Fabrication and Experimental Characterization of a MEMS Microphone Using Electrostatic Levitation

Mehmet Ozdogan, Shahrzad Towfighian and Ronald N. Miles

***Abstract*—Fabrication and acoustic performance of a microelectromechanical systems (MEMS) microphone are presented. The microphone utilizes an unusual electrostatic sensing scheme that causes the sensing electrode to move away, or levitate from the biasing electrode as the bias voltage is applied. This approach differs from existing electrostatic sensors and completely avoids the usual collapse, or pull-in instability. In this study, our goal is to fabricate a MEMS microphone whose sensitivity could be improved simply by increasing the bias voltage, without suffering from pull-in instability. The microphone is tested in our anechoic chamber and a read-out circuit is used to obtain electrical signals in response to sound pressure at various bias voltages. Experimental results show that the sensitivity increases approximately linearly with bias voltage for bias voltages from 40 volts to 100 volts. The ability to design electrostatic sensors without concerns about pull-in failure can enable a wide-range of promising sensor designs.**

***Index Terms*—MEMS microphone, fabrication, sensitivity**

I. Introduction

Advancing data analysis and signal processing technology boosted the use of sensors for Internet of Things (IoT) based portable electronics [1], [2]. Today, billions of sensors are embedded into daily use gadgets to improve the consumer experience. These smart devices can communicate and actively learn by interacting with the objects. One very common interaction process is listening to the environment which is performed by capturing and processing the sound signals collected using a single or an array of microphones. A microphone is an acoustic sensor that simply converts mechanical motions generated by sound pressure waves into electrical signals. Every year, billions of microphones have been produced and integrated into consumer products such as smartphones, laptops, hearing aids, smart wireless speakers, virtual reality headsets (VRs), game consoles etc. There are two major microphone types used in these devices: traditional Electret Condenser Microphones (ECM) and MEMS microphones. Compared to ECMs, MEMS microphones provide smaller footprint size (reduces the cost per chip), high signal to noise ratio (SNR), low power consumption and easy integration [3], [4]. These small state-of-the art sensors presents a cost effective solution to high demand on acoustic sensing for wide range of applications.

The transduction process for MEMS microphones is performed using several schemes such as capacitive [5]–[11], piezoelectric [12]–[15] and optical [16], [17]. The vast majority of the acoustic sensor market has been occupied by capacitive and piezoelectric MEMS microphones. Most of the capacitive microphones utilize electrostatic attractive force generated by one grounded moving and one biased fixed electrode separated by an air gap. As the sound waves interact with the surface of the moving electrode a detectable motion is created in the form of a vibration which is then converted to electrical signals via application specific read-out circuit (ASIC). Capacitive microphones have been broadly investigated over the decades. Some of the motivations triggered these studies are their tendency to high sensitivity, low noise, compatibility with mass manufacturing and integration [3], [4], [18]. On the market MEMS microphones are classified based on their sensitivity, signal to noise ratio (SNR), total harmonic distortion (THD), directionality, acoustic overload point (AOP) etc [3], [12], [18], [19].

In 1984, the first silicon based capacitive acoustic transducer was presented by Hohm et al. [5] with the sensitivity of $3\mathrm{mV/Pa}$ at 1 kHz. The diaphragm was made of a $8mm$ x $8mm$ x 13μm suspended Mylar. This sensitivity was obtained at 350 Volt and the air gap was 30μm. In 1991, Scheeper et al. [20] reported a silicon condenser microphone using a sacrificial layer technique. The diaphragm was made of 1μm thick silicon nitride with an air gap of 1 μm. Sensitivity was presented as 1.4 $\mathrm{mV/Pa}$ at 2 V bias. In 1998, Schafer et al. [21] presented a condenser microphone for hearing aids. Reported sensitivity at 12 V bias voltage was around 14 $\mathrm{mV/Pa}$. In 2006, Loeppert et al. presented the first commercial silicon MEMS microphone which was later sold billions of units [22].

