Room-temperature Sensing of Single Electrons using Vibrating-reed Electrometer in Silicon-on-Glass Technology

J. Jalil, *Student Member, IEEE*, Y. Ruan, and Y. Zhu, *Senior Member, IEEE*

Abstract—In the commonly-used existing silicon-on-insulator (SOI) microelectromechanical systems (MEMS) process, a silicon-oxide-silicon sandwich structure in the sensor device creates parasitic capacitance, which reduces the charge sensitivity. In this letter, for the first time, we demonstrate a vibrating-reed based electrometry system with high sensitivity and resolution in the silicon-on-glass (SOG) MEMS process. In this work, we utilize a glass substrate instead of silicon to ameliorate charge sensitivity by reducing the parasitic capacitance. An improved preamplifier circuit topology incorporating with the proposed sensor shows a sensitivity of 1.43×10^{11} V/C, which is the highest in the literature. In addition, the best charge resolution of $1.03 \text{ e}/\sqrt{\text{Hz}}@5.7 \text{ kHz}$ has achieved at room temperature and atmospheric pressure. This result provides strong evidence for the validity of our SOG based MEMS device as a charge sensor for detecting even a single electron.

Index Terms—Charge sensor, MEMS electrometer, resolution, sensitivity, silicon-on-glass (SOG), vibrating-reed (VR).

I. INTRODUCTION

The sensing of charge with high resolution plays an important role widening the use of electrometers or charge sensors in many diverse applications, such as surface charge analysis, mass spectrometry, tunneling microscopy, powder technology and aerosol science, bimolecular charge detection and ionization current measurement in ionization chambers [1]. The commercial transistor based electrometer, such as, the Keithley 6517A has a minimum charge resolution of 10 fC ($\sim 63\text{k}$ electrons) [2]. However, for bespoke scientific applications where charge noise of less than 1 fC is required, Keithley 6517A's resolution is insufficient to meet the scientific needs. Recently, both resonator type and vibrating-reed (VR) type microelectromechanical systems (MEMS) electrometers exhibit significant improvement on charge sensing [1]. Nevertheless, the resonant MEMS sensors operated at room temperature suffer a poor charge resolution due to high phase noise. Thus, a vacuum environment is vital to achieve high quality factor (Q factor) for overcoming phase noise issue to improve the device performance [3]-[8]. On the other hand, compared to the existing commercial macro-scale and resonator type MEMS charge sensors, the vibrating-reed based MEMS charge sensors exhibit superior charge resolution at room temperature, and vacuum environment is not required [9]-[13].

Until today, all micromachined charge sensing devices have been fabricated on silicon-on-insulator (SOI) substrates. Nonetheless, the existing SOI-MEMS vibrating-reed based electrometers undergo difficulty in achieving high sensitivity due to inherent parasitic capacitance (C_{pa}), which is comparable to the time-modulated sense capacitance (C_v) of few pF [9]-[13]. In this process, a single crystalline silicon (SCS) device layer lies on a buried oxide layer setting on top of a silicon substrate. Therefore, in SOI-MEMS devices, a major contributor to the parasitic capacitance is the static

J. Jalil and Y. Zhu are with Queensland Micro and Nanotechnology Centre, Griffith University, Nathan, QLD 4111, Australia. (e-mail: y.zhu@griffith.edu.au).

Y. Ruan is with Department of Precision Instruments, Tsinghua University, Beijing, People's Republic of China. (e-mail: ruanyong@mail.tsinghua.edu.cn).

Fig. 1. Schematic of preamplifier and MEMS VR charge sensor.

capacitance between the sense electrodes and grounded substrate. Even though the underlying substrate of the device is removed, the parasitic capacitance still exists in the pad area because of silicon-oxide-silicon sandwich structures. To overcome the inherent issue of the static parasitic capacitance between the pad and grounded substrate in SOI-MEMS, we propose in this letter a unique silicon-on-glass (SOG) based vibrating-reed charge sensing system. Here, a silicon/glass anodic bonding technology [14]-[15] has been exploited, and the use of glass wafer as a substrate instead of silicon can make the parasitic capacitance minimal for not forming any silicon-oxide-silicon structures. Hence, the sensor's sensitivity has been enhanced significantly in comparison with SOI counterparts. Both charge sensitivity and intrinsic noise level of the readout circuit determine the minimum charge detection of an electrometry system. Hence, a low noise and low leakage opamp based preamplifier has been designed to achieve high charge resolution.

