Comparative study on GMI properties of Co-based microwires improved by alcohol and liquid nitrogen medium-current annealing

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Abstract
This work comparatively investigates the influence of alcohol and liquid nitrogen medium-current annealing on GMI effect of rotated-dipping Co-based microwires. The temperature field distribution of Co-based microwires during current-annealing process is accordingly simulated, further to acquire experimental parameters of annealing current. Experimental results indicate that, GMI characteristics of current-annealed microwires in mentioned two mediums are both significantly improved, and GMI ratio \( \Delta Z / Z_{\text{max}} \) and magnetic field response sensitivity \( \xi_{\text{max}} \) of alcohol-medium current-annealed microwires increase more observable. When the excitation current frequency \( f = 3 \) MHz, \( \Delta Z / Z_{\text{max}} \) and \( \xi_{\text{max}} \) of microwires annealed by alcohol medium at 300 mA can reach 240.8% and 78.7%/Oe, respectively. During different type medium-current annealing, the higher-intensity annealing current can generate a larger circular magnetic field, which can effectively regulate the magnetic domain structure of Co-based microwires, so that, they tend to arrange densely and orderly, and the domain walls become much clearer. Meanwhile, the circular permeability \( \mu_c \) of microwires is significantly improved, thereby enhancing their GMI characteristics. Accordingly, the medium-current annealed Co-based microwires can be used as a typically sensitive material to provide technical support for the potential application of micromagnetic measurement field.

1. Introduction
Co-based metallic microwires possess the unique ‘core–shell’ magnetic domain structure due to their negative or near-zero magnetostriction coefficients. The toroidal magnetic domain of which can be magnetized under the excitation of alternating current and produce a larger circular magnetic permeability. At a certain frequency of alternating current, their impedance value will change significantly with a slight change of the external magnetic field, that is, the Giant Magneto-impedance (GMI) effect [1–5]. Simultaneously, Co-based metallic microwires have been widely used in magnetic sensors and have received wide spread attentions due to their high sensitivity, fast response, low power consumption, etc [6–9]. Magnetic sensors based on GMI effect of microwires have become a typical representative of the third generation magnetic sensors, and have been applied in the fields of weak magnetic field detection, geomagnetic navigation and biomagnetic measurement [10–15].

In general, during the preparation of metallic microwires, a higher cooling rate causes a relatively larger residual stress inside, which leads to the domination of stress anisotropy and causes the unconscious GMI effect [16–18]. Therefore, the researchers use modulation methods to reduce the influence of residual stress and achieve the purpose of improving the magnetic properties. Commonly used modulation methods for microwires include vacuum annealing, current annealing, stress annealing, magnetic field annealing etc [19–26]. Among, the vacuum annealing is one of the most direct and effective ways to eliminate the residual stress. Knobel M. et al [27] vacuum-anneal Fe-based metallic wires at 550 °C–600 °C, and increase \( \Delta Z / Z_{\text{max}} \) to...
200%. Under a coaction of Joule heat and toroidal magnetic field, the current annealing process can effectively reduce the residual stress, and regulate the magnetic domain structure of wires through toroidal magnetic field, thereby effectively improving GMI effect. Pirotka K R et al [28] performed current annealing on glass-coated Co68.25Fe4.5Si12.25B15 metallic wires to increase the relative impedance change rate of which to 600% at an excitation current of 15 MHz. However, when the intensity of annealing current become large, masses of Joule heat will generate inside the amorphous wires and cause the crystallization. By this time, the magnetocrystalline anisotropy becomes dominant, and the GMI effect of the metallic wires decrease greatly [29–31]. As a result, the above mentioned defects seriously limit the application of the current annealing process to regulation GMI characteristics of metallic wires. Accordingly, this paper introduces a current annealing process under the surrounding medium conditions, and during which, the annealing medium can rapidly extract Joule heat from the wire surface to prevent their severely crystallization. Therefore, the annealing current intensity can be greatly increased to generate a strongly toroidal magnetic field in the surrounding medium, and to better regulate the magnetic domain structure of the wire surface, further to enhance the GMI effect. Presently, there are relatively few studies on medium-current annealing of metallic microwires, which is neither systematic nor perfect. So, it is very necessary to carry out the relevant research work.

