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New Packaging Method Using PDMS for Piezoresistive Pressure Sensors**

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In this paper, we propose a novel wafer-level packaging (WLP) method carried out at room temperature for piezoresistive pressure sensors. We use a polydimethylsiloxane (PDMS) sheet to replace a Pyrex glass wafer for sealing the backside (or back-surface) V-grooved chambers of the pressure sensor chips. PDMS is now a well-known material in micro electronic mechanical system (MEMS) technology. It is not only cheap but also has the advantage of a simple process. We fabricated piezoresistive pressure sensors, made from the same batch, with different packaging materials of Pyrex glass and PDMS sheets. Spin coating is used to control the thickness of PDMS sheets by choosing silicon and Teflon disks as supporting substrates for the PDMS sheets. The sensors packaged by PDMS room-temperature bonding exhibited a similar performance to those packaged by conventional anodic bonding, as verified through pressure testing.

1. Introduction

Conventional piezoresistive pressure sensors are usually fabricated by sealing two substrates together, creating reference cavities for sustaining a pressure difference. An upper silicon substrate, on which bridge-type piezoresistors are implanted or diffused,

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metal conducting wire is deposited, and a diaphragm structure is formed by a backside etch process beforehand, is sealed to a second silicon or glass substrate (sometimes called a constraint wafer). This results in a chip with the active component and diaphragm structure on the top surface, with a reference cavity in the center and with a constraint substrate at the bottom. Sealing the cavity below the sensing diaphragm tightly and hermetically is very important for ensuring the precision of pressure sensors. If the seal leaks, the offset voltage of the absolute pressure sensor would change and the gage or differential pressure would have large errors.[1] Two of the most popular bonding processes used in industry to seal the cavity are the bonding with a silicon constraint using a low-temperature glass frit as a media material (silicon-to-silicon bonding)[2] and the bonding with a Pyrex #7740 glass using an anodic bonding process (silicon-to-glass bonding.[3]) Devices fabricated using these two approaches must be heated above 400–500°C, and might exhibit induced residual stress due to thermal mismatch.[4] Moreover, sodium ions may contaminate the microelectronics during the glass bonding process.[5] Therefore, in this work we propose a novel wafer-level packaging (WLP) method based on the use of a polymer material, PDMS, to replace the conventional packaging material, Pyrex #7740 glass.

In the 1990s, Whiteside *et al*. began developing soft lithography based on PDMS, and this polymer material is now very popular and promising in the bio-MEMS area. For example, PDMS has been used to fabricate micropumps,[6,7] microvalves,[8,9] microlens,[10] optical gratings[11,12] and microchannels.[13,14] It has several advantages in device fabrication and packaging. First, it can be bonded with various substrate materials, *e.g.*, single-crystal silicon, SiO_2, SiN, glass and another PDMS substrate after applying the above substrates by hydrophilic surface treatment at room temperature.[15] Second, the bonding takes only a few minutes or can even be performed right away; thus, the bonding time is much shorter than that of the anodic bonding process, which needs at least half an hour to one hour for a 4-inch wafer. Third, it is much cheaper than other silicon-based materials. PDMS costs about US$ 90 per 1 kg and can be used 60 times to package an area equivalent to that of a 4-inch wafer, whereas a 4-inch Pyrex glass wafer costs even more than US$ 20. Furthermore, PDMS has a good property against the leakage of fluid. It can even be applied as an O-ring to protect the processing wafer during chemical wet etching.[16] However, PDMS has a critical drawback of gas permeable in using as a substrate to replace the #7740 Pyrex glass.[17] This leads to that the reference pressure in the sealing chamber is not constant while going through a long-time pressure monitoring. The PDMS package method of the pressure sensors herein still has industrial applications used in real time measurement even if it is not suitable to use in a long-term or a steady observation. Moreover, in a more commercial packaging of pressure sensors, another layer of low-mechanical-strength epoxy will be coated on the sensor to protect the sensor die and bonding wires, a better hermetic sealing therefore hopes to be guaranteed. On the basis of the above arguments, we propose here a novel WLP method based on the use of using PDMS to reduce the process time and cost for piezoresistive pressure sensors.

