Wafer bonding for MEMS

- Types of Substrate Bonding Techniques
  - (Silicon) Direct
  - Plasma Enhanced
  - Anodic
  - Adhesive
  - Metallic
  
- Characterisation methods
- Conclusions
Wafer bonding technologies

Without intermediate layer:
- Si Direct
- Anodic

With intermediate layer:
- Adhesive
- Glass-frit
- Metallic
  - Solder
  - Eutectic
(Si) Direct Bonding

Prebond

Anneal ca. 1100°C

Silicon compounds
- Si - Si
- SiOx - Si
- SiOx - SiOx
- SiOxSi - Si

III-V compounds
- GaAs - GaAs
- GaAs - InP
- AlGaInP - GaP
- Si - GaAs

Other compounds
- Sapphire - Si
- Sapphire - GaAs
- Glass - Glass
(Si) Direct Bonding

Si direct bonding

Electrode
Electrical wire
Glass cover
Vacuum chamber
Glass cover
Resonator tube

Coriolis flow sensor: resonant structure

Anti-phase torsion
In-phase bending

(Si) Direct Bonding

**Comb actuator** made on SOI wafer for steering VCSEL beam
(M(O)EMS group, Chalmers Univ)

**Gyroscope** with Si cap
(Source: R. Bosch GmbH)
(Si) Direct bonding

Nanostructures

50 nm deep channel

Courtesy Univ Twente, Henri Jansen
Direct bonding

Micro / Nanochannels

Si

Poly-Si

Si$_3$N$_4$

Si$_3$N$_4$ layer straight sealing nanochannel

Courtesy Univ Twente, Henri Jansen
(Si) Direct Bonding

**Advantages**
- Strong connection due to covalent forces
- Relatively free choice of wafer material (in theory)
- New developments in LTB (plasma, spin on glass)
- Front-end compatible
- Fast process (annealing in batch)
- Wide process window

**Restrictions**
- High demands on wafer surface quality & cleanliness
- Standard annealing (high T) is not CMOS compatible
Plasma enhanced bonding

Hydrophillic:
- Si wafer
- SC1
- HF dip
- Plasma exposure
- DI water dip
- RT bonding
- SiO₂ wafer
- SC1
- SC1

Hydrophobic:
- Si wafer
- SC1
- HF dip
- Plasma exposure
- RT bonding
Plasma enhanced bonding
Different Materials

(a) Sketch of hybrid evanescent platform, (b) SEM cross-section of a polished device face
VOID GENERATION AND ITS SUPPRESSION
Si/Si SAMPLES

Reduction or absence of void generation during annealing of plasma bonded samples when:
- thermally oxidised wafers are bonded.
- cavities are present.
- varying the plasma parameters.
- the amount of water at the surface is reduced.
Plasma enhanced bonding

Advantages

- High surface energy at RT $\sim 1.6 \text{ J m}^{-2}$
- Bond withstands usual process steps
- Materials with different expansion coefficients
- CMOS compatible

Restrictions

- Thermal void generation during annealing of Si/Si
Anodic Bonding

Si and Glass (Borosilicate = Pyrex; Borofloat 33)

- Temperature 350 ... 420°C
- Electrical Power 30V – 800V, ca. 15 mA
- Mechanical Force ± 0N – hundreds V
- Environment, Vacuum or Pressure
Three-axis accelerometer with equal resolution in all 3-axis using wafer-level anodic bonding of borofloat 33 glass to a) SOI; b) Si

H. Rödjegård, P. Enoksson et al., Proceedings of Eurosensors XVIII, Rome, 2004
Nanoindenter force sensor for materials analysis inside a transmission electron microscope made by wafer-level anodic bonding of SOI to borofloat 33 glass

Anodic Bonding

Vacuum encapsulation using **localized Al / Si-to-glass bonding**

Anodic Bonding

Low CTE LTCC = 3.2 ppm

LTCC - Si anodic bonding (HITK, VIA Electronic, D)

SAM image of interface LTCC-Si

Buried metal electrode in LTCC can reduce:

• the V (ex. 500V to 30V)
• bonding time can be done in seconds
# Anodic Bonding

## Advantages

- Strong connection due to covalent forces
- Wide process window
- Most applied bond process / Wide application field in MEMS

## Disadvantages

- Material limits: Si – Glass (sputtered, spin-on-glass, LTCC)
- Formation of an oxide layer at interface may damage electronics / ??????
- Danger of warp after bonding due to internal stress
Adhesive bonding

Polymer adhesives = transform from liquid to solid phase
   = must not outgas during curing process

- **Thermoplastic** (heating and cooling)
  - PMMA, easily etchable
  - Liquid crystal polymer, low moisture uptake

- **Thermosetting** (chemical reaction forming larger molecules)
  - BCB (Dow Chemical), chemically stable < 350°C
  - SU8 (Microresist), chemically stable < 250°C
  - ULTRA-i 310 (Shipley), easily etchable, chem stable <200°C
Adhesive bonding

Sketch and optical photo of an RF-MEMS switch encapsulated by BCB bonding

(with permission IMEC, A. Jourdain)

Adhesive bonding

Device transfer by temporary adhesive bonding

• Thin (<0.3 μm) crystalline and high T annealed material films can be integrated with CMOS circuits.

