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Magnetoelectric voltage gain effect in a long-type magnetostrictive/piezoelectric heterostructure

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We report a large voltage gain of 130, together with a high magnetoelectric voltage coefficient of 7.6 V/Oe, in a long-type heterostructure made by combining a coil-wound, length-magnetized magnetostrictive $Tb_{0.3}Dy_{0.7}Fe_{1.92}$ (Terfenol-D) alloy plate and a length-polarized piezoelectric $0.7Pb(Mg_{1/3}Nb_{2/3})O_3-0.3PbTiO_3$ single-crystal plate along the length direction. The observed voltage gain is found to originate from the product effect of the electromagnetic induction in the coil and the resonance magnetoelectric effect in the heterostructure. © *2009 American Institute of Physics*. [doi:10.1063/1.3246148]

The magnetoelectric (ME) effect, which shows simultaneous ferromagnetic and ferroelectric order in the same material, has been a hot research topic in recent years due to its potential applications in many multifunctional devices, including passive magnetic field sensors, nonvolatile electric-write/magnetic-read memories, spin-wave generators, microwave filters, etc.[1] ME composites consisting of magnetostrictive and piezoelectric material phases have drawn special interest owing to their multifunctionality with improved design and application flexibilities.[2–9] In particular, the generally high ME voltage coefficient (α_V), defined as an induced electric voltage in response to an applied ac magnetic field (dV_{ac}/dH_{ac}), has led to the practical development of passive magnetic field sensors.[10]

In fact, studies on the ME effect in composites has been mainly focused on magnetic field sensing applications involving relatively small signals; that is, an electric voltage (V_{ac}) is induced from an applied ac magnetic field (H_{ac}) under the bias of a dc magnetic field (H_{bias}). Reports on high-field or high-voltage ME devices are indeed insufficient. It is only quite recently that research was performed on voltage step-up transformers based on the ME effect.[11–13] In this letter, we report a colossal voltage gain effect, which accompanies a giant ME effect, in a long-type ME heterostructure comprising a coil-wound, length-magnetized magnetostrictive $Tb_{0.3}Dy_{0.7}Fe_{1.92}$ (Terfenol-D) alloy plate arranged along the length direction with a length-polarized piezoelectric $0.7Pb(Mg_{1/3}Nb_{2/3})O_3-0.3PbTiO_3$ (PMN-PT) single-crystal plate.

Figure 1 shows the schematic diagram and photograph of the proposed heterostructure with ME voltage gain effect. The heterostructure has a coil-wound, length-magnetized magnetostrictive Terfenol-D alloy plate and a length-polarized piezoelectric PMN-PT single-crystal plate arranged along the length direction and with their interface being bonded using silver-loaded epoxy. This long-type longitudinal-longitudinal (LL) configuration is similar to the well-known Rosen-type piezoelectric transformer.[14] It is noted that the heterostructure carries two major design benefits. First, Terfenol-D has giant magnetostrictive effect, while PMN-PT has ultrahigh piezoelectric effect. Second, this long-type LL configuration utilizes the niches of both the longitudinal magnetostrictive and piezoelectric effects as the longitudinal piezomagnetic coefficient and magnetomechanical coupling coefficient in Terfenol-D and the longitudinal piezoelectric coefficient and electromechanical coupling coefficient in PMN-PT are almost two times higher than their transverse counterparts.[4] To practically realize the two major design benefits, the Terfenol-D plate was commercially supplied with dimensions $14 \times 6 \times 1$ mm^3 and having its [112] crystallographic axis oriented along the length direction. The PMN-PT plate, with the same dimensions as the Terfenol-D plate and having its ⟨001⟩ crystallographic axis arranged along the length direction, was cut from a PMN-PT ingot grown in-house using a modified Bridgman technique.[15]

The working principle of our heterostructure is essentially based on the product effect of the electromagnetic effect (or Faraday's law of electromagnetic induction) in the coil, the magnetostrictive (or magnetoelastic) effect in the

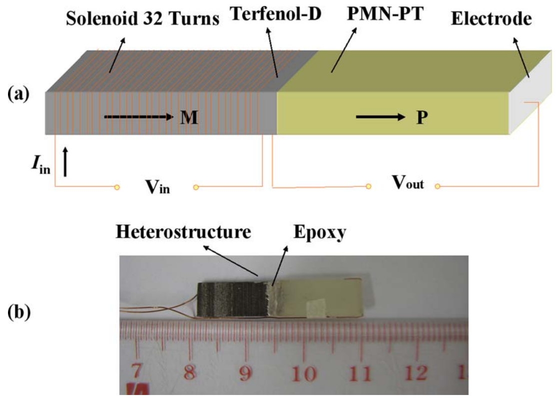

FIG. 1. (Color online) (a) Schematic diagram and (b) photograph of the proposed ME heterostructure with both voltage gain and ME effects. The arrows *M* and *P* denote the magnetization and polarization directions, respectively.