2. Pressure Sensor and Packaging Material

2.1 *Piezoresistive pressure sensor*

In 1954, Smith reported the piezoresistive effect, which is the change in resistance with applied stress, in semiconductors, *e.g.*, silicon and germanium.[18] This discovery enabled the production of semiconductor-based sensors.[19] Piezoresistive pressure sensors usually have four piezoresistors of the same resistance designed on a square diaphragm. These piezoresistors are arranged as a Wheatstone bridge circuit. Since pressure is applied on the thin diaphragm, two resistors perpendicular to the diaphragm edges are subjected to tensile stress, whereas the other two resistors parallel to the diaphragm edges are subjected to compressive stress. Such a configuration of resistance change (two increasing, two decreasing, with almost the same amount of resistance change) result in the best performance of the pressure sensor, i.e., the sensor with such structure can produce the largest output voltage. The output voltage is given by the following equation:

$$\frac{V_{\text{out}}}{V_0} = \frac{\Delta R}{R_0} = kP \tag{1}$$

where ΔR is the absolute value of the resistance change of each resistor, regardless of being perpendicular or parallel to the diaphragm edge, R_0 is the original resistance of each resistor, V_0 is the bias voltage and V_{out} is the output voltage, which varies with the applied pressure. The output voltage varies linearly with applied pressure P under the assumption of small deformation (the constant of proportionality coefficient is denoted by k.)

We take a piezoresistive pressure sensor with a diaphragm of 1680×1680 μm^2 area and of 60 μm thickness as an example. A PDMS sheet is used as an alternate substrate instead of a Pyrex glass wafer to seal the backside V-grooved cavities here. The sketch of the pressure sensor and its cross section is shown in Fig. 1. The process of this pressure

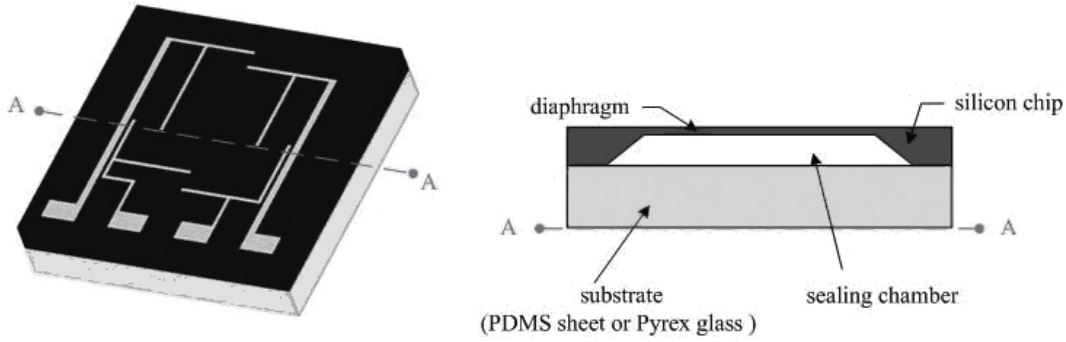


Fig. 1. The sketch of the pressure sensor and its cross section.

sensor can be separated into two parts: the first part is the semiconductor processing of boron-implanted piezoresistors and (sputtered aluminum) metal connections on the front surface of silicon wafers, and the second part is the anisotropic bulk etching on the backside of wafers. An isotropic enchant, 30 wt% KOH, is used in the back-side etching process to form the silicon diaphragm. Figures 2 and 3 show the front-side (or front-surface) view and backside view, respectively, of a 4-inch sensor wafer after fabrication. The finished surface of the wafer backside is low pressure chemical vapor deposition (LPCVD) SiN layer. This layer is used as etching mask to protect the silicon wafer during the anisotropic etching process. SiN surface can be bonded with PDMS very well, and it's unnecessary to be removed.

2.2 *PDMS material properties*

PDMS is now a well-known and popular material in the bio-MEMS area. It is transparent for convenient observation, and is a kind of inert, nontoxic, biocompatible elastomer. After adjusting the surface property using oxygen plasma at ambient temperature, PDMS is bonded with many materials including silicon, SiO_2, SiN or even another PDMS sheet. Oxygen plasma herein supplies enough energy for removing the methyl groups, and replacing them with hydroxyl dangling bonds, as shown in Fig. 4. The surface property of PDMS therefore changes from the hydrophobic state to the hydrophilic state temporarily.

