Direct Integration of Magnetoelectric Sensors with Microelectronics─Improved Field Sensitivity, Signal-to-Noise Ratio and Frequency Response

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***Abstract*— The large magnetoelectric (ME) coupling in the ME laminates makes them attractive for ultrasensitive room temperature magnetic sensors. Here we investigate the field sensitivity and signal-to-noise ratio (*SNR*) of ME laminates, consisting of magnetostrictive and piezoelectric layers (Metglas and piezopolymer PVDF were used as the model system), which are directly integrated with two different modes of low noise readout circuits ─ charge mode and voltage mode. For the sensor system with charge mode readout circuit, both the theoretical analysis and experimental results show that increasing the number of piezolayer layers can improve the *SNR*, especially at low frequencies. We also introduce a figure of merit to measure the overall influence of the piezolayer properties on the *SNR* and show that the newly developed piezoelectric single crystals of PMN-PT and PZN-PT have the promise to achieve a very high *SNR* and consequently ultra-high sensitivity room temperature magnetic sensors. The results show that the ME coefficients used in early ME composites development works may not be relevant to the *SNR*. The results also show that enhancing the piezomagnetic coefficient, for example, by employing the flux concentration effect, can lead to enhanced *SNR*. For the sensor system in-package with voltage mode readout circuits, both theories and experiments show that the system in package exhibits frequency independent field sensitivity at the whole frequency range of interests. The package ME sensors investigated here show the potential of chip scale ME magnetic sensors with high *SNR* and sensitivity.**

I. INTRODUCTION

Magnetoelectric (ME) effect is a material phenomenon featuring the interchange between the magnetic and electric energies or signals [1-6]. The large ME effect observed in ME composites, especially the ME laminates, consisting of magnetic and ferroelectric components raises the interests of using them as room temperature high sensitivity magnetic sensors [6-12]. In the ME composite sensors, the external magnetic field ΔH_a generates a change in the magnetic materials, which can be a strain ΔS (elastic coupling) if it is a magnetostrictive materials or a temperature change ΔT (thermal coupling) for a magnetocaloric material or both [6-14]. The direct coupling between the magnetic and ferroelectric components in the laminates transfers this change to the ferroelectric phase, through the piezoelectric effect for

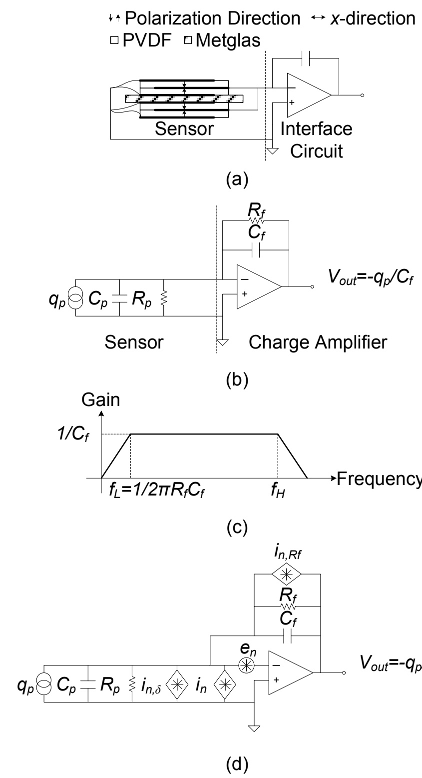
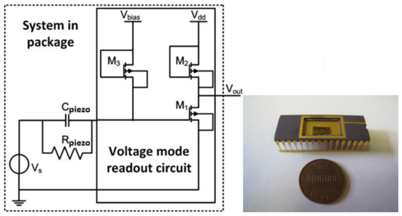


Figure 1. (a) Schematic of a multilayer ME laminate which is directly integrated with a charge sensitive readout circuit. In the figure, four piezolayers, which are electrically connected in parallel and the poling direction is indicated, are shown for the sensor. The central layer is the magnetic material. (b) Equivalent circuit for the sensor system in (a) where a feedback resistor R_f is added. (c) Frequency response of charge amplifier in (b) where the low frequency cutoff frequency is determined by the time constant R_fC_f and the high frequency cutoff is determined by the amplifier circuit. (d) Noise equivalent circuit of the sensor system in (b).