In this paper, the temperature field distributions of Co-based microwires current-annealed in alcohol and liquid nitrogen mediums are simulated firstly. And the influence of two kinds of medium-current annealing on GMI characteristics of microwires are compared. Combined with the evolution of magnetic domain structure of microwires before and after annealing, the improving mechanism of GMI effect was clarified, which can provide technical support for the development of sensitive materials in magnetic sensors.

2. Materials and methods

2.1. Experimental procedure

The mother alloy is melted several times by the non-consumable magnetron tungsten vacuum arc melting furnace at the nominal composition Co68.25Fe4.5Si12.25B15 (in at. %). During the process, the furnace is filled with an inert gas Ar for protection, the vacuum degree is $10^{-3}$ Pa, and the mother alloy precast rod of $\Phi 8$ mm and length 100 mm is prepared by copper die casting method. Subsequently, Co-based microwires with a diameter of 35 $\mu$m–40 $\mu$m and a length of 500 mm–800 mm are obtained by rotated-dipping device.

During DC current annealing, the temperature of metallic microwire core is related to the intensity of annealing current. The temperature field distribution of medium-current annealing process is simulated by modeling and mesh generation. Based on the simulation results, the process routes of current annealing in alcohol and liquid nitrogen medium are established accordingly, as shown in figure 1. The alcohol and liquid nitrogen medium-current annealing are carried out in a self-designed annealing device with different current intensities of 50 mA, 150 mA, 175 mA, 200 mA, 225 mA and 300 mA, and the annealing time is 480 s, and then air cooling.

The impedance test of Co-based microwires are conducted on an impedance comprehensive test platform consisting of HP 4192A impedance analyzer (frequency range: 5 Hz–13 MHz), Helmholtz coils ($H_{ex} = \sim 100$ Oe) and high-sensitivity fluxgate magnetometer (including range: $\pm 2$ Oe and resolution: 1 nT). The impedance test is performed by two-terminal method, and the direction of the magnetic field generated by the Helmholtz coils is perpendicular to the geomagnetic field direction in order to avoid its influence. The GMI ratio $\Delta Z/Z_{max}$ and the magnetic field response sensitivity $\xi$ can be expressed respectively as [32]:

$$\frac{\Delta Z}{Z_{max}}(\%) = \left[ \frac{Z(H_{ex}) - Z(H_{max})}{Z(H_{max})} \right] \times 100\%$$ (1)

$$\xi (%/Oe) = \frac{d}{dH_{ex}} \left[ \frac{\Delta Z}{Z_0} \right]$$ (2)

where $Z(H_{ex})$ stands for the impedance value in different external magnetic field, $Z(H_{max})$ represents the impedance value at the maximum external magnetic field intensity, $H_{ex}$ is the external magnetic field intensity provided by Helmholtz coils and $H_{max}$ is the maximum external magnetic field strength.

2.2. Simulations methodology

When the steady-state heat conduction module is used to simulate the temperature field distribution, it needs to go through three processes of pre-processing, solving and post-processing. The pre-processing process includes defining unit type and material performance parameters, creating a geometric model, and dividing the mesh to divide the temperature distribution of the fiber section. There are several items such as accuracy, and the division of the mesh is an extremely important step. Too large a mesh division width will lead to a decrease in the
accuracy of the simulation results. If the mesh division width is too small, the analysis time will increase, the computer resources occupied will increase, the mesh connection is difficult in a complex structure and other shortcomings. Therefore, the mesh division parameters (the number of model boundary meshes of the mesh size and shape) need to be set reasonably when the material parameters and geometric model are drawn up, which affects the accuracy and rationality of the temperature distribution in the calculation process. In the process of parameter setting, the cross-section diameter of the model is 40 μm, the width of the boundary single mesh is 0.65 μm, and its shape is approximately triangular.