The temperature of PDMS bonding is almost the same as the ambient temperature. The highest temperature in the PDMS process then occurs in the polymer curing procedure instead of the bonding process. A classical curing of a PDMS sheet in

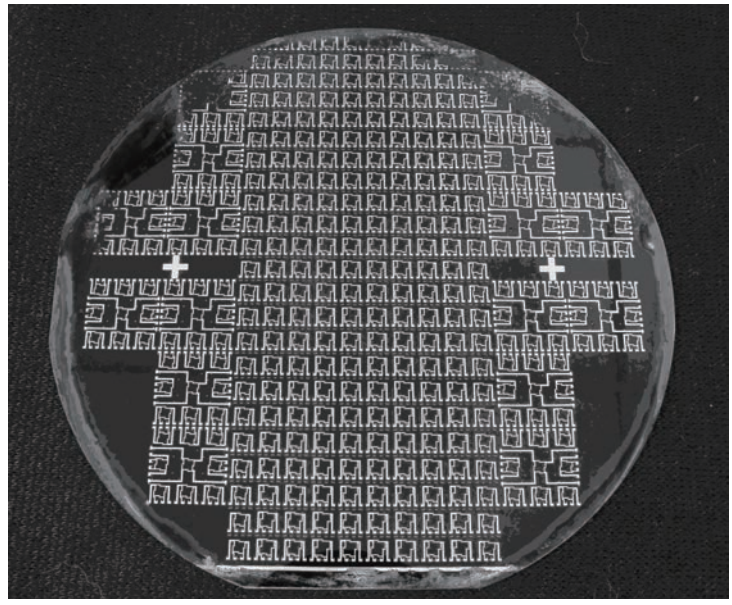


Fig. 2. A silicon wafer with pressure sensor chips: front-side view.

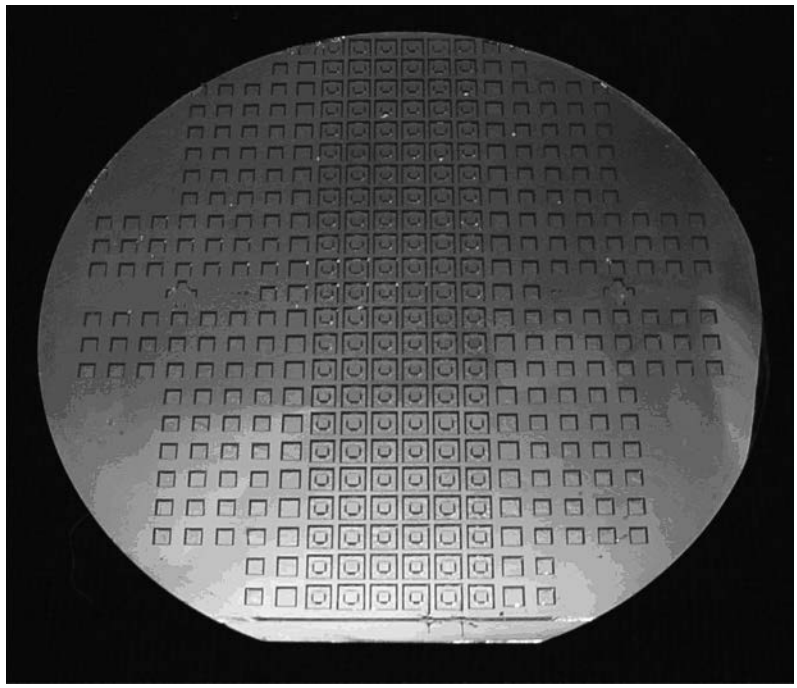


Fig. 3. A silicon wafer with pressure sensor chips: back-side view.

