A MEMS BASED ELECTROCHEMICAL SEISMIC SENSOR

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ABSTRACT

This paper presents a micro-electro-mechanical system (MEMS) based electrochemical seismic sensor where insulating spacers and sensing electrodes were contained in a plexiglass tube filled with an ion-rich electrolyte solution. Sensing electrodes and insulation spacers were fabricated based on MEMS processes and assembled by adhesive bonding in a layer-by-layer manner.

The device performance was first characterized in a customized experimental platform, with a quantified bandwidth of 0.2 - 5 Hz and a linear voltage output as a function of the input vibration amplitude. A random-vibration testing in the laboratory environment was conducted, where response correlations among seven devices were calculated as 0.976±0.017, suggesting high device repeatability. This newly proposed seismic sensor may function as a promising seismic motion detecting device in the field of geophysical prospecting where low-frequency seismic motion detection is requested.

KEYWORDS

MEMS, seismic sensor, electrochemical approach, liquid proof mass, low-frequency

INTRODUCTION

A vibration sensor for seismic detection (namely, a seismic sensor) is a key component in the field of seismology [1], such as natural disaster monitoring [2]-[6] and geophysical inspection for mineral resources [7]-[10]. A number of seismic sensors based on various principles have been developed, which can be classified into piezoelectric accelerometers [11], piezoresistive micro sensors [12], electromagnetic seismometers [13]-[15], variable-capacitance micro sensors [7]-[9], [16], eddy current sensors [10], fiber optic sensors [4], [5], [17]-[21], pendulum seismometers [22]-[24] and electrochemical sensors [6], [25].

Among all of these developed seismic sensors, the electrochemical approach is the only sensor type where a liquid proof mass combined with elastic membranes [6] instead of solid proof masses coupled with springs or pendulums was used as the vibration sensing unit. Due to the use of the liquid proof mass, the electrochemical approach is featured with a low-frequency response and thus is suitable for the low-frequency seismic signal recording in the field of seismology [6].

A conventional electrochemical seismic senor includes a sensing unit of layers of gauze electrodes immersed in an electrolyte solution [25], [26]. In order to work properly and produce consistent performance, the electrode layers should be uniform and properly aligned within the electrolyte solution, which cannot be realized by conventional net-weaving fabrication methods. This limitation renders the large-scale fabrication and application of electrochemical seismic sensors to geophysical prospecting troublesome.

To deal with this issue, previously in my group, MEMS techniques were applied for the sensing electrode fabrication [27], [28]. Although consistent electrodes were fabricated, the yield production of the MEMS processes presented in [27] was low and the silicon wafer was easy to break during fabrication for its thickness was about 100µm. In this study, improved MEMS fabrication processes were proposed to solve the problems. Characterization in the laboratory environment of the proposed devices was conducted, confirming the consistency and the performance of the low-frequency response.

DEVICE WORKING PRINCIPLE

The electrochemical seismic sensor proposed in this study mainly consists of a four-electrode sensing unit and a detecting unit (see Figure 1), consistent with previous publications [6]. The sensing unit includes five perforated insulating spacers and four perforated sensing electrodes, which is contained in a plexiglass tube filled with an ion-rich electrolyte solution and sealed by two elastic diaphragms on both ends (see Figure 1(A)). The via holes of the electrodes and insulating spacers were designed for the electrolyte solution to flow through the sensing unit.

Figure 1(B) illustrates the device working mechanism. A higher electric potential was applied to two layers of perforated sensing electrodes, forming the anodes of the

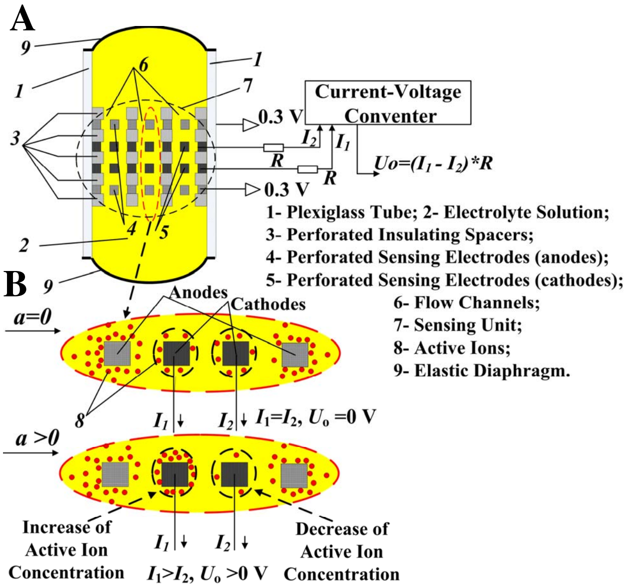

Figure 1: (A) Schematic of the device consisting of perforated insulation spacers, anodes and cathodes surrounded by an electrolyte solution. (B) Device sensing mechanism illustration: seismic motions (acceleration) lead to concentration changes of active ions around electrodes, resulting in voltage outputs.

electrochemical system while a lower electric potential was applied to the other two layers, forming the cathodes. The voltage drop between the anodes and the cathodes was 0.3 V. The electrochemical reactions occurring on the anodes and the cathodes are $3I^- - 2e^- \rightarrow I_3^-$ and $I_3^- + 2e^- \rightarrow 3I^-$, respectively. When no force is applied on the proposed seismic sensor, tri-iodide ion (I_3^-, red dots in Figure 1(B)) concentration forms a stable gradient distribution around the cathodes. Thus the current flow on two cathodes is equal (i.e. $I_1 = I_2$) and the output voltage (U_o) of the detecting circuit is zero. In case of a seismic vibration, its acceleration leads to corresponding movements of the liquid-based proof mass (electrolyte solution), which translates to changes in ion concentration gradient distributions on top of two cathodes. The ion concentration around one cathode increases while that around the other decreases, which makes one cathode current increase and the other decrease, hence producing a voltage output (U_o).

FABRICATION

The thickness of the silicon wafer for electrode fabrication was about 100 μm, and therefore it was difficult to conduct Al deposit, deep reactive ion etching and other microfabrication processes in [27] due to the handling problem. To solve this problem, a layer of SU-8 was spun on the surface of the silicon wafer to enhance its mechanical strength. The subsequent steps of the fabrication process for sensing electrodes and insulation spacers were presented in Figure 2(A) and Figure 2(B), respectively. These conventional MEMS techniques included photolithography, deep reactive ion etching, thermal oxidation and sputtering. Compared to the fabrication process in [27], wet etching and Al deposition were not necessary, simplifying the fabrication process. Five perforated insulating spacers and four perforated sensing electrodes were assembled by adhesive bonding in a layer-by-layer manner (see Figure 2(C)). Via holes were fabricated in each silicon layer based on deep reactive ion etching and used as alignment holes to enable a proper alignment among different layers, producing repeatable sensing electrodes in individual sensing units. Due to the use of MEMS technologies featured with high-resolution alignment, the consistency among different sensing layers was guaranteed. A fabricated sensing unit and a prototype device were shown in Figure 2(D).

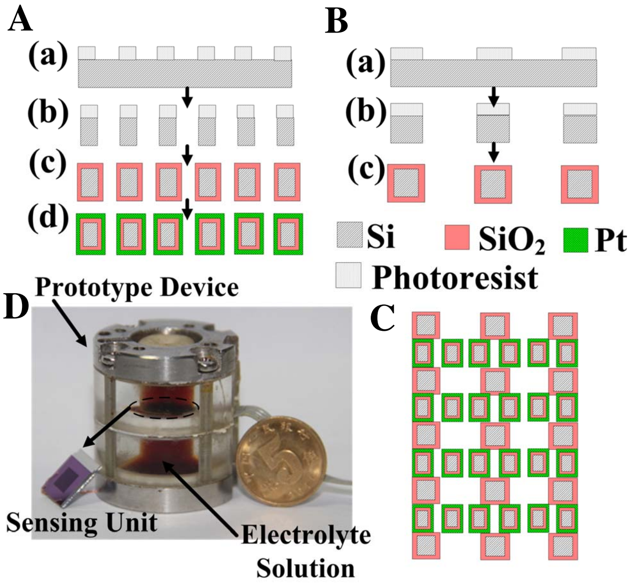

Figure 2: Fabrication processes for sensing electrodes (A), insulation spacers (B) and sensing unit assembly (C): (a) photolithography; (b) deep reactive ion etching (DRIE); (c) thermal oxidation; (d) Pt sputtering. (D) A fabricated sensing unit and a prototype device filled with the electrolyte solution.

DEVICE CHARACTERIZATION

Owing to its sensing mechanism and unique structures, the device performance characterization was conducted in a customized experimental platform instead of a vibrating table (see Figure 3). A sine wave voltage *Ui* with adjustable frequency and magnitude was applied to a coil, generating an oscillating electromagnetic field. This oscillating electromagnetic field caused the movement of a magnet, mounted on top of the seismic sensor, which further behaved as a force source on the fluid mass to mimic the seismic motion.

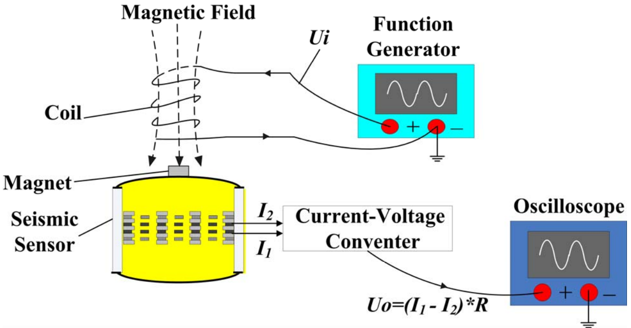

Figure 3: Device characterization platform where a sine wave voltage is applied in a coil, producing an oscillating force to cause the movement of a magnet, positioned on top of the seismic sensor. The movement of the magnet leads to vibration of the fluid mass of the seismic sensor.

Figure 4(A) shows the frequency response of the proposed devices (n=7) (amplitude of voltage *Ui*: 1V peak to peak), demonstrating that the proposed devices were capable of functioning properly from 0.2 Hz to 5 Hz, fitting in the low-frequency domain of seismic vibrations. Figure 4(B) records the dynamic range of the devices, indicating a linear relationship between input voltages representing input seismic motion amplitudes and output voltages at a specific frequency of 1 Hz.

Besides testing frequency and dynamic characteristics, effectiveness of the electrochemical seismic sensor was preliminarily validated by observing real-time responses under random vibrations. The proposed devices were placed in a quiet room of a 15-storey building and the vibration signals were recorded by data acquisition system at night. Figure 5(A) illustrates the normalized responses (the highest amplitude output was defined as 1) of 4 devices for a long period of time. The collected curves of the signals show that proposed devices responded to vibration events in a simultaneous and consistent manner. Figure 5(B) presents the detailed responses for a period of two seconds. Experimental results confirmed that devices proposed in this study demonstrated a comparable trend in response to random vibrations. The correlation of the

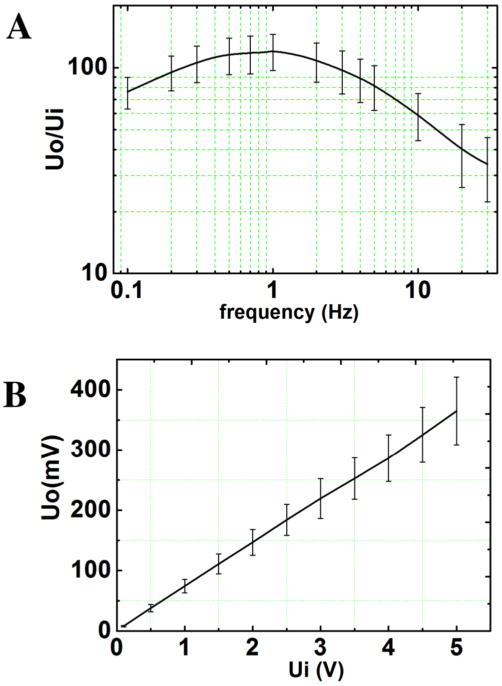

Figure 4: (A) Device frequency response, confirming the capability of low-frequency seismic motion monitoring. (B) Amplitude response, indicating a linear relationship between input voltages representing seismic acceleration values and output voltage signals (n=7).

recorded signals was calculated as 0.976±0.017 (n=7), further suggesting repeatability of the developed devices (Table 1).

Table 1: Calculated device correlation under random vibration with an averaged value of 0.976±0.017, confirming high repeatability of devices (n=7).

C	**1**	**2**	**3**	**4**	**5**	**6**	**7**
1	1.000	0.956	0.962	0.963	0.945	0.967	0.959
2	0.956	1.000	0.979	0.973	0.981	0.946	0.965
3	0.962	0.979	1.000	0.974	0.969	0.965	0.961
4	0.963	0.973	0.974	1.000	0.978	0.978	0.983
5	0.945	0.981	0.969	0.978	1.000	0.951	0.983
6	0.967	0.946	0.965	0.978	0.951	1.000	0.973
7	0.959	0.965	0.961	0.983	0.983	0.973	1.000

SUMMARY

A MEMS based electrochemical seismic sensor was studied in this paper where an optimized MEMS process was put forward for device fabrication. The frequency and dynamic characteristics were confirmed by a home-made experimental platform, demonstrating its low frequency performance and a linear relationship between input vibration and output voltage signals. The response signals under random vibration showed good consistency among seven prototype devices. The experimental results showed that the developed electrochemical seismic sensors can be used for low-frequency seismic motion monitoring.

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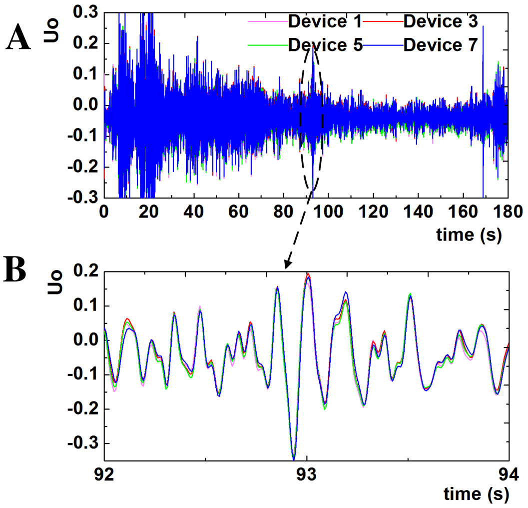

Figure 5: Normalized responses (the highest amplitude output defined as 1) of developed seismic sensors under random vibrations.

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