Dome-Shaped Diaphragm Transducer(DSDT)

INTRODUCTION

Airborne ultrasonic transducers are widely used in many measurement tasks in automation, surveillance, gas flow measurement, and distance measurement. Recently, silicon micromachining technology has been explored to fabricate various ultrasonic transducers due to the following advantages: potentially low cost due to the batch processing nature, possibility of integrating transducers and circuits on a single chip, size miniaturization and high frequency operation due to small diaphragm mass.

Ultrasonic transducers are classified according to the physical principle they employ for radiating ultrasound – two such classes of primary interest are piezoelectric and electrostatic actuation. Piezoelectric ultrasonic transducers have predominantly been used for industrial applications because they are compact, rugged, highly efficient, and operational over a wide temperature range. But piezoelectric ultrasonic transducers suffer from relatively low amplitude of deflection – and therefore low sound output – and narrow frequency bandwidth.

To address these shortcomings, we have developed a parylene piezoelectric acoustic transducer on a dome-shaped diaphragm (shown in Figure 1). The dome-shaped diaphragm has the following advantages due to its geometrical shape: residual stress in the diaphragm is released easily through its volumetric shrinkage or expansion, and the strain produced by a piezoelectric film deposited on the diaphragm produces flexural vibration effectively. Moreover, a dome diaphragm increases the figure of merit (the product of the fundamental resonant frequency squared and the dc response) because the dome structure with its spatial curvature is stronger and stiffer than other structural forms with the same overall dimensions and weight. The net outcome is a transducer with sound production capabilities typically associated with other actuation methods, coupled with the simplicity and efficiency of piezoelectric devices.

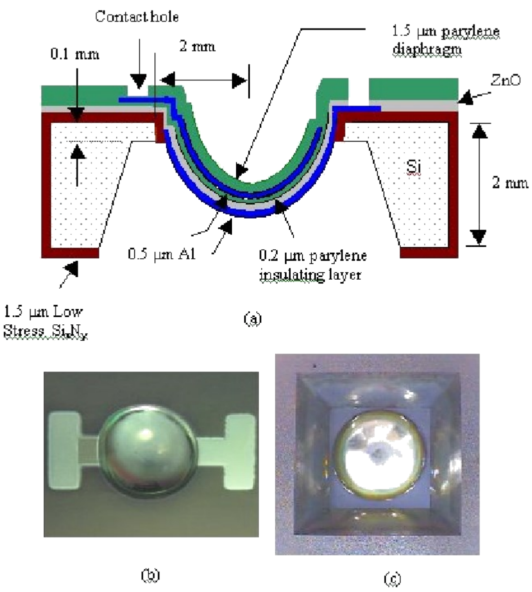

Figure 1 (a)Cross-sectional view of the parylene dome-shaped diaphragm piezoelectric acoustic transducer. (b) Top view photo of a fabricated acoustic transducer. (c) Bottom view photo of the same transducer.

