Magnetoelectric effect from mechanically mediated torsional magnetic force effect in NdFeB magnets and shear piezoelectric effect in $0.7Pb(Mg_{1/3}Nb_{2/3})O_3-0.3PbTiO_3$ single crystal

Yaojin Wang,[1,2,3,a)] Siu Wing Or,[2] Helen Lai Wa Chan,[2] Xiangyong Zhao,[1] and Haosu Luo[1]

[1]*State Key Laboratory of High Performance Ceramics and Superfine Microstructure, Shanghai Institute of Ceramics, Chinese Academy of Sciences, 215 Chengbei Road, Jiading, Shanghai 201800, People's Republic of China*

[2]*Department of Applied Physics, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong, People's Republic of China*

[3]*Graduate School of the Chinese Academy of Sciences, Beijing 10039, People's Republic of China*

(Received 16 January 2008; accepted 28 February 2008; published online 27 March 2008)

We experimentally and theoretically report the magnetoelectric effect in a composite made by sandwiching one shear mode $0.7PbMg_{1/3}Nb_{2/3}O_3-0.3PbTiO_3$ (PMN-PT) piezoelectric single crystal plate between two longitudinally magnetized NdFeB permanent magnet bars along the length direction of the PMN-PT plate. The magnetoelectric effect originates from the mechanically mediated product effect of the torsional magnetic force effect in the NdFeB bars and the shear piezoelectric effect in the PMN-PT plate. The composite exhibits a magnetoelectric voltage coefficient of ~32.7 mV/cm Oe with a flat frequency response in the measured range of 0.1–30 kHz. The induced magnetoelectric voltage shows a good linear relationship to the applied ac magnetic field with amplitude varying from 10^{-7} to 10^{-3} T. Other distinct features include no need to have a magnetostrictive phase, low Joule heating loss, and high scale-down capability. These suggest promising applications of the torsional-shear mode composite in power-free magnetic field sensors. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2901162]

The magnetoelectric (ME) effect is a polarization response to an applied magnetic field (H) or conversely a spin response to an applied electric field (E).[1] This effect has drawn increasing attention in advanced materials research owing to its potential uses in power-free magnetic field sensors, current sensors, and ME transducers. In the past decades, considerable research efforts have been placed on the ME effect, first in single-phase materials, then in two-phase bulk composites, and lately, in two-/three-phase laminated composites.[2–9] Due to the existence of a strong product effect of the magnetoelastic and elastoelectric effects, laminated composites of $Tb_{0.3}Dy_{0.7}Fe_{1.92}$ (Terfenol-D) magnetostrictive alloy and $PbMg_{1/3}Nb_{2/3}O_3-PbTiO_3$ (PMN-PT) piezoelectric single crystal have been the focus of investigations.[4] Moreover, various ME operating modes have been studied, including longitudinal-longitudinal (L-L), longitudinal-transverse (L-T), transverse-longitudinal (T-L), transverse-transverse (T-T), ring-type, push-pull, and bending modes.[4,7–10] To date, no reports have been made on composites utilizing the shear mode of PMN-PT single crystal even though the shear piezoelectric properties of PMN-PT single crystal are much higher than the transverse-extensional and longitudinal-extensional piezoelectric properties, as shown in Table I.

In this letter, we demonstrate a torsional-shear mode composite consisting of a shear mode PMN-PT piezoelectric single crystal plate sandwiched between two longitudinally magnetized NdFeB permanent magnet bars along the length direction of the PMN-PT plate. Figure 1 illustrates the geometry and working principle of the proposed composite. The shear mode PMN-PT piezoelectric single crystal plate, of dimensions 14 mm long, 7 mm wide, and 1 mm thick, and with their ⟨111⟩ and ⟨110⟩ crystallographic axes oriented in its length and thickness directions, respectively, were grown in-house using a modified Bridgman technique.[13] After being electroded with silver and polarized along the length direction in a silicone oil bath, the silver electrodes were removed from the PMN-PT samples. The de-electroded samples were then re-electroded along the thickness direction by sputtering gold near room temperature to avoid the occurrence of depolarization. The shear piezoelectric voltage coefficient ($g_{15}=d_{15}/\varepsilon_{11}^T$) was determined to be 60.5×10^{-3} V m/N by an Agilent 4294A impedance analyzer according to the IEEE resonance method.[14] The two longitudinally magnetized NdFeB permanent magnet bars were commercially supplied with the same dimensions, length of 7 mm, width of 2 mm, and thickness of 2 mm. They were galvanized using nickel and their saturation magnetization (M_s) was know to be 1870 kA/m.

