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Long Zhang, Siu Wing Or, and Chung Ming Leung

Voltage-mode direct-current magnetoelectric sensor based on piezoelectric–magnetostrictive heterostructure

Long Zhang, Siu Wing Or,[a)] and Chung Ming Leung
Department of Electrical Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong

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A dc magnetoelectric sensor operating in ac voltage driving mode is developed based on a piezoelectric–magnetostrictive heterostructure having four thickness-polarized Pb(Zr, Ti)O_3 piezoelectric plates bonded symmetrically on a length-magnetized $Tb_{0.3}Dy_{0.7}Fe_{1.92}$ magnetostrictive plate to give an electrically parallel input and an electrically series output. The dc magnetic field sensing in the sensor is evaluated theoretically and experimentally and is found to originate from a unique ac voltage-driven, dc magnetic field-tuned resonance dc magnetoelectric effect in the heterostructure. An interestingly high, linear, and *negative* ac voltage-controlled dc magnetic field sensitivity of -1.3 mV/Oe/V is obtained in a broad range of dc magnetic field of 0–400 Oe by referencing an ac voltage of ≤ 5 V peak amplitude and 116 kHz frequency at the input of the heterostructure. © *2015 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4919047]

I. INTRODUCTION

Magnetoelectric (ME) sensors based on magnetostrictive–piezoelectric laminates have attracted considerable attention from scientists and engineers over the past decade because of their passive sensing and high sensitivity (>10 mV/Oe) nature[1–5] in contrast to the active sensing and low sensitivity (5–40 μV/Oe) nature in traditional Hall sensors.[6] Today, almost all of the reported ME sensors are "ac" ME sensors in which the "ac" ME effect underpinned by the coupled magneto-mechano-electric dynamics of the constituent magnetostrictive and piezoelectric phases is weakened inherently by the decay of piezoelectric charges with time in the piezoelectric phase, especially for frequencies below 100 Hz.[7] Recently, "dc" ME sensors based on magnetic–conductive–piezoelectric and conductive–piezoelectric heterostructures have been proposed by introducing an ac current of controlled amplitude and frequency into the conductive phase of the heterostructures upon an applied dc magnetic field to be measured with/without an external magnetic biasing by the magnetic phase in order to induce Lorentz forces for stressing the piezoelectric phase and producing an ac voltage response.[8,9] A promising ac current-controlled dc magnetic field sensitivity of 3–170 μV/Oe/A has been measured for dc magnetic fields up to 2 kOe under an ac current of ≤ 300 mA peak amplitude and <15 kHz frequency. However, the need of an ac current as the reference driving signal in the metallic phase will lead to Joule heating-induced instability in these current-mode dc ME sensors.[9]

In this paper, we report theoretically and experimentally a voltage-mode dc ME sensor based on a specifically designed piezoelectric–magnetostrictive heterostructure with an electrically parallel input to reduce the input impedance and an electrically series output to increase the output sensitivity. Instead of using an ac current as the reference driving signal, our sensor employs the relatively stable and easily configured ac voltage driving to mitigate the problem of Joule heating associated with the current-mode sensors.[8,9] In fact, this ac voltage is aimed to induce a natural longitudinal resonance in the heterostructure under zero dc magnetic fields. With reference to this ac voltage-driven natural longitudinal resonance, an applied dc magnetic field to the heterostructure will result in a tuning effect in the magnetic field-dependent compliance and resonance characteristics governed by the *negative*–ΔE effect intrinsic in the magnetostrictive plate.[10] As a result, our voltage-mode sensor exhibits a unique ac voltage-driven, dc magnetic field-tuned resonance dc ME effect characterized by a high, linear, and *negative* ac voltage-controlled dc magnetic field sensitivity of -1.3 mV/Oe/V at a low reference ac voltage of ≤ 5 V peak.

II. STRUCTURE AND WORKING PRINCIPLE

Figure 1(a) illustrates the schematic diagram of the proposed voltage-mode dc ME sensor in the Cartesian coordinate system. The sensor has a piezoelectric–magnetostrictive heterostructure in which four pieces of thickness-polarized piezoelectric plates were bonded symmetrically on the top and bottom major surfaces of a length-magnetized magnetostrictive plate along the thickness and length directions using a conductive epoxy adhesive. To ensure structural integrity and promote longitudinal mode of resonance in the heterostructure, the top and bottom central air gaps, each having a width of ~0.1 mm, situating between the two piezoelectric plates bonded on the same major surface of the magnetostrictive plate, and covering the longitudinal half-wave vibration node, were filled by a non-conductive epoxy resin. To enable an electrically parallel input for reducing the input impedance and an electrically series output for enhancing the output sensitivity, the input and output sections of the

[a)]Author to whom correspondence should be addressed. Electronic mail: eeswor@polyu.edu.hk.

