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DC magnetic field sensor based on electric driving and magnetic tuning in piezoelectric/magnetostrictive bilayer

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A dc magnetic field sensor possessing an interestingly high electric voltage-driven, magnetic field-tuned dc magnetoelectric (ME) effect is developed based on a bilayer of Pb(Zr, Ti)O_3 piezoelectric transformer and $Tb_{0.3}Dy_{0.7}Fe_{1.92}$ magnetostrictive substrate. The dc ME effect in the sensor, as evaluated experimentally and theoretically, is induced by driving the bilayer at its zero-field longitudinal resonance frequency (f_{r0}) using an ac electric voltage (V_{ac}) referenced at the input of the piezoelectric transformer, as well as, by tuning the field-dependent compliance and resonance characteristics of the bilayer with the dc magnetic field to be measured (H_{dc}) upon the *negative*$-\Delta E$ effect intrinsic in the magnetostrictive substrate. The sensor shows a good linear negative response of ac ME voltage (V_{ME}) at the output of the piezoelectric transformer to a broad range of H_{dc} of 0–350 Oe under a small V_{ac} of 2.5 V peak at the designated f_{r0} of 125.3 kHz. This gives a high *negative* dc magnetic field sensitivity (S) of -1.58 mV/Oe. *© 2014 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4866516]

Magnetic field sensors based on the extrinsic magnetoelectric (ME) effect in magnetostrictive/piezoelectric laminated composites have formed an important research and development trend in the past decade.[1–4] The greatest weakness of the ME sensors is their inability to measure dc magnetic fields because the extrinsic ME effect has to be underpinned by the coupled dynamics of the magnetostrictive and piezoelectric phases in the laminated composites.[1–4] Recently, an extrinsic "dc" ME effect has been observed in metallic/piezoelectric heterostructures by direct-coupling the Lorentz force effect in the metallic phase with the piezoelectric effect in the piezoelectric phase.[5–7] However, the use of an ac current as the reference driving signal for the induction of the Lorentz force effect in the metallic phase of the heterostructures tends to induce Joule heating and electromagnetic interference (EMI) in the resulting sensors. In this paper, we report experimentally and theoretically an improved type of dc ME sensor composed of a specifically designed piezoelectric/magnetostrictive bilayer and energizable by the relatively stable and easily configured ac voltage driving to mitigate the Joule heating and EMI problems associated with the ac current-driven dc ME sensors.[5–7] By directing the dc magnetic field to be measured to tune the compliance and resonance characteristics of the bilayer on the basis of the *negative*-ΔE effect in the magnetostrictive substrate, our ac voltage-driven, dc field-tuned dc ME sensor demonstrates an interestingly high *negative* dc magnetic field sensitivity of -1.58 mV/Oe at a low reference ac voltage of 2.5 V peak.

Figure 1 shows the schematic diagram of the proposed ac electric voltage-driven, dc magnetic field-tuned dc ME sensor. The sensor has a piezoelectric/magnetostrictive bilayer structure in which a plate-type Pb(Zr, Ti)O_3 (PZT) piezoelectric transformer featuring two transverse polarizations (P) of the same direction was bonded on a plate-shaped $Tb_{0.3}Dy_{0.7}Fe_{1.92}$ (Terfenol-D) magnetostrictive substrate with a longitudinal magnetization (M) using a conductive epoxy adhesive. The piezoelectric transformer, having a 5 mm-long input (primary) section (l_1), a 2 mm-long isolation section (l_2), and a 5 mm-long output (secondary) section ($l_3 = l_1$), was formed by removing the central 2 mm section (i.e., the l_2 section) of the full-fired silver electrode on the top major surface of a transversely polarized CeramTec P8 PZT piezoelectric plate with a length ($l = 2l_1 + l_2$) of 12 mm, a width (w) of 6 mm, and a thickness (t) of 1 mm. This specific configuration provides geometric and polarization symmetries to the input and output sections which, in turn, enable a pure piezoelectric transverse mode of operation with unity voltage gain for buffering/coupling the input and output voltage signals. The magnetostrictive substrate was commercially acquired (Baotou Rare Earth Research Institute, China) to have the same dimensions as the piezoelectric transformer and with the highly magnetostrictive [112] crystallographic axis oriented along the longitudinal direction.

The working principle of the dc ME sensor in Fig. 1 is based on the driving of the bilayer at its zero-field longitudinal resonance frequency ($f_{r0} \equiv f_r$ at $H_{dc} = 0$ Oe) by a reference ac electric voltage (V_{ac}), as well as, the tuning of the field-dependent compliance and resonance characteristics of the bilayer by the dc magnetic field (H_{dc}) to be measured. In operation, a V_{ac} of constant amplitude has to be applied to the input of the piezoelectric transformer (i.e., the input of the bilayer) at the designated f_{r0} so as to drive the bilayer at its zero-field longitudinal resonance. The transverse piezoelectric transformation effect in the piezoelectric transformer will dynamically buffer/couple this V_{ac} to become an ac ME voltage (V_{ME}) of amplitude V_{ac} and frequency f_{r0} at the output of the piezoelectric transformer (i.e., the output of the bilayer).

