Large magnetoresistance in an amorphous $Co_{68.1}Fe_{4.4}Si_{12.5}B_{15}$ ferromagnetic wire

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Magnetoresistance and magnetization of an amorphous ferromagnetic wire having nominal composition $Co_{68.1}Fe_{4.4}Si_{12.5}B_{15}$ are measured from 77 to 300 K and in the presence of tensile stress σ ($0 \le \sigma \le 240$ MPa). A large negative magnetoresistance is observed with accompanying hysteresis. The maximum change in resistance that occurs at small field increases from 8.8% at $\sigma=0$ to 12.2% at $\sigma=240$ MPa; this occurs at 300 K but the change is much reduced with the decrease of temperature. The results are discussed in terms of the scattering of carriers by a domain wall and it is suggested that the magnetization reversal is mainly due to coherent rotation.

INTRODUCTION

Magnetoresistance in the ferromagnetic state of a material depends on the distribution of domains and the orientation of the magnetization with respect to the direction of the measuring current. The magnetoresistance normally probes the spin disorder on the scale of the electron mean free path and the effective field that changes the electron trajectories. The spin-disorder scattering due to a spin-orbit interaction is small when the mean free path of the carrier is either small or large, compared to the characteristic length scale of the spin disorder. Similarly, the effect of an internal field within a domain is small when $\omega_c \tau < 1$, where ω_c and τ are the cyclotron frequency and the relaxation time of the carriers, respectively. Moreover, an excess resistance in the demagnetized state of a ferromagnet can arise as a result of a nonuniform current distribution that exists at a domain-wall boundary of a 180° domain.[1] The current lines traversing the wall bend at the wall because of the sign reversal associated with the Hall effect. In such a case the magnetoresistance shows a sensitive dependence of the domain pattern and its alteration. In an amorphous alloy of a transition-metal–metalloid system, the domain structure is mainly governed by the magnetostrictive anisotropy energy and so it can be altered by applying external stress. This makes the magnetoresistance a sensitive function of an external stress. The magnetoresistance in a ferromagnetic metallic glass sample with a ribbon shape is usually small (less than 1%).[2–5] The amorphous ferromagnetic wire exhibiting a large Barkhausen jump also exhibits a small magnetoresistance.[6] On the other hand, we observe a large magnetoresistance in an amorphous wire having nominal composition $Co_{68.1}Fe_{4.4}Si_{12.5}B_{15}$. The dependences of the magnetoresistance on the magnetic field, external tensile stress, and temperature are studied. By measuring the magnetization, it is found that the magnetoresistance is approximately correlated with the square of the component of the magnetization perpendicular to the current direction. Similar and even larger magnetoresistances are usually observed in metallic multilayer structures consisting of magnetic layers sandwiched between nonmagnetic layers and neighboring magnetic layers having an antiparallel magnetic-moment configuration.[7,8]

EXPERIMENTAL DETAILS

The sample used in the measurement is an amorphous wire with composition $Co_{68.1}Fe_{4.4}Si_{12.5}B_{15}$ having a diameter of 120 μm and length 10 cm. With this dimension the ballastic demagnetizing factor is estimated to be $\sim 3\times 10^{-7}$. The resistance is measured using the four-probe method with low-frequency (82 Hz) ac current and lock-in detection. The magnetic field is applied along the long direction of the wire so that the current and applied fields are colinear. The sample is so placed that the horizontal component of the Earth's magnetic field is perpendicular to the applied field. A varying tensile stress σ applied to the specimen is kept constant during the magnetoresistance measurement. The magnetization of the sample is measured in the presence of the longitudinal field and tensile stress using a fluxmeter (Walker Scientific MP-3D model). All the measurements are carred out within the range of $77 \le T \le 300$ K. The magnetoresistance (MR) results are then presented in terms of $\Delta\rho/\rho_0=[\rho(H)-\rho_0]/\rho_0$, where ρ_0 is the saturation resistivity at a field of 1 Oe. If the resistivity at 10 Oe is used as ρ_0, the observed MR ratios are larger by about 0.1%.

