In situ tuning of omnidirectional microelectromechanical-systems microphones to improve performance fit in hearing aids

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Hearing aids are not a one-size-fits-all solution to hearing problems; they must be uniquely tuned for each wearer. There are currently no low-cost and/or effective methods for in situ tuning. This paper describes a microelectromechanical-systems (MEMS)-based dual omnidirectional microphone that can be tuned by growing metallic nanostructures. The nanostructures are grown on integrated solid electrolyte layers on a suspended parylene diaphragm using an external bias and tune the MEMS microphones in situ thereby limiting mismatch. In our tests, this tuning improved the directivity index from 3.5 (fair directionality) to 4.6 dB (excellent directionality) in normal (room temperature) operating environments. © 2008 American Institute of Physics. [DOI: 10.1063/1.2989132]

Understanding speech in noisy environments can be difficult, but the problem is compounded for those with hearing impairment. Modern hearing aids are a solution but a major challenge faced by hearing aid manufacturers has been to design devices that can accommodate different wearer needs and environments as a patient’s level or type of hearing impairment and/or physical condition can impact sound delivery within the ear so that a “universal fit” is impossible. In addition, to fully support a wearer’s needs, tuning to alter signal-to-noise ratio and directionality is required.

This paper describes a microelectromechanical-system (MEMS)-based dual omnidirectional microphone that could be used to solve hearing aid adaptation problems for both wearers and manufacturers. Laboratory tests indicate the microphone can be precisely tuned by growing metallic nanostructures on solid electrolyte layers integrated with a suspended parylene diaphragm in the microphone.

The key to improving hearing aids is to achieve directionality under real world conditions, and the key to achieving high directionality is to control and limit mismatch in composite microphones.

Existing techniques to improve microphone directionality have limits. Omnidirectional microphones can be configured as directional microphones when they are matched, but a mismatch of as little as 0.25 dB completely destroys directionality. Electronic calibration and compensation also achieve directionality, but the methods are very complex, lead to high costs, and require large systems and large power consumption. Few mechanical techniques have been demonstrated, partly because it is extremely difficult to manipulate microsized mechanical components as found in hearing aids in situ with extremely low power and high precision at room temperature.

This paper describes a method that enables us to manipulate MEMS microphone directionality in situ by growing metallic nanostructures in a controlled way at room temperature. The process overcomes the limitations of existing tuning/matching techniques and shows promise for customizing function and fit in modern hearing aids.

The schematic of a MEMS capacitive omnidirectional microphone is illustrated in Fig. 1(a). There are three major components: top/bottom electrodes, a multiple-layer diaphragm (stacked parylene/Au/parylene/SiO2/AgGeSe film from bottom to top), and cathode/anode electrodes. The air gap between top and bottom electrode can be as small as 1 μm. On the parylene diaphragm, a solid-electrolyte (Ag-doped GeSe2) film and two electrodes are used to grow silver nanostructures, which cause the diaphragm to be deformed. Thin layers of 3 μm parylene and 0.4 μm SiO2 isolate the microphone and the nanostructure growth electrodes. The GeSe2 film is saturated with silver ions by ultraviolet photodissolution to become an ion-conducting film. The silver nanostructures grow from the cathode tip (Ni) toward the anode tip (Ag) by the reduction of the Ag+ ions in the Ag-GeSe solid electrolyte.

The operating principle of the nanostructure system is similar to electrodeposition in liquid electrolyte, except this technique uses a solid-state electrolyte. AgGeSe solid elec-

FIG. 1. (Color online) (a) Schematic of a capacitive microphone integrated with an AgGeSe thin film to grow nanostructures on it and (b) 3D view of grown silver nanostructures on a parylene diaphragm, pictured by a Veeco NT9800 optical profilometer.

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trolyte allows Ag⁺ ions to transfer from the anode toward the cathode when a voltage as small as a few hundred mV is applied. Ag⁺ ions reaching the cathode are reduced to form electrodeposits that grow on the electrolyte surface toward the anode. These nanostructures cause the diaphragm surface to become rough and heterogeneous, changing its tuning via mass and stress redistribution. After testing the dual microphone’s mismatch, one omnidirectional microphone, which has a higher sensitivity, is tuned by manipulating these nanostructures to produce a sensitivity match from an incoming acoustic signal.

Figure 1(b) shows an image of grown nanostructures from a Veeco NT9800 optical profilometer. The image is of partially-grown silver electrodeposits at the cathode (Ni) tip on the Ag-rich GeSe₂ film (on a suspended parylene diaphragm). The measured height of the silver nanostructures is 30–40 nm.

Fabricating an integrated capacitive dual microphone with nanostructure tuning is a seven-mask process that includes evaporating AgGeSe solid-state electrolyte onto a parylene diaphragm suspended on a silicon substrate. The fabricated prototype is covered by AgGeSe solid electrolyte in Fig. 2(a). Figure 2(b) shows that silver can be electrochemically grown on the parylene diaphragm and grows from the cathode tip toward the anode tip by applying an external bias from 3 V. Figure 2(c) shows the back side of the substrate, which is etched by deep reactive ion etch with 1-μm-thick SiO₂ as a sacrificial layer to release the parylene diaphragm.

