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Effect of Bias Fields on off-Diagonal Magnetoimpedance (MI) Sensor Performance

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This paper investigates the performance of off-diagonal magnetoimpedance in Co-based amorphous wire subjected to dc bias fields: circular and orthogonal (with respect to the wire axis). Typically it is assumed that the wire impedance is insensitive to the orthogonal field so the wire element can be used to construct 3D sensors. Our results demonstrated the possibility of large impedance change due to this field, in the range of 10 mV/Oe. The dc current in a wire generating a circular field results in improved sensitivity due to elimination of the domain structure and smoothing the effect of the anisotropy deviations.

Keywords: Off-diagonal magnetoimpedance, Pulsed magnetoimpedance, Magnetoimpedance sensor, Linear sensor, Amorphous magnetic wire, Bias field.

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1. INTRODUCTION

The effect of off-diagonal impedance in magnetic conducting elements referred to as off-diagonal magnetoimpedance (MI) has attracted a considerable interest over the last decade due to its importance for micromagnetic sensor development. AC current passing through a magnetic wire with a helical magnetisation generates a voltage not only across the wire but also in a coil mounted on it. The coil voltage is caused by cross magnetisation processes and is described by off-diagonal impedance [1-3]. A characteristic feature of this impedance is antisymmetric behaviour with respect to dc magnetisation which results in the possibility to realise near linear dependence on an external magnetic field within a certain field interval around zero point. A linear output is a desirable sensor characteristic allowing the direction of the magnetic field to be determined. Because of this, the off-diagonal configuration is preferable for sensor applications.

Practical off-diagonal impedance sensor design based on pulsed-current excitation was developed in a number of papers and successfully applied in commercial products as miniature magnetic compass [4-6]. Pulse excitation in MI sensors is typically realised with the help of CMOS inverter IC chip [7, 8] or a microcontroller [9, 10]. In spite of its simple scheme, the pulse excitation is described by a large number of input parameters: excitation current peak value, frequency of pulse repetitions, pulse width, pulse shape (rise and fall times), and all of them affect the sensor parameters. The investigation of the effect of all these factors would be difficult utilising the mentioned schemes. In the present paper, we used a functional generator to supply various ac excitations to the MI wire to investigate the effect of pulse shape and low frequency components on the off-diagonal voltage. The latter is of a particular importance to increase the output voltage since the existence of the domain structure may eliminate this voltage completely.

2. BASICS OF OFF-DIAGONAL SENSOR DESIGN

An ac current i passing through a magnetic wire (see Fig. 1a) generates a voltage U_w which may be very sensitive to the external magnetic field. This is known as a magnetoimpedance (MI) effect. If the wire has a helical magnetisation the voltage U_c is also generated in a coil mounted on it (Fig. 1b). The ratio $Z_c = U_c/i$ may be called off-diagonal impedance. In single-domain wires with the circumferential anisotropy Z_c is antisymmetrical with respect to axial magnetic field H_{ex} having near-linear region around zero field point. This characteristic can be used in linear sensing. A practical design of such a sensor is given in [7-10] where the wire element is exited by a pulse current of C-MOS IC multivibrator or a microcontroller.

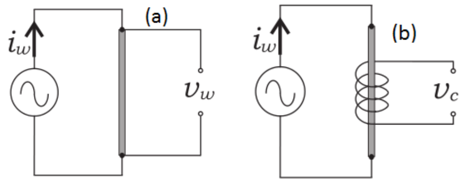

Fig. 1 – Methods of excitation and detection for MI sensing element. A high frequency current is provided to the MI element and the output voltage is measured across the wire (a) or from a coil mounted on it (b)

The off-diagonal MI can be also realised by exciting the wire by ac axial magnetic field induced by the coil and measuring the voltage across the wire. However, the coil self-inductance may considerably limit the excitation current at high frequencies. Therefore, the excitation scheme of Fig. 1b is preferable.

3. EXPERIMENTAL

The sensor design based on multivibrator or microcontroller excitation is important for practical application. But the setup suggested in Fig. 2 allows detailed investigation of the influence of various excitation pa-

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rameters on the sensor operation. The pulse generator may supply to the wire narrow current pulses of various shape and magnitude as well as a harmonic waveform with various dc bias current. The wire with a coil is placed in a long solenoid which produces a magnetic field in the range of ± 60 Oe. As a result of cross magnetization (off-diagonal MI), electromotive force is induced in the pickup coil wounded on the wire. The dependence $U_c = H_{ex}$ is captured by digital oscilloscope.

