PARYLENE-DIAPHRAGM PIEZOELECTRIC ACOUSTIC TRANSDUCERS

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ABSTRACT

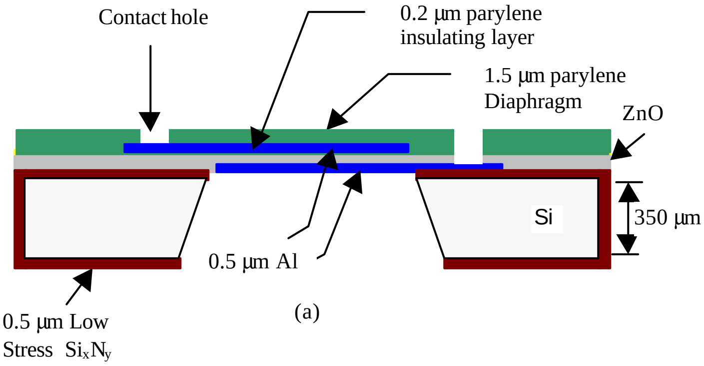
This paper reports the fabrication of piezoelectric acoustic transducers built on a 1.5 µm thick parylene diaphragms (both flat 5,000*5,000 µm^2 square diaphragm and dome-shaped 2,000 µm-radius diaphragm with circular clamped boundary on a silicon substrate) with electrodes and piezoelectric ZnO film. The main advantages of a parylene diaphragm for an acoustic transducer are its large elastic compliance and low residual stress. In fabricating the parylene-diaphragm (which has relatively low melting point) acoustic transducers, we use a silicon nitride layer as a temporary structural layer during high temperature process steps. The dome-shaped parylene-diaphragm transducers are reliably and reproducibly fabricated with a shadow mask technique with high-deposition-rate thermal Al evaporation.

INTRODUCTION

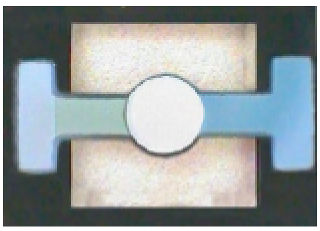
Compared to condenser type MEMS acoustic transducers (which require two relatively large plates be separated by a narrow air gap), a piezoelectric MEMS acoustic transducer built on a single diaphragm is simpler to fabricate, free from the polarization-voltage requirement, and responsive over a wider dynamic range. However, the demonstrated sensitivity of a piezoelectric MEMS microphone has been relatively low [1].

As a novel idea for producing a piezoelectric acoustic transducer, we employ a parylene as a diaphragm material. Figure 1 shows the parylene flat-diaphragm piezoelectric acoustic transducers with electrodes and piezoelectric ZnO film. The main advantage of a parylene diaphragm for an acoustic transducer is significant improvement on acoustic sensitivity and responsivity, because parylene (a polymer material) has about 50 to 100 times smaller elastic modulus than conventional diaphragm materials such as silicon nitride, polysilicon and silicon. Also, parylene diaphragm releases the residual stress in the diaphragm effectively, and can be free of the residual stress problem which has been a dominant factor affecting the performance of diaphragm-based transducers. Moreover, parylene is an excellent moisture-blocking layer, chemically inert, and biocompatible in many aspects.

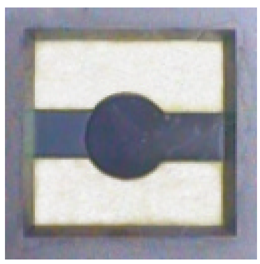
A parylene piezoelectric acoustic transducer on a dome-shaped diaphragm (shown in Fig. 2) has also been developed because a dome-shaped diaphragm has the following advantages due to its geometrical shape. Residual stress in the diaphragm is released easily through its volumetric shrinkage or expansion, and an in-plane strain (produced by a piezoelectric film sitting on a dome 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.



