Longitudinally driven giant magnetoimpedance effect in stress-annealed Fe-based nanocrystalline ribbons

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A high-frequency longitudinally driven giant magnetoimpedance (GMI) effect has been measured in stress-annealed Fe$_{73}$Cu$_1$Nb$_{1.5}$V$_2$Si$_{13.5}$B$_9$ nanocrystalline ribbons. Based on how the impedance phase varies with the external magnetic field, it becomes clear that the imaginary part of the complex permeability, $\mu''$, which is related to magnetic losses, plays an important role in the high-frequency longitudinally driven GMI effect. The transverse anisotropy field $H_k$ can be readily determined by a sharp minimum in the curve of the impedance phase as a function of the external magnetic field. This provides a new method for measuring the magnetic anisotropy field in such systems. © 2000 American Institute of Physics.

I. INTRODUCTION

The giant magnetoimpedance (GMI) effect can be observed in soft magnetic alloys possessing high permeability. It has become a topic of growing interest owing to their potential applications as miniature magnetic field sensors. A large and sensitive impedance response at room temperature can be detected for a small external magnetic field. Several recent research articles have demonstrated that the giant magnetoimpedance effect is closely related, not only to the real part of the complex permeability, $\mu'$, which is related to magnetic losses, plays an important role in the high-frequency longitudinally driven GMI effect. The transverse anisotropy field $H_k$ can be readily determined by a sharp minimum in the curve of the impedance phase as a function of the external magnetic field.

II. EXPERIMENT

The amorphous Fe$_{73}$Cu$_1$Nb$_{1.5}$V$_2$Si$_{13.5}$B$_9$ ribbons were fabricated by the melt-spinning method. Samples of width 0.8 mm, thickness 12 $\mu$m and length 40 mm were annealed under nitrogen atmosphere at 540 °C for 30 min with a tensile stress between 0 and 245 MPa applied parallel to the axis of the sample. The stress was maintained during cooling down to room temperature. Dynamic hysteresis measurements have verified the existence of an induced transverse anisotropy field $H_k$, which increases with the increasing stress in the sample.

The sample was placed in a small solenoid, with the ribbon axis along the solenoid axis, forming an equivalent impedance component. An HP4194A impedance analyzer was used to measure the impedance and its phase. High-frequency current was supplied to the solenoid, which produced an ac longitudinal driving field for the nanocrystalline ribbon sample inside the solenoid.

The equivalent impedance component can be considered as a series combination of a resistance ($R$) and a reactance ($X$). The phase of this equivalent impedance can be easily calculated from Faraday’s law and Ohm’s law:

$$\phi = \tan^{-1} \left( \frac{X}{R} \right) = \tan^{-1} \left( \frac{\mu''}{\mu'} \right),$$

where $\mu'$ and $\mu''$ are the real and imaginary parts of the complex permeability of the sample, respectively. The solenoid was situated in the center of a pair of Helmholtz coils that produced a dc external magnetic field parallel to the solenoid axis. The entire assembly is oriented such that this field is perpendicular to the Earth’s magnetic field. All data were measured at room temperature with an alternating current of $i_{pp}=5$ mA in the sample coil.
FIG. 1. External magnetic field dependence of the longitudinally driven giant magnetoimpedance ratio for Fe$_{73}$Cu$_{1}$Nb$_{1.5}$V$_{2}$Si$_{13.5}$B$_{9}$ nanocrystalline ribbons annealed under different tensile stresses.

III. RESULTS AND DISCUSSION

As the external magnetic field, $H_{\text{ex}}$, was changed between $-H_{\text{max}}$ and $+H_{\text{max}}$ the magnetoimpedance ratio $[Z(H_{\text{ex}}) - Z(H_{\text{max}})]/Z(H_{\text{max}})$ was measured for the Fe$_{73}$Cu$_{1}$Nb$_{1.5}$V$_{2}$Si$_{13.5}$B$_{9}$ nanocrystalline ribbons annealed under different tensile stresses of $\sigma = 49$, 63.7, 98, and 245 MPa, as shown in Fig. 1. The amplitude of the magnetoimpedance ratio decreases with increasing annealing stress, because the stress introduces a different transverse anisotropy $K_{\mu}(H_{\text{ex}} = 2K_{\mu}/M_s)$ in the ribbon. Since a different $K_{\mu}$ can alter the soft magnetic properties of the materials, it inevitably affects the magnetoimpedance ratio. At lower fields, the magnetic moments are mostly normal to the axial direction of these ribbons that have a transverse magnetic structure. Hence, under a longitudinal driving field, the domain wall movement makes only a small contribution to the magnetization, while the rotation of magnetic moments is mostly responsible for the magnetization. For high annealing stresses, the increased transverse anisotropy causes a reduced permeability associated with the rotation of magnetic moments, which, in turn, explains the lower amplitude of the magnetoimpedance ratio.