II. DESIGN AND FABRICATION

Vibrating-reed charge sensors use a charge modulation technique that increases the operating frequency (f) of MEMS sensors so that it can avoid flicker noise effect [9], [16]. In this technique, the input charge (Q_{in}) to be measured is loaded on the sense electrodes and up-modulated to an AC voltage signal, whose frequency is twice of the operating frequency and well above the noise corner frequency of the chosen readout electronics. Fig. 1 shows a schematic of the designed voltage-mode preamplifier and the SOG-MEMS sensing device along with on-chip test capacitance (C_T). Before being processed, the AC sensing signal (V_i) of SOG MEMS charge sensor is conditioned by a passive high-pass filter and a non-inverting operational amplifier. Both MOSFET and JFET based opamps can be implemented to design the preamplifier. However, in comparison with MOSFETs, JFET based opamps exhibit low input voltage noise and low input capacitance. Therefore, we use a low noise JFET input based opamp (AD8067) having 1 T Ω input resistance and 2.5 pF input capacitance to design the preamplifier circuit [17]. A gain resistor ($R_1 = 680 \text{ }\Omega$) and a feedback resistor ($R_2 = 47 \text{ }\Omega$) are chosen for a DC voltage gain of 15.47 V/V.

In the context of a preamplifier of charge sensor, the leakage current refers to a tiny DC current ($\sim \text{pA}$) presented in the opamp's input terminals. In high-precision electrometry, this tiny leakage current is much larger than the input charge to be measured. To

TABLE I

DEVICE PARAMETERS

Parameter	Value
Structure thickness (μm)	32
Suspension beam width (μm)	3.8
Suspension beam length (μm)	404
Undamped natural frequency (kHz)	2.85
Sense capacitor gap, g (μm)	5.6
Total spring constant (N/m)	33
Number of sense combs per side	144
Sense capacitance (pF)	2.49

Fig. 2. SOG-MEMS fabrication process.

block the leakage current flowing to the charge sensing node, a fixed isolation capacitor (C_1) is adopted to electrically isolate the charge node A from the input node B of the opamp. Thus, the reset switch in [13] is not required. Another advantage of using the isolation capacitor is to reduce the negative effect on the sensitivity due to the parasitic capacitance (C_{pb}) of PCB and opamp. The isolation capacitor is selected to be 2 pF, which is less than the parasitic capacitance (C_{pb}). Thus, it can push more charge to be accumulated on the sensing capacitor rather than the parasitic capacitor, thereby increasing the sensitivity. A high valued resistor, R_3 is used for continuous DC return path at the node B.

Before fabrication of the proposed MEMS device, the mask design layout has been prepared in Blueprint of Intellisuite software. Design parameters of the MEMS device are given in Table 1. Pyrex 7740 glass wafer as substrate and heavily doped silicon as device layer are used to fabricate the electrometer in the SOG-MEMS process. The fabrication process flow is shown in Fig. 2. Firstly, a 300 nm thick Ti/Pt/Au metallization layer (40/30/230 nm) is sputtered on the Pyrex glass wafer and patterned using lift-off process to form electrical interconnects (Fig. 2a). To ensure the quality of anodic bonding, before the metal sputtering, a self-alignment wet etch (such as buffered oxide etch) is used to recess the substrate by 250 nm. Therefore, most of the metal is embedded in the shallow trench on the glass substrate, and only 50 nm of the metal is above the glass substrate. A 6-inch single-crystal silicon (SCS) wafer (N-type, $<100>$, $0.002 \Omega\cdot\text{cm}$) is selected for the fabrication of sensor structure. A shallow silicon trench (approximate $4 \mu\text{m}$) is etched by inductively coupled plasma (ICP) etching using SPTS OMEGA RAPIER (Fig. 2b). Si and glass wafers are aligned for anodic bonding in EVG510 wafer bonder (1000 V, 400°C , 1 atmosphere pressure, 60 minutes), as shown in Fig. 2c. Afterward, Si wafer is thinned to

Fig. 3. Microphotograph of SOG-MEMS VR charge sensing device.

approximate $32 \mu\text{m}$ by KOH etching (Fig. 2d). Following, the sensor structure is defined in the photoresist by photolithography, and etched using high aspect ratio ICP etching (Fig. 2e). Finally, the photoresist is removed from the device using oxygen plasma etching (Fig. 2f). The final fabricated SOG-MEMS device is shown in Fig. 3.