The performance of conventional capacitive microphones is limited by pull-in instability, which causes the diaphragm and back plate to collapse together at a certain bias voltage because the electrostatic attractive force is much more than elastic restoring forces. The threshold voltage at which the pull-in occurs is inversely proportional to the gap between the electrodes [23]. The initial fabrication gap is therefore very important to define the pull-in point. The capacitive microphones are mostly designed around the theoretical gaps (less than 1/3rd of the initial gap) to avoid any collapse. This drawback limits the applicable bias voltage which directly affects the sensitivity. The sensitivity is the most important feature of a capacitive microphone which is proportional to bias voltage, surface area of the moving electrode and inversely proportional to the stiffness and the gap between the fixed and the moving electrode [23].

Applying a bias voltage between the electrodes enables the sensing of a capacitance change through a circuit. However, it also has a considerable impact on the effective stiffness of

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the system which makes it difficult to keep the sensitivity constant at different bias voltages. Depending on the electrode configuration, the effective stiffness may be increased (i.e repulsive, [23]) or reduced (i.e attractive, [24], [25]) with change of bias voltage. For an ideal sensor it is highly desired that its performance not be adversely affected by the electrostatic force. Recently, Miles [25] presented a compliant acoustic sensor that utilizes an electrode configuration employing a very thin moving electrode and two vertical electrodes. It was shown that this design has no influence on the motion of the sensor even for very high voltages such as 400 Volts. It also showed no pull-in failure for such high voltages. Pull-in instability could also be eliminated by using multiple techniques such as interdigitated comb-finger designs [11]. Martin et al. [18] presented a comprehensive literature review on this subject.

To enhance the sensitivity, we propose a levitation mechanism that prevents pull-in failure and enables increasing the bias voltage to boost the electrical sensitivity. In an earlier effort we reported a detailed study on the physical principle of the levitation force concept and proposed a simple mathematical model to estimate the behavior of the microphone for various scenarios [23]. In the same study we also described the effect of backvolume on the mechanical and electrical sensitivity of the device. The present paper reports the fabrication of an actual silicon-chip and acoustical performance tests. In the following section we describe the fabrication of the sensor chip. Then, we present the experimental setup to test the performance of the device. Last, we discuss the experimental results and give a conclusion.

II. Device Design and Fabrication Process

In this section, we present the structural design of the device as well as the fabrication steps. The design approach used in realizing the levitation microphone was motivated by the early studies of the repulsive force concept [26]–[28]. The microphone is composed of moving fingers attached to a thin diaphragm that is also supported via short cantilevers, see Figure 1. The diaphragm has etch holes around the edges to facilitate the release process. The chip has a backvolume of air which will ideally reduce the sound pressure on the back of the diaphragm [29]. Underneath the moving fingers, there are grounded and biased fixed fingers which will provide the levitation force due to the higher concentration of the electrostatic field on the top of the moving finger compared to its lower surface [26]. This force on the moving fingers will cause the diaphragm to lift-up and rotate around its rotation axis. This static motion will increase the initial gap around the diaphragm's perimeter and provide more room for the diaphragm to oscillate freely when exposed to sound pressure. The complete list of dimensions are given in Table I.

