National MEMS Technology Road Map

A Synthesis of Questionary Responses and Expert Meetings - 14.6.2011

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MEMS Technology Roadmap – Targets

• Select focus areas and direct more research resources on those
• Generate new long term growth opportunities for the Finnish MEMS/sensor cluster
  – Includes new opportunities for start ups/spinn offs
• Position Aalto/VTT as an internationally leading research area in MEMS and sensors, and attract best talent to Finland
Status of the Work – 14.6.2011

• The questionnaire was sent to 41 Finnish companies
  – First submission on the end of November
  – Second submission early January

• Response ratio was 37 %

• Analysis of the results
  – First workshop on 28.1.2011: overall review of the responses
  – Second workshop on 7.2.2011: synthesis of the results
    • Research review
  – Third workshop on 3.3.2011: synthesis of the results 1
    • Commercial review
  – Fourth workshop on 19.4.2011: synthesis of the results 2
  – Fifth workshop on 27.5.2011: focus areas for the future
  – Publication of the Roadmap: 14.6.2011 at the 7th Eemeli Workshop
Focus Areas in Materials

- Use will increase: piezoelectric, allotropes of carbon (CNT, graphene), SMA/MSM
- Use will diminish: glass

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**2011**

- **Piezoelectric** materials on Si
- **Ceramic** materials in MEMS
- **Polymers** materials on Si
- **Carbon Nanotubes** on Si
- **Shape Memory Alloys / Magnetic Shape Memory materials** on Si
- **Graphene** on Si

**2015**

- **Piezoelectric** materials in MEMS
- **Ceramic** materials in MEMS
- **Polymers** materials in MEMS
- **Carbon nanotubes** on Si / CNTs utilized in MEMS
- **SMA/MSM** on Si / SMA/MSM utilized in MEMS
- **Graphene** on Si / Graphene utilized in MEMS

**2020**

- **SMA/MSM** in MEMS
- **Graphene** in MEMS

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**Aalto University**
School of Science and Technology

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**VTT**
Focus Areas in the Development of Enabling Technologies

- Metal Bonding
- Laser Direct writing
- ALD (e.g. for TSVs)
- CMOS post processing MEMS
- SOI (cost pressure) → Low Cost SOI
- Surface MEMS
- Roll-to-roll processing
- Porous Silicon
- Thin film processing of new materials
e.g. graphene, shape memory alloys

2011 2015 2020
Emerging MEMS Devices

3-axial gyroscope
multi-directional microphone
color micro-display
micro-fluidistics
tunable filters
tunable capacitor
tunable inductor

tunable capacitor
atomic oscillators
microbolometer

vibration energy harvesting
image projection

solar / RF energy harvesting
thermoelectric energy harvesting

cryogenic cooler
adjustable optical lens

Today In the near future In the long run

cryogenic cooler

fuel cell
responsive drug delivery

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Packaging and Integration

Wafer Level Packaging of MEMS
- Si Capped WLP
- eWLP
- Metal wafer bonding
- TSVs

3D Stacked WLP MEMS/IC
- MEMS on CMOS
- Through encapsulant vias
- “sensor fusion”
- “responsive systems”

Plastic Packaging (e.g. LGA)
- Fan-out WLP

Over Molded and Capped Pkng

Ceramic Pkng

2011 2015 2020
National MEMS Roadmap – Focus Areas

Recommendation of national focus areas of R&D:

- Next Generation 3D Integration of MEMS based Systems
- Functional Materials in MEMS based Systems
- MEMS based Biomedical sensor/actuator systems
1. Markets or application areas

- This year:
  - Industrial: 8 of the respondents
  - Consumer: 6 of the respondents
  - Medical: 3 of the respondents

- In the future / in the long run:
  - Market positions are expected to remain stable.
  - Few respondents indicated plans of expansion to consumer or to medical markets but position in the existing markets still stable.
  - “We try to follow markets and penetrate into emerging profitable areas.”
2. Changes in customer expectations

• Customer expectations today:
  – *Primarily*: higher quality and lower cost
  – *Also*: higher volumes, and faster time-to-market; stable market growth

• Customer expectations in near future (next 5 years):
  – *Primarily*: even lower cost, higher volumes, and faster time-to-market; fast market growth
  – *Also*: higher levels of integration (not only in MEMS device level but also on the system/product level) and new technologies / technological improvements

• Customer expectations in the long run (2020 and beyond):
  – New functions and applications enabled by MEMS
  – New technologies (merger of CMOS and MEMS)
  – Competition in the markets will grow
  – More in-depth knowhow
3. Drivers for the adoption of MEMS techn.

