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Fabrication of piezoelectric MEMS devices-from thin film to bulk PZT wafer

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Abstract Integrating patterned functional piezoelectric layer onto silicon substrate is a key technique challenge in fabrication of piezoelectric Micro Electro Mechanical System (pMEMS) devices. Different device applications have different requirements on the thickness and in-plane geometry of the piezoelectric layers and thus have their own processing difficulties. In this paper, the techniques of integrating piezoelectric function into pMEMS has been discussed together with some diaphragm-based pMEMS devices which have relatively lenient requirement on patterning of the piezoelectric layers. Sol-gel thin film can meet the requirement of most of the sensor applications. The composite thick film is one of the promising solutions for thick film devices due to its good processing compatibility. Si/Pb(Zr_xTi_{1-x})O_3 wafer bonding technique makes it possible to thin down the ceramic wafer to less than 10 μm by using chemical mechanical polishing, which, therefore, provide us another approach to integrate thick piezoelectric layer on silicon to cover the need of most of the thick film devices. Directly make double side aligned electrode patterns on bulk piezoelectric wafer/plate by using photolithography opens up a new area of pMEMS. The advantage of using bulk piezoelectric wafer/plate in pMEMS is that we can select commercial available ceramics or single crystals with excellent piezoelectric properties and thus ensure the overall performance of the devices.

Keywords Piezoelectric Micro Electro Mechanical System (pMEMS) · Diaphragm type transducer · Sol-gel thin film · Composite thick film · Wafer bonding · Micromachining

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1 Introduction

Two key technique challenges have to be considered when it comes to designing and fabricating piezoelectric micro electro mechanical system (pMEMS) devices. The first one is integration of the piezoelectric function layer (film/coating) onto silicon substrate on wafer scale at low temperature; the second one is the patterning/etching of the piezoelectric layers with the resolution down to micrometer range. Different device applications have different requirements on the thickness and in-plane geometry of the piezoelectric layers and thus have their respective processing difficulties.

Piezoelectric layer can be integrated onto silicon wafer in three forms: thin films with thickness less than 3 μm; thick films with thickness ranged from several microns to 50 μm and bonded bulk plate. For those devices that need an accurately defined boundary of piezoelectric element, such as a cantilever, patterning or etching of the piezoelectric layer is inevitable. Feasible dry [1] and wet [2] etching processes with sufficient etching resolution have been developed for thin films. As a result, some thin film pMEMS devices have been demonstrated successfully [3, 4]. Whereas, there are only two ways, chemical wet etching and physical sand blasting or ion milling [5], can effectively remove thick film or bulk Pb(Zr_xTi_{1-x})O_3 (PZT) but the etching resolution and selectivity is not yet satisfactory. It is almost impossible to precisely etch thick films and PZT plate using the developed thin film etching techniques due to the slow etching rate caused by stable chemical properties of the PZT and the severe under cut resulting from the isotropic wet etching. This processing difficulty has hindered the development of thick film pMEMS devices. To deal with this issue, researchers have been seeking the technology of directly depositing patterned films on silicon substrate [6], such as ink-jet printing, aerosol deposition, screen printing and spry coating [7]. Benefiting from eliminating the need to etch the film after deposition, this kind of technology should be the best solution to fabricate thick film pMEMS devices. However, the microstructure of thus made films is not dense and therefore their piezoelectric properties are inferior to those of bulk ceramic PZT.

Wafer bonding technology enable us to directly use the excellent properties of the bulk ceramics, the device properties, without a doubt, are superior to those of other technologies. Usually, people believes that it is difficult to thin down the ceramic PZT plate to less than 50 µm-thick due to its fragility. It is true for a single PZT plate. A number of thick film technologies have therefore been developed to bridge the gap between the processing capabilities of thin film deposition techniques and the machining of bulk ceramics [8–14]. However, it was recently demonstrated that, after being well bonded to silicon wafer, the PZT plate can be thinned down to less than 10 µm by using chemical mechanical polishing [15, 16]. This thickness is almost near the upper border of the thin film technology. This encouraging result means that Si/PZT bonding technology could become a key integration technology for high power/sensitive pMEMS applications if the etching problem of the bulk PZT can be overcome or intentionally avoided by device design.