Figure 1 shows the microscope image of the microphone which we fabricated at the Cornell Nanoscale Facility (CNF) using four-mask stepper and contact lithography steps. Process flow of the fabrication is presented in Figure 2. We started with four inch (n+) silicon wafers and grew 1 μm thick thermal oxide as an insulation layer using a low-pressure chemical vapor deposition (LPCVD) furnace, **(a)**. Then, we deposited 0.2 μm thick low-stress LPCVD silicon nitride on top of the oxide layer, **(b)**. The oxide and nitride foundation layers electrically isolate the device from the bulk silicon substrate. On top of the nitride layer, 2 μm thick phosphorus-doped amorphous silicon (N+ a-Si) was deposited via the LPCVD furnace, **(c)**. Then, this amorphous layer was annealed for five hours to form polycrystalline silicon (polysilicon). Following the annealing process, wafers were exposed and etched via a Bosch etching process to create the polysilicon fixed fingers, **(d)**. On top of the fixed fingers, we deposited 4 μm thick high-temperature oxide (HTO) film as a sacrificial layer. This layer provides the initial gap between the fixed and moving fingers (diaphragm). After the deposition process, we planarized approximately 2 μm of the oxide layer using a Chemical Mechanical Polisher (CMP), **(e)**. This process removes the step difference between the diaphragm and the fixed fingers. After the CMP process we exposed and etched the oxide layer using Inductively Coupled Plasma Reactive Ion Etching (ICP-RIE) to create vias between first and second polysilicon, **(f)**. Upon etching the vias, we deposited another layer of 2 μm thick phosphorus-doped polysilicon following the same procedure in the first polysilicon deposition process, **(g)**. This layer was exposed and etched to form the moving fingers and the diaphragm, **(h)**. Then, the front side of the wafer was covered with 2.5 μm thick phoshosilicate-glass (PSG) using plasma enhanced chemical vapor deposition (PECVD), **(i)**. This film mechanically supported the diaphragm layer during the backside etching. After the PSG deposition, the backside of the wafers were exposed and etched using ICP insulator and DRIE silicon etching tools, **(j)**. Lastly, the wafers were diced and released in HF:HCl solution, **(k)**. Following the release, the chips were critical point dried (CPD) to avoid any stiction. Figure 1 shows some images of the fabricated device. The fabricated MEMS chip was bonded to a printed circuit board (PCB) using UV-cure epoxy and wire-bonded using an aluminum wire wedge-bonder.

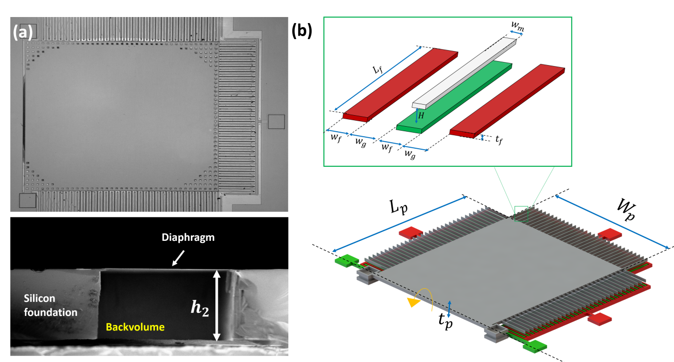

Fig. 1. (a) Microscope image for the top view of the microphone. SEM image for the cross-sectional view of the diaphragm. (b) 3D CAD model showing the diaphragm adn finger details.

Description	Parameter	Value
Diaphragm width	W_p	960 μm
Diaphragm length	L_p	1063 μm
Diaphragm thickness	t_p	2 μm
Finger length	L_f	200 μm
Finger thickness	t_f	2 μm
Moving finger width	w_m	$3 - 3.5$ μm
Fixed finger width	w_f	$7.3 - 7.5$ μm
Fixed finger seperation	w_g	$8 - 8.5$ μm
Air gap	H	2 μm
Spring thickness	t_s	2 μm
Spring width	w_s	40 μm
Backvolume depth	h_2	530 μm

TABLE I
DIMENSIONS FOR THE FABRICATED DEVICE.

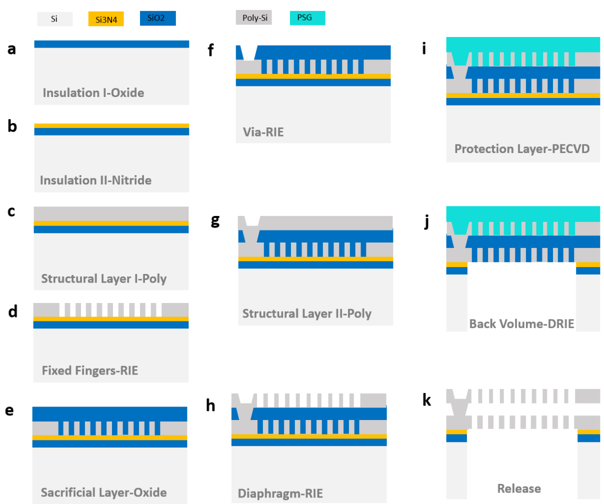

Fig. 2. Fabrication process flow of the microphone.