The working principle of the proposed torsional-shear mode ME composite is as follows (Fig. 1). Under an applied ac magnetic field (H_3) along the length direction of the composite, a torsional ac magnetic force (F_3) will be induced about the geometric central axis of the NdFeB bars. This F_3 will drive the sandwiched PMN-PT plate into shear mode vibrations, thus, producing a shear piezoelectric voltage (V_3) (or charges) based on the shear piezoelectric effect. In fact, there are two distinct differences between the proposed torsional magnetic force-induced shear piezoelectric effect in our ME composite and the magnetostrictive strain-induced transverse-extensional or longitudinal-extensional piezoelectric effect in the previously reported ME laminated

a)Author to whom correspondence should be addressed. Electronic mail: wangyaojin@hotmail.com.

TABLE I. Material parameters of $0.7PbMg_{1/3}Nb_{2/3}O_3-0.3PbTiO_3$ (PMN-PT) single crystal measured at various vibration modes.

	Piezoelectric strain coefficient (d, 10^{-12} C/N)	Piezoelectric voltage coefficient (g, 10^{-3} V m/N)	Electromechanical coupling coefficient (k, %)
Transverse-extentional mode (31)[a]	−2517	40.4	95.4
Longtudinal-extentional mode (33)[b]	2000	38.8	86.4
Shear mode (15)[c]	5980	60.5	97

[a]Cited from Ref. 11.
[b]Cited from Ref. 12.
[c]Measured properties.

composites.[4,7–10] First, our composite does not require a magnetostrictive phase, thereby minimizing the effect of Joule heating loss. Second, our composite utilizes the ultra-high shear piezoelectric properties of PMN-PT single crystal in contrast to the transverse-extensional or longitudinal-extensional piezoelectric properties (Table I). This means that the configuration of ME devices based on the current composite is generally simpler and amenable to the miniaturization.

Based on the charge model for analyzing solid rectangular bar magnets with uniform axial magnetization,[15] the magnitude of torsional magnetic force exerted by each magnet (F_3) is

$$F_3 = \mu_0 M_s A_m H_3 \cos\theta, \tag{1}$$

where $\mu_0(=4\pi\times 10^{-7}$ H/m) is the magnetic permeability of free space, M_s is the saturation magnetization of the magnet bars, A_m is the cross-sectional area of the magnet bars, H_3 is the externally applied ac magnetic field, and θ is the resulting torsional angle, as shown in Fig. 1. In our design, the piezoelectric plate is excited in shear mode vibrations so that the following shear piezoelectric constitutive equations for the plate are adopted:[16]

$$S_5 = s_{55}^D T_5 + g_{15} D_1, \tag{2a}$$

$$E_1 = -g_{15} T_5 + \beta_{11}^T D_1, \tag{2b}$$

where T_5 and S_5 are the shear stress and strain, respectively; E_1 and D_1 are the electric field strength and electric displacement along the width direction, respectively; s_{55}^D is the elastic compliance coefficient at constant electric displacement; g_{15} is the shear piezoelectric voltage coefficient; and β_{11}^T is the dielectric impermittivity at constant stress. The shear stress in the piezoelectric plate (T_5) due to the transfer of F_3 from the two magnet bars can be expressed as

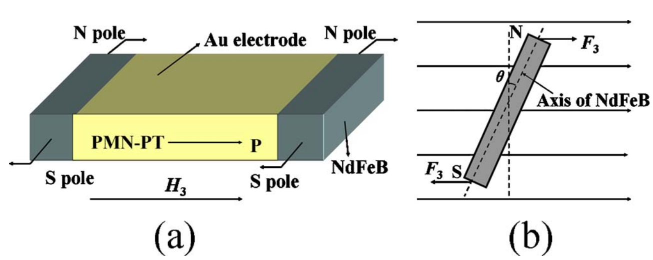

FIG. 1. (Color online) Schematic diagram and working principle of the proposed torsional-shear mode ME composite. The arrow P denotes the polarization direction in the PMN-PT plate.

$$T_5 = \frac{2F_3}{t_p l_p}, \tag{3}$$

where t_p and l_p are the thickness and length of the piezoelectric plate, respectively. By placing F_3 from Eq. (1) and T_5 from Eq. (3) into Eqs. (2a) and (2b), respectively, and considering the strain is extremely small, the ME voltage efficient (α_E) of the composite can be obtained as

$$\alpha_E = -2\frac{\mu_0 M_s A_m g_{15}}{t_p l_p}. \tag{4}$$

From Eq. (4), it is clear that α_E of the composite depends on g_{15} of the piezoelectric plate, M_s of the magnets, and the geometric parameters of the composite. Substituting the corresponding material and geometric parameters of PMN-PT and NdFeB into Eq. (4), α_E of the proposed composite is predicted to be 38.2 mV/cm Oe.