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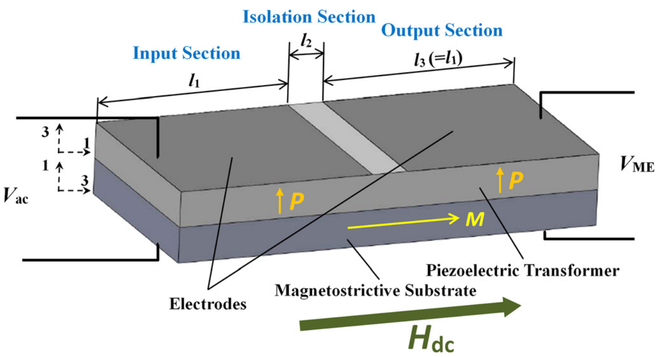

FIG. 1. Schematic diagram of the proposed ac electric voltage-driven, dc magnetic field-tuned dc ME sensor.

Applying H_{dc} to be measured to the bilayer leads to a tuning effect in its field-dependent compliance governed by the *negative*-ΔE effect in the magnetostrictive substrate. It is noted that the ΔE effect in a magnetostrictive material can be described by the relation: $\Delta E \equiv (E_H - E_0)/E_0$, where E_H and E_0 are the elastic moduli in the presence and absence of a magnetic field, respectively.[8] Hence, operating our sensor with the *negative*-ΔE effect suggests the validity of $E_H < E_0$ in the magnetostrictive substrate; that is, an increase in H_{dc} results in a decrease in elastic modulus (from E_0 to E_H), as well as, the corresponding increase and decrease in compliance (from $E_0{}^{-1}$ to $E_H{}^{-1}$) and resonance frequency (from f_{r0} to f_r), respectively, both in our magnetostrictive substrate and bilayer. Since V_{ac} is fixed at f_{r0} at the input of the piezoelectric transformer, a decrease in resonance frequency in response to an increase in H_{dc} will make the bilayer to be operated at an off-resonance capacitive state (i.e., a state beyond the resonance and in the capacitive region), so that a decrease in V_{ME} is detected at the output of the piezoelectric transformer. This implies the existence of a *negative* dc magnetic field sensitivity, defined as $S = \partial V_{ME}/\partial H_{dc}$, in our sensor for a given V_{ac} at f_{r0}.

To enable a quantitative description of the dynamic behavior of our sensor, a Mason-based dynamic magneto-mechano-electric equivalent circuit is constructed in Fig. 2. The bilayer in Fig. 1 is modeled to include the input section, the isolation section, and the output section, all on the basis of the longitudinally magnetized, transversely polarized (L–T) ME bilayers and with the additional H_{dc}-tuning effect on the compliance of the magnetostrictive substrate (s_{33}^H) governed by the *negative*-ΔE effect.[8] In Fig. 2, C_0 on the electric side is the clamped capacitance of the input or output section of the piezoelectric transformer; φ associated with the two tunable transformers denotes the H_{dc}-tuned electromechanical or mechanoelectric transformation factor of the bilayer; and Z_0 and k appeared in nine tunable acoustic impedances represent the H_{dc}-tuned characteristic acoustic impedance and wave number of the bilayer, respectively. Physically, C_0, φ, Z_0, and k can be written as

$$C_0 = \varepsilon_{33}^T (1 - k_{31}^2)(wl_1/t), \tag{1}$$

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

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

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

where $\rho = (\rho_p + \rho_m)/2$ and $s = 2s_{11}^E s_{33}^H/(s_{11}^E + s_{33}^H)$ are the density and H_{dc}-tuned compliance of the bilayer, respectively. By solving Fig. 2, the frequency (f) dependence of ac ME voltage (V_{ME}) of the sensor can be expressed in terms of V_{ac} as

$$V_{ME} = \frac{4Q_m k_{31}^2 l_1 V_{ac}}{\pi^2 (1 - k_{31}^2) l \left[\frac{f}{f_r} + jQ_m \frac{f}{f_r}\left(\frac{f}{f_r} - \frac{f_r}{f}\right)\right]} \left(1 + \frac{s_{11}^E}{s_{33}^H}\right), \tag{5}$$

where f_r and $Q_m = 2Q_m^E Q_m^H/(Q_m^E + Q_m^H)$ are the longitudinal resonance frequency and H_{dc}-tuned mechanical loss factor of the bilayer, respectively. Since s_{33}^H and Q_m in Eq. (5) depend on H_{dc}, V_{ME} also depends on H_{dc}. Therefore, the dc magnetic field sensitivity (S) of the sensor can be determined from Eq. (5) using the relation: $S = \partial V_{ME}/\partial H_{dc}$.

