IN-SITU TUNING OF MICRODEVICES FOR DIRECTIONAL MICROPHONE APPLICATIONS

Sang-Soo Je, Jere C. Harrison, Michael N. Kozicki, and Junseok Chae
Department of Electrical Engineering, Arizona State University, Tempe, AZ

ABSTRACT

This paper presents a new method to manipulate microdevices' membranes using nano-electrodeposits for directional microphones in hearing aid applications. The key to achieving high directionality is to minimize the mismatch of the omni-directional microphones using *in-situ* tuning by the integrated electrodeposition of metallic nanostructures. The nanostructures can be grown/retracted upon external bias at room temperature. The growth/retraction changes mass/stress distribution on the diaphragm of microdevices to precisely manipulate sensitivities to incoming acoustic waves. The omni-directional microphones are capacitive and have a parylene membrane integrated with the nanostructures. The microphone capacitance can be tuned up to 0.7 dB and acoustic mismatch reduces by 1.2 dB. This represents directivity index (DI) increase of 1.2 dB, which is crucial to achieve high directionality in composite microphones. The technology has many applications, including post-packaging trimming and calibration of micro-devices.

INTRODUCTION

Directionality is one of the most demanded features in modern hearing aids [1-3]. It is essential if directional microphones are to pick up sounds efficiently in the presence of ambient noise. To achieve a high directionality, each omni-directional microphone should pick up sound from all directions almost equally to the other. Technically, multiple omni-directional microphones must be matched precisely, within 0.25 dB [4], otherwise directionality is lost. Figure 1 shows directionality over two omni-directional microphones' gain mismatch in hearing aids. As indicated, a DI greater than 4.5 is required for excellent directionality in directional hearing aid applications, which corresponds to less than 0.25 dB gain mismatch between two omni-directional microphones at audio frequencies.

Figure 1: DI vs. gain mismatch between two omni-directional microphones for hearing aid applications. Less gain mismatch indicates better directionality.

Many techniques exist to allow to improve the directionality of microphones, including electronic calibration and compensation [5]. The electronic methods are complex, have large system size, high cost, and large power consumption. Few techniques that tune mechanical elements have been demonstrated [6], partially because it is hard to manipulate micro-size mechanical components *in-situ* with extremely low power and high precision at room temperature.

We have demonstrated precise manipulation of micro-size

membranes using electrodeposited nanostructures. The operating principle is similar to electrodeposition in liquid electrolyte, except this technique uses solid-state electrolyte. AgGeSe solid electrolyte allows Ag^+ ions to transfer from an anode toward a cathode upon the application of voltage. Ag^+ ions reaching the cathode are reduced to form electrodeposits which grow toward the anode. The nano-electrodeposit causes the surface to become rough and heterogeneous, and consequently, changes the mass and stress distribution [7]. The proposed MEMS capacitive microphone associated with a thin GeSe film on a parylene membrane is illustrated in Figure 2. There are 3 major parts; top/bottom electrodes, a multiple layered membrane including Ag-rich GeSe and parylene layer, and cathode/anode electrodes. The suspended membrane is made of parylene. On the parylene membrane a solid-electrolyte Ag-doped GeSe film and two electrodes to grow and retract Ag nano-electrodeposits. The GeSe film is saturated with Ag ions by UV (Ultra Violet) photo-dissolution to be a conductive film. The Ag nano-electrodeposits start to grow from the Ni tip (cathode electrode) toward to the Ag tip (anode). The air gap between top and bottom electrode is defined as small as 1 μm .

Figure 2: The proposed 3D view of the capacitive microphone integrated with nano-electrodeposits.

FABRICATION AND MEASUREMENT SETUP

Fabrication

The fabrication process of the capacitive microphone integrated with the nano-electrodeposit mechanism is illustrated in Figure 3. It is a seven-mask process including evaporated AgGeSe solid-state electrolyte on a parylene membrane suspended on a silicon substrate. The back side of the substrate is etched by Deep Reactive Ion Etch (DRIE) and SiO_2 is used as a sacrificial layer to release the parylene membrane. (a) 3000Å thick parylene is coated on top of a 3000Å thick top electrode (Cr/Au) on a 1 μm thick sacrificial oxide layer. (b) 2400Å thick GeSe solid-state electrolyte and 800Å thick Ag layer are deposited on the membrane. (c) Photo-dissolution is performed for 15 min under the UV exposure to dissolve the Ag into the GeSe layer. (d) The anode (Ag) and cathode (Ni) are evaporated and patterned to form electrodes to grow and retract the electro-deposits from the end of cathode tip. (e) To contact the silicon substrate the bottom electrode (Cr/Au) is evaporated and patterned. (f) Finally, the membrane is defined by

etching the back side of the silicon wafer using DRIE at an etch rate of $3 \mu\text{m}/\text{min}$. The membrane is released by removing the sacrificial oxide layer at the end of the process using HF for 15 min.

