Microelectromechanical Systems-Based Electrochemical Seismic Sensors With Insulating Spacers Integrated Electrodes for Planetary Exploration

Tao Deng, Deyong Chen, Jian Chen, Zhenyuan Sun, Guanglei Li, and Junbo Wang

***Abstract*— This paper presents a microelectromechanical system (MEMS)-based electrochemical seismic sensor for a planetary exploration. An insulating spacer and an electrode of the device are fabricated on one silicon wafer, thus decreasing the number of wafers, facilitating wafer-level alignment and enabling the fabrication of thin insulating spacers (50 μm). The proposed device achieves a sensitivity of 1978.2 V/(m/s) (f = 1 Hz) and a noise level of 100 (nm/s)/Hz$^{1/2}$ (3.2 ng/Hz$^{1/2}$, f = 0.02 Hz). Side-by-side random vibration experiment shows that the prosed devices have a correlation coefficient of 0.955±0.029 (n = 7), indicating a high repeatability. Moreover, the proposed devices located in Beijing can effectively record the seismic motion signal of the Nepal earthquake (over 3000 km away), suggesting a capability of detecting remote quake events.**

***Index Terms*— MEMS, electrochemical approach, seismic sensor, integrated insulating spacer, planetary exploration.**

I. INTRODUCTION

A SEISMIC sensor is a key component in the field of seismology [1], such as natural earthquake monitoring, nuclear explosion detection, geophysical exploration, etc. Modern seismic sensors mainly include electromagnetic moving-coil sensors and capacitive force-balance seismometers, which function as the basic devices in seismic exploration and seismic stations, respectively. In recent years, MEMS accelerometers have emerged in the seismic prospecting [2] and electrochemical seismometers have drawn attention for its low noise, high sensitivity and ability to work under large tilt angles [3].

As opposed to other seismometers with a solid inertial mass, electrochemical seismometers use a liquid solution as the inertial mass [4], the movement of which under seismic motion is converted to the variation of output electric currents by a four-electrode sensing unit. The advantage of using a liquid mass coupled with elastic membranes is that no mass centering and lock is needed, which facilitates the deployment and transportation of the device. The sensing unit of conventional electrochemical seismometers consists of four Pt meshes (working as electrodes) and three porous ceramic insulating spacers (separating the adjacent electrodes) [5]. The Pt meshes and ceramic insulating spacers are assembled piece by piece and then packaged by ceramic sintering. Apparently, it is impossible to implement alignment. Moreover, the baking and cooling process easily results in non-uniform porous insulating spacers because of cracking and shrinking [5]. Therefore, the traditional method is very labor intensive and has a low yield. Moreover, the parameters of the sensing unit are quite limited, resulting in difficulties on the performance optimization and adjustment for the sensor. For example, thinner insulating spacers result in higher device sensitivity [6], however, the thickness of the ceramic spacers is usually over 100 μm, thus hindering the improvement of device sensitivity.

In order to resolve these issues, MEMS techniques have been introduced by He *et al.* [7], [8] and Deng *et al.* [6]. In their work, devices with high repeatability have been fabricated; however, it is still low efficient and labor intensive to implement the process of chip-level bonding and alignment of seven layers of porous plates. Besides, owing to operation difficulties of thin wafers (with a thickness of less than 100 μm), it is also quite challenging to further decrease the thickness of the insulating spacers to increase the device sensitivity. Huang *et al.* [9] has proposed a sensing unit with good alignment and extremely thin insulating spacers (about 1 μm). However, the electrode areas are also extremely small, resulting in a limited sensitivity.

In this paper, we use one silicon wafer to fabricate an insulating spacer and the electrode together. Compared to previous processes [6], additional wafers are not needed for the insulating spacer fabrication and the thickness of the insulating spacer is significantly decreased. Meanwhile, wafer-level bonding and alignment are employed. Therefore, the proposed device has good alignment, high repeatability and high sensitivity.

II. DEVICE STRUCTURE AND WORKING PRINCIPLE

Fig. 1 (A) illustrates the structure of the electrochemical seismic sensor, which is consistent with previous publications [4], mainly consisting of a sensing unit immersed in

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Manuscript received August 31, 2015; revised October 14, 2015; accepted October 14, 2015. Date of publication October 15, 2015; date of current version January 12, 2016. This work was supported in part by the National Key Foundation for Exploring Scientific Instrument under Grant 2013YQ12035703, in part by the National High Technology Research and Development Program of China under Grant 2014AA093408, and in part by the National Natural Science Foundation of China under Grant 61431019. The associate editor coordinating the review of this paper and approving it for publication was Prof. E. H. Yang.

