

Abstract

Electrostatic Microelectromechanical System Speaker Array with Out-of-Plane Piston Displacement and Simplified Microfabrication [†]

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Abstract: This study presents a new design for a MEMS electrostatic speaker array with out-of-plane piston-like diaphragm displacement using a simplified silicon-on-insulator microfabrication process. The device comprises an array of parallel actuating membranes with small circular mechanically open but acoustically sealed apertures that enable controlled etching of the buried oxide to be released directly from the front side, but retain a high acoustic impedance acting as a flat membrane. This approach simplifies the microfabrication process, requiring only two lithography masks and increasing process tolerances. Preliminary experimental measurements validate the concept and demonstrate the electromechanical and acoustic performance compared with theoretical models.

Keywords: microspeaker; MEMS; acoustic impedance



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1. Introduction

The miniaturization of acoustic transducers, aided by microelectromechanical systems (MEMS) technology, paves the way for micro speakers to be employed in several different applications, such as in portable devices: e.g., smartphones, wearables, and hearables; where compact integration benefits from the volume reduction. The acoustic performance of MEMS speakers, measured by the sound pressure level (SPL), proportional to volume displacement; effective membrane area and deflection; and the total harmonic distortion (THD) metrics, is impacted by the reduced diaphragm size and displacement and the non-linearities of the actuation mechanisms [1]. The fundamental drum mode of vibration, common for fully clamped diaphragms, provides a lower membrane deflection and higher acoustic distortions than the piston-like movement of a spring-suspended diaphragm [2]. Viscous losses in minimized gap sizes between the decoupled structures eliminate the acoustic short circuit, and the diaphragm behaves as a continuous membrane [3]. In this work, we evaluate a MEMS electrostatic speaker concept with out-of-plane diaphragm displacement by employing a simplified silicon-on-insulator (SOI) CMOS-compatible microfabrication process, exploiting the high acoustic impedance of micro apertures to create a mechanically open but acoustically sealed diaphragm, to integrate a flat speaker array for in-vehicle audio.

2. Materials and Methods

The speaker design, shown in Figure 1a, consists of an array of circular membranes machined on the device layer of a SOI wafer. Each membrane ($\varnothing 350\ \mu\text{m}$) is supported by four peripheral suspension springs (separated by $5\ \mu\text{m}$ wide trench gaps) dimensioned for high resonance frequency to provide a flat displacement frequency response in the audible region, and to promote a piston-like fundamental mode of actuation (Figure 1b). A hexagonal arrangement of circular ($\varnothing 5\ \mu\text{m}$) openings are defined on the membrane. In

the acoustic range, these small openings are much smaller than the viscous penetration depth ($\delta = \sqrt{2\eta/\rho_0\omega}$ [4], with η the viscosity, and ρ_0 the medium density), providing high acoustic impedance and resulting in a mechanically open but acoustically sealed feature, so that the perforated membrane becomes equivalent to a flat solid piston-like diaphragm, with minimal acoustic losses. Exploiting this effect greatly simplifies the MEMS microfabrication process, requiring only two lithography steps and increasing process tolerances (the release etch time is defined by the largest separation between the openings). The back cavity below the membrane acts as an additional mass, and damping that smoothens the frequency response of the membrane.

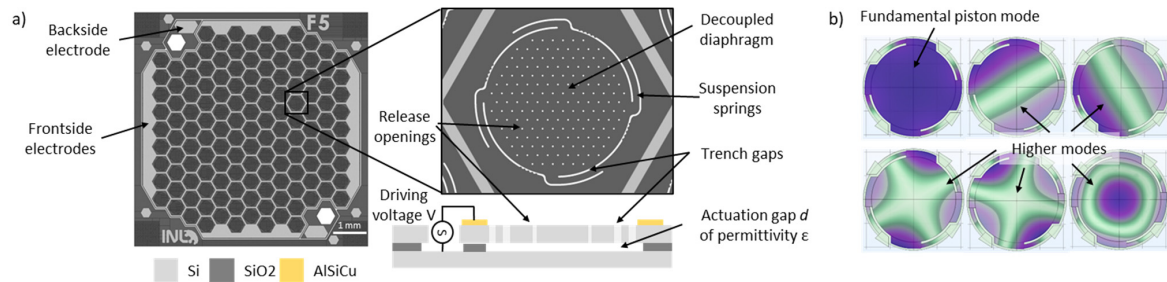


Figure 1. (a) Schematic of the microspeaker array and single diaphragm element. (b) COMSOL simulation of vibration modes for a single membrane showing a piston-like fundamental mode.

