# 3D MEMS Fabrication Using
# Low-Temperature Wafer Bonding With Benzocyclobutene (BCB)

**Tsung-Kuan A. Chou, Khalil Najafi**
*Center for Wireless Integrated MicroSystems*
University of Michigan
1301 Beal Ave, Ann Arbor, MI 48109-2122, USA

## ABSTRACT

This paper reports the development of a new technology for batch fabrication of 3D microstructures and MEMS. A boron-doped perforated electrode is formed with an integrated back cavity by using a combination of DRIE and wet bulk micromachining. The 3D structure is produced by low-temperature bonding of two pre-processed silicon wafers using the Benzocyclobutene (BCB) polymer. Structure release and chip separation are realized by through-wafer DRIE. Multi-wafer high-aspect ratio structures as thick as 500-1000μm can be fabricated for a variety of sensing and actuation applications. A high-density array of acoustic resonators and a high-sensitivity capacitive pressure sensor / microphone have been built using this technology.

**Keywords:** 3D MEMS, Wafer Bonding, BCB, DRIE.

## INTRODUCTION

Many emerging MEMS require the construction of complex 3D microstructures. Their fabrication technologies typically utilize wafer bonding, including Si-Si fusion [1] and Si-glass anodic bonding, to implement them. In Si-Si fusion bonding the high temperature (>1000°C) required for annealing and bonding prevents the use of materials, such as metals, and integrated electronics that are not compatible with high temperatures. In Si-glass bonding, although the temperature can be used below 400°C, it is difficult to precisely machine the glass or dope it as is possible with silicon. Si-Si anodic bonding with an evaporated thick glass layer as bonding media has been reported [2]. However, such process requires glass deposition and high voltage and high field, which can be potentially damaging to IC's. Therefore, to construct MEMS structures with a bonding method that is simple and compatible with IC processes is quite attractive and needed. Niklaus, et al. [3] first reported a void-free thermal compressive wafer bonding technique by using spun-on non-definable BCB with very strong bonding strength.

The technology presented here utilizes Si-Si localized wafer bonding using the photo-definable BCB polymer together with DRIE etching and bulk micromachining to produce a variety of MEMS. The test structure is shown in Figure 1. It consists of a thin diaphragm separated from a thick perforated electrode suspended over a back cavity. The device is formed by bonding two pre-processed micromachined silicon wafers, one supporting the diaphragm and the other the sense/drive electrode. Such 3D micromachining technique can be used to build most acoustic transducers, such as pressure sensors, microphones, and micropumps, and other complex machineries, such as acoustic resonators, micromirrors, and so on. This technology has been used to build: 1) a large array of acoustic

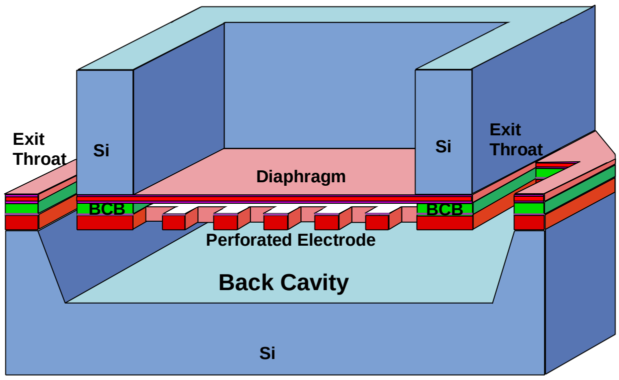



***Figure 1.*** *A proposed 3D MEMS structure.*

ejectors for micro-jet generation [4], and 2) a capacitive pressure sensor / microphone.

## PROCESS TECHNOLOGY

### *Low-Temperature Wafer Bonding With BCB*

Benzocyclobutene (BCB) is an epoxy-based polymer. It was primarily developed as a low dielectric constant material for planarization [5] that is compatible with integrated electronics. After being fully cured, BCB shows low volume shrinkage and high resistance to most wet chemicals [6]. Similar to standard photoresists, the photosensitive BCB can be spun onto a silicon wafer, and then exposed and developed to define specific patterns. After pattern definition, BCB can be slightly pre-cured or directly bonded with a companion wafer by applying pressure and temperature. The cured BCB thickness can vary from 2μm to more than 10μm depending on the spin speed and BCB specimen used.

