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High-frequency magnetoresonance absorption in amorphous magnetic microwires

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Abstract

The $Fe_{69}Si_{16}B_{10}C_5$, $Co_{75}Si_{10}B_{15}$, $Co_{68}Mn_7Si_{10}B_{15}$ amorphous microwires have been studied by the magnetoresonance absorption technique in the X (9.5 GHz), K (20–27 GHz) and Q (30–37 GHz) frequency bands. The specimens under study were metal threads of about 5 μm in diameter coated with dielectric Pyrex layer with thickness 5 μm. The dependences of magnetic resonance spectra on frequency and wire orientation have been measured. The analysis of the resonance signal parameters has revealed that well-known classical equations for FMR in a cylindrical-shaped sample could not be applied for these microwires. It is shown that due to the skin depth effect the model of hollow cylindrical tube has to be applied to explain the experimental results in the frequency range measured. The values of saturation magnetization, g-factor and anisotropy field have been estimated from the frequency dependence of the field for resonance. © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

Investigations of amorphous magnetic metal materials, shaped into microwires of few μm in diameter, attract considerable attention during recent years. These objects demonstrate significant changes of resistance in response to relatively small magnetic fields applied at room temperature. Based on these features a variety of sensors, such as displacement and position sensors, electric and magnetic field microprobes, stress sensors, and read heads for magnetic hard disks could be designed.

Recently [1–6] the giant magnetoimpedance (GMI) effect, which means a significant change in the AC electrical impedance of a microwire when subjected to the static magnetic field was discovered. A change of the impedance with positive sign (of about 220% at 90 KHz [4]), as well as with negative sign (of 70% at higher frequencies [3,5]) has been observed.

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One of the most promising applications of magnetic microwires is that they can operate at very high frequencies, i.e. up to 10^2 GHz band. The microwires with remarkable GMI response in this range could be applied in the area of millimeter-wave physics as cheap and reliable attenuators, switches, antenna elements, etc. One of their advantages is very small relaxation time, which is restricted only by spin–spin relaxation time in the wire material (10^{-12}–10^{-14} s).

In present work, we apply the magnetoresonance absorption technique to study the magnetic characteristics of soft magnetic microwires of different compositions in the wide frequency range from 9.5 to 37 GHz.

2. Samples

Samples of the microwires under study were the amorphous metal threads with diameter of about 5 μm covered by an insulating Pyrex coating layer with thickness of about 5 μm. They were prepared by the Taylor–Ulitovsky technique [7,8]. According to this technique the pellet of the amorphous metal, placed inside a Pyrex glass tube, was melted by the inductance coil and then extracted from the melt by the special rolling system. During the extraction process the water stream cooled the metallic core and its Pyrex coat. The fast cooling provided the amorphous state for both materials. The composition of the materials under investigation is described by the formulas $Fe_{69}Si_{16}B_{10}C_5$, $Co_{75}Si_{10}B_{15}$ and $Co_{68}Mn_7Si_{10}B_{15}$. Their saturation magnetostriction values, λ_s, were $+20$, -2 and $+0.1$ ppm, respectively [9].

3. Installation and technique

Magnetic resonance spectra of the samples were registered in the wide frequency band (9.5, 20–27 and 30–37 GHz) at room temperature. For X-band (9.5 GHz) the commercial *Bruker EMX* spectrometer was used for the measurements. The field derivative of microwave power absorption, $\mathrm{d}P/\mathrm{d}H$, was registered as a function of the static magnetic field H.

The high-frequency (HF) modules for K-band (20–27 GHz) and for Q-band (30–37 GHz) were specially designed for operating with standard 10 GHz-band Bruker spectrometer to extend its research capabilities. During the high-frequency measurements the amplitude modulation of HF signal was used with square-law detection of amplitude-modulated signal. Then its low-frequency envelope was transferred to the lock-in amplifier of the Bruker spectrometer and further analyzed with its software. As a result the microwave power absorption (P) as a function of the static magnetic field was detected in K and Q bands. Two types of quasi-single-mode resonators (cylindrical one and rectangular one) were designed for the high-frequency modules. The movable bottoms of resonators provide their tuning on the resonance frequency with an accuracy of about 0.5% in the range of frequency bands mentioned above. The unloaded quality factors for this set of resonators were in the range of 1–4×10^3.

