High Frequency Magneto Impedance in Amorphous Microwires

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Abstract. We report the novel results on studies of the magneto impedance (MI) effect at GHz-range in 20 µm amorphous glass-coated microwire and 40 µm melt-extracted wire with nearly-zero magnetostriction constant. Both types of wires demonstrated similar behavior although the MI effect is higher in glass-coated microwire. In high field region, when the sample is magnetically saturated, the MI dependence demonstrates typical ferromagnetic resonance behavior. In the low field region the magnetization rotation process is dominant resulting in the highest sensitivity of the impedance to magnetic field. The drawback found in the studied samples is the low field magnetic hysteresis which is undesirable for potential application. The cause of this hysteresis is found to be the helical surface anisotropy in the wires which is characterized by a nonzero angle between the anisotropy easy axis and the wire’s transversal plane.

1. Introduction
Magnetically soft amorphous microwires have recently attracted growing attention because of their excellent soft magnetic properties, giant magneto impedance effect and extremely small dimensions. The magneto impedance (MI) is understood as the dependence of the impedance of a ferromagnetic sample on the external magnetic field and its high sensitivity to magnetic field is a key factor for applications, such as, magnetic micro-sensors and tuneable composite materials among other [1, 2, 3]. A small negative magnetostriction (of about \(-10^{-7}\)) coupled with the radial stress distribution in the outer shell of the microwire determines a circumferential magnetostriction and a transverse permeability highly sensitive to axially applied magnetic field. Up to hundreds percents of the impedance changes were reported in amorphous wires with vanishing magnetostriction [4, 5]. A strong stress anisotropy is induced in amorphous wires during the solidification at a very high cooling rate. Although the magnetoelastic coupling is minimizing with reducing the magnetostriction constant, it is decisive in amorphous wires determining their magnetic properties. The annealing can be used for tailoring of the magnetic properties and MI of amorphous wires [6].

In this work, we studied two types of amorphous microwire: glass-coated produced by Taylor-Ulitovsky method [7] and melt-extracted [8]. We observed the high MI effect in the both types of wires. Also we found the magnetic hysteresis in low field region and gave the explanation of this phenomena.
2. Results and discussion

We studied the MI effect in Co$_{67.1}$Fe$_{3.8}$Ni$_{1.4}$Si$_{14.3}$B$_{11.5}$Mo$_{1.7}$ amorphous glass-coated microwire with metallic nucleus diameter $d = 21.4 \, \mu m$ and glass coating thickness of $2.4 \, \mu m$, and in Co$_{79.6}$Fe$_{4.6}$Si$_{9.2}$B$_{2.7}$Mo$_{3.9}$ melt-extracted wire with diameter $40 \, \mu m$. The impedance was measured with a vector network analyzer in reflection mode. The frequency range was $0.01–1.5 \, \text{GHz}$ external magnetic field up to $15 \, \text{kA/m}$.

Fig. 1 shows the magnetic field dependence of the real part of impedance in glass-coated microwire and melt-extracted wire. Both types of wires demonstrated similar behavior although the MI effect is higher in glass-coated microwire especially at low frequencies. The amorphous wires with vanishing magnetostriction are known to be very soft magnetic materials with low anisotropy field. Fig. 2 shows the frequency dependence of impedance at external magnetic field $1.2 \, \text{kA/m}$ which is larger than the anisotropy field $H_k$ and the sample is in magnetically saturated state. The MI dependence demonstrates typical ferromagnetic resonance (FMR) behavior with resonance frequency $f_{res}$ having maximum value of the real part of the impedance and the
imaginary part crossing zero. We plotted the $f_{res}^2(H)$ dependence in Fig. 3. The high field region of the $f_{res}^2(H)$ dependence fits very well with linear behavior predicted by the FMR theory.

In the low field region, that is up to 1.2 kA/m for glass-coated microwire, the dependence becomes nonlinear with the field (see Fig. 3). The change of MI in this region arises from the magnetization reorientation under the action of the external magnetic field. The MI exhibits highest sensitivity to magnetic field $\partial Z/\partial H$ in this region. The static bulk hysteresis loops for both sample are shown in Fig. 4. One can note that the glass coated microwire (sample 1) is magnetically much softer then the melt-extracted one (sample 2).

An observable peculiarity of the low field region is the magnetic hysteresis. The scaled view of Fig. 1 with the central part of the MI field dependence is shown in Fig. 5. Here one can note the magnetic hysteresis with width of 190 A/m for glass-coated microwire and 136 A/m for melt extension microwire. The MI hysteresis which is surface, is much higher than the bulk one (compare Fig. 4 and Fig. 5) as the latter is integral characteristic of the whole volume. Particulary this deference is high for glass-coated sample. This hysteresis is very undesirable for high sensitive magnetic field sensor application as it limits the sensor’s resolution. Nevertheless, the problem of the low-field MI hysteresis in amorphous wires has not been satisfactorily studied yet and should be further investigated.

To explain the experimentally observed hysteresis of MI, we adapted the concept of helical
anisotropy in amorphous wires [9, 10]. Fig. 6 shows the principal wire directions in microwire. Here α and θ are the angles between the anisotropy easy axis and magnetization direction with the transversal plane. The external magnetic field \( H \), applied along the \( z \) axis, makes the magnetic moment \( M_0 \) rotate through angle \( \theta \) in the field direction. The magnetization orientation can be found by minimization of the total energy \( U \) over the angle \( \theta \). The total energy includes the energy of magnetic anisotropy and the energy of external magnetic field \( H \):

\[
U = K_1 \sin^2(\theta + \alpha) - M_0 H \sin \theta,
\]

(1)

where \( K_1 \) is the anisotropy constant. We neglect the energy of the demagnetization field as the wires’ length (7 mm) is much higher than their radii. The equilibrium angle \( \theta \) is calculated from Eq. 2:

\[
H \cos \theta = H_k \sin 2(\theta + \alpha)/2,
\]

(2)

where \( H_k = 2K_1/M_0 \) is the surface anisotropy field. The modeling of the magnetization projection \( M_z/M_s = \sin \theta \) dependence on normalized magnetic field for angle \( \alpha = \pi/20 \) is shown in Fig. 7. It is clear seen that the dependence \( M_z(H) \) has hysteresis in the low field region. Therefore, as the impedance depends on equilibrium magnetization state, it will exhibit hysteresis behaviors as well.

### 3. Conclusions

Here we report the novel results on studies of the MI at GHz-range in 20 \( \mu \)m amorphous glass-coated microwire and 40 \( \mu \)m melt-extracted wire with nearly-zero magnetostriction constant. Both types of wires demonstrated similar behavior although the MI effect is higher in glass-coated microwire. At applied magnetic field above anisotropy field \( H_k \) where the sample is magnetically saturated, the MI dependence demonstrates typical ferromagnetic resonance behavior.

In the low field region, the impedance exhibits highest sensitivity to magnetic field \( \partial Z/\partial H \). The high magnetic sensitivity is obviously important for sensor application. The drawback found in the studied samples is the magnetic hysteresis that considerable affect the sensor’s resolution. This hysteresis does not change with the frequency and is attributed to the static magnetization process. The cause of the low field hysteresis is found to be the helical surface anisotropy in the wires which is characterized by a nonzero angle \( \alpha \) between the anisotropy easy axis and the wire’s the transversal plane.

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