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Low field microwave absorption and magnetization process in CoFeNi electroplated wires

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Ferromagnetic resonance (FMR), Ferromagnetic antirresonance (FMAR) and low field magnetoimpedance (MI) are the characteristic features of high frequency losses in applied fields. While some results on FMR and FMAR in CoFeNi electroplated wires were reported earlier, here we present microwave absorption in CuBe wires electroplated by 1 μm FeCoNi magnetic layer at very low fields. These data are comparatively analysed together with longitudinal hysteresis loops in order to reveal the correlation between power absorption and magnetization processes. Microwave studies are made by using the cavity perturbation method at 9.65 GHz for a DC field parallel to the sample axis, and with microwave magnetic field $h_{\rm rf}$ parallel or perpendicular to the wire axis. Two peaks have been observed in all samples, one is due to FMR, and the other is, at very low fields, related to MI. The MI peaks represent minima in power absorption. By comparing with the hysteresis loop we remark the close correspondence between the MI phenomena in the axial mode and the concomitant magnetization process.

Keywords: microwave absorption, magnetoimpedance, electroplated wires
PACC: 7530V, 7560E, 7560, 7650

1. Introduction

Properties of ferromagnetic materials in the presence of a high frequency magnetic field are an expanding area both in the basic research and technological application. Ferromagnetic resonance (FMR),[1,2] antiresonance (FMAR),[3,4] and magnetoimpedance (MI),[5–7] and magnetic dissipation[8] can be mentioned as characteristic high-frequency properties. In recent years, low-dimensional materials have been a subject of very active research. Among them one can mention thin films and multilayered structures,[7,9] glass-coated microwires[10,11] and electroplated wires.[7,12] Fabrication of such systems follows well developed methods which permit the accurate control of technological parameters, obtained properties, and precise post-preparation processing. The increase in number of materials available for research and application requires that the methods of their characterization be even more precise than before. FMR in low dimensional and nanostructured materials can be useful to characterize such material parameters as magnetization, magnetic anisotropy, high-frequency loss, frozen-in strain and magnetic inhomogeneity.[13]

Ferromagnetic resonance is often studied as the absorption, P, of microwave magnetic field by a ferromagnetic material, measured as a function of an applied DC magnetic field, H. If the magnetic field is modulated at an audio frequency, the derivative of the absorption, $\mathrm{d}P/\mathrm{d}H$, is measured instead of the absorption itself.[13] It was suggested that magnetoimpedance, the dependence of the impedance of a magnetic conductor on external magnetic field for microwave frequencies, have a straight relation to FMR[14,15] and the discussion about the frequency range relevant to the existence of the resonant absorption is still under development.[16] In 1998 microwave absorption in low magnetic fields of tens of Oe or even less was proposed for the characterization of the axial magnetization process in amorphous glass covered microwires, separately, at 9.8 and 32 GHz.[17] This low field regime of non-resonant absorption for which sample is not saturated was of special interest because it was exactly the region of high MI effects and considered as very promising for technological applications. The authors employed an *in situ* investigation of the

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magnetization processes in amorphous glass-covered microwires with positive, negative, and nearly zero magnetostrictions. The second peak in the low-field range of the resonance spectra, which is not the usual FMR signal, was analysed, and the authors concluded that the shapes of these low-field peaks contain the information about the low-field magnetization process. They also proposed a simple qualitative interpretation of the impedance behaviour. In this particular work the microwave losses were measured by using a simple cavity perturbation method.[18] In situ investigation of the magnetization process in amorphous glass covered wires was also carried out in Ref.[19] where the authors also measured the microwave absorption for the magnetic field applied parallel to the microwire axis like in Ref.[17] but instead of the absorption the $\mathrm{d}P/\mathrm{d}H$ was measured.

FMR and FMAR in CoFeNi/CuBe electroplated wires were studied in Ref.[20]. Here we present microwave power absorption in CoFeNi/CuBe electroplated wires at very low external magnetic fields. They are analysed together with longitudinal hysteresis loops in order to reveal possible correlations between power absorption spectrum and magnetization processes, to estimate the utility of microwave methods in investigating the magnetization processes in electroplated wires.