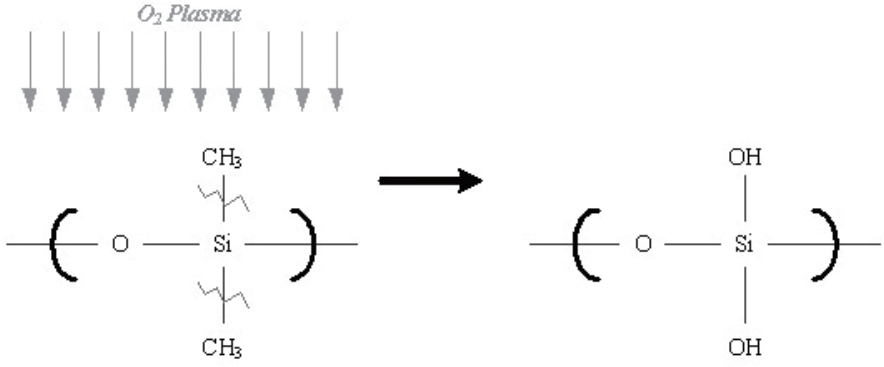


Fig. 4. Using O_2 plasma to change the surface functional groups as well as the wetting property of PDMS (from hydrophobic to hydrophilic surfaces).

general does not exceed 120°C, which is much lower than the case of anodic bonding. Moreover, PDMS has better stability and heat tolerance than other polymers in common use in the temperature range of –50 to 200°C after curing. All these properties of PDMS mentioned above ensure the durability and reliability of the pressure sensors used in a measurement of dynamic pressure after the packaging process.

3. Packaging Process

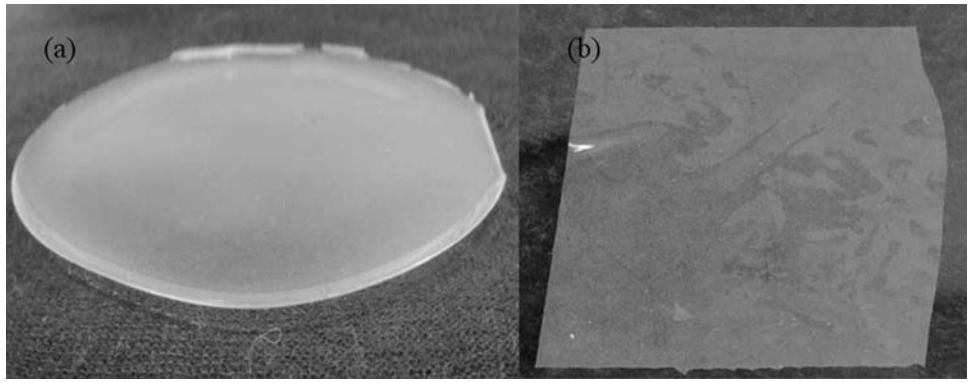
The concept behind this study is simple but very useful. We use a PDMS layer to replace a Pyrex #7740 glass layer for sealing the pressure cavity. Using this approach, a cheap and fast bonding process is achieved and the temperature throughout the process is very close to the ambient.

3.1 *PDMS substrate process*

Ensuring the thickness of PDMS is the first issue we want to confirm in this packaging method. Since a flat PDMS substrate can guarantee the perfect bonding as well as a high yield in the WLP process, we use spin coating to control the thickness of PDMS gel. To determine the effect of the PDMS thickness on the sensor performance, we prepare PDMS sheets with different thicknesses. First, we use a polished-silicon or Teflon disk (the latter is used for the thinner PDMS sheet) as the flat mold substrate for making PDMS sheets. After mixing PDMS (SYLAGARD 184A) base gel and its hardening agent (SYLAGARD 184B) homogeneously and placing the PDMS mixed gel in a vacuum chamber for 30 min to expel the trapped bubbles, we spin-coat the PDMS mixed gel on the flat mold substrate and reduce the thickness of the PDMS sheet down to 500 μm or even 45 μm. The PDMS mold is heated and solidified using a hot plate; after which, we peel off the PDMS sheet from the substrate. The samples are shown in Fig. 5. According to our experience of PDMS spin-coating, the fabricated PDMS sheet with a thickness more than 300 μm can be peeled from the silicon substrate very easily, but a thinner PDMS sheet is more difficult to be peeled. In order to overcome this problem, we use a different substrate, Teflon disk, as a flat mold substrate of the thinner PDMS sheet. The detailed processing parameters are summarized in Table 1.

3.2 *Bonding Process*

Figure 6 shows the bonding process. O_2 plasma is used to change the PDMS surface from a hydrophobic one to a hydrophilic one. We use a reactive ion etching (RIE)



(a) (b)

Fig. 5. Completed PDMS sheets: (a) 500 μm thick; (b) 45 μm thick.

Table 1
Detailed processing parameters of fabrication PDMS sheets.