Figure 3 shows the measured f dependence of V_{ME} of the sensor at four different H_{dc} of 0, 100, 200, and 300 Oe under a reference V_{ac} of 2.5 V peak. The strongest resonance appeared at ~125 kHz and the much weaker resonance located at ~35 kHz are the longitudinal and bending resonances of the bilayer, respectively.[9] Since the piezoelectric transformer in our bilayer possesses geometric and polarization symmetries at the input and the output (Fig. 1), it is favorable to excite a relatively pure and strong longitudinal resonance. The upper inset of Fig. 3 displays the zoom-in view about the longitudinal resonance in the f range of 123–127 kHz. The fact that the maximal V_{ME} (~1.9 V peak) associated with the longitudinal resonance is smaller than V_{ac} of 2.5 V peak can be ascribed to the clamping of the piezoelectric transformer by the magnetostrictive substrate. It is also seen that the resonance curves, together with the resonance peaks, exhibit a down shift to the lower f side with an increase in H_{dc}. In the absence of H_{dc} (the case of $H_{dc} = 0$ Oe), the zero-field longitudinal resonance frequency (f_{r0}) is found at 125.3 kHz. With an increase in H_{dc}, the H_{dc}-dependent s_{33}^H governed by the *negative*-ΔE effect in the

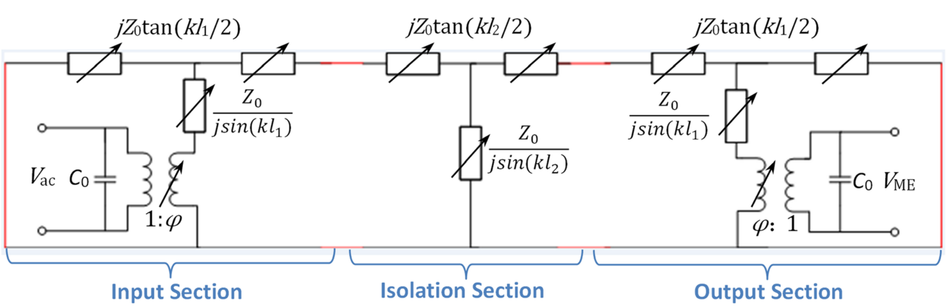

FIG. 2. Mason-based dynamic magneto-mechano-electric equivalent circuit of the sensor.

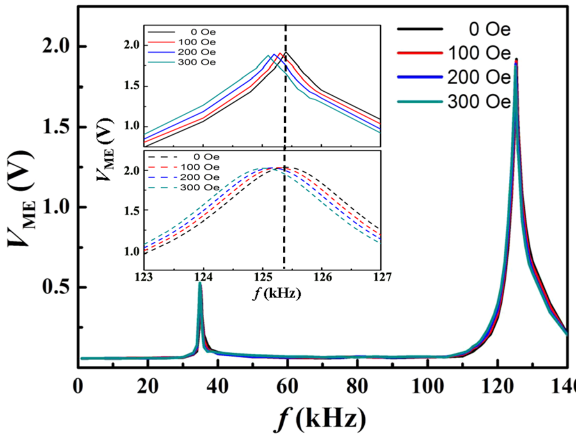

FIG. 3. Measured f dependence of V_{ME} of the sensor at four different H_{dc} under a reference V_{ac} of 2.5 V peak. The upper inset shows the zoom-in view about the longitudinal resonance in the f range of 123–127 kHz. The lower inset plots the calculated V_{ME} spectra based on Eq. (5). The vertical dotted line in the insets marks the position of $f_{r0} = 125.3$ kHz.

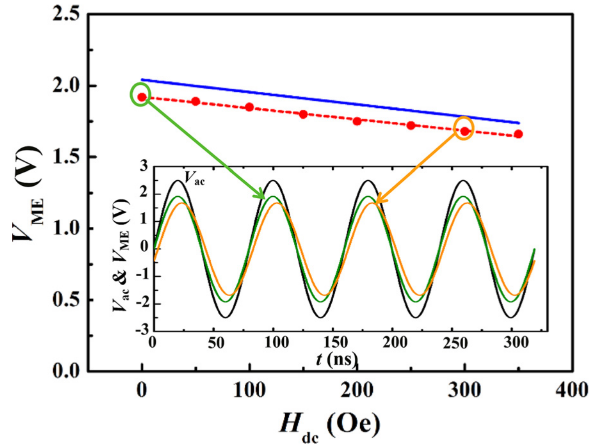

FIG. 4. Measured (symbol) and calculated (solid line) V_{ME} as a function of H_{dc} under a reference V_{ac} of 2.5 V peak at f_{r0}. The dotted line is the fitted line for the measured V_{ME}. The inset shows the waveforms of V_{ac} at 2.5 V peak and two V_{ME} produced at two different H_{dc} of 0 and 300 Oe.

