Low-voltage-driven electrostatic microspeakers with potassium-ion-electrets

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Abstract. Electrostatic microactuators require external DC biasing in order to achieve the widest possible range of displacements for a given AC input. This report proposes a novel microspeaker structure that utilizes a potassium-ion-electret to reduce the need for such DC voltage application. Electrets exhibiting quasi-permanent charges enable large fixed voltages to be integrated directly within the MEMS structure, acting as an ersatz DC bias. Prototype devices were fabricated and characterized to approximate the effects of electret incorporation on the device performance.

1. Introduction
Low-powered sensors and actuators are essential for portable electronics devices which are receiving a growing demand to realize the world of Internet-of-Things (IoT). Since battery sizes are generally proportional to their capacities, they are inappropriate for use with sensors and actuators with high power requirements as large batteries would interfere the portability of the overall module. Despite the development of more energy-efficient devices in various applications, electrostatic microspeakers still require high voltages to generate large membrane displacements. In this respect, electret materials exhibiting a quasi-permanent charge can eliminate or reduce the necessity for an externally applied DC voltage. As is shown in figure 1, with the same range of AC driving voltage, microactuators featuring electrets can generate large displacements that would otherwise require an additional DC bias. The use of electrets for microactuators also provides secondary improvements such as noise reduction and increased sensitivity as a result of the lowered driving voltage.

In this report, we introduce the use of electrets to reduce the power consumption of electrostatic microspeakers. Amongst various electret fabrication methods, the potassium-ion-electret method [1] is highly process-compatible with MEMS devices and is capable of charging the narrow features of a device with a post-fabrication process.

2. Device fabrication
Fabrication of the device consists of two steps drawn in figure 2: conventional MEMS microfabrication and potassium-ion-electret synthesis. As is shown in figure 3, the base device is made from an SOI wafer with a 20-μm-thick device layer, a 1-μm-thick BOX layer, and a 500-μm-thick handle. A circular diaphragm supported by a surrounding mesh structure is etched in the device layer, while the silicon substrate below the diaphragm is also removed using aluminum-masked DRIE. Three designs were
Figure 1. Increased electrostatic actuator displacement as a result of electret-based biasing.

Figure 2. Process flow chart of device fabrication.

Figure 3. Schematic of electrostatically-driven diaphragm chip as a microspeaker. (a) Front side. (b) Back side.

Figure 4. SEM pictures of device. (a) Individual chip. (b) Chips on fabricated wafer.

Figure 5. Interior oxide layer formed by KOH oxidation. Device layer was peeled off to reveal the pink colored oxide.

3. Results

Figure 4 shows SEM pictures of a fabricated device. After chip oxidation, an oxide layer of ~270 nm in thickness was verified at the exterior silicon surface, measured by light interferometry (FILMETRICS F20). The thickness of the final oxide between the device and handle layers was additionally verified to be 270 nm by direct stylus profilometry (KLA-Tencor Alpha-Step D-120) by peeling off the upper silicon layer as shown in figure 5.

Prepared with diaphragm diameters of 1 mm, 1.5 mm and 2 mm. The device layer diaphragm is then released through vapor HF etching of the underlying BOX layer. After finishing silicon microfabrication, the devices are oxidized for an hour at 1000 °C while exposed to N2 bubbled through a 40% KOH solution. The external oxide is then removed using CHF3 plasma etching. Finally, the oxidized device is placed on top of a silicon heater in a vacuum chamber and voltage is applied between the device layer and the substrate to polarize the oxide and to form the electret. Details of this potassium-ion-electret method are given in previous reports. [1]
To characterize the expected performance of the device with electret, tests were performed using DC bias to simulate its effect. A sinusoidal driving AC voltage of ±10 \( V_{AC} \) was applied between the diaphragm and handle layers while sweeping through a range of DC offset voltages representing the expected electret potential. Using a laser doppler vibrometer (NEO ARK MLD-103) setup, the frequency-displacement dependency of the devices without electret treatment were measured. Chips with three different diaphragm sizes were each measured in atmospheric pressure and the results are shown in figure 6. As can be seen in figure 6(a), as long as the voltage is below the pull-in voltage, higher DC bias voltage yields larger displacements and lower resonance frequencies due to the negative spring constant effect. In the final device, the addition of the polarized electret will have an effect of the DC bias voltage without applying it externally.

4. Conclusion
We have successfully fabricated electrostatic acoustic transducer chips and have measured their frequency-displacement characteristics under an applied AC voltage with DC offset to emulate the effect of electret materials. Considering the substantial formation of potassium ion containing oxide on the interior silicon surface, the effects of the final polarization of the device can be expected to rival or exceed the DC biases shown here.

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References
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