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SHORT
COMMUNICATIONS

Impedance and Magnetic Properties of CoFeCrSiB Amorphous Ribbons near the Curie Point

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Abstract—The influence of temperature on the magnetic properties and magnetoimpedance of $Co_{64}Fe_3Cr_3Si_{15}B_{15}$ and $Co_{67}FCr_3Si_{15}B_{12}$ amorphous ribbons having different Curie points are studied. The impedance and its component are found to change greatly when the ribbons pass into the paramagnetic state. This finding can be used to determine the Curie point of ferromagnets and design high-sensitivity thermal transducers.

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INTRODUCTION

Technological advances place more and more stringent requirements on external action transducers. The basic requirements are good metrological characteristics and high reliability. The search for appropriate sensor materials leads us to a new type of functional media—amorphous ferromagnetic metallic alloys.

To date, conditions allowing researchers to impart desired functionality to these materials have been studied fairly comprehensively. For example, their magnetic properties can be controlled by varying the composition of the amorphous alloy and applying heat treatment [1, 2]. The specific magnetic properties of amorphous and nanocrystalline alloys give rise to a variety of phenomena that are of fundamental and applied interest, such as the magnetoimpedance effect [3, 4]. The magnetoimpedance effect consists in the magnetic field dependence of the electrical impedance of a conductor, and this dependence is characterized by the appropriate magnetic permeability. In the case of magnetically soft amorphous alloys, the relative variation of the impedance magnitude in fields on the order of several oersteds may exceed 100%. Therefore, these materials seem promising for measuring transducers entering into sensors of weak magnetic fields, including those produced by certified biological objects [4, 5]. Since the magnetic permeability may greatly vary with temperature, there arises the problem of thermal stability of the magnetoimpedance measuring transducers. This point was touched upon, e.g., in [6, 7]. However, the behavior of the impedance and magnetoimpedance at temperatures below room temperature and near the Curie point is poorly understood.

It was found [8] that the impedance of single-crystalline FeSiBSiNb wires changes drastically near the Curie point because the circular magnetic permeability significantly drops when exchange bonds between nanocrystallites break. The sharp variation of the impedance near the Curie point can also be expected for amorphous ferromagnets. Since this phenomenon may be used in creating high-efficiency thermal transducers, investigation into the impedance of amorphous alloys near the ferromagnetic phase transition seems to be of particular importance. Moreover, the good corrosion resistance and the high strength of these materials suggest that they can be applied even under severe service conditions.

In this work, we study the influence of temperature on the magnetic properties and impedance of $Co_{64}Fe_3Cr_3Si_{15}B_{15}$ and $Co_{67}FCr_3Si_{15}B_{12}$ amorphous ribbons near the Curie point.

EXPERIMENTAL

$Co_{64}Fe_3Cr_3Si_{15}B_{15}$ and $Co_{67}FCr_3Si_{15}B_{12}$ ribbons were prepared by fast quenching from the melt on a rotating drum. The length, width, and thickness of the ribbons were, 50 mm, 2 mm, and 20 μm, respectively. Their structure was examined by X-ray diffraction analysis (PHILIPS X'PERT PRO diffractometer, $\mathrm{Cu}K_\alpha$ radiation).

The magnetoimpedance was studied in the temperature interval T = 170–400 K. To achieve temperatures below and above the room value, the samples were placed in a nitrogen vapor flow and a heated air flow, respectively. The temperature of the samples was measured with a thermocouple.

The real, R, and imaginary, X, parts of impedance Z were measured using an automated magnetoimpedance spectrometer [9] for an effective value of the variable probe current of 10 mA in the frequency range f = 0.1–70.0 MHz. The magnetoimpedance effect was studied in magnetic fields H up to 150 Oe. The external magnetic field and the variable probe current were aligned with the long side of the sample. The impedance magnitude was calculated by the formula $Z = (R^2 + X^2)^{1/2}$.

Relative change $\Delta Z/Z$ of the impedance was found from the expression

$$\frac{\Delta Z}{Z} = \frac{Z(T) - Z(T_C)}{Z(T_C)} \times 100\%,$$

where $Z(T)$ is the value of the impedance at temperature T and $Z(T_C)$ is the value of the impedance at the Curie point.