III. RESULTS AND DISCUSSION

The fabricated MEMS device is wire-bonded in an open cavity ceramic package, and tested directly on a customized PCB comprising both driver and preamplifier circuits. As shown in Fig. 3, the push-pull comb drive actuators are placed at both ends of the moving shuttle, while the parallel plate electrodes that form the sensing capacitor (C_v) are located in the middle. To maximize the capacitance variation at a given excitation voltage, actuation is carried out at the first in-plane natural frequency (f) of the MEMS structure. Known quantities of charge (Q_{in}) are introduced on the anchored sense electrodes by adding known step voltages to a 274 fF on-chip test capacitor (C_T). Increasing levels of step voltages (V_{step}) are applied to the test capacitor using a voltage source. In steps of 0.1 V, the test capacitor calibrates the amount of charge on the electrometer input, and the measured output is monitored on a digital oscilloscope in fast Fourier transform (FFT) mode. All measurements are conducted at room temperature and ambient pressure.

Initially, a sinusoidal voltage of 5 Vpp along with a DC bias voltage of 40 V is applied at 2.85 kHz to drive the device. The detection is carried out at 5.7 kHz, which is well above the flicker noise corner frequency (2 kHz), and well below the maximum bandwidth (54 MHz) of AD8067 operational amplifier. The displacement ratio (x/g) of the resonator was found to be 1/2 under a microscope. Fig. 4 shows MEMS electrometer's response with respect to input charge. The input-to-output relationship is highly linear, and the slope of the best-fit line is $3.65 \times 10^{11} \text{ V/C}$, which is the output voltage to input charge conversion gain. The overall preamplifier system voltage gain is measured to be 5.6 V/V at 5.7 kHz, while input signal is applied at the node A in Fig. 1. Therefore, the sensor's sensitivity is $6.51 \times 10^{10} \text{ V/C}$ without considering the voltage gain of preamplifier. The displacement ratio (x/g) plays a pivotal role in obtaining high charge sensitivity and needs to be as large as possible [9]-[13]. To achieve larger displacement amplitude (x) of the shuttle, the moving combs are actuated by applying a higher DC bias voltage of 46 V and AC voltage of 7.5 Vpp at 2.85 kHz. The displacement amplitude

Fig. 4. Measured MEMS electrometer output voltage change versus input charge.

of the resonator is found to be 2/3 of the sense capacitor's gap (g). Thus, a higher sensitivity of 1.43×10^{11} V/C is achieved with 2/3 displacement ratio.

The main noise sources in the proposed preamplifier are opamp input-referred voltage noise (V_n) and current noise (I_n), and thermal noises of the resistors. Input noise voltage and noise current of AD8067 are 7.5 nV/ $\sqrt{\text{Hz}}$ and 0.6 fA/ $\sqrt{\text{Hz}}$ respectively at 5.7 kHz. An optimized value of 50 G Ω for R_3 is selected to improve noise performance and ensure the output of the opamp not being saturated. The output noise voltage spectral density of the proposed circuit is 132.3 nV/ $\sqrt{\text{Hz}}$ at 5.7 kHz. Charge resolution can be derived by dividing the output voltage noise density by the output voltage to input charge conversion gain at the frequency of interest. Thus, the resolution of the device is determined to be 0.165 aC/ $\sqrt{\text{Hz}}$, which is equivalent to 1.03 e / $\sqrt{\text{Hz}}$ at 5.7 kHz.

As shown in Table 2, the proposed electrometer demonstrates excellent sensitivity and resolution compared to all SOI-MEMS based electrometers including both vibrating-reed and resonator types as well as contemporary commercial electrometers, such as Keithley 6517A [2] and Keysight B2987A [18]. The SOI-MEMS charge sensor of [10] is one of authors' previous work, and the design layout and parameters are kept the same with the sensor in this letter. Due to the reduction of parasitic capacitance of the device, the SOG-MEMS electrometer shows 2.4 times higher sensitivity compared to the SOI counterpart with the same displacement ratio of 1/2. The vibrating capacitance of the sensor is 2.49 pF, which is higher than the equivalent series capacitance of C_1 and C_{pb} . Thus, a large amount of input charge accumulates onto the vibrating capacitor. On the contrary, the input charge in [10] and [13] was distributed largely on circuit parasitic capacitances, and thereby affects the performance of sensitivity. Moreover, our proposed design shows wider dynamic range of sensitivity in contrast to [10] and [12]. Regarding charge resolution, the proposed sensor outperforms the recently published MEMS resonator type charge sensor exhibiting resolution of 9.21 e / $\sqrt{\text{Hz}}$ [8].