(a)

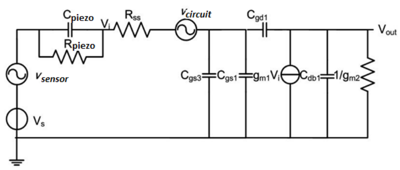


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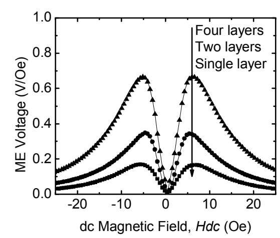
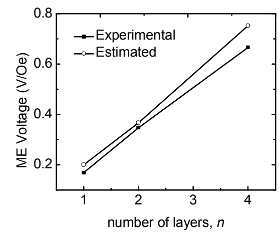
Figure 2. (a) Schematic and photography for SIP ME laminates sensor and voltage mode readout circuit, (b) Small signal circuit for voltage mode ME system with noise sources.



(a)



(b)

Figure 3. (a) ME voltage of the sensor system as a function of dc bias magnetic field for Metglas/PVDF laminates with different number of PVDF layers. The data were measured at 200 Hz and ac magnetic field H_{ac}=0.08 Oe. The feedback capacitance in charge amplifier is 10 pF. (b) Comparison of experimentally measured ME voltage with that deduced (estimated) from (5).

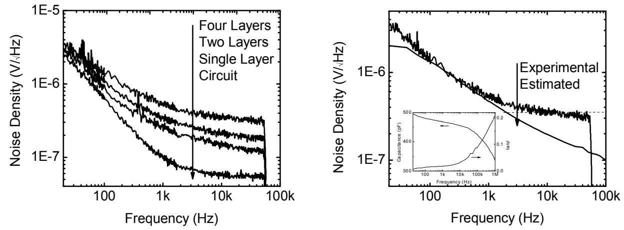
the strain or pyroelectric effect for the temperature change of the magnetic component, and generates an electric output signal. In this paper, the field sensitivity and signal-to-noise (*SNR*) ratio of the ME sensors based on the elastic coupling between the magnetic and ferroelectric components, consisting of the magnetostrictive alloy Metglas and piezoelectric polymer PVDF layers, which are directly integrated with the electronic readout circuits as schematically illustrated in Fig. 1(a) and Fig. 2(a) will be investigated.

Magnetic sensors based on the ME laminates have several inherent advantages such as compact size, simple structure, and as passive sensors that can be operated without external power supply. The simple structures of these ME effect based sensors facilitate their direct integration with advanced microelectronics, which can significantly reduce the spurious noises due to electric wiring between the sensors and signal conditioning circuitry [15]. In this paper, a system in package (SIP) approach is employed to directly integrate the ME sensor with a charge sensitive readout circuit as illustrated in Fig. 1(a) or a voltage mode readout circuit as illustrated in Fig. 2(a). As will be shown in this paper, such sensor systems have the potential to reach very high *SNR* and sensitivity. We will first present the analysis of field sensitivity $V_{out}/\Delta H_a$, the *SNR*, and system noise level for charge mode readout circuits, where ΔH_a is the external magnetic field to be measured, and then the field sensitivity and system noise level for voltage mode circuits. Integrated ME sensors are constructed and the experimental results and their comparison with theoretical analyses will be reported.

II. EXPERIMENTAL

Iron-based magnetic alloy Metglas 2605SA1 (Metglas, Inc., SC, μ_r=45,000) with thickness t_m=25 μm was used as the magnetostrictive layer, which has low saturation magnetization field and consequently needs a relatively low dc magnetic bias field (<20 Oe) to induce high magnetostrictive response [12]. The piezoelectric polymer PVDF (Ktech Corp., NM) of thickness t_p=25 μm was used as the piezoelectric layer, which can be easily fabricated into multilayer configuration (to vary the sensor area without incurring large sensor size and to take advantage of the flux concentration effect [13]) and hence makes it easier to compare with the theoretical analysis. The ME laminates of Fig. 1(a) were fabricated by bonding the Metglas and PVDF together using a non-conductive epoxy resin (5 minute Epoxy, ITW Devcon, MA). In this study, the sensor area of the piezoelectric PVDF was varied by using a multilayer configuration in which PVDF layers were connected electrically in parallel so that the magnetic field induced charge output from each layer is added together (see schematics in Fig. 1(a)).

