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Influence of an Electronic Field on the GMI Effect of Fe-based Nanocrystalline Microwire

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Abstract: In this work, a Fe-based nanocrystalline microwire of 20 mm in length and 25 μm in diameter was placed in the center of a 316 stainless steel pipe. The pipe was 500 μm in diameter and a little shorter than the microwire. A series of voltages were applied on the pipe to study the influence of the electrical field on the Giant-Magneto-Impedance (GMI) effect of the microwire. Experimental results showed that the electronic field between the wire and the pipe reduced the hysteresis of the GMI effect. The results were explained based on equivalent circuit and eddy current consumptions analysis.
Keywords: GMI; Eddy consumptions; Electronic field; Equivalent circuit

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Introduction

A giant change of alternating current (AC) impedance with respect to an external direct current (DC) magnetic field was discovered by Mohri in 1992 [1]. This phenomenon was called magneto-inductance effect at that time. Two years later, Machado found that the AC resistance of ferromagnetic material was also changed obviously with the change of the applied external field [2]. This change was called AC magneto-resistance (MR) effect. Then, Panina et al [3] thought that both the magneto-inductance effect and AC magneto-resistance effect concerned on same physical principle. This phenomenon was called Giant-Magneto-Impedance (GMI) effect. Because GMI effect (up to 500%/Oe) [4] is more sensitive than other magnetic sensors, such as tunnel magneto-resistance (<3%/Oe) [5], it has attracted much interest to develop magnetic sensors. Many effects such as suitable thermal treatments, development of new soft magnetic materials and so on, had been done to improve the sensitivity of GMI sensing element [6-9].

Previous study on GMI effect was focused on the influence of magnetic fields on the GMI ratio [10, 11]. Only few works was related to the influence of electronic field on the GMI effect. However, not only magnetic fields but also electronic fields are distributed in the practical application environments. Therefore, it is meaningful to study how the electrical fields affect the GMI effect.

In this work, we aimed at establishing a structure to study the influence of the electronic fields on the GMI effect. GMI ratio was measured with and without the applied electronic field. Through comparing the experimental results, it was found that the applied electronic fields can reduce the hysteresis of the GMI effect. The results were explained based on equivalent circuit analysis and eddy current consumptions.

Experiment Details

As shown in Fig. 1, a $Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$ microwire of 20 mm in length and 25 μm in diameter was

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placed in the center of 316 stainless steel pipe. The $Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$ microwire is annealed at 550℃ and very fine nanocrystalline bcc-FeSi grains are homogeneously formed in the amorphous matrix [8]. The pipe was 500 μm in diameter and a little shorter than the wire. A series of voltages were applied on the metal pipe. The MI effect of the microwire was carried out using a precision impedance analyzer (HP4294 A). The root-mean-square (rms) value of the AC driving current was kept constant at 10 mA, and its frequency was varied from 40 Hz to 25 MHz. The GMI ratio profiles were defined as,

$$\Delta Z/Z = \frac{Z(H_{ext}) - Z(H_{\max})}{Z(H_{\max})} \times 100\% \qquad (1)$$

where $Z(H_{\max})$ was the impedance value measured at the maximum field of 73 Oe. The external magnetic field was provided by a pair of Helmholtz coils. The sign of increasing GMI curves (H_{ext} changed from −73 Oe to 73 Oe) were "up" and the sign of decreasing GMI curves (H_{ext} changed from 73 Oe to −73 Oe) were "down". Firstly, the GMI ratio of the microwire was measured without applying a voltage on the metal pipe. Then the ratio was measured with different voltages applied on the metal pipe.

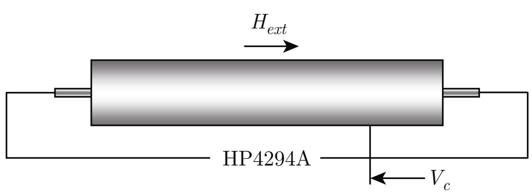

Fig. 1 The measurement system.

Results and discussion

Figure 2(a) and (b) show the GMI profiles of the microwire tested at 21 MHz, where V_{nc} and V_{3V} mean no voltage and a voltage of 3 V was applied on the metal pipe, respectively. It can be seen from Fig. 2(a) that all of the GMI profiles showed a single peak characteristic, which means the microwire has no defined circumferential anisotropy.