The samples with the length of about 3–5 mm were placed in the maximum of the electric component of high-frequency field inside the resonator. We shall call this location as an *e-location* to distinguish from *h-location* when the sample is placed in the maximum of magnetic component of HF-field. The conventional ferromagnetic resonance (FMR) is measured in the *h-location*. In the rectangular resonator for TE_{102} mode the samples were placed on the teflon pedestal which filled the resonators cross section. The height of the pedestal was chosen in a way to provide maximum of the electric component of HF-field, i.e. equal to a quarter of the working wavelength. A set of pedestals for different frequencies was used. As a result the disturbing influence of the sample on the resonance mode appeared to be about 1 dB. The location of the samples in the resonator is shown in Fig. 1a.

The choice of *e-location* in the magnetoresonance absorption measurements has been dictated by the intention to measure the samples in the same geometry as in the standard magnetoimpedance measurements. It makes possible to compare our experimental results for the parallel geometry (see below) with results received by

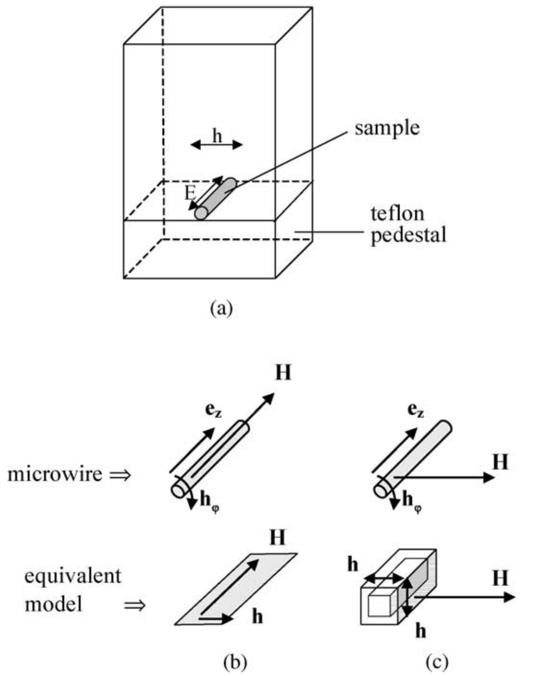

Fig. 1. The "e-location" of the samples in the magnetoresonance investigations of the microwire specimens in the rectangular resonator (a). The equivalent models for parallel (b) and perpendicular (c) orientations of the microwires are shown.

other authors. The wire samples have been directed along the electric field component of HF field in the resonator (Fig. 1a). In this case, the microwave currents flowing along the wire induce circumferential HF magnetic field in the wire. In the conventional FMR the direct absorption of a magnetic component of microwave field in a sample is measured. In contrast to this, in our experiments the absorption of circumferential magnetic component of HF field induced by electric component is measured. The dependence of this absorption on the static magnetic field showed resonant behavior. To avoid confusion with the conventional FMR we call this absorption as magnetoresonance absorption.

4. Results and discussion

K-band magnetic resonance spectra of the microwires for two orientations of the static magnetic field, parallel and perpendicular to the microwire direction, are presented in Fig. 2. The magnetic resonance spectra were measured as a function of angle (α) of the static magnetic field ($\boldsymbol{H}$) relative to the wire axis ($\boldsymbol{k}$). Spectra splittings