		Condition				
		Flat mold substrate	Mixture recipe (PDMS: hardening agent)	Spin coating recipe		Heating
PDMS sheet	500 μm thick	Polished silicon	10:1	Step 1 Step 2	100 rpm 60 s none	Heat to 120°C for 10 min using a hotplate
	45 μm thick	Teflon disk	10:1	Step 1 Step 2	500 rpm 60 s 100 rpm 60 s	Heat to 120°C for 10 min using a hotplate

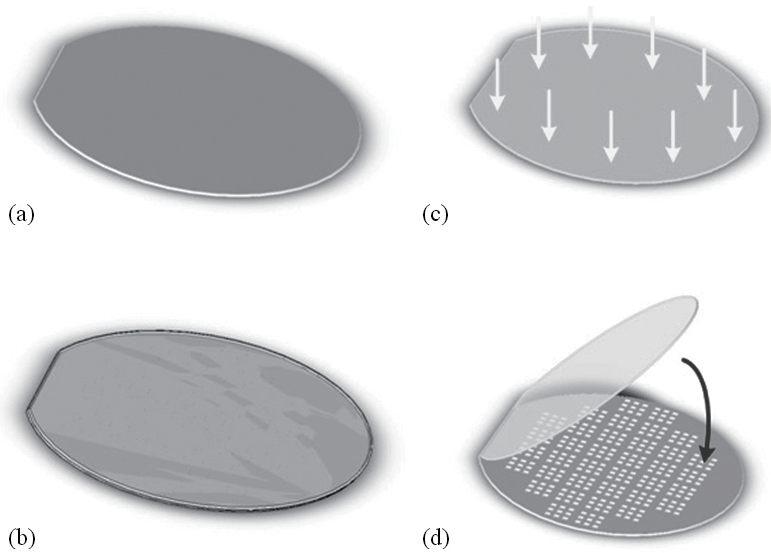


Fig. 6. Process flow of the PDMS WLP method: (a) cleaning a silicon/ Teflon substrate; (b) spin-coating PDMS on the silicon/ Teflon substrate and detaching the PDMS sheet; (c) treating the PDMS surface with O_2 plasma from hydrophobic to hydrophilic states; (d) bonding the hydrophilic PDMS surface with the back side of the fabricated wafer with piezoresistive pressure sensors at room temperature.

machine (SAMCO-RIE-1C) to generate O_2 plasma where the process parameters are as follows: the power of the RF generator is 30 W; the flow rate of oxygen is 10 sccm; the plasma treatment takes only 10 s; the default parameter of the gas pressure during the plasma treatment is 26.6 Pa. After modifying the surface property of PDMS, we can bond the PDMS sheet with the backside of a sensor wafer by applying some force to enhance the bonding strength as well as the bonding speed. The process flow is shown in Fig. 6: (a) cleaning a silicon/ Teflon substrate; (b) spin-coating PDMS on the silicon/ Teflon substrate and detaching the PDMS sheet; (c) treating the PDMS surface with O_2 plasma from hydrophobic to hydrophilic states; (d) bonding the hydrophilic PDMS

surface with the backside of the fabricated wafer with piezoresistive pressure sensors at room temperature.

Completing the economical and simple WLP process, we obtain a batch of new pressure sensors, shown in Fig. 7. After wafer dicing, we mount the pressure sensor die on a printed circuit board (PCB) and connect the contact pads between the sensor and the PCB by wire bonding. The completed sensors shown in Fig. 8 are then tested to verify their performance.

4. Experimental Setup and Testing

We utilize a pressure-testing machine[20] to perform a series of performance tests for pressure sensors after PDMS packaging. This machine (shown in Fig. 9) can control the pressure from 0 to 2000 kPa and adjust the temperature from ambient temperature to 200°C in a testing chamber of 6 inch diameter. In this study, we fix the temperature at 25°C and gradually change the pressure from 0 to 689 kPa.

The experimental setup is shown in Fig. 10. We use a power supply for providing a 5 volt DC bias and a data acquisition system to record the output signal. To avoid the temperature variation in the sealing chamber, we raised the pressure very slowly, even though one cycle of the pressure test (pressuring-venting) lasts for several hours. Each sensor was tested for at least 3 times to reconfirm the performance and reliability. The sensors were stored at 20°C and 50% relative humidity for a period of one week between every two tests.

