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Frequency dependence of the magnetoimpedance in amorphous CoP electrodeposited layers

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Magnetic properties and changes of impedance upon external field (MI) are studied in amorphous CoP magnetic layers obtained by galvanostatic electrodeposition over cylindrical Cu substrates. The magnetic layer thickness is controlled by deposition time and varies between 3 and 7 μm. Due to the columnar growth of Co, thicker layers have stronger perpendicular radial anisotropy. The field and frequency dependence of the impedance is measured in the kHz/MHz range. Although it is generally accepted that a radial anisotropy should be unfavorable to the MI effect, an increase of the MI ratio with the thickness of the magnetic layer, and thus with anisotropy, is observed. Results are explained in terms of a model considering the current distribution along the sample thickness with two well-defined regions having different transport and magnetic properties. © *2000 American Institute of Physics.* [S0021-8979(00)57108-4]

Soft magnetic materials exhibit expressive changes of ac impedance as a function of applied magnetic field, the magnetoimpedance (MI), that can be explained using the classical skin effect shown in ferromagnetic conductors.[1]

MI can be observed in rapidly quenched materials like amorphous wires[2–5] and ribbons,[6] thin films[7] and microwires.[8] Recently, MI has been also observed on nonmagnetic conducting wires electroplated with magnetic layers. Beach *et al.* found MI in BeCu wires electroplated with NiFe thin layers,[9] and explained their results without considering the skin effect. Afterwards, Usov *et al.* developed a MI theoretical model based on the skin effect for such composite wires.[10] Finally, Favieres *et al.* have reported MI on twisted CoP multilayers electrodeposited onto Cu wires which exhibit helical anisotropy.[11] The importance of MI studies lies on the development of magnetic field sensing devices.

In this work we present MI results measured at different frequencies on $Co_{90}P_{10}$ single layers electrodeposited onto Cu wires. We report the existence of MI measured in the MHz range on samples with radial anisotropy. An important observed feature is the almost absence of the two-peak behavior[12] in the MI spectra, that could be correlated with the existence of the radial anisotropy. This particular behavior for the MI with an applied field is envisaged to be very promising for applications in sensing devices.

The 10 cm long pieces of noninsulated commercial Cu wire, with a diameter of the order of 190 μm have been carefully cleaned and mounted inside an electrodeposition cell in which a chemical solution was kept in a constant temperature of 74 °C. In all samples, a thin layer of CoP was grown over the Cu wire using a constant electrolytic current density of 200 mA/cm^2 (galvanostatic mode). By keeping the current density constant, the layer thickness could be controlled by the deposition time. In this work, three samples have been obtained with layer thickness of approximately 7, 4 and 3 μm, respectively. The layer composition was determined by Atomic Emission Spectroscopy as being $Co_{90}P_{10}$ and was the same in all samples.

The magnetoimpedance has been measured in a frequency range between 0.05 and 10 MHz using a setup based on a description given previously.[13] The main difference of the set-up used here is that an optimized ac current intensity control has been developed allowing real and imaginary separation of the MI effect based on lock-in techniques. The sinusoidal ac current is applied to the sample by means of a HP33120A signal generator, which in fact is a voltage source. In order to measure and keep the current intensity constant during the experiments, a Tektronix P6022 ac current probe has been employed to monitor the flow of current through the sample. Such current probes gives a voltage output which is in phase and is proportional to the current flow (1 mV/mA), with a flat frequency response between 100 kHz and 200 MHz. This signal is then used to measure the current intensity with the aid of a SRS840 RF lock-in amplifier. The voltage source is adjusted by means of a software feedback control to keep the current intensity constant (1 mA_{RMS}) during the whole experiment. As a result of this control, any change in the sample's measured voltage can be ascribed to changes in the sample's impedance. The voltage drop across the sample is measured as a function of an external DC field. This external DC field is generated in a long solenoid, along the longitudinal axis of the sample, using a KEPCO power supply, and reaches a maximum value of 30 kA/m. Finally, it should be mentioned that the current signal is also used to

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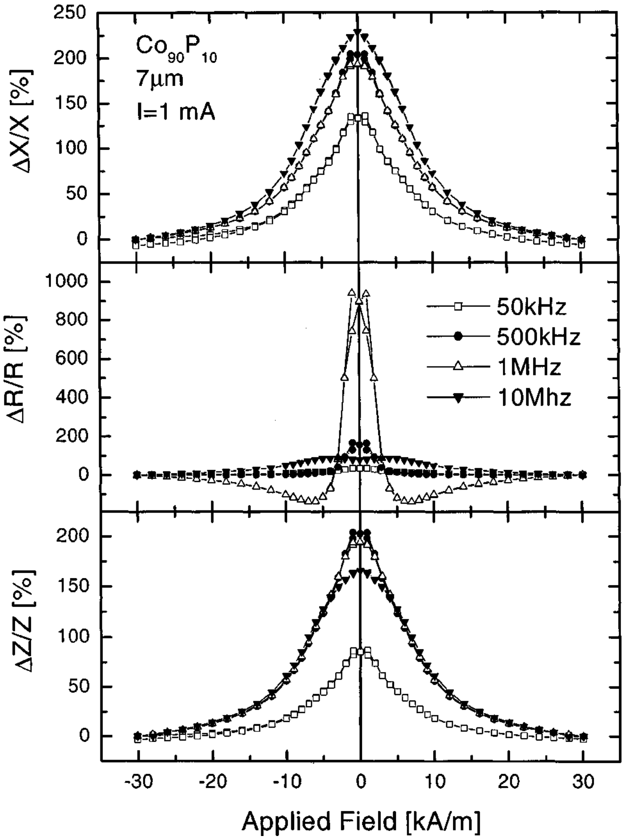

