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Thermal Conductivity and Diffusivity Measurements of Glass-Coated Magnetic Microwires Using Lock-in Thermography

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Abstract Magnetic microwires (with a diameter of a few tens of micrometers) have been introduced in the last years following the tendency in miniaturization of magnetic sensor devices. The aim of this work is to measure the thermal diffusivity (D) and thermal conductivity (K) of coated magnetic microwires made of a metallic core with glass coating. Both thermal properties are measured in amorphous and crystalline states. Lock-in infrared thermography, using a modulated and focused laser beam to heat the sample, is specially suited to study heat propagation along the wire.

Keywords Lock-in thermography · Magnetic microwires · Thermal conductivity · Thermal diffusivity

1 Introduction

The recent tendency in miniaturization of magnetic sensor devices requires development of novel advanced magnetic materials with improved magnetic properties. Among them, a family of thin wires with reduced geometrical dimensions (metallic nucleus of the order of 1 µm to 30 µm in diameter) gained special importance during the last few years [1]. Particularly, the development of a number of magnetic sensors based on the giant magneto-impedance (GMI) effect and the stress-impedance (SI) effect with C-MOS IC circuitry and advantageous features compared with conventional

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magnetic sensors has been reported [1]. Main possible applications are related to the detection of magnetic fields, small weights, and vibrations, and branches of the industry such as the car industry and medicine are main consumers of these sensors.

In this work, we have measured the thermal diffusivity of magnetic glass-coated microwires of the XBSi family, where X: Fe, Co, Ni. They consist of an amorphous metallic core surrounded by a Pyrex coating, resulting in a full diameter of about 25 μm. The method we have used, based on lock-in thermography, is specially designed to measure the thermal diffusivity of very thin filaments [2–5]. This method was calibrated with filaments of thicknesses ranging from 5 μm to 150 μm in a wide range of thermal diffusivities, from thermal insulators ($0.1\ \mathrm{mm}^2 \cdot \mathrm{s}^{-1}$) to good thermal conductors ($300\ \mathrm{mm}^2 \cdot \mathrm{s}^{-1}$) [3]. Then, taking advantage of the glass coating, the thermal conductivity of these magnetic microwires has also been obtained in both glassy and crystalline states.

2 Basics of the Technique

The technique we have used to measure the thermal diffusivity of magnetic microwires is lock-in infrared (IR) thermography [6,7], which has been widely used to measure the thermal diffusivity of solid samples. It consists of illuminating the sample by a focused laser beam, modulated at a given frequency (f), while an IR video camera records the wire temperature. A lock-in analysis of the image sequence at the modulation frequency provides the amplitude ($|T|$) and phase (Ψ) of the wire temperature. For thin filaments, heat propagation is one dimensional from the heating spot along the filament. If the sample is kept in vacuum, heat losses by conduction and convection are suppressed and only heat losses by radiation remain. Under this condition, linear relations are found when plotting the natural logarithm of the amplitude of the temperature ($\ln(|T|)$) and its phase (Ψ) as a function of the distance to the heating spot. The product of the slopes of these linear relations, $m_{\ln(|T|)}$ and m_{Ψ}, satisfies the following expression [2]:

$$m_{\ln(|T|)} \times m_{\psi} = \pm \frac{\pi f}{D}, \tag{1}$$

from which the thermal diffusivity (D) of the filament can be obtained in a simple but accurate way.

Moreover, in the case of coated filaments, Eq. 1 gives an effective value of the thermal diffusivity of the two-layer system along the filament (D_{eff}) which follows the in-parallel thermal resistor model [5],

$$D_{\mathrm{eff}} = \frac{K_{\mathrm{eff}}}{C_{\mathrm{eff}}} = \frac{K_{\mathrm{w}} v_{\mathrm{w}} + K_{\mathrm{g}} v_{\mathrm{g}}}{\frac{K_{\mathrm{w}}}{D_{\mathrm{w}}} v_{\mathrm{w}} + \frac{K_{\mathrm{g}}}{D_{\mathrm{g}}} v_{\mathrm{g}}}, \tag{2}$$

where C_{eff} is the effective heat capacity of the coated filament, v is the volume fraction, and subscripts w and g stand for wire and glass coating, respectively. As the thermal properties of the glass coating (Pyrex) are known ($K_{\mathrm{g}} = 1.12\ \mathrm{W} \cdot \mathrm{m}^{-1} \cdot \mathrm{K}^{-1}$, $D_{\mathrm{g}} = 0.65\ \mathrm{mm}^2 \cdot \mathrm{s}^{-1}$), the thermal conductivity of the wire can be retrieved.

