CHAPTER 4

FABRICATION OF PRESSURE AND TACTILE SENSORS

After the design and simulation, the proposed pressure and tactile sensors are fabricated based on the high temperature materials PSOI and 6H-SiC, to bring the sensors to the real world. Because the pressure and tactile sensor have the same structure, they are produced by the same process. In this chapter, the fabrication process of the PSOI pressure and tactile sensors is described. Then, the process for 6H-SiC sensors is developed. Because of the lack of sealing technology for 6H-SiC, high temperature adhesives are used to create a hermetic package for the pressure sensor testing. This part of the experiments will be discussed at the end of this chapter.

4.1 Fabrication of PSOI Pressure and Tactile Sensors

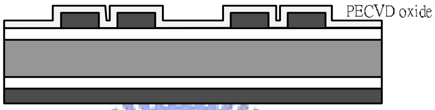
The fabrication process of the pressure and tactile sensor is illustrated in Fig. 4.1. An n-type single-side polished (100) silicon wafer is used as starting material (Fig. 4.1(a)). After growth of 100 nm of thermal oxide, 620 nm of LPCVD poly-silicon are deposited at 620°C (Fig. 4.1(b)). The doping of the poly-silicon is performed in a furnace with phosphorous gas at 1000°C. After the doping, the sheet resistance of the polysilicon is about 3.2 mΩ-cm, which corresponds to a high doping concentration of about 5×10^{21} cm^{-3}. Then, the piezoresistors are structured by a standard lithography process and RIE (Reactive Ion Etching) (Fig. 4.1(c)). Then PECVD (Plasma Enhanced Chemical Vapor Deposition) oxide with a thickness of 100 nm is deposited (Fig. 4.1(d)). Contact holes for the connection between the metal lines and piezoresistors are etched by a dip in a dilute NH_4F solution (Fig. 4.1(e)). Then, 90 nm Ni/Cr and 110 nm gold are sputter deposited sequentially and structured by adequate etchants (Fig. 4.1(f) and (g)). The contacts are annealed at 500°C for 20 minutes to form an ohmic contact between Ni/Cr and polysilicon. The structure of the circular membrane with a center-boss is defined on a sputtered aluminum layer on the backside of the wafer by a double-side mask aligner (Fig. 4.1(h) and (i)). RIE is used to create deep cavities into the silicon wafer (Fig. 4.1(j)). The pressure sensors are complete after this final process step. For the tactile sensor, the aluminum mask layer on the supporting frame is removed and further RIE is used to create the height difference between the center boss and the supporting structure (Fig. 4.1(l)).

The fabricated sensor shown in Fig. 4.2 has a dimension of 4×4 mm^2. After measurement, the radius of the center boss is 0.47 mm, the outer radius of the membrane is 1.695 mm and the thickness of the membrane is 150 µm.

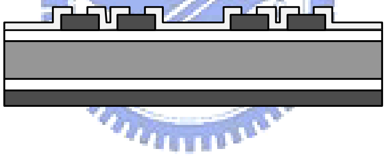
(a) start from an n-type single-side polished (100) silicon wafer

(b) grow 100 nm thermal oxide and 620 nm LPCVD poly-Si

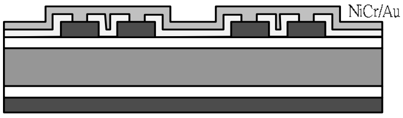
(c) pattern poly-Si



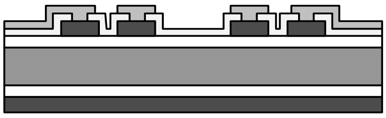
(d) deposit PECVD oxide.



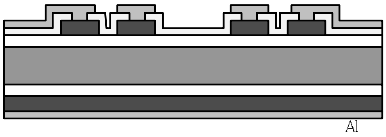
(e) open contact holes.



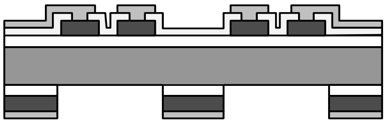
(f) sputter NiCr/Au.



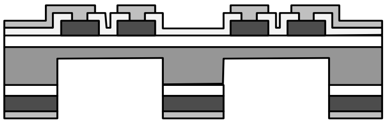
(g) pattern metal lines.



