High Frequency Magneto-Impedance Measurements in Amorphous Wires

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Abstract **-**Magneto-impedance spectra in 100 kHz - 14GHz frequency range were measured at different magnetic fields in CoFeSiB amorphous wires. Three types of measuring techniques were used for three different frequency ranges (100 kHz- 110 MHz, 1 MHz – 3 GHz, 10 MHz – 14 GHz), the results were compared in order to establish the accuracy of the measurements and the limitation of each measuring cell. For each measuring technique there is a frequency domain determined by the measuring cell characteristics (geometry, losses, etc.). Over the maximum limit of the frequency domain unpredictable behavior could appear and the same measurement using different technique did not match. High GMI ratio, up to 400%, was found for CoFeSiB amorphous glass covered microwires at frequencies close to 50 MHz.

I. Introduction

Magnetic amorphous wires with nearly zero magnetostriction show high sensitivity of the giant magneto-impedance (GMI) effect, being promising for magnetic sensors applications. An intensive study of GMI effect in such wires has been performed by researchers during the last years. The GMI effect sensitivity in amorphous wires depends mainly on the wire composition, which is responsible for the magnetostriction constant but also on the mechanical stresses induced by the fabrication process. The stress distribution determines the value of the circumferential magnetic anisotropy constant and the value of the magnetic permeability at the wire surface.

The GMI effect consists of significant changes of the impedance value of a magnetic conductor (wire, ribbon, thin layers) passed by a high frequency current when it is subjected to a DC bias magnetic field. The oscillating magnetic field produced by the AC exciting current inside the sample induces rotations of the magnetic moments and domain wall motions; these effects might not involve the entire sample cross section, because the penetration depth of the electromagnetic fields inside the material is a function of the relative magnetic permeability and frequency [1-2].

The AC circular magnetic field, H_φ, generated by the driving current flowing trough the magnetic conductor determines changes of the circular component of the magnetization, M_φ. The applied DC bias magnetic field affects the circumferential permeability of the magnetic conductor, determining modifications of the ac current penetration depth, which are closely related to the impedance value at a given frequency. This is the interpretation in terms of the classical skin effect in a magnetic conductor assuming the scalar character for the magnetic permeability. The electrical impedance, Z, of a magnetic conductor in this case is given by [1]:

$$Z = R_{DC}krJ_0(kr)/2J_1(kr) \quad (1)$$

with

$$k = (1+j)/\delta \quad (2)$$

where J_0 and J_1 are the Bessel functions, r – wire radius and δ the penetration depth given by:

$$\delta = (\pi\sigma\mu_\varphi f)^{-1/2} \quad (3)$$

Recently this model was modified by taking into account the tensor characteristic of the magnetic permeability and impedance. It was theoretically shown that the dependence of the GMI spectra is mainly determined by the type of the magnetic anisotropy. The circumferential anisotropy leads to the observation of the maximum GMI ratio as a function of the DC bias magnetic field. In order to achieve highest GMI effect the magnetic anisotropy should be as smaller as possible. The development of the new sensitive sensors based on the GMI effect requires high sensitivity at low external magnetic field.

II. Experiment

CoFeSiB nearly zero magnetostrictive glass covered microwares with metallic core radius 20 μm and different glass coating thickness have been used as sample in the experiment.

For hi frequency the used sample holder consists in a coaxial (microwave) cavity with the sample playing the role of the central conductor. The sample ends were fixed to the sample holder by using silver loaded adhesive (fig 1 d, f). The maximum frequency of the applied AC current for a given sample length is limited by the $\lambda/4$ condition. The sample length has to be no longer than $\lambda/4$, above this length resonant phenomena could appear. For frequencies up to 3 GHz the maximum sample length is around 25 mm while for 5 mm sample length the frequency could achieve, theoretically, 15 GHz. The measurement frequency could be increased further, but this will determine the sample length to become shorter and very difficult to prepare. Also the glass cover and specific domain structure could be affected by reducing to much the sample length. A pair of Helmholtz coils has been used to produce an axial DC bias magnetic field for measurements performed with impedance analyzers because of the bigger test fixtures size and cables connections compared with the test fixture for network analyzer, a connection cable in fact, that enable us to use a long solenoid which could produce much stronger fields.

