MEMS Sensors and Energy Harvesting: IoT Game Changer through MEMS Integration and Advanced Materials

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Content

• Silex and PZT, a Brief Overview
• IoT:
  – Driver for Smart Sensors and Energy Harvesting Devices
  – EU development program incentive, Smart-MEMPHIS
• TSV Technology:
  – A building block for reduced die-size
  – Impact on device manufacture
• Piezo-MEMS development:
  – PZT, not one but several materials
  – PZT Results
Sil-Via®: TSV for Functional MEMS Sensor Integration

Examples of products manufactured at Silex:

- Accelerometers*
- Cantilevers
- Cell Analysis
- Drug Delivery
- Electrodes
- Filter structures
- Flow sensors*
- Gyros*
- IC Interposers*
- Lab-on-chips*
- Microphones*
- Mirrors*
- MUTs*
- Needles*
- Optical Membranes
- Optical Benches*
- Pressure sensors*
- Print heads*
- RF switches
- Resonators*
- Touch Membrane
- µBatteries*
- IR Sensors

* Sil-Via® TSV implemented
A ceramic material with compelling properties:

- **Piezoelectric:**
  - Mechanically stressed => Develops voltage
  - Voltage applied => Physically changes shape

- **Dielectric**
  - Large dielectric constant

- **Pyroelectric:**
  - Temperature change => Develops voltage

- **Ferroelectric:**
  - Spontaneous electric polarization

- PZT’s piezoelectric, dielectric and pyroelectric properties in particular make it a desirable material in MEMS processing.

- PZT and metal films can be deposited on the surface of Si wafers, and patterned to create actuating or sensing structures in devices of various types.
PZT – Crystal Orientations

<100>
- Highest Figure of Merit (FOM) for actuation and energy harvesting
- Can be formed by use of a buffer layer of specially treated PZT or some other material
- Composition is important to achieve the desired trade off between piezoelectric properties and temperature stability

<111>
- Can easily be formed on <111> Pt layer

Source: S. TROLIER-MCKINSTRY & P. MURALT (Journal of Electroceramics, 12, 7–17, 2004)
1Materials Research Institute and Materials Science and Engineering Department, Penn State University
2Ceramics Laboratory, Swiss Federal Institute of Technology EPFL, Lausanne, Switzerland
Piezo-MEMS Applications

- **Power MEMS**
  - Energy harvesters

- **Acoustics**
  - MUTs
  - Loudspeakers

- **Actuators**
  - Micromirrors
  - For inertial sensors (vibrating gyroscopes...)
  - Microfluidics
    - Micropumps, microvalves, droplet generators, nozzles...
  - Lens autofocus and other MOEMS
  - Timing devices (resonators)
  - Piezoelectric Micromachined Ultrasonic Transducers (p-MUT)

- **Sensors**
  - Inertial
    - Vibration sensors
  - IR sensors (Pyroelectric effect)
  - Piezoelectric Micromachined Ultrasonic Transducers (PMUT)
  - Microphones

- **Integrated Passive Devices (IPD)**
  - MIM Capacitors

Note: PZT material optimized slightly different for each application!
Internet of Things and Everything (IoT, IoE)

- World of connected all things around us.
- Enabled by:
  - IPv6 providing $3 \times 10^{38}$ IP addresses, one for every “thing”.
  - Fog and Swarm connectivity/computing (below the Cloud).
  - Sensors.
- Bold forecasts for IoX:
  - Cisco: $19$ trillion by 2020, over $20\%$ of the global 2020 GDP
  - GE: $15.5T \text{ by 2020.}$
  - Networked sensors are expected to represent $5\%$ of IoX, $\$1T \text{ by 2020.}$
- First major IoE startup: NEST.
  - Acquired for $3.2$B by Google.
  - New Era for startups?

IoT Benefit: Wireless Sensor Networks (WSN) Analytics

100s of sensor types will be needed to collect information about monitored objects.

Once information is collected, it can be used to optimize processes, providing financial incentives for development.

Source:
Introduction to TSensors (Trillion Sensors) Initiative
Dr. Janusz Bryzek
Chairman and CEO, TSensors Summit
IoT - the 3rd MEMS Wave
MEMS Sensors: A Key Enabler for IoT and WSN

Sensors & Applications for IoT

Legend:
- Sensor
- Level of demand

Source: Yole Development
There are predictions of one trillion sensors being produced per year by 2020. They all need power, so Energy Harvesting becomes crucial.