Actually, some of the pMEMS devices, such as those based on diaphragms, have relatively lenient requirement on the precision of the patterns of the piezoelectric layers. In these cases, the device boundary is not defined by the edge of the piezoelectric layer but defined by clamping conditions of the diaphragm or even a specially designed electrode pattern. So the etching process, if required, is just used to expose the electrode pad beneath the piezoelectric layer and the precision of the pattern is not crucial for the performance of the devices. Taking advantage of this feature makes it possible to implement mass production of diaphragm type pMEMS devices by using thick film technology or Si/PZT bonding technology even though the patterning/etching resolution of the PZT is not satisfactory. Following this idea, some diaphragm-based pMEMS devices have been developed. In this paper, these devices, including mass sensitive biosensors with sol-gel thin film; micromachined ultrasonic transducer with composite thick film; acoustic transducer with bonded PZT plate and even a transducer made on a single piezoelectric plate with specially designed electrode patterns, will be introduced together with their respective piezoelectric integration techniques.

2 Thin film biosensors

Thin film integration technologies are, relatively speaking, well developed for pMEMS applications. For mass production, large area deposition technology is preferred and the uniformity of the piezoelectric films on wafer scale is quite important for the performance consistency of the devices. Considering these requirements, sputtering, metal-organic chemical vapor deposition and sol-gel are promising technologies for commercial production of thin film pMEMS.

A diaphragm type piezoelectric mass sensitive biosensor is one of the unique pMEMS devices developed by using the thin film integration technology. The working principle of the mass sensors is that the resonant frequency of the diaphragm decreases in response to a mass loaded onto its surface. The sensors are usually excited by a voltage through converse piezoelectric effect and the impedance spectrum is utilized for monitoring the change of the resonance frequency.

The mass sensitivity S_m of a multilayer piezoelectric diaphragm can be expressed as [17]

$$S_m = \lim_{\Delta m \to 0} \frac{\Delta f}{f_0} \cdot \frac{1}{\Delta m} = -\frac{1}{2} \cdot \frac{1}{\sum_i \rho_i d_i} \quad (1)$$

where Δm is the mass per unit area loaded to the surface of the diaphragm, $\Delta f = f - f_0$ is the frequency shift in response to the mass loading Δm, ρ_i and d_i are the density and thickness of the ith layer in the diaphragm. It can be seen from Eq. 1 that the mass sensitivity of the sensor is determined by the mass per unit area of the diaphragm, $\Sigma \rho_i d_i$. Therefore, the etching quality would not affect the properties of the sensor if we do not etch the PZT on the diaphragm. For a micro diaphragm consists of a 0.8 µm-thick piezoelectric layer on a 2 µm-thick silicon oxide layer, the theoretical mass sensitivity (48.8 m^2/kg) obtained by Eq. 1 of the first flexural mode is about 30 times higher than that of a quartz crystal microbalance (QCM) operating at 6 MHz (1.4 m^2/kg) [18].

The piezoelectric micro-diaphragm consists of 0.8 µm-thick PZT on 2.0 µm-thick silicon oxide layer was fabricated by combining sol-gel PZT thin film and MEMS technology. Figure 1 compares the schematic structure and the photos of the fabricated sensors on a silicon wafer. The quarter circles on front side are exposed bottom electrode pads. The 0.8 µm-thick PZT was wet etched by HCl based recipe [2]. The three white circles connected together are the top electrode of the diaphragm (centre ones) and their bonding pads. The etched parts (bottom electrode pads) of the devices are intentionally designed far away from the core part (diaphragm) of the sensor. From the back side photo of the sensors, we can clearly see the diaphragm (reaction chamber) and the device boundary made by deep reactive ion etching (DRIE). The active electrode is at the center of the diaphragm and covers 50% of the whole diaphragm area.