In addition, the steady-state heat conduction model is established to simulate the internal energy exchange process inside the metallic microwire, following the Fourier’s law:

\[ q^n = -k \cdot (dT/dx) \]  

where \( q^n \) is the heat flux density, \( k \) denotes the thermal conductivity, \( T \) is the microwire temperature and \( x \) represents the distance along the heat conduction direction. Meanwhile, combined with the thermal property parameters of Co-based microwires (glass transition temperature: \( T_g = 459.6 \, ^\circ\text{C} \) and initial crystallization temperature: \( T_{x1} = 561.8 \, ^\circ\text{C} \) [20], the crystallized thickness \( T_d \) of the microwire is determined, and further to obtain the current intensity range (50 mA–300 mA) of medium annealing.

3. Results and discussion

3.1. Simulation of temperature field distribution of the alcohol and liquid nitrogen medium-current annealing processes

Figure 2 exhibits the temperature field distribution of Co-based microwires annealed in alcohol medium at different annealing current intensities. As is shown in the graph, when the current intensity is 50 mA, the core temperature of the microwire is lower than its initial crystallization temperature (\( T_{x1} = 561.8 \, ^\circ\text{C} \)), namely the heat generated by the current is insufficient to crystallize the microwire. When the current intensity is above 150 mA, the crystallization start to occur in its core and with the precipitation of a small amount of nanocrystals. During which process, alcohol medium can quickly extract Joule heat and prevent the further enlargement of crystallization area. When the current intensity reaches 300 mA, the range of crystallization is so large that it could affect the GMI effect of microwires. Accordingly, the current intensity range of the alcohol medium annealing is selected from 50 mA to 300 mA.

Compared with the figure above, figure 3 exhibits the temperature field distribution of Co-based microwires annealed in liquid nitrogen medium. And when the current intensity is 50 mA, the core temperature is 90 °C, which is also lower than the initial crystallization temperature, namely there is no obvious crystallization inside. As the current intensity increases to 150 mA, the core temperature becomes 595 °C, which is higher than the initial crystallization temperature. Though there is no large-area crystallization, the process will be accompanied
by a small amount of nanocrystals. However, when the current intensity reaches 300 mA, the crystallization range is significantly increased, and thus, the current intensity of the liquid nitrogen medium annealing ranges from 50 mA to 300 mA. According to the simulation results, as a cooling medium, the liquid nitrogen has a better thermal conductivity than the alcohol medium.

Based on the temperature field distributions in the above simulation and combined with the thermal properties of Co-based microwires, the relationship between the internal crystallized thickness $T_d$ and the current intensity $I_m$ is obtained, as plotted in figure 4. During the process of medium-current annealing, the $T_d$ rises with the increase of the annealing current intensity, the core of the microwire begins to crystallize at the current intensity of 150 mA, and the thickness is about 0.2 $\mu$m. When the crystal intensity is 225 mA, the crystallization thickness exceeds 2 $\mu$m, and which of the two medium-current annealings are around 3 $\mu$m and 2.5 $\mu$m, respectively. At a current of 300 mA, the crystallization thickness increases rapidly, reaching 5.6 $\mu$m and 5 $\mu$m, respectively, and the microwires show obvious crystallization. Therefore, it is further proved that the current intensity of alcohol and liquid nitrogen medium annealing is reasonable between 50 mA and 300 mA, which can effectively control the crystallized thickness of Co-based microwires.