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Digital Object Identifier 10.1109/JSEN.2015.2491783

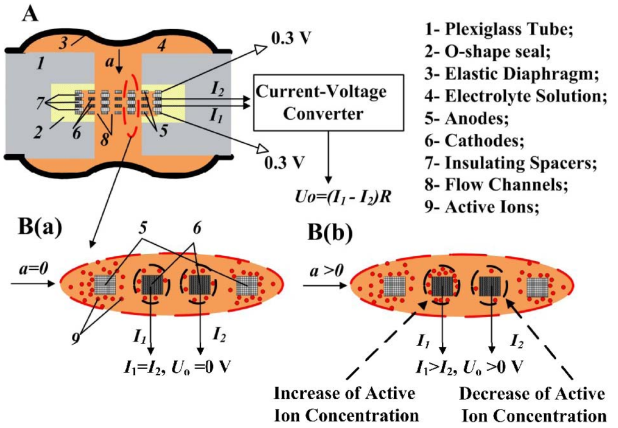

Fig. 1. (A) Schematic of the device consisting of a sensing unit, including porous insulation spacers, anodes and cathodes, sandwiched between two rubber O rings and immersed in an electrolyte solution, which is contained in a plexiglas tube both ends of which are sealed by elastic diaphragms. (B (a)) The active ions concentrations surrounding both cathodes are equal and in equilibrium when no external acceleration is applied, thus no voltage signal is output. (B (b)) In case of acceleration, the ion concentration around one cathode increases while the ion concentration around the other decreases, resulting in a voltage output.

an electrolyte solution contained in a Plexiglas tube both ends of which are sealed by an elastic diagram. The sensing unit includes four electrodes and three insulating spacers separating adjacent electrodes, the arrangement of which is anode-cathode-cathode-anode forming two identical pairs of electrodes. The voltage between the anode and cathode is 0.3 V and the electrochemical reactions occurring on the anode and cathode are $3I^- - 2e^- \rightarrow I_3^-$ and $I_3^- + 2e^- \rightarrow 3I^-$, respectively [10], resulting in an increasing concentration of I_3^- around the anode and an decreasing concentration around the anode. When no acceleration is applied, a steady ion concentration distribution is established. The active ions concentration (I_3^-) surrounding both cathodes is equal, leading to no voltage output (Fig. 1 (B (a))). In case of acceleration caused by the ground motion (Fig. 1 (B (b))), the I_3^- concentration around one cathode increases while the other decreases, thus the two cathodes output anti-phase currents, which are further converted to a voltage signal proportional to the input acceleration.

III. FABRICATION

The fabrication process includes DRIE, thermal oxidation, sputtering, adhesive bonding and wire bonding (Fig. 2). Fig. 2(A) and Fig.2 (B) illustrate the fabrication of the insulating spacers integrated anode and cathode, respectively, where on one side, a 50-μm-thick porous insulating spacer is fabricated by the DRIE process (b) and on the other side, DRIE (c) is applied to form via holes. In addition, thermal oxidation (d) is applied to produce a layer of silicon dioxide to ensure the insulation of adjacent electrodes and Pt is sputtered onto the upper surface of the wafer to function as the electrode (e). Benzocyclobutene (BCB) is dispensed onto the electrodes by a manipulator (f). Wafer-level alignment and bonding of the anodes and the cathodes is performed on a lithography machine (g & h).

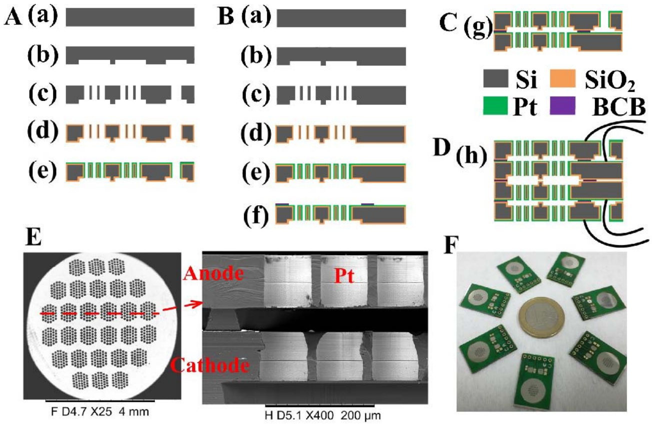

Fig. 2. Fabrication processes for anodes (A) and cathodes (B): (a) wafer cleaning; (b) deep reactive ion etching (DRIE) for insulating spacers; (c) DRIE for flow channels; (d) thermal oxidation; (e) Pt sputtering; (f) Benzocyclobutene (BCB) dispensed. (C) Wafer level alignment and adhesive bonding. (D) Wire bonding. (E) SEM image of the sensing unit: top view (left) and cross-section view (right) illustrating the alignment of a pair of anode and cathode. (F) A small batch of proposed sensing units.