The Q value obtained in air from the real part of the impedance spectrum (see Fig. 2) is as high as 219 at a quite

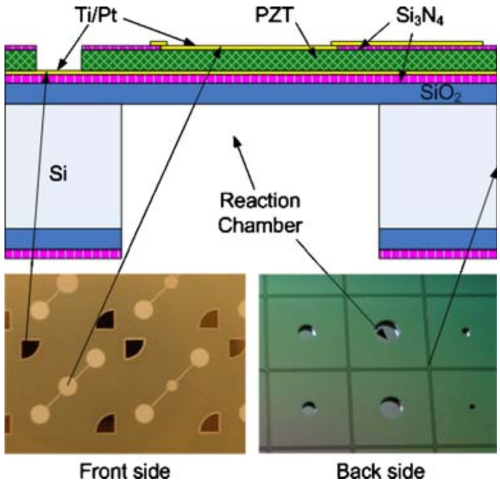

Fig. 1 Comparison between the schematic structure and the fabricated piezoelectric diaphragm type biosensors on Si wafer

lower operating frequency of around 122 kHz. The obtained Q value of the flexural mode sensor is comparable with that (200–300) of a typical film bulk acoustic resonator (FBAR) with a structure of ZnO on silicon nitride operating at around GHz [19]. This means the flexural vibration mode has the similar resolution in detecting frequency shift compared to thickness mode employed by FBAR.

When working as a biosensor, the surface area of the piezoelectric diaphragm should be first immobilized with a bioreceptor. Once an interested biological entity is captured by the bioreceptor, the change in mass can be detected via shift in resonant frequency. We observed the frequency shift after immobilizing biological entities on the back side reaction chamber of the sensor. A protein A functionalized surface is prepared to specifically capture immunoglobulin G (IgG). The goat IgG captured by protein A has an elegantly orientation that makes its Fab fragment open to corresponding antigens. The impedance spectra (Fig. 3) clearly show a frequency depression of 860 Hz after the

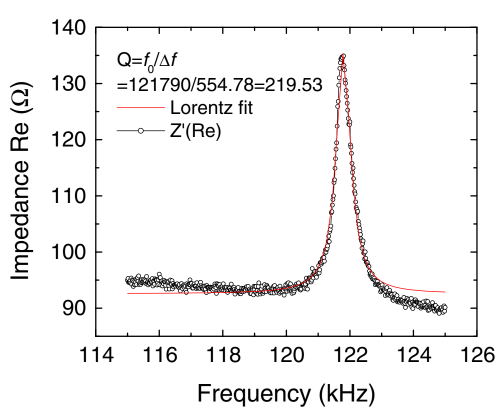

Fig. 2 Real part of the impedance spectrum of a diaphragm with diameter of 0.8 mm. The Q factor is as high as 219 at relatively lower operating frequency compared with FBAR

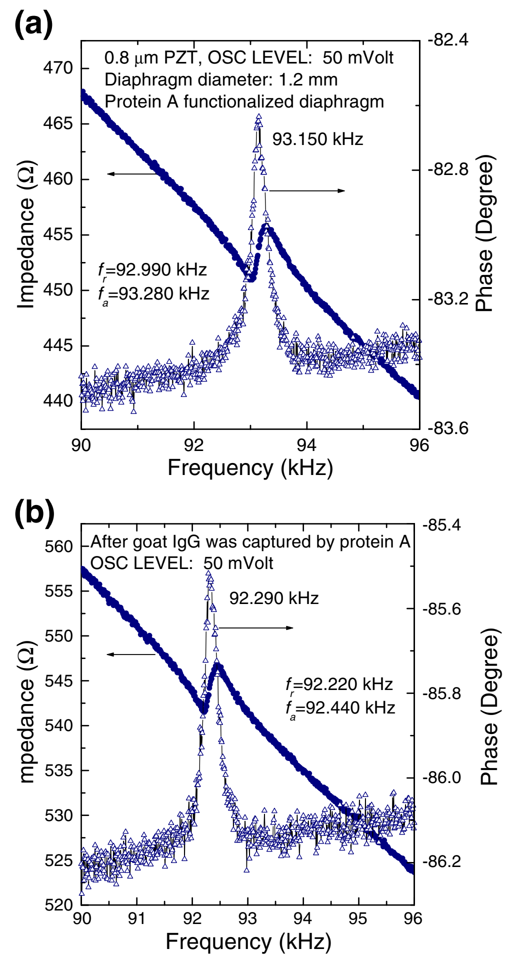

Fig. 3 Impedance spectra of a biosensor with diameter of 1.2 mm. (**a**) Protein A functionalized diaphragm. (**b**) After goat IgG was captured by protein A. A frequency shift of 860 Hz was observed from phase curves after the goat IgG was captured by protein A

goat IgG was captured by the protein A, indicating that the flexural mode micro diaphragm has a potential to be used as a biosensor. Besides, its low working frequency permits the use of low-cost electronics thus providing an alternative to the QCM sensor.

