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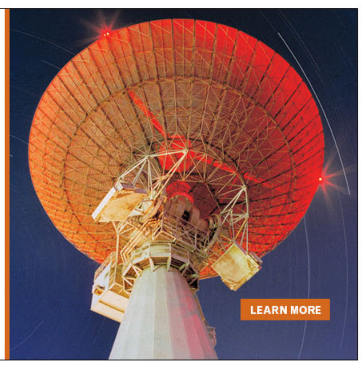

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JOURNAL OF APPLIED PHYSICS **109**, 074507 (2011)

Enhanced sensitivity to direct current magnetic field changes in Metglas/$Pb(Mg_{1/3}Nb_{2/3})O_3$–$PbTiO_3$ laminates

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We have developed Metglas/$Pb(Mg_{1/3}Nb_{2/3})O_3$–$PbTiO_3$ magnetoelectric (ME) laminates that have notably larger ME coefficients, with maximum values of up to 45 V/cm Oe. Based on this giant ME effect, the dc magnetic field sensitivity for Metglas/PMN–PT laminate sensors was improved by a factor of >3, relative to that for Metglas/$Pb(Zr,Ti)O_3$ (PZT)-based ones of the same geometry. Our new ME sensor can detect dc magnetic field changes as small as (i) 5 nT at 1 kHz and (ii) 1 nT near the resonant frequency in a shield chamber. © *2011 American Institute of Physics*. [doi:10.1063/1.3569629]

I. INTRODUCTION

There are many types of magnetic sensors, including giant magnetoresistive (GMR), flux-gate, and superconducting quantum interference devices (SQUID). They have low noise floors on the order of 10^{-10}, 10^{-12}, and 10^{-14} $T/\sqrt{Hz}$, respectively in the frequency range of $1 < f < 10^3$ Hz.[1–3] Such low noise floors offer the opportunity to develop highly sensitive magnetometers. However, there are some limitations to these conventional magnetic sensors in applications. For example, SQUIDs require extremely low operational temperatures, fluxgates have magnetic hysteresis and offset values under zero magnetic fields, and both flux gate and GMRs require considerable power.

An alternative type of magnetic sensor has recently been developed based on a giant magnetoelectric (ME) effect.[4] The ME effect was first observed about 50 years ago in Cr_2O_3 single crystals, which had a ME voltage coefficient of $\alpha_{ME} \approx 20$ mV/cm Oe.[5] Since 2001, ME laminated composites have been found that have ME voltage coefficients several orders of magnitude higher than that of single phase materials.[6] Long-type sandwiched laminate structures comprised of magnetostrictive Metglas and piezoelectric $Pb(Zr,Ti)O_3$ or PZT layers have values of $\alpha_{ME} \leq 22$ V/cm Oe.[7] Room temperature, passive, and highly sensitive magnetic sensors have been developed based on these ME heterostructures. In addition, geomagnetic sensors based on these Metglas/PZT-fiber laminates[8] have been shown capable of sensing earth's field and inclination, and detecting changes there within.

Dong *et al*.[9,10] developed an equivalent method by which to understand the ME coefficients of heterostructural composites. Following this method, α_{ME} should be linearly proportional to the piezoelectric voltage coefficient $g_{33,p}$, and a function of the piezoelectric coupling coefficient $k_{33,p}$. Here, we have developed multi-push–pull longitudinal–longitudinal or L–L mode Metglas/$Pb(Mg_{1/3}Nb_{2/3})O_3$–$PbTiO_3$ (PMN–PT) single crystal fiber ME laminates. Due to higher values of $g_{33,p}$ and $k_{33,p}$, the maximum value of α_{ME} for these sensors is about a factor of 3 higher than that for Metglas/PZT laminates of similar geometry. This enhancement in α_{ME} results in a three times increase in dc magnetic field sensitivity when driven in an active mode: enabling detection of dc magnetic field changes of $H_{dc} \leq 1$ nT.