FIG. 1. Real (R), imaginary (X) and total (Z) magnetoimpedance ratios as a function of frequency in the electrodeposited wire with a 7 μm thick CoP layer.

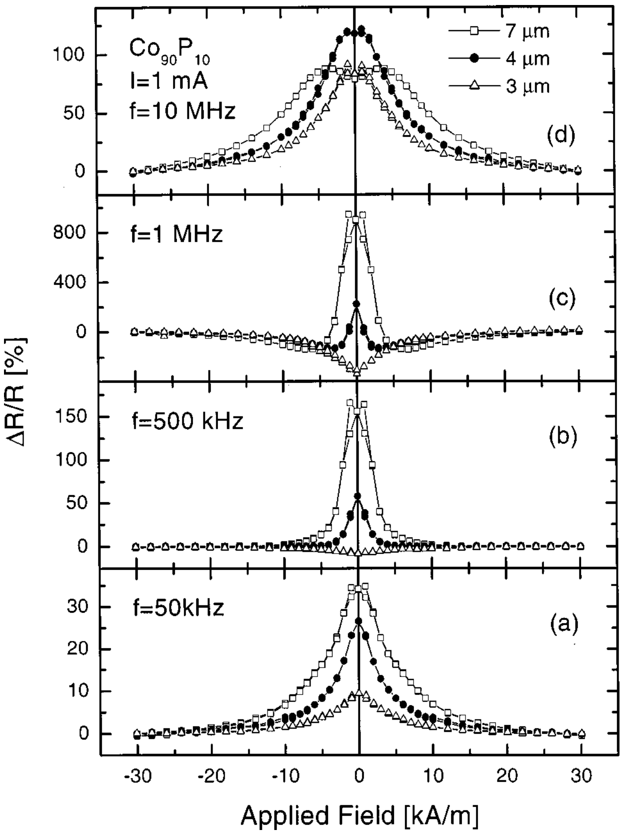

FIG. 2. Real magnetoimpedance ratio measured in CoP electrodeposited wires with different thicknesses, at (a) 50 kHz, (b) 500 kHz, (c) 1 MHz and (d) 10 MHz.

make the phase adjustments for each measured value. Therefore the in phase signal corresponds to the real part of the sample's impedance, while the out phase signal can be associated to the reactance of the sample. The MI ratios were defined in the conventional way, considering the impedance at the maximum applied field as reference.

Figure 1 shows the real, imaginary and total components of the magnetoimpedance ratio for the sample with 7 μm of CoP measured at different frequencies using an ac current of 1 $\mathrm{mA_{RMS}}$. A dramatic increase of the real MI ratio, reaching about 1000% at a frequency of 1 MHz, was found in the real component. This maximum ratio has been observed previously.[14]

In Fig. 2 we report the thickness dependence of the real MI ratio for all samples measured at 50 kHz (a), 500 kHz (b) and 1 MHz (c) and 10 MHz (d). These results can be explained considering the particular geometry of the ferromagnetic layer with respect to the sample. The electrodeposited layers form a thin tube over the Cu substrate. When the ac current is flowing through the sample, considering a certain magnetic permeability, its frequency will settle a defined penetration depth. At 50 kHz, the penetration depth δ is approximately 300 μm for Cu. Even though the presence of the magnetic layer can change this penetration depth substantially, it is expected that the current would be flowing almost through the whole cross section. The MI observed is due to the ferromagnetic behavior of the CoP layer. In electrodeposited layers it is known that a magnetic anisotropy is developed during the deposition procedure, and that this anisotropy changes from planar to radial depending on the layer thickness.[15–17] The different anisotropies lead to distinct permeability values, and, therefore, to different MI behavior. The sample with thicker ferromagnetic layer shows the largest MI effect. The anisotropy should be approaching the radial direction in this case, and the changes of permeability due to the external DC field are larger than in thinner layers.

A new behavior is observed at 500 kHz and 1 MHz [Figs. 2(b) and 2(c)]. At low DC field values the current is flowing mainly in the CoP layer, in which the conductivity and permeability are very different[18] from the Cu core. The increase of the DC field increases the penetration depth, and a monotonic reduction of the impedance is observed. When the penetration depth crosses the CoP/Cu interface a sudden change of behavior in the MI is expected, as observed in Figs. 2(b) and 2(c). By changing the CoP layer thickness, the DC field on which this crossing effect is observed also changes. In summary, at 500 kHz and 1 MHz the crossing effect is dominant.

