Piezoelectric Cantilever Microphone and Microspeaker

Seung S. Lee[+], R.P. Ried[*], and Richard M. White[*]

Berkeley Sensor & Actuator Center
An NSF/Industry/University Cooperative Research Center
[+]Department of Mechanical Engineering
[*]Department of Electrical Engineering and Computer Sciences
University of California, Berkeley, CA 94720

Abstract

A micromachined piezoelectric cantilever transducer, which works both as a microphone and as a microspeaker, has been fabricated and tested. The 2000x2000x3 μm^3 cantilever has a zinc oxide (ZnO) piezoelectric thin film on a supporting layer of low-pressure chemical-vapor-deposited (LPCVD) low-stress silicon nitride. A highlight of the fabrication process which may also be relevant for other micromachined structures is the technique for producing a flat, multilayer cantilever. The measured microphone sensitivity is fairly constant at 2 mV/μbar in the low frequency range and rises to 20 mV/μbar at the lowest resonant frequency of 890 Hz. The 2 mV/μbar sensitivity is the highest reported to date for a microphone with a micromachined diaphragm. When measured into a 2 cm^3 coupler with 4 V(zero-peak) drive, the microspeaker output sound pressure level (SPL) is 75 dB at 890 Hz. It increases to approximately 100 dB SPL at 4.8 kHz with 6 V(zero-peak) drive. The measured microphone frequency response agrees well with the results of an ABAQUS simulation.

Introduction

There is growing interest in the micromachining of acoustic transducers, chiefly microphones [1,2,3]. Among the advantages of micromachining over conventional fabrication are improved dimensional control, extreme miniaturization, the ability to integrate with on-chip circuitry, and potential low-cost as a result of batch processing.

Microphones are basically pressure sensors that detect airborne sound pressures that are ten orders of magnitude lower than ambient pressure. Hence, a microphone needs an extremely compliant diaphragm to have an acceptable sensitivity [4].

In this article, we present a piezoelectric transducer built on a micromachined *cantilever*. Earlier micromachined microphones had diaphragms that were clamped on all four edges. In comparison, the cantilever diaphragms are much more compliant. The cantilever is free from the tension found in clamped-clamped diaphragms, which decreases the transducer response [5]. Use of the cantilever produces a microphone with a sensitivity greater than all previously reported microphones with micromachined diaphragms [6,7]. In addition, when the device is driven electrically as an output transducer (microspeaker), the relatively large deflections of the free end produce significant acoustic output.

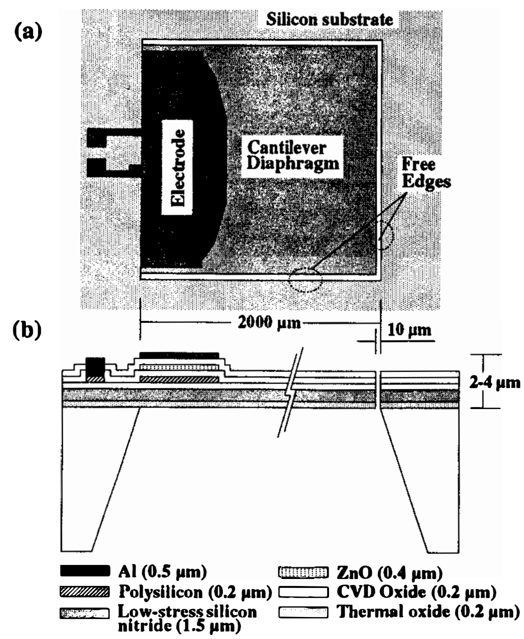

Figure 1. (a) Top view and (b) cross section of the piezoelectric cantilever microphone and microspeaker.