3 Experimental Results and Discussion

The scheme of the lock-in thermography setup we have used is given in Fig. 1. The laser power is in the range from 50 mW to 200 mW. The filament is kept in a vacuum chamber at a pressure below 10^{-2} mbar. A sapphire window allows the IR emission from the filament to reach the IR video camera (FLIR SC7000 with the following technical specifications: spectral range from 3 μm to 5 μm, image size of 320 $\times$ 256 px, detector pitch of 30 μm, and maximum frame rate of 380 Hz). To optimize the spatial resolution, a 50 mm focal length lens is used at the minimum working distance. In this way, each pixel measures the average temperature over a square of 150 μm on a side in the sample.

In this work, three glass-coated microwires have been measured: $Fe_{74}B_{13}S_{11}C_2$, $Co_{77.5}B_{15}Si_{7.5}$, and $Ni_{77.5}B_{15}Si_{7.5}$. The Pyrex coating was removed by introducing the coated wire in pure fluorhydric acid for 5 min. These magnetic microwires are manufactured in an amorphous state (they belong to the category of metallic glasses). However, by means of an electrical current of a few tens of mA, the temperature of the wire rises above the glass transition temperature (around 600 K). By keeping the wire at this temperature for one hour, the magnetic microwire becomes crystalline. Accordingly, for each composition we have performed four measurements: with and without Pyrex coating in both amorphous and crystalline states.

Figure 2 shows ln ($|T|$) and Ψ of $Co_{77.5}B_{15}Si_{7.5}$ as a function of the distance to the heating spot at $f = 0.71$ Hz: on the left, the results for bare wires, and on the right, the results for coated wires. In each figure, dots stand for amorphous wires, while crosses denote crystalline filaments. As can be observed, good symmetry between left and right branches together with long straight lines covering several radians demonstrates the quality of the data. By applying Eq. 1, the thermal diffusivity for each filament is obtained. Table 1 summarizes the thermal-diffusivity values for all the magnetic microwires measured in this work. For statistical purposes, five specimens of each composition have been measured. Besides, data were collected at three modulation frequencies: 0.21 Hz, 0.71 Hz, and 1.21 Hz. The resulting uncertainty is 5 %.

Finally, from the thermal diffusivity of the glass-coated microwire (D_{eff}) and the thermal diffusivity of the bare metallic microwire (D_{w}), the thermal conductivity of