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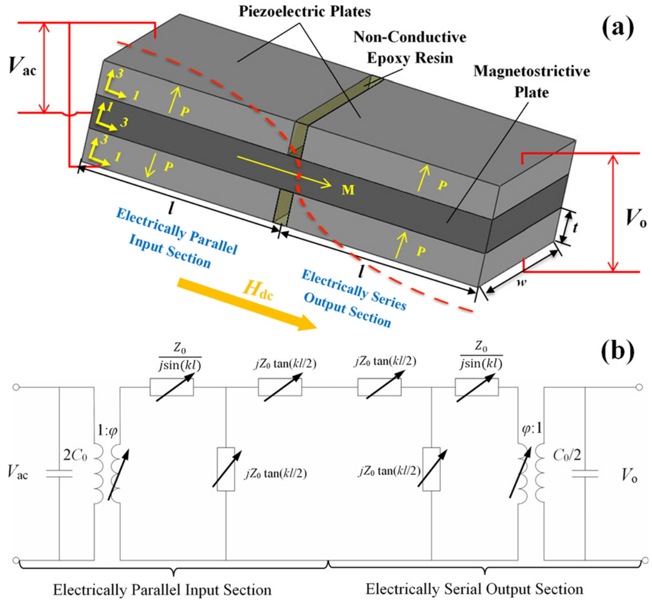

FIG. 1. (a) Schematic diagram of the proposed voltage-mode dc ME sensor based on a piezoelectric–magnetostrictive heterostructure with an electrically parallel input and an electrically series output. (b) Mason-based dynamic magneto-mechano-electric equivalent circuit.

heterostructure were arranged with their piezoelectric plates having the opposite and the same polarization (P) directions, respectively. The piezoelectric plates, each having a length (l) of 6 mm, a width (w) of 6 mm, a thickness (t) of 1 mm, and two full-fired silver electrodes on the top and bottom major surfaces, were made from CeramTec P8 Pb(Zr, Ti)O_3 piezoelectric ceramic. The magnetostrictive plate, having a slightly increased length of 12.1 mm ($\approx 2l$), the same width and thickness as those of the piezoelectric plates, and the highly magnetostrictive [112] crystallographic axis oriented along the length direction, was made from Baotou Rare Earth $Tb_{0.3}Dy_{0.7}Fe_{1.92}$ magnetostrictive alloy.

The working principle of the voltage-mode dc ME sensor in Fig. 1(a) can be described by a unique ac voltage-driven, dc magnetic field-tuned resonance dc ME effect in the heterostructure. This involves the driving of the heterostructure at its natural longitudinal resonance frequency under zero dc magnetic fields ($f_{r0} \equiv f_r$ at $H_{dc} = 0$ Oe) by a reference ac voltage (V_{ac}), and on the basis of the V_{ac}-driven f_{r0}, the tuning of the magnetic field-dependent compliance (s_{33}^H) and resonance characteristics of the heterostructure by the dc magnetic field (H_{dc}) to be measured in accordance with the *negative*–ΔE effect intrinsic in the magnetostrictive plate. In the absence of H_{dc}, the use of a V_{ac} of controlled amplitude at f_{r0} at the electrically parallel input of the heterostructure will drive the heterostructure to resonant at its f_{r0}. The piezoelectric plates forming the input and output sections will dynamically couple and amplify this V_{ac} to become an ac output voltage (V_o) at f_{r0} at the electrically series output of the heterostructure. In the presence of H_{dc}, the H_{dc}-dependent s_{33}^H in the magnetostrictive plate will be modified or tuned by H_{dc} according to the *negative*–ΔE effect described by the relation: $\Delta E \equiv (E_H - E_0)/E_0$, where $E_H < E_0$ is valid and E_H and E_0 are the elastic moduli in the presence and absence of a magnetic field, respectively.[10,11] In other words, an increase in H_{dc} from zero will decrease E_0 to E_H which, in turn, will increase $E_0^{-1} \equiv s_{33}^H|_{H_{dc}=0}$ to $E_H^{-1} \equiv s_{33}^H|_{H_{dc}>0}$ and decrease f_{r0} to f_r in the magnetostrictive plate and thus in the heterostructure. Because of the driving of the heterostructure at f_{r0} by V_{ac}, a decrease from f_{r0} in response to an increase in H_{dc} will change the operational state of the heterostructure from the initially preset resonance resistive state to an off-resonance capacitive state. This will lead to a decrease in V_o amplitude. Therefore, our sensor features a negative dc magnetic field sensitivity for a given V_{ac} at f_{r0}, defined as $S_{V_{ac}} = \partial V_o/\partial H_{dc}$. Accordingly, the V_{ac}-controlled dc magnetic field sensitivity (S) is also negative and can be defined as $S = \partial S_{V_{ac}}/\partial V_{ac}$.