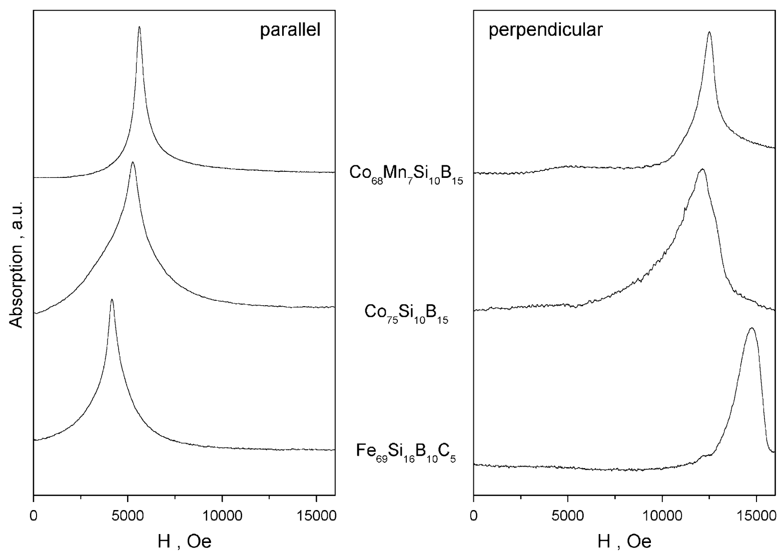

Fig. 2. The magnetoresonance spectra for $\nu = 27.0\,\mathrm{GHz}$ of the amorphous microwires in both orientations (parallel and perpendicular) of the static magnetic field with respect to the microwire axis.

or remarkable line distortions toward the perpendicular direction were observed in the X-band. Therefore, the digital integration of the X-band signal (dP/dH) was performed. Next, similar to the K and Q bands, the DC magnetic field corresponding to the peak value of absorption was assigned as the resonance field, and full-width at half-maximum (FWHM) of the resultant absorption signal envelope was used as the linewidth. Angular dependences of the resonance field and the linewidth for the X-band measurements are shown in Fig. 3. The dependences of the resonance field on the wire orientation in the K ($\nu = 24\,\text{GHz}$) and Q ($\nu = 33\,\text{GHz}$) bands are shown in Fig. 4. Finally, the dependences of the resonance magnetic fields on frequency in extremal (parallel and perpendicular) orientations of the samples are presented in Fig. 5(a) and (b) as the frequency versus resonance field plots.

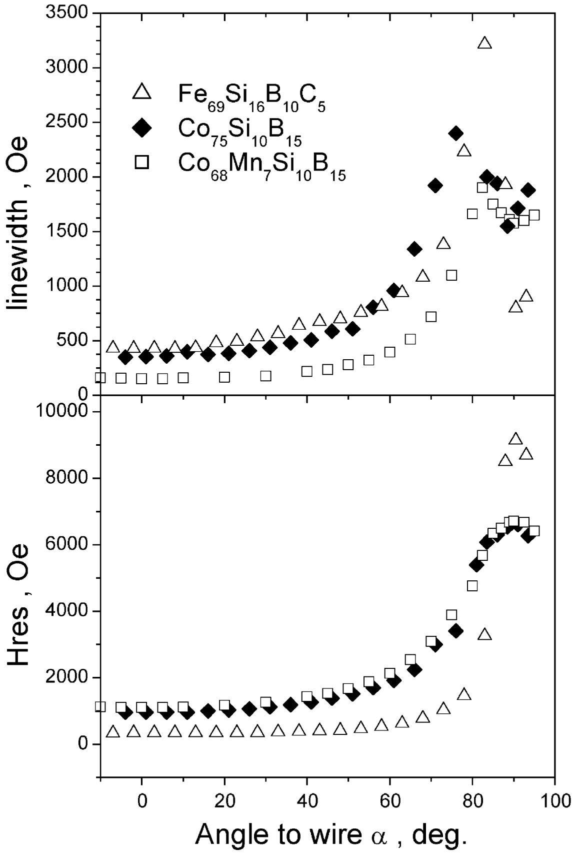

Fig. 3. The dependence of resonance field (H_{res}) and linewidth of absorption spectra on the microwire orientation (α) with respect to the static magnetic field in the X ($\nu = 9.5\,\text{GHz}$) band.