RESULTS AND DISCUSSION

The variation in electrical resistance of the wire with external stress arises because of changes in the electrical resistivity (ρ) and the dimensions of the wire and can be expressed as

$$\frac{\Delta R}{R}=(1+2\nu)\frac{\Delta L}{L}+\frac{\Delta\rho}{\rho}\ , \qquad (1)$$

where ν is Poisson's ratio, which can be taken as $\simeq \frac{1}{3}$ for Co-based amorphous alloys,[9] and the strain $\Delta L/L=\sigma|E$, E being Young's modulus. In the saturated state of magnetization, $\Delta\rho/\rho$, as a result of external stress, is found to be small and therefore for the large field region shows a stress variation of $\Delta R/R \simeq \frac{5}{3}\sigma/E$. The plot of $\Delta R/R$ vs σ [Fig. 1(a)] shows the linear variation with σ, and the

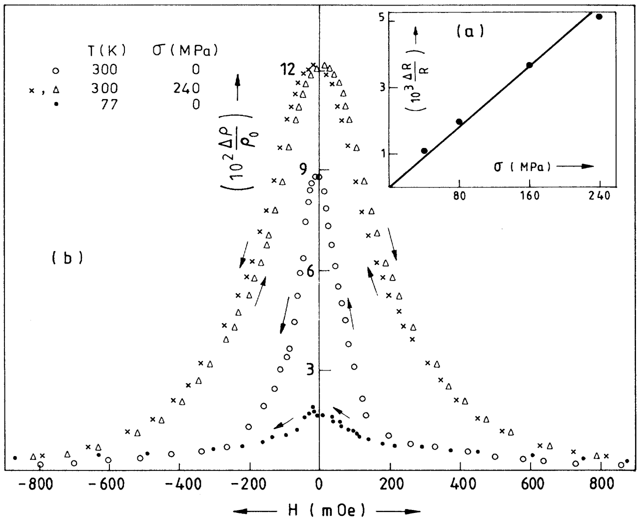

FIG. 1. (a) Variation of saturated magnetoresistance $\Delta R/R$ with the applied tensile stress σ at 300 K. (b) Magnetoresistance $\Delta\rho/\rho_0$ as a function of applied magnetic field H at temperature $T=300$ K with $\sigma=0$ (○) and $\sigma=240$ MPa (×,△) and at $T=77$ K, with $\sigma=0$ (●).

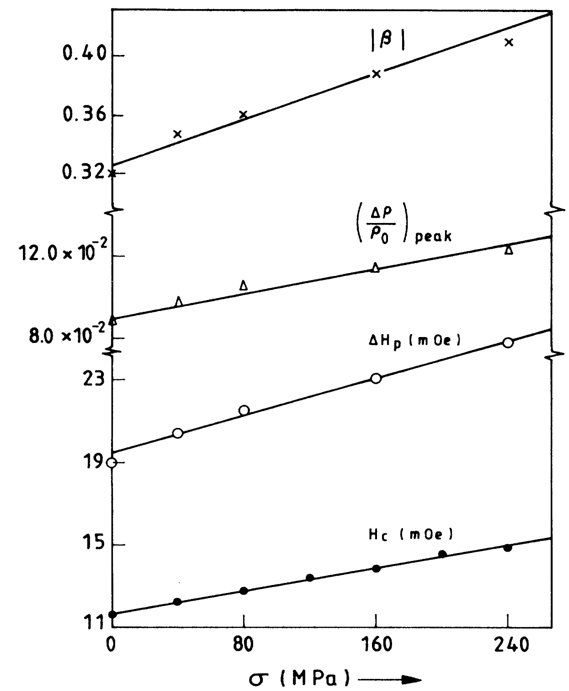

FIG. 2. Variation of the coercive field H_c (●), field separation between the two peaks in forward and reverse directions, ΔH_p (○), peak value of $\Delta\rho/\rho_0$, $(\Delta\rho/\rho_0)_{\text{peak}}$ (△), and the parameter $|\beta|$ (×) with the applied stress σ at 300 K.

value of E as follows from the slope of the curve comes out to be 156 GPa. This value is comparable to the magnitude of $E=175$ GPa of amorphous alloys having a similar composition $Co_{74}Fe_6B_{20}$.[10]

The magnetoresistance $\Delta\rho/\rho_0$ at 300 K, when the field is decreased from 0.8 to -0.8 Oe, is displayed in Fig. 1(b). The magnetoresistance at higher magnetic field (> 1 Oe) is small, whereas it increases sharply near zero field. The peak in $\Delta\rho/\rho_0$ appears at slightly negative field when the field is scanned from positive to negative values. On reversing the field, a hysteresis, which is prominent around the low-field region, is observed. A typical hysteresis of $\Delta\rho/\rho_0$ at 300 K and $\sigma=240$ MPa is presented in Fig. 1(b). The field separation (ΔH_p) between peaks in the forward and reverse directions and the maximum value of $\Delta\rho/\rho_0$ are increasing functions of the external stress (Fig. 2). The peak value of the magnetoresistance at 300 K changes from 8.8% at zero stress to 12.2% in the presence of 240 MPa tensile stress. On cooling the sample to 77 K, the magnetoresistance is much reduced.

The dc M-H variation of the longitudinally magnetized wire is shown in Fig. 3. Because of the small negative magnetostrictive coefficient, the growth of magnetization slows down in the presence of tensile stress. The coercive field H_c is slightly increased with external stress (Fig. 2), whereas the reverse is the case for the remanent magnetization.