FABRICATION

A. OVERVIEW

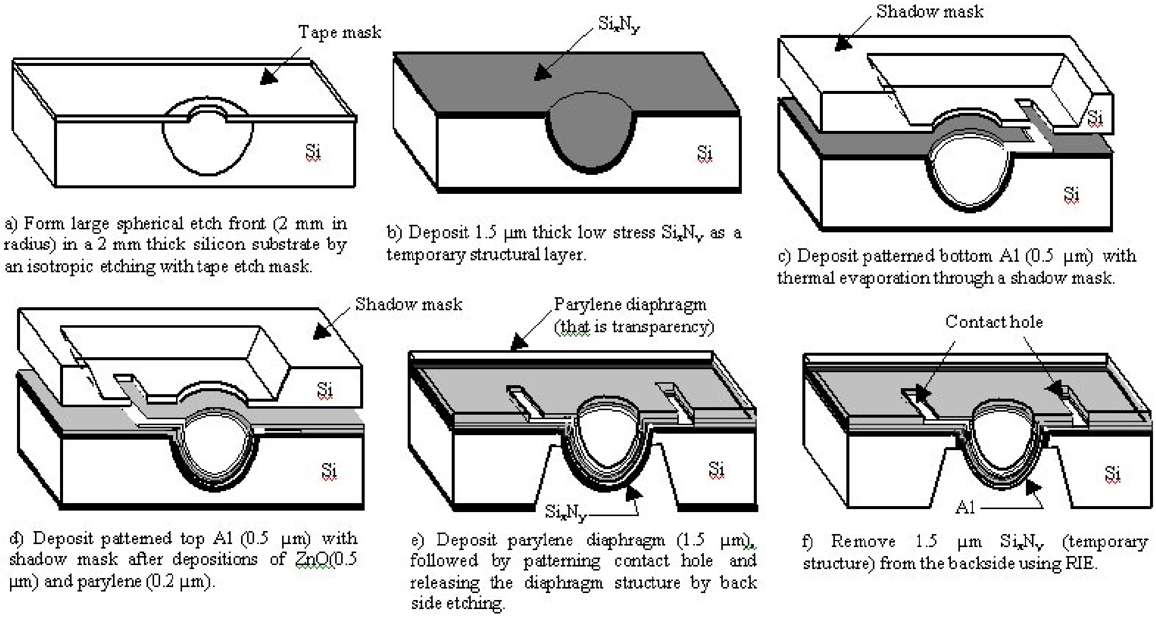

Figure 2 Brief processing steps to fabricate the parylene dome-shaped diaphragm piezoelectric acoustic transducer with the shadow-mask delineation technique.

First, a wide tape (polyethylene backing with acrylic adhesive, commonly called a 4” label protection mailing tape) is fixed to the silicon substrate. Before applying the tape, an additional sacrificial layer, such as SiN_x or SiO_2, has been deposited to prevent any possible contamination from the tape in subsequent processing steps. Also, this additional layer can be used as an etch mask layer in a later step. The tape is patterned with reactive ion etching (RIE) in oxygen plasma, and it will serve as the etch mask for isotropic wet etching of the dome shape. A thin aluminum film serves as an etch mask while patterning the tape, and it is then removed by a home-made Al etchant that does not attack the tape. After applying additional tape to the bottom and side of the silicon wafer, we etch the silicon front side in an isotropic silicon etchant to form the spherical dome shape. We use a combination of 49% hydrofluoric, 70% nitric, and 99.5% acetic acids (with a ratio of 2:3:3) at 50 °C, which minimizes the dependence of the etch rate on crystal plane. The etching is performed in a Teflon beaker, without any agitation for uniform etch-stop effect. Following the wet etching, the tape is detached by dissolving its adhesive in IPA or heated toluene. The additional sacrificial layer (mentioned in the second sentence of this paragraph) can be used at this point as an etch mask layer during a secondary, shorter etch, which cleans up the dome shaped structure, i.e., improves the circularity and surface roughness.

After forming the dome-shaped cavity on silicon wafer, we carry out the following steps to form the parylene piezoelectric diaphragm. We deposit 1.5 μm thick, slightly compressively stressed, silicon nitride as a temporary structural layer. Next, we evaporate a 0.5 μm thick bottom aluminum electrode using a shadow mask (see below), then sputter-deposit 0.5 μm thick ZnO as the piezoelectric layer. An insulating layer of 0.2 μm thick parylene is deposited prior to the top electrode (also evaporated aluminum with 0.5 µm thickness). Finally, the primary diaphragm support layer of 1.5 µm thick parylene is deposited. To release the diaphragm, anisotropic KOH etching is performed from the back side, followed by removal of the temporary nitride support layer. Figures 3 and 4 show partially and fully completed dome-shaped diaphragm transducers.

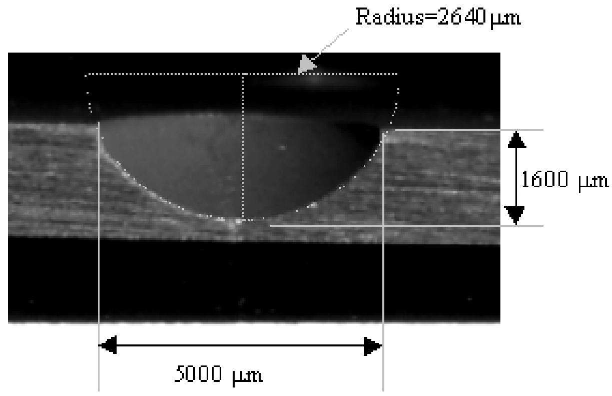

Figure 3 Cross-sectional view of a spherical cavity formed in a 2 mm thick silicon wafer.