Figure 2 shows the induced ME voltage (V_3) over an applied magnetic field (H_3) range of $10^{-7}-10^{-3}$ T at a drive frequency of 1 kHz. It is clear that V_3 has an excellent linear response to H_3 in the whole range. A higher detection sensitivity of $10^{-9}-10^{-11}$ T could be obtained if shielding of magnetic noise could be adopted and composite fabrication could be improved. From the slope of the plot, the ME voltage coefficient (α_E) at 1 kHz is determined to be 32.7 mV/cm Oe. This experimental α_E coincides reasonably well with the predicted α_E of 38.2 mV/cm Oe based on Eq. (4). Nevertheless, the obtained α_E is higher than most of the

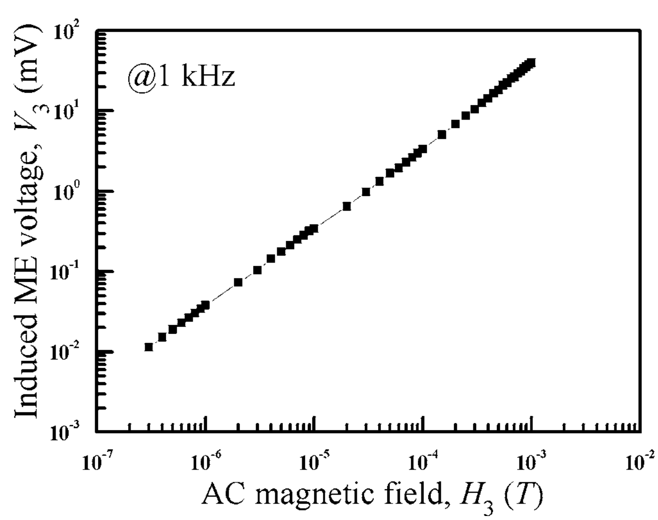

FIG. 2. Induced ME voltage (V_3) over an applied magnetic field (H_3) range of $10^{-7}-10^{-3}$ T at a drive frequency of 1 kHz.

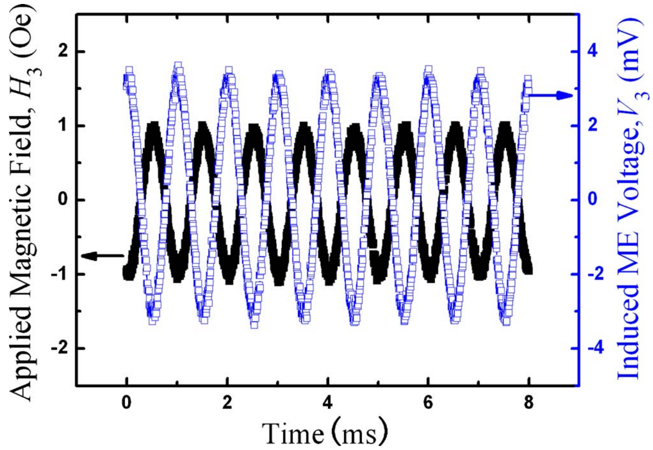

FIG. 3. (Color online) Waveforms of applied magnetic field (H_3) (magnitude of 1 Oe peak) and induced ME voltage (V_3) at a frequency of 1 kHz.

conventional magnetostrictive-piezoelectric ME composites operating at zero bias (or dc) magnetic field.[4,5,7–10]

Figure 3 shows the waveforms of applied magnetic field (H_3) (magnitude of 1 Oe peak) and induced ME voltage (V_3) at a frequency of 1 kHz. Stable signal conversion between the applied H_3 (1 Oe peak) and induced V_3 (3.27 mV peak) is evident. Besides, H_3 and V_3 are of opposite phase, which agrees with the prediction provided by Eq. (4).

Figure 4 shows the ME voltage coefficient (α_E) in the frequency (f) range of 0.1–30 kHz at a constant magnetic field amplitude of H_3=1 Oe. It is obvious that α_E has an excellent flat response in measured f range. As a comparison, reluctance coils fall short in providing valid detection at low frequencies because of the low rate of change of magnetic