(a)



(b)



(c)

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

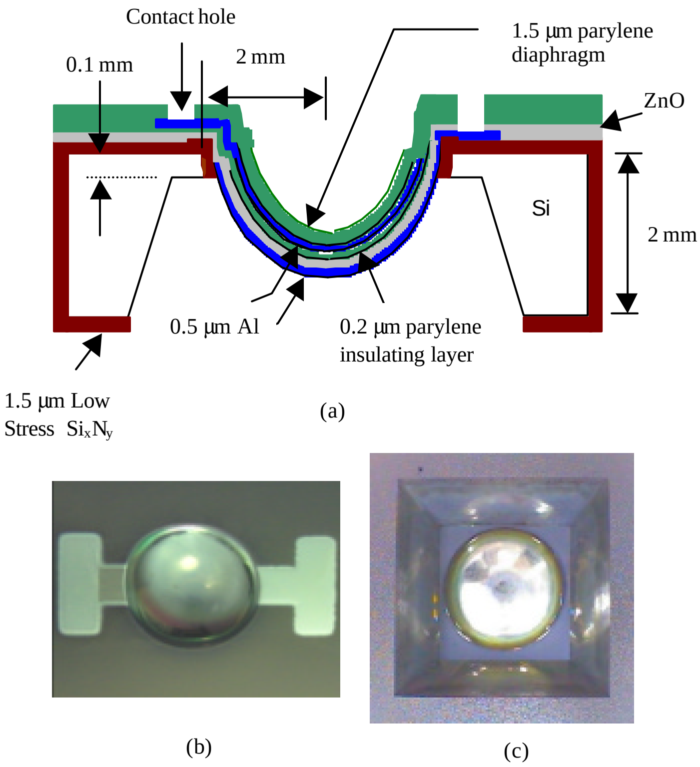


Figure 2 (a)Cross-sectional view of the parylene dome-shaped diaphragm piezoelectric acoustic transducer. (b) Top view photo of a fabricated acoustic transducer. (c) Bottom view photo of the same transducer.

This paper describes the fabrication techniques for the parylene-diaphragm piezoelectric acoustic transducers for both flat and dome-shaped-diaphragm structures including the patterning technique using a shadow mask with high deposition rate of thermal evaporation. To demonstrate the effectiveness of a parylene diaphragm for an acoustic transducer, we have fabricated a conventional SiN diaphragm transducer on a same wafer with the same materials, following the same fabrication steps except the diaphragm materials. Then the performance of the parylene diaphragm piezoelectric transducer is compared with the SiN diaphragm piezoelectric transducer for a microspeaker.

FABRICATION

A. Parylene Flat-Diaphragm Acoustic Transducers

A schematic of the process flow for the parylene flat diaphragm acoustic transducer is shown in Fig. 3. In fabricating the micromachined parylene-diaphragm (which has relatively low melting point) acoustic transducers, we use a silicon nitride layer as a temporary structural layer during high temperature process steps. The silicon nitride is removed after completing all high temperature steps followed by a parylene deposition as shown in Step 10 in Fig. 3.

First, 0.5 µm thick low stress silicon nitride is deposited by low pressure chemical vapor deposition (LPCVD) on a bare silicon as a temporary structural layer. Then a 0.5 µm thick bottom Al is deposited by thermal evaporation and patterned. Then 0.5 µm thick piezoelectric ZnO film is sputter-deposited at 275 °C, followed by depositions of 0.2 µm thick parylene as insulating layer, and 0.5 µm thick top Al. After patterning the top Al, we deposit 1.5 µm thick parylene for the diaphragm support layer, and then open contact holes for access to the bottom and top electrodes. In order to release the diaphragm structure, the silicon nitride on the wafer backside is patterned into a square opening, and the bulk of the silicon is removed by KOH from the wafer backside. Finally, the silicon-nitride temporary structure layer is removed from the backside by a reactive ion etcher (RIE) without any etch mask to release the parylene diaphragm transducer.

