Fabrication and characterization of all-thin-film magnetoelectric sensors

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ac magnetic field sensors based on thin-film magnetoelectric (ME) devices operating at room temperature have been fabricated. The ME layers consist of a sol-gel derived $Pb(Zr_{0.52}Ti_{0.48})O_3$ film and a sputter deposited $Fe_{0.7}Ga_{0.3}$ film on Si cantilevers. The ME coupling is substantially improved by depositing a Pt layer at the interface. The ME coefficient up to 1.81 V/Oe cm is obtained at the mechanical resonant frequency of 333 Hz and at dc bias magnetic field of 90 Oe. Clear reduction in the substrate clamping effect is observed as the Si cantilever thickness is systematically reduced down to 35 μm. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3157281]

The principle of the magnetoelectric (ME) effect is that the magnetic field induced strain (λ) in the magnetostrictive component is transferred to a strain (ε) in the piezoelectric component through elastic coupling, resulting in a piezo-induced voltage. Such a composite ME effect can exceed the intrinsic ME effect in a single-phase compound by many orders of magnitude, and the corresponding ME coefficient $\alpha_{ME}=dE/dH$ is determined by the product of the individual responses of the magnetostrictive and the piezoelectric materials, $(dE/d\varepsilon)_{\text{piezoelectric}}\times(d\lambda/dH)_{\text{magnetostrictive}}$. Bulk ME laminates, typically millimeters to centimeters in lateral dimensions and at least hundreds of microns in thickness, are relatively inexpensive to fabricate and have been used to demonstrate detection of pico-Tesla ac magnetic field at room temperature with almost zero power consumption.[1,2] However, such bulk devices often suffer from uneven and unreliable adhesion between the magnetostrictive and the piezoelectric components which critically undermines the elastic coupling and consequently the ME effect. This is especially the case for operation of bulk sensors at their resonance frequencies of tens of kilohertz. Such high resonant frequencies can also result in significant eddy current losses due to the conductive nature of the magnetostrictive alloys and further lower the efficiency of energy conversion.[3,4]

From the application point of view, it is desirable to pursue all-thin-film ME sensors, which can readily facilitate fabrication of sensor arrays as well as integration with other circuit components. Other advantages of all-thin-film ME devices over bulk devices include the fact that the ME coupling is achieved through natural adhesion of one thin film deposited on another, which is much more reliable than gluing laminated devices with epoxy resin. Thin film multilayers also allow engineering of the interface state between magnetostrictive and piezoelectric films by inserting a spacer layer to optimize the ME coupling. In addition, eddy currents are effectively eliminated because the magnetostrictive film is very thin. Recently, ME effects in AlN-($TbCo_2$/FeCo) thin-film devices have been reported.[5]

In this letter, we report on fabrication and characterization of all-thin-film ME devices consisting of sol-gel derived $Pb(Zr_{0.52}Ti_{0.48})O_3$ (PZT) and magnetron sputtered $Fe_{0.7}Ga_{0.3}$ (FeGa) layers on Si cantilevers. Both the interface effect and the Si substrate clamping effect on the ME coefficient are studied.

One important design consideration of a composite cantilever device is the position of the neutral plane (t_n) from the bottom of the structure. The position can be calculated using the expression[6]

$$t_n=\frac{1}{2(E_{Si}t_{Si}+E_{SiO_2}t_{SiO_2}+E_{PZT}t_{PZT}+E_{FeGa}t_{FeGa})}\{E_{Si}t_{Si}^2+E_{SiO_2}[(t_{Si}+t_{SiO_2})^2-t_{Si}^2]+E_{PZT}[(t_{Si}+t_{SiO_2}+t_{PZT})^2-(t_{Si}+t_{SiO_2})^2]+E_{FeGa}[(t_{Si}+t_{SiO_2}+t_{PZT}+t_{FeGa})^2-(t_{Si}+t_{SiO_2}+t_{PZT})^2]\},$$

where E and t are the Young's modulus and the thickness of each layer which comprises the composite beam. For typical values of materials' parameters we used here, we find that t_n is 17–19 μm, which is well inside the Si substrate for our devices whose Si cantilever thicknesses are varied from 151 to 35 μm in the current study.

We estimate the mechanical resonant frequency (f_r) of a cantilever using

$$f_r=\frac{\lambda_n^2}{L^2}\sqrt{\frac{E_{Si}I_{Si}+E_{SiO_2}I_{SiO_2}+E_{PZT}I_{PZT}+E_{FeGa}I_{FeGa}}{\rho_{mean}F}},$$

where λ_n is an integration constant determined by the boundary conditions (for the first mode of a cantilever beam $\lambda_1=1.875$), L is the length of the cantilever beam, F is the area of cross-section of the beam, I is the moment of inertia of each layer, and ρ_{mean} is the average specific mass density (Ref. 6, and references therein). The resonant frequencies we obtain for typical thicknesses used here are in hundreds of hertz, in agreement with the measured f_r of ~300 Hz for a

