Giant Magnetoelectric Effect in Nanofabricated $Pb(Zr_{0.52}Ti_{0.48})O_3$-$Fe_{85}B_5Si_{10}$ Cantilevers and Resonant Gate Transistors

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Magnetoelectric (ME) laminates show higher ME coefficients than that of natural multiferroics (e.g. Cr_2O_3, BiTiO) by up to several orders of magnitude. Recent studies on bulk ME sensors using $Fe_{85}B_5Si_{10}$ (Metglas) /polyvinylidene fluoride composite show a high ME voltage coefficient of 21V/cm·Oe at 20 Hz [1]. However, bulk sensors suffer from poor epoxy bonding, aging and difficulty of integration with CMOS electronics. Here, we report, for the first time, the monolithic nanofabrication of $Pb(Zr_{0.52}Ti_{0.48})O_3$ (PZT)-$Fe_{85}B_5Si_{10}$ ME cantilevers (Fig.1(a)) on silicon substrate which achieve 0.46 V/cm·Oe at 20 Hz and 1.8 V/cm·Oe at a resonance frequency of 8.4 KHz. Also, ME cantilever based resonant gate transistors (RGT) (Fig.1 (b)) has been designed and analyzed in comparison with ME cantilever. A 10X signal to noise ratio improvement can be reached by ME RGT. This shows the compatibility of the nanofabricated cantilever ME sensors with the Si process technology and paves the way for the future integration of MEMS based ultra-sensitive magnetic sensors with advanced Si nanoelectronics.

ME cantilever fabrication and characterization: Fig.2 shows the SEM picture and process flow of a fully released ME cantilever. First, a 0.93um thick PZT was deposited on Pt (100nm) coated SOI substrate using a sol-gel technique, followed by 50nm Pt adhesion layer (sputtered at 5mTorr, 200W dc), 260nm Metglas (5mTorr, 150W rf) and a 60nm Cr/Au top electrode deposition. The oxide etcher, Tegal 6500, was used to etching through the PZT layer and accesses the bottom electrodes. The cantilever beams (area ~ 200um*40um) were then patterned and etched down to the Si substrate. Finally, XeF_2 based dry etch was used to release the cantilevers. We individually characterize the sputtered Metglas and the PZT thin films. The Metglas/silicon cantilever was made to characterize the magnetostriction using laser vibrametry. A 0.4ppm/Oe magnetostrictive coefficient ($d_{33,m}$) was achieved without annealing, as shown in Fig. 3(a). The PZT films showed an effective piezoelectric coefficient $e_{31,f}$ of 7 C/m^2 (Fig. 3(b)) [2]. Fig. 3(c) gives the ME coefficient (α_{ME}=0.46V/cmOe at H_{dc}=25Oe) of the composite PZT/Metglas cantilever. The measured α_{ME} is samller than the expected value because of the lower Fe composition (~70%) in the Metglas layer. Table I compares the low frequency (at 20Hz) α_{ME} in this work with the one reported in recent literature [3, 4]. This shows the good ME response for the scaled PZT/Metglas cantilever sensor. And fig. 3(d) gives the frequency response where α_{ME} (1.8 V/cm·Oe) increases further by a factor of 4 at the resonance frequency. The noise performance of the sensor has also been investigated in order to evaluate the signal to noise ratio (SNR) of the cantilever sensor. The equivalent circuit with noise source of the whole measurement system and charge amplifier output with 0.7 Oe ac input magnetic field are shown in Fig. 4 (a) and (b). We measure the sensor capacitance as well as the dielectric loss (Fig. 4(c)) in order to calculate the sensor noise. Fig. 4(d) compares the calculated noise versus the measured noise of both sensor and amplifier. It shows that the total noise is dominated by the dielectric loss noise of the cantilever sensor. From the above results, we have the SNR of the whole system of 790 (Hz$^{1/2}$/Oe) and the minimum detectable magnetic field of 100nT/Hz$^{1/2}$.

ME RGT design and analysis: In Fig. 5(a), the equivalent circuit of ME RGT is demonstrated. The PZT/Metglas resonant gate is sensing the input ac magnetic field and results in the capacitance (air gap) change between the resonant gate and transistor gate. And the corresponding oxide charge change can be detected by the transistor and is reflected by the drain current. The voltage mode readout circuit [3] will be used to detect the response of the ME RGT (Fig.5 (b)) and Fig. 5(c) shows the layout of the readout circuit on which the resonant gate will be built. The noise performance of the voltage mode readout circuit is shown in Fig. 5 (d). This 1/f noise from the circuit is considered to be the dominated system noise since the resonance gate has the lowest dielectric loss (air) noise. Finally, we compare the SNR of ME cantilever and ME RGT at resonance in Table II. The output noise PSD at resonance frequency is reduced by 100X because of the less sensor noise, so the total SNR of ME RGT will be enhanced 10X in comparison to ME cantilever and a minimum detectable field of 10nT/Hz$^{1/2}$ can be achieved. The ME RGT is still under fabrication.

