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Strong self-biased magnetoelectric charge coupling in a homogenous laminate stack for magnetic sensor

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ABSTRACT

In this study, we report a strong self-biased magnetoelectric (ME) charge coupling in homogenous two-phase magnetostrictive/piezoelectric laminate stack. The proposed ME stack Ni/PZT-stack is made up of hard-processing Nickel foils (Ni) and a tape-casting multilayer Pb(Zr, Ti)O_3 (PZT) plate with high capacitance. Resonant ME couplings of Ni/PZT-stack with different thickness ratio (n) of Ni foil are investigated in detail. The experimental results show that the Ni/PZT-stack with $n = 0.4$ has maximum zero-biased resonant ME charge coefficient ($\alpha_{Q,r}$) of 47.52 nC/Oe, which is far larger higher than that previously reported for other ME laminates. The proposed self-biased miniature ME structure may be useful for multifunctional devices such as electromagnetic energy harvesting, magnetic-to-electric generators or magnet field sensing based on a charge-detection method.

1. Introduction

Magnetoelectric (ME) composites consisting of magnetostrictive and piezoelectric components have larger ME effect than that of any natural signal-phase ME material by several orders of magnitude [1]. The extrinsic ME effect has been widely investigated both by theory and through experiment in various magnetostrictive and piezoelectric ME composites operated in several different modes [2–4]. It has been shown that the ME response of the laminated composites is determined by several major aspects: (a) the materials characteristics and mechanical coefficients of the constituents [2–13]; (b) the composition ratio of the piezoelectric and magnetostrictive layers [8–10]; (c) the type of boundary constituents [11]; and (d) the composition structure [4,12–15].

From previous reports, large ME charge couplings are important for developing applications, such as electromagnetic energy harvesters [16], magnetic-to-electric generators [17,18] or magnet field sensor based on a charge-detection method [19,20]. However, most of the reported ME composites in the literature has small charge induced from the ME effect due to the low dielectric capacitance [2–18]. For the magnetostrictive phase, the most severe limitation results from the dependence of the piezomagnetic coefficient d_m on dc bias field (H_{dc}) [1–20]. To overcome these limitations arising from an external bias magnetic field, more and more researchers have focused on self-biased ME effect in the composites [21–25]. For the piezoelectric phase, the PZT have been the first choice in the design of ME laminate composite [2–4]. Unfortunately, the charge induced from the effect is small due to the low dielectric capacitance. And high cost and low Curie temperature of piezoelectric single crystal fibers and complex fabrication process present challenges in implementation at commercial scale [26,27]. As a result, for the physically interesting, technologically important and environmental perspective, it is indeed to design a novel laminate composite consisting of self-biased magnetostrictive component with simple processing and new PZT candidates with high capacitance, which should have large self-biased ME charge coupling.

In this paper, we report a large self-biased ME charge coupling in a homogenous laminate stack. The laminate stack is consisting of a PZT multilayer stack as the piezoelectric component and hard-processing Nickel (Ni) as the magnetostrictive component. By using single-phase homogenous magnetostrictive hard-processing Ni without any complicated synthesis processes, a strong self-biased effect can be obtained. And with use of the PZT multilayer stack with high capacitance, a dramatically giant ME charge coupling is observed. Such brand-new configurations yield the giant ME charge coupling at zero-biased magnetic field. And the preparation

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method is simple and feasible.

2. Experimental

Fig. 1(a) shows the schematic illustration of tape-casting multilayer PZT plate with high capacitance. The piezoelectric multilayer stack was prepared with PZT-8 powders by a tape casting method. Then it was polarized in the thickness direction under an electric field of 3.5 kV/mm. The multilayer had a dimension of 20 × 3 × 0.6 mm^3 with 15 layers and 40 μm per-layer. From Fig. 1(a), the positive and negative electrodes for each 40 μm layer of the PZT stack are in parallel, yielding a large capacitance of 236 *nF* for the multilayer PZT stack. The Ni foils (provided by Baoji metal Materials and Equipment Manufacturing Co., Ltd., China) was cut with the dimension of 12 × 6 × 0.1 mm^3. As shown in Fig. 1(b), the multilayer ME composites Ni/PZT-stack was obtained by bonding the piezoelectric plate and Ni foils together with epoxy adhesive and pressed using a hydraulic press to make the epoxy layers as thin and perfect as possible.

In experiments, a pair of neodymium permanent magnets (NdFeB) was used to provide the dc bias magnetic field (H_{dc}). A signal generator (Tektronix AFG3021B) provided a controllable input current to a long straight solenoid coil which was used to generate a small ac magnetic field (H_{ac}). We measured the induced charge Q with a charge amplifier connected to an oscilloscope. Then the ME charge coefficient can be obtained, $\alpha_Q = \partial Q_{ME}/\partial H_{ac}$.