In addition, it can be seen clearly that there is a hysteresis for increasing and decreasing fields in Fig. 2(b) [12, 13]. The magnitude of the GMI for an increasing field is smaller than that for a decreasing field. When there is no voltage applied on the pipe, the difference of maximum GMI ratio for increasing and decreasing fields is 40%. After a voltage was applied on the pipe, the difference of maximum GMI ratio for increasing and decreasing fields is only 30%. Hence, it can be concluded that the hysteresis of GMI profile is reduced when a voltage was applied on the metal pipe.

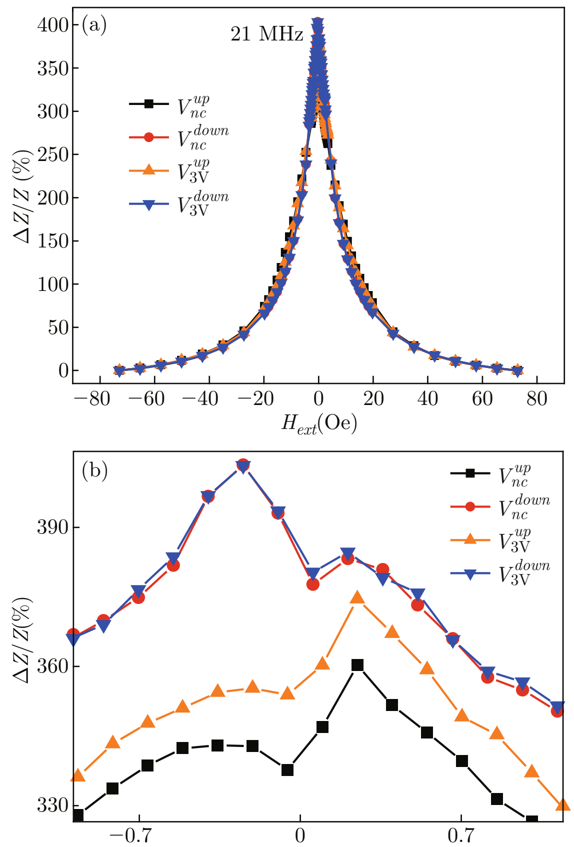

Fig. 2 (a) GMI ratio variations as a function of magnetic field measured at 21 MHz with and without voltage applied the pipe. (b) The enlarging of the peak in (a).

Figure 3 shows that the GMI ratio of the microwire changes as a function of external magnetic fields with different voltage applied on the pipe tested at 15 MHz. It can be seen from Fig. 3 that no much difference was found in GMI ratios with the applied voltage of 0 V, 3 V, 5 V and 10 V. The difference of maximum GMI ratio with respect to different applied voltages is very

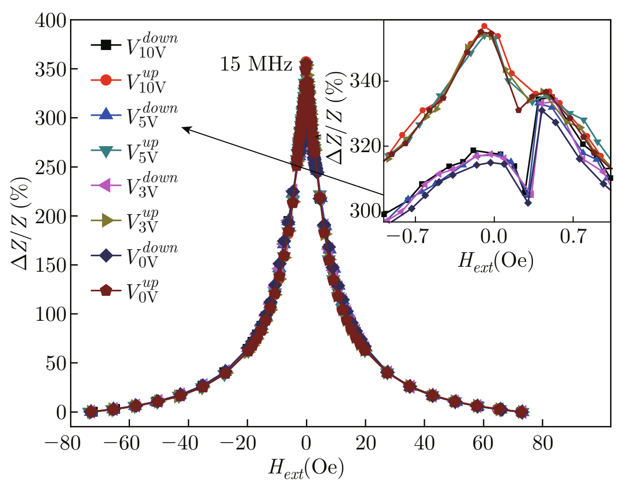

Fig. 3 GMI ratio variations as a function of magnetic field measured at 15 MHz with different voltage applied.

small. The possible causes of this phenomenon will be analyzed hereinafter.

Electromagnetic interaction will affect the impedance as long as there is a ferromagnetic material around a conductor [14]. So the reduction of GMI hysteresis may be caused by the electromagnetic interaction between the microwire and the pipe. An equivalent circuit, as shown in Fig. 4, was used to analyze the experimental results. In the equivalent circuit, the microwire and the pipe were evenly divided into n sections. Here, R_p and L_p are the resistance and inductance of each section of the stainless steel pipe. R and L are the resistance and inductance of each section of the microwire. Z_r and Cap are the radial impedance and capacitance of each section, respectively.