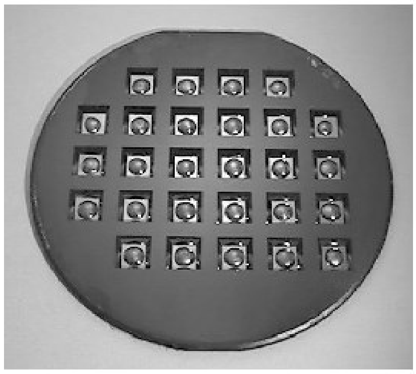

Figure 4 Photo taken from the backside of a completed 3" silicon wafer that contains dome-shaped-diaphragm piezoelectric ultrasonic transducers with circular clamped boundaries.

B. SHADOW MASK PATTERNING

High-resolution patterning on a 3 dimensional structure, such as our dome-shaped cavity, is a problem often encountered in MEMS fabrication. Spin-coated photoresist cannot evenly cover a 3 dimensional microstructure. Even if a uniform coating can be obtained with a special coating method, it is still difficult to expose the photoresist on and around the sharp edge of the dome-shaped cavity. Thus, we have developed the following technique with a shadow mask in order to achieve a high-resolution lithography over a dome shaped structure without any electrode disconnection problem at the sharp edge boundary.

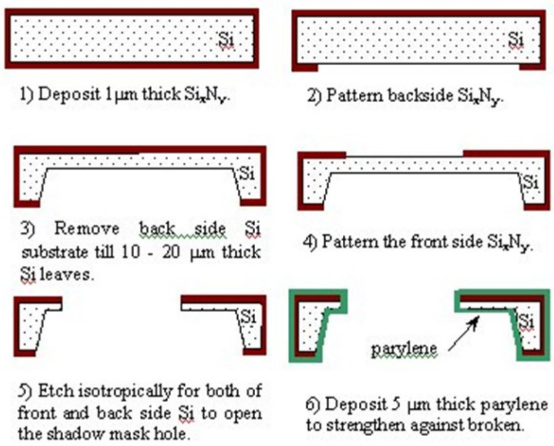

Figure 5 Processing steps to fabricate the shadow mask using anisotropic and isotropic etchings.

We first fabricate a shadow mask on a (100) oriented 3" silicon wafer by using isotropic and anisotropic etchings as schematically illustrated in Fig. 5. First, 1 µm thick LPCVD low stress silicon nitride is deposited on a silicon wafer, and the backside nitride is patterned with

CF_4 RIE. This nitride acts as a mask for anisotropic etching in 44% aqueous KOH solution at 75 ºC until 10-20 mm thick silicon diaphragms are obtained as shown in Step 3 of Fig 5. After the front-side silicon nitride is patterned, the silicon is etched isotropically from both the front side and backside to open the shadow mask hole. We have observed that the combination of 49% hydrofluoric, 70% nitric and 99.5% acetic acids with a ratio of 1:4:3 is an effective and easy to work with isotropic etchant. Finally, a 5 µm thick parylene is deposited to make the shadow mask diaphragm sturdy. Figure 6 shows the bottom view photo of the completed shadow mask made on a 3" silicon substrate. This mask is used for patterning the bottom and top electrodes over a dome-shaped diaphragm as shown in Fig.2 (c), (d).

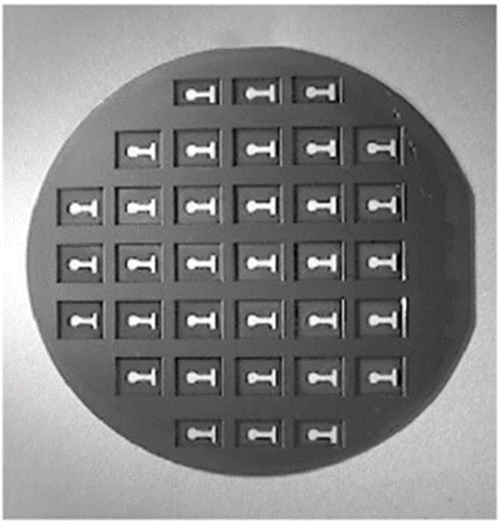

Figure 6 Bottom view photo of the micromachined shadow mask made on a 3" silicon substrate. This mask is mainly used to deposit the patterned bottom and top electrodes conformably over the dome diaphragm (at Steps 12 & 15 in Fig.2).

