Temperature Effects on the Magnetization and Magnetoimpedance in Ferromagnetic Glass-Covered microwires

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Abstract. The effect of temperature on static and dynamic magnetization in Co-based amorphous microwires was investigated with the aim of potential applications in miniature temperature sensors. The wires of two compositions with different magnetostriction and Curie temperature in glass-cover and after removing the glass layer demonstrated very different temperature behaviour of the magnetization loops and magnetoimpedance. The mechanisms of the temperature effects are related to the residual stress distribution due to fast solidification, the difference in thermal expansion coefficient of metal and glass and the proximity to the Curie temperature. The interplay of these factors may result in a very strong temperature dependence of magnetoimpedance in a moderate temperature range (room temperature – 373K). Such elements may be incorporated in various composite materials for a local temperature monitoring.

1. Introduction
The development of magnetic sensing materials with improved performance, microsize and wireless operation are increasingly critical for different applications. The present work tackles this problem through the investigation and design of temperature properties of micron-sized amorphous magnetic wires as embedded sensing elements. Ferromagnetic microwires have a number of specific magnetic properties such as a magnetic bi-stability [1-3] and very large magnetoimpedance (MI) [4-6]. All these effects can find applications in various sensors. For commercial applications, the thermal stability of sensing elements is mandatory; however, the magnetic properties of amorphous alloys may show the temperature dependence even for temperatures which are much lower than the Curie temperature. This is related with the internal stress distribution which is changed by heating. The other source of internal stresses is related with the presence of interfaces like in glass-coated microwires where there is a difference in thermal expansion coefficients of glass and metal. Finally, approaching the Curie temperature which can be tuned by the alloy composition will impose very strong temperature variations of all magnetic parameters. Therefore, understanding the influence of various sources of internal stresses on the temperature dependence of magnetic structure in amorphous elements is important for sensor design.

The magnetic anisotropy in amorphous alloys is mainly determined by magnetoelastic interactions [7], which explains why the internal stresses coupled with the magnetostrictive parameter strongly affect the magnetic structure. The saturation magnetostriction which depends on the alloy composition [8] may also depend on the internal stresses which further enhance the stress-dependence of the magnetization.
process. Tuning the magnetic structure with external stimuli will result in a corresponding dependence of magnetoimpedance [9].

Since the presence of glass coating adds an additional source of magnetoelastic anisotropy it would be interesting to compare the magnetic properties in as-prepared state and after glass removing [10, 11]. The removal of glass showed a remarkable impact on the magnetisation process in low magnetostrictive wires owing to the interface stress release. Consequently, the microwires without glass may possess higher temperature stability of magnetic properties and more sensitive magnetoimpedance [12]. Along with this, the temperature stability will be also improved by appropriate heat treatments [13].

In this paper, we are interested in the temperature effects on the magnetic anisotropy and the related static and dynamic magnetic properties including magnetization loops and magnetoimpedance in glass-covered amorphous microwires of Co-rich compositions having a small saturation magnetostriction. We have studied the effect of temperature on magnetic hysteresis loop and the magnetoimpedance for as-prepared microwires and after glass removing. We have used the wires made of alloy compositions with a relatively high and low curie temperatures.

2. Materials and Experimental details
We investigated the effect of temperature (from room temperature up to 373 K) on the hysteresis loops and magnetoimpedance in glass coated microwires before and after glass removing. Glass-coated microwires were fabricated by a modified Taylor–Ulitzovsky method [14, 15]. Microwires of two compositions Co_{66.91}Fe_{3.83}Ni_{14.4}B_{11.5}Si_{14.59}Mo_{1.69} (sample No.1, T_c = 573 K) and Co_{23.09}Fe_{7.14}Ni_{13.08}B_{13.85}Si_{12.26} (sample No.2, T_c=335K) were used. In as-prepared stay, the wires had a different magnetostriction coefficients: small and negative for sample No. 1 and positive for sample No. 2. The glass cover was removed by chemical method with hydrofluoric acid solution. The geometric parameters of microwires were examined by an optical microscope.

The Curie temperature and crystallization temperature were estimated from DSC curves using standard IT application. The experimental magnetization loops were measured by an inductive method having two detection differential coils having 3mm of the inner diameter and 5mm of length. The magnetization coils were excited by a current of frequency up to 500Hz producing a magnetization field with an amplitude of 1000A/m. To obtain the hysteresis curves, the generated voltage signal was digitally integrated into a very small detection coil.

The high-frequency impedance was deduced from S21-parameters measured using a vector network analyser (Hewlett Packard 8753E) in a special cell designed for temperature measurement at frequencies of 1-100 MHz.