B. Parylene Dome-Shaped Diaphragm Acoustic Transducers

Figrue 4 illustrates the summary of the fabrication of the parylene dome-shaped-diaphragm transducers. There are two main steps to fabricating such a large 3-D diaphragm acoustic transducer. The first one is to

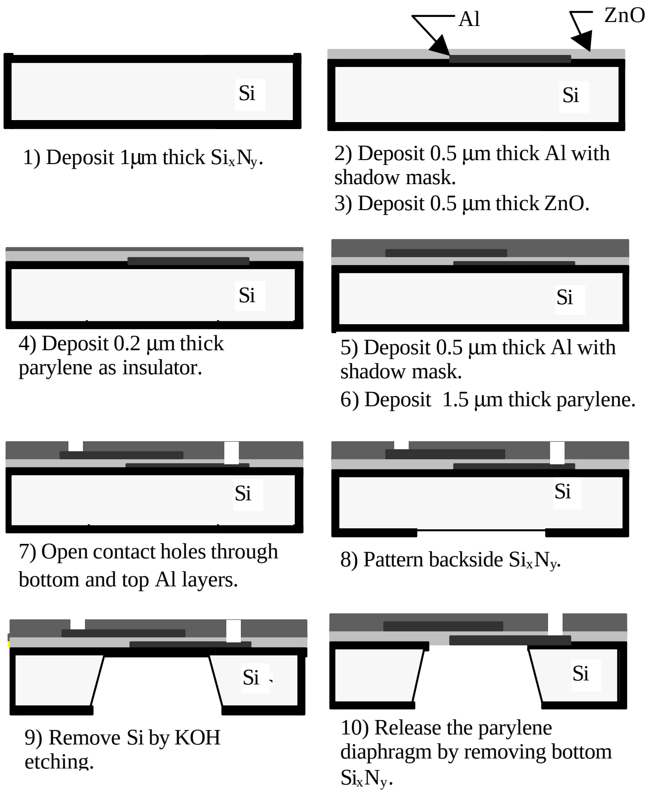
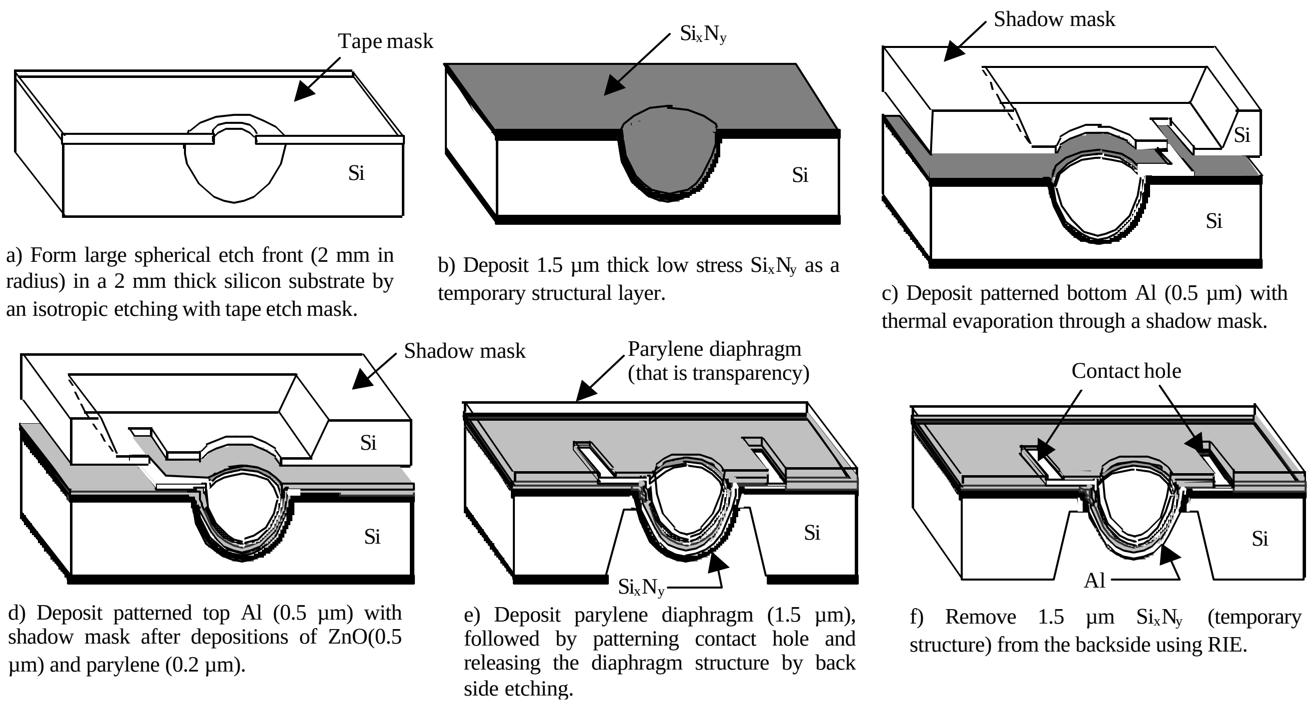