Two parallel electromagnets (Model HF-7H, Walker Magnetics Group, Inc.) were employed to provide both ac (at frequencies from 10 Hz to 1 kHz) and dc magnetic fields. A function generator (Model DS360, Stanford Research Systems, Inc., CA), which generates a sine wave superimposed with an offset voltage, was used to drive the electromagnet and generate the ac and dc magnetic fields. The electric signal from the charge amplifier connecting the PVDF was measured using a lock-in amplifier (Model SR830 DSP, Stanford Research Systems, Inc.) as well as an oscilloscope. The capacitance and loss tangent of PVDF layer were measured using a precision LCR meter (HP4284A, Agilent Technologies, Inc.). A charge sensitive readout amplifier with a feedback capacitor C_f=10 pF was fabricated and the ME laminate was directly integrated with the readout circuit. Since the low cutoff frequency is determined by $1/2\pi R_f C_f$ (Fig. 1(c)), R_f = 1 GΩ was chosen to achieve a reasonable low cutoff frequency. A common source voltage amplifier based on NMOS technology was fabricated on silicon substrate. By introducing the active biasing circuitry and system in package integration method, we reach high input impedance and reduce the stray capacitance. The noise spectral density was measured by an FFT Dynamic Signal Analyzer (Model 35670A, Agilent Technologies, Inc.). A faraday cage was designed and constructed to attenuate the environmental magnetic fields and electric noise and the whole magnetic characterization set-up was placed inside this shielding cage.



(a) (b)

Figure 4. (a) Noise spectral density for Metglas/PVDF laminates with varying number of PVDF layers, (b) Comparison of the experimentally measured noise spectral density for laminates with four layers PVDF with that deduced from (8). (The inset shows the capacitance and tanδ of the PVDF as a function of frequency which are used in the calculation).

III. Sensitivity Analysis and Results

A. Integrated ME Sensor with Charge Mode Readout Circuit

The charge amplifier of Fig. 1(b) is based on the charge transfer from the ME sensor to the feedback capacitor C_f. The voltage across the feedback capacitor is

$$V_{out} = \frac{q_p}{C_f + \frac{C_p + C_f}{A_d}} \approx \frac{q_p}{C_f} \tag{1}$$

where q_p is the charge generated in the piezolayer, which is PVDF, of the ME laminate due to an external magnetic field ΔH_a, A_d is the open-loop gain of the op-amp, C_f is the capacitance of the feedback capacitor, and C_p is the capacitance of PVDF.

The field sensitivity of the sensor system $V_{out}/\Delta H_a$, where ΔH_a is the change of external magnetic field to be measured, can be derived from the piezoelectric constitutive equations and the elastic coupling between the Metglas and PVDF layers (non-slippery contact between the two layers). The piezoelectric constitutive equations of the piezolayer, which relate the elastic stress T and strain S to the electric field E and electric displacement D, are

$$\begin{aligned} S_p &= s_p^E T_p + d_p E \\ D_p &= d_p T_p + \varepsilon^T E \end{aligned} \tag{2a}$$

While the constitutive equations of the magnetostrictive layer are

$$\begin{aligned} S_m &= s_m^H T_m + d_m H_a \\ B_m &= d_m T_m + \propto^T H_a \end{aligned} \tag{2b}$$

where the coefficients define the sensitivity of a piezoelectric or magnetic material in performing signal transformation between the elastic and electric or magnetic forms: d_p is the piezoelectric coefficient, d_m is the piezomagnetic coefficient of the magnetostrictive layer under

TABLE I. The output referred noise power density resulting from different noise sources at 1 kHz.

Symbol	At 1 kHz	v_n^2 (10^{-14} V^2/Hz)
$i_{n,\delta}$ (Four Layers PVDF)	30 fA/√Hz	23
i_n	10 fA/√Hz	2.5
$i_{n,Rf}$	4 fA/√Hz	0.4
e_n	7 nV/√Hz	11.3

dc magnetic bias field, s_p^E and s_m^H are the elastic compliance coefficients, ε^T is the dielectric constant, μ^T.is the permeability. The subscripts p and m denote the parameters of the piezoelectric and magnetostrictive layers. For the sensor system in Fig. 1(b) in which the PVDF piezolayer is in short-circuit condition, i.e., E=0, then the constitutive equations (2a) can be simplified to,