In each of the curves in Fig. 1, a plateau is observed for small external fields. This is because very little rotation of the magnetic moments can take place when the external field is smaller than the anisotropy field ($H_{\text{ex}} < H_k$), resulting in only insignificant variations of magnetoimpedance in this range. This plateau becomes wider for those samples that were subject to higher stresses during annealing, consistent with the expectation that $H_k$ becomes larger for high stress samples. When $H_{\text{ex}} \geq H_k$, the orientation of magnetic moments is forced to change from the transverse direction to the axial direction, and, consequently, the magnetoimpedance is observed to decrease drastically, approaching saturation. Therefore, the downward transition observed in the magnetoimpedance ratio curve should occur when the external field $H_{\text{ex}}$ equals the transverse anisotropy field $H_k$.

In order to further understand the relations between the longitudinally driven giant magnetoimpedance effect and the transverse anisotropy field $H_k$, the field dependence of the phase of the complex impedance has been studied for the Fe$_{73}$Cu$_{1}$Nb$_{1.5}$V$_{2}$Si$_{13.5}$B$_{9}$ nanocrystalline ribbons annealed under different tensile stresses. Figure 2 shows that the measured phase angle, $\phi$, has an interesting profile as $H_{\text{ex}}$ is changed from $-H_{\text{max}}$ to $+H_{\text{max}}$. Compared with the curves in Fig. 1, the variation of the phase is found to be similar to that of the magnetoimpedance ratio in the range of $H_{\text{ex}} < H_k$, i.e., both curves gradually decrease with an increasing external magnetic field. At $H_{\text{ex}} = H_k$, the phase reaches a sharp minimum, and when $H_{\text{ex}} > H_k$, the phase rises again drastically to a common final value of 84°. According to Eq. (1), for $\phi$ to have a minimum, either $\mu'$ is a minimum or $\mu''$ is a maximum. The former is impossible because the magnetoimpedance ratio curves in Fig. 1 are all monotonic around $H_{\text{ex}} \approx H_k$. Therefore, the imaginary part $\mu''$ must have a maximum at $H_{\text{ex}} = H_k$.

To confirm the above experimental results, we have also measured the field dependence of the phase of magnetoimpedance longitudinally driven at three frequencies (100 kHz, 300 kHz, and 1 MHz) for the nanocrystalline Fe$_{73}$Cu$_{1}$Nb$_{1.5}$V$_{2}$Si$_{13.5}$B$_{9}$ ribbon that was annealed under a 98 MPa stress. Figure 3 shows that, for any $H_{\text{ex}}$ value (especially when $H_{\text{ex}} \geq H_k$), the phase $\phi$ decreases monotonically when driven at 100 kHz. The variation of $\mu''$ caused by eddy

FIG. 2. External magnetic field dependence of the magnetoimpedance phase for Fe$_{73}$Cu$_{1}$Nb$_{1.5}$V$_{2}$Si$_{13.5}$B$_{9}$ nanocrystalline ribbons annealed under different tensile stresses.

FIG. 3. External magnetic field dependence of the magnetoimpedance phase measured at different driving frequencies for the Fe$_{73}$Cu$_{1}$Nb$_{1.5}$V$_{2}$Si$_{13.5}$B$_{9}$ nanocrystalline ribbon annealed under the tensile stress of 98.0 MPa.
current losses is relatively small at low frequencies. Therefore the change in $f$ is mainly due to the decrease of $\mu'$ as $H_{ex}$ increases. For a driving frequency of 300 kHz, the phase increases at first when $H_{ex}$ is slightly higher than $H_k$, and then decreases slowly with increasing $H_{ex}$. This is due to more eddy current losses under this higher driving frequency. Both $\mu''$ and $\mu'$ have comparable variations with the external field and thus lead to a small resultant variation in $f$. As for the 1 MHz case, the domain wall movement increases with the increase of the driving frequency. This is accompanied by higher eddy current losses and a maximum $\mu''$ value\(^{10}\) (thus a minimum in $f$) when the onset of a significant increase of domain wall movement occurs at $H_{ex} = H_k$. With the further increase of the external magnetic field in the range of $H_{ex} > H_k$, the domain wall movement vanishes quickly because the external magnetic field increasingly inhibits it.\(^{11}\) This leads to the sharp decrease of $\mu''$ and the corresponding rise of the phase.

In conclusion, the external magnetic field dependence of the imaginary part of the complex permeability $\mu''$, which is closely related to the magnetic losses, produced by domain wall movement, plays an important role in the high-frequency longitudinally driven giant magnetoimpedance effect. This can be easily measured through the phase of the complex magnetoimpedance. Furthermore, a value of the transverse anisotropy field $H_k$ can be readily determined by the sharp minimum in the field dependence of the magnetoimpedance phase.

**ACKNOWLEDGMENTS**

This work is supported by the China National Climbing Project of Nanomaterials Science and the Phosphor Project.