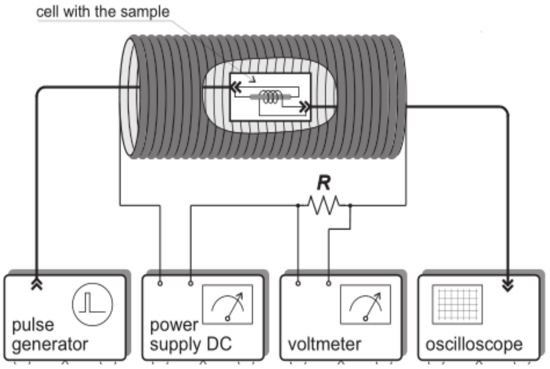

Fig. 2 – Experimental setup for off-diagonal MI

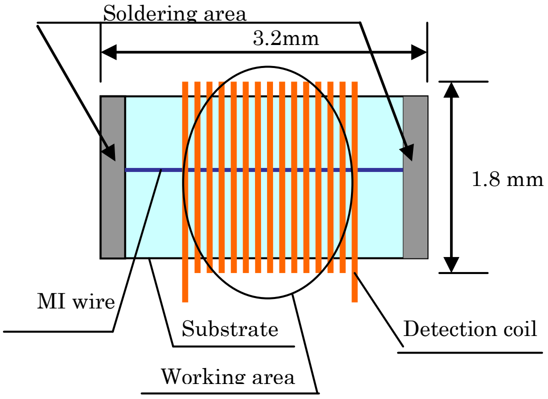

Fig. 3 – Schematics of non-diagonal MI sensor element consisting of Co-based amorphous wire on a polymer substrate and detection coil (40 mm diameter, 40 turns)

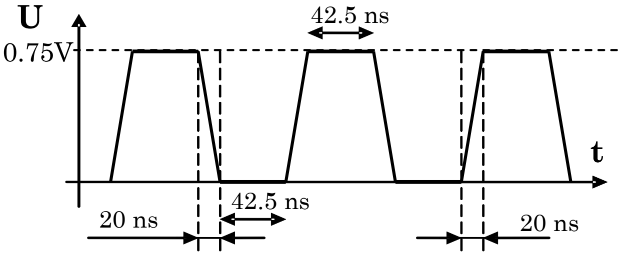

Fig. 4 – Pulsed excitation waveform applied to MI element. The peak of current in a wire is 5.77 mA

The sensor output was also investigated in orthogonal fields produced with a help of two Helmholtz coils.

An amorphous glass-coated wire of composition $Co_{66.94}Fe_{3.83}Ni_{1.44}B_{11.57}Si_{14.59}Mo_{1.69}$ was used as MI element. The metal core diameter was 16 µm and the total diameter was 16.8 µm. The wire of length was fixed on a plastic substrate. In the off-diagonal configuration, the high frequency excitation is applied across the MI element and the output signal is taken from the coil mounted on it. A detection coil was made of 40 µm diameter copper wire and had 40 turns. The overall sensor dimensions are 3.2 × 1.8 × 0.5 mm. The sensing element is shown in Fig. 3.

Two kinds of high frequency excitation waveforms produced by functional generator were supplied to the MI wire: pulsed and sinusoidal with a dc bias. The pulsed waveform is shown in Fig. 4. In this case, the rise / fall time is 20 ns which corresponds to a frequency of 50 MHz and the frequency of pulse repetitions is 8 MHz.

The analysis of frequency response of the sensor reviled that the LC-resonance of the sensor cell is around 8 MHz. The sinusoidal excitation with this frequency produced the largest output voltage as shown in Fig. 5. It is seen that there is another resonance mode with a frequency of 4 MHz.

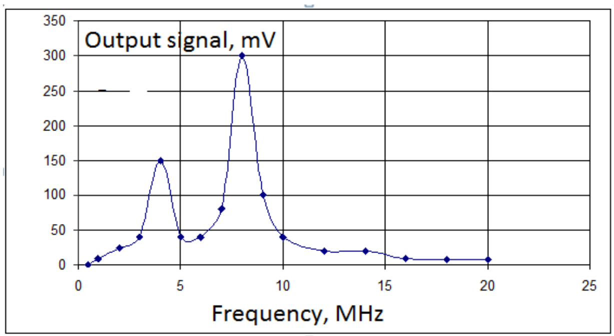

Fig. 5 – Frequency characteristics of the sensor output at sinusoidal excitation with zero dc bias current and in the presence of axial field of 1.5 Oe

4. EXPERIMENTAL RESULTS AND DISCUSSIONS

Typical output sensor characteristics as functions of external field are shown in Fig. 6 for different soldering methods. A pulsed excitation waveform shown in Fig. 4 was supplied to the MI wire. The soldering temperature was 300 °C and 100 °C for samples 1 and 2, respectively, and conducting glue at room temperature was used for sample 3. It is seen that the soldering method does not change significantly the curves where the sensitivity is maximal.