$$\Delta D_p = \frac{d_p \Delta S_p}{s_p^E} \tag{3}$$

From (3), the charge generated in the piezopolymer PVDF from the strain ΔS_m of the Metglas, which is the strain generated due to external magnetic field H_a in (2b) when T_m=0, can be found

$$\Delta q_p = \frac{d_p A_p \Delta S_m}{s_p^E \left(1 + \frac{s_m^H t_p}{s_p^E t_m}\right)} \tag{4}$$

where A_p is the total area of PVDF piezopolymer layer. Here a perfect elastic coupling between the piezolayer and magnetostrictive layer is assumed. The field sensitivity $V_{out}/\Delta H_a$ of the sensor system is,

$$\frac{V_{out}}{\Delta H_a} = \frac{d_p A_p}{C_f s_p^E \left(1 + \frac{s_m^H t_p}{s_p^E t_m}\right)} \frac{\Delta S_m}{\Delta H_a} \tag{5}$$

where $\Delta S_m/\Delta H_a$ is the piezomagnetic coefficient of the Metglas in the dc field biased state. Since the elastic modulus of the PVDF layer ($1/s_p^E$ ~3 GPa) is much smaller than that of Metglas ($1/s_m^H$ ~110 GPa), the term in the denominator $1 + s_m^H t_p / s_p^E t_m$ ~ 1 for the studies carried out in this paper. (5) shows the dependence of the field sensitivity of the ME sensor on the material parameters such as the peizo-coefficient d_p, the piezomagnetic coefficient $\Delta S_m/\Delta H_a$, and the elastic compliance s_p^E of the piezolayer. Moreover, (5) also shows that the sensitivity can be increased by increasing the piezolayer area A_p and using a smaller feedback capacitor C_f. Indeed, as shown in Fig. 3(a), increasing the piezopolymer PVDF layer number in the ME laminate composites from one to four yields a ~four times increase in the sensitivity of the integrated magnetic sensor. Fig. 3(b) presents a comparison of the results calculated from (5) using the piezomagnetic coefficient of Metglas reported and the properties of PVDF piezo-films with the experiment data of Fig. 3(a) [12], which shows a good agreement between the two. (In (5), A_p is increased by four times and t_p/t_m is also increased by four

TABLE II. COMPARISON OF DIFFERENT PIEZOELECTRIC MATERIALS (ASSUME $t_p=t_m$) ON THE *SNR* OF THE ME SENSORS.

	d_{31}(pC/N)	$1/s^E_p$(GPa)	ε_{pr}	tanδ% (at 1 kHz)	FOM of Piezolayer*
PVDF	16	3.3	10	2	12
PZT [17]	125	80	1250	0.4	259
PMN-PT [18]	2740	25	5000	0.5	1116
PZN-PT [19]	2800	15	5500	<1	498

$$\text{FOM of Piezolayer} = \frac{d_p}{\sqrt{\varepsilon_p \tan\delta}} \frac{1}{s_p^E(1+\frac{s_m^H t_p}{s_p^E t_m})}$$

times when the PVDF layer number is increased from one to four. Since the change of $1+s_m^H t_p / s_p^E t_m$ is small, the ME voltage shows a four times increase).

For sensors, the *SNR* is an ultimate limiting factor on the detection level of the sensor. This *SNR* should also take into consideration the noises in the electronic readout circuit. Fig. 1(d) includes the major noise sources in the sensor system here: R_p represents the dielectric loss of the piezolayer ($R_p = 1/\omega C_p \tan\delta$) which is one of the primary noise sources of the ME sensor and has the spectral current density,

$$i_{n,\delta}=\sqrt{4kT\omega C_p \tan\delta} \tag{6}$$

where C_p is the PVDF capacitance and tanδ is the dielectric loss tangent. The total output spectral noise voltage density, including that from the charge sensitivity readout is [16],

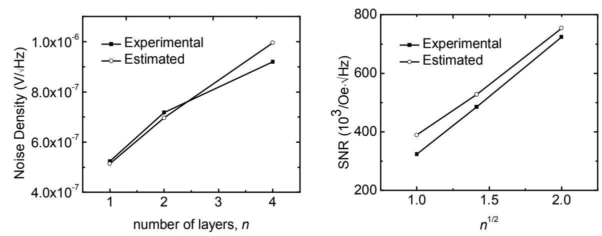
$$v_{n,total}^2=(i_{n,\delta}^2+i_n^2+i_{n,R_f}^2)\frac{1}{(\omega C_f)^2}+e_n^2(1+\frac{C_p}{C_f})^2 \tag{7}$$

where i_n and e_n are the input referred current noise density and input referred voltage noise density of the op-amp, respectively. The experimentally measured output referred noise is presented in Fig. 4(a).