The MEMS microspeaker device (Figure 2a) was fabricated on a $\phi 200$ mm SOI wafer with a 10 μm device layer and $d = 2$ μm buried oxide (BOX) on a 500 μm handle layer. First, an AlSiCu alloy was sputtered and patterned (using direct write lithography (DWL) exposure followed by wet etch) to define the electrode pads and conductive path around each membrane. Then, a SiO₂ layer was chemical vapor deposited and patterned (using DWL and reactive ion etching (RIE)) to define the hard mask for the deep RIE of the device layer that followed. Finally, the membranes were released with HF vapor etching.

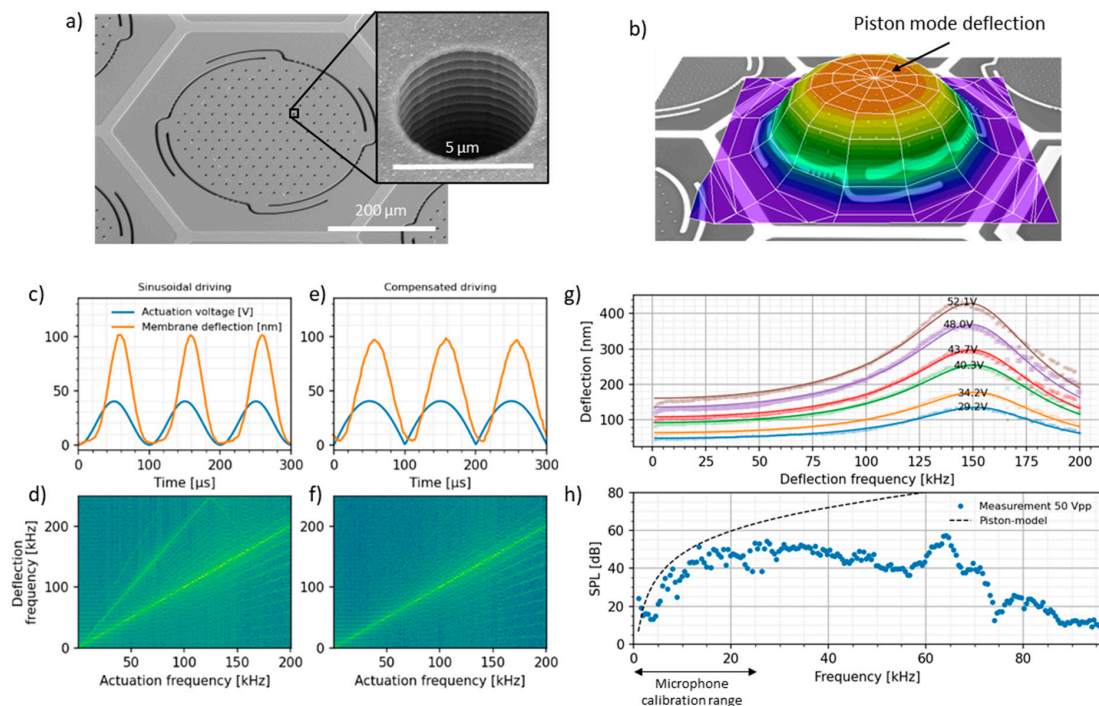


Figure 2. (a) SEM image of one microspeaker membrane and etch openings. (b) Piston-like RMS deflection measurement. Membrane deflection for a sinusoidal actuation (c,d) and compensated (e,f) voltage signal. Frequency response of the (g) membrane deflection and (h) SPL of the microspeaker.

3. Experimental Results and Discussion

The electrostatic force between the suspended membrane and the fixed bottom-electrode given by $F_e = \frac{1}{2} \frac{\epsilon A}{(d-x)^2} V^2$, where x is the membrane displacement. A linearization procedure compensates the non-linear behavior observed when actuating with a sinusoidal signal (Figure 2c–e), eliminating the harmonic distortion. Membrane deflection is measured with a Polytec MSA-500 (Waldbronn, Germany) interferometer showing the piston-like deformation (Figure 2b) and its frequency response (Figure 2g). A preliminary evaluation of the free field SPL output of the array microspeaker (Figure 2h) captured with a MiniDSP UMIK-2 (Hong Kong) microphone at 10 cm in an anechoic chamber shows a similar curve to the SPL for a vibrating piston model, within the calibrated frequency range of the microphone.

These results validate the simplified microfabrication of an electrostatic MEMS speaker device taking advantage of the thermoviscous effect in small apertures to create a mechanically open but acoustically sealed opening to facilitate HF release of the MEMS structure. The electromechanical performance of the device was characterized, and the preliminary acoustic measurements indicate some agreement with a simplified acoustic piston model in the audible region.

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