The frequency of the AC current trough the probe should be high enough, usually above 100 kHz, in order to have significant change of the impedance with the applied DC bias magnetic field. On the other hand, to study de magneto-impedance effect at frequencies above 10 MHz the sample holder (measuring cell) should have special design and the electrical cables should have special HF specifications.

In the classical magneto-impedance setup the impedance of the magnetic conductor is calculated from the measured voltage, V_1, and the current value, I, calculated using the voltage measurement across an accurately known low value resistor, R.

$$\boxed{|Z_x| = V_1/I = R\,(V_1/V_2)} \qquad (4)$$
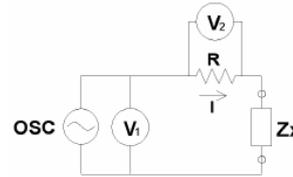
The conventional volt-amperometric (V-I) technique progressively looses sensitivity on increasing frequency, and is usually limited to a few MHz; at high frequencies, it is not even applicable, because the wavelength of the driving current becomes comparable to the geometrical dimensions of the samples (usually some centimeters or less). Due to these limitations for hi frequency it is important to use different measurement techniques for different frequency ranges. For measurements three types of instruments (Agilent) with different measurement techniques was involved: the Agilent 4294A impedance analyzer based on the auto balancing bridge method with a frequency range 40 Hz – 110 MHz, the Agilent 4991A that use the RF volt-amperometric technique with a frequency range 1 MHz – 3 GHz and the Agilent N5230A vector network analyzer with the frequency range 10 MHz – 50 GHz.

In the auto balancing bridge method the current, flowing through the wire, also flows through the reference resistor. The potential at the low terminal is maintained at zero volts (thus called a "virtual ground"), because the current through the resistor balances with the wire current by operation of the current to voltage converter amplifier. The wire impedance is calculated using voltage measurement at High terminal and that across the reference resistor. The Agilent 4294A impedance analyzer employ the current to voltage converter consisting of sophisticated null detector, phase detector, integrator (loop filter) and vector modulator to ensure a high accuracy for a broad frequency range over 1 MHz. This type of instrument can attain to a maximum frequency of 110 MHz. [3]

The RF V-I measurement method is based on the same principle as the V-I method, but it is configured in a different way by using an impedance matched measurement circuit (50 Ω) and a precision coaxial test port for operation at higher frequencies. There are two types of the voltmeter and current meter arrangements; which are suited to low impedance and high impedance measurements. Impedance of the device under test (wire) is derived from measured voltage and current values. The current that flows through the wire is calculated from the voltage measurement across a known low value resistor, R. In practice, a low loss transformer is used in place of the low value resistor, R. The transformer limits the low end of the applicable frequency range. [3]