The custom-made low-noise charge sensitive readout circuit used in this experiment has the output referred noise, resulting from e_n and i_n, much smaller than that from the dielectric loss at low frequency and hence these noises can be neglected (see Table I). Therefore at low frequencies (<1 kHz), the total noise is dominated by the noise due to the dielectric loss,

$$v_{n,total}=\frac{i_{n,\delta}}{\omega C_f} \tag{8}$$

This is confirmed experimentally, as shown in Fig. 4(b). At frequencies below 1 kHz the theoretical noise curve, which is calculated from the capacitance and dielectric loss tangent, matches the measured noise curve very well. The resulting



(a) (b)

Figure 5. (a) Output referred noise density at 200 Hz as a function of the number of PVDF layers (dots) and its comparison with that deduced (open circles) from (8), (b) *SNR* at 200 Hz as a function of the square root of the number of PVDF layers (dots) and the comparison with that deduced from (9) (open circles). Lines are drawn to guide eyes.

$SNR = V_{out} / v_{n,total}$ at low frequencies (<1 kHz), hence, can be derived as

$$SNR=\frac{\Delta S_m}{\Delta H_a}\frac{d_p}{\sqrt{\varepsilon_p \tan\delta}}\frac{1}{s_p^E(1+\frac{s_m^H t_p}{s_p^E t_m})}\sqrt{\frac{\omega t_p A_p}{4kT}} \tag{9}$$

Equation (9) reveals several ways to improve the *SNR* of the ME sensor system:

For the magnetostrictive material in the laminates, it is highly desirable to possess a large piezomagnetic coefficient $\Delta S_m/\Delta H_a$. The Metglas used here possesses the highest piezomagnetic coefficient among commercially available materials [11,12]. Moreover it has been shown that for Metglas, $\Delta S_m/\Delta H_a$ can be significantly enhanced by exploiting flux concentration effect due to its very high magnetic permeability [13].

Since $SNR \propto \frac{d_p}{\sqrt{\varepsilon_p \tan\delta}}\frac{1}{s_p^E(1+\frac{s_m^H t_p}{s_p^E t_m})}=FOM$. Here a figure of merit (FOM) of piezoelectric material is introduced to describe the influence of various parameters of the piezoelectric on the *SNR*. Therefore piezoelectric materials with high d_p, low ε, low tanδ is required to achieve a large *SNR*. Common commercially available piezoelectric materials are compared in Table II. It's shown that the *SNR* could be improved remarkably by using piezoelectric single crystals of PMN-PT and PZN-PT [18,20].

Since $SNR \propto \sqrt{\frac{\omega t_p A_p}{4kT}}$, increasing the sensor volume and working at high frequencies can increase the *SNR*.

In our experiment, multilayer PVDF were used to demonstrate the influence of A_p on the field sensitivity and *SNR*. Fig. 5 presents the output referred noise density and *SNR* at 200 Hz as a function of the number of PVDF layers *n*, which shows that increasing the piezolayer volume can improve *SNR*. Experimental results also confirm the results deduced from (7) and (9).

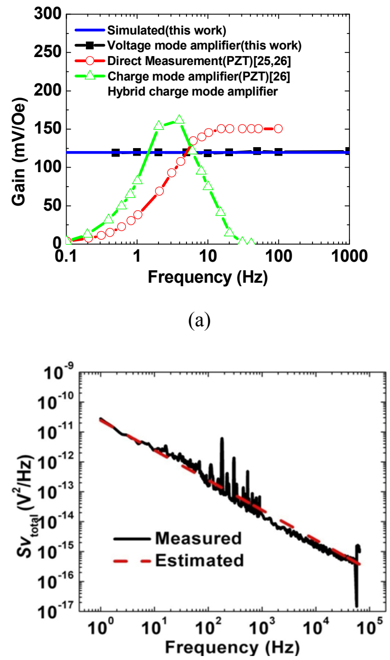


Figure 6. Output response of voltage mode sensing system (a) Frequency response and its comparison with other detection techniques, (b) Calculated and measured total input noise power spectral density.