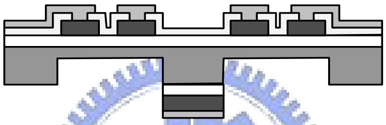
(h) sputter Al on the backside of the wafer.



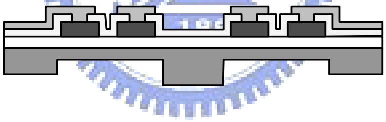
(i) pattern the circular membrane with center boss structure.



(j) etch to form the sensor structure.



(k) remove Al, poly-Si, SiO_2 and etch Si on the frame of the sensor.



(l) remove all Al, poly-Si and SiO_2 on the backside of the wafer.

Figure 4.1. Fabrication process of the PSOI pressure and tactile sensor.

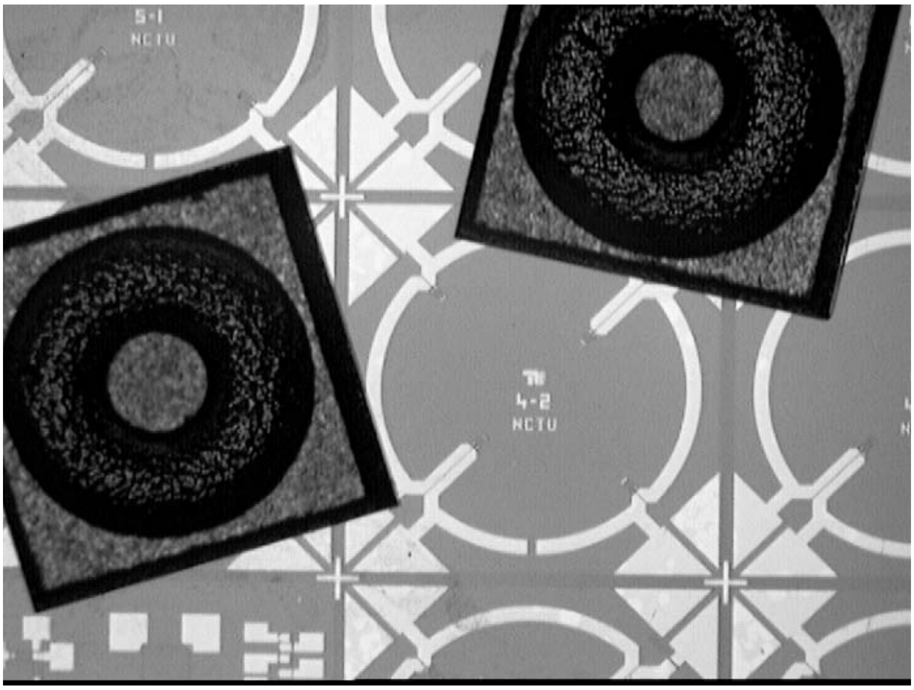


Figure 4.2. Photography of the fabricated pressure and tactile sensors. The background is a processed wafer with piezoresistors and metal lines. There are two chips, which show the circular membrane with center boss structure on the backside.

4.2 Fabrication of 6H-SiC Pressure and Tactile Sensors

Before using 6H-SiC for MEMS applications, the 3D structuring process, or so-called bulk micromachining, has to be developed. So far, no wet etchants are known that have the ability to etch 6H-SiC at room temperature. However, a feasible way to etch SiC at room temperature is electrochemical etching[58]. Therefore, the electrochemical etching of both n- and p-type 6H-SiC were investigated[59][60] and are described in Appendix I and II respectively. After the development of both the n-and p-type 6H-SiC bulk micromachining, the p-type 6H-SiC substrate is used because the etching of p-type 6H-SiC does not generate porous SiC as n-type does. Therefore, a thermal oxidation at high temperature is not required after the anodization process. To insulate the piezoresistors on the p-type substrate, an n-type, 6H-SiC epi-layer is used.