Physically, the dynamic behavior of our sensor can be described by a Mason-based dynamic magneto-mechano-electric equivalent circuit in Fig. 1(b). The heterostructure in Fig. 1(a) is modeled to include the electrically parallel input section and the electrically series output section based on the length-magnetized, thickness-polarized (L–T) ME laminates as well as the said H_{dc}-tuning effect on s_{33}^H governed by the *negative*–ΔE effect in the magnetostrictive plate.[10] Since the width of the non-conductive epoxy resin-filled air gaps ($\approx$0.1 mm) is small compared to the lengths of the piezoelectric (=6 mm) and magnetostrictive (=12.1 mm) plates, they are not considered here. Referring to Fig. 1(b), C_0 in the input and output capacitors denotes the clamped capacitance of the piezoelectric plates; φ in the input and output tunable transformers represents the H_{dc}-tuned electromechanical and mechanoelectric transformation factors of the heterostructure, respectively; and Z_0 and k in the six tunable acoustic impedances indicate the H_{dc}-tuned characteristic acoustic impedance and wave number of the heterostructure, respectively. C_0, φ, Z_0, and k can be expressed as follows:

$$C_0 = \varepsilon_{33}^T(1 - k_{31}^2)(wl/t), \tag{1}$$

$$\varphi = wd_{31}/s, \tag{2}$$

$$Z_0 = wt\sqrt{\rho/s}, \tag{3}$$

$$k = \omega\sqrt{\rho s}, \tag{4}$$

where $\rho = (2\rho_p + \rho_m)/3$ and $s = 3s_{11}^E s_{33}^H/(s_{11}^E + 2s_{33}^H)$ are the density and H_{dc}-tuned compliance of the heterostructure, respectively. By solving the equivalent circuit in Fig. 1(b), the frequency (f) dependence of ac output voltage (V_o) of the sensor can be obtained as a function of V_{ac} as

$$V_o = \frac{8Q_m k_{31}^2 V_{ac}}{3\pi^2(1 - k_{31}^2)\left[\frac{f}{f_r} + jQ_m\frac{f}{f_r}\left(\frac{f}{f_r} - \frac{f_r}{f}\right)\right]}\left(2 + \frac{s_{11}^E}{s_{33}^H}\right), \tag{5}$$

where f_r and $Q_m = 3Q_m^E Q_m^H/(2Q_m^E + Q_m^H)$ are the longitudinal resonance frequency and H_{dc}-tuned mechanical loss factor of the heterostructure, respectively. It is noted that V_o in Eq. (5) depends on H_{dc} since s_{33}^H and Q_m^H depend on H_{dc}. From Eq. (5), $S_{V_{ac}}$ of the sensor can be determined from the slope of the $V_o - H_{dc}$ plot for a given V_{ac}. Then, S can be deduced from the slope of the $S_{V_{ac}} - V_{ac}$ plot.