3.2. Influence of alcohol and liquid nitrogen medium-current annealing on GMI properties of Co-based microwires

Figure 5 presents the GMI properties curves of alcohol medium current-annealed Co-based microwires. The GMI ratio $\Delta Z/Z_{\text{max}}$ (%) curves of microwires indicate the variation of highest value points and equivalent anisotropy field values at various excitation frequency. When the current intensity are 50 mA, 150 mA, 175 mA and 200 mA, respectively, at $f = 100$ kHz–3 MHz, the GMI curves exhibits a ‘single peak (S-P)’ characteristic near zero field. While at $f = 5$ MHz–13 MHz, the GMI curves appears a ‘double peaks (D-P)’ feature (namely the equivalent anisotropy field $H_k$) near 1 Oe, but when the current intensity is 50 mA, at $f = 13$ MHz, $H_k$ increases from
1 Oe to 2 Oe. When the current intensity are 225 mA and 300 mA, at \( f = 100 \) kHz–1 MHz, the S-P characteristic occurs near the zero field. Whereas, with a current intensity of 225 mA, and at \( f = 3 \) MHz–10 MHz, the curve exhibits a D-P characteristic around 1 Oe, and when the frequency is increased to 13 MHz, the \( H_k \) rises from 1 Oe to 2 Oe. When the current intensity is 300 mA, at \( f = 3 \) MHz–8 MHz, the curves exhibit a D-P characteristic around 1 Oe, and at \( f = 10 \) MHz and 13 MHz, the \( H_k \) increases from 1 Oe to 2 Oe. The equivalent anisotropy field

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**Figure 3.** Temperature field distribution of Co-based microwires at different current intensities during liquid nitrogen medium-current annealing process: (a) 50 mA; (b) 150 mA; (c) 175 mA; (d) 200 mA; (e) 225 mA; (f) 300 mA.

**Figure 4.** Relationship between crystallization thickness and current intensities of Co-based microwires current-annealed in different type mediums: (a) alcohol; (b) liquid nitrogen.
$H_0$ of Co-based microwires annealed at different current annealing intensity is related to the changing of frequency, which leads to the phenomenon of both S-P and D-P on GMI curves.

Figure 6 shows the GMI properties curves of Co-based microwires current-annealed in liquid nitrogen medium. It can be seen that the GMI ratio $\Delta Z/Z_{max}(\%)$ of various current intensity modulation microwires increase firstly and then decrease with the rising of the excitation frequency, while their peaks are different. When the current intensities are 50 mA, 150 mA, 175 mA, and 200 mA, at $f = 100$ kHz–5 MHz, the GMI curves exhibit S-P characteristic near zero field, and at $f = 8$ MHz–13 MHz, D-P feature appear near 1 Oe. At current intensity of 225 mA and $f = 1$ MHz–5 MHz, the GMI curves appear S-P near zero field, and when $f = 8$ MHz–13 MHz, the GMI curves exhibit D-P characteristic around both 1 Oe and 2 Oe. As the current intensity is
300 mA, at \( f = 100 \text{ kHz} \), the GMI curves exhibit S-P characteristic near zero field and D-P feature around both 1 Oe and 2 Oe at \( f = 1 \text{ MHz}–13 \text{ MHz} \). Similarly, the S-P and D-P phenomena appearing on the GMI curves of Co-based microwires annealed in liquid nitrogen medium is related to the change of the equivalent anisotropy field values at different current annealing intensities.

