Advanced techniques for NDT of MEMS devices & WL packaging

Challenges for 3D ICs and systems

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Outline

• Motivation: MEMS devices are 3D systems
  ✓ Packaging constraints
  ✓ Need new techniques for wafer level packaging (WLP) assessment

• Case study: non destructive testing of MEMS accelerometers
  ✓ Failure mechanisms
  ✓ IR microscopy
  ✓ X-ray tomography

• Advanced characterization of the hermeticity of WLP
  ✓ Issues with the MIL-STD approach
  ✓ Membrane deflection technique
  ✓ In situ quantification through FT-IR analysis
Packaging constraints

- Protect the mechanical (moving) part from any contamination / damage
- Control the atmosphere
  - ✔️ hermetically sealed cavity
- In case not achieved: performances loss, permanent failure...
- MEMS process costs are balanced between the fabrication of the MEMS itself and its packaging
- Need to develop or derive new techniques to assess the packaging

From MEMSPACK FP7 program (IMEC lead)
NDT of MEMS accelerometers

- BOSCH BMA180 (tri-axial low-g acceleration sensor for consumer market)
- IR imaging and OBIRCH
  - Sample preparation: removal of the polymer packaging
  - Direct observation of the combs

Sensing part

Y-axis (in plane)

Z-axis (out of plane)
NDT of MEMS accelerometers

- **BOSCH BMA180** (tri-axial low-g acceleration sensor for consumer market)
- **X-ray tomography**
  - Lower resolution (here 5µm voxel size)
  - Easy understanding of the device
NDT of MEMS accelerometers

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Context

- Wafer Level Packaging
  ✓ Small volume ($1 \leq V (\text{mm}^3) \leq 10$)
  ✓ High levels of hermeticity for MEMS as small as $10^{-14}$ atm.cc.s$^{-1}$

- Helium leak detection method range
  ✓ The detection limit of the He mass spectrometer is $5 \times 10^{-11}$ atm.cc.s$^{-1}$

- Two methods will be investigated in this context:
  ✓ Measurement of membrane deflection when exposed to different pressures, by optical profilometry
  ✓ Measurement of the variation of gas concentration in a sealed silicon cavity, by FT-IR
Test structure : WLP

- Test vehicle specification
  - Si-Si micro-cavity
  - Thickness membrane: 65µm
  - AuSi Eutectic sealing ring
  - Volume 0.046 cm³
Experimental protocols

• Membrane deflection
  ✓ Deflection measurement of the cavity without gas by optical profilometry
  ✓ Pressurization stage to 5 bars during 96 hours with He
  ✓ Measurement of the variation of the membrane deflection by optical profilometry

• FT-IR spectroscopy method
  ✓ Reference measurement of the cavity without gas by FT-IR
  ✓ Pressurization stage to 5 bars during 96 hours with N₂O
  ✓ Evaluation of the gas concentration inside the cavity by FT-IR spectrometer
Membrane deflection

- Based on the measurement of the deformation of cap as function of an external pressure
  - If $P_{\text{int}} < P_{\text{ext}}$ the deflection is negative ($w < 0$)
  - If $P_{\text{int}} = P_{\text{ext}}$ the deflection is null ($w = 0$)
  - If $P_{\text{int}} > P_{\text{ext}}$ the deflection is positive ($w > 0$)
Membrane deflection

- Optical detection of membrane deflection principle
  - Measurement of membrane deflection performed at t0
  - Helium pressurization applied to the package during t1
  - After bombing, variation of the membrane deflection is measured

- For squared membrane $P_{\text{diff}}$ and $w$ are related by:

$$P_{\text{diff}} = C_1 \frac{tw_0}{a^2} \sigma + C_2 \frac{tw_0^3}{a^4} \frac{E}{1 - \nu} + C_3 \frac{E}{1 - \nu^2} \frac{t^3w_0}{a^4}$$

- Helium leak rate can be deduced by Howell-Mann’s equation

$$P = P_E \left( 1 - e^{-\frac{Lt_1}{VP_0} \sqrt{\frac{M_{\text{air}}}{M_{\text{gas}}}}} \right) e^{-\frac{Lt_2}{VP_0} \sqrt{\frac{M_{\text{air}}}{M_{He}}}}$$
Membrane deflection