2. Experimental

$Cu_{98}Be_2$ non-magnetic wires were electroplated by FeCoNi 1 μm magnetic layer. CuBe substrate was mechanically polished prior to the electrodeposition to reduce roughness. In order to obtain as less as possible level of the internal stresses, a pure Cu buffer layer of about 4 μm in thickness had been deposited onto a non-magnetic wire just before the magnetic layer was electroplated. The resistivity of both parts was checked by four point techniques. For the highly conductive core its resistivity was about 3.9 $\mu\Omega$cm and for the magnetic shell its resistivity was about 15 $\mu\Omega$cm. Table 1 lists the data on geometrical parameters, composition and post-preparation treatments used for all samples. The heat treatments were done in the Ar flow in order to avoid oxidation. The lengths of the wires for microwave experiments are all 8 mm, i.e. the whole wire fitted inside the resonance cavity.

Table 1. Description of the samples.

sample	diameter of$Cu_{98}Be_2$/μm	composition of magnetic layer	post deposition treatment
AP	100	$Fe_{20}Co_6Ni_{74}$	none
AC	100	$Fe_{20}Co_{16}Ni_{64}$	AC field annealing in Ar atmosphere 1h, 300°C, field amplitude of 1.5 kA/m
TU	60	$Fe_{20}Co_{16}Ni_{64}$	none

The quality of the deposited layers and their thickness were checked by scanning electron microscopy, SEM. Figure 1 shows the examples of the evaluation of the quality and the thickness of the magnetic layer mechanically detached from the non-magnetic core. The longitudinal hysteresis loops, i.e. $M(H)$ curves for the external field applied parallel to the wire axis were measured by conventional inductive fluxmetric method at 10 Hz. The applied magnetic field was swept in a range from –500 to +500 A/m. In the case of complicated shape of the hysteresis loop (sample AC) the first derivative $\mathrm{d}M/\mathrm{d}H$ was used in order to estimate the specific features of $M(H)$ loops (Fig.3).

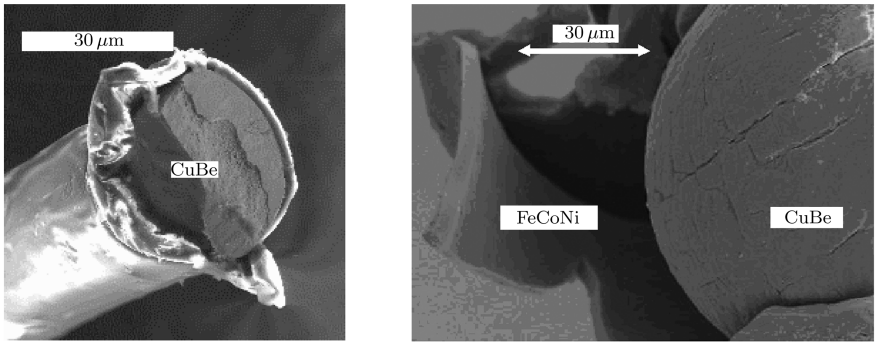


Fig.1. SEM images of the CuBe/FeCoNi electroplated wire. The magnetic layer was mechanically detached from a non-magnetic core wire.

Microwave studies were made by using the cavity perturbation method based on the usage of conventional homodyne spectrometer.[18] The power absorption of the microwave magnetic field at 9.65 GHz was measured as a function of H (Figs.3 and 4). Earlier we have applied this technique to studying FMR and FMAR in electroplated wires.[20] The measurements have been done with a DC magnetic field parallel to the wire axis. Two configurations for the microwave field, $h_{\rm rf}$, were employed, that is axial ($H||h_{\rm rf}$) and transverse ($H\perp h_{\rm rf}$). Figure 2(a) shows the principal diagram of the resonance cavity for microwave studies and the position of the sample during measurement. The wires have been placed at the bottom of the cavity in order to avoid the absorption of the microwave electric field, $e_{\rm rf}$.[10] For this geometry one can write the corresponding equations for the power absorption taking into account the ratio between skin depth, δ, and radius of the wire, r, as follows:

$$\delta \gg r, \quad P = \frac{1}{2}\omega\chi'' h_{\rm rf}^2; \tag{1}$$

$$\delta \ll r, \quad P = \frac{1}{2}R_{\rm s}h_{\rm rf}^2,$$

$$R_{\rm s} = {\rm Re}\left[(1+j)\sqrt{\frac{\omega\mu}{2\sigma}}\right] = \frac{1}{\sigma\delta} = \sqrt{\pi f\mu\rho}, \tag{2}$$

where $R_{\rm S}$ is the real part of the surface impedance, ω is the angular frequency, χ'' is the imaginary component of the magnetic susceptibility, μ is the dynamic permeability, σ is the conductivity, and ρ is the electrical resistivity.

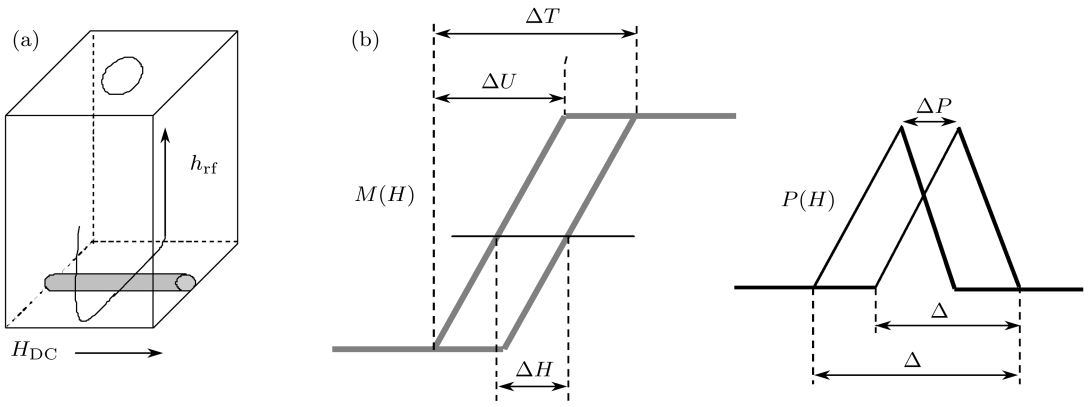


Fig.2. Resonance cavity and sample position for $h_{\rm rf}$ transversal (a) and definition of the parameters of the hysteresis loops and low field microwave absorption spectra for the evaluation of their shapes (b).

3. Results and discussion

Figure 3(a) shows the power absorption spectrum of sample AP at 9.65 GHz. There is a clear peak in the absorption at 76 kA/m. In this field the wire is saturated and the observed peak corresponds to the FMR phenomenon.[20] Near zero field a minimum was observed. Similar minima in absorption were observed in the other two samples, AC and TU (Figs.3 and 4). That is, two absorption peaks were observed for all samples mentioned in Table 1: one is related to FMR, and the other, in a very low DC magnetic field, is related to magnetoimpedance. The MI peaks observed here are connected with a minimum of power absorption in contrast with what was recently observed for amorphous ribbons, where the measurements were done using the dP/dH.[21] The observed low-field effects have been further investigated in more detail with $h_{\rm rf}$ either parallel or transverse to the wire axis with the static field maintained along the wire. For comparison, the hysteresis loops of the samples and their derivatives are also shown (Figs.3 and 4).

From the shape of the hysteresis loops we conclude that the hard magnetization axis is close to the axis of the wire in as-prepared AP and TU samples (the easy magnetization axis is probably circumferential). Annealing for 1 h at 300 °C in an alternating magnetic field with an amplitude of 1.5 kA/m and frequency 50 Hz (sample AC), results in the appearance of the axial anisotropy component and more complex shape of the hysteresis loop (Fig.3).