At high frequency (>1 kHz), the noise is dominated by the op-amp noise e_n and i_n for the sensor system here,

$$v_{n,total}=\sqrt{i_n^2\frac{1}{(\omega C_f)^2}+e_n^2\left(1+\frac{C_p}{C_f}\right)^2} \qquad (10)$$

The resulting *SNR* is

$$SNR=\frac{\Delta S_m}{\Delta H_a}\frac{d_pA_p}{s_p^E\left(1+\frac{s_m^Ht_p}{s_p^Et_m}\right)}\frac{1}{\sqrt{\frac{i_n^2}{\omega^2}+e_n^2(C_f+C_p)^2}} \qquad (11)$$

Equation (11) indicates that at high frequencies the *SNR* depends mainly on d_p and $\Delta S_m/\Delta H_a$, the sensor area A_p, and the noise level of the op-amp.

It is noted that in developing ME composites, most of the focus has been paid to enhancing the ME coefficients $\Delta E/\Delta H_a$ and/or $\Delta D/\Delta H_a$, where ΔE and ΔD are the change of electric field and charge density induced in the ME composite due to the magnetic field ΔH_a [6-14,21]. Hence, due to the relatively small dielectric constant of PVDF, the ME laminates of Metglas/PVDF exhibit "giant" ME response [13,22]. However, the results in this paper show that these ME coefficients may not be relevant in developing ME materials for magnetic sensors, which is probably one major area of applications for the ME composites. For example, even though the Metglas/PVDF laminates possess very large ME coefficient $\Delta E/\Delta H_a$, the *SNR* of this type of ME laminates is not high compared with ME composites based on piezoceramics.

B. Integrated ME Sensor with Voltage Mode Readout Circuit

Fig.2 (a) shows the main features of the package voltage mode ME detection system investigated. The readout circuit consists of a common source amplifier with two diode connected transistors M2 and M3, which act as the active load and bias, separately. The equivalent circuit model of ME system, shown in Fig.2 (b), yields the total output response at low frequency,

$$\frac{V_{out}}{\Delta H_a}\approx-\alpha_{me}t_{piezo}\sqrt{\frac{(W/L)_1}{(W/L)_2}} \qquad (12)$$

where $\alpha_{me}=\Delta E/\Delta H_a$ is the ME voltage coefficient, t_{piezo} is the piezoelectric layer thickness, and $(W/L)_1$ and $(W/L)_2$ are the dimensions (width/length) of M1 and M2, respectively. In general, one can assume α_{me} as a constant under the first order resonant frequency [23]. This result shows that the field sensitivity depends only on the sizes of the sensor and transistors.

As illustrated in Fig. 2(b), the total noises include both the intrinsic sensor noise $v_{n,sensor}$ and the detection circuit noise $v_{n,circuit}$. The total voltage spectral density is dominated by the dielectric loss noise, which can be estimated by

$$v_{n,sensor}^2=i_{n,\delta}^2(R_p\|C_p)^2=\frac{4kT}{\omega C_p}\frac{\tan\delta}{(1+\tan\delta)^2} \qquad (13)$$

where k is the Boltzmann constant, T is the absolute temperature, ω is the angular frequency, and $\tan\delta$ is the loss tangent of the piezoelectric layer. For detection circuit, thermal noise and flicker noise are the main noise sources, however, at low frequency, flicker noise dominates. So the total circuit input voltage noise spectral density can be approximately written as

$$v_{n,circuit}^2\cong\frac{1}{C_{ox}}\left(\frac{K_ng_{m2}^2}{(WL)_2g_{m1}^2}+\frac{K_n}{(WL)_1}\right)\frac{1}{f}=\frac{2K_n}{f(WL)_1C_{ox}} \qquad (14)$$

where C_{ox} is the oxide capacitance per area, K_n is the flicker noise coefficient, and f is the frequency. In this case, by adding (13) and (14), the total system voltage noise spectral density is

$$v_{n,total}^2=v_{n,sensor}^2+v_{n,circuit}^2=\frac{4kT}{\omega C_{piezo}}\frac{\tan\delta}{(1+\tan\delta)^2}+\frac{2K_n}{f(WL)_1C_{ox}} \qquad (15)$$