3 Thick film ultrasonic transducers

During the past few years there has been a significant progress towards implementation of thick film pMEMS devices for required large generative force, such as sensors and actuators used in liquid, micro pumps for micro fluidic devices, micromanipulators for medical applications, piezoelectric micromachined ultrasonic transducers (pMUT) for high frequency medical imaging, and so on. Among them the pMUT is an interesting example.

The concept of pMUT array was first demonstrated by both L. E. Cross's group at Pennsylvania State University with sol-gel PZT thin films [20] and by B.T. Khuri-Yakub's

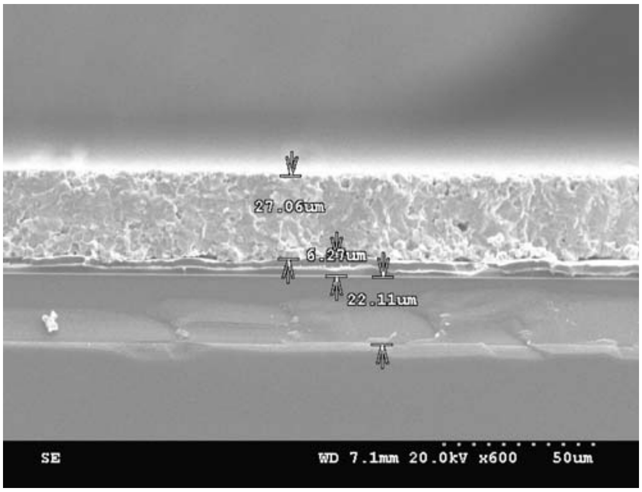

Fig. 4 SEM images of the cross section of PZT/Si bonding interface

group at Stanford University with ZnO thin films [21]. The performance of a single pMUT element was further investigated extensively by Nava Setter and Paul Muralt's group at the Swiss Federal Institute of Technology with 2–4 μm thick sol-gel PZT films on SOI wafers [22] in terms of the microfabrication process and improvement of the coupling coefficient. Single pMUT element containing 2 μm-thick, textured PZT thin films has been fabricated and demonstrated in the frequency range of 60 kHz (1 mm

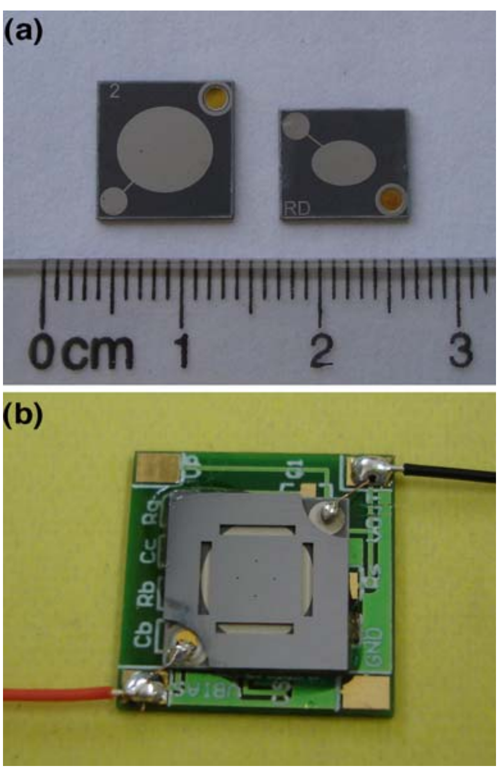

Fig. 5 Fabricated acoustic transducers using Si/PZT wafer bonding technology. (**a**) Individual transducers after dicing (without back cap). (**b**) A final device with bonded back cap can be used as both microspeaker and microphone