Figure 7 illustrates the statistics of the GMI ratio \([\Delta Z/Z_{\text{max}}]_{\text{max}}\) and the magnetic field response sensitivity \(\xi_{\text{max}}\) of as-cast and current-annealed Co-based microwires. Compared to the performance parameters of the as-cast state, both the alcohol and liquid nitrogen medium–current annealing process increase the \([\Delta Z/Z_{\text{max}}]_{\text{max}}\) at different excitation frequencies, and also improve the GMI characteristics to some extent. As shown in figure 7(a), for the as-cast state, 50 mA, 150 mA, 175 mA, and 300 mA alcohol medium-annealed Co-based microwires, the \([\Delta Z/Z_{\text{max}}]_{\text{max}}\) reach their maximum values of 185.2%, 270.2%, 210.1%, 260.5% and 251.4%,
respectively at $f = 3$ MHz, and when the current intensity are 200 mA and 225 mA, at $f = 5$ MHz, the $[\Delta Z/Z_{\text{max}}]_{\text{max}}$ are 250.3% and 200.1%. For Co-based microwires current annealed in liquid nitrogen medium, when the current intensities are 50 mA, 150 mA, 175 mA, 200 mA, 225 mA, and 300 mA, respectively, the $[\Delta Z/Z_{\text{max}}]_{\text{max}}$ reaches 210.2% 260.1%, 258.0%, 255.3%, 250.2%, correspondingly. Among, the $[\Delta Z/Z_{\text{max}}]_{\text{max}}$ of the alcohol medium current-annealed Co-based microwires reaches a peak at 270.2% as the current intensity of 50 mA and $f = 3$ MHz, and which is 10.1% higher than the liquid nitrogen medium current-annealed microwires of 260.1%. As can be seen in figure 7(c)), for the alcohol medium current-annealed microwires, when the current intensity is 200 mA and $f = 10$ MHz, the $\xi_{\text{max}}$ reaches 65.2 %/Oe and which is 3.36 times higher than that of the as-cast state of 19.4 %/Oe. When current intensity is 300 mA, at $f = 3$ MHz, 5 MHz, 8 MHz, 10 MHz and 13 MHz, the $\xi_{\text{max}}$ reach 59.5 %/Oe, 78.7 %/Oe, 70.3 %/Oe, 57.9 %/Oe and 47.4 %/Oe, respectively, and the $\xi_{\text{max}}$ gets highest at $f = 5$ MHz, which is 78.7 %/Oe, and is 4.27 times higher than the as-cast microwires of 18.4 %/Oe. As for liquid nitrogen medium current-annealed Co-based microwires, the $\xi_{\text{max}}$ reaches 43.1 %/Oe at a current intensity of 150 mA and $f = 3$ MHz, and 50.7 %/Oe at a current intensity of 225 mA and $f = 8$ MHz. Especially, when the current intensity is 300 mA, the sensitivities at different frequencies are all significantly improved, and can reach 86.4 %/Oe, 93.4 %/Oe, 77.9 %/Oe, 68.1 %/Oe and 53.7 %/Oe, at $f = 3$ MHz, 5 MHz, 8 MHz, 10 MHz and 13 MHz, respectively. Among which, the highest sensitivity is 93.4 %/Oe at 5 MHz, which is 5.07 times higher compared to the as-cast microwires of 18.4 %/Oe. In a word, both the alcohol and liquid nitrogen medium-current annealing process can effectively improve the magnetic field response sensitivity, and the liquid nitrogen medium-current annealing is better.

Figure 8 is the statistics of maximum response field $H_p$ and equivalent anisotropy field $H_0$ of as-cast and medium current-annealed Co-based microwires. The maximum response field value can be determined by the magnetic field position where the maximum value of the magnetic field response sensitivity is. For the alcohol medium current-annealed microwires, when the current intensity is 150 mA, at $f = 3$ MHz, the $H_p$ is increased from 2 Oe of the as-cast state to 3 Oe. When the current intensity is 300 mA, at $f = 1$ MHz, the $H_p$ is increased from 1 Oe to 2 Oe, as shown in figure 8(a)). As for the liquid nitrogen medium current-annealed microwires, when the current intensities are 50 mA, 150 mA, 175 mA and 225 mA, at $f = 5$ MHz, the $H_p$ increases from 2 Oe to 3 Oe and for the current intensities of 50 mA and 150 mA, at $f = 8$ MHz, the $H_p$ increases from 1 Oe to 2 Oe, as is seen in figure 8(b)). Accordingly, the medium-current annealing process increases the intensity of response magnetic field at a certain frequency. As shown in figure 8(c)), for the alcohol medium current-annealed...
microwires, when the current intensities are 50 mA and 225 mA, at $f = 13$ MHz, the $H_k$ increases from 1 Oe of as-cast state to 2 Oe. As the current intensities of 150 mA, 175 mA and 200 mA, the $H_k$ of microwires at various frequencies are basically the same as those of the as-cast state. When the current intensity increases to 300 mA, at $f = 10$ MHz, 13 MHz, the $H_k$ increases from 1 Oe to 2 Oe. The rising temperature in the cores of the microwires leads to an increasing of the coercive force and affects the equivalent anisotropy field, and especially when the current intensity is 300 mA, at $f = 10$ MHz and 13 MHz, the $H_k$ increases to 2 Oe, which is doubled than the as-cast state. As exhibited in figure 8(d), for the microwires current annealed in liquid nitrogen medium, the equivalent anisotropy field $H_k$ is constant at various frequencies and the current intensities of 50 mA, 150 mA, 175 mA and 200 mA, in compared with the as-cast state. When the current intensity increases to 225 mA, at $f = 5$ MHz and 13 MHz, the $H_k$ increases from 1 Oe to 2 Oe, and when the current intensity continues to increase to 300 mA, at $f = 1$ MHz, the $H_k$ increases from 0 Oe to 1 Oe, and to 2 Oe at $f = 3$ MHz, 8 MHz and 10 MHz. Since the core temperature is close to its crystallization temperature, the coercive force is increased so that the equivalent anisotropy field increases, and especially at the current intensity of 300 mA and $f = 13$ MHz, the $H_k$ increases to 3 Oe, which raises substantially compared with the as-cast state. Current-annealing with a large intensity in different mediums of Co-based microwires, the detectable range of magnetic field is accordingly enhanced at a relatively high frequency.