Figure 3 Processing steps to fabricate the parylene flat-diaphragm piezoelectric acoustic transducer.

produce a large spherical etch front (2 mm in radius) in a 2 mm thick silicon substrate by an isotropic silicon etching with a 75 µm thick tape as an etch mask as shown in Fig. 4 (a). In order to produce such a large dome-shaped cavity with good uniformity, novel process techniques have been developed including the chemical isotropic etching with tape mask, high yield backside etching, and self-limiting etching behavior in wet isotropic etching [2]. The second main step is to deposit the needed thin films to form piezoelectric transducers. In this step, a shadow mask technique with high-deposition-rate thermal evaporation has been developed to pattern the top and bottom electrodes conformably on the dome shaped cavity.

First, a tape (polyethylene backing with acrylic adhesive, commonly called a 4” label protection mailing tape, purchasable from MANCO Inc.) is pasted on the silicon substrate. Before pasting the tape, additional sacrificial layer, such as SiN or SiO2, can be used 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 step to improve the etch-front circularity and smoothness simultaneously. The tape is patterned in a reactive ion etcher (RIE) with oxygen plasma. In this RIE step, Al is used as an etch mask. Then, the Al film is removed by an Al etchant (1g KOH: 10g K3Fe(CN)6: 100ml DI water) which rarely deteriorates the tape adhesion. After pasting another tape on the bottom and side of the silicon wafer, we etch the silicon front side in an isotropic silicon etchant to form spherical etch fronts, followed by detaching the tape by dissolving the tape adhesive in IPA (at room temperature for 2 hrs) or heated toluene. We use the 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) which is placed in a 50 ^{o}C water bath. 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 etching to improve the circularity and surface roughness of the etch front.

After forming the dome-shaped etch cavity on silicon wafer, we carry out the following steps to form a parylene piezoelectric transducer as shown in Fig. 4 (b) to (f). We deposit 1.5 µm thick slightly compressive silicon nitride as a temporary structural layer, evaporate 0.5 µm thick bottom Al with a shadow mask, and sputter-deposit 0.5 µm thick piezoelectric ZnO, followed by deposition of 0.2 µm thick parylene as an insulating layer. Then we evaporate 0.5 µm thick top Al with a shadow mask, deposit 1.5 µm thick parylene as the diaphragm support layer, and then open the contact holes. We then pattern the silicon nitride on the wafer backside into a square opening, and remove the bulk of the silicon from the wafer backside by KOH to release the diaphragm structure. Finally, the silicon nitride temporary layer is removed from the backside to produce the parylene dome-shaped diaphragm transducer.



a) Form large spherical etch front (2 mm in radius) in a 2 mm thick silicon substrate by an isotropic etching with tape etch mask.

b) Deposit 1.5 µm thick low stress Si_xN_y as a temporary structural layer.

c) Deposit patterned bottom Al (0.5 µm) with thermal evaporation through a shadow mask.

d) Deposit patterned top Al (0.5 µm) with shadow mask after depositions of ZnO(0.5 µm) and parylene (0.2 µm).

e) Deposit parylene diaphragm (1.5 µm), followed by patterning contact hole and releasing the diaphragm structure by back side etching.

f) Remove 1.5 µm Si_xN_y (temporary structure) from the backside using RIE.

Figure 4 Brief processing steps to fabricate the parylene dome-shaped diaphragm piezoelectric acoustic transducer with the shadow-mask delineation technique.

