AIP Applied Physics Letters

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Citation: Applied Physics Letters **86**, 182506 (2005); doi: 10.1063/1.1923184
View online: http://dx.doi.org/10.1063/1.1923184
View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/86/18?ver=pdfcov
Published by the AIP Publishing

APPLIED PHYSICS LETTERS **86**, 182506 (2005)

Circumferential-mode, quasi-ring-type, magnetoelectric laminate composite—a highly sensitive electric current and/or vortex magnetic field sensor

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(Received 14 February 2005; accepted 16 March 2005; published online 28 April 2005)

A quasi-ring-type magnetoelectric (ME) laminate composite consisting of a circumferentially poled piezoelectric $Pb(Zn_{1/3}Nb_{2/3}O)_3$-4.5 at. % $PbTiO_3$single-crystal ring and two circumferentially magnetized magnetostrictive TERFENOL-D rings was fabricated and found to have a giant ME voltage coefficient of 2.2 V/Oe, or equivalently a ME field coefficient of 5.5 V/cm Oe, over the frequency range of $0.5 < f < 10^5$ Hz. This circumferential-mode quasiring ME laminate can detect ac currents (noncontact) as small as 10^{-7} A, and/or a vortex magnetic field as small as 6×10^{-12} Tesla. In addition, we demonstrated current sensing capability of the quasiring laminate in a power electronics module. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1923184]

The magnetoelectric (ME) effect[1] in materials that are simultaneously ferromagnetic and ferroelectric has been a research topic in recent years, due to potential applications as magnetic sensors, electric current sensors, and magnetic-electric transformers. ME materials of single phase, multiple phases, and laminate composites have been reported.[2–16] It is known that piezoelectric/magnetostrictive composites have better ME properties than single phase materials.[2–16] Previous investigations have focused on ME laminates whose piezoelectric/magnetostrictive layers consist of simple configurations of disc, square, or rectangular shapes. These geometries are only suitable for detection of magnetic fields of constant direction. However, in many situations, there is a need to detect ac rotating (or vortex) magnetic fields, excited by wires carrying a current I. There is a need for such vortex sensors in power integrated circuits[17,18] and superconducting films.[19]

Recently,[20,21] we reported that a laminate made from a $Pb(Zr,Ti)O_3$ (PZT) piezoelectric ring-type layer laminated between two TERFENOL-D ($Tb_{1-x}Dy_xFe_{2-y}$) ring-type layers could be used for vortex magnetic field detection. Using this ring-type laminate, a ME voltage coefficient of 0.26 V/Oe and a magnetic field sensitivity of $\sim 10^{-9}$ Tesla were achieved. Unfortunately, these values were much lower than that achieved using a longitudinally magnetized and longitudinally or transversely polarized (i.e., L-L or L-T) mode of a long-type magnetostrictive TERFENOL-D/piezoelectric single-crystal PMN-PT laminate, which was found to have a ME voltage coefficient up to 0.4 V/Oe and a magnetic field (constant direction) sensitivity of $\sim 10^{-11}$ Tesla.[14] In this letter, we shall show that a quasi-ring-type laminate consisting of one single-crystal $Pb(Zn_{1/3}Nb_{2/3})O_3$-4.5 at. % $PbTiO_3$ (PZN-4.5PT) laminated between two TERFENOL-D rings has a higher ME voltage coefficient and field sensitivity than either prior ring-type[20,21] or L-T or L-L long-type laminates.[11–14] Here, we have chosen PZN-4.5PT as the piezoelectric layer material,[22] as it is known to have much higher piezoelectric properties than the PZT previously used in ring-type laminates.

The configuration of the laminate studied in this investigation was as follows. A PZN-4.5PT single crystal cut into a quasiring geometry and with a circumferential ([001] direction) polarization was laminated between two TERFENOL-D layers of similar geometry, as shown in Fig. 1. The outer and inner diameters and thickness of the rings were 8, 3, and 2.5 mm, respectively. Since this composite ring configuration consists of circumferentially magnetized magnetostrictive and circumferentially poled piezoelectric quasiring layers, it is designated as a C-C mode ME laminate.[13,20,21] This configuration intensifies the principle strain/vibration in the circumferential direction of the TERFENOL-D ring layers under a vortex magnetic field drive. Correspondingly, it achieves the maximum electromechanical coupling of the piezoelectric single-crystal layer, by using the maximum circumferential strain/vibration and the maximum piezoelectric and electromechanical coefficients in the circumferential direction. Because the piezomagnetic and piezoelectric layers are mutually coupled via strain $S(z)$ and stress $T(z)$ in the laminate, application of an ac vortex magnetic field H_{ac} along the circumferential direction of the magnetostrictive ring layers puts the piezoelectric one into forced oscillation along the same direction. This excites a radial symmetric vibration mode in the piezoelectric, generating a voltage across each segment of the piezoelectric quasiring layer, via the longitudinal piezoelectric constant $d_{33,p}$.