For all samples the orientation dependence (Figs. 3 and 4) was typical for the ferromagnetic resonance absorption: in the perpendicular orientation ($\boldsymbol{H} \perp \boldsymbol{k}, \alpha = 90^\circ$) the absorption lines are shifted to the high magnetic fields, in the parallel one ($\boldsymbol{H} \| \boldsymbol{k}, \alpha = 0^\circ$) they are shifted to the low-field region. From the graphs in Fig. 3 it is seen that the resonance fields in parallel and perpendicular orientations differ much more for the sample $Fe_{69}Si_{16}B_{10}C_5$ than for other samples. This reflects the fact that the saturation magnetization of $Fe_{69}Si_{16}B_{10}C_5$ exceeds those for $Co_{75}Si_{10}B_{15}$ and $Co_{68}Mn_7Si_{10}B_{15}$ samples.

We can estimate effective values of g-factor and saturation magnetization (M_s) by using the well-known Kittel equations for a long cylinder

$$H \perp k : h\nu = g\beta\sqrt{H(H - 2\pi M_S)},$$
$$H \| k : h\nu = g\beta(H + 2\pi M_s),$$

where h is the Planck's constant, β is the Bohr magneton, and g is the spectroscopic splitting factor.

The use of extremal values of resonance field for parallel and perpendicular geometry in X, K, and Q bands (9.5, 24 and 33 GHz, correspondingly, see Figs. 3 and 4) result in very unreasonable values of g-factor (from 1.1 up to 2.0), although the g-value expected is about 2.1. Furthermore, the values of the material characteristics, saturation magnetization M_s and g-factors, are changing appreciably with the microwave frequency (g-factor changes up to 70%, while M_s up to 40%). An attempt to fit the observed frequency dependencies in parallel orientation (Fig. 5a) by use of the FMR formulas for a sample of the cylindrical shape did not result in reasonable values of g-factor and magnetization either. These are not surprising results because it has been shown by Menard et al. [10] in their calculations of the magnetoimpedance at high frequencies ($\geqslant 1\,\text{GHz}$) that due to the effect of skin depth the resonant mode in coaxial cylindrical conductor is a nonuniform solution, which is quite different from the usual FMR uniform mode. It is remarkable that the resonance condition for this

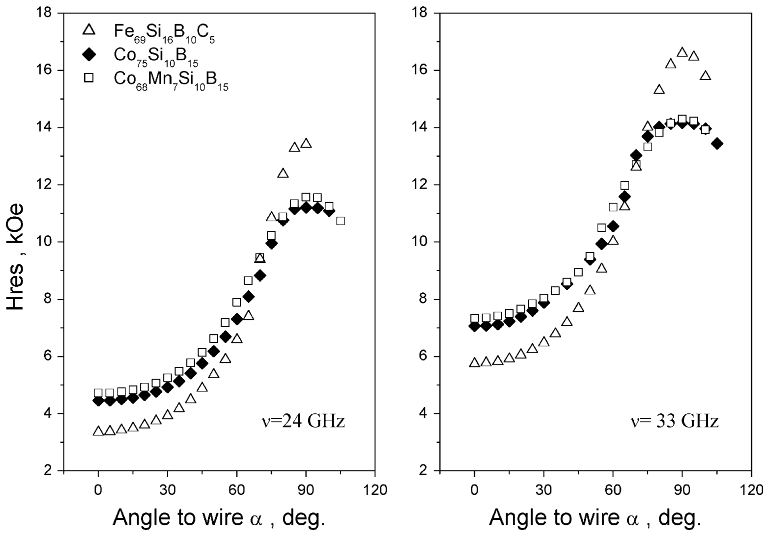

Fig. 4. The dependence of resonance field (H_{res}) of magnetic resonance signal on the microwire orientation (α) with respect to the static magnetic field in the K ($\nu = 24$ GHz) and Q ($\nu = 33$ GHz) bands.

mode appeared to be nearly the same as uniform solution of thin plate with the static field aligned parallel to the plane. From physical point of view, if the condition $\delta/a \ll 1$ is fulfilled, the resonating outer layer of a wire may be considered as a thin sheet of thickness δ and width $2\pi a$ (Fig. 1b), where a is the radius of wire, δ is the skin depth.