A test of BCB (Dow Cyclotene 4024) residual stress on silicon wafer was performed after curing at 250°C for 30min. The results showed about 30MPa of tensile stress, which is lower than that induced by other adhesive bonding materials. In a series of tests BCB-patterned wafers were thermal-compressively bonded to a bare silicon wafer. The bonding quality was found to depend on the pre-cure condition, bonding pressure, curing temperature and time. Since many MEMS devices are very sensitive to bonding pressure, which may induce unwanted stress on the structures, the goal is to use the lowest compressive pressure required for good bonding. To inspect the bonding quality, the bonded wafers were forced apart. When testing wafers bonded with an applied pressure of 150kPa at a temperature of 250°C for 30 minutes, it was found that more then 90% of the patterned BCB was transferred from the host wafer onto the second silicon wafer, while the original pattern also remained on the host wafer as well. Figure 2 shows the patterns transferred onto a bare silicon wafer after bonding. This indicates that it is necessary to destroy BCB (tensile strength ~87MPa) in order to split the bonded wafers apart. Few localized voids were found at bonding interface especially if the pre-cure process was not performed. However, such voids are acceptable in many applications. A void free bond can be achieved with proper pre-cure condition and higher bond pressure (>1MPa).

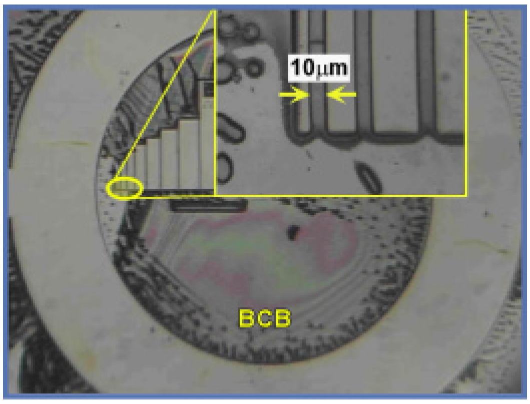



***Figure 2.*** *BCB pattern transferred from the host wafer to a second wafer after bonding.*

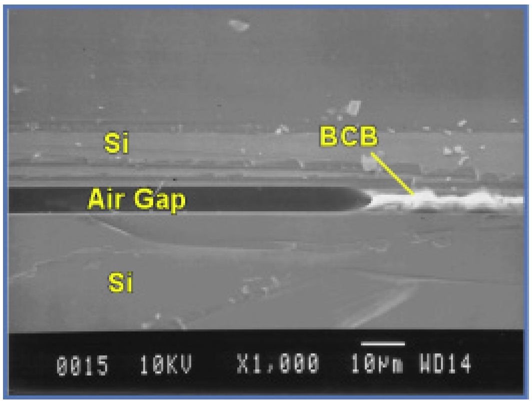



***Figure 3.*** *Cross-section of bonded wafer with BCB.*

It was also found that patterned BCB does not produce appreciable distortion in feature size after such bonding condition as shown in Figure 2. The 10μm wide and 6μm thick BCB still retains its shape after bonding. Bonding results were examined under SEM. It can be seen from Figure 3 that BCB can serve as the air gap spacer as well as the bonding media between two wafers. The final air gap is defined by the cured BCB thickness. Therefore, one can easily change the air gap by changing the thickness of spun-on BCB. It was found that the air gap variation was less than 5% across the 4" silicon wafer.

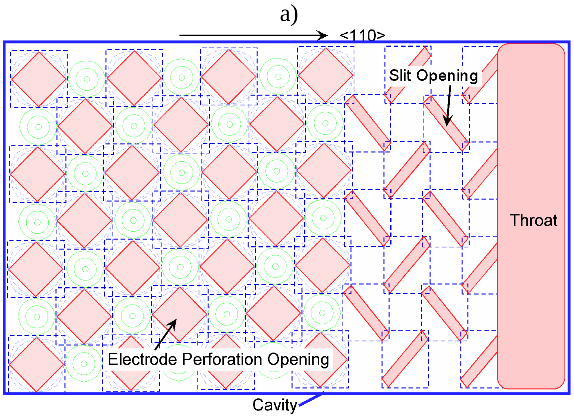
In summary, bonding with BCB provides the following advantages: 1) low temperature and low stress bonding, 2) uniform air gap spacing, 3) variable thickness, and 4) high chemical resistance. It can be used not only as the bonding media but also as the spacer between two structures with sufficient strength and uniformity. Furthermore, it can be used as a protective layer to insulate specific regions from the harsh post-bonding process.

### *Perforated Electrode With Integrated Back Cavity*

Capacitive sensors and actuators require two electrodes for their operation. One of these electrodes often needs to be perforated to reduce damping. The technology reported here allows the formation of a perforated electrode and a back cavity for these devices. As shown in Figure 1, the perforated electrode is formed with a back cavity on the same silicon wafer. DRIE and wet bulk micromachining are used to form this structure.