III. EXPERIMENTAL SETUP

The acoustic tests for the microphone were performed in the anechoic chamber at Binghamton University. Figure 3 shows the schematic of the experimental setup. We applied various DC voltages to the voltage fixed electrodes. This DC voltage introduced an-out-of plane motion to the diaphragm and increased the initial gap between the diaphragm and the fixed electrodes. The sound pressure was created by a loud-speaker by sweeping a broad range of pure tone signals (100 Hz-20 Khz). The incident pressure measured using a Bruel & Kjaer 4138 reference microphone. The electronic output from the chip was detected using a charge amplifier read-out circuit. The circuit consisted of an operational amplifier (OPA 657), capacitors (1 pF) and feedback-resistors (10 GΩ). The sensitivity plot was obtained by measuring the output voltage relative to the sound pressure. All these input/output signals were obtained using a National Instruments PXI-1033 Data Acquisition System.

IV. RESULTS AND CONCLUSION

Electrical response obtained by a charge amplifier-based read-out circuit is depicted in Figure 4. The figure shows the measured electrical voltage relative to sound pressure (Volt/Pa) for a wide range of bias voltages. These results demonstrate the feasibility of using a capacitive sensing approach that levitates the diaphragm, rather than pulling it toward the biasing electrode. It is shown that utilizing the levitation concept enables improving the sensitivity of a MEMS microphone simply by increasing the DC bias voltage without any pull-in failure. This approach can enable designs that employ large bias voltages without adversely impacting the diaphragm's mechanical response.

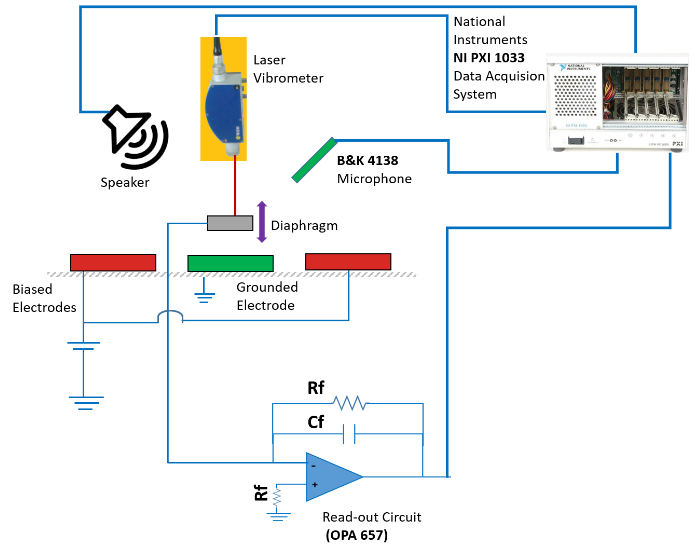

Fig. 3. Experimental setup for device testing in the anechoic chamber at Binghamton University. A charge amplifier based read-out circuit is used to obtain the electrical response of the microphone.

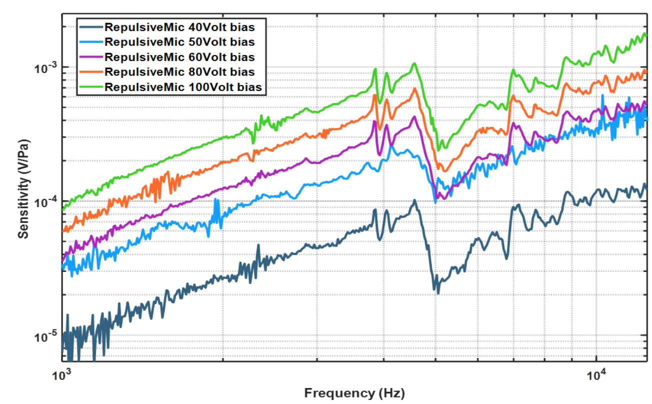

Fig. 4. Measured experimental results showing the sensitivity of the device at various bias voltage.

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