Thermal Laser Stimulation for MEMS characterization and failure analysis, from principles to case studies

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Purpose

• Demonstrate how techniques primarily dedicated to Integrated Circuit Failure Analysis can be used for MEMS expertise

• Give a focus on Thermal Laser Stimulation techniques that are not only helpful for fault localization but also to study reliability behavior of MEMS devices

• Show how it brings unique information that could not be easily found by other means

• Validate it through two case studies
Outline

• Introduction
• Thermal Laser Stimulation
  – Apparatus
  – Resistance change principle and application
  – Seebeck effect imaging principle and application
• Micro-Heating Elements Suspended on Thin Membranes
  – Micro-heating sample description
  – Reliability test results
  – TLS studies
• Micro-relay
  – Sample description
  – TLS studies
• Conclusions
Introduction

• How can we perform MEMS expertise?
  – Material / mechanical approach
    • Physical characterization to access material properties
      – Surface and volume
      – Thermal, optical, mechanical
      – Tools: Nanoindenter, profilometer, interferometer
    • Specific failure mechanism
      – Mobile parts …
  – Electronic point of view
    • Electronic function: sensor, signal processing, actuator
    • Electronic FA Tools
  – Two complementary approaches to cover “system” approach

• Specific approach mixing “mechanical” and “electrical” (i.e. contact)
TLS Principle : LSM
TLS Principle: OBIRCH, TIVA

- Resistivity slightly changes with temperature. Under local thermal laser stimulation, local resistivity change occurs

\[ \Delta R = \frac{\rho_0 L}{S} \left( \alpha_{TCR} - 2\delta_T \right) \Delta T \]

- Other materials
  - Metal \( \alpha_{TCR} > 0, \delta_T > 0 \)
  - Polysilicon or doped Si, \( \alpha_{TCR}, \delta_T > 0 \)

- Voltage source (OBIRCH: K. Nikawa)

- Current source (TIVA: E. Cole)

\[ \alpha_{TCR} = 4.29 \times 10^{-3} \]

\( \delta_T = 2.36 \times 10^{-5} \)

\[ \Delta I = -\left( \frac{\Delta R}{R^2} \right) V \]

\[ \Delta V = \Delta R \cdot I \]
TLS application in IC Failure Analysis

- Direct defect localization (short circuit)
- Circuit BICMOS ($I = 85 mA$)
  - Leakage current on some I/O
    - $I > 100 \mu A$ instead of $I < 10 \mu A$
  - 4 interconnection layers

BS TLS (20x)

BS EMMI (20x)

Si \(\sim 290 \mu m\)
Lightly doped

W short (électrodes Drain-Source)

PMOS transistor
TLS principle: Seebeck Effect Imaging

- **Seebeck Effect**
  - Two materials
  - Temperature difference
  - => induce a voltage between material

- **NB_TLS**
  - No Biased TLS
  - SEI Seebeck effect imaging

- $\Delta V = V_{12}$

![Diagram showing two materials M1 and M2 with temperature $T > T_0$ and a laser input.]

<table>
<thead>
<tr>
<th>Material</th>
<th>$Q_{12}$ ($\mu$V/°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al / W</td>
<td>7.0</td>
</tr>
<tr>
<td>Al / n+ Poly</td>
<td>-121</td>
</tr>
<tr>
<td>Al / n+ Si ($10^{20}$cm$^{-3}$)</td>
<td>-105</td>
</tr>
</tbody>
</table>

\[ V_{12} = (Q_1 - Q_2)(T - T_0) = Q_{12}(T - T_0) \]
NB TLS application in IC Failure Analysis

- **Vias M1-M2**
- **R=7.14 (spec R=0.8 Ohm)**

Courtesy of Abdellatif Firiti, ST Microelectronics
Micro-Heating Elements Suspended on Thin Membranes (MHESTM)

- **Manufacturing process**
  - Si nitride (0.5 µm) deposited on Si substrate
  - Pt (210 nm) and Ta (15 nm) coating
  - Second Si nitride deposit (0.5 µm)
  - Si etching

**Applications:**
- Thermal sensor
- Thermal actuator
- Gaz sensor
- …

![Diagram of MHESTM structure](image)
MHESTM reliability test

- **Performed by the Neuchâtel Institute of microtechnology**
  - Temperature measured using micro-thermocouples
  - Warping, buckling measured using an optical profilometer
  - Record of resistance value versus temperature
  - Degradation at 575°C after 2000h (resistance increases)

- «MEMS» Failure Analysis
  - Electro migration / stress migration site at the spiral start
    - Identification of some critical process steps
    - Why did we get this? => real time monitoring is mandatory
    - Optical microscopy did not give results
NB TLS on MHESTM (1)

- *Initial (before any kind of stress)*
  - SEI Image
  - Thermocouples
  - => Bad homogeneity

- Other acquisitions
  - After stress
    - Start
    - 5,8 V (138 mW)
    - Stop
    - Ambient temperature
    - NB TLS Measure
    - Start again
NB TLS on MHESTM (2)

• **Aging monitoring**
  – From 0h to 14h
  – 3 different samples
  – Same signature

• **NB-TLS applications**
  – Characterization of different process flow
    • Homogeneity issues
    • Thermal stress only
    • Mechanical stress only
MHESTM: complementary analysis (1)

MEB: Back scattered A+B (composition mode)
MHESTM: complementary analysis (2)

- X microanalysis
Micro-relay: sample description

- Mobile part (B, C, D)
- Hinge (A)
- 2 end contact in // (D)
- 2 medium contact in //
- Contact by electrostatic force (C moves down)
NB-TLS on Micro-relay

- 20x magnification
- Neither applied current nor applied voltage
- Good contact (bottom left)
- Poor contact (top)
- Open contact (bottom right)
Micro-relay: complementary analysis (1)

- **SEM pictures of contacts**
  - Bottom left
  - Bottom right
  - Upper left (= upper right)

- **No evidence between poor and good contact**
Micro-relay: complementary analysis (2)

• **TLS analysis**
  – Check where current is flowing
  – Confirm previous NB-TLS results

• **Evidence of reliability risk**
  – Unbalanced current flow
  – Faster wear out of good contact (current flow)
  – Faster wear out of poor contact (resistance => power dissipation)

• **NB-TLS validation**
  – Reliable results (good contact)
  – No invasive (neither current nor voltage)
Conclusions

• **Thermal Laser Stimulation has been used for MEMS expertise**
  – Complement mechanical characterization by giving electric signature
    • Not Invasive, Contact less, Submicron spatial resolution
    • Well known on purely electronic behavior (such as ESD)
  – Fast access to cross parameters (mechanical + electrical), no vacuum (SEM)
  – Very helpful for reliability studies

• **Other microelectronics FA tools can be used for MEMS expertise**
  – According to mechanism Particle, fracture, fatigue, wear, stiction, ESD…
  – RX, SAM, FIB, SEM, STEM, TEM, AFM (and electrical modes)
  – Real time analysis can be performed by dynamic tools (derivate from SDL, PICA …)

• **Cross parameters**

• **Reliability**