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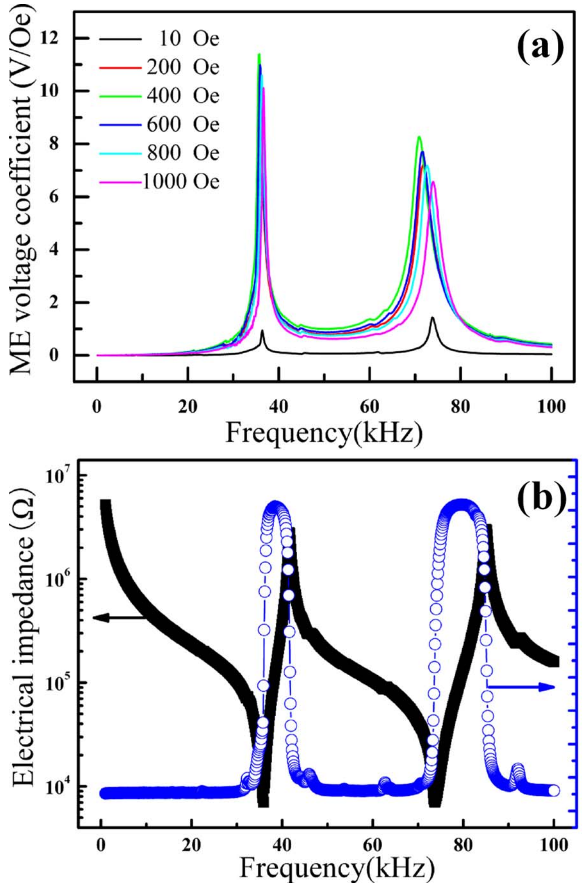

FIG. 2. (Color online) (a) Frequency dependence of ME voltage coefficient (α_V) of the heterostructure under various H_{Bias} and (b) electrical impedance spectrum of the heterostructure.

Terfenol-D plate, and the piezoelectric (or elastoelectric) effect in the PMN-PT plate. In other words, an ac magnetic field (H_{ac}), which is excited by an ac electric current (I_{in}) associated with an ac electric voltage (V_{in}) in a coil of N turns wrapped around the Terfenol-D plate, is applied along the longitudinal direction of the heterostructure as illustrated in Fig. 1. This H_{ac} induces an ac magnetostrictive strain in the Terfenol-D plate based on the magnetostrictive effect which, in turn, is transferred dynamically to stress the PMN-PT plate. As a result of the piezoelectric effect, the transferred dynamic stress produces an ac electric voltage (V_{out}) across the length of PMN-PT plate. When the frequency of V_{in} is equal to the resonance frequency of the heterostructure, the ME effect will be greatly enhanced, giving a much amplified V_{out} from a given V_{in}. Thus, our heterostructure will exhibit a large voltage gain due to the resonance ME effect.

The ME properties of the proposed heterostructure were measured using an in-house automated measurement system under free-free condition.[9] Figure 2(a) shows the frequency dependence of ME voltage coefficient (α_V) of the heterostructure under various H_{bias}. Two giant sharp resonance peaks, which correspond to the half-wavelength (or fundamental) and full-wavelength (or second) longitudinal shape resonances of the heterostructure, respectively, are observed for various H_{bias}. α_V has a strong dependence on H_{bias} due to the H_{bias}-dependent piezomagnetic coefficient of the Terfenol-D plate.[9] The maximum value of α_V is found to be 11.6 V/Oe at the fundamental shape resonance frequency of 36 kHz under an optimal H_{Bias} of 400 Oe. The resonance ME effect makes the heterostructure to be favorable for ME transducer applications. To give a physical insight into the resonance ME effect, the electrical impedance spectrum of the heterostructure was measured as shown in Fig. 2(b). Two resonance peaks are observed at 36 and 72 kHz, which agree well with the results of ME voltage coefficient spectrum in Fig. 2(a). The results clearly demonstrate that the resonance α_V occurs at the electromechanical resonance of the heterostructure.