According to Ref. [11] at resonance frequencies ~ 10 GHz the skin depth $\delta \leqslant 1\,\mu$m. At higher frequencies (up to 36 GHz) we expect even smaller skin depths. Thus, instead of the solid cylinder we have to use the model of hollow cylinder for overall frequency range of our measurements, and especially in the high-frequency bands. This is a reason why the classical FMR solution for the plate in the parallel geometry may be accepted as a good approximation for the high-frequency impedance of the cylindrical wire.

The well-known Kittel formula [12] for the thin film, $h\nu = g\beta\sqrt{H(H + 4\pi M_s)}$, has commonly been used in the first calculations of GMI frequency dependence for microwires. More recently [13–15], it has been shown that the anisotropy fields should also be taken into account. Moreover, it is well known that the combination of the magnetoelastic anisotropy with the shape anisotropy gives the special domain structure of the soft amorphous wires with different regions in the wire cross section (it is the structure that is responsible for GMI response at low frequencies and very small magnetic fields) [16]. It is known (see Refs. [3,17,18], for example) that the magnetoelastic anisotropies in the microwires are induced by stresses quenched in microwire core. These stresses appear in the process of microwire fabrication due to difference in the thermal expansion coefficients between the coating glass and the metal core. As a result, the resonance condition is modified as follows: $h\nu = g\beta\sqrt{(H + H_a)(H + 4\pi M_s)}$.[1] The best fits using this model (Fig. 5a) show excellent matching to experimental results with quite reasonable values of g-factor, saturation magnetization M_s and anisotropy field H_a (Table 1).

For perpendicular orientation (Fig. 5b), we have described the experimental situation qualitatively by the model of hollow square cross section bar consisting of two slabs of the skin depth thickness, which are parallel to static magnetic field, and

[1] It should be noted here that this formula is generally valid only in the case if the easy axis of anisotropy field is along the wire axis. In the case when the hard axis direction is parallel to the wire, the resonance condition is modified to $h\nu = g\beta\sqrt{(H - H_a)(H + 4\pi M_s - H_a)}$. But due to rather small values of anisotropy fields concerned, the same equation, as in the main text, can be used in both cases (positive H_a for easy axis and negative H_a for hard axis).

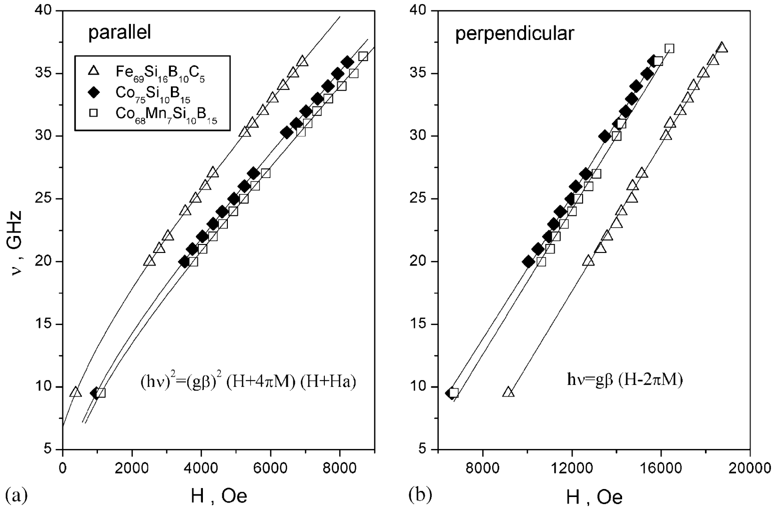

Fig. 5. The dependence of magnetic resonance field (H) on frequency (ν) in the parallel (a) and perpendicular (b) orientations. Solid lines (both orientations) present the best fits with use of the models discussed.