In bulk micromachining, highly boron-doped silicon has been used as etch stop in anisotropic wet etchants, such as EDP (Ethylene Diamine Pyrochatechol), KOH, or TMAH (Tetramethyl Ammonium Hydroxide). When a deep-boron-diffused (100) plane of silicon is perpendicularly etched through by DRIE, the exposed lightly doped silicon can be further etched by anisotropic wet etchants with high selectivity

a)

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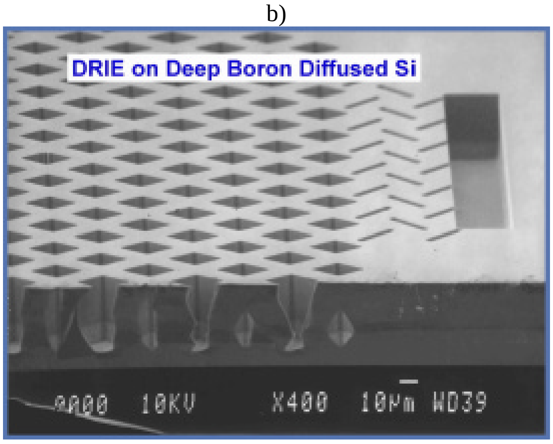


***Figure 4. a)*** *Schematic Illustration on the formation of perforated electrode and acoustic cavity.* ***b)*** *DRIE through deep-boron-diffused silicon.*

between (100) and (111) planes. Figure 4a illustrates the formation of the back cavity. Perforations on the electrode are square openings rotated by 45° from the <110> direction. When exposed to a wet etchant, the openings are undercut and the etch will expand the actual opening underneath the deep-boron-diffused silicon, as shown by the dashed square pattern in Figure 4a. With the undercut openings overlapping one another, further etch will clear all lightly doped silicon between the perforation holes (circular pattern) and, thus, form a

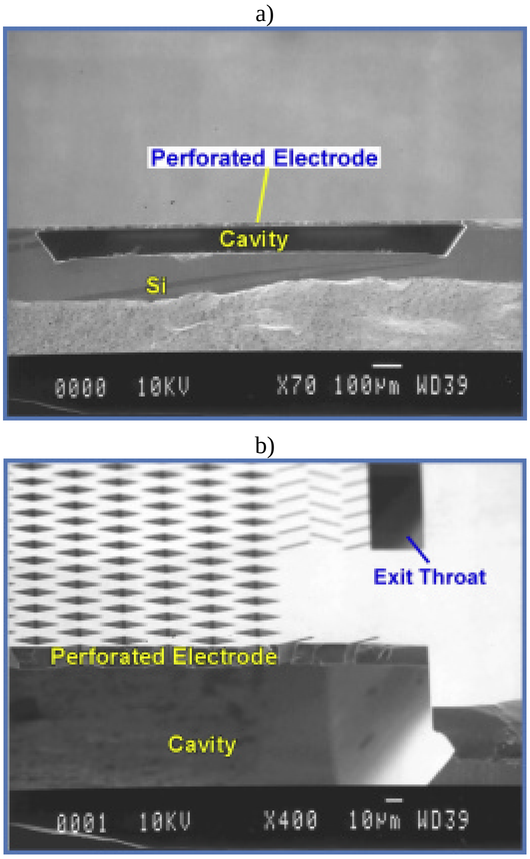


***Figure 5. a)*** *Cross-section of fabricated back cavity.* ***b)*** *Close-up of perforateted electrode and back cavity.*

continuous cavity under the perforated region. It is possible to leave some regions un-etched, as illustrated by the region labeled throat in Figure 4a If the cavity requires throat exits to be located at the edges aligning to the [110] directions, one can use cross-aligned slit openings between the throats and perforations so that the exit windows will not be excluded from the back cavity due convergent etching profiles.

To demonstrate this technique, a (100) silicon wafer was first deep boron diffused to create the electrode thickness of ~15µm. The perforation windows and exit throats were then vertically DRIE down by ~35µm, which is shown in Figure 4b. Note that the throat is aligned to the wafer major/minor flat, i.e. parallel to the [110] directions. The wafer was then anisotropically etched in TMAH solution at 85°C for 1.5 hours. EDP was not used due to its severe saturation problem when the solution was trapped in the cavity. In such case, the bottom profile of cavity became very rough. Figure 5a shows the SEM results with cavity depth of about 120µm by TMAH. It can be clearly seen that the electrode is totally released and suspended above the cavity. The etched cavity exhibits a smooth profile. A close-up view of the etched cavity is depicted in Figure 5b.