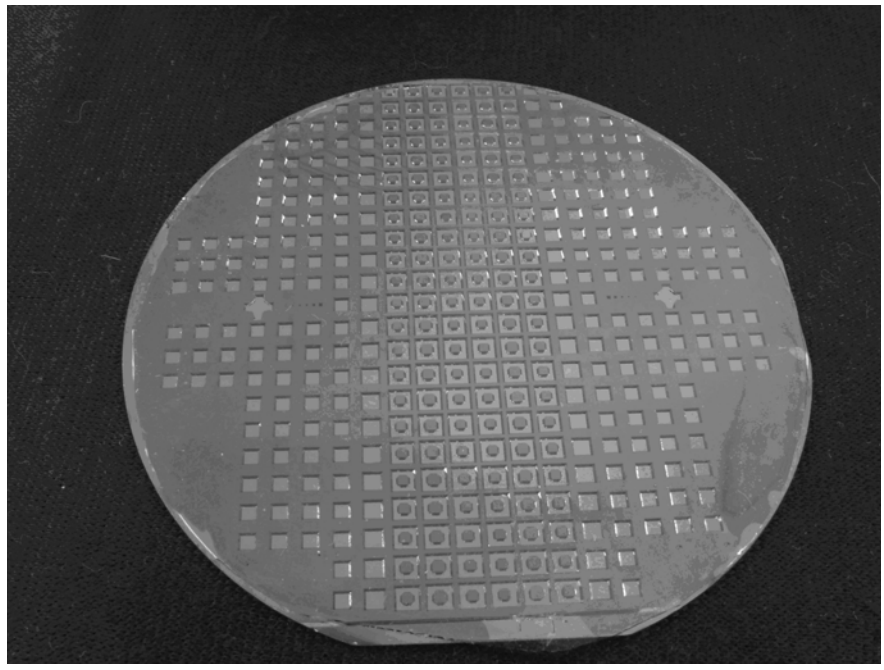


Fig. 7. Sensor wafer after PDMS WLP.

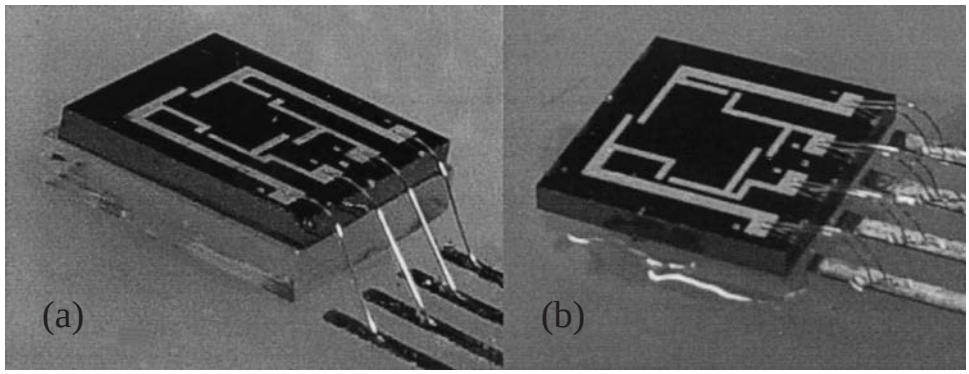


Fig. 8. Pressure sensors with PDMS bases of different thicknesses: (a) 500 μm thick; (b) 45 μm thick.

