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Tailoring giant magnetoimpedance effect of Co-based microwires for optimum efficiency by self-designed square-wave pulse current annealing

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ABSTRACT

Herein, we systematically studied the effect of a novel square-wave pulse current annealing (SPCA) on the magnetic properties and microstructure of Co-based melt-extracted amorphous wires, and efficiently tailored the related experimental parameters by using numerical calculation of transient temperature rise during SPCA process. We obtained the optimal SPCA treatment (at 50 Hz, with amplitude of 90 mA for 480 s) can remarkably enhance the GMI property of as-prepared wires. At 10 MHz, the maximum GMI ratio $[\Delta Z/Z_0]_{max}$ and maxima response sensitivity ξ_{max} of SPCA-treated wire increases to 202.60% and 305.74%/Oe, which is nearly two times and 1.5 times of 104.80% and 208.14%/Oe for as-cast wire, respectively. Especially, at 5 MHz, $[\Delta Z/Z_0]_{max}$ of SPCA-treated wire increases to 185.81%, which is 2.5 times of 73.69% for as-cast wire, and ξ_{max} of SPCA-treated wire increases to 346.65%/Oe by less than two times of 190.16%/Oe for as-cast wire. From mictrostructural perspective, the notably observed role of atomic order orientation regimes and circular magnetic domain during stress releasing or structural relaxation by the co-action of high-density pulse magnetic field energy and thermal activation energy determines the optimum efficiency of SPCA, further to enhance circumferential permeability. In conclusion, SPCA treatment is expected to effectively improve GMI property of microwires, which can be used as sensitive materials for potential sensor application in detecting weak magnetic field.

1. Introduction

So far, much interest has been paid to the novel giant magnetoimpedance (GMI) effect of amorphous microwires due to their high-performance applications as promising sensor elements particular to weak magnetic field (WMF) detection [1–4]. In comparison with in-rotating water-spinning and glass-coated spinning techniques, melt-extraction shows the high solidification rate and excellent softly magnetic properties [5–7]. Importantly, superior GMI property is the basic requirement for choosing sensitive materials including wires, ribbons or films by using a diversity of tailoring or post-processing techniques, i.e. furnace annealing, Joule annealing and magnetic field annealing etc. [6,8]. One of the most frequently used techniques is Joule annealing owing to the specially and symmetrically geometric shape of microwires induced strong circumferential anisotropy and suitable stress releasing during annealing process [9,10].

As previously reported, all kinds of alternating current (current source type: AC or PC) annealing processes have been conducted [11]. Zhou et al. [12] reported that the effect of AC Joule-heating for melt-spun CoFeSiB amorphous ribbon on GMI property, and $[\Delta Z/Z_0]_{max}$ increased to about 180% at 900 kHz for 30 min with an AC current density of 2.8×10^7 A/m^2 owing to the easy magnetization axis, magnetic anisotropy and domain structure. Sinha et al. [13] observed $[\Delta Z/Z]_{max}$ of CoMnSiB glass-coated microwire increased from 66% of as-cast to 129% after short-duration (12 s) PC annealing with amplitude of 100 mA, due to the increase of outer shell domain volume. Atalay et al. [14] investigated that the variation relationship between magnetization and Young's modulus of PC-treated $Fe_{77.5}Si_{7.5}B_{15}$ amorphous wires, and measured the coercivity and anisotropic energy density with the variation of current intensity and tensile stress, further revealed the proper PC annealing compared with other traditional annealings can effectively release inner residual stress and improve the soft magnetic property. Overall, in contrast to convention current annealings, SPCA as a distinctive Joule-heating modulation technique for

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obtaining application-oriented magnetically sensitive materials, it also can effectively abstain the crystallization phenomenon caused by relatively large current density, meanwhile improve magnetic anisotropy and microstructural relaxation with an excellent GMI effect under pulse or alternating circumferential magnetic field. Whereas, there also lacks the systematic study on SPCA technique for microwires combining with transient temperature rising characteristic and the comparison of magnetic domain structure, which is closely related to GMI property. Therefore, it is worthwhile to explore the related research work on the relation of GMI properties and domain structure of as-cast and SPCA-ed wire.

In this work, we aim to achieve the optimized SPCA modulation parameters resorting to the numerical calculation of transient temperature rise. The specially proposed SPCA parameters are assessed according to its effectiveness on GMI property to acquire the candidate sensitive material for practical applications of GMI sensor.

2. Experimental details

The mother alloy ingot with nominal composition of $Co_{68.2}Fe_{4.3}B_{15}Si_{12.5}$ (in at. %) was firstly prepared by arc-melting and copper mold casting methods. Secondly, the top-end of club-shaped alloy with the diameter of 8 mm in BN crucible was melted by induction coil in precision melt-extraction facility. Finally, the microwires with diameter of 30 μm were fabricated by the edge of a high velocity (~30 m/s) rotating Cu wheel with a diameter of 320 mm and around 60° knife edge in purified argon atmosphere.