Table 1

Sample	$Fe_{69}Si_{16}B_{10}C_5$	$Co_{75}Si_{10}B_{15}$	$Co_{68}Mn_7Si_{10}B_{15}$
g-factor	2.139 ($\pm$0.022)	2.134 ($\pm$0.023)	2.138($\pm$0.03)
M_s, G	1016 ($\pm$33)	740 ($\pm$32)	648 ($\pm$41)
H_a, Oe	396 ($\pm$17)	15 ($\pm$32)	$-$10($\pm$53)

other two slabs that are perpendicular to the external field (Fig. 1c). The direction of the circumferential high-frequency field is represented in the model to be always parallel to the slab surface and perpendicular to the bar (i.e. wire) axis. The parallel pumping geometry is realized for the "parallel" slabs, so the contribution of these parts of bar to the overall magnetoresonance response is assumed to be negligible. Therefore, only the perpendicular to the external static field parts of the square bar are expected to contribute mainly in the magnetoresonance signal. Then, following closely the derivation of FMR formulas by Kittel [12], we established that in our model the resonance condition has the same form as for thin plate aligned perpendicular to the static magnetic field, but the value of demagnetizing factor should be changed for $2\pi M_s$, i.e. we have $h\nu = g\beta(H - 2\pi M_s)$. This is because the demagnetization factor, N_z, entering the macroscopic induction in the direction of the external DC field, $B_z = H_z - N_z M_s$, must be 2π in the direction (z) perpendicular to the slab or cylinder, not 4π as for the thin film.

The above model approximation represents the real situation only in a qualitative manner. Therefore, the fit of the model to the experimental data on frequency dependence in Fig. 5b could not provide the accurate values of magnetization (and anisotropy fields if they are included in the above equation), but the values of g-factor appeared to be reasonable and very close to the values obtained from the fit in parallel orientation. We obtained the following values: $g = 2.10$, 2.09, and 2.07; $M_s = 954$, 537, and 583 for $Fe_{69}Si_{16}B_{10}C_5$, $Co_{75}Si_{10}B_{15}$, and $Co_{68}Mn_7Si_{10}B_{15}$ compositions, respectively. It is remarkable that the model of hollow cylindrical tube appropriately describes also the orientational dependencies of the resonance field. The values of g-factor obtained from the model formulas are in the range 2.1–2.3, the values of magnetization are similar to those obtained from frequency plots, and these values *do not vary* with the microwave frequency.

When approaching the perpendicular orientation the linewidth increases (Fig. 3). We may suggest that the following sources are responsible for the broadening of the resonance line in the perpendicular orientation:

- the spread of resonance fields caused by the fact that the sample is placed in the unconventional magnetic resonance location (see Fig. 1c);
- the influence of inhomogeneity of the composition and other local material structure parameters;
- the influence of the anisotropy fields in the surface layer of wire.

As was mentioned above, the stresses, quenched in microwire core, result in a special kind of the anisotropy field distribution. It is known (see Ref. [17], for example) that the easy axes of magnetization rotate from longitudinal orientation at the central axis of the wire to (1) a circular one at the wire surface if material has a negative or nearly zero magnetostriction coefficient (as it is in our case for $Co_{75}Si_{10}B_{15}$ and $Co_{68}Mn_7Si_{10}B_{15}$ microwires), or (2) a radial one for positive magnetostriction ($Fe_{69}Si_{16}B_{10}C_5$ microwire). Therefore, the inhomogeneity of the anisotropy fields in various microscopic parts of wire should affect the magnetoresonance linewidth in the perpendicular orientation much more than for the parallel one.

5. Conclusions

We summarize in conclusion that:

1. Magnetic properties of soft magnetic microwires have been measured in the wide high-frequency band (9.5–37 GHz).
2. It was revealed that for 5-μm diameter wires with rather small conductivity the role of the skin layer in the magnetic absorption remains fundamental.
3. It was established that the model of hollow cylindrical tube rather than bulk cylinder is suitable to describe the magnetoresonance absorption of the samples in the high-frequency band.
4. The values of the spectroscopy g-factor, saturation magnetization, and anisotropy field have been estimated for the amorphous microwires. They are: for $Fe_{69}Si_{16}B_{10}C_5$—$g = 2.139$, $M_s = 1016\,G$, $H_a = 396\,Oe$; for $Co_{75}Si_{10}B_{15}$—$g = 2.134$, $M_s = 740\,G$, $H_a \sim 15\,Oe$; and for $Co_{68}Mn_7Si_{10}B_{15}$—$g = 2.138$, $M_s = 648\,G$, $H_a \sim -10\,Oe$.

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