- **Today:**
  - *Primarily:* low cost of devices
  - *Also:* small dimensions and improved performance of devices (e.g. accuracy, lower power consumption)

- **In the near future** *(within the next 5 years)*
  - *Primarily:* low cost and improved performance as before
  - *Also:* Integration of MEMS with other technologies (healthcare, ubiquitous sensors)

- **In the long run** *(2020 and beyond)*
  - Ubiquitous sensors
  - Sensor fusion
  - More intelligence at the sensor level ⇔ “Intelligent fully integrated devices”
  - Near field communication
4. Infrastructure and support needs for R&D

• **Today**
  – Infrastructure:
    *Primarily*: prototyping
    *Also*: lithography, etching, poly filling, surface micromachining
  – Support:
    *Primarily*: simulation
    *Also*: platform to meet “players in the field”

• **In the near future** (within the next 5 years)
  – Infrastructure:
    *Primarily*: design, prototyping, foundry
    *Also*: polymer dotting, gas mixtures, laser drilling, TSV/TGS/TCV
  – Support: **MEMS Center of Excellence in Otaniemi**

• **In the long run** (2020 and beyond)
  – Infra: MID line
  – Support: graphene processing, CNT manufacturing
5. Needs regarding education and expertise

• Today:
  – Two types
    • *Experts*: specific areas from materials to processing; from MEMS design to verification (good knowledge in physics)
    • *Multidisciplinaries*: People with interdisciplinary view; focus on system level

• In the near future:
  – More emphasis on system integration and MEMS software
  – Good knowledge in physics
    • Materials and processing
    • Electronics
    • Nanoscale and semiconductor physics
      – Quantum effects
    • Modeling

• In the long run:
  – Requirements not much different
6. Emerging MEMS based devices

- Majority of the respondents described improved versions of existing MEMS devices:
  - **Consumer / industrial markets**
    - Devices with better accuracy
      - E.g. different kinds of physical sensors, chemical sensors, silicon timing circuits
    - Devices with low power consumption
      - Self-operational sensor networks
      - Systems with energy harvesting capability
  - **Bio-medical markets**
    - Personal health monitoring systems ("a megatrend of the future")
    - Lab-on-chip
    - Responsive bioMEMS (combined sensors and actuators)
    - Devices and applications:
      - Microfluidistics (e.g. micro-pumps and micro-reservoirs) for drug delivery
      - Micro-needles
      - Microbolometers (devices for measuring energy of incident electromagnetic radiation)
      - Graphene based chemical sensors
7. Functional limits of MEMS devices

- **Accelerometers**: accuracy (high-end), “sensitivity/cost” (low-end)
- **RF switches**: reliability, cost of fabrications
- **Gyroscopes**: current consumption, dynamic range, sensitivity, accuracy, cost
- **Chemical sensors**: expensive to manufacture
- **Thermopiles**: low power efficiency, costly to manufacture
- **Photometers**: wavelength range too narrow
- **FPI**: wavelength range narrow, high tuning voltage
- **IR emitters**: stability over time, power consumption, expensive to manufacture
- **Silicon oscillators**: thermal stability
- **Gas or fluid analysis**: lack of materials or manufacturing technologies
8. System development in MEMS applications

System development was seen as a very important area in future development. Here are some comments:

- “New unforeseeable applications require the whole detection and information chain to be on the same technological level”

- “System development will have bigger business potential than MEMS device manufacturing”

- “Active MEMS functionality together with integrated CMOS control logic and analog electronics”

- “In future this [system development] is essential”; “Pure MEMS is nothing”
9. Reliability challenges of current MEMS devices

• From the **use environment** point of view:
  – Mechanical shock impacts and vibrations
  – Rapid changes of temperature
  – Moisture and contaminations; corrosion

• From **processing** point of view:
  – Detection of defects caused during manufacturing:
    • Weak bond interfaces
    • Structural defects (voids in SOI)
  – High temp. deposition of silicon structures

• From the **device** point of view:
  – Materials stability
  – Biocompatibility of medical MEMS applications (medical device standards and regulations of authorities)
10. Reliability challenges of future devices

• Detection of failures modes and their root causes
  – How to differentiate issues arising from different sources (material, device processing, final assembly etc.)

• Modeling of reliability
  – Finding a suitable lifetime models becomes more challenging when approaching nano-scale dimensions

• Packaging
  – Combination of IC packaging and more sensitive MEMS devices is real challenge to mechanical reliability and humidity resistance.