3.3. Characterization of magnetic domain structure of as-cast and medium-current annealed Co-based microwires

Figure 9 shows the typical ‘core–shell’ model with toroidal domain and domain wall of Co-based microwires, the actual surface magnetic domain structure and its corresponding schematic diagrams of as-cast and current-annaled in different mediums. The magnetic domain distribution of the as-cast microwires with an average width of 1.49 μm is scattered and disordered, the toroidal domain structure is relatively irregular, and the magnetic domain in some regions are distributed along the axial direction, as shown in figure 9(a)). After the alcohol medium-current annealing process, the domain walls moving makes the magnetic domain arranged in an orderly and tight manner, and the average width of which become 1.45 μm, as presented in figure 9(b)). While the average domain width is 1.37 μm after current-annaealing in the liquid nitrogen medium, and the arrangement of magnetic domains are orderly, as shown in figure 9(c)). Consequently, the magnetic domain structure of Co-based microwires after medium-current annealing tends to be ordered and tightly arranged, the
toroidal magnetic domains are arranged regularly, the magnetic domain transition boundaries are clear, and the average width is reduced. The alcohol medium-current annealing process can more effectively regulate the magnetic domain structure on the surface, increase the volume fraction of the toroidal magnetic domain, and can arrange the toroidal magnetic domains in a more orderly way. Different from the simulation results, during the liquid nitrogen medium-current annealing process, however, there is a loop-closed air gap, due to its lower boiling point, between the microwire and the liquid nitrogen, which plays a key role in hindering heat conduction to a certain extent, so that the internal heat cannot be quickly exported, resulting in partial crystallization. In contrast, the alcohol medium-current annealing does not have an air gap, which is more effective in improving the GMI property.

3.4. Mechanisms analysis of the improved GMI effect of Co-based microwires by current-annealed in different mediums

Generally, the domain structure of the magnetic material determines their magnetic properties. Among, the magnetic domain width, arrangement, the domain wall movement and the magnetic moment rotation are main basis for evaluating the magnetic properties. And the as-cast Co-based microwires possess the quantity residual stress, a disordered surface magnetic domain distribution, an irregular magnetic domain width. In an axial external magnetic field, the atomic magnetic moments in magnetic domains of the metallic microwires cores are difficult to rotate due to the pinning effect of residual stress, besides, the magnetic anisotropy is mainly stress anisotropy, and the softly magnetic properties and GMI performance are poor, as revealed in figure 9(a)) and its corresponding schematic diagram. The medium-current annealing process can greatly improve the annealing current intensity while avoiding the crystallization and more effectively reducing the residual stress. During which, the high annealing current intensity produces a large toroidal magnetic field, and under the coaction of Joule heat and magnetic field energy, the magnetic domain structure is effectively regulated. Figures 9(b), (c) and their corresponding schematic diagrams demonstrate that the magnetic domains on the surface of the
microwires tend to arrange in a regular order, and the atom magnetic moments in the toroidal magnetic domain are arranged in the toroidal direction, while the atom magnetic moments of the cores are distributed along the axial direction (namely easy magnetization direction). When the Co-based microwires are under alternating current and external magnetic conditions, the moving speed of domain walls is accelerated in a low frequency, and the domain wall boundary tends to be clear. However, the magnetic moment rotating action is enhanced in a high frequency, and the atomic magnetic moment rotation change causes the impedance variation increment to increase rapidly [33], which eventually leads to an improvement in GMI performance.