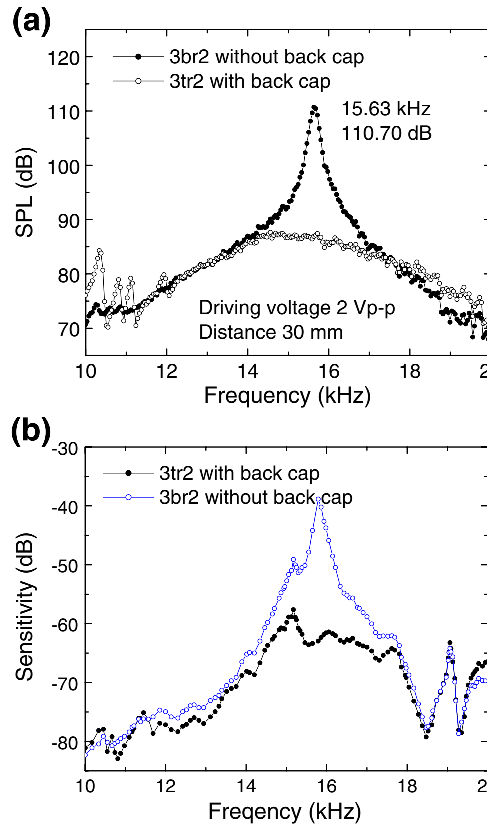

Fig. 6 Acoustic transmitting and receiving performances of the transducers with and without back cap. (**a**) Output SPL as a speaker at vicinity of its resonant frequency of 15.63 kHz. (**b**) Sensitivity as a microphone in response to a commercial speaker

diameter) to 1.8 MHz (300 μm diameter), but the performance of the pMUT array has not been reported yet. Okuyama's Group at Osaka University has successfully developed a two-dimensional receiving array with demon-

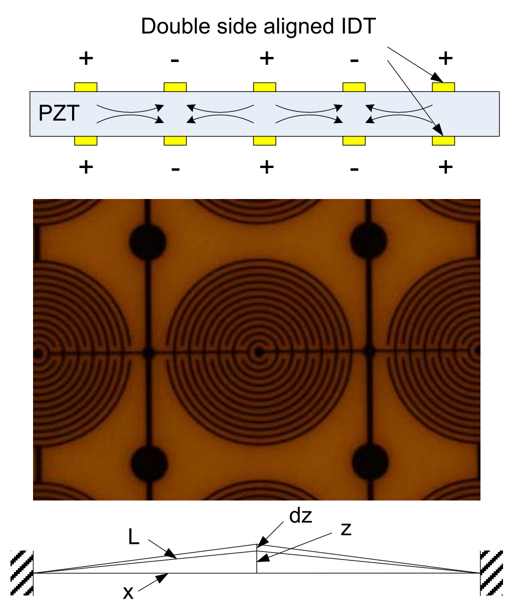

Fig. 7 Design concept of a circular piezoelectric diaphragm transducers and array with ring-shaped IDT electrodes

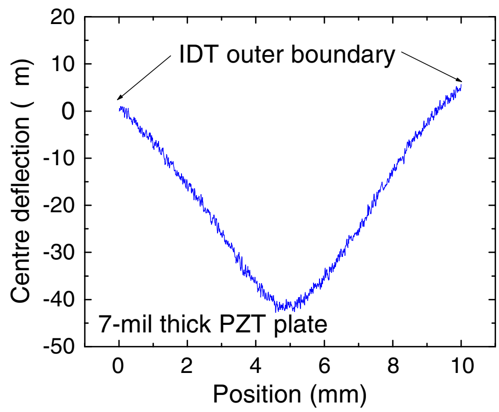

Fig. 8 Surface deflection of an IDT transducer with radius of 5 mm made on a 175 μm-thick PZT plate after poling. The initial height at the center is around 40 μm

strated high directivity using 1–2 μm thick sol-gel PZT thin film [23]. The operating frequency around 100 kHz can be used for the airborne three-dimensional imaging. Simulation result confirms that pMUTs are potentially suited for 10 MHz medical applications. For the Si substrate, to obtain a 3 MHz transducer for imaging in water, the optimal thickness would be 12 μm PZT on 18 μm Si [22]. However, it is a big challenge to prepare such thick PZT films on silicon wafers.