The Device and Its Fabrication

Figure 1 shows a top view and a cross-section of the cantilever transducer. Figure 2 shows the process flow which has three main parts: diaphragm formation (steps 1-4), frontside processing (steps 5-11), and releasing the free edges of the cantilever (steps 12-14). The chief processing challenge is to fabricate a *flat* thin multilayer cantilever diaphragm. For this we need a cantilever having a

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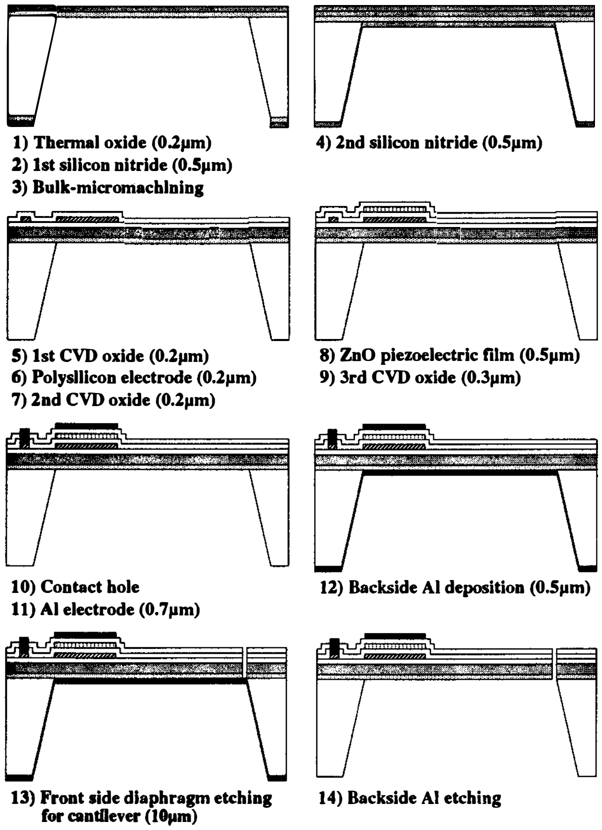

Figure 2. Microfabrication process flow.

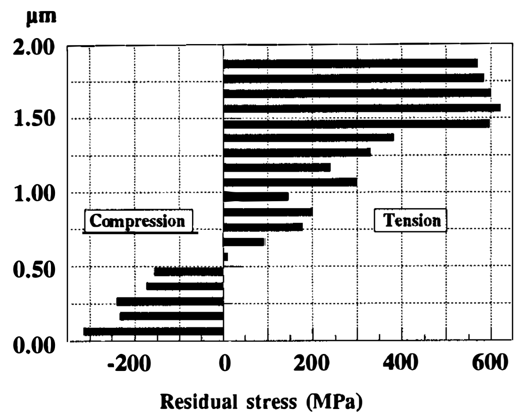

Figure 3. Residual stress vs. distance from the bottom of low-stress silicon nitride layer (835 °C and 4:1 volume ratio of reactant gas).

controlled distribution of residual stress. This is achieved through a two-step silicon nitride deposition for reasons that are explained in the next section.

The fabrication starts with 4-inch silicon wafers covered with a 0.2-μm-thick thermal oxide. The first 0.5-μm-thick LPCVD low-stress silicon nitride layer is deposited at 835 °C and 300 mTorr from a vapor having a 6:1 volume ratio of dichlorosilane (SiH_2Cl_2) to ammonia (NH_3). An orientation-dependent etchant (KOH or EDP) is used to release the silicon nitride diaphragm by etching the silicon wafer from the backside. A second 0.5-μm-thick silicon nitride layer is deposited on both sides of the diaphragm (reactant gas ratio 4:1).

The 0.2-μm-thick LPCVD polysilicon electrodes are then formed on the diaphragm over a 0.2-μm-thick low-temperature oxide (LTO) layer. A 0.5-μm-thick layer of ZnO is then RF-magnetron sputtered onto a second, 0.2-μm-thick LTO layer. The wafers are annealed for 25 minutes at 950 °C after the polysilicon and LTO depositions. After a 0.3-μm-thick LTO layer is laid down to encapsulate the ZnO and contact windows have been opened, aluminum (Al) is sputter-deposited and patterned to form the top electrode [8].