II. EXPERIMENTAL DETAILS

To fabricate Metglas/PZT and Metglas/PMN-PT laminates, we obtained PZT (Smart Materials, Sarasota, FL) and PMN-PT (Ceracomp Co., Ltd., Korea) fibers, and Metglas foils (Vitrovac Inc., Hanau, German). The piezoelectric properties for these PZT and PMN-PT fibers are given in Table I. Five pieces of piezoelectric fibers of 180 μm in thickness were oriented along the long axes to form a layer that was 10 mm wide and 40 mm long. Two interdigitated Kapton-based electrodes were then bonded to the top and bottom surfaces of the piezoelectric layer in a multi-push–pull geometry. Three Metglas foils of 80 mm in length and 10 mm in width were then laminated to both the top and bottom surfaces of the piezoelectric layer, in order to achieve the optimized volume ratio between piezoelectric and magnetoelectric phases.[11] Details of the laminate fabrication method can be found in Ref. 7.

III. RESULTS AND DISCUSSION

First, the ME voltage coefficient α_{ME} was measured as a function of dc magnetic field H_{dc} for the different ME laminates. In this test, a lock-in amplifier (SR-850) was used to apply the driving signal to a pair of Helmholtz coils, which generated an ac magnetic field of $H_{ac} = 1$ Oe at frequency of $f = 1$ kHz. A dc magnetic field H_{dc} was then applied along the long axis of the ME laminates using permanent magnets. Figure 1(a) shows α_{ME} as a function of H_{dc} for Metglas/PMN–PT and Metglas/PZT laminates. In Fig. 1(a), we can see that α_{ME} for the two ME laminates had similar trends with H_{dc}; however, the values of α_{ME} for the Metglas/PMN–PT laminate was notably higher than that for the Metglas/PZT one. In particular, the maximum value of α_{ME} for the Metglas/PMN-PT laminate was 45 V/cm Oe, which was

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TABLE I. The critical piezoelectric properties for PZT and PMN–PT fibers.

	$d_{33,p}$ (pC/N)	$g_{33,p}$ (mV m/N)	k_{33}
PZT[a]	440	25.5	0.72
PMN-PT[b]	2000	32.4	0.93

[a]Cited from Smart Material Corp., USA.
[b]Cited from Ceracomp Co., Ltd., Korea.

about three times larger than that for the PZT based one of similar size (i.e., 15 V/cm Oe). This is the highest value of α_{ME} reported to date for any ME composite, at least by a factor of 2.

Figure 1(b) shows the ME voltage coefficient for Metglas/PZT and Metglas/PMN–PT laminates as a function of ac magnetic field frequency, while sweeping through the electromechanical resonance (EMR). The fundamental resonant frequencies for the PZT and PMN–PT based sensors were 31.5 and 27.8 kHz, respectively. In Fig. 1(b), we can see (i) a strong EMR enhancement in α_{ME} that has previously been reported[7] and (ii) that values of $\alpha_{ME} > 1100$ V/cm Oe can be reached for PMN–PT laminates, which was about $3\times$ larger than that for PZT ones.

Next, the dc magnetic field sensitivity was characterized for both sensors using an active method:[12] a 200-turn coil was wrapped around the sensor that carried a small ac current provided by the lock-in amplifier to drive the ME sensors. Voltages were then induced in the piezoelectric layer by small changes in H_{dc}, which were measured by the amplifier. In all of these measurements, we kept the signal-to-noise ratio constant at SNR = 10. Figures 2(a) and 2(b) show the induced output voltages from the Metglas/PZT laminates in response to small changes in H_{dc} at driving frequencies of $f = 1$ and 10 kHz, respectively. It can be seen that the dc magnetic field variations as small as $H_{dc} = 15$ nT can be detected for $f = 1$ kHz and $H_{ac} = 0.1$ Oe. Even higher sensitivity to small changes in H_{dc} were found for $f = 10$ kHz and $H_{ac} = 0.1$ Oe: where changes as low as 12 nT could be detected at a constant SNR = 10.