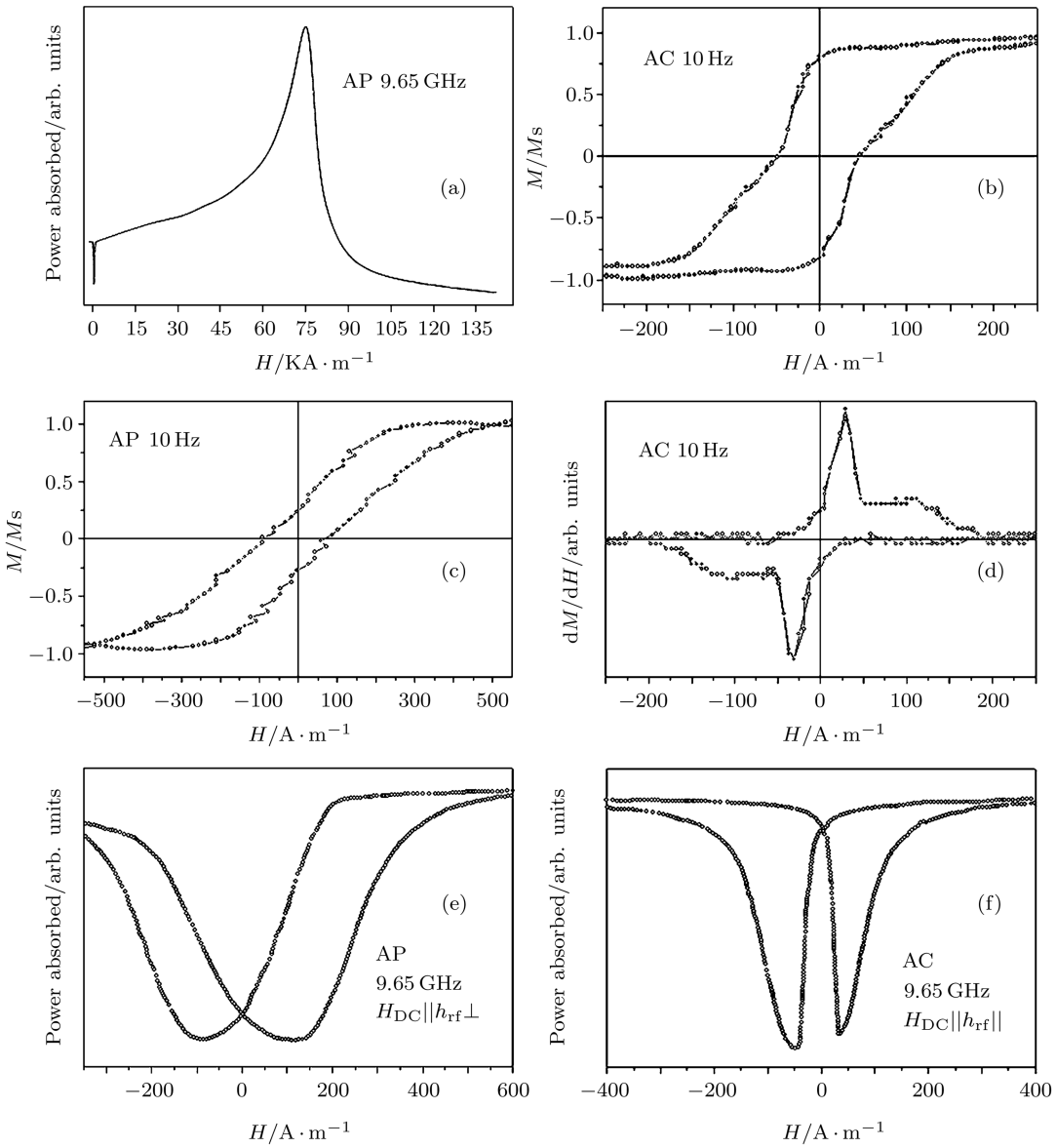


Fig.3. Measured data for samples AP and AC.