A novel composite film technology has been demonstrated to overcome this limitation [6, 12]. Low temperature sol-gel processing was modified by mixing with ceramic powder to yield a hybrid technique capable of integrating thick films on Si substrate. Piezoelectric films with thicknesses of 3–20 μm, which satisfy the requirement of MHz pMUT, have been successfully fabricated using this approach at a low temperature of 650 °C [24, 25]. Such a low temperature process is compatible with the large scale Si processing technology. A two-dimensional transducer array and its beam forming ability have been demonstrated by using this composite film technology [26]. It shows that the composite film technology is a feasible film integration technique for thick film pMEMS application although the wet etching quality of the thick film is not satisfactory; the ratio of undercut to film thickness is always larger than 1:1 due to porous microstructure of the thick film. However, there are still a number of challenges to realize MHz level pMUT arrays for immersion ultrasonic imaging. From device design side, the key technical problem is how to increase electromechanical coupling factor whilst optimize the operating frequency and eliminate crosstalk between elements. From processing side, the reproducibility and consistency of resonance frequencies of each element and the packaging of the array are also challenging.

4 Si/PZT wafer bonding

Thin and thick film integration technologies have been widely investigated for pMEMS application. Whereas bulk ceramic plate is seldom employed because it is difficult to thin down the ceramic plate to less than 50 μm by lapping due to its brittleness. However, bulk PZT with a thickness of about 10 μm or less can be obtained by lapping PZT after bonding it to Si wafer at 450 °C by employing gold as the intermediate layer [15, 16], which opens up a promising approach for commercializing MEMS devices. Dicing, sand blasting, wet etching or KrF excimer laser can be employed to define PZT pattern or separate individual elements.

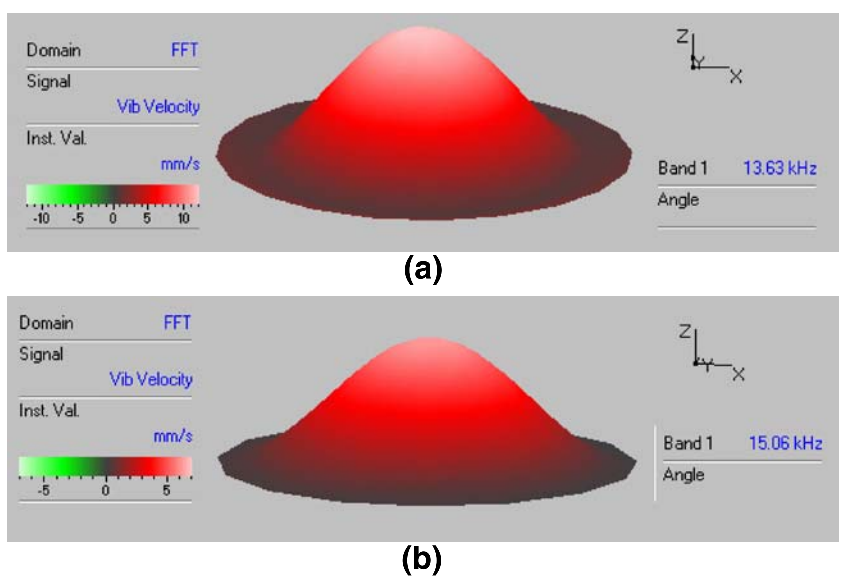

Fig. 9 Comparison of the vibration velocity responses between two different diaphragm type transducers. (**a**) The d_{33} IDT transducer with diameter of 10 mm and thickness of 225 μm. The maximum velocity is around 12 mm/s at resonant frequency of 13.63 kHz. (**b**) The d_{31} bimorph transducer with diameter of 6.6 mm and total thickness of 60 μm. The maximum velocity is around 7 mm/s at resonant frequency of 15.06 kHz