The magnetoresistance in a ferromagnetic material arises from (i) an increase in the electron-scattering cross section due to the spin-orbit interaction and (ii) the effect of the internal field that curves the electron trajectory.[1] The spin-orbit interaction makes the electron-scattering cross section dependent on the direction of the current and magnetization within a domain. When the magneti-

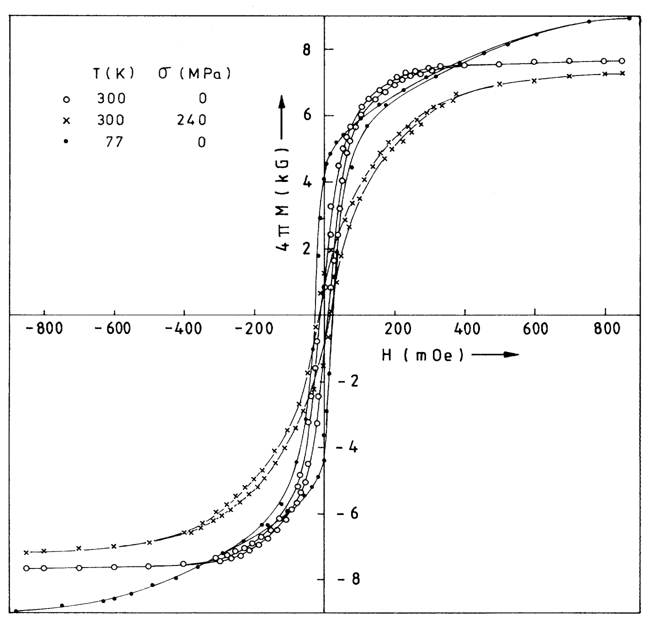

FIG. 3. dc hysteresis loop at temperature $T=300$ K with stress $\sigma=0$ (○) and $\sigma=240$ MPa (×) and at $T=77$ K, $\sigma=0$ (●).

zation M is parallel to the current J, the resistance is higher than the orthogonal situation of M and J. On the other hand, the effect of the internal field on the magnetoresistance is to decrease the resistance when J and M are colinear. As the electron mean free path (also the relaxation time) is small in the amorphous state, the magnetoresistance due to spin-disorder scattering and the effective field is expected to be also small. An excess resistance can arise in a situation when the domain walls normal to the direction of current exist. Because of the Hall effect, a nonuniform current distribution is produced which generates an eddy-current loop centered on the wall. The field generated by the eddy current exerts a dragging force on the domain wall, and when this field is large compared to H_c, the domain will be dragged. When an electron exerts a dragging force on a domain, a reaction force due to the domain acts on the electron and this results in an excess resistivity. The domain structure of as-quenched negative magnetostrictive alloys is such that it has a bamboo domain and the direction of the domain magnetization is circumferential[11] in order to reduce the magnetostatic energy. As the crystalline anisotropy is negligible in the amorphous state, the anisotropy arises as a result of the presence of frozen-in stress within the wire. Because of the low magnetostriction coefficient ($\lambda=-0.08\times10^{-6}$),[12] the magnetoelastic anisotropy is small, resulting a small value of H_c. It makes the wire axis a hard direction of the magnetization.

The domain walls are therefore normal to the current direction in the absence of a magnetic field. As H_c is small, the excess resistivity due to the presence of a normal wall is expected to be large. The magnetoresistance, when the current is normal to the domain wall, is usually described by the relation[1,13]

$$\frac{\Delta\rho}{\rho_0}=\frac{\rho(H)-\rho_0}{\rho_0}=|\beta|^2\left[1-\left[\frac{M_z}{M_s}\right]^2\right], \tag{2}$$

where ρ_0 is the resistance when the sample is in the saturated state and M_z is the component of magnetization in the direction of the field H. We note that $[1-(M_z/M_s)^2]$ is related to the square of the component of the magnetization perpendicular to the field.[13] The parameter β is related to the Hall coefficient and depends on the temperature and stress. We analyze the data using relation (2). Using the results of Figs. 1 and 3, the magnetoresistance $\Delta\rho/\rho_0$ is plotted against $(M_z/M_s)^2$ in Fig. 4. Here M_s is obtained from the high-field data of the magnetization. The data do not fit Eq. (2) over the whole region of M_z. The deviation is observed near $M_z=0$ and M_s at room temperature. At higher stress the region of M_z, over which the parabolic dependence is obeyed, is reduced compared to the case with $\sigma=0$. On the other hand, low-temperature data are described well by Eq. (2). The magnitude of the coefficient $|\beta|$ at 300 K is reduced from 0.41 at $\sigma=240$ MPa to 0.32 at $\sigma=0$ (Fig. 2) and, with the decrease of temperature $|\beta|$, decreases to 0.14 at 77 K and $\sigma=0$. These values are smaller compared to $\beta=0.55$ of pure crystalline cobalt.[1]