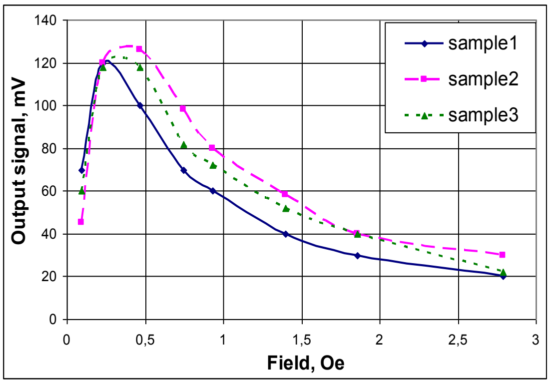

Fig. 5 – Output characteristics of 3 MI wire samples with different soldering process. The soldering temperature was 300 °C and 100 °C for samples 1 and 2, respectively, and conducting glue at room temperature was used for sample 3

Therefore, the soldering process even at relatively high temperatures does not change substantially the magnetic structure. In fact, a moderate temperature may improve the MI sensitivity. This can be related with a relaxation of certain internal stresses. The sensitivity is in the range of 600-700 mV/Oe and the linearity range is ± 0.3 Oe.

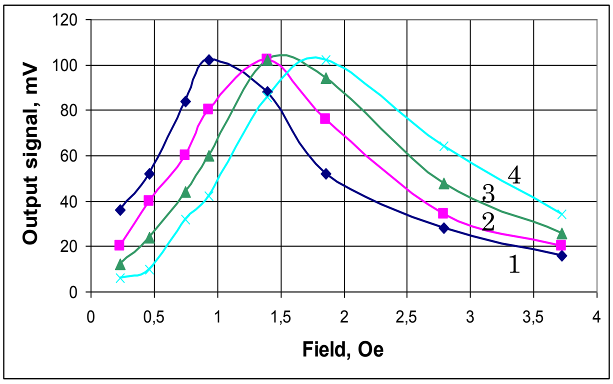

Fig. 7 – Effect of axial bias field on off-diagonal sensor response. DC current in a wire is: 1 – 0 mA, 2 – 1.59 mA, 3 – 3.17 mA, 4 – 4.76 mA

The range of linearity is rather small and if necessary the operational point could be moved by applying a dc axial bias using the same detection coil. The output signal for different axial bias is shown in Fig. 7. For a dc current of 4.76 mA creating a field of about 1.4 Oe in the direction opposite to the sensed field the linearity region is 0.6-1.3 Oe. It is also seen that the curves for different axial bias cannot be obtained by shifting along the field axis. This behaviour can be attributed to the existence of deviations of the easy anisotropy from the circular direction.

The sensor is sensitive to the field applied along the wire and the orthogonal field should not produce noticeable changes. This was investigated by considering the sensor output in orthogonal fields and the corresponding characteristics are shown in Fig. 8. It is seen that the sensitivity in the low field region indeed almost does not change; however, a rather large change in the range of 10 mV/Oe is seen for larger axial fields when the main contribution to the voltage response is related with the change in ac permeability. The analysis of off-diagonal impedance for a single-domain wire shows that the effect of the radial field of the order of few Oe should be negligible since the demagnetising field is about 3 kOe. However, the orthogonal field has a circular component depending on the position on the wire. For ideal homogeneous helical magnetisation this component will not affect the averaged ac permeability. However, due to deviations of the anisotropy, this influence may be noticeable. The normal field may also affect the circular domain coercivity since the existence of circular domain structure is probably related with the surface inhomogeneity and radial magnetisation. This behaviour requires additional investigation which is important for the development of 3D sensors with the use of orthogonal system of amorphous wires.

