Outline

1 Introduction

2 Basic IC fabrication processes

3 Fabrication techniques for MEMS

4 Applications

5 Mechanics issues on MEMS
2. Basic IC fabrication processes

2.1 Deposition and growth

2.2 Photolithography

2.3 Etching

2.4 Bonding
2.4 Bonding

• Bonding is the process to assemble individual components in micromachining

• In order to construct a complete micromachined device, micromachining of individual components as well as assembly of these components is required

• Bonding process can be achieved by several techniques
  + Silicon fusion bonding (SFB)
  + Anodic bonding (silicon - glass)
  + Silicon - silicon anodic bonding
  + Others
• Bonding applied to improve reliability


Figure source: L. O'Connor, Mechanical Engineering, 1992
• Bonding applied to reduce space and cost, for example, micromachined membrane for pressure sensor

  + Bulk micromachining through backside etching

  + Bonding
• Bonding is required to construct the devices

+ Gas chromatograph

+ Microfluid devices

1. Valve

J. Tiren, L. Tenerz, and B. Hok,

2. Pump

S. Shoji and M. Esashi, J.
Micromechanics and Microeng., 1994
+ Microfluid system
+ Capacitive accelerometer

E. Peeters, S. Vergote, B. Puers and W. Sansen, 1992
- MEMS packaging

- Die Level
  Ceramic Package

- Wafer Level
  Bonded Wafer Packages

  - Cronos Relay: Die level release and ceramic package
  - Motorola Accelerometer: Wafer bonded package with **glass frit seal** and **lateral feedthroughs** (sealed MEMS is then placed into ceramic package)
  - Bosch Gyroscope: Wafer bonded package with **glass frit seal** and **lateral feedthroughs**
  - Shellcase Image Sensor: Wafer bonded package with **adhesive seal** and "**T-contact interconnect**"
• Wafer bonding - MEMS packaging

Approaches

- Non-intermediate
  - Fusion Bonding
  - Anodic Bonding

- Intermediate
  - Adhesive Bonding
  - Organic
    - Epoxy Bonding
    - PR Bonding
  - Inorganic
    - Eutectic Bonding
    - Glass Frit Bonding
    - Solder Bonding
2.4.1 Silicon Fusion Bonding

• Silicon fusion bonding (SFB) or silicon direct bonding (SDB) - let the polished sides of two silicon substrates contact, and then annealed them at high temperature. A bond which is as strong as bulk silicon is formed between the substrates during annealing.

• There are three steps in the process
  
  + First, the substrates are cleaned in a strong oxidizing solution to form a hydrophilic surface on substrate (i.e. surface with a high density of hydroxyl groups)
  
  + The substrates are then squeezed together and these two substrates will stick firmly together due to hydrogen bonds
  
  + Finally the substrates are annealed at high temperature and strong bonds (Si-O) are developed during annealing.
Below 200°C, hydrogen seems to be responsible for the bonding of hydrophilic surface.

T>700 °C, chemical reactions occur and a bond between the hydroxyl groups probably form directly which is responsible for the bond strength.

T>1000 °C, covalent bond between SiO unit.

SiOH : (OH$_2$)$_2$ :HOSi : (OH$_2$)$_2$

SiOH : SiOH+(H$_2$O)$_4$

Si-O-Si+H$_2$O

I.A. Maia, J.R. Senna, 1998
• The bonding quality can be inspected by infrared imaging system

• Bonding quality – the existing of voids

Void Formation
• Insufficient wafer flatness
• Surface contamination
• Particulates
• Trapped air
• Interface bubbles

\[ R = \left[ \frac{2}{3E'} \frac{t^3_w}{\gamma} \right]^{1/4} h^{1/2} \]

\[ E' = \frac{E}{(1 - \nu^2)} \]

\( r \) : Surface energy of each wafer
\( E \) : Young’s modulus
\( \nu \) : Poisson's ratio

Diameter of 1µm → unbonded area with a diameter of 1 cm
• Interface bubbles – density test

S. Mack, H. Baumann, and U. Gosele. 1996
The interface bubbles in bonded silicon pairs usually disappear after annealing at temperature over 1000°C.

The samples were then annealed at 600°C.
2.4.2 Anodic Bonding

- Anodic bonding - this is the process used to bond silicon to glass. The glass can be in the form of a plate or substrate, or a thin film between two silicon substrate.

- There are two steps in the process
  
  + Place a glass substrate and a Si substrate on a heating plate (under 450°C). At the elevated temperature, the ions in the glass is allowed to move.

  + Apply high negative voltage to the glass, the ions become mobile and drift to the cathode. When the glass and the Si substrate is pulled by the electrostatic force, the oxygen ions left on the glass surface will bond with the silicon atoms.
Silicon

NaOH

Glass

300~500°C

200~1000V

power supply

Heater
After bonding glass near bonding interface

After bonding glass surface

Na : 0.1140186916  Glass Surface  O : 8.770491803
Na : 0.0637149028  Bonding Face  O : 15.69491526

Silicon

H. A. Yang, master thesis, 2002
Several important issues during bonding

+ The glass must be slightly conductive when heated to the temperature well below its softening point

+ The **thermal expansion coefficients** of the two materials should be as close as possible.

