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Effect of load resistance on magnetoelectric properties in FeGa/BaTiO$_3$/FeGa laminate composites

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ABSTRACT

The electrical resistance load effects on an ME laminated composite of FeGa/BaTiO$_3$/FeGa are investigated. The results show that (i) The ME voltage coefficient increases and tends to be saturated with the increase in electrical resistance load, (ii) the cutoff frequency and the resonance frequency both shift to the lower frequency side and approach to the values under open-circuit condition with the increase in electrical resistance load, and (iii) the ME output power can be adjustable by changing the attached electrical resistance load to achieve the best active status. The present study provides the basis for the design of ME sensors and their electronic circuits.

1. Introduction

The magnetoelectric (ME) effect in materials which are simultaneously ferromagnetic and ferroelectric has been a research topic in recent years [1,2]. The ME effect can be used for many applications, such as microwave field, smart sensors and signal processing [3–5]. Materials exhibiting ME effect can be classified into two classes, single-phase materials and composites. Since single-phase ME materials are not suitable for industrial applications due to their generally low ME coefficients, the development of multiple-phase ME composite materials consisting of magnetostrictive and piezoelectric phases based on extrinsic ME coupling has been the main evolutional tend in the recent decade [6–8].

The magnetostrictive–piezoelectric layered laminates have been shown to have much better ME properties at resonance [9,10]. In magnetostrictive layer, the receiving AC magnetic field is converted to mechanical vibration. Magnetostrictive materials have high energy density and very high magnetomechanical coupling effect; thus, ME composites can produce higher mechanical stress and power output than piezoelectric materials. This feature enables ME composites to possess an ideal sensing and ME energy conversion ability around resonance. Previous studies have been mainly focused on magnetic field sensing applications, aiming to exhibit the AC magnetic field (H_{ac}), DC magnetic field (H_{dc}) and frequency (f) dependences of ME coefficient (α). Above research are indeed insufficient. An important consideration in the design and operation of any ME sensor is the effect of electrical resistance load (R_L) on the ME coupling for effectively interfacing with the subsequent signal processing and electronic circuits.

It is only quite recently that research was performed on the influence of load on the ME materials. For example, Terfenol-D/PZT/Terfenol-D composite transducer described by Dai et al. [11] achieved a power of 2.11 mW at resonant frequency of 51 Hz. Wang et al. [6] also fabricated a Terfenol-D/PMN-PT/Terfenol-D laminated composite, which reached the maximum value of ~1.9 mW at $R_L = 3.9\,\mathrm{k\Omega}$. Numerous researchers selected Terfenol-D/PZT or PMN-PT-based ME materials as research system [12–14]. However, these rare-earth materials are expensive and PZT or PMN-PT is now facing a big challenge due to the environmental hazard by its toxic lead. FeGa alloy (or Galfenol) is a good magnetostrictive material, i.e. high mechanical strength, good ductility, large magnetostriction at low saturation fields, and BaTiO$_3$ (BTO) is a typical piezoelectric material containing nothing injurious to the environment. It provides a choice to synthesize high performance lead-free ME laminate. In this paper, we investigate the electrical resistance load effect R_L on the ME coupling in a laminated composite formed by FeGa/BTO/FeGa.

2. Experimental details

Fig. 1 illustrates the schematic diagram of the measurement principle. The composite was made by sandwiching one thickness-polarized BaTiO$_3$ piezoelectric disc between two thickness-magnetized FeGa magnetostrictive alloy discs. The FeGa rod was grown by a Bridgman method and then was cut into disk-shaped plates

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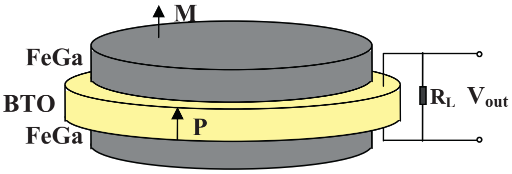

Fig. 1. Schematic diagram of the measurement principle.