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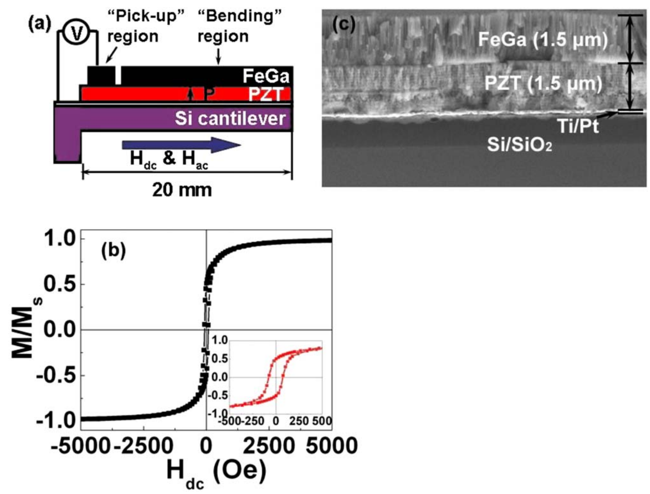

FIG. 1. (Color online) Cross-section of the thin-film ME device. (a) Schematic illustration of the fabricated structure. (b) The normalized magnetization vs applied magnetic field curve of a typical $Fe_{0.7}Ga_{0.3}$ film showing that the saturation magnetization field is ≈2000 Oe. The insert shows the low field region of the same curve. (c) SEM image of interface state of an actual PZT/FeGa thin-film ME device.

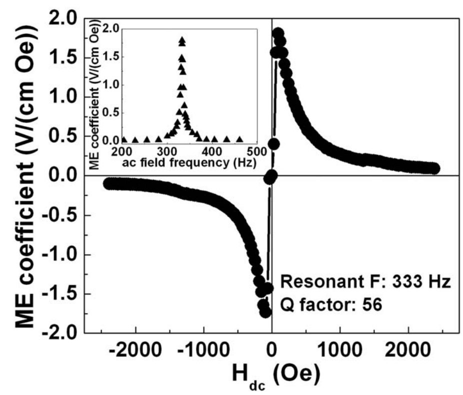

FIG. 2. The ME coefficient of a PZT/Pt/FeGa device as a function of dc magnetic field at its mechanical resonant frequency. The insert shows ac magnetic field frequency dependence of the ME coefficient of the device.

composite beam with a 35 μm thick Si cantilever.

Figure 1(a) shows the schematic of a thin-film ME sensor. The Si beam dimensions are 4.5×20 mm^2. The device heterostructure consists of a 1.5 μm thick sol-gel PZT film and a 1.5 μm thick $Fe_{0.7}Ga_{0.3}$ film sputtered at room temperature on top. The transverse piezoelectric coefficient as high as 117 pC/N has been reported in sol-gel PZT films.[7] We previously measured the saturation magnetostriction of room-temperature deposited FeGa thin films, and the effective saturation magnetostriction (λ_{eff}) of a $Fe_{0.7}Ga_{0.3}$ film was found to be typically 70 ppm.[8] Figure 1(b) shows the *MH* loop of a typical FeGa film. The saturation field is ≈2000 Oe, and the insert indicates that the coercive field is ≈90 Oe. The multilayer structures are fabricated on Pt precoated micromachined Si cantilevers to minimize the clamping effect of the Si substrate, which acts to reduce the ME coupling of the thin films.

As seen in the schematic side view [Fig. 1(a)], the FeGa layer is patterned to cover most of the cantilever area. Active bending of the cantilever from magnetostriction is mostly due to this region, which we refer to as the bending region. An isolated 1 mm^2 FeGa pad is patterned at the root of the cantilever where the stress from bending is concentrated, and this “pick-up” pad is used to measure the transduced piezovoltage.

A cross-sectional scanning electron microscopy (SEM) image of a PZT/FeGa bilayer shows a clear interface boundary with both layers displaying columnar microstructures along the growth direction [Fig. 1(c)]. Such a sharp, well-defined interface cannot be attained in glue-bonded bulk laminates. To optimize the ME coupling with respect to the interface state, three types of devices with different interfaces have been fabricated. They are a direct-contact bilayer of PZT/FeGa and ones with a 40 nm thick Ti or Pt spacer layer deposited in between.

The ME measurements are performed in air with dc and ac magnetic fields (H_{dc} and H_{ac}, respectively) applied along the length direction of the cantilever. Each sol-gel PZT pick-up pad is poled with 210 kV/cm for 15 min. The PZT layer and the FeGa layer couple via the piezoelectric d_{31} mode. A lock-in amplifier is used to measure the induced ME voltage across the PZT film. For a particular value of dc bias magnetic field, when the frequency of H_{ac} is tuned to the f_r of the cantilever, the ME device exhibits a strong voltage gain. All the ME data reported below are measured at the mechanical resonant frequencies of the devices and at optimum dc bias magnetic field unless otherwise noted.