+ **Temperature** and **voltage** are two major parameters need to be controlled to obtain better bonding

+ The surface has to be smooth, although this requirement is not as critical as in the fusion bonding process
When two different materials are combined, for example during a bonding process, a problem due to the mismatch of their thermal expansion coefficients may arise. This may lead to thermal stress as the temperature changes and break the bonded wafers. Using materials having sufficiently close thermal expansion coefficient can reduce thermal stress.

<table>
<thead>
<tr>
<th></th>
<th>Thermal expansion coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>PYREX 7740</td>
<td>32.5×10^{-7}/°C</td>
</tr>
<tr>
<td>Silicon</td>
<td>30.9×10^{-7}/°C</td>
</tr>
</tbody>
</table>
• **Bonding strength**

Table 1. Bond-no bond matrix with 1.5 mm thick glass at 1 atm in air.

<table>
<thead>
<tr>
<th>DC Voltage</th>
<th>300 °C</th>
<th>350 °C</th>
<th>375 °C</th>
<th>400 °C</th>
<th>425 °C</th>
<th>450 °C</th>
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<tbody>
<tr>
<td>175 V</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>350 V</td>
<td>-</td>
<td>1.0 MPa</td>
<td>1.8 MPa</td>
<td>2.0 MPa</td>
<td>3.3 MPa</td>
<td>3.4 MPa</td>
</tr>
<tr>
<td>530 V</td>
<td>1.2 MPa</td>
<td>1.95 MPa</td>
<td>2.4 MPa</td>
<td>2.8 MPa</td>
<td>3.65 MPa</td>
<td>3.6 MPa</td>
</tr>
<tr>
<td>700 V</td>
<td>1.5 MPa</td>
<td>2.2 MPa</td>
<td>2.75 MPa</td>
<td>2.8 MPa</td>
<td>3.5 MPa</td>
<td>3.75 MPa</td>
</tr>
<tr>
<td>880 V</td>
<td>3.3 MPa</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1050 V</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3.75 MPa</td>
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</table>

Table 2. Bond-no bond matrix with 1.5 mm thick glass at 3.5 x 10^{-5} mbar in air.

<table>
<thead>
<tr>
<th>DC Voltage</th>
<th>300 °C</th>
<th>350 °C</th>
<th>375 °C</th>
<th>400 °C</th>
<th>425 °C</th>
<th>450 °C</th>
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</thead>
<tbody>
<tr>
<td>175 V</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>350 V</td>
<td>-</td>
<td>0.9 MPa</td>
<td>1.2 MPa</td>
<td>2.45 MPa</td>
<td>2.4 MPa</td>
<td>2.4 MPa</td>
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<tr>
<td>530 V</td>
<td>-</td>
<td>1.9 MPa</td>
<td>2.1 MPa</td>
<td>2.4 MPa</td>
<td>2.6 MPa</td>
<td>2.6 MPa</td>
</tr>
<tr>
<td>700 V</td>
<td>1.8 MPa</td>
<td>2.0 MPa</td>
<td>2.2 MPa</td>
<td>2.3 MPa</td>
<td>2.5 MPa</td>
<td>2.5 MPa</td>
</tr>
<tr>
<td>880 V</td>
<td>-</td>
<td>2.4 MPa</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1050 V</td>
<td>-</td>
<td>2.5 MPa</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

A Coma and B Puers, 1995
- **Bonding strength**

<table>
<thead>
<tr>
<th>Voltage &amp; Temperature</th>
<th>Bonding Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>350°C ; 350V</td>
<td>1.6879 MPa</td>
</tr>
<tr>
<td>350°C ; 500V</td>
<td>1.8330 MPa</td>
</tr>
<tr>
<td>350°C ; 650V</td>
<td>2.1899 MPa</td>
</tr>
<tr>
<td>350°C ; 800V</td>
<td>2.5351 MPa</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Voltage &amp; Temperature</th>
<th>Bonding Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>350°C ; 500V</td>
<td>1.8330 MPa</td>
</tr>
<tr>
<td>370°C ; 500V</td>
<td>2.2701 MPa</td>
</tr>
<tr>
<td>380°C ; 500V</td>
<td>2.3677 MPa</td>
</tr>
<tr>
<td>400°C ; 500V</td>
<td>3.1425 MPa</td>
</tr>
</tbody>
</table>

• **Bonding mechanism – point vs planar electrodes**

- **Point electrode**: starts from the spot below the point cathode electrode, and this bonding phenomenon can prevent gas trapped inside the interface.