Source: MicroGen, Berlin 2014
Power-MEMS / Energy Harvesters: A Solution to the IoT Battery Problem

IoT problem: Battery life!

“Energy is a challenge. To power trillions of sensors requires energy and per unit it will have to be reduced from today’s levels. It will need to be derived from light, vibration, thermal energy scavengers.”

– Janusz Brysek, Ph.D. Chairman and CEO T Sensors Summit Inc.

Overall IoT & pEH market sizes

✓ Piezoelectric Vibration Energy Harvesting $7-14B addressable market in 2019

* Source: T Sensor Summit, Stanford University, Oct 23-25 2010 (see slide 4 for original graph)
** Source: IDTechEx www.IDTechEx.com/energy (Jan 2014) (see pie chart on slide 33 for pie chart breakdown)
Energy Harvesting: A Key Enabler for IoT and WSN

Energy Harvesting Technologies
Technology overview: time to market

- Mechanical
- Thermal
- PV
- MEMS process
- Thin Film technologies
- Standard thermo-electric technologies
  - Includes MEMS devices
  - Vibrational Electrostatic technologies
  - Vibrational Piezoelectric technologies
  - Vibrational Electromagnetic technologies
- Pulse technologies (Electromagnetic & Piezoelectric)
- CMOS integrated PV
- cSi/aSi solar cells

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Energy Harvesting Applications

- Building
  - Switches
  - Wireless sensors
- Industry
  - Wireless sensors for machine monitoring
- Transportation
  - Helicopter
  - Trains sensors
- Automotive
  - TPMS
  - Wireless sensors
- Others
  - Medical
  - Electronics
  - Environmental
IoT Related Applications for Sensor Networking Power Module with Integrated MEMS Vibration Harvester
Silex is currently leading a H2020 European Consortium with the objectives to develop MEMS based piezo materials for smart system integration.

The partners and role in smart-MEMPHIS:

<table>
<thead>
<tr>
<th>Partners</th>
<th>Country</th>
<th>Role</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (CO) SILEX MICROSYSTEMS</td>
<td>Sweden</td>
<td>Coordinator MEMS mfg Expert Harvester materials and manufacture</td>
</tr>
<tr>
<td>2 ACREO SWEDISH ICT</td>
<td>Sweden</td>
<td>Integration, testing</td>
</tr>
<tr>
<td>3 SORIN CRM SAS</td>
<td>France</td>
<td>Packaging into a pacemaker, animal testing</td>
</tr>
<tr>
<td>4 FRAUNHOFER-GESELLSCHAFT ZUR FOERDERUNG DER ANGEWANDTEN FORSCHUNG E.V</td>
<td>Germany</td>
<td>Packaging the components using flat paner technology</td>
</tr>
<tr>
<td>5 CHALMERS TEKNISKA HOEGSKOLA</td>
<td>Sweden</td>
<td>Energy storage using supercapacitors</td>
</tr>
<tr>
<td>6 LINKOPINGS UNIVERSITET</td>
<td>Sweden</td>
<td>Designing the energy management ASICS Dissemination</td>
</tr>
<tr>
<td>7 VERMON SA</td>
<td>France</td>
<td>Structural health monitoring, Exploitation</td>
</tr>
<tr>
<td>8 aixACCT Systems GmbH</td>
<td>Germany</td>
<td>Piezo MEMS material testing</td>
</tr>
<tr>
<td>9 SPINVERSE OY</td>
<td>Finland</td>
<td>Dissemination, exploitation, management</td>
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</table>
Lead less pacemaker motivation for integrated MEMS vibration harvester

Illustration source: blogs.umnhealth.org/9-19-2014

Source: www.smart-MEMPHIS.eu
published with permission © Sorin Group
Sil-Cap®
Hermetically Capped Piezo-MEMS Structures for pEH

SMART
MEMPHIS

Smart-MEMPHIS Objectives:

- Use Silex SmartBlock® WL bonding processes with integrated TSVs
- Multi-axis (3DOF) mechanical Silicon resonator vibration structure with low resonance frequency (< 100 Hz)
- Integrated piezo material (PZT based) with optimal FOM for energy harvesting
- Low temperature vacuum hermetic bonding (using getter for high vacuum/high Q)
- Mechanical force feedback for active frequency tuning
- Achieves smallest footprint and highest MEMS quality and reliability
TSV Motivators

- Simplified packaging -> reduced cost
- Reduced form factor -> reduced cost
- The development has been rapid as previously reported by Yole Development.
VIA technologies

Substrate is single crystal, highly doped silicon

An insulating material fills the via trench

Via post is formed out of the low-resistivity substrate

Metal-VIA® aspect ratios for improved reliability.