In the case of Network analysis method the impedance is calculated using the reflection coefficient ($\Gamma_{dut}=(Z_{dut}-Z_0)/(Z_{dut}-Z_0)$). The reflection coefficient is obtained by measuring the ratio of an incident signal to the reflected signal. A directional coupler or bridge is used to detect the reflected signal and a network analyzer is used to supply and measure the signals. Since this method measures reflection at the device under test, it is usable in the higher frequency range. [3]
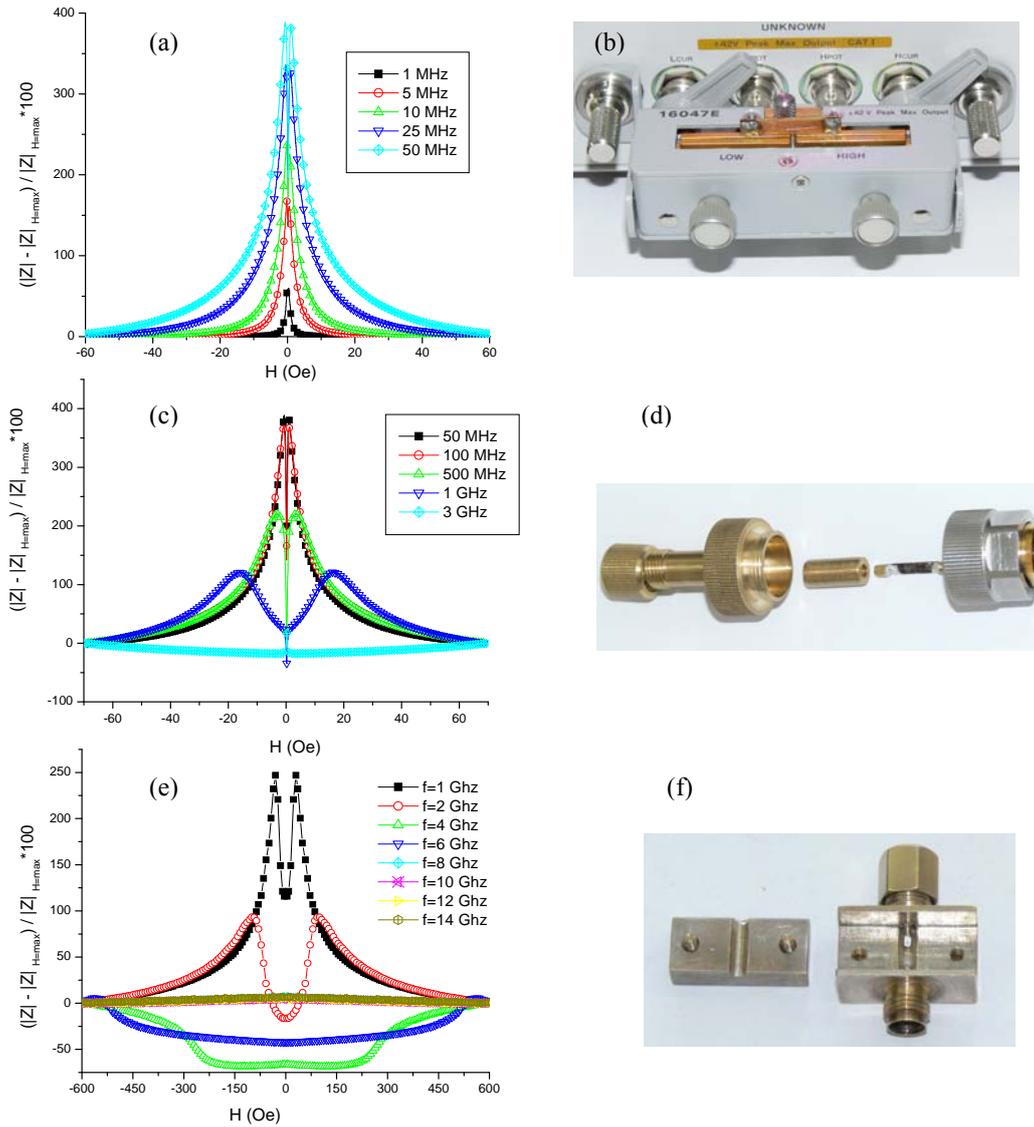
III. Results and Discussions

Figure 1. Magneto-impedance and giant magneto-impedance measurements for CoFeSiB amorphous wires with metallic core radius 20 µm and glass coating thickness 5 µm using three different techniques: a, b) GMI curves obtained by auto-balancing bridge method (Agilent 4294A) using a standard Agilent fixture (fig 1.b) in the 500 KHz – 100 MHz frequency range; c, d) GMI curves obtained by RF V-I method (Agilent 4991A) using a custom measuring cell with impedance matched at 50 Ω for 7 mm connector (fig 1.d) in the 50 MHz – 3 GHz frequency range; e, f) Magneto-impedance curves obtained using a vector network analyzer (Agilent N5230A) and a custom measuring cell with impedance matched at 50 Ω for 2.4 mm connector (fig 1.f) in the 50 MHz – 14 GHz frequency range;