- **Planar cathode**: short bonding time, but has gas-trapping problem.

• Special electrode design – radial type

Both of Germany patents DE4423164 and DE4426288 was used radiate to Improvement of bonding time and quality of Anodic bonding, but the free oxygen from air helps the anodic bonding to occur, it make the bonding time of the wafer edge is faster than other position of the wafer.
• Special electrode design – spiral type
2.4.3 Silicon-Silicon Anodic Bonding

- Silicon-silicon anodic bonding - this technique adopts the idea of silicon-glass anodic bonding

Silicon and silicon is electrostatic bonded together by a thin deposited glass layer
• The surface of the silicon to be bonded should be polished.

• The minimum deposited glass film thickness is about $3 \, \mu m$ and the voltage applied is from ~50 volts to ~200 volts.

• The thermal residual stress effect can be reduced since the silicon substrates have the same thermal expansion coefficients, and the only thermal stress comes from the very thin glass film.
• Bonding for three layers

Michael Harz, 1992
Before bonding

Newton Ring

Approaches

- Non-intermediate
  - Fusion Bonding
  - Anodic Bonding

- Intermediate
  - Adhesive Bonding
    - Organic
      - Epoxy Bonding
      - PR Bonding
    - Inorganic
      - Eutectic Bonding
      - Glass Frit Bonding
      - Solder Bonding
2.4.4 Others

- Low temperature glass bonding – The silicon substrates are bonded by a deposited (sputtered) low melting point glass. Thus the applied electric field is not necessary

  + The sealing temperature may down to 200°C

- Polymer bonding

  + Photoresist, polyimide, epoxy
  + Not hermetic seal
  + Aging
Organic Wafer Bonding - Polymer
• BCB Bonding
• BCB Bonding Results
  + BCB thickness of 18 µm
  + Hard-curing at 250°C
  + Tensile strength 9.52 MPa

J. Oberhammer and G. Strmme, Sweden, 2004
• **SU-8 Bonding**

S. Li, C. Freidhoff, R. M Young and R. Ghodssi, 2003
Inorganic Wafer Bonding – Glass Frit
• Inorganic glass frits require high temperature, but achieve better sealing properties

75°C for 15 min to evaporate organic solvent, then heat up to 375°C to burn out grease.
• Glass frit layer can be patterned to achieve localized or selective bonding
• Slight curvature, roughness, and even topology can be compensated by reflowing glass
• Sealing can be hermetic

S. Park and M. Kim, 2000
Inorganic Wafer Bonding – Eutectic Bonding
• Eutectic:
  In a 2-component phase diagram where there is either partial or no solid solubility between the components, there is a eutectic point, corresponding to the composition of the lowest melting temperature

• In the Sn/Pb system, the temperature of the eutectic point is 183°C and the composition is 61.9% Sn and 38.1% Pb by weight
• Au-Si eutectic

+ Au – Si eutectic temperature about 370°C at 31% Au/Si
+ Bonding temperature is below Al interconnect melting point
• Deposit 150A Cr/1500A Pt 1500~5000A Au film on substrate.
• Heat up to 425-500 in N₂ ambient.
Assembling three-dimensional microstructures using gold-silicon eutectic bonding

Samples from the bonding at 455°C and 520°C with Cr and Au layers could not be separated by a wedge anywhere along the edge of the bonded silicon plates.

## Wafer Bonding Methods

<table>
<thead>
<tr>
<th>Techniques</th>
<th>Advantages</th>
<th>Drawbacks</th>
</tr>
</thead>
<tbody>
<tr>
<td>“Surface” bonding</td>
<td>Hermetic</td>
<td>Flat surface required</td>
</tr>
<tr>
<td>Anodic</td>
<td>strong bond</td>
<td>high-voltage</td>
</tr>
<tr>
<td>Fusion (Direct)</td>
<td>strong bond</td>
<td>high temp</td>
</tr>
<tr>
<td>Surface-activated</td>
<td>varies</td>
<td>varies</td>
</tr>
<tr>
<td>Metallic interlayer</td>
<td>Hermetic</td>
<td>Specific metals required</td>
</tr>
<tr>
<td>Eutectic</td>
<td>strong bond</td>
<td>flat surface req’d</td>
</tr>
<tr>
<td>Thermocompression</td>
<td>non-flat surface ok</td>
<td>high force</td>
</tr>
<tr>
<td>Solder</td>
<td>self-aligning</td>
<td>solder flow possible</td>
</tr>
<tr>
<td>Insulating interlayer</td>
<td>Non-flat surface ok</td>
<td>Varies</td>
</tr>
<tr>
<td>Glass frit</td>
<td>hermetic</td>
<td>large area</td>
</tr>
<tr>
<td>Adhesive</td>
<td>versatile</td>
<td>medium-hi temp</td>
</tr>
<tr>
<td></td>
<td></td>
<td>non-hermetic</td>
</tr>
</tbody>
</table>