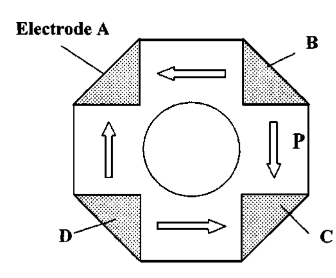

FIG. 1. Quasiring configuration of piezoelectric PZN-4.5PT single crystal poled along the [001] direction.

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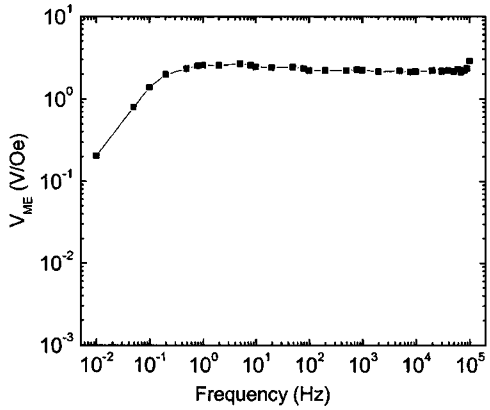

FIG. 2. ME voltage coefficients of the C-C quasiring laminate as a function of drive frequency.

First, we investigated the small ac sinusoidal magnetic signal response of our quasiring C-C mode laminate. During measurements, a thin long-straight wire was inserted at the center of the C-C quasiring, which generated a small ac vortex magnetic field H_{ac}, via an input ac current $I(H_{ac} = I/2\pi a)$, where a is mean radius of the C-C quasiring. A charge amplifier combining with a lock-in amplifier method was used to detect the induced ME voltage. The ME voltages induced across the two electrodes between one segment of the piezoelectric single-crystal PZN-4.5PT quasiring layer (see Fig. 1) was measured over a wide frequency range of $10^{-2} < f < 10^5$ Hz at a constant vortex magnetic field of $H_{ac} = 1.0$ mOe, as shown in Fig. 2. In this figure, the ME voltage coefficient (dV/dH_{ac}) can be seen to have a near flat response to H_{ac} in the frequency range of $0.5 < f < 10^5$ Hz. The maximum ME voltage coefficient was 2.2 V/Oe, or an equivalent ME field coefficient of 5.5 V/cm Oe, under a dc magnetic bias of $H_{dc} = 500$ Oe. This nonresonance magnetic field sensitivity is $\sim 10\times$ higher than that of our previous ring-type TERFENOL-D/PZT laminate,[20] and it is also notably higher than other long-type ME laminates under nonresonant conditions.[2–16] At lower frequencies of $10^{-2} < f < 0.1$ Hz, the induced ME voltage of our C-C quasiring was found to decrease with decreasing frequency, presumably due to a low-frequency limit of its *RC* circuit.[23]

Next, the ME voltage induced across one segment of the piezoelectric quasiring layer was measured as a function of H_{ac} (or equivalently a current I_{ac} carried by the wire) over a magnetic field range of $10^{-12} < H_{ac} < 10^{-8}$ Tesla (or equivalently, $10^{-7} < I_{ac} < 10^{-3}$ A) at frequencies of $f = 1$ and 3×10^4 Hz. Figure 3 shows the measured ME voltage under a bias of $H_{dc} = 500$ Oe, as a function of a low-level H_{ac}. The induced ME voltage of the C-C quasiring laminate was found to be a linear function of H_{ac} (or current I_{ac}) over this range. The limiting H_{ac} (or equivalent I_{ac}) that could be detected by the C-C mode quasiring laminate was 6×10^{-12} Tesla (or equivalently 9.4×10^{-8} A) at a frequency of $f = 3 \times 10^4$ Hz. At a lower frequency of $f = 1$ Hz, the limit of H_{ac} (or I_{ac}) was 6.1×10^{-11} Tesla (or 9.2×10^{-7} A). The ME voltage was also found to depend on H_{dc}, reflecting the dc-biased piezomagnetic behavior of TERFENOL-D (Ref. 24), which is maximum near the inflection point of the quadratic strain-magnetic field $(\varepsilon - H)$ curve.