In the present study, the microwave effects were observed for all electroplated wires in both geometries. Figure 2(b) shows graphically the definition of the parameters to evaluate the change in shape of the $M(H)$ and $P(H)$ curves. For the axial orientation, the minimum of $P(H)$ occurs at a coercive field, H_c, and the width of the microwave absorption peak, Δp, is close to the width of half hysteresis loop measured from saturation to saturation, Δup (Table 2). This relation was observed for all samples.

We have analysed the shapes of the $P(H)$ responses and the inductive $M(H)$ loops and found the correlation between the magnetization process and the power absorbed at microwave frequency. Figure 5 shows an example of this similarity. For the convenience of visual comparison, the field dependence of the absorbed power $P(H)$ was reconstructed as follow: the left part of the graph, from the point of the minimum of absorbed power, was mirrored with respect to the horizontal axis, forming a kind of hysteresis loop reconstructed from the absorbed power, which appears to be very similar to the inductive hysteresis loop. In this particular case, although the shape of the $M(H)$ curve is very complicated they show a high similarity. The question arises whether this similarity is fortuitous depends on very particular conditions of the experiments, or in appropriate conditions, and low field microwave experiments could be effectively used for the study of the magnetization processes in soft magnetic samples of different geometries.

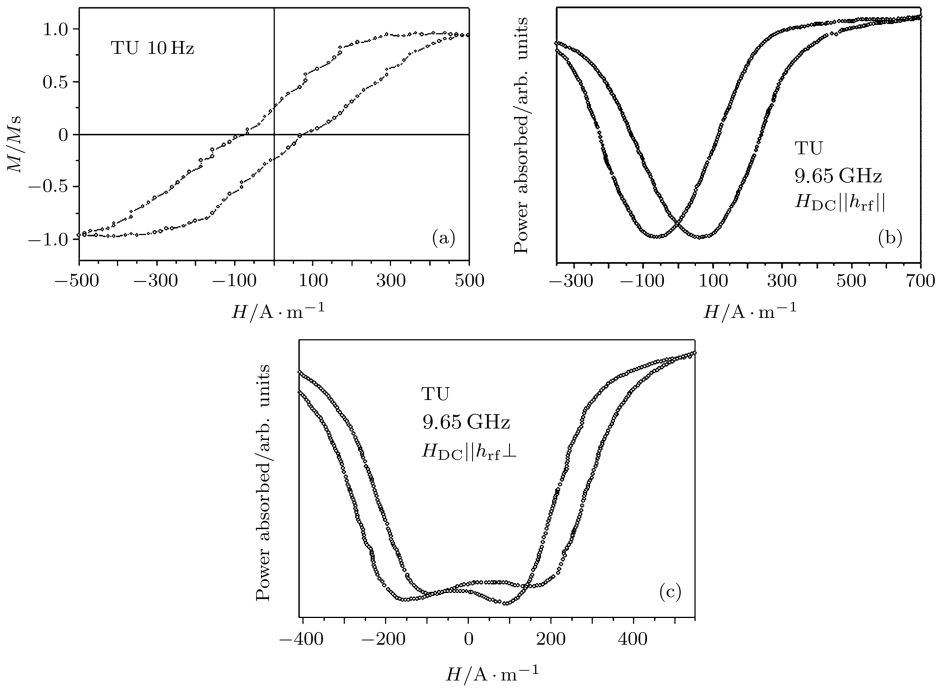


Fig.4. Measured data for sample TU.

Table 2. Low-field microwave absorption data and parameters of hysteresis loops for FeCoNi/CuBe electroplated wires in selected states.