When no voltage was applied on the pipe (V_{DC} did not exist), the current flowed in the equivalent circuit was shown as the black thin arrows. The value of voltage drops successively on each section. Then the current $I_{section\_n}$ which flowed in each section of R_p, L_p, Z_r and Cap was the same. Ignoring the phase difference of each $I_{section\_n}$, the adjacent $I_{section\_n}$ in each Cap were just opposite to each other. So there was almost no current flowing through the Cap and Z_r from the microwire to the pipe except for the two ends of the structure. The total effect of Cap was every weak in this situation.

When a voltage was applied on the pipe, the current in the equivalent circuit flowed via the red thick arrows as shown in Fig. 4. An AC current flowed through all of the Cap and Z_r from every section of the microwire to the pipe. Then, there is a relatively strong effect of capacitance. Since the capacitances always hinder the change of the voltage on the microwire, they would hinder the change of the impedance [15]. It can be believed that energy stored in the capacitance of Cap will compensate the energy consumption in the microwire. Hence, the hysteresis of the GMI was reduced.

To study the influence of the frequency on the reduction of GMI hysteresis, the maximum GMI spectrum is shown in Fig. 5. The hysteresis of GMI profile increased with the frequency increasing. However, the hysteresis became smaller in all frequency range when a voltage was applied on the pipe. It is well known that the eddy consumption increases with the frequency. So the reduction of GMI hysteresis with the applied voltage maybe is relative to the overcoming of eddy consumption.

Figure 6 shows the cross-section of the microwire and the top view of the microwire's surface. When an AC current, $I = I_m sin\omega t$, flowed through the microwire, it would generate a circumferential magnetic flux density B. At the same time, there was a voltage decrease on the microwire from left end to right end. According to Lenz's law, an induced electromotive force always gave rise to a current whose magnetic field B' opposes the original change in magnetic flux B. The direction of the induced field B' was circumferential, but opposite to B when the amplitude of the current I increased, in first (0-$\pi/2$) and third (π-$3/2\pi$) quarter of the cycle. In contrast, the direction of the induced field B' was circumferential, but parallel to B when the amplitude of the current I decreased, in second ($\pi/2\pi$-π) and forth ($3/2\pi$-2π) quarter of the cycle. The eddy current consumptions were mainly relative to the B'.

When a voltage was applied on the metal pipe, a mutative electric field E was distributed between the microwire and metal pipe. An AC radial conduction current J_f will flow through the microwire to the metal pipe based on the above-mentioned equivalent circuit analysis. If we ignore the displace current, the current J_f will induce a magnetic field B'' according to Maxwell equation (2).

$$\nabla \times \vec{H}'' = \vec{J}_f \tag{2}$$

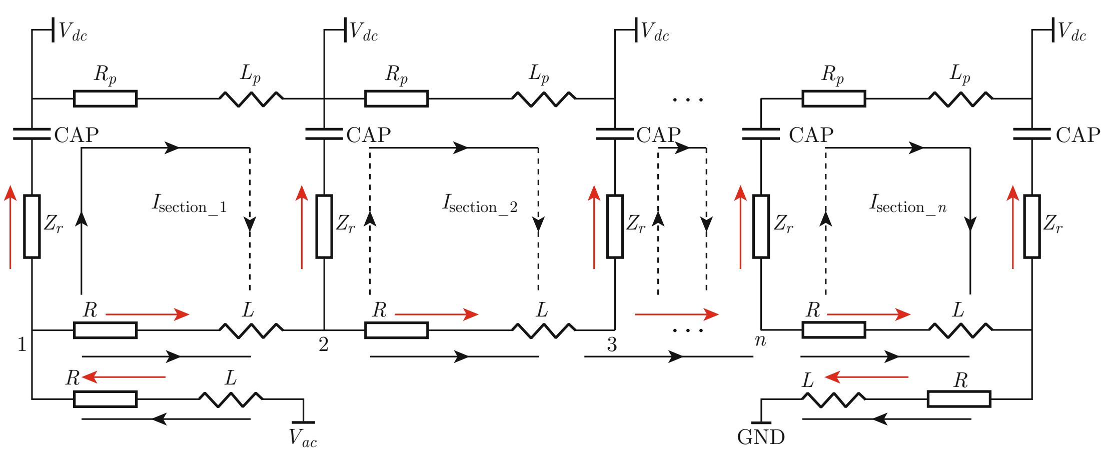

Fig. 4 Equivalent circuit.