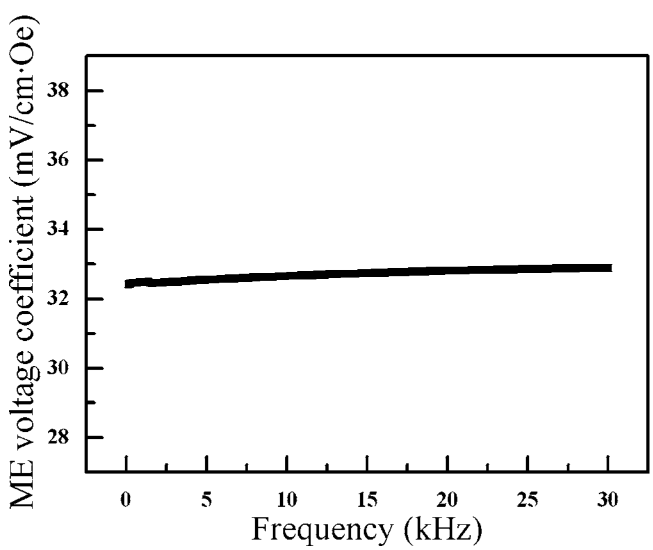

FIG. 4. ME voltage coefficient (α_E) in the frequency (f) range of 0.1–30 kHz at a constant magnetic field amplitude of H_3=1 Oe.

fluxes.[9] Due to the electrical insulation of the magnet bars, the possible eddy-current-induced thermal losses in the magnet bars are negligible even the composite is exposed to a high drive frequency of 30 kHz. Consequently, the current composite can stably work under a wide range of frequency.

In summary, we have developed a torsional-shear mode composite by sandwiching a shear mode PMN-PT plate between two longitudinally magnetized NdFeB bars along the length direction of the PMN-PT plate. The experimental and theoretical results have demonstrated the existence of a large α_E in excess of 32 mV/cm Oe in the composite. A good linear relationship between H_3 and V_3 in the H_3 range of 10^{-7}–10^{-3} T has been observed, besides a flat frequency response from 0.1 to 30 kHz. The composite does not require a magnetostrictive phase and has low Joule heating loss and high scale-down capability, making it a promising ME material for realizing power-free magnetic field sensors.

This work was supported by the Research Grants Council of the HKSAR Government (PolyU 5255/03E and PolyU 5122/05E), the Niche Areas Project of The Hong Kong Polytechnic University (1-BB95), the 863 High Technology and Development Project of the People's Republic of China (2006AA03Z107), the Natural Science Foundation of China (50432030, 50777065, and 50602047), the Scientific Innovation Program of Chinese Academy of Sciences (KGCX2-YW-111-7), Shanghai Municipal Government (06DZ05016), and Innovation Funds from Shanghai Institute of Ceramics of Chinese Academy of Sciences (SCX0608).

[1]L. D. Landau and E. Lifshitz, *Electrodynamics of Continuous Media* (Pergamon, Oxford, 1960), p. 119.
[2]V. J. Folen, G. T. Rado, and E. W. Stalder, Phys. Rev. Lett. **6**, 607 (1961).
[3]J. Ryu, A. V. Carazo, K. Uchino, and H. Kim, J. Electroceram. **7**, 24 (2001).
[4]S. X. Dong, J. F. Li, and D. Viehland, Appl. Phys. Lett. **83**, 2265 (2003).
[5]S. W. Or, T. L. Li, and H. L. W. Chan, J. Appl. Phys. **97**, 10M308 (2005).
[6]Y. M. Jia, S. W. Or, J. Wang, H. L. W. Chan, X. Y. Zhao, and H. S. Luo, J. Appl. Phys. **101**, 104103 (2007).
[7]S. X. Dong, J. F. Li, and D. Viehland, Appl. Phys. Lett. **89**, 252904 (2006).
[8]S. X. Dong, J. Y. Zhai, F. M. Bai, J. F. Li, and D. Viehland, Appl. Phys. Lett. **87**, 062502 (2005).
[9]S. X. Dong, J. F. Li, and D. Viehland, J. Appl. Phys. **96**, 3382 (2004).
[10]Z. P. Xing, S. X. Dong, J. Y. Zhai, L. Yan, J. F. Li, and D. Viehland, Appl. Phys. Lett. **89**, 112911 (2006).
[11]J. Peng, H. S. Luo, D. Li, H. Q. Xu, T. H. He, and W. Q. Jin, Appl. Phys. Lett. **85**, 6221 (2004).
[12]H. S. Luo, G. S. Xu, H. Q. Xu, P. C. Wang, and Z. W. Yin, Jpn. J. Appl. Phys., Part 1 **39**, 5581 (2000).
[13]H. S. Luo, G. S. Xu, H. Q. Xu, P. C. Wang, and Z. W. Yin, Jpn. J. Appl. Phys., Part 1 **39**, 5581 (2000).
[14]*IEEE Standard on Piezoelectricity, ANS/IEEE Std 176-1978* (IEEE, New York, 1978).
[15]E. P. Furlani, *Permanent Magnet and Electromechanical Device: Materials, Analysis, and Applications* (Academic, San Diego, 2001).
[16]T. Ikeda, *Fundamentals of Piezoelectric* (Oxford University Press, Oxford, 1990).