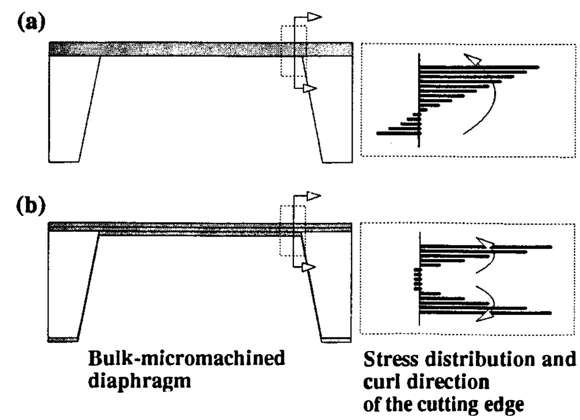

Figure 4. Stress distribution and curl direction of the cut edges (indicated by the arrows) of (a) the conventional silicon nitride diaphragm, and (b) the modified silicon nitride diaphragm.

A 0.5-μm-thick Al film is sputter-deposited on the backside of the diaphragm in order to support the diaphragm during the frontside cutting process that produces the cantilever. The thickness of the backside Al is restricted to a value that depends on the stresses of the multilayer diaphragm, since Al has its own residual tensile stress. Thicker Al layers (roughly 1.5 μm or more) are found to break the diaphragm because of their high tensile stress, and thinner Al layers are found not to support the diaphragm during the frontside cutting process.

The cantilever is released by using an LTO wet etch and silicon nitride dry etch (SF_6/He) of the frontside multilayer diaphragm, followed by a wet etch ($K_3Fe(CN)_6$/KOH) of the underlying, supporting Al layer.

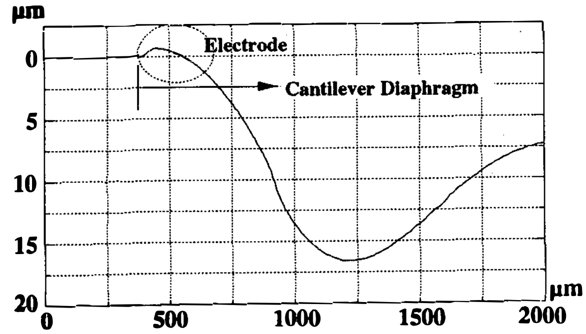

Figure 5. Profile of a completed transducer as measured by a profilometer.

The wafers are diced with a diamond saw, and individual microphones are glued and wire-bonded to ceramic packages which have a 3 mm-diameter ventilation hole formed by a diamond drill. The ventilation hole can be left open during testing or sealed to form a 15 mm^3 back-cavity volume.

Fabricating Flat Transducers

Transducers fabricated with designs prior to that shown in Fig. 2 were significantly curled upward or downward. This is undesirable because it decreases the effective device area upon which the sound wave impinges (microphone) or which launches the sound wave (microspeaker).

The downward curl is due to the high residual compressive stress of the ZnO layer. It was found that the curl is considerably reduced by patterning the ZnO so that it is not contiguous to the silicon-support portion of the cantilever.

The upward curl arises because of the *gradient* of residual stress of the silicon nitride layer, which is illustrated in Fig. 3. The stress profile of Fig. 3 has been obtained by successively removing thin layers of the film and measuring wafer curvature [9]. The stress distribution in the silicon nitride seems to be related to annealing during the deposition at 835 °C. The earlier a layer is deposited, the longer this layer is annealed. The gradient in the residual stress generates a moment that causes the upward curl, as illustrated in Fig. 4(a)

Figure 4(b) shows the solution used in the process flow of Fig. 2 in order to produce a cantilever with a symmetric stress distribution in the silicon nitride. The initial 0.5-μm-thick silicon nitride layer is deposited with a 6:1 reactant gas ratio to form the diaphragm prior to bulk-micromachining. The low (50 MPa) residual tensile stress of the thin, initial diaphragm makes it more resistant to rupture [10].

