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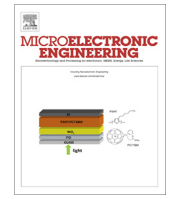

Current sensors using Fe–B–Nd–Nb magnetic metallic glass micro-cantilevers

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ABSTRACT

We report on the development of MEMS current sensors composed of $Fe_{67.5}B_{22.5}Nd_{6.3}Nb_{3.7}$ (FBNN) magnetic metallic glass thin films. These current sensors are based on free-standing cantilever structures that benefit from the superior mechanical properties of the metallic glass, such as high fracture toughness and high yield strength. The resonant frequency of the proposed FBNN cantilever was 3.85 kHz in the fundamental flexure mode when the length, width and thickness of the cantilever were 750 μm, 150 μm and 3 μm, respectively. A feed wire with a diameter of 500 μm was placed close to the FBNN cantilever, and a downshift in the resonance peak was observed when the current intensity through the feed wire increased. The sensitivity of this frequency shift to the current intensity was 5.0 $\sqrt{\text{Hz}}$/A when the distance between the cantilever and the wire was 500 μm.

1. Introduction

Network-based power control systems represented by smart grids are being actively researched and implemented for field testing in large-scale power transmission systems [1,2]. In addition, the demand for power control systems for household applications is also increasing because of progress in technologies such as solar batteries, fuel cells, capacitor systems, and heat pump-type water heaters. As a result, the development of micro current sensors to monitor power flow for household systems is drawing research attention.

In these applications, it is becoming difficult to satisfy the sensor requirements. The sensors must be both compact and low-cost, but long sensor lifetimes and ease of installation are also in demand. We therefore focused our attention on metallic glass thin films (MGTFs) as component materials for these sensors, and developed a resonator-type non-contact current sensor using a micromachined MGTF cantilever, as shown in Fig. 1. As the schematic shows, a piezoelectric transducer actuates the cantilever to maintain resonance by implementing an oscillator circuit loop.

MGTFs are expected to improve both the lifetime and the reliability of these sensors because of their outstanding mechanical properties, such as high fracture toughness and high yield strength [3–6]. The flexible formability of MGTFs under viscous flow conditions within the temperature range between the glass transition and crystallization, which is called the supercooled liquid region (SCLR), is also a very attractive property. Residual stress can cause the linearity of the mechanical response of the sensor to deteriorate. Using this flexible formability property, we can suppress such residual stresses and improve the linearity of the cantilever motion.

Recently, we developed the $Fe_{67.5}B_{22.5}Nd_{6.3}Nb_{3.7}$ metallic glass thin film (FBNN-MGTF) [7]. One of the best features of the FBNN film is its wide SCLR (96 K), which means that the film has high thermal stability from the metallic glass state up to crystallization. Another excellent feature is the film's magnetic properties, including high saturation magnetization (∼0.9 T) and low coercivity (<20 A/m), which should be useful for the detection of magnetic fields induced by currents. The fracture toughness and the Young's modulus of the FBNN-MGTF are 6.36 MPa $m^{1/2}$ and 79.4 GPa, respectively, which are double and half of the values of the same properties of Si, respectively. The fracture toughness in particular is the highest recorded value among the thin films developed to date for micro-electromechanical systems (MEMS) [8]. The FBNN-MGTF can therefore offer large displacement operation without being destroyed, and is attractive for use in high sensitivity sensors based on mechanical resonance.

In this study, the FBNN-MGTF free-standing cantilever was fabricated by batch fabrication processes based on MEMS technologies. The feasibility of the proposed current sensor based on the FBNN-MGTF cantilever was then verified.

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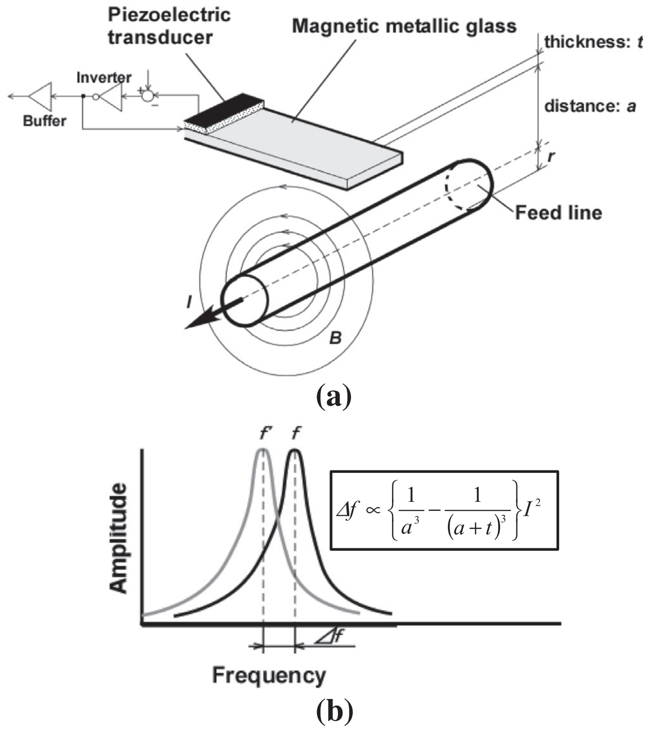

Fig. 1. (a) Schematic illustration of the FBNN-MGTF-based current sensor, and (b) its ideal output response.