Figures 3(a) and 3(b) show similar sensitivity measurements to small changes in H_{dc} at a constant SNR = 10 for Metglas/PMN–PT laminates. In Fig. 3, one can see that the sensitivity for the Metglas/PMN-PT laminates was significantly enhanced relative to that for the Metglas/PZT ones. In Fig. 3(a), the sensitivity to dc magnetic field changes for PMN–PT laminates can be seen to be 5 nT at 1 kHz and $H_{ac} = 0.1$ Oe: which was three times higher than that for PZT based ones with a constant SNR. Further, as can be seen in Fig. 3(b), the sensitivity at $f = 10$ kHz can also be seen to be $3\times$ higher for Metglas/PMN–PT than Metglas/PZT. This enhancement in dc field sensitivity is a direct consequence of the higher values of α_{ME} for the Metglas/PMN–PT laminates. Please note that the value of $|\partial\alpha_{ME}/\partial H_{dc}|$ was also much larger for Metglas/PMN–PT than Metglas/PZT, over the range of -5 Oe $< H_{dc} < 5$ Oe, as can be seen in Fig. 1(a).

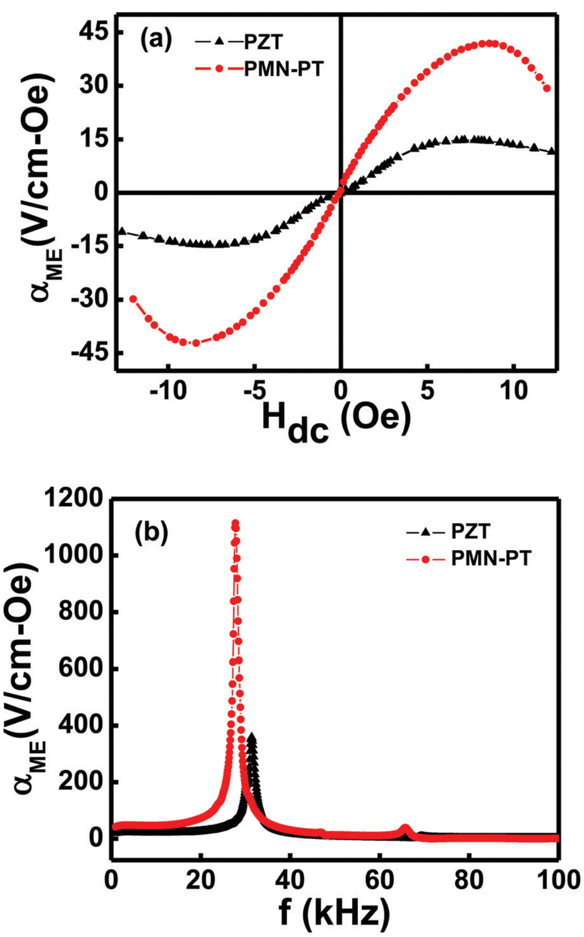

FIG. 1. (Color online) ME voltage coefficient of Metglas/PZT and Metglas/PMN–PT laminates: (a) α_{ME} as the function of dc bias H_{dc} at $f = 1$ kHz, and (b) α_{ME} as a function of ac magnetic drive frequency.