After bulk-micromachining, the second 0.5-μm-thick low-stress silicon nitride is deposited with a 4:1 gas ratio. The larger tensile stress (250 MPa) of the second layer is used to maintain diaphragm flatness during subsequent processing steps. Since the second silicon nitride deposition occurs on both sides of the original diaphragm, the stress gradients become symmetric. The first silicon nitride layer is also annealed during the second layer deposition and its stress distribution becomes negligible. The result is a relatively flat cantilever. This technique of producing a flat cantilever despite the stress gradient in the component films may have applications to other micromachined structures.

Figure 5 shows the profile of a completed transducer as measured by a Tencor Alphastep 200 profilometer. The out-of-plane deflection of the transducer is less than 20 μm. We have verified with non-contact optical measurements that the profile of Fig. 5 is accurate to within experimental error of 3 μm. Across a given wafer, the majority of the transducers had out-of-plane deflections below 35 μm.

Design and Simulation

In order to understand the device characteristics and process of designing for specific desired responses, we need a reliable model of the device. We use a combination of finite-element simulations and analytical modeling to calculate the microphone output voltage as a function of the frequency of the acoustic excitation.

Using ABAQUS, we have determined the strains developed in the cantilever at different excitation frequencies and integrated the strain across the electrode area. Since we have not yet modeled the acoustical damping of the microphone, we chose a damping factor for ABAQUS such that the simulated and measured quality factor Qs of the lowest resonant peaks would be identical.

The microphone output voltage at a particular frequency is proportional to the integral of the strains generated across the assumed electrode area. In this electrode design process, the equivalent circuit model is also considered, which includes the effects of capacitive loading [8]. Through the design iterations, the electrode pattern shown in Fig. 1(a) was found to produce the best low-frequency response. Figure 6 shows the simulated microphone frequency response (curve A) of the transducer with a low-frequency sensitivity of 3.8 mV/μbar.

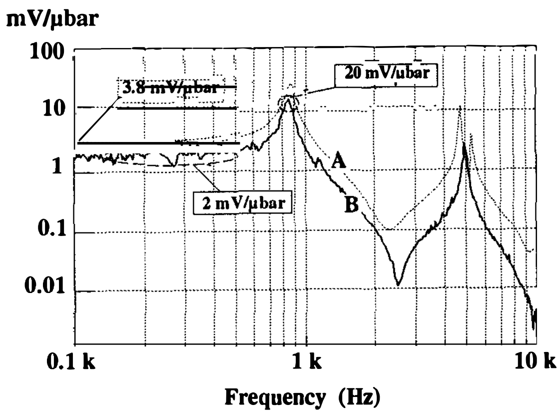

Figure 6. Measured microphone frequency response (curve B) of the transducer compared with the ABAQUS simulation result (curve A) from 100 Hz to 10 kHz.

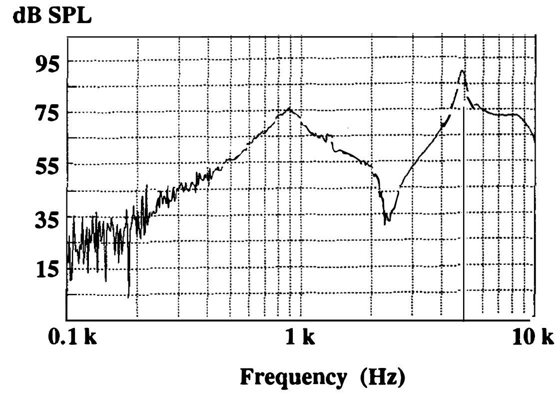

Figure 7. Microspeaker output pressure into a 2 cm^3 coupler in the 100 Hz to 10 kHz range with 4 V(zero-peak) drive.