Figure 3: Fabrication process flow.

The fabricated single microphone covered by AgGeSe solid electrolyte is shown in Figure 4 (a). Ag is electrochemically deposited from the Ni cathode tip toward the Ag anode tip by applying an external bias from 3 to 5 V (Figure 4 (b)). The dual microphones for the directionality test are shown in Figure 4 (d). Figure 5 (a) shows the fully grown silver electrodeposits at the cathode (Ni) tip on the membrane. Figure 5 (b) shows that the height of the grown silver nano-electrodeposits is up to 90 nm while the film roughness is less than 10 nm. The growth is dendritic but generally moves toward the anode. Due to the grown and retracted silver nano-electrodeposits on the suspended parylene membrane, the membrane deflects and consequently changes the spring constant. However, after full retraction, traces and residues of silver electrodeposits remain on the membrane and prevent it from returning to its original state [8].

Figure 4: The fabricated single microphone integrated with nano-electrodeposits (a) Top view, (b) Grown Ag nano-electrodeposits, (c) backside view, and (d) the fabricated dual microphone integrated with nano-electrodeposits.

Figure 5: SEM photographs of grown silver dendrite from a Ni tip on parylene membrane (top) and an optical profilometer (Veeco NT9800) photograph of the height of the silver dendrite and film roughness (bottom).

Electrical/Acoustic Measurement Setup

The microphone is glued on a PCB where the capacitance to voltage converter for readout is implemented (Figure 6). The fabricated dual microphone and electrical/acoustic test setup (top) and a manipulator with $1 \mu\text{m}$ resolution in the Faraday cage (bottom) are shown in Figure 7. The readout circuits and microphone are placed inside of the Faraday cage to avoid electromagnetic noise. An additional shield for the readout circuit is provided to protect from electrical coupling. Operation of the circuit is described below.

With no acoustic excitation, electric current through a $10 \text{ M}\Omega$ resistor balances ohmic leakage through the microphone to bias the top microphone electrode with a constant charge at 135 mV. When the microphone is excited acoustically, a change in capacitance causes a voltage change in the charge fixed to the microphone membrane. The induced voltage change on the microphone passes through an isolation capacitor as displacement current, and is amplified by an AD8607 amplifier with 37x closed circuit gain. The circuit output is analyzed using an Agilent 35670a Dynamic Signal Analyzer. The microphone is excited acoustically by a Knowles FK-6260 micro-speaker, which is aligned precisely 5 mm above the microphone using $1 \mu\text{m}$ resolution translation stages.

The acoustic readout circuit response shows a passband starting at 2 kHz and ending at 58 kHz, with a peak capacitance to voltage conversion of 250 mV/pF for a microphone with a steady state capacitance of 20 pF . The response shows both high and low frequency loss, including loss in the audible frequencies we intend to measure. Circuit response at low frequencies is reduced due to charge retaining limitations of the bias resistor. When the RC time constant is the same order of magnitude as the signal period, voltage discharge across the bias resistor dominates the circuit loss. Assuming the microphone capacitance is 20 pF (the theoretically expected value), the RC time constant is 200 ms. As a result, signals below 5 kHz see significant attenuation. The low frequency cutoff can be improved with a larger resistor; however, doing so reduces the overall amplification of the circuit. The bias resistance of $10 \text{ M}\Omega$ is chosen to balance the circuit bandwidth and peak output. Circuit response at high frequencies is reduced due to bandwidth limitations in the amplifier, and at sufficiently high frequencies, signal leakage as displacement current through the microphone.

Figure 6: The schematic of the capacitive readout circuits (left) and PCB implementation with the fabricated single microphone (right)

Figure 7: Electrical and acoustical test setup (top) and a Knowles microspeaker and the fabricated dual microphone on a manipulator with 1 μ m resolution in the Faraday cage. The implemented PCB is shield to protect undesired electrical coupling (bottom).

DEVICE CHARACTERIZATION AND RESULTS

We first characterize the microphone using the readout circuits. The microspeaker (FK-6260 from Knowles electronics) generates acoustic input and the output of the readout circuits is measured (Figure 8). The fabricated microphone was vertically separated 5 mm away from the microspeaker using the 1 μ m resolution XYZ linear translation stages. The customized readout circuits show from -38 dB (given 75 dB SPL input, which corresponds to 0.1 V microspeaker input) to -25 dB (given 88 dB SPL input, which corresponds to 0.4 V microspeaker input).

The dual microphone mismatch is characterized electrically by an LCR meter, Agilent 4284A (Figure 9). The gain mismatch of the microphone is monitored *in-situ* while the nano-electrodeposits are grown. Initial gain mismatch of the dual microphone at 0.2 V DC bias is the blue line. Now we grow the nano-electrodeposits on the selected microphone. The mismatch between microphones decreases by more than 7.3% when the electrodeposits are grown for 20 sec and at 3 V DC external bias. Upon the growth of nano-electrodeposits the microphone mismatch is improved by at least 0.7 dB at all over the audible frequency ranges (the red line).