Based on the analysis above, we construct a small size ME sensor for testing and integration, which is a unimorph mode laminate made of Metglas (15 mm×5 mm×0.5 mm) and PVDF (10 mm×3 mm×0.025 mm) [13]. And the detection circuit is fabricated by 5 μm NMOS processing line at the Penn State University Microfab. We design the sizes of the transistors, $(W/L)_1 = 100\ \mu\text{m}/10\ \mu\text{m}$ and $(W/L)_2 = (W/L)_3 = 10\ \mu\text{m}/10\ \mu\text{m}$, which have achieved high input impedance and reduced the flicker noise level as much as possible. For integration, the ME sensor is wire bonded to the detection circuit within a package. By extracting the parameters of sensor and transistors, we have C_s = 130 pF, $\tan\delta$ = 0.02, C_{ox} = 0.115

μF/cm^2, and K_n = 1.2×10^{-23} V^2•F [24]. Substituting these to (15) yields that the total noise is dominated by the circuit. Fig.6 (a) and (b) show the experimental results of the frequency and noise response of the integrated sensor system, which match well with the simulated results analyzed above. Comparing to the other detection techniques investigated in the literature and the charge mode detection investigated here [25,26], the voltage mode ME sensor can detect the signals in the frequency range of biomedical interest, especially at very low frequencies.

IV. Conclusion

In summary, the field sensitivity and *SNR* of magnetoleectric laminates which were directly integrated (SIP) with custom-made low-noise charge sensitive readout circuit and voltage mode readout circuit are investigated. The ME laminates of Metglas/PVDF were experimentally studied and the performance are compared with the prediction from the theoretical analysis. For charge sensitive readout ciruit, the results indicates that increasing the electrode area (number of layers) of the piezolayer (here PVDF) can enhance the field sensitivity and *SNR*. The paper introduces a FOM to characterize the overall influence of the piezolayer properties on the *SNR* and show that newly developed piezoelectric single crystals of PMN-PT and PZN-PT have the potential to reach very high *SNR* for ME magnetic sensors. The results also show that the ME coefficients which are presently used to compare the ME materials developed may not be relevant when using these ME materials for magnetic sensors. The results provide a general approach to improve the field sensitivity and *SNR* of ME sensor materials and systems. For voltage mode readout circuit, on the other hand, we systematically analyze the frequency response and noise of our in package Metglas/Polyvinylidene fluoride ME voltage mode sensing system. Both simulations and experiments show a good frequency response of our system. Also this design provides a low cost and chip-scale magnetic detection system at the frequency range of interest for biomedical application.

Acknowledgment

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[1] L. D. Landau and E. M. Lifshitz, "Electrodynamics of Continuous Media," Oxford: Pergamon Press, 1960, pp. 119.

[2] G. T. Rado and V. J. Folen, "Observation of the magnetically induced magnetoelectric effect and Evidence for antiferromagnetic domains," Phys. Rev. Lett., vol. 7, pp. 310–311, 1961.

[3] R. Ramesh and N. A. Spaldin, "Multiferroics: progress and prospects in thin films," Nature Mater., vol. 6, pp. 21–29, 2007.

[4] W. Eerenstein, N. D. Mathur, and J. F. Scott, "Multiferroic and magnetoelectric materials," Nature, vol. 442, pp. 759–765, 2006.

[5] M. Fiebig, "Revival of the magnetoelectric effect," J. Phys. D, vol. 38, pp. R123, 2005.

[6] C. W. Nan, M. I. Bichurin, S. X. Dong, D. Viehland, and G. Srinivasan, "Multiferroic magnetoelectric composites: historical perspective, status, and future directions," J. Appl. Phys., vol. 103, 031101–031101-35, 2008.

[7] J. Ryu, S. Priya, A. V. Carazo, K. Uchino, H. E. Kim, "Effect of the magnetostrictive layer on magnetoelectric properties in Lead Zirconate Titanate/Terfenol-D laminate composites," J. Amer. Ceramic Soc., vol. 84, pp. 2905–2908, 2001.

[8] S. X. Dong, J. F. Li, and D. Viehland, "Characterization of magnetoelectric laminate composites operated in longitudinal-transverse and transverse–transverse modes," J. Appl. Phys., vol. 95, pp. 2625–2630, 2004.

[9] K. Mori and M. Wuttig, "Magnetoelectric coupling in Terfenol-D/polyvinylidenedifluoride composites," Appl. Phys. Lett., vol. 81, pp. 100–101, 2002.

