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Multiplied magnetoelectric effect in multi-faceted magnetoelectric composite

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A four-faceted magnetoelectric (ME) composite consisting of one cuboid bonded Terfenol-D composite and four plates of $Pb(Zr,Ti)O_3$ (PZT) was fabricated. The ME voltage coefficients were measured along the length direction of the composite when PZT plates were parallelly or serially connected. Results show that the ME voltage coefficient remains almost the same when increasing the number of PZT in parallel mode. By contrast, the ME voltage coefficient increases multiplicatively with the increasing of the number of PZT in serial mode. This multi-faceted structure scheme offers an effective approach to improving ME effect and downsizing the ME devices. © *2014 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4863056]

Magnetoelectric (ME) effect represents the ability of a certain class of materials to convert magnetic energy to electric energy, and vice versa. This energy conversion ability makes the ME materials the promising candidates for various potential applications, such as energy harvester,[1,2] current and magnetic field sensors,[3–5] and microwave devices.[6–8] Besides the single phase magnetoelectric compounds (Cr_2O_3, Ca_3CoMnO_6, hexagonal $Ho_{1-x}Dy_xMnO_3$),[9–11] ME composites have attracted much attention in recent years. ME composite with bi-layered laminates, tri-layered laminates, disk-ring, and various other combining configurations between different piezoelectric and piezomagnetic components have been developed.[12–15]

Giant magnetostrictive material (GMM) based ME composites consisting of Terfenol-D alloy or Terfenol-D composite have been extensively investigated.[16–20] The ME voltage coefficient at resonance frequency can be up to 100 times as high as that at sub-resonance frequencies.[21] To broaden the response frequency, Wan *et al*. fabricated and measured a combined structure where several Terfenol-D/epoxy- $Pb(Zr,Ti)O_3$ (PZT) bi-layered composites were connected in parallel and series. There appear different resonant frequencies and phase angles when changing the size of the ME composites. The combined structure showed a much wider frequency response to external field than the single bi-layered structure. However, the ME effect reduced at the resonant frequency due to the shunt capacitance and current loss.[22] In the present study, a ME composite with multi-faceted structure scheme was proposed. Specifically, the four-faceted Terfenol-D/$Pb(Zr,Ti)O_3$(PZT-5H) ME composite consisting of one cuboid bonded Terfenol-D composite and four plates of PZT has been fabricated. The ME effect of this kind of composite has been further improved by employing the multi-faceted structure scheme.

The preparation process was shown in Fig. 1. A homogeneous mixture consisting of 3 wt. % epoxy resin binder and 97 wt. % Terfenol-D powder with randomly distributed sizes of 0–180 μm was compacted under a pressure of 154 MP accompanied with a 2 T oriented magnetic field along the length direction of the sample at 130 °C. Four commercial PZT-5H ceramic plates with a dimension of $25 \times 10 \times 1\,mm^3$ were polarized along the thickness direction and bonded with the cuboid bonded Terfenol-D composite ($33 \times 10 \times 10\,mm^3$) through glue to form a four-faceted composite. Each PZT plate is electrically isolated from the Terfenol-D composite and other PZT plates. The ME voltage coefficient $\alpha_{E,31}$ was measured in the ME measurement system, in which the dc bias and ac magnetic field were applied along the length direction of the sample.[23] The output voltage δV across the sample was measured via an oscilloscope. The ME voltage coefficient was obtained based on $\alpha_{E,31} = \delta V/(t_{PZT}\delta H)$, where t_{PZT} is the thickness of PZT, δH is the amplitude of AC magnetic field generated by Helmholtz coils. In the experiment, the AC current through the coil with the amplitude of $\delta H = 1.2$ Oe is equal to 1 A.