III. RESULTS AND DISCUSSION

Figure 2 shows the measured V_o as a function of f at four different H_{dc} of 0, 100, 200, and 300 Oe under a given V_{ac} of 2.5 V peak. For all H_{dc}, the single sharp resonance detected at $\sim$116 kHz is the fundamental longitudinal resonance with half-wave vibrations along the length of the heterostructure. The appearance of this single sharp resonance suggests the existence of good structural integrity in our heterostructure via the filling of the air gaps ($\approx$0.1 mm) between the piezoelectric plates and covering the half-wave vibration node by a non-conductive epoxy resin (Fig. 1(a)). The upper inset of Fig. 2 gives the zoom-in view about resonances in the f range of 112–120 kHz. It is clear that the measured resonance V_o (denoted as V_{or}) at different H_{dc} varies between 3 and 3.5 V peak, which is 1.2–1.4 times larger than the reference driving V_{ac} of 2.5 V peak. This is a result of the resonance amplification effect enabled in part by good structural integrity and in part by the electrically parallel input and series output connections in our heterostructure. The fact that the resonance curves (including V_{or} and f_r) shift to the lower f side, while V_{or} becomes smaller, in response to an increase in H_{dc} can be explained by the V_{ac}-driven, H_{dc}-tuned resonance dc ME effect in the heterostructure described in Secs. I and II. In more detail, the natural longitudinal resonance frequency (i.e., f_{r0}) of our heterostructure is found to be 116 kHz at $H_{dc} = 0$ Oe. By increasing H_{dc}, the H_{dc}-dependent s_{33}^H in Eq. (5) that is governed by the *negative*–ΔE effect in the magnetostrictive plate will increase, making the heterostructure to become more compliant and to resonate at a lower f_r.[12] Since Q_m^H in Eq. (5) is also dependent upon H_{dc}, an increase in H_{dc} will decrease the value of Q_m^H, causing the heterostructure to exhibit a higher mechanical loss and to produce a lower V_{or}. On the basis of this interesting V_{ac}-driven, H_{dc}-tuned resonance dc ME effect (Fig. 2), and in light of the fact that it is more practical to measure signal amplitude rather than signal (resonance) frequency, we suggest to simply preset the initial operational state of our sensor at f_{r0} (i.e., in the resonance resistive state) by driving a V_{ac} of 2.5 V peak at $f_{r0} = 116$ kHz into the electrically parallel input of the heterostructure. This will produce a V_{or} of $\sim$3.5 V peak at the electrically series output of the heterostructure. By keeping V_{ac} unchanged and noticing V_{or}, an applied H_{dc} to be measured beyond 0 Oe will shift the resonance curve to the lower f side, thereby changing the operational state of the sensor into an off-resonance capacitive state. As the heterostructure is still driven at f_{r0} by V_{ac}, an off-resonance V_o, being smaller than V_{or} ($\approx$3.5 V peak at $H_{dc} = 0$ Oe), will be produced instead. Therefore, a negative response of V_o to H_{dc} will result with reference to V_{or} at $H_{dc} = 0$ Oe. This indicates the presence of a *negative* $S_{V_{ac}}$ ($= \partial V_o/\partial H_{dc}$ for a given V_{ac}) and a *negative* S ($= \partial S_{V_{ac}}/\partial V_{ac}$) in our sensor. For comparison, the lower inset of Fig. 2 plots the calculated V_o spectra based on Eq. (5) and supplier-provided material parameters: $k_{31} = 0.3$, $Q_m^E = 1000$, $Q_m^H = 26$, $s_{11}^E = 7.28$ pN/m^2, and $s_{33}^{H\,-1} = 18.5 \times 10^9$–$7.3 \times 10^6 \cdot H_{dc}$ m^2/N. The reason why the calculated spectra are rather flat and round can be ascribed to the use of a constant value of 26 for Q_m^H. Nonetheless, the calculated spectra agree reasonably well with the measured ones, confirming the validity of our results and discussion.

Figure 3 shows the H_{dc}-dependence of the measured V_o in the H_{dc} range of 0–1000 Oe under a given V_{ac} of 2.5 V peak at f_{r0} (=116 kHz). It is seen that V_o decreases linearly from 3.47 V peak (=V_{or}) at 0 Oe to 2.82 V peak at 400 Oe. It then reaches the minimal value of $\sim$2.7 V peak at $\sim$550 Oe before exhibiting a slowly increasing trend with increasing H_{dc} to 1000 Oe. It is known from Eq. (5) and Fig. 2 that V_o is a function of s_{33}^H which, in turn, depends on H_{dc}. Thus, the initial decrease in V_o with increasing H_{dc} is mainly attributed to the H_{dc}-tuning effect on s_{33}^H governed by the *negative*–ΔE effect in the magnetostrictive plate. The linear response of V_o to H_{dc} from 0 to 400 Oe implies the maximum range of H_{dc} measurement of up to 400 Oe in our sensor. The upper

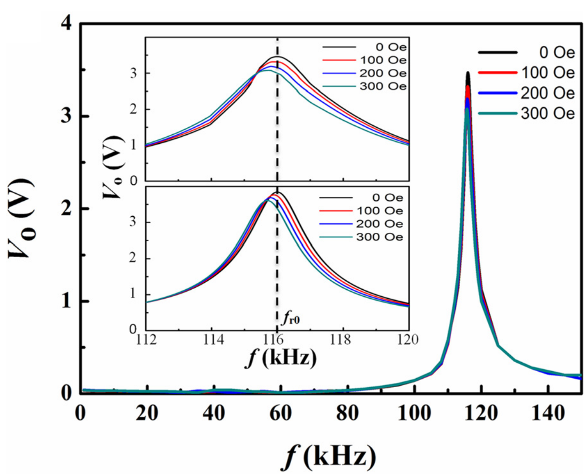

FIG. 2. Measured V_o as a function of f at four different H_{dc} of 0, 100, 200, and 300 Oe under a given V_{ac} of 2.5 V peak. The upper inset gives the zoom-in view about the fundamental longitudinal resonance in the f range of 112–120 kHz. The lower inset plots the calculated V_o spectra for comparison.

