NEW STAND-ALONE PACKAGED THERMAL SENSORS BASED ON THERMOELECTRIC EFFECT

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CEA / Liten - Thermoelectricity Laboratory
Introduction: CEA Tech

• **CEA**: 16,000 researchers and administrative staff
• 4,500 are working to bring manufacturers a broad range of Key Enabling Technologies

**Thermoelectric Lab (LTE)**
At Grenoble site (CEA-LITEN division)

www.cea.fr/english-portal/cea-tech
- Develop TE technology (material and modules) from TRL3 → TRL6
- Address key technological challenges (improve TE material performance)

→ Technical results presented here are financed by an R&D contract between CEA and HotBlock OnBoard SAS
1 - Context

2 - General points on Thermoelectricity and Thermal Sensors

3 - General properties of thermoelectric sensors
   3.1 - Wafers characteristics
   3.2 - Chips packaging & performances

4 - Conclusions / Perspectives
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4 - Conclusions / Perspectives
• Global context
Continuous increase of applications in portable systems (mobile phones, lab top, etc.) inducing by a continuous increase of microelectronic chips number
→ leads to a critical level of the thermal management in microelectronic field
→ Too high temperatures can damage strongly the chips or even destroy them
→ The control and management of the heat is a key issue for the future development of microelectronic systems

• State-of-the art
No stand-alone thermal component allowing the direct measurement of thermal flow at low scales. Only in-IC thermal sensors can be found in literature, usually based on bipolar transistors
→ SoA in-IC thermal sensors are power consumer (need analogical polarization currents of some µA) and no predictive

• Our proposal
Development of a new kind of stand-alone thermal components, power free, predictive and can be used directly near the hot points of interest, based on thermoelectric effect
What is thermoelectrics?

- Energy harvesting
- Cooling
- Thermal sensors
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Some years ago...

- **1821**: T. J. Seebeck: a potential difference is created when a temperature difference is applied at the extremities of a material.

\[ V = S \times \Delta T \]

where \( S_i = \text{Seebeck coefficient or thermoelectric power (µV.K}^{-1}) \)

- By convention: \( S < 0 \) for n type materials
  
  \( S > 0 \) for p type materials
• **1834**: J.-C. *Peltier*: when a current is applied through a solid, there is a moving of heat from one side to the other side.

• **1838**: H. *Lenz*: when a current goes through a material in contact with another material, there is a production, and vice versa, an absorption of heat at its extremities.

• **1950s**: A. *Ioffe*: discovery of TE properties of doped semiconductor materials.
**Standard structure of a thermoelectric device**

![Thermoelectric device diagram]

### Effect

<table>
<thead>
<tr>
<th>Effect</th>
<th>Seebeck effect</th>
<th>Peltier effect</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Principle</strong></td>
<td>Temperature gradient induces Seebeck voltage</td>
<td>Electrical current induces cooling/heating effect</td>
</tr>
</tbody>
</table>
| **Applications** | → Power generation  
  → Thermal flow sensor | → Cooling  
  → Thermal management |
• Three important properties for TE materials:
  \[ S = \text{TE power (μV.K}^{-1}) \]
  \[ \sigma = \text{electrical conductivity (S.m}^{-1}) \]
  \[ \lambda = \text{thermal conductivity (W.m}^{-1}.K}^{-1}) \]

• Definition of the dimensionless figure of merit
  \[ ZT = \frac{\sigma \times S^2}{\lambda} \]

→ The best TE materials correspond to highly doped semiconductors
• Working mode of common thermal sensors

\[ Q_{th} = \frac{T_h - T_c}{R_{th}} \]

where
- \( Q_{th} \) = thermal flow (W)
- \( T_h \) = hot side temperature (K)
- \( T_c \) = cold side temperature (K)
- \( R_{th} \) = thermal resistance (K/W)

Common thermal sensor.

• Thermoelectric thermal sensors (TES)

→ based on the Seebeck effect

\[ U = N \times S_{np} \times \Delta T \]

where
- \( U \) = generated voltage (V)
- \( N \) = np junctions number (-)
- \( S_{np} \) = Seebeck coefficient of the np junction (µV/K)

Thermoelectric sensor.
• Planar TES

→ Here, thermal flow is planar and TE legs are made from lines

• Main characteristics of planar TES

→ Area $A_{TES}$ (mm$^2$)
  - $A_{TES} = L_{TES} \times l_{TES}$
  - in general, as low as possible

→ Sensitivity $S_e$ (mV/K)
  - $S_e = U \times \Delta T$
  - in general, as high as possible

→ Electrical resistance $R_{int}$ ($\Omega$)
  - $R_{int} = N \times \rho_{n,p} \times L_{TES} / (l_{n,p} \times e_{TE})$
  - in general, as low as possible

→ Thermal resistance $R_{th}$ (K/W)
  - $R_{th} = L_{TES} / (\lambda_{n,p} \times l_{n,p} \times e_{TE})$
  - in general, as low as possible
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4 - Conclusions / Perspectives
• Strategy

- Thermal management by independent sensors (first manufacturing of such components)
- Sensors developed in microelectronic technologies at industrial scales
- Process flow made on standard 8 inches silicon substrates
- Standard packaging QFN (Quad Flat No leads) from microelectronic technology

• Main technological steps

- 1 - Wafers process flow
  - Full wafer sensors manufacturing.