The frequency dependence of $\alpha_{E,31}$ with different number of PZT plates in parallel and serial mode was measured under the DC magnetic field of $H_{DC} = 700$ kOe as shown in Figs. 2 and 3. There appears a strong resonance peak at about

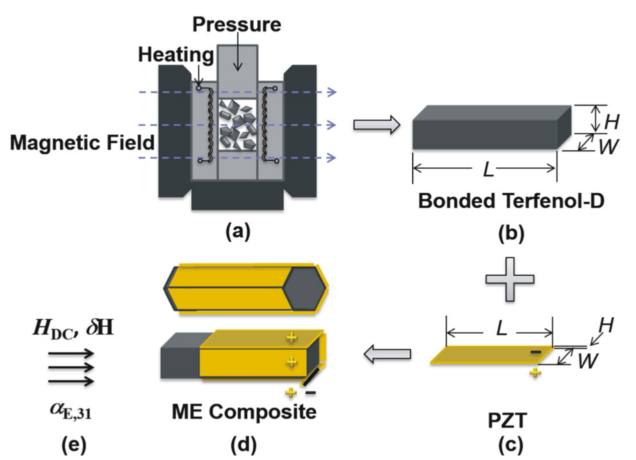

FIG. 1. The illustration of preparation process and ME measurement of the bonded Terfenol-D/$Pb(Zr,Ti)O_3$ ME composites.

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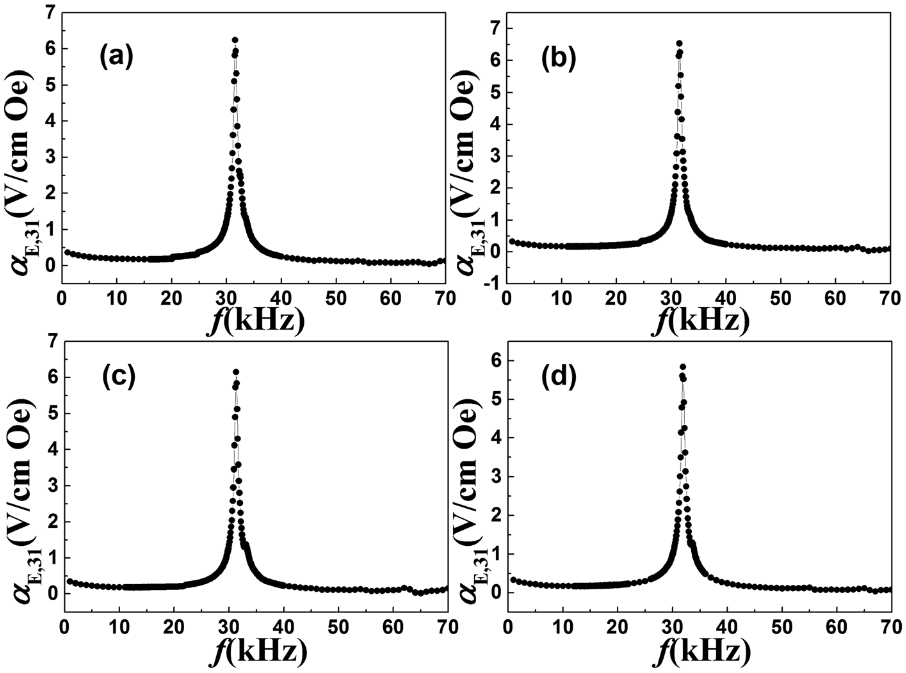

FIG. 2. The frequency dependence of $\alpha_{E,31}$ in parallel mode when $H_{DC} = 700$ Oe (a) 1 PZT; (b) 2 PZT plates; (c) 3 PZT plates; and (d) 4 PZT plates.

31.6 kHz in all four cases. As for the parallel mode, the $\alpha_{E,31}$ remains about 6 V/cm Oe when increasing the number of PZT from 1 to 4. However, the $\alpha_{E,31}$ increases multiplicatively with the number of PZT in serial mode. The $\alpha_{E,31}$ is improved up to about 24 V/cm Oe when four PZT plates was serially connected.

Usually, a piezoelectric resonator is assumed to be a LCR oscillator model.[22] Given that the four PZT plates are bonded on one single Terfenol-D composite and each PZT plate resonates at the same frequency in this study, the model can be simplified. Only the PZT layers are taken into account when discussing the multiplied ME output voltage. Fig. 4 shows the sketch map of parallel mode and serial mode in this study. Due to the identical properties of the four PZT plates, the total capacitance in parallel and serial mode can be derived

$$C_p = C_1 + C_2 + C_3 + C_4 = 4C_0. \tag{1}$$

$$\frac{1}{C_s} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \frac{1}{C_4} = \frac{4}{C_0}. \tag{2}$$