The fabrication process of the 6H-SiC pressure and tactile sensor is illustrated in Fig. 4.3. The 1.5 inch 3.5° off-axis p-type 6H-SiC wafers with a doping level about 2.8×10^{18} are bought from Cree[61]. The n-type 6H-SiC epi-layer has a doping level about 2.5×10^{17}, a thickness of 0.46 μm and is situated on the polished Si-face of a p-type 6H-SiC substrate. 1 μm aluminum is first deposited on the surface of the epi-layer and then structured by a standard lithography process and a dip in aluminum etchant (Fig. 4.3(b)). This aluminum is used as the passivation layer during the etching of 6H-SiC epi-layer by RIE. Because of the strong covalent binding of 6H-SiC and the low power of the plasma generator (200 W RF power and 150 mTorr pressure) the etching rate of 6H-SiC is low. The etching depth of 6H-SiC is measured by Tencor Alpha-step profiler after 30 minutes etching time. During the etching, a carbon electrode is used instead of an aluminum electrode to achieve a smooth, shiny surface after the etching[62]. As depicted in Table 4.1, the etching rate and the roughness increase as the concentration of SF_6 increases. In order to obtain a smoother surface, a recipe with O_2:SF_6 = 16:8 is used. Because the thickness of epi-layer is about 670 nm, an etching time of 40 minutes is used to achieve a slight over-etching (Fig. 4.3(d)).

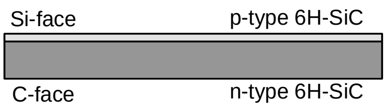
After the formation of n-type 6H-SiC piezoresistors, the aluminum layer is removed (Fig. 4.3(e)). A wet thermal oxidation is performed at 1050°C for 8 hours (Fig. 4.3(f)). Then, LPCVD (Low Pressure Chemical Vapor Deposition) polysilicon is deposited on the both sides of the wafers (Fig. 4.3(g)). The polysilicon and oxide on the backside of the wafer is structured as passivation layer for the anodic etching by RIE and an HF dip, respectively (Fig. 4.3(h) and (i)). Meanwhile, the polysilicon and oxide on the front side of the wafer are removed.

To form the working electrode for the p-type 6H-SiC substrate, aluminum of 1 μm thickness is sputtered on the front side of the wafer and patterned to avoid contacts between the n-type 6H-SiC piezoresistors (Fig. 4.3(j) and (k)). A rapid thermal annealing is performed at 800°C for 6 minutes. The p-type 6H-SiC substrate is then etched in a 2% HF solution at 50 mA/cm^2 for 4 hours (Fig. 4.3(l)). After the etching, the aluminum on the front side of the wafer and the polysilicon and oxide on the backside of the wafer is removed with respective etchants (Fig. 4.3(m)).

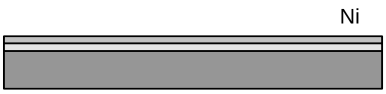
The WSi_2 high temperature metallization scheme was chosen according to the work by Gottfried [63] because he demonstrated that ohmic contacts between WSi_2

and 6H-SiC can withstand temperatures up to 450°C in air. A PECVD (Plasma Enhanced Chemical Vapor Deposition) oxide of 500 nm thickness is deposited at 350°C and used as the insulating layer (Fig. 4.3(n)). The contact holes for piezoresistors are opened (Fig. 4.3(o)). WSi_2 with a thickness of 100 nm is sputtered and patterned by wet etching and RIE, respectively (Fig. 4.3(p) and (q)). The ohmic contact between WSi_2 and 6H-SiC piezoresistors is achieved by a thermal annealing for 30 minutes at 1050°C in Argon. Then, 1 μm thick aluminum is then sputtered on the WSi_2 and patterned as the metal lines. Another PECVD oxide of 300 nm thickness is deposited as a passivation layer and the pad windows are opened (Fig. 4.3(r) and (s)). Finally, thick Al wires are bonded on the bonding pads (Fig. 4.3(t).

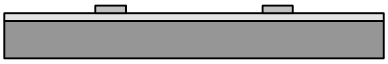
Fabricated 6H-SiC pressure/tactile sensors are illustrated in Fig. 4.4. The etched membrane is transparent, so the 1 Euro-Cent in the background of the sensors can be seen from that picture.



(a) start from an n-type (0001) 6H-SiC wafer with p-type 6H-SiC epi-layer.



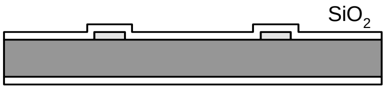
(b) sputter Ni.



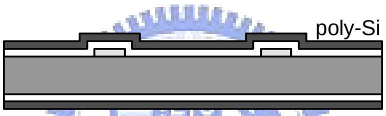
(c) pattern Ni.