AC	MI ||	$\Delta pp = 85$ A/m	$\Delta p = 250$ A/m	$\Delta T = 500$ A/m
	H hys. loop	$\Delta H_c = 95$ A/m	$\Delta up = 220$ A/m	$\Delta T = 400$ A/m
TU	MI ||	$\Delta pp = 140$ A/m	$\Delta p = 900$ A/m	$\Delta T = 1000$ A/m
	H hys. loop	$\Delta H_c = 145$ A/m	$\Delta up = 800$ A/m	$\Delta T = 1000$ A/m
	MI⊥	-----	$\Delta p = 950$ A/m	$\Delta T = 1000$ A/m
AP	MI⊥	Δpp= 210 A/m	$\Delta p = 900$ A/m	$\Delta T = 1100$ A/m
	H hys. loop	$\Delta H_c = 160$ A/m	$\Delta up = 750$ A/m	$\Delta T = 1000$ A/m

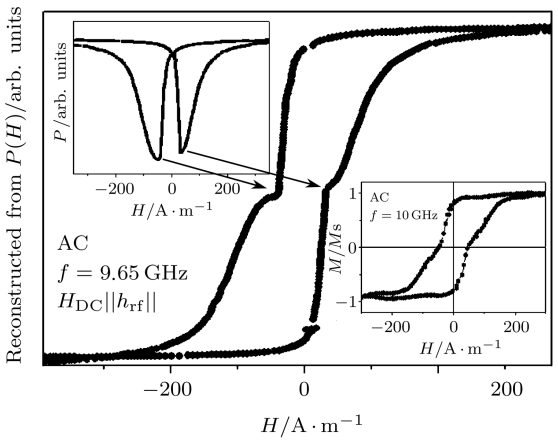


Fig.5. Hysteresis loop reconstructed form the low field microwave absorption data. The left inset: $P(H)$ initial data; the right inset: inductive hysteresis loop of the same sample.

There is no doubt that in the low field regime the magnetization and hence the magnetic permeability varies in a very complex manner and it seems to be a main controlling phenomenon for the MI. Therefore, in order to explain the observed phenomenon, in general one should solve the Maxwell's equations in cylindrical symmetry both for parallel and perpendicular geometries, of which the analytical solutions can be found in the queasistatic approximation only for some particular cases.[22]

The value of the coercive field, ΔH_c, seems close to the width of the MI response measured from peak to peak, Δpp, for the h_{rf} parallel to the sample axis. The MI response in a low field is related to the magnetization process. It can be characterized by a reduction in absorbed power, with a minimum at the coercive field (when the magnetization of the sample is zero).

Presumably, at H_c, the magnetization is circumferential and the spins are perpendicular to h_{rf}. This corresponds to the case of microwave absorption in

metallic ferromagnetic films in the FMR geometry. Thus, the minimum in MI is likely to be related to the minimum in the permeability.

For h_{rf} transverse to the wire, the width of the MI effect, ΔT, corresponds to the width of the hysteresis loop, but the width from peak to peak, Δpp, does not correspond to ΔH_c, as it happens in the axial measurements. In this geometry, h_{rf} must follow the contour of the wire and there are spins which have components along h_{rf} for the applied fields less than the saturation one. In contrast, for h_{rf} parallel to the wire axis, h_{rf} and the spins are perpendicular to at H_c and parallel to each other at saturation and above. Thus the transverse geometry is more complicated to sort out.

Much research has to be done in order to understand the interrelation between the magnetization processes and low field microwave absorption but it become more and more clear that the phenomenon is rather general. It appears in the magnetic materials of different types including electroplated wires. Apart from the fundamental interest, low field magnetoabsorption can be interesting from the point of view of possible technological applications. Here, it is very tempting to suggest that this effect could be exploited to construct a low field microwave modulator.

4. Conclusions

CuBe/FeCoNi electroplated wires with different anisotropies show low-field microwave absorption which can be interpreted to be due to a magnetoimpedance caused by the low-field magnetization process. The width of the hysteresis loop at zero magnetization ($\Delta H_c = 2H_c$) is similar to that of the MI from peak to peak, Δpp, for the geometry of the microwave magnetic field parallel to the sample axis. The shape of the hysteresis loop reconstructed from the microwave measurements is very similar to that measured by inductive method, indicating very good correlation between these two methods in the particular case of the electroplated wires with studied characteristics.

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