Hollow VIA plating allows Tc conformance

Redundant hermetic seals preserves cavity vacuum

Latest development: Metal VIAs in glass (TGV)

Other solutions:
Poly-Si VIAs
Mono-Si with air-gap isolation
Melted glass over metal pins
Si introduced into glass
Technical solutions and their cost competitiveness
Sil-Via® and TSV integration for form factor reduction

Indeed, if TSV induce additional cost (~75$ in this case), one needs to consider that when TSV are smartly implemented into the MEMS wafer design, it can drive further down the cost of the FE. In this particular case, the cost of the MEMS die is now just about 10% of the total resonator module, which is quite impressive. It means that most of the cost distribution is now into the ASIC and final package parts. Which can further indicate where to put next development efforts in the future…

MEMS External Inspection – SEM View
- Two Through Silicon Via (TSV)
- TSV Diameter: ~50μm
- TSV width: ~7.7μm

Synthesis of the cost analysis

- The ASIC wafer cost is estimated at (medium yield estimation).
- The ASIC die cost is estimated at (medium yield estimation).
- The production of the MEMS is assumed to be realized by Silex Microsystems on 150mm wafers.
  - The MEMS wafer cost (Cap + Resonator) is estimated at (medium yield estimation).
  - The MEMS die cost is estimated at (medium yield estimation).
- Packaging and final test of the component are assumed to be subcontracted in Malaysia.
  - The packaging cost is estimated at .
- The component manufacturing cost ranges from to according to yield hypotheses.
Sil-Cap® Hermetically Capped MEMS

Key building block for motion Sensors

- Based on Silex SmartBlock® Processes
- Sil-Via® TSVs adaptable to multiple designs and sensor types
- Achieves smallest footprint and highest MEMS quality and reliability
Incite is together with Smart-MEPHIS are some of the drivers for recent PZT development at Silex.

**WP2 - Imaging**

Using system requirement input from WP1, WP2 designs and realizes in-body ultrasound imaging functionalities for catheters. WP2 consists of partners with component, assembly, software and system integration expertise that is needed for the ultrasound imaging catheter demonstrator. Activities include:

**Demonstrator activities:**
- Design, fabricate and test MEMS ultrasound transducer arrays (CMUT).
- Perform acoustic modelling to optimize transmit and driving schemes.
- Design and realize catheter tip ASIC for driving and reading out imager.
- Investigate advanced interconnect and data link technologies.
- Test imagers, interconnect, data link and ASIC components.
- Integrate the components into a ultrasound imaging catheter demonstrator, including data/signal processing interfaces.
- Perform bench testing of integrated system.

**Research activities:**
- Design, fabricate and test MEMS ultrasound transducer arrays (PMUT).
- Investigate advanced interconnect, integration and processing technologies for further miniaturization.
- Investigate new driving schemes for optimal CMUT imaging.
- Develop and validate ultrasound simulation model to guide next-generation device designs.

Source: [www.incite-project.eu](http://www.incite-project.eu)
### Piezoelectric Materials: Pros and Cons

**PZT; Sol-Gel vs. Sputtered**

<table>
<thead>
<tr>
<th></th>
<th>Sol-Gel</th>
<th>Sputtered</th>
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</thead>
<tbody>
<tr>
<td>Initial investment</td>
<td>Low-Medium</td>
<td>High</td>
</tr>
<tr>
<td>Manufacturing cost</td>
<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td>Film composition tuning</td>
<td>Flexible</td>
<td>Less Flexible</td>
</tr>
<tr>
<td>Breakdown Voltage</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Self Poling</td>
<td>Difficult</td>
<td>Easier</td>
</tr>
<tr>
<td>Curie Temperature</td>
<td>Lower</td>
<td>Higher</td>
</tr>
</tbody>
</table>

Note: With established **self-poling** (wafer-level poling 2nd best option) and **high enough** curie temperature Sol-Gel becomes extremely attractive.
PZT Developments

- SILEX PZT on C-SOI smartBlock® technology
- Successful process of 1.2 mm thick crack-free <100> PZT films is now established for p-MUTs using a novel high throughput sol-gel composition (200-220 nm/layer instead of 50-80 nm)
- Low leakage current PZT and improved bottom electrode barrier and buffer/seed-layer materials have been explored
Etched and diced test wafer
PZT Electro Mechanical Testing (e31)