In order to get CVD-like conformal deposition across the sharp boundary edge of the dome-shaped cavity, high deposition rate of Al thermal evaporation is used in conjunction with the shadow mask. As illustrated in Fig. 7, we obtain the conformal deposition by reducing the mean free path of Al particle due to a high evaporation rate, while maximizing the distance between Al source and the substrate. We find that a good conformal deposition is obtained at an evaporation pressure of 3 mTorr (for which mean free path = 1.7 cm, deposition rate = 50A/sec) with distance between Al source and substrate being equal to 25 cm.

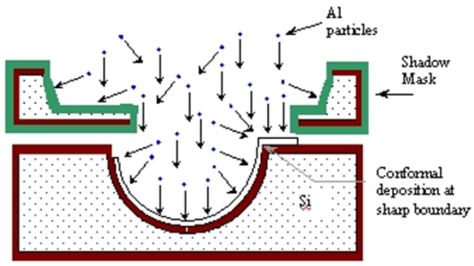

Figure 7 Schematic representation of CVD-like conformal deposition (along the sharp boundary of a dome-shaped diaphragm) with a shadow mask. For this step, we need a high deposition rate of thermal evaporation to increase conformability by reducing the mean free path of Al particle. (Evaporation pressure=3 mTorr, mean free path of Al = 1.7 cm, distance between Al source and target = 30 cm, deposition rate = 50A/sec)

PERFORMANCE OF TRANSDUCER

To demonstrate the effectiveness of our dome-shaped diaphragm as an ultrasonic acoustic transducer, we have fabricated a conventional flat SiN_x diaphragm transducer with the same materials. The area of the flat diaphragm is designed to be the same as that of the dome-shaped diaphragm, so that we may compare the acoustic outputs of the two different structures. Figure 8 shows the flat diaphragm transducer; note the wrinkling from residual stress in the silicon nitride support layer.

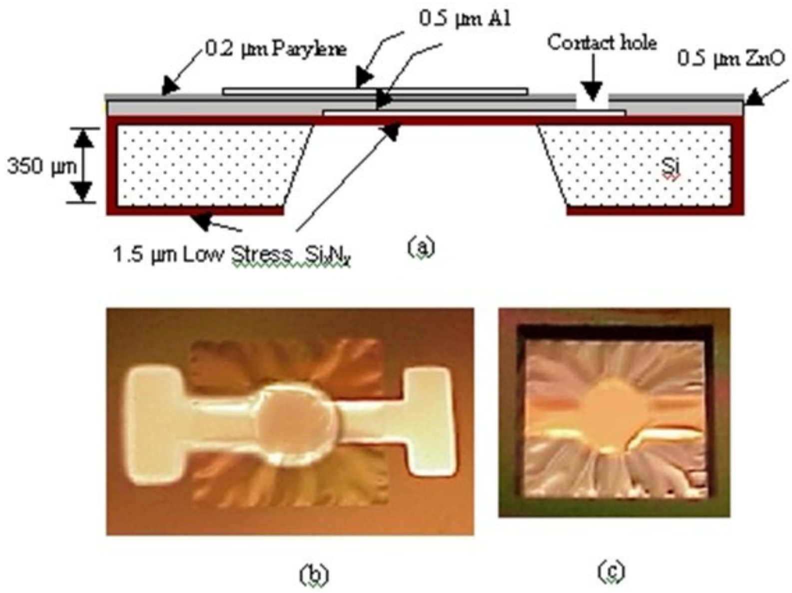

Figure 8 Piezoelectric ultrasonic transducers built on a nominally flat diaphragm which is wrinkled due to compressive residual stress: (a) cross-sectional view drawing, (b) top view photo of the fabricated transducer, and (c) bottom view photo of the same transducer.