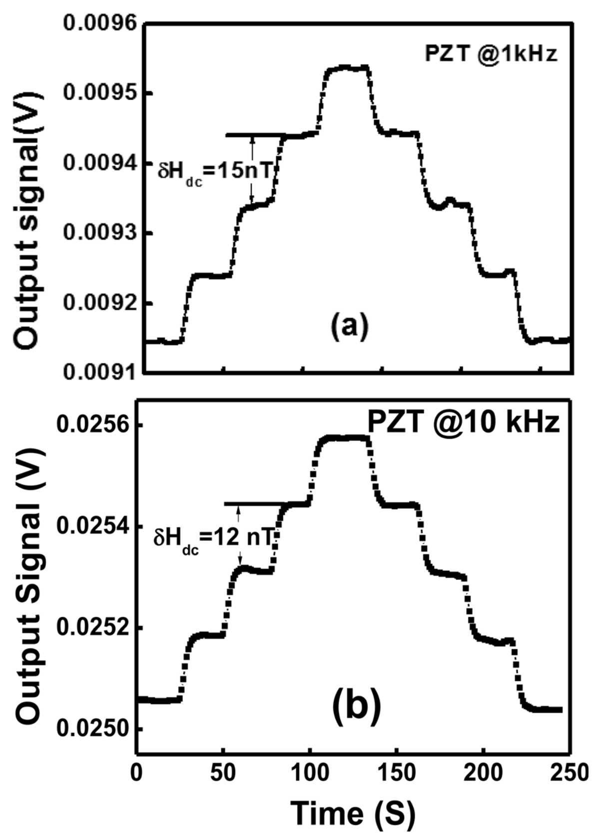

FIG. 2. Sensitivity of Metglas/PZT laminate to small dc magnetic field changes under ac drive conditions of: (a) at $f = 1$ kHz and $H_{ac} = 0.1$ Oe, and (b) at $f = 10$ kHz and $H_{ac} = 0.1$ Oe.

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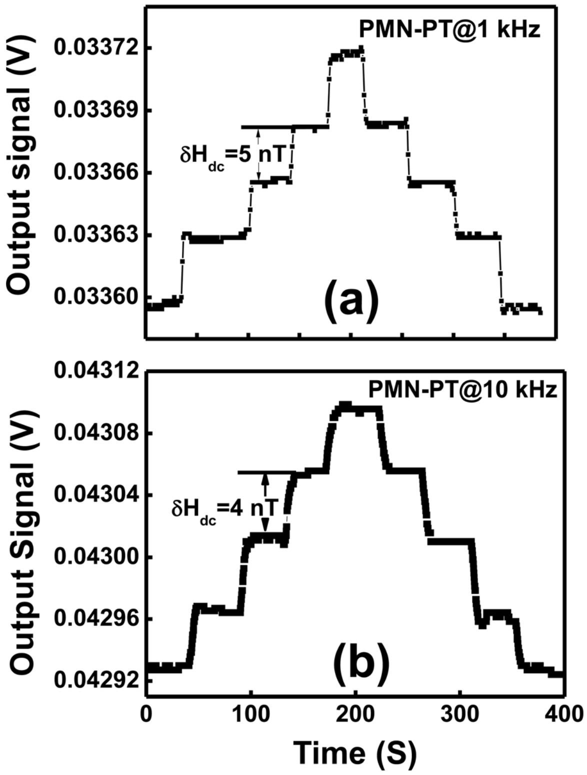

FIG. 3. Sensitivity of Metglas/PMN–PT laminate to small dc magnetic field changes under ac drive conditions of: (a) at $f = 1$ kHz and $H_{ac} = 0.1$ Oe, and (b) at $f = 10$ kHz and $H_{ac} = 0.1$ Oe.

Finally, the sensitivity to small dc magnetic field changes for Metglas/PMN–PT laminates was studied under the EMR conditions ($f = 27.8$ kHz). As α_{ME} is extremely high in this case [see Fig. 1 (b)], the ME sensor was placed in a magnetically shielded chamber to reduce exposure to environmental noise. Figure 4 shows the induced output voltage to small step changes in a dc magnetic field. Clearly, the Metglas/PMN–PT laminates can detect changes of $H_{dc} \leq 1$ nT. This represents a notable improvement in dc field sensitivity relative to lower frequencies using the same laminates ($4–5\times$), to PZT-based laminates ($12–15\times$), and to prior reports (about $10\times$).[12]

These dc field sensors might be used for a navigation based on variations in Earth's field, that is given an accurate database of $H_{earth}(x,y,z;t)$ such as tabulated by the National Geophysical Data Center.[13] Some migratory animals are believed to use a biological detection method for H_{earth} to assist them, in conjunction with other cues, in their navigation.[14,15] In consideration the average change in the variation of H_{earth} is 0.02 nT/m (Ref. 13), the dc field sensitivity of ≤ 1 nT for our ME sensor could offer the potential of localization or navigation with a precision of 50 m.