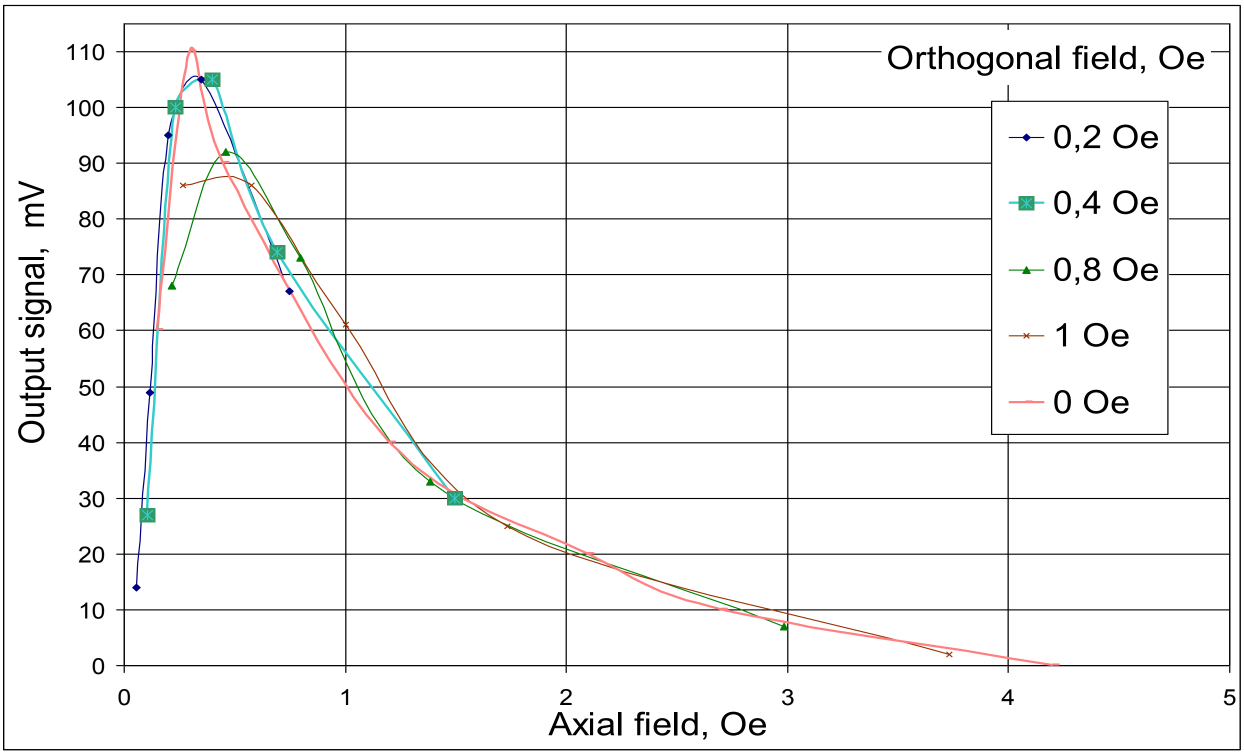

Fig. 8 – Sensor output as a function of axial field with orthogonal field as a parameter

Existence of a domain structure substantially deteriorates the sensor performance. In the case of ideal circular anisotropy and bamboo domain structure the output signal would be zero. The pulsed current excitation containing low frequency components suppresses the circular domain structure. However, if the field generated by low frequency harmonics is too large, the sensor sensitivity will decrease due to increase of the magnetic hardness in circular direction. To investigate the conditions for optimal bias, a sinusoidal excitation with a dc bias was used. The frequency of excitation was 8 MHz. The sensor output in the presence of dc current flowing through the wire is shown in Fig. 9.

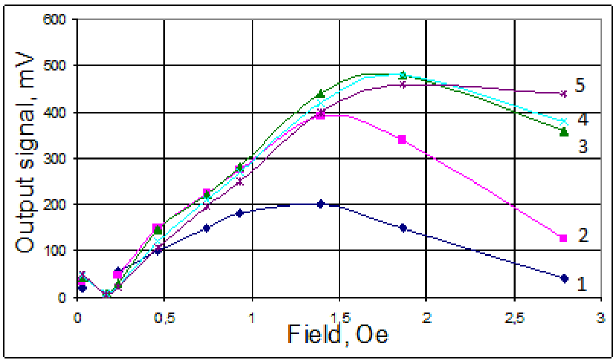

Fig. 9 – Sensor output at a sinusoidal excitation with a frequency of 8 MHz vs axial field in the presence of dc current: 1 – 0 mA, 2 – 2.31 mA, 3 – 7.7 mA, 4 – 9.24 mA, 5 – 13.09 mA

It is seen that the sensitivity and linearity region increase with increasing the dc current. However, for relatively large current of 10-15 mA the sensitivity in the low frequency region almost does not change, but at higher fields the sensitivity drops considerably. For the considered sensor configuration the optimal bias is around 2-3 mA. This current generates a circular magnetic field about 0.4 Oe at the wire surface (considering that the wire radius is about 10 μm). This field is larger than the typical value of circular coercivity so the domain structure is eliminated. This field may also decrease the effect of the anisotropy deviation from the circular direction which also results in the improved sensitivity.

5. CONCLUSIONS

The main aim of this work was to investigate the effect of dc bias fields on the characteristics of off-diagonal magnetoimpedance sensor. It was revealed that the effect of the orthogonal field (with respect to axial field) may be quite strong which imposes some limitations on the use of magnetic wires for the construction of 3D sensors. The dc current in a wire generating a circular field results in improved sensitivity due to elimination of the domain structure and smoothing the effect of the anisotropy deviations.

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