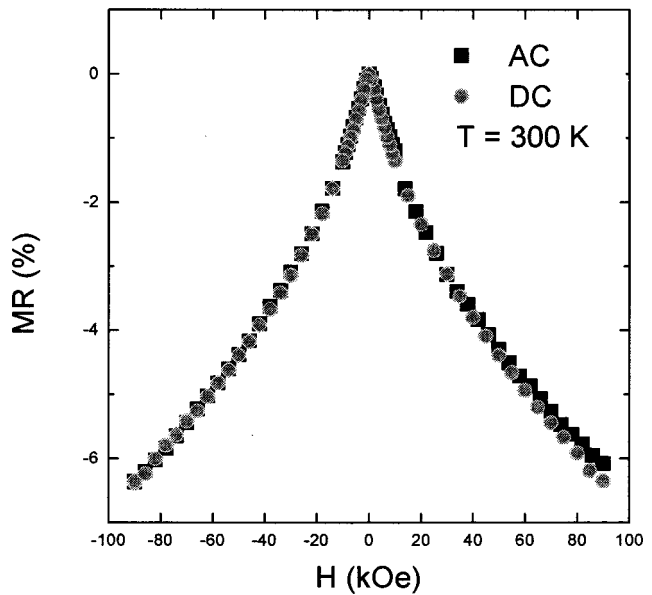


FIG. 5. dc and ac ($f=975$ Hz) magnetoresistance of the as-cast microwires measured at 300 K.

reducing the scattering probability and thus reducing the GMR. Magnetoresistance decreases to 0.9% for the annealed sample (Fig. 3). The effects of annealing at the mentioned temperature on the particle size have been well documented, for example, see Ref. 11.

Shown in Fig. 4 is the data of magnetoresistance of the as-cast microwires taken at 77 K. Magnetoresistance reaches 8.15% in a magnetic field $H=9$ T. The observed magnetoresistance shows on indication of saturation in such a high field. As temperature increases to 300 K the magnetoresistance decrease to 6.35% (Fig. 5).

AC magnetoresistance was measured at room temperature from 1 to 975 Hz. AC magnetoresistance taken at 975 Hz is shown in Fig. 5 along with the dc data. There is no observable frequency dependence of the magnetoresistance over the frequency range used. It should be pointed out that the GMR observed in our Fe–Ni–Cu microwires is distinct from the giant magnetoimpedance (GMI) found in amorphous and nanocrystalline soft magnetic microwires.^{12,13} GMI arises from a combination of skin effect and strong field dependence of circumferential magnetic permeability associated with circular domain wall movements. It diminishes at zero frequency and depends on the orientation of the magnetic field relative to the current. The effect is seen in very low field. These are not characteristic of the Fe–Ni–Cu microwires presented in this article.

IV. CONCLUSIONS

The magnetotransport properties of glass-coated Fe–Ni–Cu microwires prepared by Taylor's technique have been studied. GMR observed in the microwires originates from the spin-dependent scattering of electrons by the Fe nanoparticles imbedded in the nonmagnetic Cu-rich matrix. Negative magnetoresistance reaches 8.15% at 77 K and 6.35% at 300

K in a magnetic field of 9.0 T. There is no significant difference between $I \perp H$ and $I \parallel H$ configurations, which is characteristic of GMR. The observed magnetoresistance in the Fe–Ni–Cu microwires is distinguishable from the giant magnetoimpedance commonly seen in soft magnetic microwires. Upon annealing the sample at 500 °C for an hour, the magnetoresistance decreases. The effect of such heat treatment is the growth of the magnetic Fe nanoparticles which reduces the spin-dependent scattering responsible for the GMR.

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