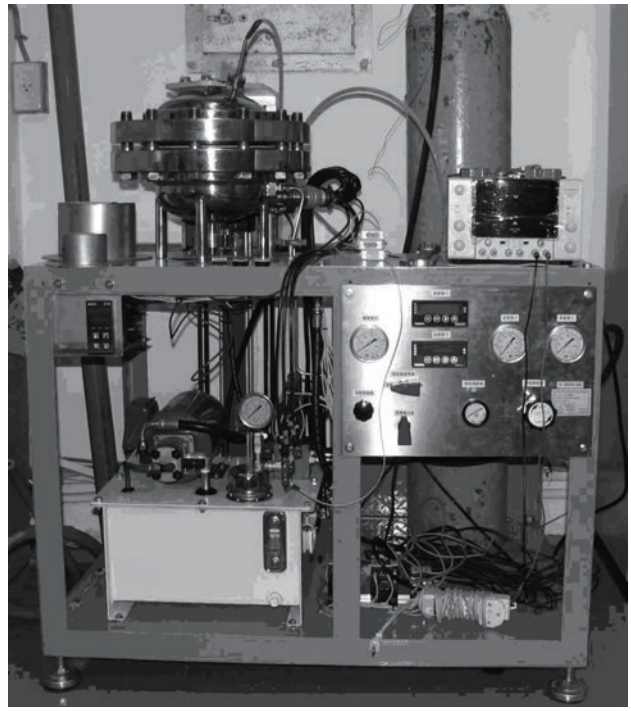


Fig. 9. Pressure testing machine developed by Tamkang University.[20]

We also compare the performance data of three sensors with different packaging materials or thicknesses in Table 2, and the output voltages of these pressure sensors are shown in Fig. 11. We adopt the "terminal-based scheme" to determine the degree of nonlinearity. This corresponds to that the maximum deviation of the calibration curve

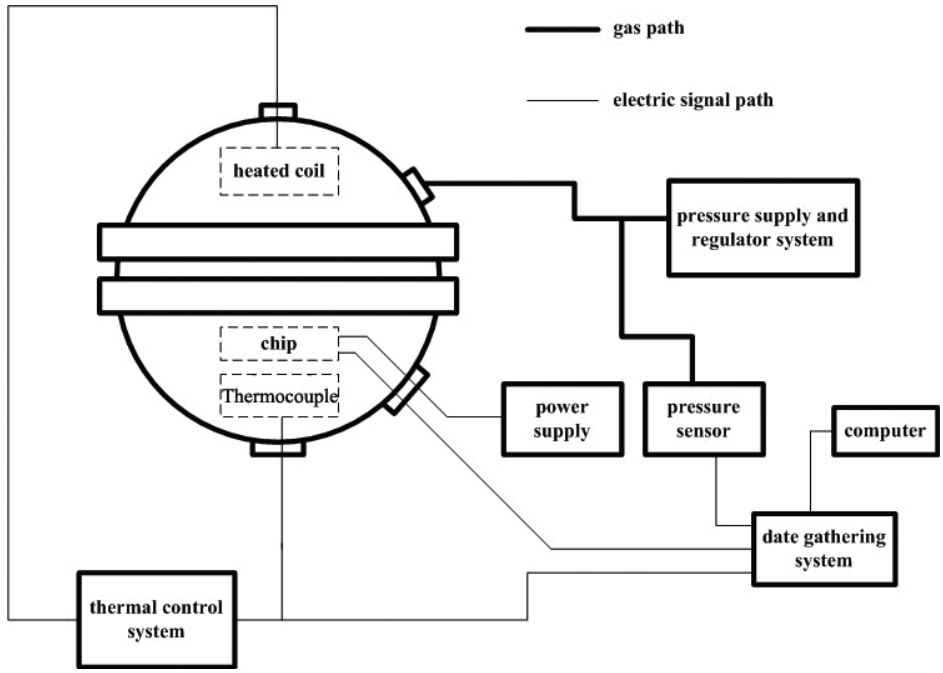


Fig. 10. Sketch of the experimental setup.[20]

from a straight line intersecting the calibration curve at zero and full-scale values will occur. As shown in Fig. 11, these three testing curves are almost identical. The overall performance of these three pressure sensors shows no obvious difference.

According to the results, the negative effect of degassing phenomena come from PDMS luckily seems not apparent during the pressuring-venting stage of experiment. In a global manner, the sensitivity of the sensor is about 0.25 mV/V/kPa, the nonlinearity is 2.5±0.4%, and the hysteresis is less than 0.5%. This proves preliminarily that the sensor packaged using a PDMS thin film has a performance comparable to those of conventional anodic bonded sensors.

The sensitivity of the pressure sensor packaged using a PDMS film of 500 μm thick is lower than the case of 45 μm. This is attributed to the fact that PDMS is a hyperelastic material. In other words, a PDMS can be deformed slightly by applied pressure and the reference pressure in the sealing chamber is changed consequentially. For this reason, a thicker PDMS can absorb a greater portion of pressure loading from the ambient environment on the pressure sensor than a thinner one, and consequently decrease the portion of pressure loading on the sensing diaphragm and the output signal as well. Additionally, the pressure sensor packaged by a PDMS film with a thickness of 45 μm has almost the same sensitivity as the one packaged by a Pyrex glass wafer. This is because the 45-μm-thick PDMS is too thin to absorb pressure loading in the range of 68.9–689 kPa, and can be regarded as an almost invisible sealing material in the entire packaging framework.