• Transfer bonded devices can have small feature sizes (<1 μm) and small via contacts (< 3x3 μm²).

# Adhesive bonding

## Advantages

- Low bonding T ⇒ CMOS compatibility
- No special surface quality; any wafer material
- Low cost, easy to use, high yield process

## Disadvantages

- No hermetic seal
- Alignment accuracy depends on adhesive thickness
Metallic bonding

<table>
<thead>
<tr>
<th>Wafer metallization</th>
<th>Eutectic Bonding</th>
<th>Solder (10-50 μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al, 1 μm</td>
<td>AuSi, 363°C</td>
<td>SnPb_{37}, 180°C</td>
</tr>
<tr>
<td></td>
<td>AlGe, 420°C</td>
<td>SnAg, 220°C</td>
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<tr>
<td></td>
<td>AuSn, 280°C</td>
<td></td>
</tr>
</tbody>
</table>

Metal systems used for metallic bonding.
Metallic bonding

0, 1 and 2 level packaging of an RF-MEMS switch by SnPb solder ball,

a) sketch, b) X-ray image of “the MEMS

A. Jourdain et al., Proceeding MEMS 2005
## Metallic bonding

### Advantages

- Medium process temperature (200 – 400°C)
- Hermetic seal easy to achieve

### Disadvantages

- Demands on wafer topography
- Precautions electrical feedthrough
Characterisation

Non-contact

- **infra-red** (non-bonding areas larger than 20 µm)
  - multiple internal reflection geometry-Fourier IR spectroscopy (MIRS-FTIR) can be used to investigate the chemistry of the bonded interface,

- ultrasound imaging,

- **X-ray diffraction topography** (lateral resolution of 1 µm),

- **scanning acoustic microscopy** (lateral resolution of 4 µm),
Characterisation

Fracture surface energy
- Maszara test \( W = E \cdot t^3 \cdot y^2 / 8 \cdot L^4 \)

Bond strength
- pull test,
- burst test,

Hermeticity
- membrane test,
- He-leak,
- resonator/pressure.

Electrical properties of bonded interface
- IV,
- CV,
- R
Characterisation

Dependence of the upper \textit{fine} leak rate $R$, on the cavity volume $V$ for a dwell time of 100, 300 and 900sec.
Characterisation

Theoretical and measured Q-values versus air pressure, for a double-lid structure oscillating in the anti-phase torsion mode.
Conclusions

• Different bonding methods can be used for MEMS

When and which:
• Mechanical aspects
• Hermiticity
• Thermal budget / stability
## Overview of bonding principles possible for use in MST

<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>Surface Energy/Bond Strength</td>
<td>0.1 - 2.5 J m⁻²</td>
<td>0.02 - 2.8 J m⁻²</td>
<td>0.03 - 6 J m⁻²</td>
<td>5-50 MPa</td>
<td>16-148 MPa</td>
<td>3-10 MPa</td>
<td>0.2-2.7 J m⁻²</td>
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<tr>
<td>Surface Roughness</td>
<td>6 Å</td>
<td>4 Å</td>
<td>≤ 20 nm</td>
<td>≤ 5 nm</td>
<td>≥ 1 μm</td>
<td>≥ 1 μm</td>
<td>6 Å</td>
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<tr>
<td>Wafer Bow</td>
<td>1–25 μm (4 inch)</td>
<td>1–25 μm (4 inch)</td>
<td>&gt; 10 μm (4 inch)</td>
<td>&gt;10 μm (4 inch)</td>
<td>&gt; 10 μm (4 inch)</td>
<td>&gt; 10 μm (4 inch)</td>
<td>1-25 μm (4 inch)</td>
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<td>Spontaneous Bonding</td>
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<td>spontaneous</td>
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<td>Tanneal</td>
<td>RT-1000 °C</td>
<td>RT-700 °C</td>
<td>RT-500 °C</td>
<td>300-600 °C</td>
<td>160-800°C</td>
<td>&lt; 200 °C</td>
<td>RT-450 °C</td>
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<tr>
<td>Surface Treatment</td>
<td>RCA HNO</td>
<td>HF dip HNO₃+HF</td>
<td>cleaning</td>
<td>cleaning</td>
<td>cleaning</td>
<td>cleaning</td>
<td>RCA H₂O Dip</td>
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<tr>
<td>Applied External F</td>
<td>slight pressure heat</td>
<td>slight pressure heat</td>
<td>50–1500 V</td>
<td>50–600 V</td>
<td>heat or/and pressure</td>
<td>heat pressure</td>
<td>slight pressure heat</td>
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<td>Long-Term Stability</td>
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<td>+</td>
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<td>o</td>
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<tr>
<td>Materials</td>
<td>Si, SiO₂…</td>
<td>Si…</td>
<td>Si, glass…</td>
<td>Si, glass…</td>
<td>Au/Si, Si/Ge</td>
<td>Si, PolySi,…</td>
<td>Si, SiO₂, InP,…</td>
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</tbody>
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