- Membrane deflection of the test vehicle after pressurization at different dwell times
  - Membrane deflection increased => cavity internal pressure increased
  - Test vehicle is not hermetic \( L = 3.4 \times 10^{-9} \text{ atm.cm}^3 \text{s}^{-1} \)

Variation of the membrane deflection as a function of dwell time

Surface topography after bombing stage
FT-IR spectroscopy method

- Based on evolution of gas concentration into the package

✓ Using FTIR
  - Initial FTIR measurement without gas (vacuum or air)
  - Package is submitted to N\textsubscript{2}O bombing pressure during a time \( t \)
  - FTIR measurement after bombing
  - Obtain the transmission spectrum of the gas contained in the cavity \( T_{\text{Gas}} \)

![Absorption spectrum of the tracer gas](image)

Absorption spectrum of the tracer gas

\[
\frac{T_{\text{Test}}}{T_{\text{reference}}} = T_{\text{gas}}
\]
FT-IR spectroscopy method

- Calculus of partial pressure of gas in the cavity using Beer-Lambert law and ideal gas law
  - Beer-Lambert law \(- \log(T) = \omega \cdot l \cdot C\)
  - Ideal gas law
    \[- \log(T) = \frac{\omega \cdot l}{RT} P\]

- Leak rate can be deduced by Howell-Mann’s equation

\[
P = P_E \left( 1 - e^{-\frac{Lt_1}{Vp_0} \sqrt{\frac{M_{air}}{M_{N2O}}}} \right) e^{-\frac{Lt_2}{Vp_0} \sqrt{\frac{M_{air}}{M_{N2O}}}}
\]
FT-IR spectroscopy: results

- IR spectra of the test vehicle after pressurization with 10min dwell time
  - N2O penetrated in the cavity during the bombing stage
  - N2O clearly visible
  - Principal absorption peak at 18%
FT-IR spectroscopy: results

- IR spectra of the test vehicle at different dwell times after pressurization
  - N2O pressure variation inside the cavity decreases with time
  - Confirms the leak

![Graph showing IR spectra at different dwell times](image)

IR spectra of the test vehicle at different dwell times after pressurization
(Transmission peak between 2210 and 2240 cm\(^{-1}\))
Resolution of both methods

- **Optical leak method by membrane deflection**
  - Depend on the geometry and mechanical properties of the membrane
  - The minimal deflection that can be measured is determined by the accuracy of the interferometer
  - Resolution increases with the bombing pressure and duration: \(2 \times 10^{-12} \text{atm.cm}^3\cdot\text{s}^{-1}\)

- **FT-IR spectroscopy method**
  - Depend on the size of the package
  - The signal to noise ratio of the measurement by FTIR
  - Resolution increases with the bombing pressure and duration: \(6 \times 10^{-12} \text{atm.cm}^3\cdot\text{s}^{-1}\)
Synthesis

Helium leak test
- Helium pressurization stage
- Short dwell time
- Mass spectrometer measurement
- Determination of the leak rate

Pros
- Standard, fast, simple

Cons
- Detection limit, not adapted for small packages
- Diffusion of helium through Si

FT-IR test
- Transmittance measurement before pressurization
- N₂O pressurization stage
- Short dwell time
- Transmittance measurement after pressurization
- Subtraction of both spectra
- Determination of the leak rate

Pros
- High resolution

Cons
- Not adapted for metallic cap
- Large spot size (~1mm)

Optical leak test
- Membrane deflection measurement before pressurization
- Helium pressurization stage
- Short dwell time
- Membrane deflection measurement after pressurization
- Determination of the leak rate

Pros
- High resolution, depending on package geometry (cap thickness)

Cons
- Membrane stiffness and width to be compatible with the interferometer
- Diffusion of helium through Si
Conclusion

• Take up the challenge of reliable wafer level packaging for MEMS devices!
• New tools to be developed, others to be derived from the microelectronics equipments

• Non destructive testing and failure localization are key issues for MEMS devices, as they are very sensitive to any “unpackaging” process

• Direct measurement of the leak rates for micro-packages enables a reliability assessment of the device