magnetostrictive substrate increases, making the bilayer to be more compliant and so resonant at a lower frequency.[8] This essentially produces a down shift in both resonance curves and resonance peaks as obtained in the upper inset of Fig. 3. By utilizing this H_{dc}-induced resonance tuning effect, and by setting V_{ac} (=2.5 V peak) at f_{r0} (=125.3 kHz) as the reference signal in our sensor, an increase in H_{dc} from 0 to 300 Oe ($\Delta H_{dc} = 300$ Oe) causes a decrease in V_{ME} from 1.9 to 1.7 V peak ($\Delta V_{ME} = -200$ mV peak) because the bilayer is operated at different off-resonance capacitive states. Interestingly, the negative response of V_{ME} to H_{dc} indicates the presence of a *negative* S ($=\partial V_{ME}/\partial H_{dc}$) in our sensor for a given V_{ac} at f_{r0}. Besides noticing the decrease in V_{ME} at a fixed f_{r0}, it can also track the decrease in f_r at the expense of increasing the complexity of measurement. Since magnetostriction is always positive in the Terfenol-D substrate irrespective of the applied magnetic field direction,[8] a reversal of the direction (or sign) of H_{dc} would not alter the observed H_{dc}-induced resonance tuning effect. The lower inset of Fig. 3 plots the calculated V_{ME} spectra based on Eq. (5) for comparison. The supplier-provided material parameters, including $k_{31} = 0.3$, $Q_m^E = 1000$, $Q_m^H = 26$, $s_{11}^E = 7.28$ pN/m^2, and $s_{33}^{H\,-1} = 18.5 \times 10^9 – 7.3 \times 10^6 \cdot H_{dc}$ m^2/N, were adopted in Eq. (5). As Q_m^H of constant value of 26 was used, the calculated spectra are rather flat and round. Nonetheless, the measured spectra agree reasonably well with the calculated spectra, confirming the validity of our results and discussion.

Figure 4 plots the measured and calculated V_{ME} as a function of H_{dc} under a reference V_{ac} of 2.5 V peak at f_{r0}. The measured and calculated data are extracted from the V_{ME} spectra illustrated in Fig. 3. It is clear that the measured V_{ME} not only exhibits a good linear negative response to H_{dc}, but also has a good agreement with the calculated V_{ME}. From the slopes of the plots, the measured and calculated S are found to be -1.58 and -1.70 mV/Oe, respectively. This measured S is much larger than the recently reported ac current-driven, Lorentz force effect-based dc ME sensors of 0.3–17 μV/Oe (at a reference ac current of 100 mA peak),[5–7] as well as the traditional Hall sensors of 5–40 μV/Oe. Moreover, our sensor features the distinct advantage of voltage driving. The inset of Fig. 4 shows the waveforms of V_{ac} at 2.5 V peak and two V_{ME} produced at two different H_{dc} of 0 and 300 Oe. The cleanliness of the two V_{ME} waveforms implies the stable operation of the sensor. It is interesting to note that V_{ac} and V_{ME} are essentially in phase at $H_{dc} = 0$ Oe, but they exhibit a phase difference of $\sim 15°$ when H_{dc} is elevated to 300 Oe. This phase difference gives an evidence of the operation of the bilayer at an off-resonance capacitive state.

We have developed an interesting type of dc ME sensor featuring a high voltage-driven, field-tuned dc ME effect in a bilayer of piezoelectric transformer and magnetostrictive substrate based on the driving of the bilayer at its f_{r0} by a reference V_{ac} and the tuning of the H_{dc}-dependent s_{33}^H and f_r of the bilayer by H_{dc} in accordance with the *negative*-ΔE effect intrinsic in the magnetostrictive substrate. We have also shown experimentally and theoretically the resonance characteristics of the sensor, thereby confirming the existence of a good linear negative response of V_{ME} to a broad range of H_{dc} of 0–350 Oe under a small V_{ac} of 2.5 V peak at the designated f_{r0} of 125.3 kHz and a high *negative* S of -1.58 mV/Oe in the sensor. An improved S could be obtained by elevating V_{ac}. As our sensor does not rely on any reference ac current, it can mitigate the Joule heating and EMI problems faced by the previously reported ac current-driven dc ME sensors.

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