Finally, we measure *in-situ* tuned microphone acoustic readout circuit response over audible frequencies between 1 kHz to 10 kHz and monitor the mismatch reduction upon the growth of the nano-electrodeposits. Figure 10 (a) shows that the tuned microphone produces smaller capacitance changes due to reduced membrane displacement. It is believed that the modification of membrane stiffness is changed by grown and retracted nanostructures. The microphone mismatch shown in Figure 10 (b) is improved from 0.6 dB to 0.16 dB after the tuning, which corresponds to fair directionality improving to excellent directionality at 3 kHz.

Figure 11 shows acoustic responses over electrodeposit growth time. The mismatch after *in-situ* tuning reduces from 2.76 dB to 1.56 dB, which represents DI increases from 3.5 dB (fair directionality) to 4.7 dB (excellent directionality). The gain mismatch of microphones is precisely controlled by *in-situ* silver nano-electrodeposits growth/retraction under a normal operating environment such as room temperature and no specific setup. Specifically, if the initial mismatch of non-tuned microphones is small, then it can be manipulated to reduce the mismatch to within 0.25 dB.

Figure 8: Capacitance output of a microphone from readout circuits over input sound pressure from the Knowles microspeaker (dB SPL).

Figure 9: Mismatch reduction upon the growth of the nano-electrodeposits in electrical *in-situ* measurement using the LCR meter.

Figure 10: (a) Nanostructures tuned microphone acoustic readout circuit response over an audio frequency range and (b) reduced mismatch using nanostructures tuned microphone acoustic response over a selected frequency range.

Figure 11: Acoustic responses upon nano-electrodeposits growth; showing the improvements of gain mismatch and DI.

CONCLUSION

We demonstrate a directional microphone using multiple matched omni-directional microphones. It is performed by an *in-situ* tuning technique using integrated nanostructures on the membrane of a microphone. The tuning is to minimize the mismatch of multiple microphones to achieve better directionality. The omni-directional microphones are capacitive and have a parylene membrane integrated with the nanostructures. The silver nanostructures with approximately 100 nm heights are controlled by

external bias at room temperature. The nanostructures can be grown and retracted to precisely manipulate the sensitivity to incoming acoustic waves by the change of mass/stress distribution on the parylene diaphragm of the microphone. The readout circuits to interface MEMS microphones have bandwidth of 56 kHz and SNR of approximately 40 dB at 1 kHz. To reduce noise sources, such as 60 Hz coupling from the power grid we place the acoustic measurement setup in a custom built Faraday cage. The microphone capacitance is tuned up to 0.7 dB at all over the frequency ranges and acoustic mismatch reduces by 1.2 dB. This represents DI increase of 1.2 dB, which is crucial to achieve a highly directional microphone. The presented technique has many potential applications, including post-packaging trimming and calibration of micro-devices.

ACKNOWLEDGMENT

The authors would like to acknowledge Mr. Yongmo Yang, the staff of the Center for Solid State Electronics Research (CSSER) at Arizona State University, Prof. Tom Milster's group at the University of Arizona, and Knowles electronics for their continuing support. We also appreciate the US National Science Foundation (US NSF) supporting this work under Grant #0627777 and #0652136.

REFERENCES

1. M. C. Killion, R.S., L. Christensen, D. Fabry, L. Revit, P. Niquette, and K. Chung, "Real world performance of an ITE directional microphone," *Hear. J.* vol. 51, No. 4, pp. 24–38 (1998).
2. D. B. Hawkins and W. S. Yacullo, "Signal-to-noise ratio advantage of binaural hearing aids and directional microphones under different levels of reverberation," *J. Speech Hear Disord.*, vol. 49, pp. 278–286 (1984).
3. S. Kochkin, Customer satisfaction with single and multiple microphone digital hearing aids, Better hearing (www.betterhearing.org).
4. J. Tchorz, Effects of microphone mismatch in directional hearing instruments, *Hearing review* (2001).
5. J. J. Yao and N. C. MacDonald, "A micromachined, single-crystal silicon tunable resonator," *J. Microelectromech. Syst.*, vol. 6, pp. 257–264 (1996).
6. W. Zhang, R. Baskaran, and K. L. Tumer, "Changing the behavior of parametric resonance in MEMS Oscillators by tuning the effective cubic stiffness," *MEMS 2003 conference*, pp. 173–176 (2003).
7. M. N. Kozicki and M. Mitkova, "Mass transport in chalcogenide electrolyte films - materials and applications," *Journal of Non-Crystalline Solids*, vol. 352, pp. 567–577 (2006).
8. S. Je and J. Chae, "Precise manipulation of micro-device membranes using electrodeposited nano-structures," *NEMS 2008* (2008).