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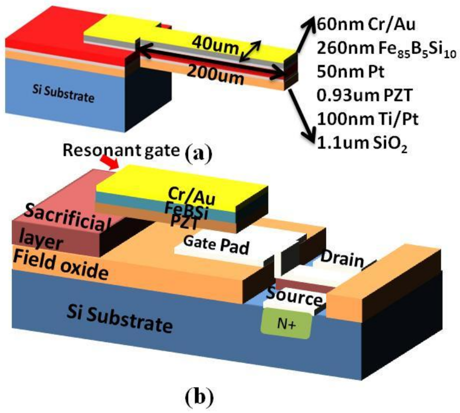

Fig.1Schematic for Magnetoelectric(ME) (a) cantilever and (b) resonant gate transistor(RGT).

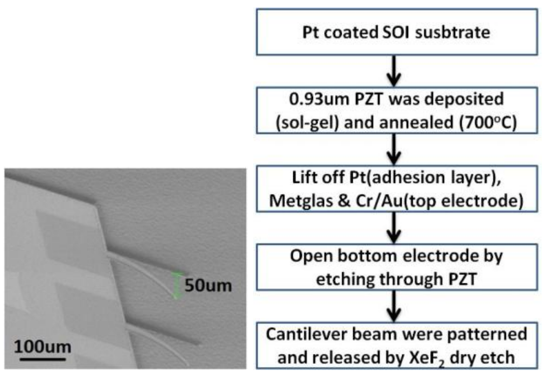

Fig. 2 SEM and process flow for ME cantilevers.

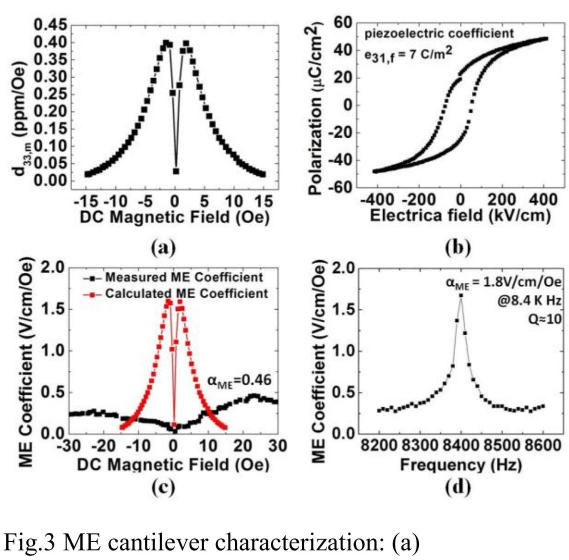

Fig.3 ME cantilever characterization: (a) Magnetostriction of Metglas (b) PE loop & piezo coefficient of PZT (c) Measurement vs. calculated ME coefficient (d) ME coefficient at resonance(8.4K Hz)

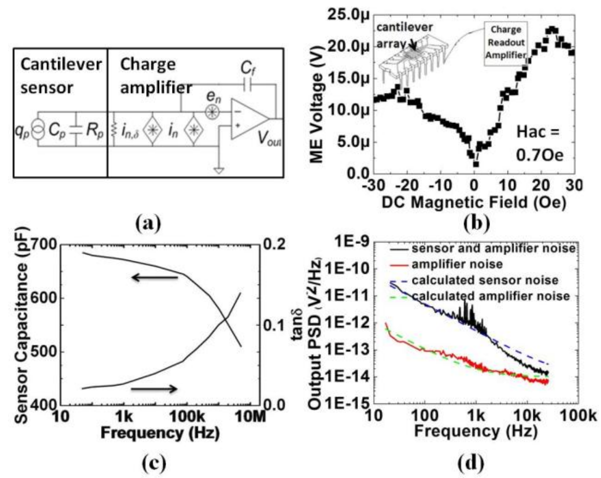

Fig. 4 (a) Equivalent circuit with noise source (b) ME cantilever output voltage versus DC magnetic field(input ac magnetic field equals 0.7Oe) (c) Sensor capacitance and dielectric loss vs. frequency (d) noise power spectrum density(PSD) of amplifier and sensor

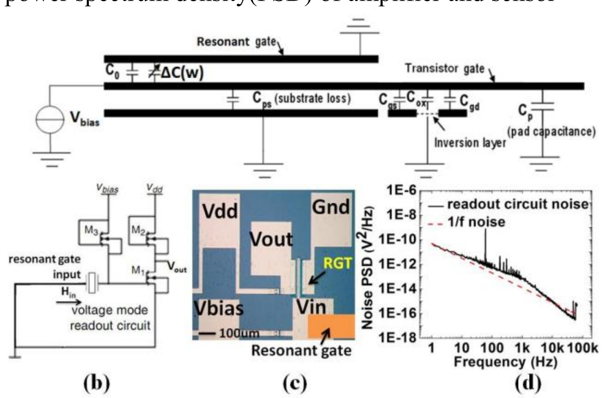

Fig. 5 (a) Equivalent circuit of ME RGT (b) Voltage mode readout circuit diagram (c) ME RGT readout circuit layout (c) Noise PSD for the readout circuit

Table I ME coefficient comparison

At 20 Hz	PZT/FeBSi (this work)	PZT/FeGa [3]	BaTiO/FeB Si [4]
α_{ME} (V/cmOe)	0.46	0.1	0.055

Table II SNR comparison

Sensor at resonance	α_{ME} (V/cmOe)	Noise (V^2/Hz)	SNR ($Hz^{1/2}$/Oe)
Cantilever	1.7	1e-13	790
RGT	1.6	1e-15	79,00