- 2 - Chips manufacturing
  - Chip after slimming and cutting steps.

- 3 - Chips packaging
  - Finalized packaged sensors.
• Thermoelectric materials

→ TE materials chosen in the semiconductor family (best TE performances)
→ TE materials chosen to be compatible with standard microelectronic technology
→ n and p highly doped Si-based materials

• Geometry

→ TES geometry defined by its length, width, junctions’ number and lines’ width and spacing
→ 3 geometries (named G1, G2 and G3) chosen to provide a diversified scale of sensors characteristics
→ These 3 geometries have the same length total $L_{TES}$ and width $l_{TES}$ but with different junctions’ number and lines’ width, i.e.:

\[
\begin{align*}
N_{G3} & < N_{G2} < N_{G1} \\
I_{n,p_G1} & < I_{n,p_G2} < I_{n,p_G3}
\end{align*}
\]
• Structures implemented on wafers

  → Materials TE properties characterization (both types n and p)
    - Seebeck coefficient measurement
    - Electrical resistivity measurement

  → Sensors tests structures characterization (for geometries G1, G2 and G3)
    - Sensitivity measurement
    - Electrical resistance measurement

  → Sensors products structures
    → No measurement at the wafer level, directly sent to the packaging step

  → In total, 2750 sensors products and 2500 tests structures (materials and sensors) per wafer
• Characterization tool

→ All tests structures (materials and sensors) are measured by using an industrial wafer probes tool

→ Measures can be made in temperature

*TE prober used for the TE characterization of materials and sensors.*
Sensors tests structures

- Electrical resistances $R_{\text{int}}$

  → Measured by a standard 4-probes method

![Graph showing electrical resistances $R_{\text{int}}$ as a function of temperature.]

<table>
<thead>
<tr>
<th>$R_{\text{int}}$ (k$\Omega$)</th>
<th>27 °C</th>
<th>75 °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>G1</td>
<td>3250</td>
<td>3290</td>
</tr>
<tr>
<td>G2</td>
<td>424</td>
<td>429</td>
</tr>
<tr>
<td>G3</td>
<td>43.8</td>
<td>44.4</td>
</tr>
</tbody>
</table>

Evolution of electrical resistances of sensors tests structures as a function of geometry and temperatures.

→ Slight increase of $R_{\text{int}}$ with the temperature
→ Increase of $R_{\text{int}}$ with the geometry $R_{\text{int}_{G3}} < R_{\text{int}_{G2}} < R_{\text{int}_{G1}}$
  (in good correlation with $N_{G3} < N_{G2} < N_{G1}$ and $I_{n,p_{G1}} < I_{n,p_{G2}} < I_{n,p_{G3}}$)
Sensors tests structures

• Sensitivities $Se$

$\Delta T_c = \frac{1}{TCR_c} \frac{\Delta R_c}{R_c}$ and $\Delta T_h = \frac{1}{TCR_h} \frac{\Delta R_h}{R_h}$

$Se = \frac{V}{\Delta T_h - \Delta T_c}$

Measure of $\Delta T_c$

Measure of $\Delta T_h$

<table>
<thead>
<tr>
<th>G1</th>
<th>G2</th>
<th>G3</th>
</tr>
</thead>
<tbody>
<tr>
<td>45.6</td>
<td>17.5</td>
<td>5.8</td>
</tr>
<tr>
<td>48.9</td>
<td>18.8</td>
<td>6.3</td>
</tr>
</tbody>
</table>

Evolution of sensitivities of sensors tests structures as a function of geometry and temperatures.

→ Slight increase of $Se$ with the temperature

→ Increase of $Se$ with the geometry $Se_{G3} < Se_{G2} < Se_{G1}$ ($N_{G3} < N_{G2} < N_{G1}$)
- 3.2 -
Chips packaging & performances

Courtesy of HotBlock OnBoard SAS.
• Packaging specifications

→ Standard 16-pins QFN (Quad Flat No leads) package

→ Sensors size: $3 \times 3,2 \times 0,8 \text{ mm}^3$

→ Bumping with gold balls

→ Electrical connections between chip and packaging are made by electrical paths into the support

*Bottom view of sensors.*

*Schematic cross view of a sensor.*
• Heat transfer inside the sensor

Schematic cross view of the thermal transfer between the hot and cold sources, inside the packaged TE sensors.

Schematic bottom view of heat transfer inside the sensor.
• Packaged sensors characterization system

→ Development of a specific TES characterization system

→ TES brazed directly on PCB (Printed Circuit Board), including two heating elements on both sides of TES and thermocouples to control precisely the temperatures.