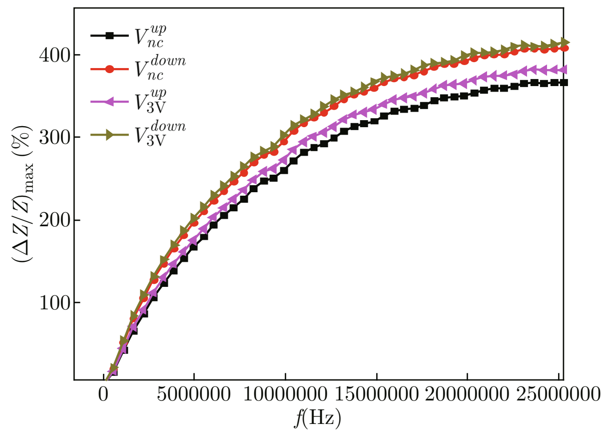

Fig. 5 GMI spectrum of the microwire with and without voltage applied the pipe.

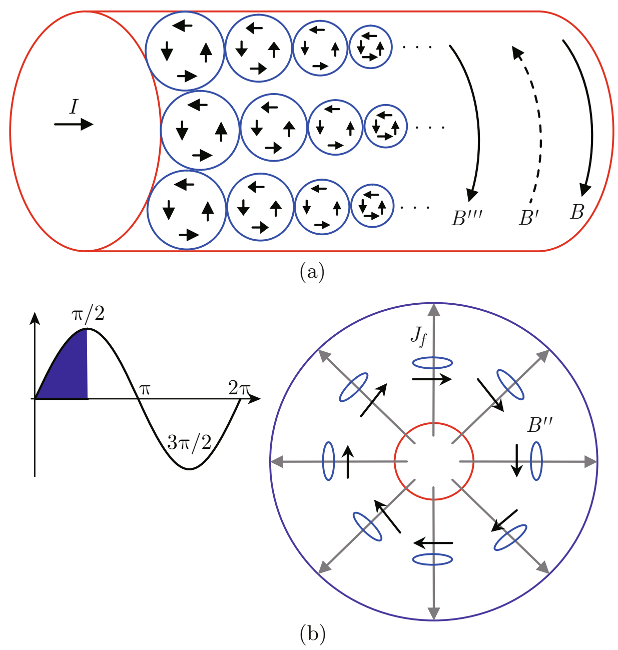

Fig. 6 The Cross-section of the microwire and metal pipe and the top view of the microwire's surface (0-$\pi/2$). (a) Cross-section of wire and metal pipe. (b) The top view of the microwire's surface.

In first (0-$\pi/2$) quarter of the cycle, the direction of J_f was from the microwire to the pipe. Then the direction of B'' can be confirmed by right-hand screw rule. It can be seen from Fig. 6 that the longitudinal component of B'' was counteracted by its adjacent B''. The circumferential component of B'' has a total effect of B'''. Since the amplitude of the voltage on wire decreased from left end to right end, then the circumferential component of B'' at left part was larger than that at right part. Therefore, the direction of B''' was in circumferential and parallel to B in first (0-$\pi/2$) quarter of the cycle. Then the direction of B''' was in circumferential and opposite to B' in first (0-$\pi/2$) quarter of the cycle.

It is easy to analyze the whole cycle in the same way. In the whole cycle, the direction of B''' was in circumferential direction and parallel to B when the amplitude of I increased. And B''' was in circumferential direction and opposite to B when the amplitude of I decreased. So the direction of B''' was always against to that of B'. Then the eddy current energy consumptions were decreased.

A conclusion can be made that the structure with an applied voltage decreased the eddy current consumptions partly. This conclusion agrees with the experimental phenomenon shown in Fig. 5. So it is reasonable to believe that the reduction of the GMI hysteresis was due to the decrease of the eddy current consumptions. Since the value of voltage applied on the pipe didn't influence J_f, the effects of different applied voltages were similar.

Conclusions

The GMI hysteresis was reduced when the microwire was placed in the center of a metal pipe on which a voltage was applied. A radial capacitance distributed between the microwire and the pipe hindered the energy change. When a DC voltage was applied on the pipe, the effect of the capacitance was strong enough to reduce the GMI hysteresis of the microwire. In detail, the corresponding magnetic flux density B''' induced by the radial mutative electric field E which gave rise to conductive current J_f fights against the B' which was just relative to the eddy current energy consumptions. So the eddy current energy consumptions were decreased. The structure is meaningful to reduce the hysteresis of the GMI sensors.

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