Figure 2 shows a typical ME coefficient versus applied dc magnetic field for a PZT/Pt/FeGa multilayer device fabricated on a 35 μm thick Si cantilever. The ME coefficient (α_{ME}) of 1.81 V/cm Oe is observed at the bias field of 90 Oe, which is consistent with the coercive field of the FeGa film [Fig. 1(b)]. The optimum bias field of our thin-film device is much smaller than that of 750 Oe previously reported for a FeGa/PZT/FeGa bulk laminate,[9] indicating that our FeGa film is magnetically much softer. The frequency dependence of the ME coefficient of the thin-film device is plotted in the inset of Fig. 2. The f_r is 333 Hz, and the quality factor Q is 56, which is comparable to that of bulk devices.[10,11] In comparison to this PZT/Pt/FeGa device, similarly fabricated and measured PZT/FeGa and PZT/Ti/FeGa devices yield ME coefficients of 0.93 and 1.11 V/cm Oe, respectively.

Compared with the ME coupling of the direct-contact PZT/FeGa, it is somewhat improved by depositing a Ti spacer layer. This indicates that the adhesion between the PZT film and the FeGa film is already good. In contrast, we find that the induced ME voltage is nearly doubled by depositing a 40-nm-thick Pt layer between the PZT and FeGa films. Pt is a high work function electrode material, and the multilayer structure with PZT sandwiched by Pt films makes the top and bottom surfaces of the PZT film equipotential. This helps block the possible leakage current path in the PZT film, subsequently leading to enhanced ME transduction. Additionally, having a spacer Pt layer reduces the chance of oxide layer formation at the interface, which is detrimental to the ME signal and operation of the device.

Another factor which significantly affects the ME coupling of the thin-film devices is the mechanical constraint arising from the substrates. Nan *et al.*[12] reported weak ME effects in the 2–2 connectivity schemes and attributed it to the large in-plane constraint of a film from the substrate. We have made PZT/Pt/FeGa multilayers on a series of Si cantilevers with different thicknesses to study the substrate clamping effect. The measured ME coefficients for different

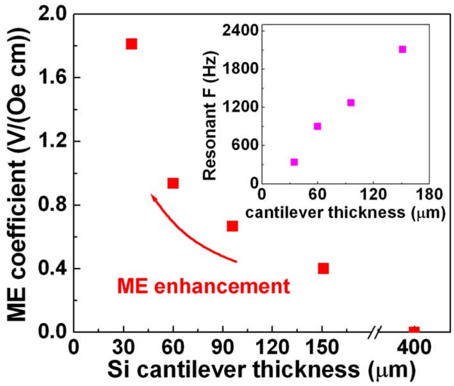

FIG. 3. (Color online) The ME coefficient as a function of cantilever thickness. The PZT/Pt/FeGa devices with 1 mm^2 pick-up region are poled with 210 kV/cm, operated at 90 Oe dc bias magnetic field and excited at their resonant frequencies. The inset shows the linear relationship between the resonant frequency and the thickness of the cantilevers.

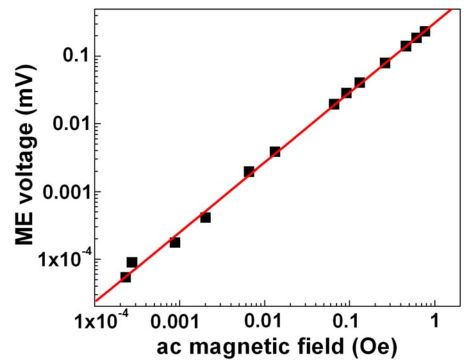

FIG. 4. (Color online) The ME voltage as a function of ac magnetic field at 333 Hz (resonant frequency) and at 90 Oe dc bias field. The straight line indicates a linear fit of the data. The device has PZT/Pt/FeGa multilayer structure and is fabricated on a 35 μm thick Si cantilever. Two 1 mm^2 pick-up regions are wired in series.

Si cantilever thicknesses are plotted in Fig. 3. Substantial increase in the ME coefficient is observed as the cantilever thickness is reduced. The f_r has a linear relationship with the beam thickness, as seen in the inset of Fig. 3. We are not able to detect any ME signal from a PZT/Pt/FeGa multilayer deposited on an unetched 400 μm thick Si substrate.

To evaluate the ac magnetic field sensitivity of the current thin-film ME devices, the induced ME voltage is measured as a function of ac field amplitude, using a PZT/Pt/FeGa multilayer structure on a 35 μm thick Si substrate. For this specific measurement, to improve the sensitivity of the all-thin-film devices, two 1 mm^2 pick-up regions are wired in series. Figure 4 shows a linear relationship between the ac magnetic field and the output ME voltage. The current device is able to detect 2.3×10^{-8} T (2.3×10^{-4} Oe) ac magnetic field with the 50 nV noise floor. By incorporating various cantilever Q and signal enhancing techniques, such as the stress concentrator and a stray capacitance compensation circuit, we expect to be able to substantially increase the signal and boost the sensitivity. Sensor arrays are also being pursued.

In summary, all-thin-film ME devices have been demonstrated on micromachined Si cantilevers which minimize the substrate clamping effect. The interface between the magnetostrictive FeGa and piezoelectric PZT layers has been optimized by depositing a Pt layer in between. The thin-film ME device displays the ME coefficient as large as 1.81 V/cm Oe.

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