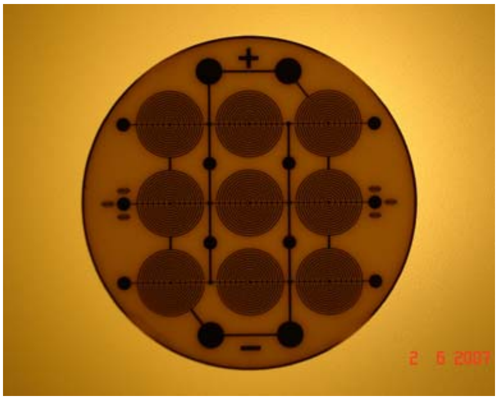

Fig. 10 An IDT transducer array fabricated on a 2-in. PZT wafer

Recently, we developed a polymer bonding technology to directly integrate bulk PZT to Si wafer. A diaphragm-type acoustic transducer was fabricated by using this integration technology. A 300 μm thick PZT plate with diameter of 90 mm was bonded to a 4″ SOI wafer with 20 μm thick device layer. The bonding was made by using Karl Suss SB6 wafer bonder at 160 °C under three bar pressure for 30 min. A special Si back cap with perforated acoustic holes made by DRIE is also bonded on the diaphragm to broaden the acoustic frequency spectrum. Key techniques of the fabrication include a low-temperature bonding technique using spin on polymer (Cytop from AGC, Japan) [27], design of electrode interconnect, chemical mechanical polishing (CMP) for thinning down the bulk PZT, and DRIE of silicon.

Figure 4 clearly shows the high quality bonding interface after thinning down the PZT plate by CMP. The thickness of the PZT is around 26 μm, two layers of polymer are totally 4 μm in thickness and the 20 μm thick device layer is also clearly seen. Figure 5 shows the fabricated transducers. The transducer is less than 0.5 mm in thickness (without acoustic cap and printed circuit board) and has a potential to be used as a microspeaker for mobile phones. The low temperature bonding and lapping does not degrade the performances of PZT. The effective electromechanical coupling coefficient k^2 measured from impedance spectrum is 4.91%. The good electromechanical performances of the transducer are attributed to the good piezoelectric properties of the bulk PZT ceramic.

The acoustic cap with perforated through holes was fabricated by DRIE on 200 μm-thick silicon wafer. The holes locations and diameter were optimized according to our previous study [28]. Figure 6(a) gives frequency dependence of the output sound pressure level (SPL) of fabricated speakers. Before bonding the acoustic cap, the maximum SPL measured at distance 30 mm is 110 dB at its resonance frequency. After mounting the acoustic cap, the SPL is suppressed to around 85 dB, but the bandwidth of the speaker is broadened significantly. Following this phenomenon, transducers with flat frequency characteristics can be obtained at the vicinity of its resonance frequency. This is very important for the transducers work as both transmitter and receiver.

In fact, the fabricated transducer can be used either as speaker or as microphone due to the nature of piezoelectricity. Figure 6(b) shows the sensitivity of the same transducer when they work as a microphone. A commercial speaker (JBL HLS410) was used as sound source. Similarly, mounting the acoustic cap can get a relatively flat response in the vicinity of the resonance frequency. The sensitivity is around −60 dB with reference to 1 V/Pa. The transducer without back cap has sharp response and the maximum sensitivity is −40 dB.

The advantage of this method is that we can select commercial available ceramics or single crystals with excellent piezoelectric properties and thus obtain good coupling factor of the device since $k^2 \propto e_{31}^2/\varepsilon$. The main problem we currently meet is the thickness uniformity at the whole wafer level after CMP. Despite of this problem, PZT/Si wafer bonding technology should become the key technology for mass production of relatively larger pMEMS devices.

5 Transducers made on PZT wafer

To date, the basic fabrication process for pMEMS devices is to integrate piezoelectric layers on a passive substrate,

Table 1 Comparison among the planar piezoelectric integration technologies for pMEMS.

	Thin film	Thick film	Bonded bulk plate
Layer thickness	Less than 2 μm	2 to 50 μm	10–100 μm
Process temperature	500–700 °C	650–900 °C	R.T. to 550 °C
Piezoelectric properties	Good	Inferior to thin film	Very good
Integration technologies	Well developed	Developed	Developed
Patterning and etching	Easy	Difficult	Very difficult
	Wet, dry and lift-off	Wet and ion milling	Wet, laser, dicing and sand blasting
Main application	Sensors	Actuators Transducers	Actuators Transducers

such as Si, SiO_2, Si_3N_4, poly Si and so on, and form a bimorph structure by using micromachining. Is it possible to make a micro device on piezoelectric wafer without a substrate? The answer is yes. Nowadays, it is easy to make double side aligned electrode patterns on both side of the piezoelectric wafer/plate by using photolithography technology, which facilitates the design, fabrication of various novel smart structures defined by different electrode patterns on PZT wafer, such as interdigitated (IDT) electrodes. Some new smart structure, actuator, or transducer array can be developed following this idea. And the mechanism of the new structure also needs to be investigated. A circular piezoelectric diaphragm transducer and array with ring-shaped IDT electrodes was thus fabricated on a PZT plate.