Experimental Results

Microphone Testing

The microphone frequency response has been measured in an electrically-shielded anechoic chamber containing a calibrated microphone (B&K 4135). The test and reference microphones are placed at the same distance from the source of acoustic signals, which is the end of a 6.5 mm diameter tube that leads into the chamber from an external conventional loudspeaker.

Figure 6 shows the typical measured microphone sensitivity (curve B) of the cantilever device when tested without backing. The microphone sensitivity is fairly constant at 2 mV/µbar in the low frequency range and rises to 20 mV/µbar at the lowest resonant frequency of 890 Hz. The 2 mV/µbar is the highest reported for a microphone with a micromachined diaphragm. The low-frequency sensitivity and the resonant frequencies are in good agreement with the simulation result. Independent testing shows that backing with a 15 mm^3 cavity will reduce the low-frequency sensitivity by about 8 dB, to around 0.8 mV/µbar.

Microspeaker Testing

We measured the acoustic output of the cantilever device into a 2 cm^3 coupler with a calibrated B&K microphone. Figure 7 shows the microspeaker output in the 100 Hz to 10 kHz frequency range with 4 V(zero-peak) input drive. The resonant frequencies coincide with those of the microphone response at 890 Hz and 4.8 kHz, as we expect. Figure 8 shows the sound pressure level produced by the microspeaker in the 1 kHz to 50 kHz frequency range. Figure 9 shows that the output pressure is proportional to the input drive voltage from 0.1 to 6 V(zero-peak) at 4.8 kHz. The highest output pressure corresponds to approximately 100 dB SPL.

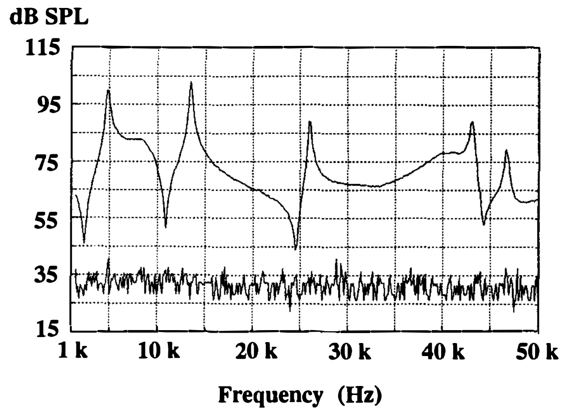

Figure 8. Microspeaker output pressure into a 2 cm^3 coupler in the 1 kHz to 50 kHz range with 4 V(zero-peak) drive. The lower trace is the noise level of the B&K 4135 reference microphone.

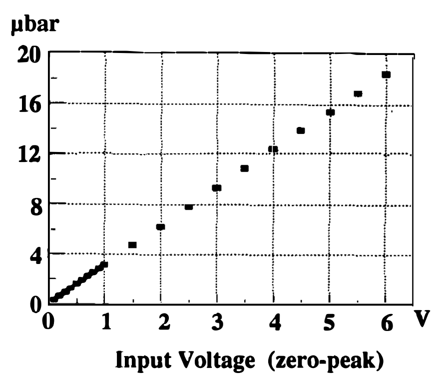

Figure 9. Microspeaker output pressure vs. input voltage measured at 4.8 kHz.

Conclusions

A piezoelectric micromachined cantilever microphone and microspeaker has been fabricated and tested. By controlling the distribution of residual stress, we were able to make 2000 μm-long cantilevers whose maximum out-of-plane deflections were typically no more than 35 μm. The microspeaker output is proportional to the input drive, and rises to approximately 100 dB SPL at 4.8 kHz and 6 V(zero-peak) drive. The microphone sensitivity is fairly constant at 2 mV/μbar in the low frequency range, and is 20 mV/μbar at the lowest resonant frequency of 890 Hz. The high microphone sensitivity and the high microspeaker output are due to the high compliance of the cantilever diaphragm. Future work will include modelling of acoustic leakage around the perimeter of the cantilever into the back cavity volume.

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