(d) etch p-type 6H-SiC by RIE with a carbon electrode.

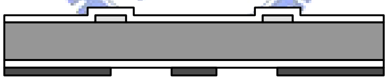
(e) remove Ni.



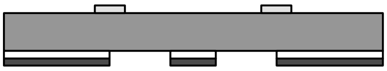
(f) grow thermal oxide.



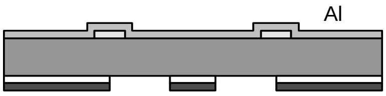
(g) deposit LPCVD poly-Si.



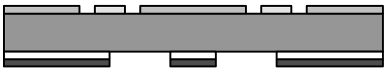
(h) remove poly-Si on the front side and pattern the sensor structure on the back side of the wafer.



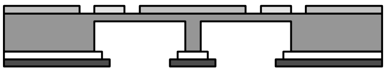
(i) remove thermal oxide.



(j) sputter Al.

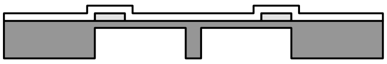


(k) pattern Al electrodes.

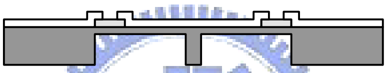


(l) Electrochemical etching of 6H-SiC substrate.

(m) remove poly-Si, thermal oxide and Al.

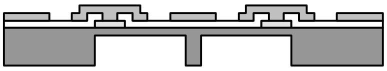


(n) grow thermal oxide.

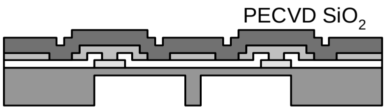


(o) open contact holes.

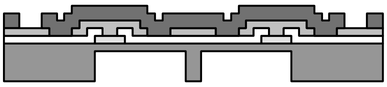
(p) sputter 100nm WSi_2 and 1μm Al.



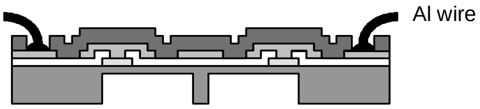
(q) pattern WSi_2/Al.



(r) deposit 300nm PECVD SiO_2.



(s) pattern PECVD SiO_2.



(t) Al wires bonding.

Figure 4.3. Process of 6H-SiC pressure and force sensors.

Table 4.1. Etching rate and roughness of 6H-SiC by RIE with different gas concentrations after 30 minutes.

Process	**Depth**	**Etching rate**	**Roughness (p.p.)**
O_2:SF_6 = 16:8	600 nm	20 nm/min	200 nm
O_2:SF_6 = 14:10	800 nm	26.7 nm/min	400 nm
O_2:SF_6 = 12:12	700 nm	23.3 nm/min	500 nm
O_2:SF_6 = 4:20	1200 nm	40 nm/min	1 um

