Low-frequency voltage mode sensing of magnetoelectric sensor in package

F. Li, F. Zhao, Q.M. Zhang and S. Datta

An in-package voltage-sensing integrated magnetometer for low frequency neural recording at room temperature is presented. The detection system consists of a voltage mode CMOS amplifier with an active biasing circuit and a Metglas/Polyvinylidene fluoride (PVDF)-based magnetoelectric (ME) unimorph sensor measuring 10 × 3 × 0.025 mm in volume, representing the smallest ME sensor volume reported to date. Over the frequency range of interest (0.5 Hz–1 kHz), both theories and experiments are in excellent agreement and the fabricated magnetometer exhibits a frequency independent signal-to-noise ratio (SNR) at the system level. The magnetometer achieves a SNR of 3000 and detects a minimum detectable field of 30 nano-Tesla waveform. This system in package provides a feasibility demonstration of integration of ME sensors directly with NMOS readout electronics aimed at tiny magnetic field detection for bio-imaging applications.

Introduction: The magnetoelectric (ME) effect [1] is defined as the induction of electrical polarisation upon application of a magnetic field $\boldsymbol{H}$ and/or the magnetisation upon application of an electric field $\boldsymbol{E}$. The composite bimorph of a magnetostrictive layer (e.g. Terfenol-D and Metglas) and a piezoelectric layer (e.g. $Pb(ZrTi)O_3$ (PZT) and Polyvinylidene fluoride (PVDF)), which have strong coupling between the magnetostrictive and piezoelectric layers, exhibits a large ME coupling coefficient and can act as a sensitive magnetic sensor [2] at room temperature. Conventional ME detection techniques, such as direct measurement (e.g. a sensor directly wired to a lock-in amplifier) and charge mode sensing have been developed for magnetic signal detection capability at nano-Tesla level [3–5]. Although high sensitivity has been achieved, both the direct sensing and the charge mode sensing approaches are limited by the sensor volume or poor low frequency response. In this Letter, we adopt a voltage mode sensing technique with an ME sensor to demonstrate an excellent low-frequency response at an equivalent signal-to-noise ratio (SNR) value. By introducing the active biasing circuitry and system in package integration method, we achieve high input impedance and reduced parasitic capacitance. For the first time, we demonstrate an in-package voltage mode sensing NMOS circuit with the smallest ME sensor to date, and a high constant SNR and nano-Tesla waveform detection capability at low frequency range suitable for neural recoding is shown.

Modelling and analysis: Fig. 1*a* shows the schematic of our in-package voltage mode ME sensing system. The readout circuit consists of a common source amplifier with two diode connected transistors M_2 and M_3, which act as the active load and bias, respectively. The equivalent circuit of the ME sensor at low frequency, is shown in Fig. 1*b*. The output of the magnetometer system, $V_o(\omega)$, against the slowly varying input magnetic field, $H(\omega)$, is given by:

$$\frac{V_o(\omega)}{H(\omega)} \simeq -\alpha_{me} t_{piezo} \sqrt{\frac{(W/L)_1}{(W/L)_2}} \quad (1)$$

where α_{me} is the ME voltage coefficient, t_{piezo} the ME sensor thickness, and $(W/L)_1$ and $(W/L)_2$ are the aspect ratios of M_1 and M_2, respectively. In general, we assume that α_{me} is a constant at low frequency [3]. This result shows that the frequency response of the sensing system depends only on the relative size of the sensor and amplifying transistor.