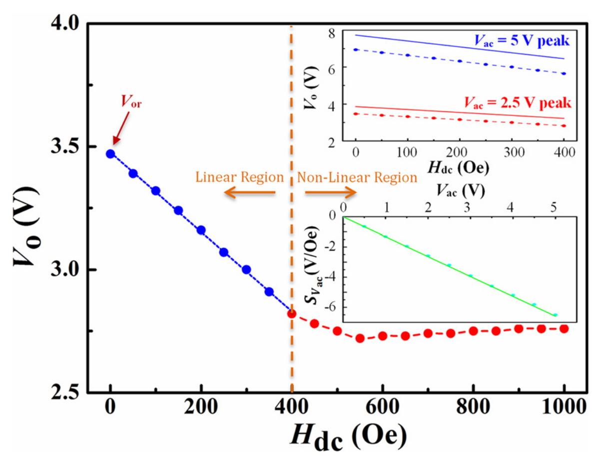

FIG. 3. Measured H_{dc} dependence of V_o in the H_{dc} range of 0–1000 Oe under a given V_{ac} of 2.5 V peak at f_{r0} (=116 kHz). The upper inset shows the H_{dc} dependence of the measured and calculated V_o in the linear H_{dc} range of 0–400 Oe under two given V_{ac} of 2.5 and 5 V peak at f_{r0}. The lower inset displays the V_{ac} dependence of the measured and calculated $S_{V_{ac}}$ in the V_{ac} range of 0–5 V peak at f_{r0}. The symbols and solid lines are the measured and calculated data, respectively, while the dotted lines are the fitted lines to the measured data.

inset of Fig. 3 illustrates the H_{dc} dependence of the measured and calculated V_o in the linear H_{dc} range of 0–400 Oe under two given V_{ac} of 2.5 and 5 V peak at the same f_{r0} (=116 kHz). The measured V_o driven at these two different V_{ac} not only exhibits good linear negative responses to H_{dc} but also shows good agreements with the calculated V_o. From the slopes of the plots, the measured and calculated $S_{V_{ac}}$ are found to be −3.2 and −3.3 mV/Oe for $V_{ac} = 2.5$ V peak, as well as, −6.5 and −6.6 mV/Oe for $V_{ac} = 5$ V peak, respectively. The lower inset of Fig. 3 displays the V_{ac} dependence of the measured and calculated $S_{V_{ac}}$ in the V_{ac} range of 0–5 V peak at f_{r0} (=116 kHz). The measured and calculated $S_{V_{ac}}$ agree very well with each other so that they show very close linearly decreasing trends with increasing V_{ac}. From the slopes of the plots, the measured and calculated S of our sensor are obtained to be −1.30 and −1.32 mV/Oe/V, respectively. The measured S is much larger than the recently reported current-mode dc ME sensors of 3–170 μV/Oe/A (Refs. 8 and 9) as well as the traditional Hall sensors of 50–600 μV/Oe/A.[13]

IV. CONCLUSION

We have developed a voltage-mode dc ME sensor, featuring an interestingly high ac voltage-driven, dc magnetic field-tuned resonance dc ME effect in a piezoelectric–magnetostrictive heterostructure with an electrically parallel input and an electrically series output. We have also evaluated theoretically and experimentally the proposed resonance dc ME effect in the sensor by driving the heterostructure at its f_{r0} (when $H_{dc} = 0$ Oe) using a reference V_{ac}, and by tuning its H_{dc}-dependent s_{33}^{H} (and Q_m^H) and so its resonance characteristics with the H_{dc} to be measured in accordance with the *negative*–ΔE effect intrinsic in the magnetostrictive plate. The results have confirmed the existence of high and good linear negative responses of V_o to a broad range of H_{dc} (=0–400 Oe) under a relatively small V_{ac} (=0–5 V peak) at the designated f_{r0} (=116 kHz), as well as, a high, linear, and *negative* V_{ac}-controlled dc magnetic field sensitivity (S) of −1.3 mV/Oe/V, in the sensor. As our sensor does not require any reference driving currents, it can eliminate instability arisen from Joule heating, as found in the previously reported current-mode dc ME sensors as well as the traditional Hall sensors.

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