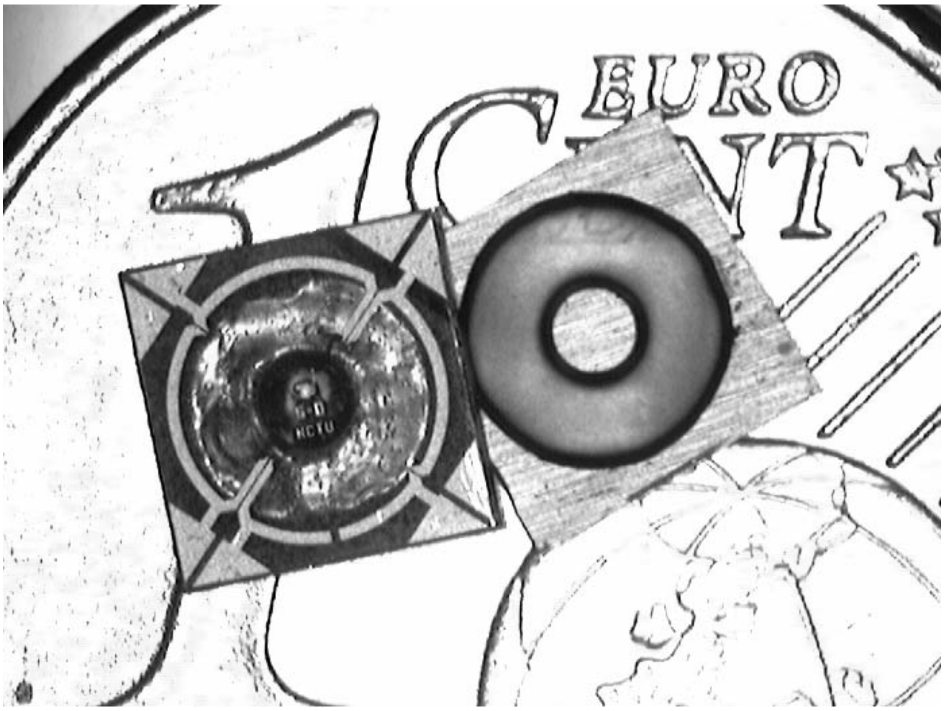


Figure 4.4. Photography of the fabricated 6H-SiC pressure and tactile sensors. The background is a 1 Euro cent.

4.3 Package with High Temperature Adhesives

To test the fabricated pressure sensor, a hermetic package that is capable of working in high temperature environment is needed. This requires a hermetic encapsulation, an electric-isolating carrier and electric wire bonding. The carrier for the sensor should have similar thermal expansion as 6H-SiC (5.2×10^{-6}/K) and good electric insulating properties. Alumina ceramic is used in the experiment because it has a thermal expansion coefficient of 8.3×10^{-6}/K, which is closer to 6H-SiC in comparison to the other ceramic materials, and it can be structured and cut by a laser drill or a dicing saw.

For wire bonding, 1 mm thick aluminum wire is used and bonded by a wedge-wedge bonder by Kulicke & Soffa, Model 4523. Prior to bonding the wires to the chip, the bonding parameters such as bonding loop, bonding tail, first and second ultrasonic power, bonding time and clamping force are adjusted to obtain the maximum bonding strength. The bonding strength is tested by a pull tester, Royce Instruments System 220. After bonding at room temperature, an average pull-off force of 7.37g is obtained. To perform thermal testing of the bond connections, the bonded wires are placed inside a furnace at 450°C . After 4, 8, 12 and 16 hours, a pull-off test is performed to inspect the change in the bonding strength. As illustrated in Fig. 4.5, the pull-off force of the bonded thick aluminium wire first decreases and then stabilizes at about 4.7g after 4 hours of high temperature treatment.

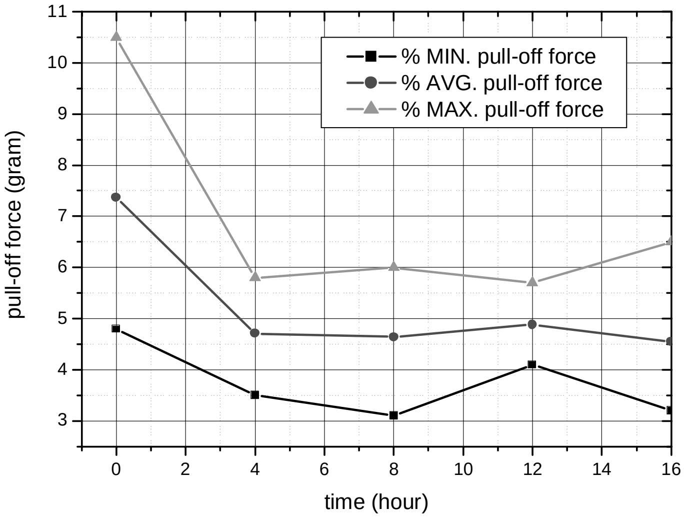


Figure 4.5. Degradation of the pull-off force of the bonded wires during the 450°C treatment.

A hermetic encapsulation for high temperature is a challenging task. Especially for 6H-SiC, there is no anodic bonding process like silicon and Pyrex 7740, maybe due to the low oxidation rate of SiC in comparison to silicon. Because 6H-SiC will be sublimated before it melts, fusion bonding is also not feasible. The glass frit is a good choice to bring two different kinds of materials together with a good hermetic encapsulation. However, it requires a high temperature to melt the glass adhesive and the melting point of the glass is normally near or higher than the melting point of aluminum wire. Therefore, high temperature adhesives are used in the experiment.