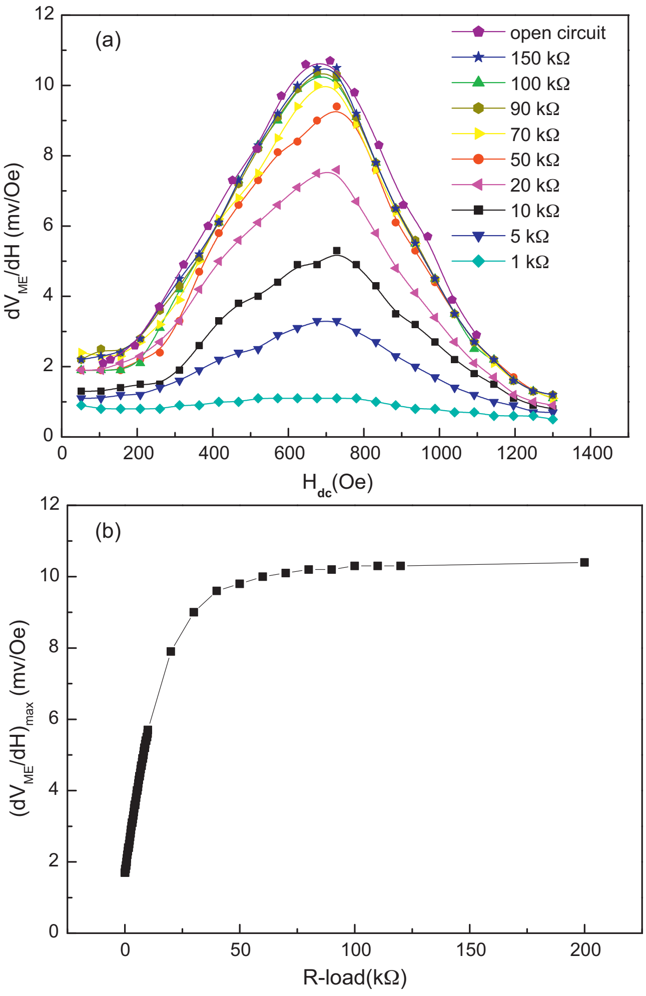

Fig. 2. (a) ME voltage coefficient dV_{ME}/dH as a function of DC magnetic field (H_{dc}) under various electrical resistance load (R_L) values for the ME laminated composite at an applied AC magnetic field (H_{ac}) of 1 Oe peak and a frequency of 1 kHz. (b) The $[dV_{ME}/dH]_{max}$ as a function of R_L.

of 10 mm in diameter and 1 mm in thickness. Detailed experimental method and properties of FeGa alloys have been reported in our previous study [15]. Commercial BaTiO$_3$ discs of Ø12 mm × 1.5 mm were used in this study. FeGa and BTO discs were stacked using silver epoxy (E-Solder No. 3021, ACME Division of Allied Products Co., USA) and cured at 80 °C for 4 h for good mechanical coupling. As shown in Fig. 1, an electrical resistance load with various resistance values of 1–200 kΩ was connected electrically in parallel with the ME voltage (V_{ME}) output of the composite for the ME property measurement using a dynamic method. Detail of the measurement system and procedure can be found elsewhere [15].

3. Results and discussion

The ME voltage coefficient dV_{ME}/dH induced across the ME laminated composite was measured as a function of DC magnetic field under various electrical resistance load values, as shown in Fig. 2(a). A constant AC magnetic field of H_{ac} = 1 Oe was applied and the frequency of H_{ac} was 1 kHz. It is noted that dV_{ME}/dH has a strong dependence on H_{dc} for all cases due to the H_{dc}-dependent piezomagnetic coefficient of the FeGa magnetostrictive alloy plate [14]. The maximum value of dV_{ME}/dH is found to be 10.8 mV/Oe under an optimal H_{dc} of 700 Oe for the composite in open-circuit condition (i.e., in the absence of R_L). Fig. 2(b) plots $[dV_{ME}/dH]_{max}$ as a function of R_L. It is clear that $[dV_{ME}/dH]_{max}$ increases initially with increasing R_L and then seems to be saturated at $R_L > 50$ kΩ. It can be explained that the ME laminated composite output power already could not come up with further increase in R_L.