Finally, at 10 MHz the penetration depth is very small, and the current is flowing mainly in the CoP layer, even at a maximum DC field. As a consequence, changes of impedance by the DC field should mainly follow the magnetic behavior of the layer, and no crossing effects should be observed. In fact, the 10 MHz curves are very similar to the 50 kHz curves, since the impedance variation in both cases are only related to the permeability changes of the CoP layer, and no crossing effects are expected to be dominant.

Some theoretical models of MI effects in ferromagnetic wires have been proposed recently. Ménard and co-workers[19] as well as Kraus[20] developed models based on the simultaneous solution of the appropriate Maxwell equations and the Landau–Lifshitz equation of spin motion. In these models, the impedance of a ferromagnetic wire is described as a function of the frequency, current intensity, magnetic external field applied to the sample and some other parameters. The solutions are given in terms of Bessel functions of the first kind.

In this work we also developed a model to describe the impedance, but considering the special geometry of our samples, in which we have a tubular CoP ferromagnetic layer over a nonmagnetic Cu cylindrical core. Taking the suggestion given by Ménard *et al.*[19] we have considered Bessel functions of the second kind in the general solution for the components of the magnetic fields and magnetizations (h_r, h_ϕ, h_z and m_r, m_ϕ, m_z),

$$h_r,h_\varphi,m_r,m_\varphi \propto a_1 J_1(kr)+a_2 N_1(kr);$$

$$h_z,m_z \propto a_1 J_0(kr)+a_2 N_0(kr). \tag{3}$$

After considering the proper boundary conditions in the CoP/Cu interface, it is possible to obtain a homogeneous linear system in which the complex superficial impedance can be determined as a function of the applied field, frequency and the layer thickness. It has been shown by Yelon *et al.* that the superficial impedance of a wire is, except for a geometrical factor, equivalent to the total impedance.[21] It should be mentioned that this model does not consider any anisotropy, which in fact exists in our samples. Using the characteristic values of the sample, considering the correct CoP layer thickness, applied to this model, we were able to calculate the MI ratios at 1 MHz. Figure 3 shows the effect of a layer on the MI ratios as a function of the applied field. It is possible to see a good qualitative agreement with the experimental results obtained in the samples with 7 μm and 4 μm thickness of the magnetic layer, showing that this model is appropriate [see Figs. 2(b) and 2(c)]. For the sample with 3 μm of magnetic layer, a change of anisotropy direction is expected[17] and this can be the reason for the observed differences between model and experiments, since the model does not account for anisotropy effects.

A magnetoimpedance effect has been observed in $Co_{90}P_{10}$ layers electrodeposited over Cu wires. Their magnetoimpedance effect increases with the layer thickness, and the observed behavior can be explained considering the influence of the layer thickness. Moreover, the magnetoimpedance ratio increases with frequency, as expected from the general accepted trend considering the penetration depth model. These materials are very promising for applications where high magnetic fields are necessary, e.g., high current sensors.

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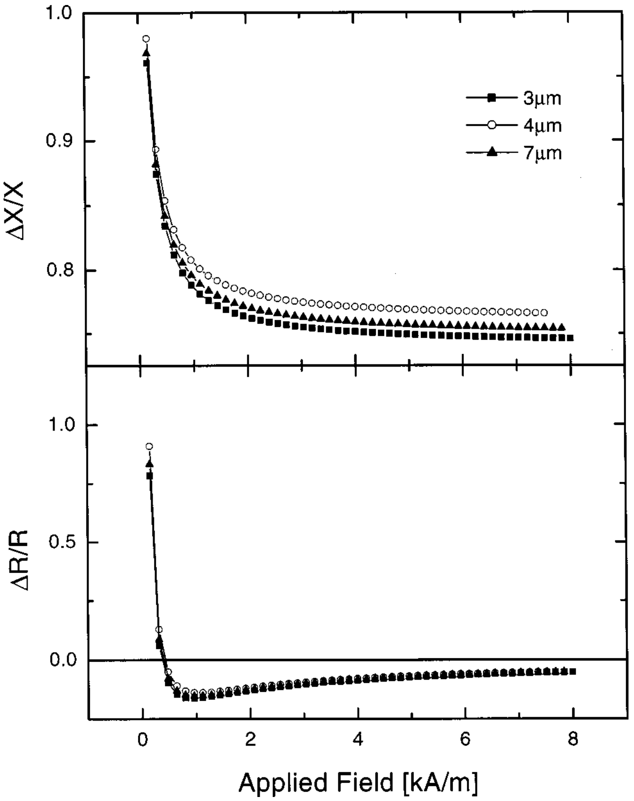

FIG. 3. Calculated impedance, at 1 MHz current frequency, of the electrodeposited system as a function of the magnetic field.

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