We measured the acoustic output of the dome-shaped and flat diaphragm transducers with B&K 4135 reference microphone 2 mm away from the transducers. Figure 9 shows the measured SPL (sound pressure level) of a flat diaphragm transducer and a dome-shaped-diaphragm transducer as a function of frequency. In ultrasonic range of about 15 kHz to 200kHz, the SPL of a flat diaphragm transducer is much lower than that of a dome-shaped-diaphragm transducer. Moreover, in the case of a flat (and wrinkled) diaphragm transducer, we observe significantly distorted acoustic outputs at certain frequencies, and also low-frequency sound being produced when the transducer is operated at a high frequency. This kind of distortion is due to the wrinkling in the diaphragm, which can be avoided if the diaphragm is slightly tensile stressed. However, we have not observed any sound output with a transducer built on a slightly tensile stressed diaphragm.

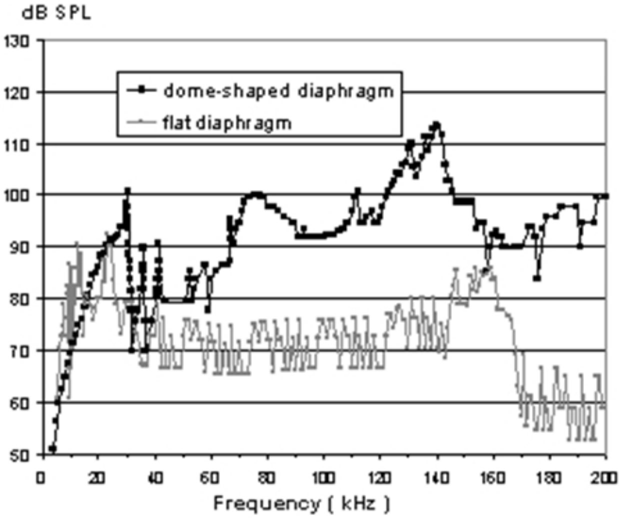

Figure 9 The output sound pressures of the two ultrasonic transducers in 100 Hz – 200 kHz range when the transducers are driven by a 11 V_{rms} sinusoidal source. The acoustic output is measured by B&K 4135 reference microphone 2 mm away from the transducers.

We expect our transducer to produce sound pressure at frequencies above 200 kHz, but our equipment only allows for accurate characterization of sound pressure level up to 200 kHz. Finally, Fig. 10 shows a typical sound pressure output of our dome-shaped-diaphragm transducer as a function of the driving voltage, and demonstrates that the linearity of our transducer's response is quite good.

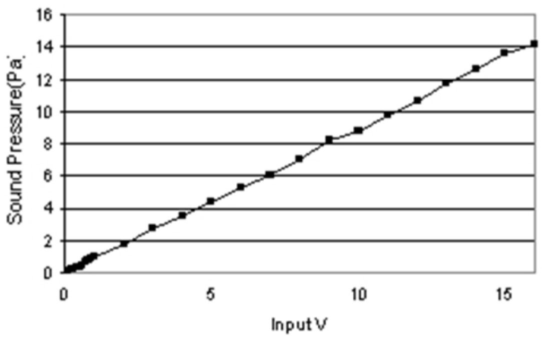

Figure 10 Typical sound pressure output of the dome ultrasonic transducer vs. the driving voltage amplitude measured 2 mm away from the transducers at 145kHz.

SUMMARY

Dome-shaped-diaphragm piezoelectric ultrasonic transducers have successfully been fabricated on a 1.5 μm thick parylene diaphragm with aluminum electrodes and ZnO piezoelectric film. In order to achieve a high-resolution lithography over a dome shaped diaphragm and to avoid the electrode disconnection problem at sharp edge boundary, a shadow mask technique with high deposition-rate thermal evaporation has been developed. The transducer's sound output (measured with B&K 4135 microphone 2 mm away from the transducer) is 70 - 113 dB SPL in 10 – 200 kHz ranges. To demonstrate the advantage of a dome-shaped diaphragm, we have fabricated conventional flat diaphragm transducers, so that we can compare the acoustic output of the two different devices. The dome-shaped transducer generates much higher sound output than the flat diaphragm in 15 - 200 kHz range, and without harmonic distortion. The sound-pressure level at 50 mm away from the dome transducer is measured to be around 0.5 Pa at 145 kHz. The linearity of the dome-shaped transducer's response is also measured to be very good.