GMI effect is characterized by GMI ratio usually defined as:

$$\Delta Z/Z \ (\%) = 100 \ x \ \{|Z(H)| - |Z(H_{max})|\}/|Z(H_{max})| \qquad (5)$$

where $|Z|$ is the impedance modulus and H_{max} is the maximum applied field at which the sample is considered to be magnetically saturated. Another way to define GMI ratio is

$$\Delta Z/Z \ (\%) = 100 \ x \ \{|Z(H)| - |Z(H=0)|\}/|Z(H=0)| \qquad (6)$$

this is usually the case when the GMI curve shows double peaks and low field behavior must be investigated. The shift of the maximum towards higher fields as the frequency increases can be explained considering the existence of a radial anisotropy profile in the wire. An increase in the frequency is associated with a decrease in the penetration depth of the AC current trough the sample. For very high frequencies the current is flowing only trough a layer close to the surface of the material. The observed increase with frequency of the magnetic field values where GMI ratio reach maximum can be explained considering that the anisotropy is not homogeneous in all the wire section, but increase close to the surface. As the local anisotropy is higher, the peaks move toward higher values of the applied magnetic field. For very high frequencies, the anisotropy can be so large that the maximum applied field is not enough to saturate the sample (fig 1.c, e). In the same time at very high frequency (above 3 GHz) the GMI curves starts to change sign while the maximum is shifted to magnetic field values greater than the maximum applied field. The field at which the maximum GMI value is displayed on this case may not be related to or only to anisotropy energy, another possible explanation is the appearance of the ferromagnetic resonance [4]. The change of sign of the GMI curve is due to the normalization at highest applied field instead of zero or saturation magnetic field (the way the magnitude of the GMI effect is expressed).

In the figure 1 graphs c) and e) the difference between GMI curves obtained for frequencies between 1 GHz and 3 GHz using the RF V-I method (Agilent 4991A) and Network analysis method (Agilent N5230A) can be observed. In the case of RF V-I method using Agilent 4991A and the 7 mm custom measuring cell (fig. 1. graph f) stray peaks appear around zero magnetic field for frequencies above 1 GHz. The reason for the peaks appearance seams to be the self resonance of the measuring cell.
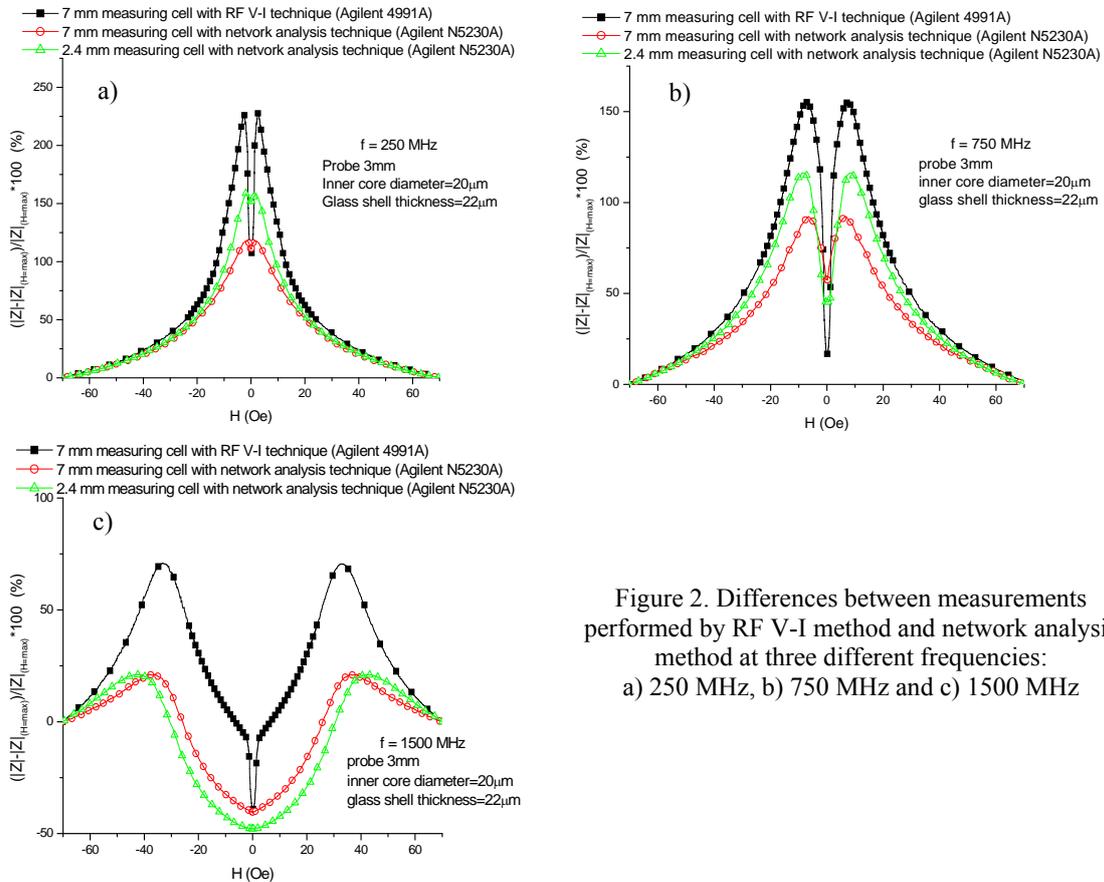