From the temperature dependence of the magnitude of the impedance, its temperature sensitivity normalized to $Z(T_C)$ was calculated,

$$S_Z = \frac{\partial Z}{\partial T}\frac{1}{Z(T_C)} \times 100\%.$$

Temperature sensitivities S_R and S_X of the real and imaginary parts, respectively, were calculated in the same way.

The temperature behavior of the magnetic properties was studied with a vibrating-coil magnetometer in the temperature range 90–420 K. The ribbons in this case were 9 mm long.

RESULTS AND DISCUSSION

According to X-ray diffraction analysis data, the ribbons were amorphous. The reflection intensity slightly increased only in the 2θ range 40°–55°. Heating of the samples in the temperature interval studied did not change their structure.

Magnetometric data show that the magnetization of the ribbons of both compositions monotonically drops with rising temperature (Fig. 1). Although the compositions of the alloys differ insignificantly, their Curie points differ markedly. For the $Co_{64}Fe_3Cr_3Si_{15}B_{15}$ alloy, the Curie point is near 250 K (Fig. 1a), while that for the $Co_{67}FCr_3Si_{15}B_{12}$ alloy is about 380 K (Fig. 1b). Thus, slightly varying the composition of the alloy, one can vary its Curie point in wide limits.

Unlike the magnetization, the impedance in a zero magnetic field first grows with increasing temperature and only then declines, as follows from the temperature dependences of $\Delta Z/Z$ (Fig. 2). Such behavior of the impedance is more pronounced for $Co_{67}FCr_3Si_{15}B_{12}$ ribbons (Fig. 2b). The ascending part of the curve indicates that the magnetic permeability rises, which, in view of the temperature dependence of the magnetization (Fig. 1), may be associated with a considerable decrease in effective magnetic anisotropy [7]. Near the phase transition, the impedance, as well as the magnetization, significantly drops. The temperature at which the impedance of the ribbons reaches a minimum is their Curie point. At higher temperatures, the impedance slightly grows, since the conductivity of the alloy decreases.

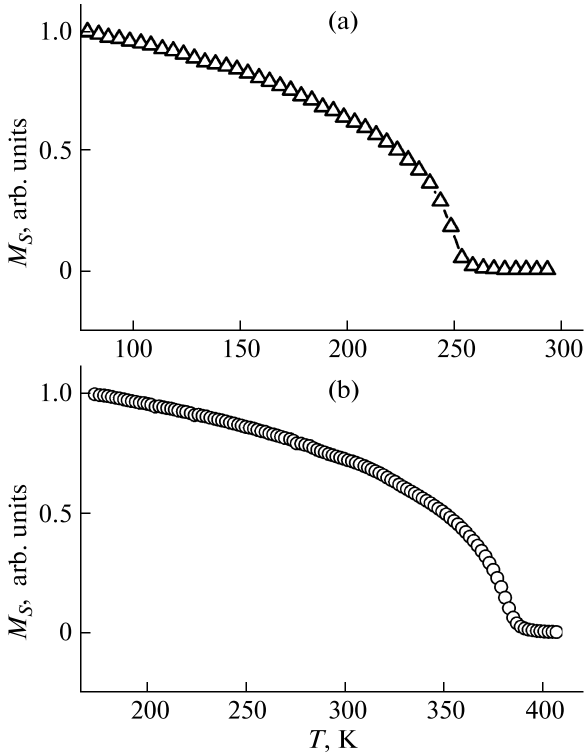

Fig. 1. Relative temperature variation of the magnetization for the (a) $Co_{64}Fe_3Cr_3Si_{15}B_{15}$ and (b) $Co_{67}FCr_3Si_{15}B_{12}$ ribbons.

The temperature variation considerably influences the variation of the impedance in an external magnetic field (Fig. 3). From magnetic dependence $Z(H)$ of the impedance, it follows that at temperatures below the Curie point, the impedance rises to maximum value Z_{max} with increasing magnetic field strength, which depends on the temperature and variable current frequency. As H grows further, the impedance declines monotonically. With an increase in the temperature, the ascending and descending portions of the magnetic dependence of the impedance become less pronounced, approaching the zero-field value of the impedance. At the Curie point or higher, the impedance depends on the external magnetic field only slightly, because the alloy passes into the paramagnetic state and the magnetoimpedance effect fades out.