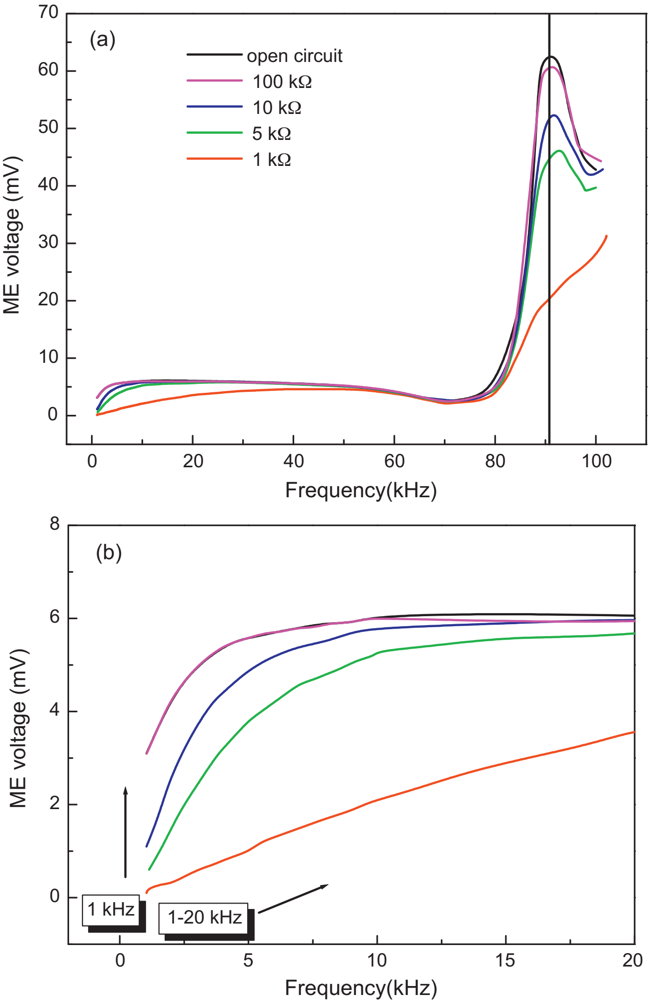

Fig. 3. (a) Frequency (f) dependence of ME voltage for the ME laminated composite at an applied AC magnetic field of 1 Oe peak and under various electrical resistance load values (including the open-circuit condition). (b) Zoom-in view for the low-frequency non-resonance range of 1–20 kHz.

Fig. 3(a) shows the frequency (f) dependence of ME voltage for the ME laminated composite at an applied AC magnetic field (H_{ac}) of 1 Oe peak and under various electrical resistance load values (including the open-circuit condition). At resonance, the ME response of the laminate is greatly enhanced. With the increase in R_L, the resonance ME voltage increases gradually and approaches to the maximum value of ~65 mV under open-circuit condition. While, the resonance frequency (f_r) shifts to the higher frequency side with decreasing load resistance R_L. In the low-frequency non-resonance range of 1–20 kHz in Fig. 3(b), there is a roll-off in ME voltage with the decrease in f for various R_L, and the cutoff frequency (f_{cut}) decreases with increasing R_L. Assuming that the magnetic field to be sensed is sinusoidal, the cutoff frequency for detection is $f_{cut} = 1/2\pi\tau$ [16], where $\tau = NRC_0$ is the time constant, C_0 is the capacitance of an individual piezoelectric layer, N is the