The mechanism of adhesion is complex and has been investigated for years. The bonding of an adhesive to an object or a surface is the sum of a number of mechanical, physical, and chemical forces that overlap and influence one another.

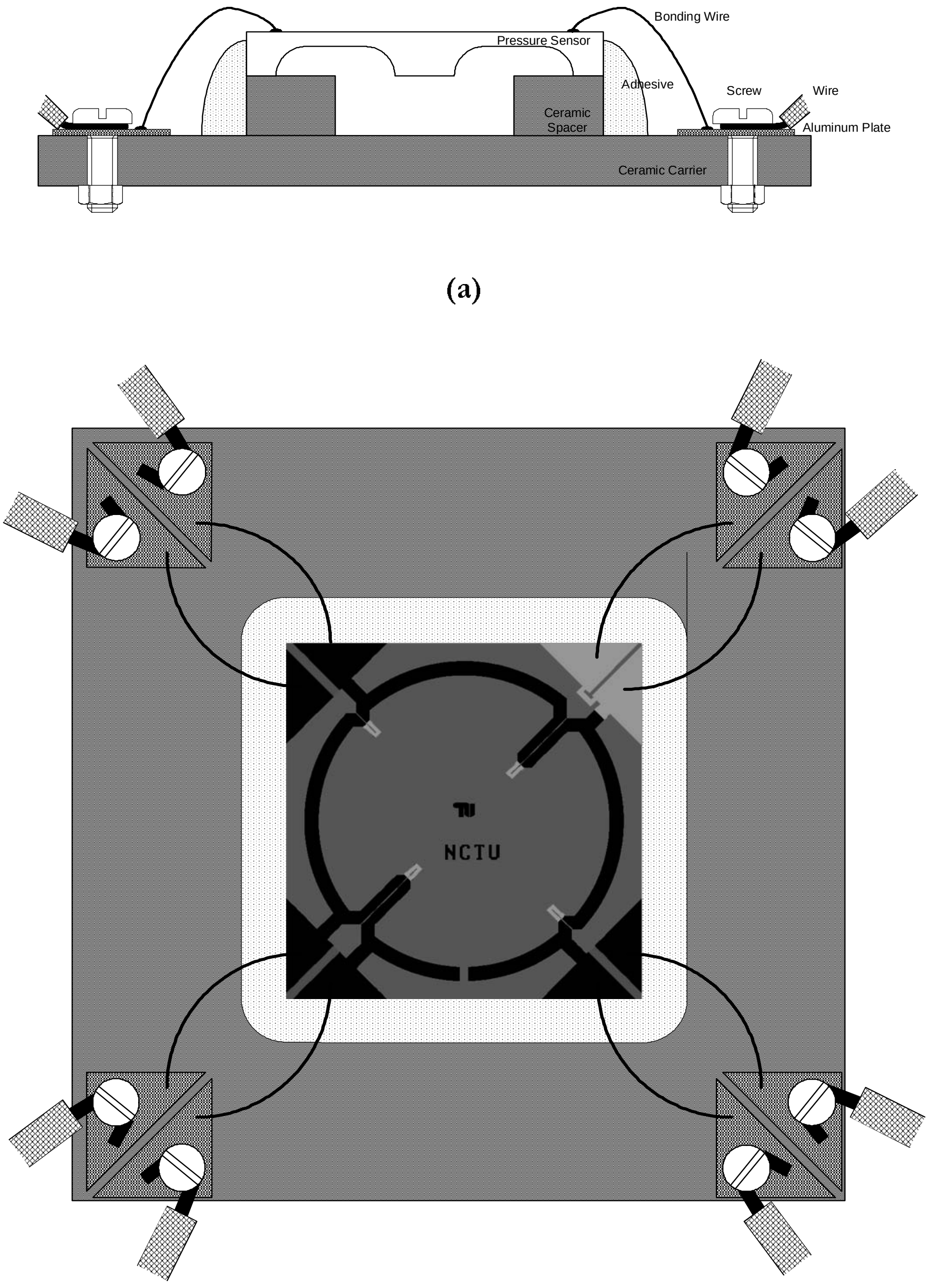
Because of the high temperature properties, ceramic adhesives are tested first. Ceramabond 503, Ceramabond 670 from Aremco Products, Inc.[64], Cotronics 7030 from Cotronics, Inc.[65] and Thermokitt Roth from Carl Roth, GmbH[66] are tested. However, all of them have low adhesive strength and do not provide hermetic encapsulation due to the existence of pores in the adhesives. Then, high temperature epoxies are tried out. Epoxy 526N and Epoxy 570 from Kager, GmbH[67], Epoxy P1011, Epo-Tek 353ND-10 from Epoxy Technology[68] and Epoxy H77 from Polytec, GmbH[69] are tested and demonstrated hermetic at room temperature. However, after the thermal cycling test, only Epo-Tek 353ND-10 can stand up to 450 °C. The experimental results are summarized in Table 4.2.