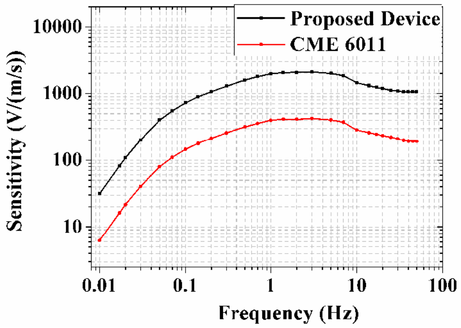

Fig. 3. Amplitude frequency response of the proposed device, indicating that the sensitivity of the proposed device is about five times higher than that of its commercial counterpart.

The scanning electron microscope (SEM) image (Fig. 2 (E)) shows that the anode and cathode are in good alignment and the sidewall of the via holes is coated with Pt thus increasing the electrode surface area. Fig. 2 (F) presents a small batch of the proposed sensing units.

The sensing unit is then placed in a plexiglas tube both ends of which are sealed with an elastic membrane. To protect the membrane from interfering by air flow, the packaged device is assembled in a metal shell, which is crucial for the liquid and membrane based electrochemical seismic sensors.

In the above processes, the proposed sensing unit integrates an insulating spacer with an electrode on one wafer, decreasing the number of wafers from 7 to 4. Moreover, the thickness of the insulating spacer can be changed from several micrometers to over 100 μm by this method, which depends on the etching depth on the backside, as shown in Fig. 2 (A). From the perspective of micromachining, the largest thickness can not exceed that of the wafer and the smallest thickness is subject to the DRIE resolution.

IV. EXPERIMENTAL RESULTS

The amplitude response of the proposed device is characterized on a vibration table. The converting resistance R

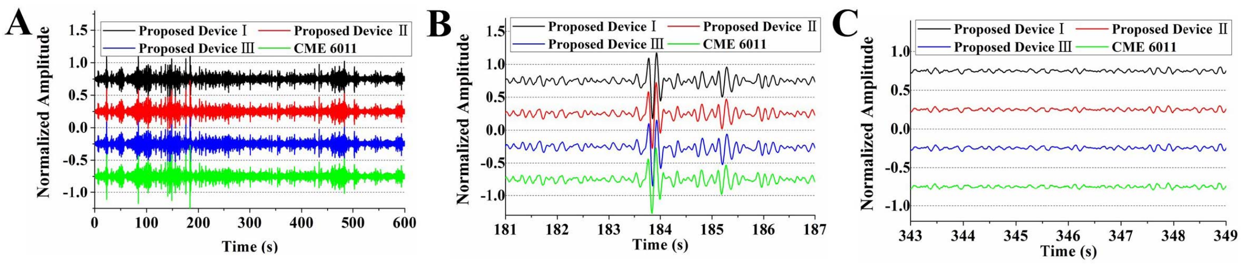

Fig. 4. Normalized responses (the highest peak-peak value defined as 1) of the proposed devices under random ground motions: A) ten minutes of seismic motion signals; B) responding to strong seismic signals (amplitude=0.15 mm/s, time=184 s); C) responding to weak seismic signals (amplitude=6.60 μm/s, time=344 s).

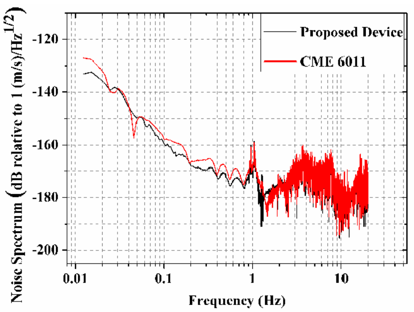

Fig. 5. Self-noise power spectrum density of the proposed device which is close to that of its commercial counterpart.

and the voltage between the anode and cathode are set to 1 kΩ and 0.3 V, respectively. The proposed device achieves a sensitivity of 1978.2 V/(m/s) about 5 times higher than that of its commercial counterpart CME 6011 (R-sensors, Russia): 398.1 V/(m/s) ($f = 1$ Hz) when using the same detecting circuits (Fig. 3). The sensitivity superiority of the former can be attributed to its 50-μm-thick insulating spacer, which is obviously thinner than that of the latter (about 150 μm). The device reported in [6] has an acceleration sensitivity of about 300 V/(m/s^2) ($f = 1$ Hz) where a 0.3 V bias voltage and a 100 kΩ conversion resistor are used. If a 1 kΩ conversion resistor is used as that in this study, the device sensitivity is only about 3 V/(m/s^2). When converted to velocity sensitivity, the device sensitivity is 18.8 V/(m/s), which is less than 1% of that of the devices proposed in this work. The reason is that the devices in [6] have extremely small electrode areas, which are far less than that of the latter.

Seven prototype devices are placed side by side on the ground in the lab and ten minutes of seismic motion signals are recorded (i.e., converted to voltage signals and saved digitally). The correlation coefficient between the ith and jth device is

$$\rho_{ij} = \frac{\sum_{k=1}^{L} U_i(k)U_j(k)}{\sqrt{\sum_{k=1}^{L} U_i^2(k) \sum_{k=1}^{L} U_j^2(k)}} \tag{1}$$

where U_i and U_j are the recorded signals of the ith and jth device, respectively, and L is the data length [11]. When the sampling frequency is 100 Hz, L equals to 60 000 (ten minutes). The correlation coefficient of seven devices is

$$\rho = \overline{\rho} \pm \sigma \tag{2}$$

where $\overline{\rho}$ and σ^2 are the mean and the variance of the seven correlation coefficients, respectively, which have expressions of

$$\overline{\rho} = 1/\left(\frac{n(n-1)}{2}\right)\sum_{i=1}^{n}\sum_{j=i+1}^{n} \rho_{ij} \tag{3}$$

$$\sigma^2 = 1/\left(\frac{n(n-1)}{2} - 1\right)\sum_{i=1}^{n}\sum_{j=i+1}^{n} \left(\rho_{ij} - \overline{\rho}\right)^2 \tag{4}$$

where n is the number of the devices (here, $n = 7$) [12]. As stated above, seismic data with a certain length are chosen for calculation which includes both weak and strong signals. The correlation coefficient reflects the overall correlation among the seven devices in a period of time. According to the recorded data, we calculate the correlation coefficient as 0.955±0.029, demonstrating a strong correlation (i.e., the proposed devices have a high repeatability). The uniformity is explicitly demonstrated by Fig. 4(A). Ten minutes of normalized seismic motion signals recorded by the proposed devices are showed, which include responses to both strong and weak seismic signals with an amplitude of 0.15 mm/s when time = 184 s (Fig. 4(B)) and 6.60 μm/s when time = 344 s (Fig. 4(C)), respectively. The amplitude of the strong signals is over 20 times of that of the weak ones. We can clearly see that all of the devices simultaneously respond to the ground motions in the same way, no matter the signals are strong or weak.

The noise test indicates that the proposed device achieves a noise level below 100 (nm/s)/Hz$^{1/2}$ (3.2 ng/Hz$^{1/2}$, $f = 0.02$ Hz) (Fig. 5), which is close to its commercial counterpart and well below the state-of-art capacitive MEMS accelerometers. The low noise level is one of the advantages of the electrochemical approach.

Fig. 6 shows a remote earthquake event (Nepal, Apr. 25, 2015) which was recorded by the proposed device and CME 6011, located in Beijing about 20 Km away from the seismometer STS-2.5 (Streckeisen, Switzerland) of the Global Seismic Network (GSN) station BJT. The seismic wave with highest amplitude arrived at 06:29:00, Apr. 25, 2015 (GMT) with a duration of 72 s (the period is 12 s). The example validates that the proposed device can effectively record the remote quake event, which is over 3000 km away. Note that the

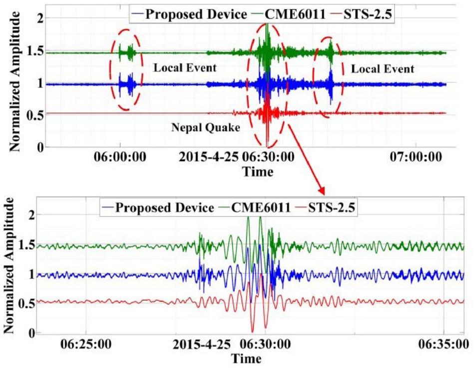

Fig. 6. Response to the Nepal quake (Nepal, Apr. 25, 2015), confirming that the proposed device is capable of remote quake events monitoring.

site where the proposed devices and CME 6011 were located was much noisier than that where STS-2.5 was placed and the former two seismometers have detected two local events caused by human activity nearby.

V. CONCLUSION

This paper presents a MEMS based electrochemical seismic sensor with insulating spacer integrated electrodes. The newly proposed design fabricates an electrode and an insulating spacer on one silicon wafer, decreasing the number of wafers from 7 to 4 and facilitating the wafer-level alignment and bonding. Moreover, the insulating spacer thickness can be significantly decreased to achieve a higher device sensitivity. The experimental results confirm that the proposed devices are characterized by a high sensitivity and repeatability, low noise and a capability of effective response to remote quake events.

ACKNOWLEDGMENT

The authors would like to thank their colleagues F. Xiong, J. G. Zhang, X. Guan, and Z. W. Wu (the State Key Laboratory of Transducer Technology, Institute of Electronics, Chinese Academy of Sciences, Beijing, China) for the assistance with the micro-fabrication process.

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