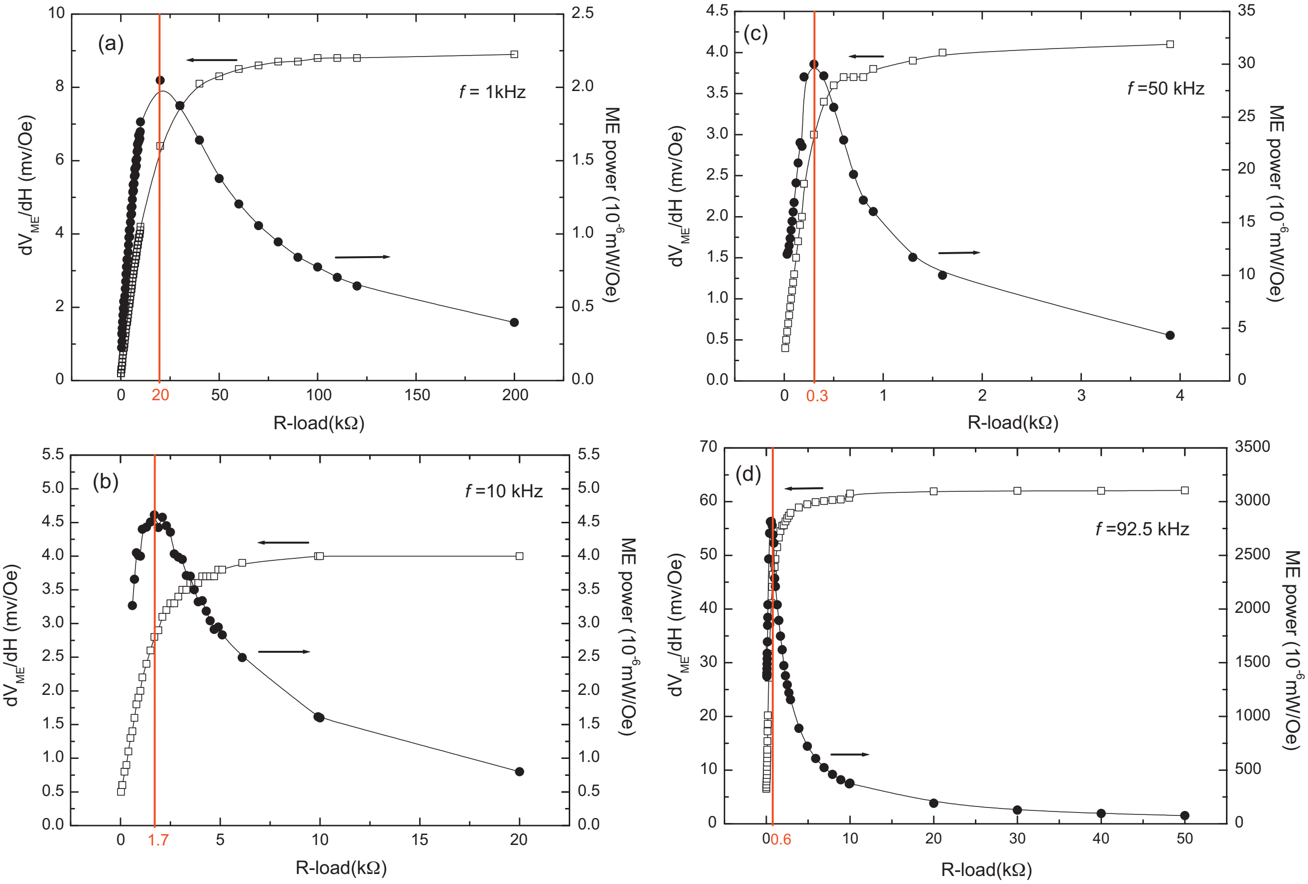

Fig. 4. ME voltage coefficient dV_{ME}/dH and corresponding output power (P) as a function of electrical resistance load under various frequency.

number of piezoelectric layers, and R is the parallel resistance of the composite's resistance (R_C), the electrometer's input resistance (R_E), and the electrical resistance load. R can be approximately set to R_L since R_L is generally smaller than R_C and R_E. In addition, an electrometer with high input resistance (>$10^9\ \Omega$) is important to obtain a large time constant τ. As a result, the value of f_{cut} is decreased by a factor of $1/R$ by increasing the electrical resistance load R_L.