Table 4.2. Summary of the tested adhesives.

Adhesives	Curing Process	Hermetic R.T.	Hermetic until	Comment
Ceramabond 503	1h RT 1h 100°C 1h 200°C 1h 370°C	not	--	--
Ceramabond 670	1-4 h 80°C	yes	120°C	The volume of the adhesive increases sharply.
Cotronics 7030	4h RT 2h 65°C	not	--	--
Thermokitt Roth	2h 80°C	not	--	--
Ceramabind 643	1h RT 1h 100°C 1h150°C	not	--	There are rips on the adhesive.
Epoxie 526N	2h 100°C 2h 160°C	yes	225°C	Smooth and hard surface of the adhesive is generated.
Epoxie 570	1h RT 20min 80°C 15min 175°C	yes	120°C	The adhesive is very soft after the curing.
Epoxy P1011	1h 160°C	yes	120°C	Porous
Epoxy H77	0.5h 150°C	yes	350°C without pressure	--
Epo-Tek 353ND-10	1h 200°C	yes	450°C	High thermal expansion

Fig. 4.6 illustrates the schematic of the package for the testing of the pressure sensor. Between the pressure sensor and the ceramic carrier, there is a spacer, which is also made by an alumina based ceramic plate. This spacer has a hole in the center in order to let the center boss of the pressure sensor suspend. The adhesive is applied to

bind the sensor, spacer and the carrier together. The hermetic sealing is needed to separate the pressure inside and outside the sensor. Because the adhesive is applied in ambient environment, the pressure inside the sensor is about 1 bar. After the curing process for the adhesive, the aluminum plate and the high temperature conducting wire are fastened by the screws. Then, thick aluminum wires are bonded to the aluminum plate. Fig. 4.7 shows the package of a PSOI piezoresistive pressure sensor.



(b)

Figure 4.6. (a) Cross-section view and (b) top view of the package for the testing of the high temperature pressure sensor.

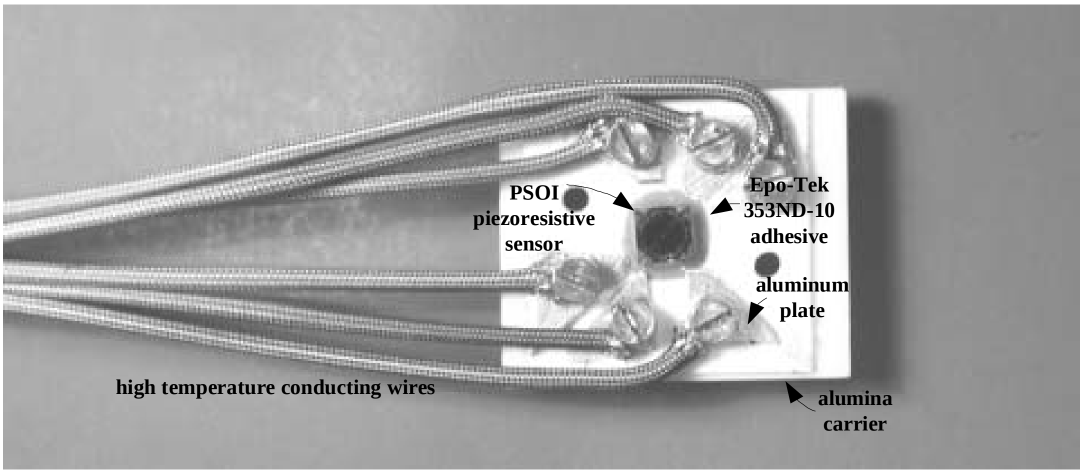


Figure 4.7. Photography of a packaged PSOI piezoresistive pressure sensor.