PZT developments

E31 Measurement highest e31 after 150°C poling

Sample information:
- Thickness: 10.525 ± 0.005 mm
- Area (mm²): 1000
- Material: PZT
- Substrate: Silicon Kite [1]
- Substrate Thickness: 377 μm

- Conditions:
- Measurement Parameters
- Test Results

e31 Measurement:
- e_{31} Coefficient [C/m²]: -17.6

Advanced Customized Characterization Technologies
PZT Characteristics

Additional measurement results during optimizations

I/V measurements (480nm sol-gel PZT)

C/V measurements
Silex PZT – Characteristics & Attributes

• **Industry-Benchmark Levels for FOM:**
  - Piezoelectric effect $e_{31}^2$: >-15 C/m² with high wafer uniformity
  - Young’s modulus: 75GPa
  - Relative permittivity $\varepsilon_r$: 1,200 (tunable from 700 to >1,400)
  - Breakdown voltage: 80-130V/µm depending on PZT type
  - Leakage current: <200nA/cm² (up to BDV)
  - Reliability testing evaluation in progress with good preliminary results.

• **Volume Production-Oriented Manufacturability:**
  - Sol-gel method for spin coating on Si substrates
    - Higher flexibility than sputtered film for film composition tuning
  - High density, thick layer for high throughput without film cracking
  - State-of-the-art deposition process in <100> & <111> orientations

• **Figures of Merit (FOM) for different applications:**
  - $e_{31}^2/\varepsilon_r$ for actuators & energy harvesting
  - $e_{31}/\varepsilon_r$ for sensors
  - $\varepsilon_r$, leakage current and BDV for capacitors
N-Series PZT enables deposition of films up to 4 µm thick

Spin-coating
- Sol-Gel is deposited
- Wafer is rotated to spread the Sol-Gel evenly
- Layer thickness is controlled to 220 nm by rotation speed

Pyrolysis
- Film is dried at 80°C
- Film is pyrolysed on 450°C hot plate to remove solvent

Crystallization
- Film is annealed at 700°C in Rapid Thermal Processor (RTP) to crystallize PZT
- Rapid heating is required to form Perovskite rather than Pyrochlore structure

Source: Mitsubishi Materials
Silex PZT Processing – N Series Sol-Gel Deposition

- High production throughput based on thick individual layers
  - Up to 4x that of conventional Sol-Gel
  - Single layers >200 nm thick
- Up to 4 µm thick crack free films in <100> orientation
- Preserved piezoelectric and electric properties
- Self-polarization (in situ) possible
- Improved yield, reduced costs

Top Electrode - 200 nm Au

PZT

Bottom Electrode

SiO₂

Si

1.2 µm <100> PZT with only 6 layers

4 µm <100> PZT with 20 spin coating iterations

4 µm <100> PZT with 20 layers
Summary - Conclusions

• The IoT drive is here already and MEMS plays a very important part.

• The drive and belief generated spurs broader cooperation among companies and in addition government incitements enables further development through cross-pollination.

• VIA technology has already helped enable reduced size and cost and will continue to do so in combination with direct integration.

• Additional development and industrial adaptation of materials can act as further enablers. PZT, for example, is getting ready for a broader industrial adaptation.
Acknowledgements

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  – **smart-MEMPHIS**, has received funding from the European Union’s Horizon 2020 research and innovation program under grant agreement No 644378.
Silex Microsystems Overview

• A Premier, Global Foundry Services Company
  — Founded in 2000, headquartered near Stockholm, Sweden
  — ‘Pure play’ (no own products)

• An Innovation Leader
  — Leveraging proprietary TSV-related technologies to push the boundaries of 3D substrate processing and product integration

• A Dedicated and Reliable Manufacturing Partner
  — 2,200 m² of state-of-the-art, separate 6” and 8” wafer fabs
  — Volume production oriented
  — ISO 9001:2008 certified

Silex Provides

• Processing services including MEMS, CMOS post processing, WLP, TSV/TGVs, Interposers,…..

• Comprehensive Process libraries and 3D ‘building blocks’

• A well proven New Product Introduction (NPI) process

• State of the Art MEMS fab facilities

• A highly experienced team of engineers

• Experience with regards to high volume production in CE market
Silex: A Leading Enabler of Innovative MEMS Products and Sensors

Examples of Sensors and MEMS devices manufactured at Silex over the years

- Pressure sensors for measuring blood pressure in coronary arteries
- Microphones for mobile telephones
- Mirrors for optical switching
- Lab-on-chip for DNA analysis

Silex Microsystems
Thank you for your attention!

Please, visit our booth to learn more about our activities!