Normalized temperature sensitivity S_Z of the impedance magnitude reaches a maximum near the phase transition for the ribbons of both compositions at a variable current frequency of about 2 MHz (insets to Fig. 2). For the $Co_{64}Fe_3Cr_3Si_{15}B_{15}$ and $Co_{67}FCr_3Si_{15}B_{12}$ alloys, the maximum value equals 8 and 9%/K, respec-

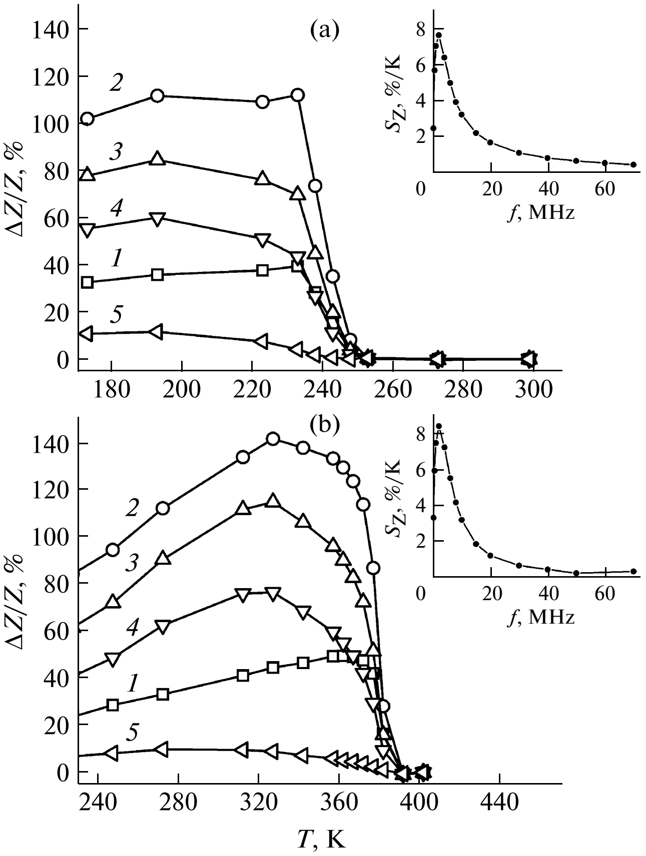

Fig. 2. Relative temperature variation of the impedance magnitude for the (a) $Co_{64}Fe_3Cr_3Si_{15}B_{15}$ and (b) $Co_{67}FCr_3Si_{15}B_{12}$ ribbons. Curves $\Delta Z/Z$ (T) were obtained at a variable current frequency of (*1*) 0.1, (*2*) 2.0, (*3*) 6.0, (*4*) 10.0, and (*5*) 70 MHz. The insets show the frequency dependences of maximal normalized temperature sensitivity S_Z of the impedance magnitude.

tively. These values are an order of magnitude higher than the sensitivity of platinum thermistors.

Although the temperature sensitivity of the impedance is rather high, the sensitivity of impedance transducers may be raised further by detecting the components of the impedance, rather than its magnitude. It was shown [2, 5] that the relative variations of the impedance components in a magnetic field may exceed those of the impedance magnitude.

The frequency dependences of the impedance components suggest that there exists variable current frequency f_{XR} below which temperature sensitivity S_X of the imaginary part is higher than temperature sensitivity S_R of the real part. Above this frequency, the situation is reversed (Fig. 4). At a frequency of 100 kHz, S_X equals 100%/K for the ribbons of both compositions. As the frequency rises, sensitivity S_X declines considerably, whereas S_R increases. The intense growth of S_R is observed at a variable current frequency of 6 MHz: here, S_R reaches a value of 10%/K and then remains almost independent of the frequency. Consequently, the imaginary part of the impedance has the highest temperature sensitivity, the maximal value of S_X being observed at low frequencies of the variable current. This greatly simplifies the measurement procedure. This counts in favor of using the imaginary component of the impedance in impedance thermal transducers.