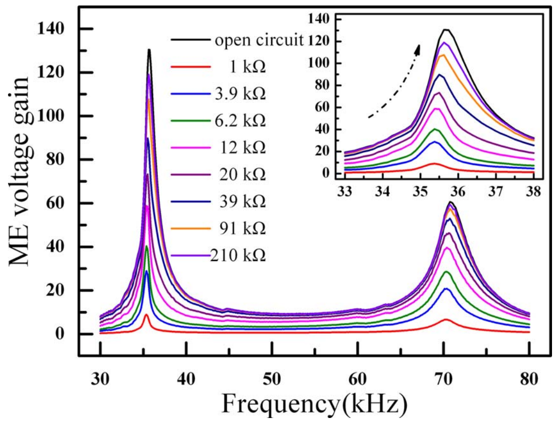

FIG. 3. (Color online) Voltage gain of the heterostructure as a function of frequency with a constant V_{in} of 0.1 $\mathrm{V_{rms}}$ at various resistive loads and under an optimal H_{bias} of 400 Oe. The inset shows the zoom-in view of the fundamental shape resonance region.

Figure 3 shows the voltage gain of the heterostructure as a function of frequency with a constant V_{in} of 0.1 $\mathrm{V_{rms}}$ at various resistive loads and under an optimal H_{bias} of 400 Oe. The inset of Fig. 3 is the zoom-in view of the fundamental shape resonance region. A maximum voltage gain of ~130 is seen under open-circuit condition. In fact, the voltage gain and resonance frequency increase gradually with increasing load resistance. Compared to conventional piezoelectric transformers,[16] the input part (i.e., the Terfenol-D plate) of the heterostructure has a very high energy density of 4.9–25 $\mathrm{kJ/m^3}$.[17,18] Thus, our heterostructure is a promising candidate for miniature voltage transformers or ME converters.

Figure 4 shows the voltage gain and the corresponding power of the heterostructure as a function of resistive load

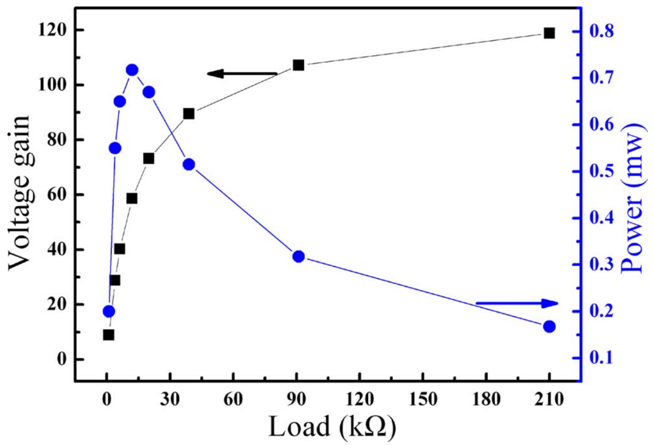

FIG. 4. (Color online) Voltage gain and power of the heterostructure as a function of resistive load at a constant V_{in} of 0.1 $\mathrm{V_{rms}}$.

($P=V_{\mathrm{in}}^2/R$) at a constant V_{in} of 0.1 $\mathrm{V_{rms}}$. The data was obtained directly from Fig. 3 at the fundamental resonance frequency. It is clear that the voltage gain increases, while the power increases initially reaching a maximum value of 0.73 mW ($V_{\mathrm{in}}=0.1\ \mathrm{V_{rms}}$) at a 12 k$\Omega$ load and then decreasing, with increasing resistive load. The similar load effect has also been observed in piezoelectric transformer.[16] Nevertheless, an improved power could be obtained if an increased V_{in} or an increased number of turns of solenoid is used.

In summary, we have reported a colossal voltage gain effect, in conjunction with a giant ME effect, in a long-type heterostructure of a coil-wound Terfenol-D alloy plate and a PMN-PT single-crystal plate. The maximum voltage gain and ME voltage coefficient have been found to be ~130 and 7.6 V/Oe, respectively at the fundamental shape resonance of the heterostructure under open-circuit condition and for an optimal bias magnetic field of 400 Oe. The heterostructure has great potential for use in miniature solid-state voltage transformers or ME converters.

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