3. Result and discussion
The magnetization curves for wires in as-prepared state and after glass removal are shown in figure 1. For sample No.1 after removing the glass the hysteresis changes dramatically: from an inclined loop to a loop of a bi-stable type. This indicates a change in the easy anisotropy direction: from nearly circumferential to nearly axial. In the case of sample No.2 (positive magnetostriction) the type of hysteresis after glass removing does not change but the coercivity reduces from 51 down to 20 A/m. this indicates that indeed the metal-glass interface imposes an additional stress. In the case of a negative magnetostriction in as-prepared state, the glass removal and associated stress release may cause a change in the sign of the magnetostriction- it becomes positive which results in the abrupt change of hysteresis. In the case of a positive magnetostriction in as-prepared state, the glass removal and the associated stress release decreases the magnetostrictive anisotropy and coercivity.
Figure 1. Hysteresis loops of microwires with composition Co\textsubscript{66.94}Fe\textsubscript{3.83}Ni\textsubscript{1.44}B\textsubscript{11.51}Si\textsubscript{14.59}Mo\textsubscript{1.69} (sample No.1, T\textsubscript{c}=573K) and Co\textsubscript{23.67}Fe\textsubscript{7.14}Ni\textsubscript{43.08}B\textsubscript{13.85}Si\textsubscript{12.26} (sample No.2, T\textsubscript{c}=335K) in as prepared state (with glass, depicted by red line) and after glass removal (depicted by blue line).

Figure 2. Real part of the impedance of glass-coated microwires of composition Co\textsubscript{66.94}Fe\textsubscript{3.83}Ni\textsubscript{1.44}B\textsubscript{11.51}Si\textsubscript{14.59}Mo\textsubscript{1.69} (sample No.1) before (a) and after (b) glass removing for different temperatures. Applied frequency is 80 MHz.

MI of glass-coated wires of alloy No. 1 exhibits strong variation with temperature: two symmetrical peaks gradually merge and a single peak at a zero field is seen at a temperature of 335K (which is still much lower than the Curie temperature) as seen in figure 2 a. However, after glass removal, the impedance temperature dependence considerably weakens which indicates the major role of glass-metal interface in forming the magnetoelastic anisotropy and associated temperature effects. For sample No.2 which has a positive magnetostriction, an axial anisotropy and a relatively low Curie temperature, in both as-prepared and after glass removal states a considerable temperature dependence of MI is observed. In this case the major temperature effect is associated with approaching the Curie temperature.
In this case, the major factor determining the temperature sensitivity is related with the interplay of a low Curie temperature and reduced anisotropy. Controlling the value of $T_c$ the impedance temperature dependence can be realized in the desired temperature range.

4. Conclusion

We have determined that the magnetization and magnetoimpedance in glass-coated microwires may show remarkable temperature dependence. This is related with the temperature dependent internal stress distribution and with the variation of magnetic parameters when approaching the Curie temperature. In the case of high Curie-temperature alloys, the effect of internal stresses on the temperature stability of magnetoimpedance in intermediate temperature range may be reduced by glass removal. This is important for commercial applications of MI wires. However, for alloys with a relatively high Curie temperature the temperature influence on MI may be even stronger after glass removal owing to reduced anisotropy? Which can be interesting for designing temperature sensitive elements.

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References

[1] Chiriac H and Ovari T A 1996 Applications Progr. Mater. Sci. 40 333
[2] Zhukov A and Zhukova V 2009 Nova Science Publishers, New York ISBN: 978-1-60741-770-5
[3] Vazquez M, Chiriac H, Zhukov A et.al 2011 Phys. Status Solidi A 208 493
[4] Panina L and Mohri K 1994 Appl. Phys. Lett. 65 1189
[5] Knobel M and Pirota K R 2002 J. Magn. Magn. Mater. 242/245 33
[6] Tannous C 2004 Materials in Electronics 15 125
[7] Zhukov A, Ipatov M, Garcia C, Gonzalez J, Panina L, Blanco J M and Zhukova V 2008 PIERS
Proceedings, Hangzhou, China

[8] Zhukov A 2006 Adv Func Mat 16 675
[9] M, Roy R K, Panda A K, Greve D W, Ohodnicki Jr.P R, McHenry M E 2014 J. Appl. Phys. 105 222407
[10] Zhukova V, Ipatov M and Zhukov A 2009 Sensors 9 9216
[11] Shevyrtalov S, Chichay K, Ershov P, Khovaylo V, Zhukov A, Zhukova V and Rodionova V 2015 Acta Physica Polonica A 127 603
[12] Panina L V and Mohri K 1994 Applied Physics Letters 65 1189
[13] García C, Zhukov A, Gonzalez J, Zhukova V and Blanco J M 2006 Journal of Optoelectronics and Advanced Materials 8 1706
[14] Taylor G F 1924 Physical Review 23 655
[15] Vázquez M, Advanced magnetic microwires, in: H.Kronmuller, S.Parkin 2007 (Eds.), Handbook of Magnetism and Advanced Magnetic Materials, Wiley, Chichester, UK 2193