It can be assumed that the four PZT plates are under the same stress state when vibrating under the AC magnetic field if the minor difference between each bonding interface is ignored. The piezoelectric effect in PZT arises from the stress-induced charge polarization. So every PZT plate exhibits the same amount of stress-induced charge which is denoted by Q_0. In parallel mode, the negative and positive charges are accumulated, respectively. Thus, the total charge is denoted by $Q_p = 4Q_0$. However, the opposite charges on the two contact surfaces cancel each other out in the circuit

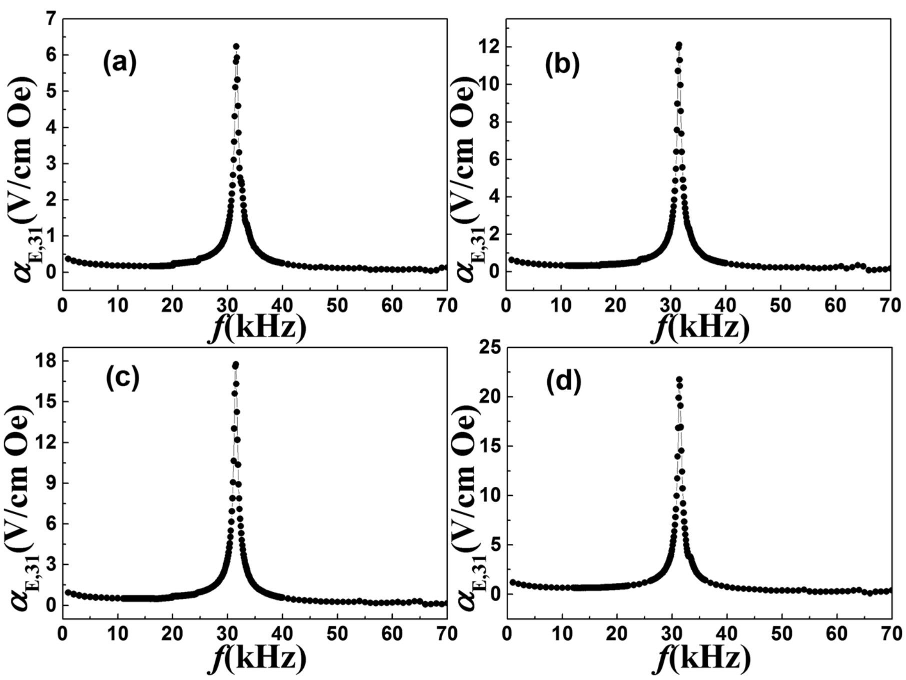

FIG. 3. The frequency dependence of $\alpha_{E,31}$ in serial mode when $H_{DC} = 700$ Oe (a) 1 PZT; (b) 2 PZT plates; (c) 3 PZT plates; and (d) 4 PZT plates.

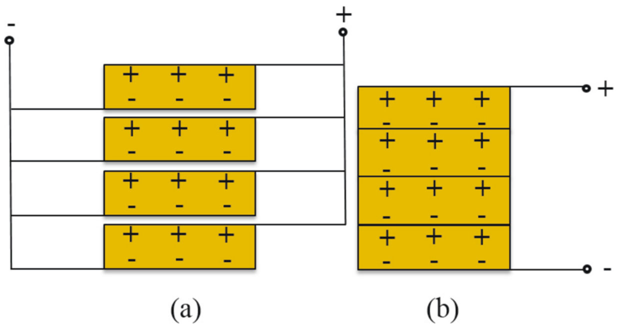

FIG. 4. The sketch map of (a) parallel mode and (b) serial mode.

for the case of serial mode. The total charge in serial mode is denoted by $Q_s = Q_0$. Thus, the ME voltage in parallel mode is $U_p = Q_p/C_p = U_0$, which indicates that the $\alpha_{E,31}$ remains the same when increasing the number of PZT from 1 to 4. The ME voltage in serial mode is $U_s = Q_s/C_s = 4U_0$. That explains the multiplicative increases of $\alpha_{E,31}$ with the number of PZT in serial mode. Accordingly, the ME voltage coefficient will be multiplied in the five-faceted, six-faceted or other ME composites with this multi-faceted structure scheme.

In conclusion, the ME voltage coefficient is multiplied by employing the multi-faceted structure scheme. The $\alpha_{E,31}$ is improved up to about 24 V/cm Oe when four PZT plates was serially connected. This multi-faceted structure scheme offers an effective approach to improving ME effect and downsizing the ME devices other than exploiting new material systems.

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