Pulse current annealing was conducted by passing through amorphous wire a square-wave alternating current (with frequency of 50 Hz, the current intensity I_m range of 50–110 mA and annealing time for 480 s) supplied by a self-designed PC annealing device [15]. Fig. 1 presents the circuit schematic diagram of SPCA with amplitude modulation and frequency conversion. And the device is composed of square-wave signal generation circuit (U1A), frequency dividing circuit (U3), frequency-selecting circuit (U2A), metal oxide semiconductor (MOS) switching circuit (Q1 and Q2), amplitude modulation circuit (X1), oscillograph (XSC1) and universal meter (XMM1 and XMM2). The wire was fixed by two terminals using small brass clamps placed in PCB experimental board in SPCA device, and the wire was naturally cooled in air after SPCA treatment.

As-cast and SPCA-ed wires were examined by X-ray diffraction with CuKα radiation (Rigaku D/max-γB). The magnetic property was evaluated by a commercial Magnetic Property Measurement System (SQUID-VSM) from Quantum Design and the applied field is up to 2 T. The domain observation of wires was performed by a Nanoscope III multimode atomic force microscope including magnetic force microscope (MFM) from Digital Instruments. A Veeco micro-etched silicon probe tip was magnetized along the tip axis by using a permanent magnet and combined tapping and lift mode. The impedance measurements were performed using Aligent 4294A precision impedance analyzer at frequency range of 40 Hz–110 MHz. And the effective sample length for impedance measurement is around 22 mm. GMI ratio $\Delta Z/Z_0$ and magnetic field response sensitivity ξ are respectively defined as [16]:

$$\frac{\Delta Z}{Z_0}(\%) = \left[\frac{Z(H_{ex}) - Z(H_0)}{Z(H_0)}\right] \times 100\%; \quad \xi = \frac{d\left[\frac{\Delta Z}{Z_0}(\%)\right]}{dH_{ex}} \qquad (1)$$

where $Z(H_{ex})$ is the impedance under external field H_{ex} applied by a long solenoid is below 5.0 Oe. $Z(H_0)$ is the initial impedance at 0 Oe, and the equivalent anisotropy field H_k in GMI profiles is the corresponding magnetic field of maximum GMI ratio $[\Delta Z/Z_0]_{max}$. All measurements were performed at room temperature (25 °C).

3. Results and discussion

The related annealing experimental parameters including amplitudes or current density, annealing times and frequency are efficiently optimized and confirmed by numerical calculation of transient temperature rising characteristic according to lumped thermal capacity of transient heat conduction during the self-designed SPCA process. The average temperature $T_{avg.}$ of SPCA-ed wires can be effectively evaluated by using the same method of numerical calculation for transient temperature rise during SPCA treatment based on energy conservation law, which was described in our previous Ref. [11]. Accordingly, SPCA transient temperature rise of amorphous wire at 0–0.5 s was shown in Fig. 2(b). And $T_{avg.}$ of microwires under different PC amplitudes (50–120 mA) were calculated by integration as follows: 353.38 K for 50 mA; 377.01 K for 60 mA; 420.24 K for 75 mA; 472.88 K for 90 mA and 558.10 K for 110 mA. Large PC amplitude seriously degrades the magnetic property and GMI performance, especially $T_{avg.}$ of 120 mA is close to the Curie temperature 660 K and crystallization temperature of 786 K. Therefore, 50–120 mA, as the referred range of SPCA amplitude is given to conduct in the following experiments according to the numerical calculation results.

Fig. 3 indicates SPCA amplitude dependence of maxima GMI ratio $[\Delta Z/Z_0]_{max}$ and equivalent anisotropy field H_k of annealed wire at different frequencies of 100 kHz–20 MHz. $[\Delta Z/Z_0]_{max}$ values increase as PC amplitude increasing, and reach their summit

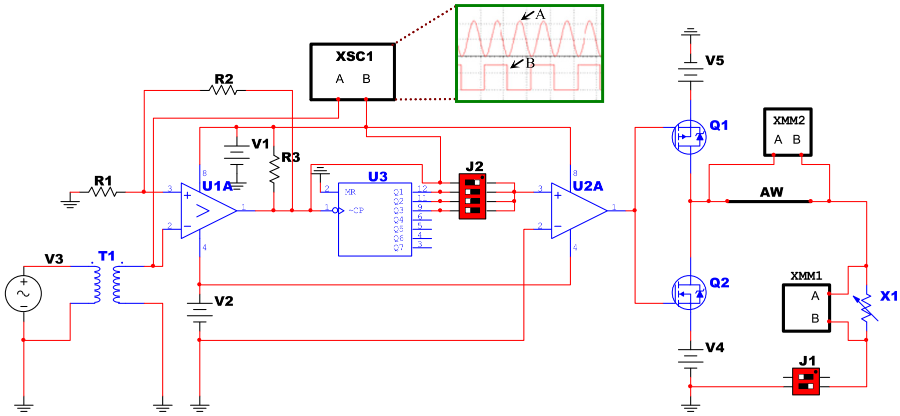

Fig. 1. Circuit schematic diagram of square-wave pulse current annealing (SPCA) used for amplitude modulation and frequency conversion. The rectangle inset indicates the sine-wave and square-wave output oscillogram of channel A (as denoted in upper side) and channel B (as denoted in lower side) in XSC1, respectively.