The SNR of any ME sensor system depends not only on the sensing mode (charge against voltage mode), but also on the system level noise performance. As illustrated in Fig. 1*b*, the various noise sources include the intrinsic sensor noise v_{sensor} as well as the detection circuitry noise $v_{circuit}$. The total noise voltage spectral density of the sensor is dominated by the dielectric loss noise, which can be estimated by

$$v_{sensor}^2 = i_d^2 \times \left(\frac{R_{piezo}/}{C_{piezo}}\right)^2 = \frac{4kT}{\omega C_{piezo}} \frac{\tan\delta}{(1+\tan\delta)^2} \quad (2)$$

where $i_d^2 = 4kT\omega C_{piezo}\tan\delta$ is the dielectric noise current, k the Boltzmann constant, T the absolute temperature, ω the angular frequency, and $(\tan\delta = 1/(\omega R)_{piezo} C_{piezo})$, the loss tangent of the piezoelectric layer. For the detection circuitry, the flicker noise dominates at low frequency. So the total input voltage noise spectral density of the readout circuitry can be expressed as [6]

$$v_{circuit}^2 \cong \frac{1/(C_{ox}(K_n g_{m2}{}^2/(WL)_2 g_{m1}^2 + K_n/(WL)_1)2\pi)}{\omega} \quad (3)$$

where C_{ox} is the oxide capacitance per area, K_n the flicker noise coefficient, and ω the angular frequency. The active biasing transistor M_3 does not contribute to $v_{circuit}$ since there is negligible voltage drop across it. Combining (1), (2) and (3), we rewrite the SNR expression for the whole system as

$$SNR = \frac{V_o}{H(j\omega)\overline{v_{no}}} = \frac{V_i}{H(j\omega)\overline{v_{ni}}} = \frac{\alpha_{me} t_{piezo}}{\sqrt{\int_{\omega_L}^{\omega_H} [4kT/\omega C_{piezo} \tan\delta/(1+\tan\delta)^2 + 1/C_{ox}(K_n g_{m2}^2/(WL)_2 g_{m1}^2 + K_n/(WL)_1)2\pi/\omega] \mathrm{d}\omega}} \quad (4)$$

where $\omega_L = \pi$ rad Hz and $\omega_H = 100\pi$K rad Hz. This shows that for a given AC magnetic field, the SNR of a voltage mode ME system is constant over the frequency range of interest.

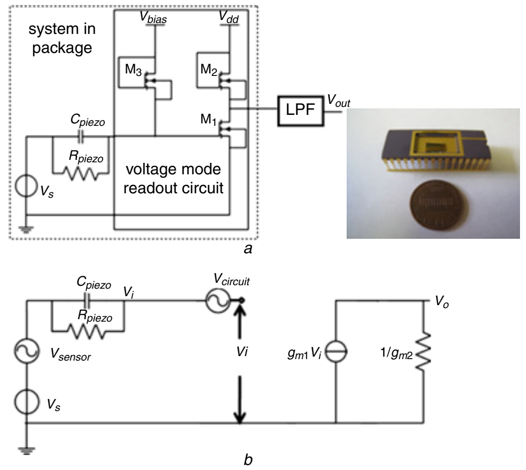

Fig. 1 *ME laminates sensor and voltage mode readout circuit*

a Schematic and photography for system in package
b Small signal circuit for voltage mode ME system with noise source at low frequency

Results and discussion: Based on the analysis above, we constructed a compact ME sensor for integration with the voltage sensing NMOS-only circuit. The ME sensor consists of a laminate made of Metglas (15 × 5 × 0.5 mm) and PVDF (10 × 3 × 0.025 mm) [1]. The single-ended common source amplifier detection circuit is fabricated by a 5 µm NMOS-only process. We designed the aspect ratio of the transistors as $(W/L)_1 = 100\ \mu m/10\ \mu m$ and $(W/L)_2 = (W/L)_2 = 10\ \mu m/10\ \mu m$, which result in high input impedance and reduce the flicker noise level to the optimum level. For integration, the ME sensor is wire-bonded to the detection circuit within a package. By extracting the parameters of the sensor and the bias/amplifier transistors, we have $C_{piezo} = 130$ pF, $\tan\delta = 0.02$, $C_{ox} = 0.115\ \mu F/cm^2$, and $K_n = 1.2E-23\ V^2 \cdot F$ [7]. Figs. 2*a* and *b* show the gain and the noise measurement results of the entire system against frequency (with a 50 kHz lowpass filter), which are in excellent agreement with the simulated results. Compared to the other detection techniques previously demonstrated [4, 8], the voltage mode ME sensor has a better frequency response in terms of a stable gain over a wide frequency range of interest. Fig. 3*a* shows the SNR and the minimum detectable magnetic field (MDF) against frequency. In Fig. 3*a*, the analytical result is consistent with the measurement results which shows that the SNR is constant (~3000) over the frequency range of 0.5 Hz to 1 kHz. This is further illustrated in Fig. 3*b*, which shows the detected waveform in real-time of the MDF at 90 Hz and 1 kHz, respectively. At both 90 Hz and 1 kHz, the MDF of the Metglas/PVDF voltage sensing system in package is 30 nT.