SHADOW MASK PATTERNING

High-resolution patterning on a 3 dimensional structure, such as our dome-shaped cavity, is a problem often met in a micromachining process. The usual spin coating of photoresist (PR) cannot cover a 3 dimensional microstructure well. Even if a uniform coating can be obtained with a special coating method (such as an electroplating method using PEPR2400), there is still a problem with the PR exposure in the case of the dome-shaped cavity. This problem is due to the fact that the effective PR thickness near the sharp edge of the dome cavity is too thick compared to that of a flat area. 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.

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 silicon nitride is patterned with a CF_4 RIE. Then the silicon backside is etched anisotropically with 44% aqueous KOH solution at 75 ^{o}C till rather thick (10-20 µm thick) silicon diaphragms are obtained as shown in Step 3 in Fig 5. After the front-side silicon nitride is patterned, the silicon is etched isotropically from both 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 at room temperature minimizes the dependence of the etch rate on crystal plane, and is effective in controlling the etching time. Finally, a 5 µm thick parylene is deposited to make the shadow mask diaphragm sturdy.

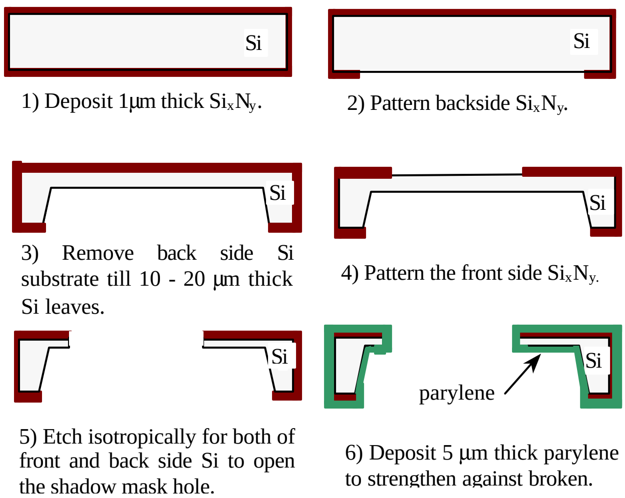


Figure 5 Processing steps to fabricate the shadow mask using anisotropic and isotropic etchings.

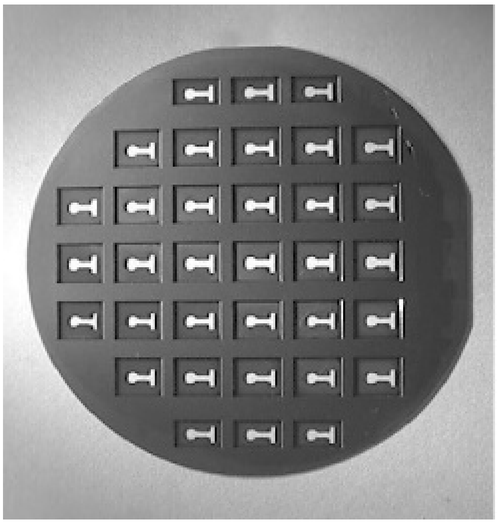


Figure 6 Bottom view photo of the micromachined shadow mask made on a 3" silicon substrate. This mask is mainly used to deposit the patterned bottom and top electrodes conformably over the dome diaphragm (at Steps (c) & (d) in Fig.4).

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.4 (c), (d).

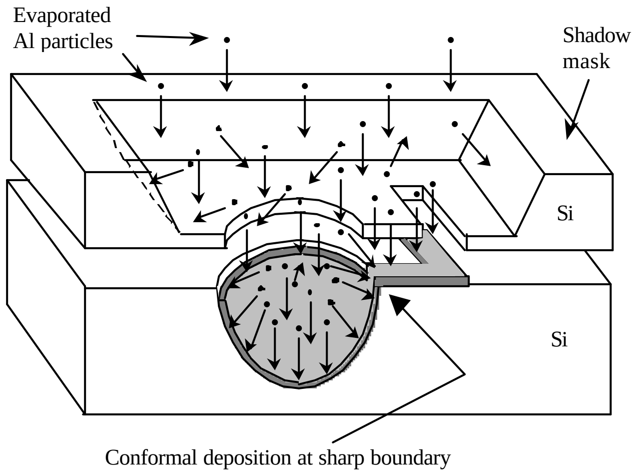
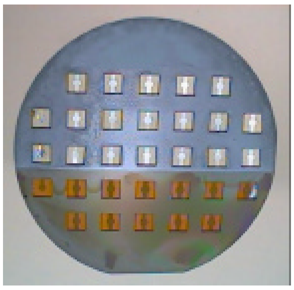