## 3D MICROSTRUCTURE FABRICATION

The process flow of proposed 3D microstructure is illustrated in Figure 6. There are two wafers pre-processed before the bonding: the cavity wafer and the diaphragm wafer. The P-type (100) cavity wafer was first deep-boron diffused on both

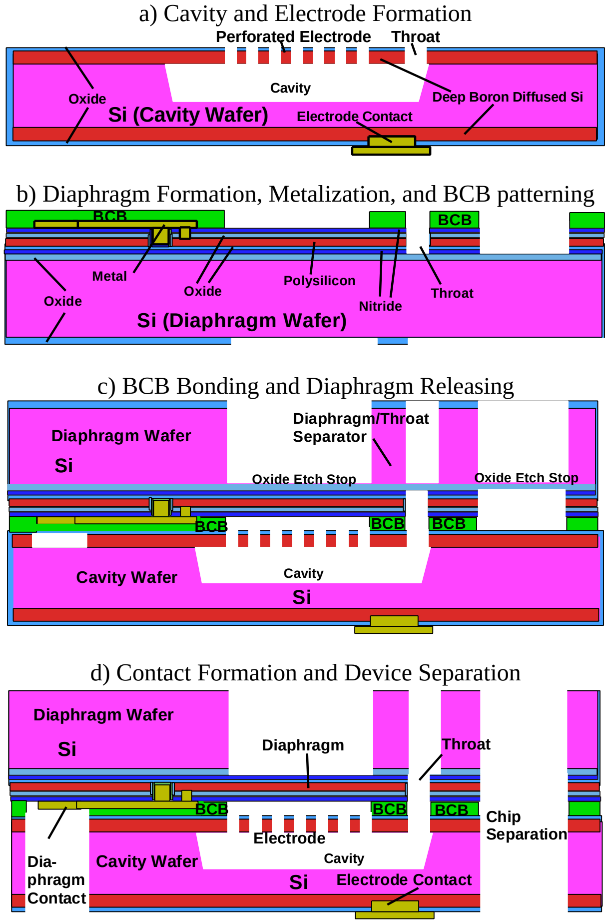


***Figure 6.*** *Process flow of 3D MEMS strucutre.*

sides for about 15µm. The residual stress of this deep-boron diffused silicon was about 20-30MPa. The wafer was then coated with 200nm LPCVD silicon dioxide at 950°C. This dielectric layer was used as both electrical insulator and TMAH etch stop. Electrode perforations and cavity exits (called "throats") were etched by BHF and DRIE through the oxide and boron-diffused silicon. Back cavity was finally formed by anisotropic wet etching in 10% TMAH solution at 85°C for 1hour15min. The cavity was about 100µm deep.

The diaphragm wafer was first thermally oxidized with about 1µm silicon dioxide. This oxide layer serves as etch stop when the diaphragm is released by DRIE in later process. The wafer was then coated with LPCVD silicon nitride (~175nm), oxide (~250nm) at 950°C, and polycrystalline silicon (~1.25µm) at 588°C. The polysilicon layer was then boron-doped at 1175°C for 35min and patterned as the electrically conductive membrane. LPCVD silicon dioxide (~250nm) and nitride (~175nm) were then deposited to cap the polysilicon layer. The resulting average residual stress of nitride / oxide / polysilicon / oxide / nitride / composite membrane was about 60-80MPa. One can tune the membrane stress and stiffness by changing the combination thickness of polysilicon, oxide, and nitride. Contact via on polysilicon diaphragm was then opened and followed by interconnect metallization (1µm Al or Cr/Au). The cavity exit opening on the diaphragm side was patterned. The photosensitive BCB was then spun and patterned on the a)

b)