Fig. 4 shows the ME voltage coefficient dV_{ME}/dH and corresponding output power (P) as a function of electrical resistance load under various frequencies. The ME output power is calculated by $P = V_{ME}^2/R_L$ at $H_{ac} = 1$ Oe peak. It is observed that the dV_{ME}/dH increases, while the ME power increases initially reaching a maximum value and then decreasing, with increasing electrical resistance load R_L. The similar load effect has also been observed in other systems with piezoelectric element [17]. Because the ME output power is directly proportional to the square of ME voltage and the ME voltage is directly proportional to the AC magnetic field, the ME output power is directly proportional to the square of the AC magnetic field. In this manner, an enhanced P could be obtained if an increased H_{ac} could be used or composite fabrication technique could be improved. In Fig. 4, the optimum load $R_{Load,opt}$ is labeled by red color. When $R_{Load} = R_{Load,opt}$, the circuit has maximum output power. At $f = 1$ kHz, the $R_{Load,opt}$ is 20 kΩ. However, when f elevates to 50 kHz, $R_{Load,opt}$ is decreased to 0.3 kΩ. Near the resonance frequency of $f_r = \sim 92.5$ kHz, the P reaches the maximum value of $\sim 3\ \mu$W (at $R_{Load,opt} = 0.6$ kΩ), compared to the value of $\sim 2 \times 10^{-3}\ \mu$W at $f = 1$ kHz, an enhancement of ~ 1500 times.

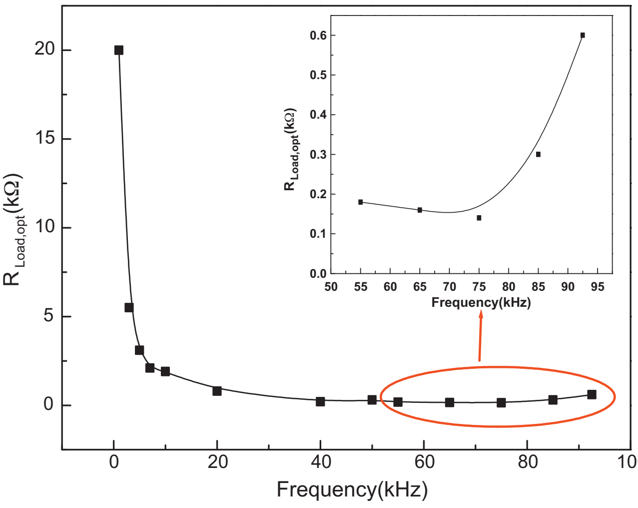

Fig. 5. The optimum electrical resistance load ($R_{Load,opt}$) as a function of frequency. When $R_{Load} = R_{Load,opt}$, the circuit has maximum output power.

Fig. 5 shows the optimum electrical resistance load ($R_{Load,opt}$) as a function of frequency (f). It is observed that the $R_{Load,opt}$ first rapidly declines and then tends to be stable in the small value with increasing frequency. The inset of Fig. 5 is the zoom-in view of the curve near the resonance frequency region. The $R_{Load,opt}$ ascends gradually with the frequency f near to the resonance frequency f_r. In brief, the P in the proposed device can be adjustable by changing the attached electrical resistance load to achieve the best active status.

4. Conclusions

The electrical resistance load effect on an ME laminated composite of FeGa/BTO/FeGa has been investigated. It has been observed that dV_{ME}/dH increase with increasing R_L and to be saturated at $R_L > 50\,k\Omega$. While, with the increase in R_L, the f_{cut} and f_r shift to the lower frequency side and approach to the values under the open-circuit condition. Moreover, the output power P is adjustable by changing the attached electrical resistance R_L. In the lower frequency ranges, the P is low and the $R_{Load,opt}$ is large. However, as the frequency increases, the P increases significantly, and the $R_{Load,opt}$ sharply decrease. The results form the fundamental set of data for designing ME sensors and their signal-processing and electronic circuits.

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