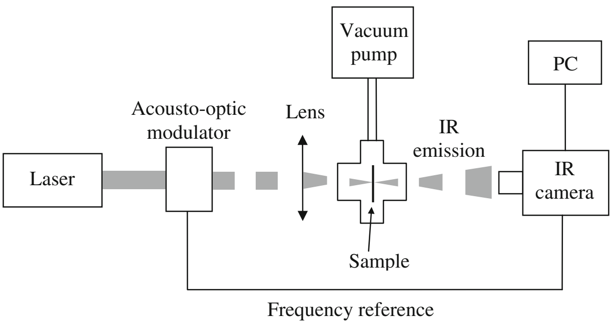

Fig. 1 Diagram of the experimental setup

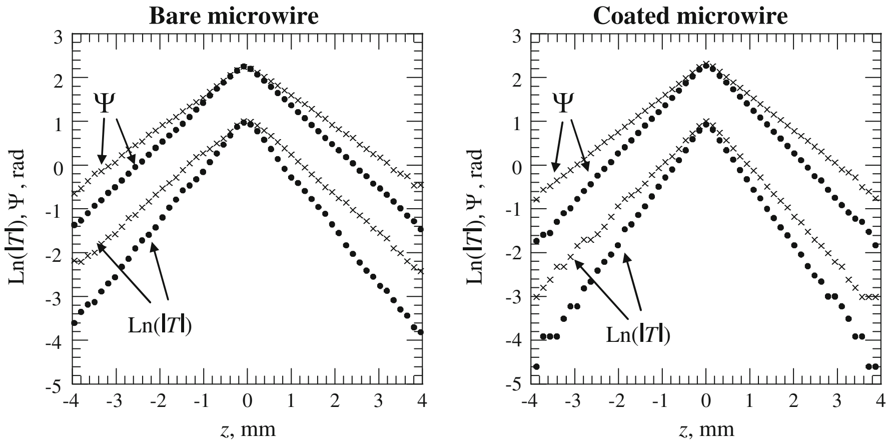

Fig. 2 Lateral dependence of $\ln(|T|)$ and Ψ at a frequency $f = 0.71$ Hz for a bare $Co_{77.5}B_{15}Si_{7.5}$ microwire of diameter 17.8 mm (*left*) and a Pyrex-coated version of diameter 22.8 mm (*right*). *Dots* stand for amorphous wires and *crosses* for crystallized filaments

Table 1 Summary of the thermal-diffusivity data of both glass-coated and bare-magnetic microwires

Material	Diameter of microwire (μm)	Diameter of metallic core (μm)	Glass-coated wire		Bare wire	
			D amorphous ($mm^2 \cdot s^{-1}$)	D crystalline ($mm^2 \cdot s^{-1}$)	D amorphous ($mm^2 \cdot s^{-1}$)	D crystalline ($mm^2 \cdot s^{-1}$)
$Fe_{74}B_{13}S_{11}C_2$	26.6	19.4	1.35	2.18	1.72	3.10
$Co_{77.5}B_{15}Si_{7.5}$	22.8	17.8	1.60	2.55	1.94	3.35
$Ni_{77.5}B_{15}Si_{7.5}$	29.8	16.3	1.67	2.20	3.53	4.67

The uncertainty is 5 %

Table 2 Summary of the thermal-conductivity values of amorphous and crystalline magnetic microwires obtained from Eq. 2

Material	ν_{wire}	K amorphous ($W \cdot m^{-1} \cdot K^{-1}$)	K crystalline ($W \cdot m^{-1} \cdot K^{-1}$)
$Fe_{74}B_{13}S_{11}C_2$	0.53	4.97	7.88
$Co_{77.5}B_{15}Si_{7.5}$	0.61	5.97	8.76
$Ni_{77.5}B_{15}Si_{7.5}$	0.30	7.80	11.7

The uncertainty is 10 %

the magnetic microwire is obtained (K_w) by solving Eq. 2. The results of the thermal conductivity are summarized in Table 2, for both amorphous and crystalline samples. The uncertainty is 10 %, which is much higher than for thermal diffusivity mainly due to the uncertainty in the wire diameters [5].

As can be observed, for each composition, both the thermal diffusivity and thermal conductivity increase by a factor of about 1.5 in the crystalline sample with respect to the amorphous one. This result indicates that the heat capacity ($C = K/D$) remains constant, as expected since it is a property depending on the sample composition and not on its structure. Anyway, the enhancement is not very strong, since the crystallization process produces a polycrystalline sample with very small nanocrystals, and therefore, the resulting large amount of grain boundaries limits the electron and phonon mean free paths. Besides, results are in good qualitative agreement with values found in the literature for ribbon samples of this type of metallic glasses [8].

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References

1. A. Zhukov, V. Zhukova, *Magnetic Properties and Applications of Ferromagnetic Microwires with Amorphous and Nanocrystalline Structure* (Nova Science Publishers, New York, 2009)
2. C. Pradere, J.M. Goyhénèche, J.C. Batsale, S. Dilhaire, R. Pailler, Int. J. Therm. Sci. **45**, 443 (2006)
3. A. Mendioroz, R. Fuente, E. Apiñaniz, A. Salazar, Rev. Sci. Instrum. **80**, 074904 (2009)
4. A. Salazar, A. Mendioroz, R. Fuente, Appl. Phys. Lett. **95**, 121905 (2009)
5. A. Salazar, A. Mendioroz, R. Fuente, R. Celorrio, J. Appl. Phys. **107**, 043508 (2010)
6. X.P.V. Maldague, *Theory and Practice of Infrared Technology for Nondestructive Testing* (Wiley, New York, 2001)
7. O. Breitenstein, M. Langenkamp, *Lock-in Thermography* (Springer, Berlin, 2003)
8. C.L. Choy, K.W. Tong, H.K. Wong, W.P. Leung, J. Appl. Phys. **70**, 4919 (1991)