A condenser microphone modeled as a voltage-controlled capacitor is shown in the interface circuit in Fig. 3(a). The operating principle is as follows. A small current passes across the high impedance bias resistor (\(R_p\)) to deposit a quantity of charge on the microphone. Acoustic excitation changes the voltage of these electrodes; the resulting voltage change translates to a displacement current to the positive amplifier terminal. Resistor values chosen here provide approximately 100× amplification and only ac passes through the output isolation capacitor (\(C_1\)).

The frequency response of the circuit is limited by several aspects of its design. At low frequencies, the impedance of the resistive discharge path is not sufficient to prevent charge from leaking back into the power supply. The lowest frequency in the circuit’s passband is then subject to the \(RC\) time constant of the microphone/bias-resistor network. Given the parameters of the circuit, the \(RC\) time constant is 200 μs, corresponding to 5 kHz. At high frequencies, the impedance of the microphone becomes irrelevant. For a 20 pF microphone, the impedance to ground through the microphone is 10 MΩ at 5 kHz, the same as the discharge path back to the power supply. While the bias resistor can be increased to achieve a more favorable passband, the amplifier’s positive terminal stabilizing resistor (\(R_1\)) must be increased to prevent the same effects from taking place across that path. The stability of the circuit was compromised when \(R_1\) was increased beyond 100 MΩ. Circuit simulations verify these limiting constraints with a passband starting at 0.1 kHz and ending at 200 kHz and a peak capacitance to voltage conversion of 300 mV/pF for a microphone with 20 pF base capacitance.

In the physical testing phase, the microphone is glued on a PCB and capacitance is used via voltage converter to provide the readout. The readout circuits and microphone are placed inside a Faraday cage to avoid electromagnetic noise. The microphone is excited acoustically by a Knowles FK-6260 microspeaker aligned precisely 4 mm above the diaphragm using linear transition stages. The microspeaker is driven by a signal generator providing up to 0.5 V. The circuit output is measured using an Agilent 35670a Dynamic Signal Analyzer. An additional shield for the readout circuit is provided to protect from electrical coupling.

Without an acoustic input, this setup produced noise peaks as high as 3 mVrms at multiples of 60 Hz and sharp
peaks as high as 142 $\mu$Vrms between 31 and 250 kHz. Switching power supplies used by the measurement equipment were likely responsible for noise over 31 kHz. Radiating energy from the power grid and leakage through the dc power supply were assumed to be responsible for the 60 Hz noise. When the acoustic measurement setup was inside the Faraday cage, however, no spurs were visible above the noise floor beyond 31 kHz. Agilent dc power supplies were replaced with Li-ion batteries to remove the 60 Hz noise originating from the power supplies. Acoustic frequency harmonics were observed at the output when the readout circuit was directly exposed to the Knowles microspeaker. Figure 3(b) shows the microphone sensitivity over an audio frequency range measured in an electromagnetic interference (EMI)-shielded test fixture. The sensitivity is swept over a frequency of 1 to 10 kHz at the input acoustic excitation of 88 dB SPL.

The mass and stress redistribution created by the deposited nanostructures causes diaphragm displacement which provides the tunability; growing nanostructures on a suspended 1.6-mm-diameter polyimide and parylene diaphragm provides the tunability; growing nanostructures on a suspended 1.6-mm-diameter polyimide and parylene diaphragm affects, 14% and 29% of its spring constant, respectively. Figure 4(a) shows the acoustic responses over nanostructures growth time. The mismatch after in situ tuning reduces from 2.7 to 1.6 dB, showing a directivity index (DI) increase from 3.5 (fair directivity) to 4.6 dB (excellent directivity) at 3 kHz. Figure 4(b) shows the relationship between sensitivity mismatch and DI, and a red solid line corresponds to 3 kHz. It represents the reduction in mismatch and the increase in DI from 1 to 2 after the growth of silver nanostructures. The microphone mismatch is precisely controlled by in situ silver nanostructure growth in a normal operating environment (room temperature/laboratory environment). Results indicate that if the initial mismatch of nontuned microphones is small, manipulating nanostructures can reduce mismatch to within 0.25 dB, thereby providing true directionality.

This study demonstrates in situ tuning performed by growing electrodeposited metallic nanostructures on solid electrolyte layers integrated with the suspended parylene diaphragm of a MEMS microphone. The laboratory results of this study suggest that “nanoionic” technology can produce precision tuning/directionality. These results show the method’s potential for use in hearing aids, where customized directionality improves the fit to patients’ needs.

The method presented shows how tuning with integrated nanostructures offers a step toward decreasing the inconsistencies that patients encounter in everyday situations, eliminating conventional limitations and lowering costs associated with directional tuning. Results suggest the method may lead to a cost-effective resolution for test time and equipment and improve custom fitting for patients’ needs. These issues should be further pursued through additional research and development.

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References

3. S. Kochkin, see http://www.betterhearing.org