Picture of the TES characterization system.
• Sensors reactivity to a thermal variation

→ Very good reactivity of sensor voltage as a function of thermal flow (example with geometry G3)

Evolution of sensor voltage $V_{\text{sensor}}$ and temperature difference $\Delta T$ as a function of time $t$. 
• Sensors stability to a thermal balance

→ Very good stability of sensor voltage as a function of thermal flow both for high and low $\Delta T$ (example with geometry G3)

Evolution of sensor voltage $V_{sensor}$ as a function of time $t$ for low and high temperature difference $\Delta T$. 
• Sensors sensitivities as a function of geometry

<table>
<thead>
<tr>
<th>Sensitivity (mV/K)</th>
<th>27 °C</th>
<th>75 °C</th>
</tr>
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<tbody>
<tr>
<td>G1</td>
<td>7.5</td>
<td>7.7</td>
</tr>
<tr>
<td>G2</td>
<td>2.14</td>
<td>2.8</td>
</tr>
<tr>
<td>G3</td>
<td>0.71</td>
<td>0.9</td>
</tr>
</tbody>
</table>

→ Sensitivity increases ($S_{eG3} < S_{eG2} < S_{eG1}$) with the junctions number ($N_{G3} < N_{G2} < N_{G1}$)

→ Slight increase of Se with the temperature: due to the increase of the TE materials Seebeck coefficient with the temperature
Sensors characterization

• Influence of packaging on TE performances

→ Electrical resistances $R_{int}$: identical to those measured on sensors tests structures: no influence of packaging on the electrical resistance

→ Sensitivity $S_e$:

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<th>Sensitivity (mV/K)</th>
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<th>75 °C</th>
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</thead>
<tbody>
<tr>
<td>G1 on wafer</td>
<td>45,6</td>
<td>48,9</td>
</tr>
<tr>
<td>G1 packaged</td>
<td>7,5</td>
<td>7,7</td>
</tr>
<tr>
<td>G2 on wafer</td>
<td>17,5</td>
<td>18,8</td>
</tr>
<tr>
<td>G2 packaged</td>
<td>2,14</td>
<td>2,8</td>
</tr>
<tr>
<td>G3 on wafer</td>
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<tr>
<td>G3 packaged</td>
<td>0,71</td>
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→ sensors packaging leads to a decrease of factor 6 to 8 on their sensitivity
Sensors characterization

- Influence of packaging on heat transfer

\[ \text{Hot source } T_h \]

\[ \text{TC}_{\text{hot}} \quad \text{TC}_{\text{cold}} \]

chip
  - substrate
  - active layers
  - gold ball
  - metal line
  - support

thermal loss through the substrate
thermal loss through the support

→ decrease of sensor sensitivity mainly due to thermal losses through substrate and support
• Sensors architecture optimization

→ Manufacturing of TES with new optimized architecture to decrease the influence of packaging and so increase their sensitivities
→ The new architecture optimizes the thermal flow transfer from TES pins to the chip (deposited patent)

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<th>Sensitivity (mV/K)</th>
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<tr>
<td><strong>G1 standard</strong></td>
<td>7,5</td>
<td>7,7</td>
</tr>
<tr>
<td><strong>G1 optimized</strong></td>
<td>8,4</td>
<td>7,91</td>
</tr>
<tr>
<td><strong>G2 standard</strong></td>
<td>2,14</td>
<td>2,8</td>
</tr>
<tr>
<td><strong>G2 optimized</strong></td>
<td>2,58</td>
<td>3</td>
</tr>
<tr>
<td><strong>G3 standard</strong></td>
<td>0,71</td>
<td>0,9</td>
</tr>
<tr>
<td><strong>G3 optimized</strong></td>
<td>0,78</td>
<td>1,05</td>
</tr>
</tbody>
</table>

→ All optimized structures increase the sensors sensitivity, up to ≈ 20%
→ The influence degree depends on the geometry and ΔT
• Sensors stability as a function of time

→ Sensor under continuous thermal flow during 2 days

Sensor sensitivity (Geometry G2) under continuous thermal flow ($T_{hot} = 110$ °C) during 2 days.

→ Excellent stability of sensors in time
**Sensors characterization**

- Tests in dynamic regime

  → Sensors under dynamic thermal flow to observe their reactivity

  - Transient voltage source
  - Oscilloscope for the viewing of the applied voltage
  - TES

  → Excellent reactivity of sensors under dynamic thermal flow
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4 - Conclusions / Perspectives
→ **First manufacturing** of such packaged thermoelectric thermal flow sensors (stand-alone, predictive, power free)

→ **High sensitivities** are obtained (45 mV/K for the on wafer chips and 8 mV/K for the packaged sensors)

→ Packaging of chips leads to a 6 – 8 factor decrease of sensitivity

→ **New thermal architecture** of TES leads to 20 % increase of sensitivity

→ TES present **stable and reactive responses** in time and for low and high temperature difference

→ TES available as **HBOB products commercialized** with the trademark µFlux Tracker®

→ TES technology **patented** by CEA and HotBlock OnBoard SAS

→ New generation of TES manufacturing in progress to limit more the influence of packaging on thermal flow transfer and so to increase more TES sensitivity
THANKS FOR YOUR ATTENTION