The thermal variation of the peak value of $\Delta\rho/\rho_0$ at zero stress shows a sharp decrease as the temperature is lowered from room temperature (Fig. 5). Within $77<T\leq200$ K, the magnetoresistance is nearly constant. The values of the magnetic field ($\Delta H_p/2$) where the peak of $\Delta\rho/\rho_0$ occurs and the coercive field H_c both increase as the temperature is reduced. We note that these fields are comparable. At $H\simeq H_c$, the domain magnetization is perpendicular to the field and the domains are perpendicular the current direction. So the magnetoresistance due

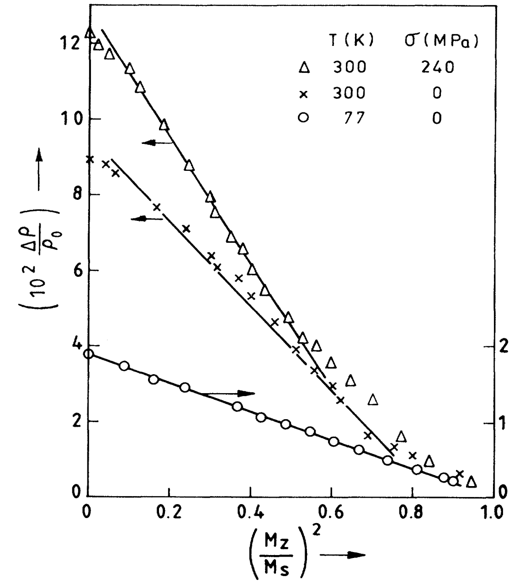

FIG. 4. Dependence of magnetoresistance $\Delta\rho/\rho_0$ with the square of the component of magnetization parallel to the applied field in reduced units, i.e., $(M_z/M_s)^2$ at temperature $T=300$ K with $\sigma=0$ (×) and $\sigma=240$ MPA (△) and at $T=77$ K, $\sigma=0$ (○).

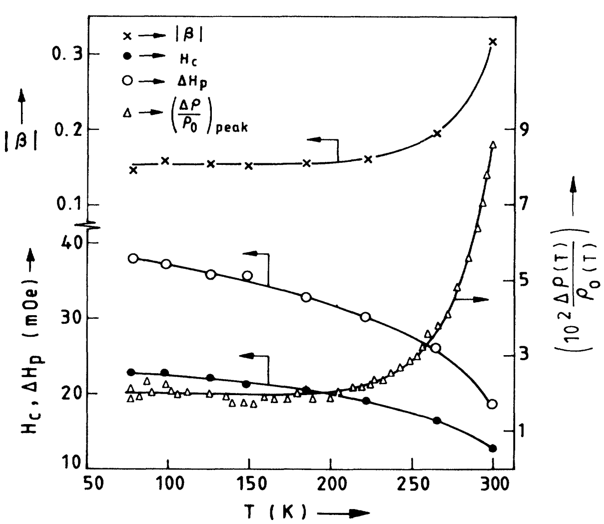

FIG. 5. Temperature dependence of coercive field H_c (●), field separation between the two peaks in forward and reverse directions, ΔH_p (○), peak value of ($\Delta\rho/\rho_0$), $(\Delta\rho/\rho_0)_{\rm peak}$ (△), and the parameter $|\beta|$ (×).

to the domain drag effect attains its highest value. The parameter $|\beta|$ increases with an increase in temperature (Fig. 5). Since an extraordinary Hall coefficient in a ferromagnet has a similar thermal variation, it indicates that the large value of $|\beta|$ is associated with an extraordinary Hall coefficient.

The magnetization reversal in a ferromagnet occurs by various processes such as domain-wall displacement and coherent rotation. The domain-wall displacement of 180° contributes a little to the magnetoresistance. On the other hand, coherent rotation of the magnetization removes the perpendicular domain and hence the resistance decreases with the growth of magnetization. The large negative magnetoresistance thus suggests that magnetization reversal is mainly through coherent rotation. We note that a small magnetoresistance is observed in amorphous ferromagnets with a large magnetostriction coefficient.[4] The possible origin of this large magnetoresistance in this sample is related to the small magnetostriction coefficient and large anamolous Hall coefficient in Co-based alloys.[1]

CONCLUDING REMARKS

A large longitudinal magnetoresistance has been observed in Co-Fe-Si-B amorphous wire at room temperature, and it is enhanced in the presence of stress. The magnetoresistance decreases sharply with temperature. This large value of the negative magnetoresistance suggests that magnetization reversal is predominantly due to the rotational process.

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