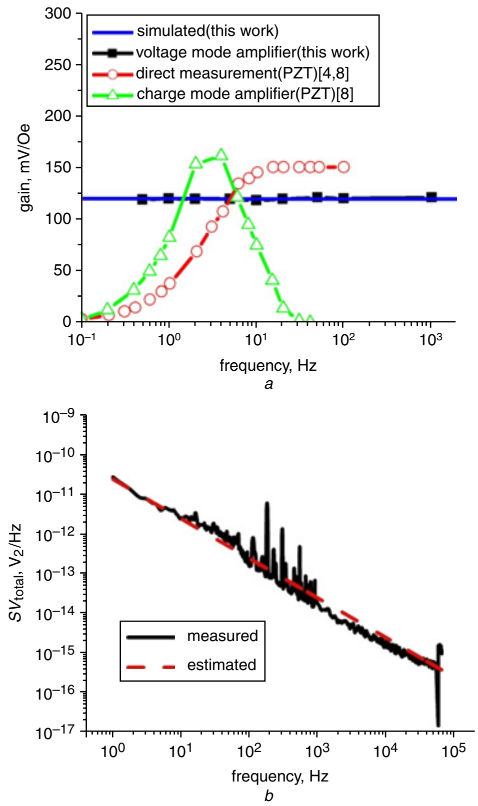

Fig. 2 *Output response of voltage mode sensing system*

a Frequency response compared with other detection techniques
b Calculated and measured total input noise power spectral density

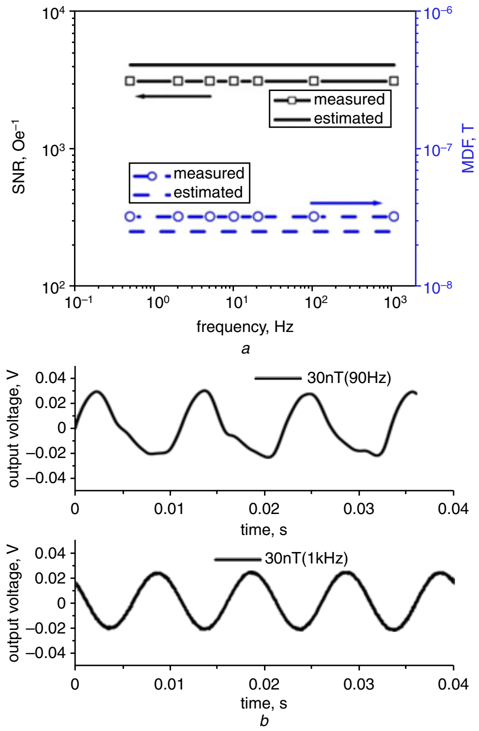

Fig. 3 *Performance of system in package*

a SNR and MDF
b Real-time waveforms of MDF at 90 Hz and 1 kHz
Instrumental and environmental 60 Hz power noise results in distortion at 90 Hz waveform since they are close to each other

Conclusion: We systematically analysed the frequency response, noise and SNR of an in-package Metglas/PVDF ME voltage mode sensor integrated directly with transistor microelectronics. Both simulation and experiment show excellent frequency response with constant gain and SNR over a wide frequency range of interest (0.5 Hz–50 kHz). This design provides a feasibility demonstration of a low-cost, room-temperature MFD system with compact sensor size targeted towards future array-based chip scale magnetometers for neural magnetic signal recording in biomedical applications.

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One or more of the Figures in this Letter are available in colour online.

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