IV. CONCLUSION

A new MEMS vibrating-reed electrometry system in SOG process has been designed, fabricated and characterized. The response is shown to be linear within the range of input charge tested at room temperature and atmospheric pressure. By selecting a lower voltage noise opamp, the further reduction of the noise floor of the readout circuit could be possible for improving charge resolution to sub-electrons. The high charge sensitivity of SOG-MEMS electrometer

TABLE II

COMPARISON OF MEMS AND COMMERCIAL ELECTROMETERS AT ROOM TEMPERATURE

Year [Ref]	Sensor type	Wafer	Pressure	Sensitivity	Resolution ($e/\sqrt{\text{Hz}}$)
2004 [2]	Transistor	-	Ambient	-	63k
2014 [18]	Transistor	-	Ambient	-	6.3k
2017 [6]	Resonator	SOI	33 mTorr	$4.4 \times 10^{-4} \text{ Hz/fC}^2$	203k
2015 [4]	Resonator	SOI	40 mTorr	$1.3 \times 10^{-3} \text{ Hz/fC}^2$	131k
2008 [3]	Resonator	SOI	4 mTorr	$1.2 \times 10^{-3} \text{ Hz/fC}^2$	25k
2018 [7]	Resonator	SOI	Vacuum	$7.86 \times 10^{-3} \text{ Hz/fC}^2$	16k
2016 [5]	Resonator	SOI	20 mTorr	$6.3 \times 10^{-4} \text{ Hz/fC}^2$	7.9k
2018 [8]	Resonator	SOI	Vacuum	$22.7 \times 10^{-3} / \text{fC}$	9.21
2008 [12]	VR	SOI	Ambient	$1.28 \times 10^{10} \text{ V/C}$	52.4
2013 [13]	VR	SOI	Ambient	$2.7 \times 10^9 \text{ V/C}$	23
2008 [10]	VR	SOI	Ambient	$2.74 \times 10^{10} \text{ V/C}$	6
This work*	VR	SOG	Ambient	$6.51 \times 10^{10} \text{ V/C}$	2.36
This work†	VR	SOG	Ambient	$1.43 \times 10^{11} \text{ V/C}$	1.03

* and † denote displacement ratio of the SOG-MEMS vibrating-reed sensor of 1/2 and 2/3, respectively.

shows the potential in low-cost, portable instrumentation systems. The temperature sensitivity, long-term output drift and system integration of the sensor will be investigated in our future work.