Figure 7 shows the design concept of the transducer. Double side aligned ring-shaped IDT electrodes were made on both side of a PZT wafer. In-plane d_{33} mode was used to excite the transducer. The device (diaphragm) boundary was defined by the outer diameter of the IDT electrodes. The unique feature of this transducer derives from the ring-shaped electrodes. Because of the ring-shaped IDT electrodes, the piezoelectric deformation occurs only within the area covered by the IDT electrodes. Since the diaphragm is rigid clamped at its circumference, it will deflect at the center after polarization. Assuming the PZT plate is stiff enough, from the geometry relations, we can get

$$dz = \frac{L}{z} dL = \frac{L}{z} n d_{33} V \tag{2}$$

where L (~x) is the outer radius of the IDT, n is the number of turns of the IDT, z is the initial height at the centre after poling. If $L/z=30$, $n=10$, dz will be 300 times larger than that induced by pure d_{33} in thickness direction!

It can be seen from Eq. 2 that the displacement response dz strongly depends on the initial height z at the center. Figure 8 shows a measured surface deflection of a transducer with a step profiler. It confirms that a diaphragm with radius of 5 mm made on a 175 μm–thick plate has around 40 μm initial height z after poling. But cracks along radius direction occurred due to d_{31} effect. Poling field should therefore be carefully selected.

Figure 9 compares the vibration velocity responses of the fundamental resonant mode between the d_{33} IDT transducer and the d_{31} bimorph transducer as shown in Fig. 5(a). Both transducers were excited by a 2 V_{peak} diving voltage. The IDT transducer with diameter of 10 mm made on a 225 mm-thick PZT wafer has little bit higher velocity response than d_{31} type bimorph with diameter of 6.6 mm. It shows the two transducers have the similar piezoelectric response. However, they are totally different in driving mechanism. Compare with the d_{31} bimorph type transducer, the structure and fabrication of the IDT transducer is very simple. IDT transducer arrays can also be easily fabricated on PZT wafer without etching and bonding processing. Figure 10 shows an IDT transducer array fabricated on a 2-in. PZT wafer. The synchronous vibration of all the transducers in the array has been demonstrated by using a scanning laser Doppler vibrometer when all the transducers are parallel connected and excited simultaneously.

The preliminary results reveal that it is possible to make a micro device on a piezoelectric wafer without any substrate, which opens up a new direction for the development of pMEMS devices and arrays.

6 Summary

Various technologies for integrating piezoelectric function onto silicon wafer, ranged from thin film deposition to PZT/Si wafer bonding, have been developed for the fabrication of the pMEMS devices. A comparison of these technologies is summarized in Table 1. Fabrication technologies of thin film pMEMS devices are relatively mature due to the availability of various thin film deposition and etching technologies. Etching processes of thick film and bonded bulk PZT, however, have not been well developed. Considering this process difficulty, directly depositing patterned films so as to eliminate the etching of the films could be the next fabrication technologies of the thick film pMEMS. The Si/PZT wafer bonding technique provides the possibility of thinning down the ceramic PZT wafer to as thin as 10 μm and could become a useful integration technology for pMEMS applications. This technology will greatly promote the commercialization of the pMEMS devices. For planar integrated piezoelectric thick film or bonded PZT, low cost wet etching is an effective way to fabricate some diaphragm-type devices, if the etching precision can be ignored by intentionally designed etching area. In addition, it is possible to make a micro device on a piezoelectric wafer without any substrate. The advantage of this technique is that the devices can be defined through electrode patterns on both side of the PZT and no etching process is needed. This technique may open up a new direction for development of pMEMS devices and arrays.

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