Figure 7 Schematic representation of CVD-like conformal deposition (along the sharp boundary of a dome-shaped diaphragm) with a shadow mask. For this step, we need a high deposition rate of thermal evaporation to increase conformability by reducing the mean free path of Al particle. (Evaporation pressure=3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

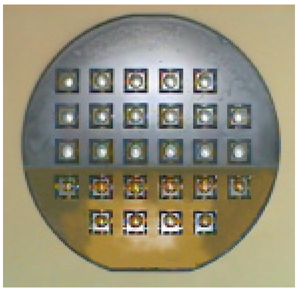
In order to get CVD-like conformal deposition across the sharp boundary edge of the dome-shaped cavity, high deposition rate of Al thermal evaporation is used in conjunction with the shadow mask. As illustrated in Fig. 7, we obtain the conformal deposition by reducing the mean free path of Al particle 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.

TRANSDUCER PERFORMANCE

To demonstrate the effectiveness of a parylene diaphragm for an acoustic transducer, we have fabricated a conventional SiN diaphragm transducer on a same wafer with the same materials, following the same fabrication steps except the diaphragm materials. Figure 8 shows the photos taken from the backside of a completed 3“ silicon wafer that contains both the parylene devices (the first 3 rows) and the SiN devices (the last 2 rows) for two wafers that contain flat-diaphragm (a) and dome-shaped-diaphragm (b) transducers.



(a)



(b)

Figure 8 Photos taken from the backsides of completed 3” silicon wafers that contain both parylene (upper transparent diaphragms) and SiN (lower yellowish diaphragms) piezoelectric acoustic transducers with flat diaphragm transducers (a) and dome-shaped-diaphragm transducers (b).

Figure 9 compares the sound output produced by a flat parylene-diaphragm device with that by a flat SiN-diaphragm device. The sound output from the parylene flat-diaphragm device is measured to be 0.6 Pa at the resonant frequency as shown in Fig. 9 (when the transducer is driven by a 11 V_{rms} sinusoidal source and measured with B&K 4135 microphone 2 mm away from the transducer).

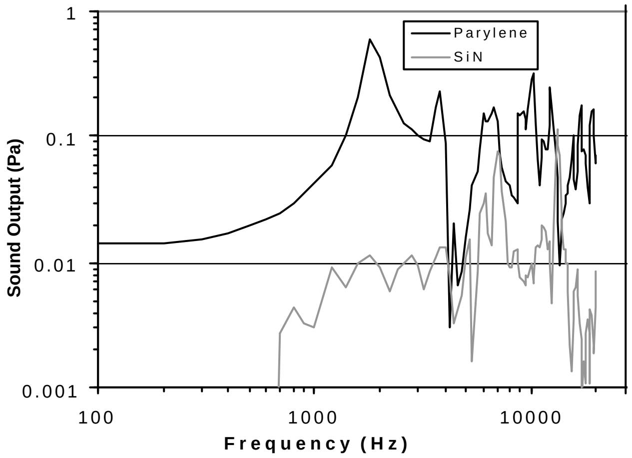


Figure 9 The sound output pressures of the flat parylene and SiN diaphragm transducers in 100 Hz – 20 kHz range when the transducer is driven by a 11 V_{rms} sinusoidal source and measured with B&K 4135 reference microphone at 2 mm from the transducers.

SUMMARY

We have successfully fabricated piezoelectric acoustic transducers built on a 1.5 µm thick parylene diaphragms (both flat 5,000*5,000 μm^2 square diaphragm and dome-shaped 2,000 µm-radius diaphragm with circular clamped boundary on a silicon substrate) with electrodes and piezoelectric ZnO 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 shadow mask is made on a (100) oriented 3” silicon wafer by using isotropic and anisotropic etchings.

ACKNOWLEDGMENTS

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