REFERENCES

- [1] J. Jalil, Y. Zhu, C. Ekanayake, and Y. Ruan, "Sensing of single electrons using micro and nano technologies: a review," *Nanotechnology*, vol. 28, no. 14, p. 142002, Mar. 2017, <https://doi.org/10.1088/1361-6528/aa57aa>.
- [2] *Low level measurements handbook*, Keithley Instruments Inc., Cleveland, Ohio, USA, 2004 [Online]. Available: <http://web.mit.edu/8.13/8.13d/manuals/LowLevMsHandbk.pdf>, Accessed on Feb. 21, 2016.
- [3] J. E. Y. Lee, B. Bahreyni, and A. A. Seshia, "An axial strain modulated double-ended tuning fork electrometer," *Sens. Actuator A-Phys.*, vol. 148, no. 2, pp. 395-400, Dec. 2008, <https://doi.org/10.1016/j.sna.2008.09.010>.
- [4] J. Zhao, H. Ding, and J. Xie, "Electrostatic charge sensor based on a micromachined resonator with dual microlevers," *Appl. Phys. Lett.*, vol. 106, no. 23, p. 233505, Jun. 2015, <https://doi.org/10.1063/1.4922458>.
- [5] H. Zhang, W. Yuan, J. Huang, B. Li, and H. Chang, "A high-sensitivity micromechanical electrometer based on mode localization of two degree-of-freedom weakly coupled resonators," *J. Microelectromech. Syst.*, vol. 25, no. 5, pp. 937-946, Oct. 2016, DOI:10.1109/JMEMS.2016.2598780.
- [6] D. Chen, J. Zhao, Y. Wang, Z. Xu, and J. Xie, "An electrostatic charge sensor based on micro resonator with sensing scheme of effective stiffness perturbation," *J. Micromech. Microeng.*, vol. 27, no. 6, p. 065002, Apr. 2017, <https://doi.org/10.1088/1361-6439/aa6b41>.
- [7] D. Chen, J. Zhao, Y. Wang, Z. Xu, and J. Xie, "Sensitivity manipulation on micro-machined resonant electrometer toward high resolution and large dynamic range," *Appl. Phys. Lett.*, vol. 112, no. 1, p. 013502, Jan. 2018, <https://doi.org/10.1063/1.5009276>.
- [8] J. Yang, H. Kang, and H. Chang, "A micro resonant electrometer with 9-electron charge resolution in room temperature," in *Proc. IEEE Micro Electro Mechanical Systems (MEMS)*, Belfast, Jan. 2018, pp. 67-70, DOI: 10.1109/JMEMS.2018.8346484.
- [9] P. S. Riehl, K. L. Scott, R. S. Muller, R. T. Howe, and J. A. Yasaitis, "Electrostatic charge and field sensors based on micromechanical resonators," *J. Microelectromech. Syst.*, vol. 12, no. 5, pp. 577-589, Oct. 2003, DOI: 10.1109/JMEMS.2003.818066.
- [10] J. Lee, Y. Zhu, and A. Seshia, "Room temperature electrometry with SUB-10 electron charge resolution," *J. Micromech. Microeng.*, vol. 18, no. 2, p. 025033, Jan. 2008, <https://doi.org/10.1088/0960-1317/18/2/025033>.
- [11] Y. Zhu, J. Lee, and A. Seshia, "System-level simulation of a micro-machined electrometer using a time-domain variable capacitor circuit model," *J. Micromech. Microeng.*, vol. 17, no. 5, pp. 1059-1065, Apr. 2007, <https://doi.org/10.1088/0960-1317/17/5/028>.
- [12] Y. Zhu, J. E. Y. Lee, and A. A. Seshia, "A resonant micromachined electrostatic sensor," *IEEE Sensors J.*, vol. 8, no. 9, pp. 1499-1505, Jul. 2008, DOI: 10.1109/JSEN.2008.923597.

- [13] G. Jaramillo, C. Buffa, M. Li, F. J. Brechtel, G. Langfelder, and D. A. Horsley, "MEMS electrometer with femtoampere resolution for aerosol particulate measurements," *IEEE Sensors J.*, vol. 13, no. 8, pp. 2993-3000, Jun. 2013, DOI: 10.1109/JSEN.2013.2266335.
- [14] J. He, X. Huang, L. Zhang, D. Zhao, F. Yang, W. Wang, and D. Zhang, "Mechanical strength of anchormicrobeam combined structure fabricated by silicon-on-glass process," *IET Micro Nano Lett.*, vol. 9, no. 10, pp. 660-663, Aug. 2014, DOI:10.1049/mnl.2014.0251.
- [15] J. Wang, Z. Yang, and G. Yan, "A silicon-on-glass Z-axis accelerometer with vertical sensing comb capacitors," in *Proc. IEEE 7th Int. Conf. Nano/Micro Engineered and Molecular Syst. (NEMS)*, Kyoto, May 2012, pp. 583-586, DOI: 10.1109/MEMSYS.2018.8346484.
- [16] H. Paleosky, R. K. Swank, and R. Grenchik, "Design of dynamic condenser electrometers," *Rev. Sci. Instrum.*, vol. 18, no. 5, pp. 298-314, May 1947, <https://doi.org/10.1063/1.1740941>.
- [17] Analog Devices, Datasheet AD8067 [Online]. Available: <http://www.analog.com/media/en/technical-documentation/data-sheets/AD8067.pdf>, Accessed on: Apr. 1, 2017.
- [18] Keysight B2980 Series Femto/Picoammeter Electrometer/High Resistance Meter, Keysight Technologies [Online]. Available: <https://literature.cdn.keysight.com/litweb/pdf/B2980-90010.pdf>, Accessed on Sep. 28, 2018.