Table 2
Comparison of pressure sensors with different packaging materials.

			Packaging base		
			Pyrex #7740	500 μm thick PDMS	45 μm thick PDMS
Comparison	Process condition	Bonding temp.	500°C	Room temperature	Room temperature
		Bonding time	60 min	Less than 1 min	Less than 1 min
		WLP material cost for a wafer	US $20.00	US $1.50	US $1.50
	Performance	Sensitivity (pressure-increasing)	0.249 mV/V/kPa	0.244 mV/ V/kPa	0.248 mV/ V/kPa
		Sensitivity (pressure-decreasing)	0.249 mV/ V/kPa	0.245 mV/ V/kPa	0.248 mV/ V/kPa
		Non-linearity (pressure-increasing)	2.9%	1.6%	1.7%
		Non-linearity (pressure-decreasing)	2.7%	2.0%	2.0%
		Hysteresis	0.4%	0.1%	0.1%

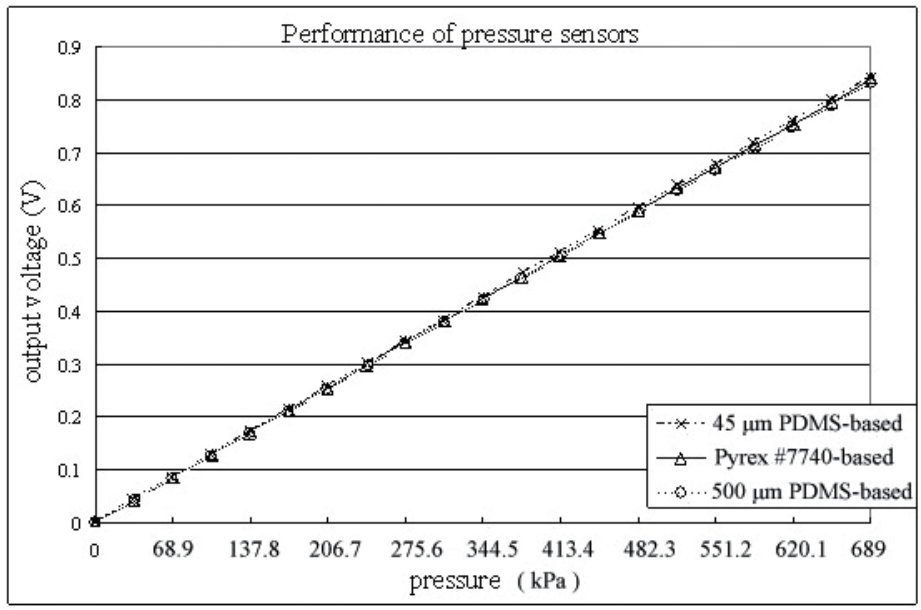


Fig. 11. Signal output of pressure sensors using different packaging substrates.

5. Conclusions

How to lower the fabrication cost and speed up the well-known process of piezoresistive bulk-machined pressure sensors is a very important issue in MEMS industry. In this study, we investigated a novel packaging approach of using PDMS as a substitute of conventional Pyrex glasses to meet the above requirements. PDMS WLP not only reduces the chip cost of pressure sensors but also shortens the processing time

successfully. The room-temperature bonding of PDMS to sensor wafers additionally avoids the problem of thermal mismatch during bonding. The performance of this newly packaged pressure sensor as well as those of the conventional ones packaged by anodic bonding were verified through actual pressure testing in this work, and the PDMS packaging is proven to have a good response in a pressure environment of 689 kPa. Although the disadvantage of PDMS's gas permeability leads to the unsuitability of applying this kind of pressure sensors to some situations, for example the long-term monitoring or steady pressure measurement, it still can be used as a sensor in a short-term or an unsteady mode. In summary, this new concept of PDMS WLP, through our experimental investigation of cost-effective features, is expected to have a promising potential in real applications.

Acknowledgement

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