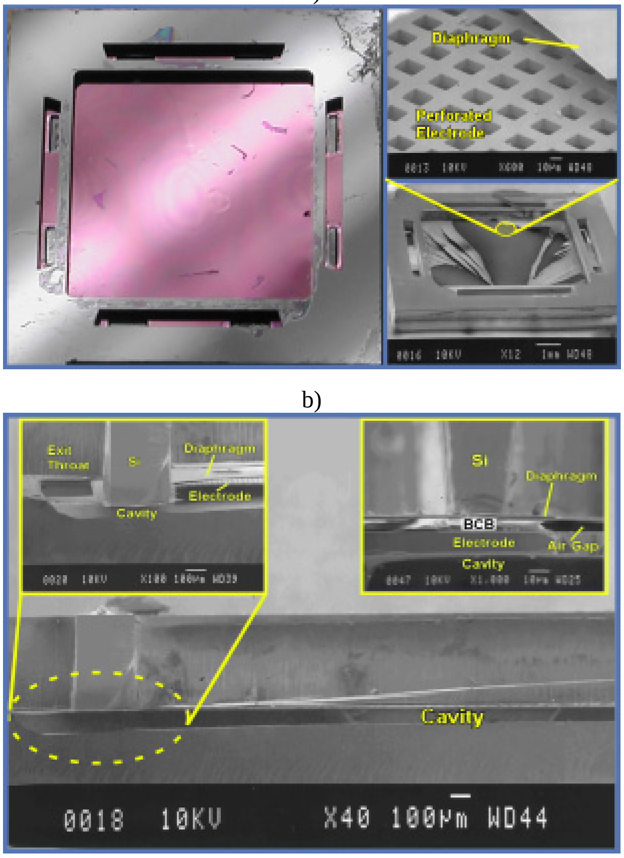


***Figure 7. a)** A fabricated capacitive pressure sensor / microphone by novel 3-D MEMS technique. **b)** Close-up view of fabricated device.*

diaphragm wafer (Figure 6b). The cavity wafer was finally aligned and bonded to the diaphragm wafer under ~150kPa applied pressure at 250°C for 30min. Note that the patterned BCB was used to not only bond the wafers but also serve as the air gap spacer between perforated electrode and diaphragm. The resulting BCB thickness was about 5.5 µm in this case. The membrane was then released by DRIE on the diaphragm wafer as shown in Figure 6c. The DRIE etch-stop oxide was then removed by BHF. Finally, the diaphragm contact opening, through wafer hole, and device separation were performed simultaneously by DRIE on the cavity wafer (Figure 6d). Note that individual devices / chips do not need extra dicing process for separation. This makes possible the device / chip to be any shapes without suffering the limitation of dicing tools.

## RESULTS

Two 3D MEMS structures were fabricated by using the proposed technology: acoustic resonator and capacitive pressure sensor / microphone. Details on fabricated high-density ejector array are presented by Chou, et. al. [4]. The fabricated acoustic resonators have demonstrated capability of producing micro air jets at velocities higher than 0.25m/s 2mm away from the cavity throats.

The fabricated pressure sensor / microphone using proposed 3D MEMS structure and process is shown in Figure 7a.

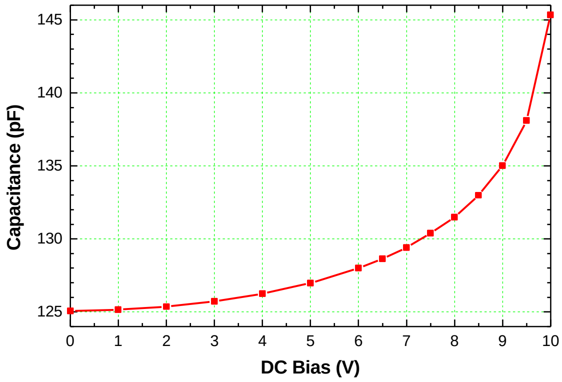


***Figure 8.** Measured capacitance versus applied DC voltage.*

The diaphragm is 6x6mm$^2$ with its first resonant frequency at about 18kHz. The cross-sectional views of different portions of the device are shown in Figure 7b. The back cavity has exit openings in this case, which can be used for condenser microphone applications. For pressure sensor applications, one can fabricate the cavity without air exhaust. Meanwhile, different perforations can be used depending on the device applications. The measured capacitance as a function of applied DC voltage bias is shown in Figure 9. This device exhibits a total capacitance of 125pF at zero voltage bias, which includes a parasitic capacitance of about 70pF. Such parasitic capacitance can be easily reduced below 20pF by changing the design. The total measured $\Delta C$ is ~20pF with voltage changing from 0V to 10V (~20Pa equivalent pressure), which is equivalent to ~1pF/Pa. The pull-in voltage is higher than 10V.

## CONCLUSION

This paper presents a novel 3D MEMS fabrication technology. The key element of the technology is the use of BCB for low-temperature wafer bonding. Meanwhile, BCB serves as the air gap spacer in the structure for capacitive transducers. Silicon DRIE and bulk micromachining are also used to produce the final 3D structure. A high-sensitivity capacitive pressure sensor / microphone has been fabricated based on the proposed technology. This technology has demonstrated a robust and simple process in fabricating complex MEMS structures for various applications.

## ACKNOWLEDGMENTS

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