GMI effect of Co-based microwires is closely related to the skin effect. And according to the Maxwell equations, the impedance $Z$ and the skin depth $\delta$ can be expressed as [34, 35]:

$$
\begin{align*}
Z &= \frac{1}{2} R_{DC} (kr) \frac{J_0(kr)}{J_1(kr)} \\
\langle J \rangle &= 1 + j \\
\delta &= \frac{\rho}{\sqrt{\pi f \mu_s}}
\end{align*}
$$

where $R_{DC}$ is the DC current resistance, $J_0$ and $J_1$ stand for the zero-order and the first-order Bessel function, respectively, $r$ is the radius of wires, $j$ is the imaginary number, $\rho$ is the resistivity, $f$ is the frequency of the excitation current, and $\mu_s$ is the toroidal permeability. As it describes, the value of $Z$ is closely related to $\mu_s$, and which is usually reflected in the toroidal magnetic domain distribution of the Co-based microwires [36]. So the environmental medium (i.e. alcohol, liquid nitrogen, oil, etc) can greatly increase the annealing current intensity and induce a higher toroidal magnetic field to increase the circular magnetic permeability $\mu_s$ to further achieve the purpose of regulating the magnetic domain structure and finally improving the GMI effect.

4. Conclusions

In summarizing, this paper investigates the influence of alcohol and liquid nitrogen medium-current annealing on the magnetic properties of Co-based microwires, and we can draw the following conclusions:

(1) Based on the temperature field distribution simulation of microwires during the alcohol and liquid nitrogen medium-current annealing processes, the crystallization thickness of wire cores increases with the rising of annealing current intensity. When the intensity $I_m$ increases from 150 mA to 300 mA, the core crystallization thickness $T_d$ increases from 0.2 $\mu$m to 5 $\mu$m.

(2) Both alcohol and liquid nitrogen medium-current annealing can significantly improve the GMI property, namely $|\Delta Z/Z|_{\text{max}}$ and $\xi_{\text{max}}$ of annealed Co-based microwires are dramatically enhanced. At $f = 5$ MHz and the annealing current intensity of 300 mA, the $|\Delta Z/Z|_{\text{max}}$ and $\xi_{\text{max}}$ of the alcohol-medium annealed microwires are increased to 240.8% and 78.7 %/Oe, respectively, and $H_k = 1$ Oe. While the liquid nitrogen medium annealed microwires are 220.4% and 93.4 %/Oe, respectively. Analogously, when $f = 13$ MHz, and at the annealing current intensity of 200 mA, the $|\Delta Z/Z|_{\text{max}}$ and $\xi_{\text{max}}$ of the alcohol medium annealed microwires are increased to 160.4% and 60.6 %/Oe, respectively, while the liquid nitrogen medium annealed microwires are 100.2% and 20.4 %/Oe. Therefore, the alcohol medium current-annealed Co-based microwires have a more excellent GMI performance.

(3) The magnetic domain structure of current-annealed Co-based microwires tend to arrange orderly. Comparatively, the surface magnetic domains of the alcohol medium current-annealed microwires are more regular, and domain walls are much clearer, which are matched with their excellent GMI characteristics. During the medium-current annealing process, the residual stress was mostly released under Joule heating, and the distribution of the toroidal domain are modulated effectively under the large magnetic field, even significantly enhances the circular permeability, finally achieves the improved GMI property.

Acknowledgments

This work was financially supported by National Natural Science Foundation of China (NSFC) under grant nos. 52061035, 51871124, 51561026 and 51401111, Ministry of Education Fok Ying-tung Foundation for Young Teachers (no. 161043), ‘Grassland Talents’ Project of Inner Mongolia Autonomous Region (no. CYYC9025),
Data availability statement

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

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