3. Results and discussion

The ME coupling effect is a product property of the piezomagnetism, the piezoelectricity of the corresponding phases and their coupling, which can be characterized by $\alpha_Q = \partial Q_{ME}/\partial H = kd_m d_p$. where *k* is a coupling factor between the two phases, d_m and d_p is the ME coefficient of the composite. Therefore, first we measured H_{dc} dependence of dynamic magnetostrictive coefficient ($d_{33,m}$) for the hard-processing Ni foil under free conditions, as shown in Fig. 2. The vibration velocity *v* of the sample was measured by Doppler vibrometer (Polytec OFV-5000). Then the piezomagnetic coefficient was calculated by $d_{33,m} = d\lambda/dH = v/(\pi f l H_{ac})$. Here *f* is the vibration frequency, *l* is the length, and H_{ac} is the external AC magnetic field.

The $d_{33,m}$ of hard-processing Ni foil shows a hysteretic behavior during H_{dc} sweep (clockwise direction). Importantly, large zero-biased $d_{33,m}$ is observed. As H_{dc} increases from −600 Oe to 0 Oe, $d_{33,m}$ increases to a peak value of −15.1 *nm*/*A* for $H_{dc} = -51$Oe. The $d_{33,m}$ at $H_{dc} = 0$ Oe is −13.3 *nm*/*A*. As H_{dc} increases from 0 Oe to 100 Oe, the $d_{33,m}$ decreases down to zero for $H_{dc} = 45$Oe. Beyond this zero-crossing, a further decrease in H_{dc} results in an increase in $d_{33,m}$ for 45 Oe < H_{dc} < 140 Oe. A peak value of 13.1 *nm*/*A* is observed at $H_{dc} = 140$ Oe and then decreases down for $H_{dc} > 140$ Oe. The results demonstrate that the hard-processing Ni foil with hysteretic behavior is effective to obtain self-biased effect.

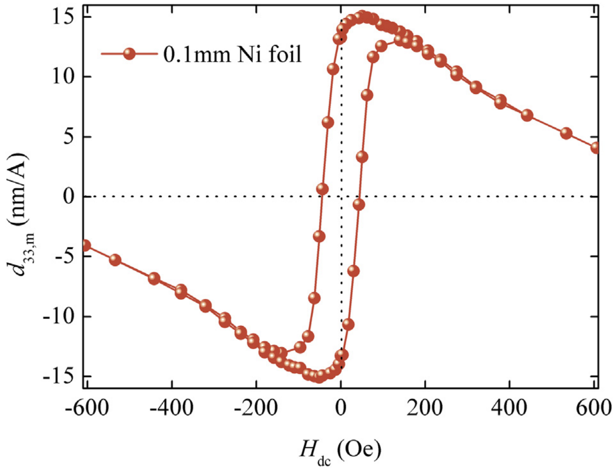

Fig. 2. The piezomagnetic coefficient $d_{33,m}$ as a function of H_{dc} for hard-processing Ni foil.

Fig. 3(a) show the zero-biased ME charge coefficient $\alpha_Q = \partial Q_{ME}/\partial H$ as a function of frequency around resonance. In this figure, the thickness of Ni foil is 0.1 mm, or the thickness ration *n* [$n = t_m/(t_m + t_p)$, with t_m or t_p being the respective thickness of the Ni and the PZT layer, respectively] of Ni foil in ME stack is 0.143. It is clearly that the α_Q reaches 41.5 nC/Oe at resonance frequency $f_r = 91.78$ kHz. For the ME composite consisting of mechanically coupled magnetostrictive and piezoelectric layers, the resonance frequency of ME composite is [28].

$$f_r = \overline{V}/2l \qquad (1)$$

where $\overline{V} = 1/(\rho s_{11})^{-1/2}$ (ρ and s_{11} are the average density and equivalent elastic compliance, respectively) is the average acoustic velocity. Fig. 3(b) shows the estimated and measured values of resonance frequency (f_r) for the ME stack as a function of the volume fraction *n* of the Ni phase. The variation of f_r with respect to n

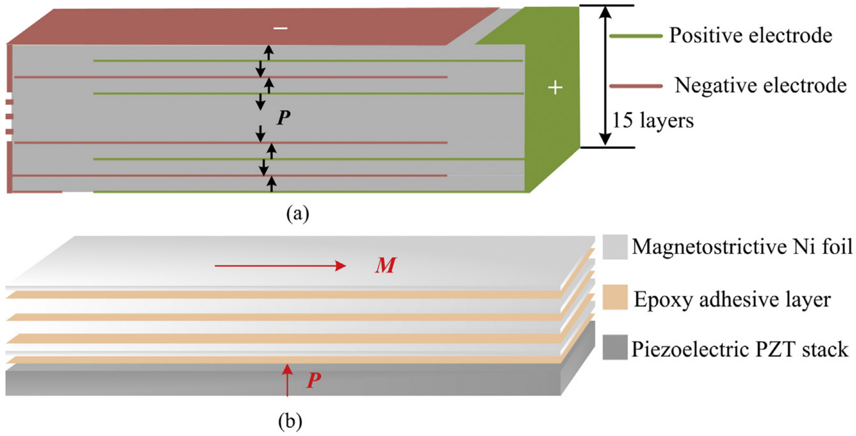

Fig. 1. (a) Schematic illustration of the tape-casting multilayer Pb(Zr, Ti)O_3 (PZT) plate with high capacitance, (b) schematic illustration of the ME stack Ni/PZT-stack of multilayer Ni and PZT multilayer stack. The arrows *M* and *P* designate the magnetization and polarization directions, respectively.