[10] J. Zhai, Z. Xing, S. Dong, J. Li, and D. Viehland, "Detection of pico-Tesla magnetic fields using magneto-electric sensors at room temperature," Appl. Phys. Lett., vol. 88, pp. 062510–062510-3, 2006.

[11] P. M. Drljaca, F. Vincent, P.-A. Besse, and R. S. Popovic, "Design of planar magnetic concentrators for high sensitivity Hall devices," Sens. Actuators A, vol. 97, pp. 10–14, 2002.

[12] S. X. Dong, J. Y. Zhai, J. F. Li, and D. Viehland, "Near-ideal magnetoelectricity in high-permeability magnetostrictive/piezofiber laminates with a (2-1) connectivity," Appl. Phys. Lett., vol. 89, pp. 252904–252904-3, 2006.

[13] Z. Fang, S. G. Lu, F. Li, S. Datta, Q. M. Zhang, and M. El Tahchi, "Enhancing the magnetoelectric response of Metglas/polyvinylidene fluoride laminates by exploiting the flux concentration effect," Appl. Phys. Lett., vol. 95, pp. 112903–112903-3, 2009.

[14] S. G. Lu, Z. Fang, E. Furman, Y. Wang, Q. M. Zhang, Y. Mudryk, K. A. Gschneidner, Jr.,V. K. Pecharsky, and C. W. Nan, "Thermally mediated multiferroic composites for the magnetoelectric materials," Appl. Phys. Lett., vol. 96, pp. 102902–102902-3, 2010.

[15] H. J. Weller, D. Setiadi, and T. Binnie, "Low-noise charge sensitive readout for pyroelectric sensor arrays using PVDF thin film," Sensors & Actuators, vol. 85, 267–274, 2000.

[16] R. Pallás-Areny and J. G. Webster, "Sensors and Signal Conditioning," New York: J. Wiley, 2001, pp. 418.

[17] http://www.americanpiezo.com/

[18] Y. Lu, D.-Y. Jeong, Z.-Y. Cheng, Q. M. Zhang, H. Luo, Z. Yin, and D. Viehland, "Phase transitional behavior and piezoelectric properties of the orthorhombic phase of $Pb(Mg_{1/3}Nb_{2/3})O_3$–$PbTiO_3$ single crystals," Appl. Phys. Lett., vol. 78, pp. 3109–3111, 2001.

[19] http://www.microfine-piezo.com/

[20] S. E. Park and T. R. Shrout, "Ultrahigh strain and piezoelectric behavior in relaxor based ferroelectric single crystals," J. Appl. Phys., vol. 82, pp. 1804–1811, 1997.

[21] M. I. Bichurin, V. M. Petrov, and G. Srinivasan, "Theory of low-frequency magnetoelectric effects in ferromagnetic-ferroelectric layered composites," J. Appl. Phys., vol 92, pp. 7681–7683, 2002.

[22] J. Zhai, S. X. Dong, Z. Xing, J. F. Li, and D. Viehland, "Giant magnetoelectric effect in Metglas/polyvinylidene-fluoride laminates," Appl. Phys. Lett., vol. 89, pp. 083507–083507-3, 2006.

[23] Z. Xing, J. Li, D. Viehland, "Noise and scale effects on the signal-to-noise ratio in magnetoelectric laminate sensor/detection units," Appl. Phys. Lett., vol. 91, pp. 182902–182902-3, 2007.

[24] F. Li, S. Lee, Z. Fang, P. Majhi, Q. Zhang, S. K. Banerjee, and S. Datta, "Flicker noise improvement in 100 nm Lg Si0.50Ge0.50 strained quantum-well transistors using ultra-thin Si cap layer," IEEE Electron Device Letters, vol. 31, pp. 47–49, 2010.

[25] Z. Xing, J. Li, D. Viehland, "Modeling and the signal-to-noise ratio research of magnetoelectric sensors at low frequency," Appl. Phys. Lett., vol. 91, pp. 142905–142905-3, 2007.

[26] Z. Xing, J. Zhai, S. X. Dong, J. Li, D. Viehland and W. G. Odendaal, "Modeling and detection of quasi-static nanotesla magnetic field variations using magnetoelectric laminate sensors," Meas. Sci. Technol., vol. 19, pp. 015206–015206-9, 2008.