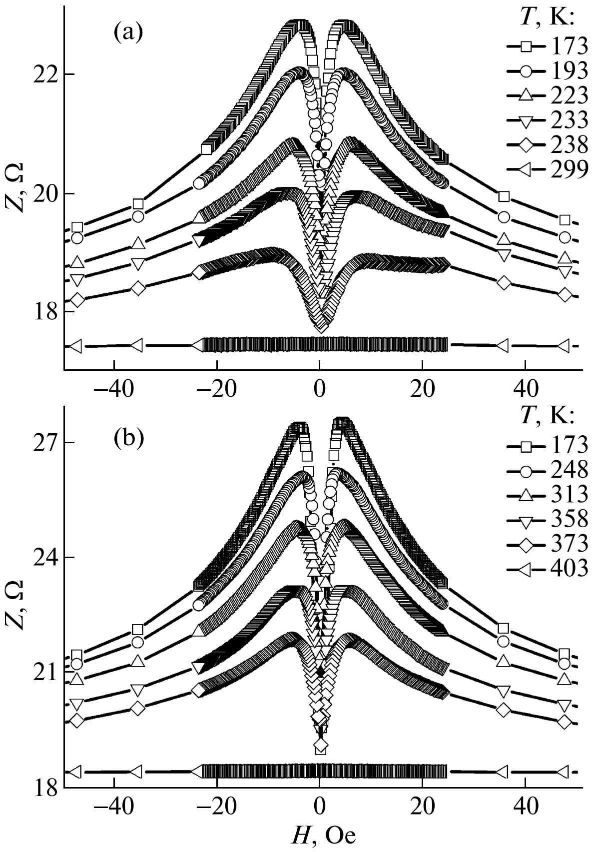

Fig. 3. Magnetic field dependences of the impedance for the (a) $Co_{64}Fe_3Cr_3Si_{15}B_{15}$ and (b) $Co_{67}FCr_3Si_{15}B_{12}$ alloys. The curves were obtained at a variable current frequency of 70 MHz in the temperature interval 173–403 K.

Thus, the considerable change in the impedance properties of these ribbons near the ferromagnetic phase transition can be used both to determine the Curie point and to create thermal transducers offering a high sensitivity in a narrow temperature interval. By varying the composition of the alloy, one can control the Curie point to achieve a maximal sensitivity of the transducer in a desired temperature range. Such transducers would be useful in designing thermal anemometers, gas analyzers, and other devices. In addition, they can be applied in multifunctional sensor networks simultaneously monitoring several physical parameters, such as magnetic field strength and temperature. The possibility of using the same physical (magnetoimpedance) effect would greatly simplify the architecture of this multifunctional sensor network.

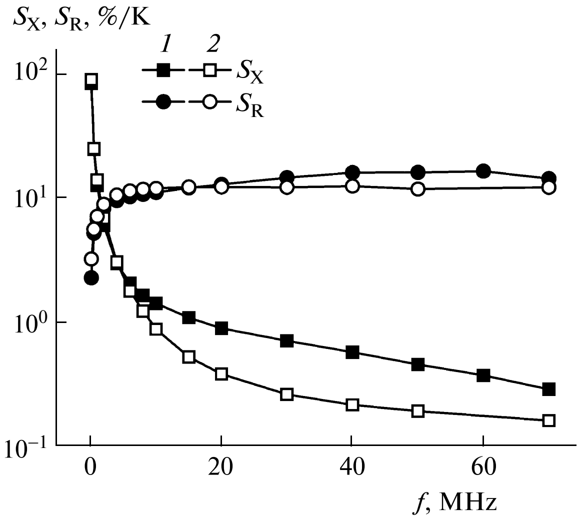

Fig. 4. Frequency dependences of the maximal values of normalized temperature sensitivities of the imaginary, S_X, and real, S_R, parts of the impedance for the (*1*) $Co_{64}Fe_3Cr_3Si_{15}B_{15}$ and (*2*) $Co_{67}FCr_3Si_{15}B_{12}$ ribbons.

CONCLUSIONS

$Co_{64}Fe_3Cr_3Si_{15}B_{15}$ and $Co_{67}FCr_3Si_{15}B_{12}$ amorphous ferromagnetic ribbons were prepared by fast quenching from the melt. Magnetometric and magnetoimpedance measurements give 250 and 380 K for the Curie points of these alloys. For the ribbons of both compositions, the magnitude and components of the impedance change considerably near the ferromagnetic phase transition. This finding can be used for creating high-sensitivity thermal transducers and also for precisely determining the Curie point of amorphous ferromagnetic alloys.

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