Finally, we investigated the current sensing capability of the C-C mode quasiring laminate, by measuring the strong ac (switching) magnetic signal response. The ring was inserted into a commercial SemiKron half-bridge power electronics module (SK100 MB 10) (Ref. 25) that was operated in the switching mode with the current switched from 2 to 10.8 A and frequency up to 10^4 Hz. Figure 4(a) is an example of the switching current wave form. The induced ME voltage as shown in Fig. 4(b) was measured and recorded directly by an oscilloscope without charge amplification. It is clear that the induced ME voltage was in phase with the current wave form shown in (a) and there was no significant distortion in the sensing wave form. The induced ME voltages at $f = 10^4$ Hz under a small bias of $H_{dc} = 100$ Oe (applied using small permanent magnets) was 0.12, 0.38, and 0.68 V in response to a peak current of I_{ac} at 2, 6.5, and 10.8 A, respectively. (Please note that the ME voltage coefficients under a small H_{dc} are much lower than that under an optimum bias of $H_{dc} = 500$ Oe.) At higher frequencies of $10^4 < f < 10^5$ Hz, a good impulse response to the input switching current I_{ac} was still observed, however a phase shift was evident, due to eddy current losses in TERFENOL-D. It may be possible to reduce the degree of the phase shift by decreasing the thickness of the magnetostrictive layers, i.e., by

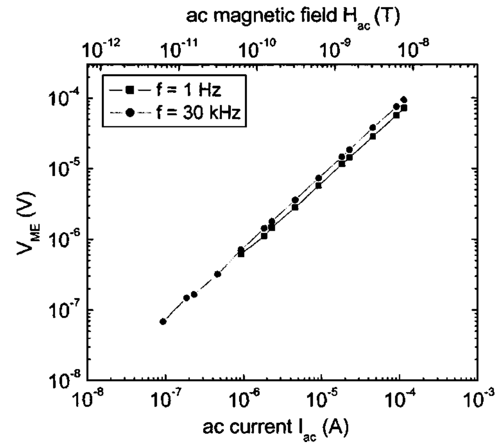

FIG. 3. ME response of the C-C quasiring laminate to low-level ac vortex magnetic field from $10^{-12} < H_{ac} < 10^{-8}$ Tesla, and low-level ac current from $10^{-8} < I_{ac} < 10^{-4}$ A at $f = 1.0$ Hz and 30 kHz, respectively.

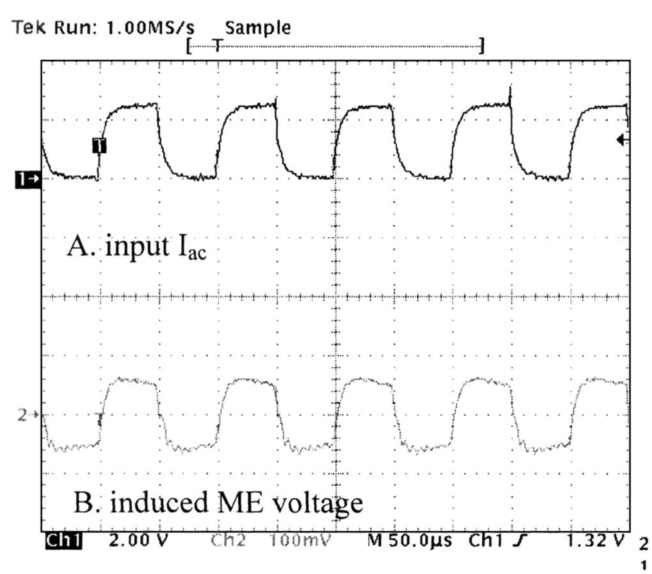

FIG. 4. ME response of the C-C quasiring laminate to large switching currents $(2 < I_{ac} < 10$ A) in a half-bridge integrated power electronics module (IPEM) at $f = 10$ kHz.

decreasing the eddy current effect. Considering that most power electronics modules are operated at specific switching frequencies, typically ranging from 10^3 to 3×10^4 Hz (Ref. 26), as determined by power converter specifications, our quasi-ring-type current sensor could be used for power conversion without concerning for phase shifting or distortion of the wave form. Potential advantages of using the ME ring current sensor in these applications are small size, high sensitivity, ease of circuitry isolation, and elimination of separate external power source.

In summary, a small quasi-ring-type ME composite consisting of a PZN-4.5PT crystal ring laminated between two TERFENOL-D rings was prototyped. The laminate was operated in a C-C mode for low-level sensing of minute electric currents (noncontact mode) and/or vortex magnetic fields. The results demonstrate: (i) a giant ME voltage coefficient of 2.2 V/Oe (or equivalently a field coefficient of 5.5 V/cm Oe); (ii) electric current and magnetic field sensitivities of 10^{-7}A and 6×10^{-12} Tesla, respectively; and (iii) current sensing capability within power electronics modules.

This research was supported by the Office of Naval Research under Grants No. N000140210340, N000140210126, and MURI N000140110761.

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