2. Fabrication of the FBNN-MGTF cantilever

We first explain the fabrication flow for the FBNN-MGTF free-standing cantilever. Fig. 2 shows a cross-sectional illustration of the required fabrication procedures. Basically, the cantilever was fabricated by a lift-off process. The Si(100) substrate, which is 200 μm thick, was cleaned using a standard RCA clean (Fig. 2(i)). Then, the first photoresist (PMGI SP-8: Micro Chem Co., Ltd.) layer was spin-coated on the surface and baked at 185 °C (Fig. 2(ii)). The photoresist thickness was 4 μm. Next, a second thin photoresist layer (OFPR800: Tokyo Ohka Kogyo Co., Ltd.) was stacked on top of the first layer and patterned photolithographically (Fig. 2(ii)). In this step, overhang structures can be formed in the photoresist bi-layer because the underlying photoresist was nearly isotropically dissolved during development of the top layer. A 3-μm-thick FBNN-MGTF was deposited on the overhang structure of the photoresists by electron cyclotron resonance (ECR) ion beam sputtering with a $Fe_{72}B_{24}Nb_4$ and $Fe_{56}B_{20.8}Nd_{20}Nb_{3.2}$ composite target (Fig. 2(iii)) [7]. Then, all photoresist layers were removed to form the FBNN-MGTF cantilever by immersion in 80 °C N-Methyl-2-pyrrolidonr (NMP) (Fig. 2(iv)). Finally, the cantilever was released by backside etching of the Si substrate by Bosch process-based deep reactive ion etching (RIE) (Fig. 2(v)).

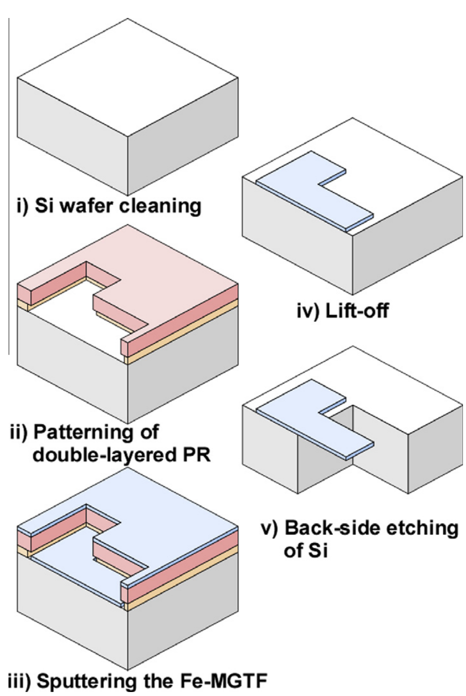

Fig. 2. Cross-sectional illustrations of the stages of the fabrication procedure.

The MGTF cantilever was fabricated fully using MEMS technologies. Fig. 3 shows scanning electron microscopy (SEM) images of the fabricated cantilevers. It was thus confirmed that a large number of FBNN-MGTF freestanding structures with low residual stress were successfully fabricated on a single wafer.

3. Feasibility for current sensors

We verified the application potential of the FBNN-MGTF micro-cantilever for the non-contact resonant-type current sensors using the setup shown in Fig. 4. A 500-μm-diameter tungsten (W) wire was placed close to the FBNN-MGTF cantilever. The cantilever was 750 μm long, 50 μm wide and 3 μm thick. The cantilever die was fixed on a piezo-stage, and was shaken externally by frequency sweeping from 3.6 kHz to 4 kHz. The vibration velocity of the cantilever tip was monitored by a laser Doppler velocimeter (LDV) (UHF-120: Polytec Inc.). The amplitude and phase of the cantilever vibration were measured by a synchronous detection method using the vibration frequency of the stage.

Fig. 5 shows the frequency characteristics of the cantilever vibration. The cantilever resonated with its fundamental flexure mode at 3.85 kHz. When the current through the wire increased, the resonant frequency of the cantilever decreased. This is caused by softening of the cantilever, which is caused by the magnetic field induced by the current [9]. The magnitude of the frequency shift, Δf, can be calculated using the following equations:

$$\Delta f = \frac{\mu - \mu_0}{16\pi^3\sqrt{mk}} \left\{ \frac{1}{a^3} - \frac{1}{(a+t)^3} \right\} I^2 \equiv A(a)^2 I^2, \text{ and} \quad (1)$$

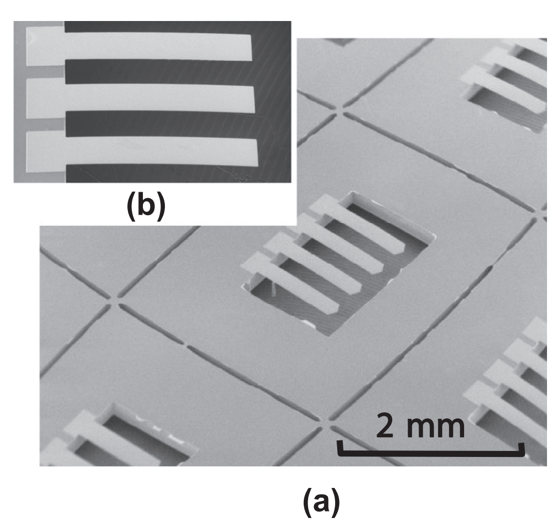

Fig. 3. Scanning electron microscopy images of the FBNN-MGTF cantilevers: (a) batch fabricated cantilever arrays, and (b) enlargement of the cantilevers.