IV. SUMMARY

We have realized a significant enhancement in α_{ME} (by $3\times$) and the dc magnetic field sensitivity (by up to $10\times$) by using PMN–PT fibers in heterostructured composites, relative to the values of PZT fibers. The ME voltage coefficient for Metglas/PMN–PT laminates reached values of 45 V/cm Oe at $f = 1$ kHz, and of 1100 V/cm Oe at the EMR. The dc field sensitivity of these Metglas/PMN–PT laminates was then found to be 4 nT under a constant drive of $H_{ac} = 0.1$ Oe at $f = 10$ kHz. Even smaller dc field changes of ≤ 1 nT were also detected at the EMR. Such high sensitivities to small dc field changes have the potential for localization or navigation based on variations in the geomagnetic field.

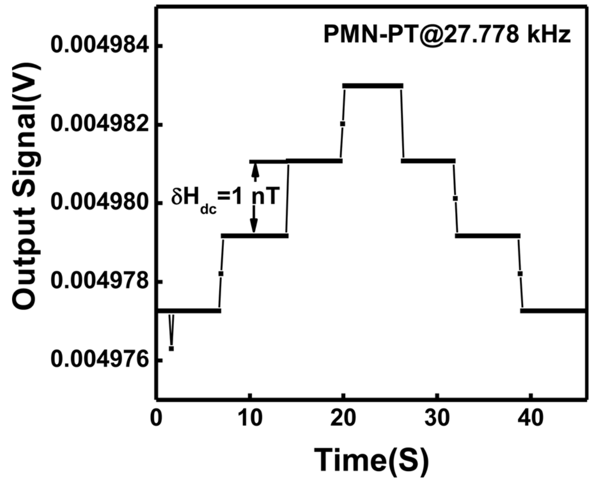

FIG. 4. Sensitivity of Metglas/PMN–PT laminate to small dc magnetic field changes under ac drive field of $H_{ac} = 0.1$ Oe at the resonant frequency.

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[1]P. Eitenne, G. Creuzet, A. Friederich, and J. Chazelas, Phys. Rev. Lett. **61**, 2472 (1988).
[2]K. Shirae, IEEE Trans. Magn. **20**, 1299 (1984).
[3]H. Bartehelmess, M. Halverscheid, B. Schiefenhovel, E. Heim, M. Schilling, and R. Zimmermann, IEEE Trans. Appl. Supercond. **11**, 657 (2001).
[4]J. Y. Zhai, S. X. Dong, J.-F. Li, and D. Viehland, Appl. Phys. Lett. **88**, 062510 (2006).
[5]G. T. Rado and V. J. Folen, Phys. Rev. Lett. **7**, 310 (1961).
[6]C-W. Nan, M. I. Bichurin, S. Dong, D. Viehland, and G. Srinivasan, J. Appl. Phys. **103**, 031101 (2008).
[7]S. X. Dong, J. Y. Zhai, J.-F. Li, and D. Viehland, Appl. Phys. Lett. **89**, 252904 (2006).
[8]J. Y. Zhai, S. X. Dong, Z. P. Xing, J.-F. Li, and D. Viehland, Appl. Phys. Lett. **91**, 123513 (2007).
[9]S. X. Dong, J. F. Li, and D. Viehland, IEEE Trans. Ultrason. Ferroelectr. Freq. Control. **50**, 1253 (2003).
[10]S. X. Dong, J. F. Li, and D. Viehland, J. Mater. Sci. **41**, 97 (2006).
[11]J. Das, J. Gao, Z. Xing, J. F. Li, and D. Viehland, Appl. Phys. Lett. **95**, 092501 (2009).
[12]S. X. Dong, J. Y. Zhai, J.-F. Li, and D. Viehland, Appl. Phys. Lett. **88**, 082907 (2006).
[13]http://www.ngdc.noaa.gov/geomag/.
[14]W. Cochran, H. Mouritsen, and M. Wikelski, Science **304**, 405 (2004).
[15]K. J. Lohmann, C. M. F. Lohmann, L. M. Ehrhart, D. A. Bagley, and T. Swing, Nature **428**, 909 (2004).

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