• Reliability assurance of device level software
  – Challenges emphasized at design phase testing
11. Improvements in methods of reliability evaluation

- Accelerated lifetime tests
  - Tests should take better into account unique characteristics of different MEMS devices
  - Methods for device level evaluation are relatively developed; development of evaluation methods should be focused on
    - System level tests (lack of design specifications)
    - Wafer level tests
    - Die level tests

- Methods of failure analyses
  - Methods that support identification of root cause (e.g. from material, device processing, final assembly…)
  - Ways to test small gaseous leaks

- Methods of reliability simulation
  - More comprehensive (multi-physics) simulation tools are needed
12. Materials in MEMS applications

- Silicon, polysilicon, structurally modified silicon
  - **Today**: dominant
  - **In the near future**: remain as basic materials; + SOI and porous Si
  - **In the long run**: will be used; hybrid materials start to emerge (e.g. Si + graphene)

- Alternative semiconductor materials (e.g. SiGe, SiC, GaN, diamond)
  - **Today**: in certain specific applications
  - **In the near future**: usage may increase in certain niche applications
  - **In the long run**: will remain as materials for niche applications
12. Materials in MEMS applications

- **“Structural”** materials (e.g. polymers, glass, metals, graphene, CNT, etc.)
  - **Today**: polymers and glass are commonplace
  - **In the near future**: carbon based MEMS in prototyping, metal MEMS emerging, use of polymers will increase (BioMEMS applications little bit behind), use of glass will decrease (demand for CMOS compatibility)
  - **In the long run**: CNTs in high volume, graphene adopted, devices will become “multimaterial”, use of polymers will increase in BioMEMS

- Functional materials
  - **Today**: Piezo, MSM and molecularly imprinted materials are promising
  - **In the near future**: use of piezoelectric materials gaining share, first MSM MEMS prototypes, environmentally reactive materials; other materials in niche applications
  - **In the long run**: ?
12. Materials in MEMS applications

• **Encapsulation materials**
  – **Today**: polymers, metals, glass
  – **In the near future**: thin film, silicon (~WLP)
  – **In the long run**: (thin) metals, silicon, polymers; glass will lose share

• **Amorphic materials**
  – **Today**: in niche applications
  – **In the near future**: wider use of amorphous thin films and wire possible
  – **In the long run**: not a significant growth of use expected
13. Changes in the use of materials

- Glass in sealing will lose share, metal sealing will grow
- Integration towards hybrid materials a likely direction

14. Emerging technologies in volume processing

- Deep reactive ion etching
- Nano imprinting, pico dotting, ALD
- Via technologies, laser processing,
- Carbon-based materials processing
- Different CMOS compatible MEMS approaches will be competing against each other
15. Evolution of processes technologies

- Traditional electronics manufacturing processes
  - **Today**: answers were mixed: e.g. from ”dominant” to “some processes”, and from “merger of MEMS into CMOS clear” to “separate ASIC inside MEMS components”
  - **In the near future**: Basis of real mass production, “MEMS above CMOS [ever] more common ”
  - **In the long run**: “Basic tools will remain”, NEMS emerge, ever more intelligence/logic integrated into sensor level

- Silicon-based SOI and surface MEMS
  - **Today**: Both coexist ; surface MEMS dominates; SOI based MEMS breaking through in specific areas.
  - **In the near future**: Surface MEMS dominates (low performance CE), SOI based MEMS has strong position (“high performance”).
  - **In the long run**: “Unless SOI cost cannot be driven down, alternate solutions will appear”
15. Evolution of processes technologies

- **CMOS post-processing MEMS**
  - **Today**: Emerging technology; few examples existing in volumes; niche
  - **In the near future**: Competes with other CMOS compatible MEMS, the concept will be tested.
  - **In the long run**: Good potential to have significant share

- **Via technologies**
  - **Today**: Studied; emerging in volume
  - **In the near future**: Increasing, common in interposers and in some MEMS devices, Cu vias (via last) will dominate.
  - **In the long run**: widely used, via last processes dominate; via first in some niche applications
15. Evolution of processes technologies

- Roll-to-roll and/or other low-cost processes
  - **Today**: Studied, only very few applications; promising technology
  - **In the near future**: First volume sensors made with R-to-R with inkjet, laser processing appears in volume; Modest usage.
  - **In the long run**: Low cost processes start to replace lithography, etching, deposition (…laser, inkjet, printing); Will be important.

- Improvement of a single process step conventional technologies (e.g. lithography, etching, film deposition)
  - **Today**: Very important; e.g. higher etch rates in DRIE, faster and more uniform deposition processes in TSV materials.
  - **In the near future**: Will be important; e.g. dry resists (combined with laser lithography) can replace conventional liquid resists
  - **In the long run**: Will be important
16. Revolutionary processing technologies

- Molecular level manipulation
  - Nanostructures

- 3D printing of packages

- Direct Writing

- Molecular or structural shrinking (BioTech)
17. Obstacles for the adoption of the emerging process technologies

- Price/cost (process development, equipment, etc.)
- Intellectual property rights
- "courage, passion, far too few people having dreams"
- Too small volumes to justify investment in R&D
- “Too obscure business to justify investment in manufacturing”
18. Package or integration concepts

- **Today:**
  - Standard/cost efficient e.g. over molded, encapsulated plastic packages
  - