Molecular Electronic Transducer-Based Low-Frequency Accelerometer Fabricated With Post-CMOS Compatible Process Using Droplet as Sensing Body

Hai Huang, Mengbing Liang, Rui Tang, Jonathon Oiler, and Hongyu Yu

Abstract—This letter reports a low-frequency micro-accelerometer implementing a liquid-state sensing body, based on molecular electronic transducer (MET) in post-CMOS compatible microfabrication technology. The device employs a sub-microliter electrolyte droplet encapsulated in oil as the sensing body, and a MET electrode configuration as the sensing read-out mechanism. The promising and unique performance of the MET design allows the fabricated device to achieve 10.8 V/G (G = 9.81 m/s²) sensitivity at 20 Hz with nearly flat response over the frequency range from 1 to 50 Hz, and a low noise floor of 75 µG/√Hz at 20 Hz.

Index Terms—Accelerometer, electrolyte droplet, microelectromechanical systems (MEMS), molecular electronic transducer, post-CMOS compatible.

I. INTRODUCTION

ACCELEROMETERS with small size, low noise, and high sensitivity at low frequencies are important in a broad range of disciplines including seismology and resource detection in the oil industry. Micro solid-state inertial sensors have been developed [1]–[3] with fundamental mechanism as a mass-spring system consisting of a suspended proof mass. The resonant frequency of a micro solid-state inertial sensor is, however, often in the high-frequency regime, and their low-frequency response is relatively weak. Inspired by the exceptional ability to convert mechanical signals to electric current in electrochemical systems, pioneering studies of liquid-state motion sensors based on molecular electronic transducer (MET) provide an alternative paradigm [4]–[6]. As opposed to solid-state accelerometers, MET accelerometers use a liquid-state inertial mass. The MET transducing electrochemical cell (Fig. 1) consists of the sensing channels with four electrodes separated by dielectric spacers and a highly flexible rubber diaphragm. A concentrated iodine/iodide electrolyte is filled in the channel acting as the inertial proof mass. Compared with solid-state accelerometers, MET accelerometers have no moving solid mechanical parts subject to possible damage, enabling inherent ability to withstand high shock. In addition, they have high sensitivity and low self-noise in the low-frequency range with properly selected parameters of the transducer.

Despite the rather high output parameters obtained, the conventional MET devices have, however, a number of limitations including high cost, high scatter of parameters due to manual production of transducers requiring individual tuning of corresponding electronics for each sensor, early decrease in sensitivity in the high-frequency range due to large internal dimensions, and restricted possibilities to optimize the performance. These shortcomings motivated the development of a MET sensor employing microelectromechanical systems (MEMS) techniques which reduces the device size and improves the sensitivity and reproducibility and gives the possibility of optimization by tuning the physical parameters during fabrication [7]. The 3-D structure of the device in [7], however, provides great challenges in fabrication and packaging, which is also costly because of the involvement of focused ion beam milling. More importantly, the fabrication process is not CMOS compatible and hard to integrate into modern electronic system. Therefore in this letter, a droplet-based horizontal MEMS MET accelerometer made with a post-CMOS compatible microfabrication process with high-volume manufacturing compatibility is developed. This device combines the advantages of both MET and MEMS technology. In addition, its post-CMOS compatible fabrication processes which only contain deposition of four electrodes on a planar substrate, are much simpler compared with solid-state CMOS MEMS accelerometers [8]–[10], which include complicated
fabrication of mass-spring system. Furthermore, the novel idea of using an oil film as the sealing diaphragm eliminates the complicated 3-D packaging.

II. DEVICE FABRICATION

The schematic of the device is shown in Fig. 2, consisting of a planar four-electrode (Anode-Cathode1-Cathode2-Anode) MET cell located in a solid rectangular housing channel on a silicon substrate with low-pressure chemical vapor deposited silicon nitride. It is shown that this structure has promising performance comparable with ring electrodes in open holes when the device size is reduced to microscale [6].

Fig. 3 shows the fabrication processes. First, four electrodes made of 10/100 nm Ti/Pt are deposited by E-beam evaporation and patterned with standard planar photolithography and a lift-off process, with electrode width of $h = 100$ μm and interelectrode spacing of $d = 30$ μm [Fig. 3(b)]. Second, surface modification is performed to reduce the hysteresis of droplet deformation. Lift-off process is applied to coat the electrodes with the hydrophobic CYTOP thin film and patterned such that there is a hydrophilic spot surrounded by hydrophobic areas [Fig. 3(c)]. A rectangular glass housing is adhesively bonded to the device surface to form the channel with 1 mm in both width and height [Fig. 3(d)]. Before the final assembly of the device, a 0.8 μL concentrated iodine/iodide electrolyte droplet and a small amount of mineral oil are sequentially dispensed by micropipettes in the hydrophilic area covering platinum electrodes [Fig. 3(e)]. This oil-encapsulated electrolyte droplet replaces the complex 3-D assembly of soft membranes and electrolyte in [7] and acts as the sensing body. The oil not only prevents the droplet from evaporating, but also works as the elastic diaphragm to contain the droplet, which allows it to be stabilized in the center. Finally, the top glass ceiling is assembled [Fig. 3(f)]. The fabrication process as well as the packaging is simple and compatible with batch processing.

III. OPERATION PRINCIPLE

When an electric potential (0.5 V) is applied to the anode/cathode pairs, an electrochemically induced current based on reversible electrochemical reactions between anodes and cathodes appears regardless of the presence of mechanical motion of the droplet [6]. In the presence of an external acceleration, the droplet moves relative to the electrodes due to inertia. Besides diffusion, an additional convective transport of ions between the electrodes occurs, resulting in a significant change in the concentration gradient near the electrode surface, and hence a change in the output current. The amplitude of the differential cathode current provides the signal read out [6]. The equation that governs motion of the electrolyte droplet is

$$\frac{d^2V}{dt^2} + \frac{R_h S_h}{\rho L} \frac{dV}{dt} + \frac{k}{\rho L} V = -S_{ch} a \quad (1)$$

where $V$ is the volume of fluid passing through the channel, $a$ is the external acceleration, $R_h$ is the hydrodynamic resistance that is solely determined by the fluid viscosity and the channel geometry in laminar flow condition [7], $k$ is the coefficient of volume stiffness and depends only on the characteristics of the oil film, $\rho$ is the density of the droplet, $S_{ch}$ is the cross-sectional area of the channel, and $L$ represents the length of the droplet. The $kV/\rho L$ term describes the restoring force from the oil.

Through transforming (1) to the frequency domain and using an approximated expression of the electrochemical transfer function of MET in the frequency domain [11], the overall frequency-dependent transfer function of the device which is a superposition of the transfer functions of the mechanical and electrochemical systems can be obtained as

$$|H(\omega)| = \frac{\rho L}{\sqrt{(\frac{\rho L}{S_{ch}})^2 \left(\frac{\omega^2 - \omega_0^2}{\omega r^2}\right)^2 + R_h^2}} \cdot \sqrt{1 + \left(\frac{\omega_0}{\omega_{up}}\right)^2} \quad (2)$$

where $\omega_0 = (k/\rho L)^{1/2}$ is the mechanical resonant frequency of the device, $C (A/(m^2/s))$ is the conversion factor of the electrochemical cell, and $\omega_{up} = D/d^2$ is the diffusion frequency with interelectrode distance $d$, and diffusion coefficient $D$. It can be seen from (2) that there are two poles in the transfer function: $\omega_0$ and $\omega_{up}$, determining the low/high cutoff frequency and bandwidth. One of the advantages of scaling down in $d$ is that the resulting significant increase in $\omega_{up}$ enables $\omega_{up} \gg \omega_0$ and therefore the high cutoff frequency above which the sensitivity starts to decay significantly is increased and the bandwidth is broadened.

IV. EXPERIMENTAL RESULTS

Experimental validation is conducted using a device with $d = 30$ μm, $h = 100$ μm, and $R_h \approx 5 \times 10^7$ kg/(m^4/s). The sensor is mounted on a vibration exciter which can
generate sinusoidal vibration with controlled frequency and acceleration. The acceleration is monitored in situ using a reference accelerometer. The output voltage of the device under controlled acceleration at 20 Hz (Fig. 4) shows that within 0.6 G acceleration range, the measurement sensitivity has a constant value of 10.8 V/G. The sensor is then sequentially subjected to a series of excitations whose amplitudes are approximately constant (0.35 G) covering 1–200 Hz frequency range. The measured normalized frequency response of the device under 20 Hz sinusoidal input accelerations within 0.6 G magnitude.

Fig. 4. Experimental result of sensitivity of the device under 20 Hz sinusoidal input accelerations within 0.6 G magnitude.

Fig. 5. Experimental result of the normalized sensitivity frequency response of the device in comparison with the theoretical analysis. Resonant frequency is down shifted to ~30 and ~25 Hz when ~150% and ~200% electrolyte droplet volume are applied, respectively.

Fig. 6. Measured output signal spectrum under a 0.35 G sinusoidal excitation at 20 Hz (n = 5), showing an input-referred noise floor of 75 μG/√Hz.

of the channel, or introducing a hydrophobic surface modification to the channel wall. The main fabrication variations that affect the device performance come from the use of micropipette to dispense the electrolyte droplet and oil. The resulting variations of the droplet mass and the spring constant \(k\) will affect the resonant frequency and cause the shift of sensitivity curve. As shown in Fig. 5, the resonant frequency is shifted to ~30 and ~25 Hz when ~150% and ~200% electrolyte droplet volume are applied, respectively. Therefore, it is critical to precisely control the volume of the droplet and oil for optimized repeatability of the sensors.

V. Conclusion

In conclusion, an electrolyte droplet-based MET accelerometer which uses a liquid-state proof mass with good sensitivity and noise floor in the low-frequency range of 1–50 Hz is developed. In addition to the advantages of combining MET and MEMS technologies, the fabrication is post-CMOS compatible and much simpler compared with solid-state mass-spring-based CMOS MEMS accelerometers. In addition, the idea of using oil as a sealing membrane reduces the complexity of packaging. The dynamic behavior of the device is researched by analytically investigating the transfer function in the frequency domain. The analytical model of the dynamic behavior is experimentally validated by comparing the normalized measurement frequency response of the device under systematically varied external excitations with the theoretical one. This letter provides the feasibility of the development of liquid-state accelerometers with desired frequency response and simple post-CMOS compatible fabrication processes.

References