Figure 2. Differences between measurements performed by RF V-I method and network analysis method at three different frequencies:
a) 250 MHz, b) 750 MHz and c) 1500 MHz

The condition for resonance at this frequency is satisfied only for zero applied magnetic field. By applying the bias magnetic field the resonance frequency is shifted to high values due to the modifications of the permeability of the sample inserted in the measuring cell. The limitation of the RF V-I 7 mm measuring cell seems to be close to 1GHz, for high frequency more accurate results are obtained by moving to the network analysis technique as it can be seen on the figure1 graph e.

To clearly show the difference between the measurements performed by RF V-I method and network analysis method probes with the same length was prepared and inserted in the measuring cells (about 3mm in length, 20 microns diameter of the metallic inner core and 22 microns thickness of the glass shell). Also the same measuring cell (7mm) was used for both measuring methods at different frequencies to put into evidence the limits of the measuring techniques and the influence of the measuring cell characteristics. In the figure 2 a it is clear that the GMI spectra at 250 MHz obtained by the RF V-I technique did not mach with the spectra obtained by network analysis even though two different measuring cell was used (7 mm and 2.4 mm) The network analysis technique seems to be not the best choice for this frequency domain. At a little bit higher frequency (750 MHz) the slope of the GMI curves are the same Fig. 2 b and we can conclude that for this frequency domain both measuring techniques are adequate. Going up with the frequency around 1 GHz we rich the limit of the RF V-I measuring technique as revealed by the GMI curves presented in the graph 2 c. Another interesting observation is that the magnitude of the GMI ratio is affected both by the measuring technique and measuring cell characteristics.

IV. Conclusions

For each measuring technique there is a frequency domain determined by measuring cell characteristics (geometry, losses, etc.) and probe characteristics (geometry, permeability). Over the limits of each frequency domain unpredictable behavior could appear and the same measurement using different techniques and/or measuring cells did not match (fig 1. graph c and f at frequencies over 1 GHz and fig 2.). The measurement results for different samples can not be directly compared if they are not performed in the same conditions for booth the method and the measuring cell.

The strongest GMI response is present in Co rich wire shaped amorphous alloys because of theirs specific magnetic domain structure consisting of an axially magnetized inner core and a circumferentially magnetized outer shell. The circumferential permeability behavior plays an important role in this effect, being closely related to the above mentioned domain structure. High GMI ratio, up to 400%, was found for CoFeSiB amorphous glass covered microwires at frequencies close to 50 MHz (fig.1 graph a and c). The estimation of the GMI magnitude is useful if we want to compare the behavior of different types of probes in the low magnetic field range.

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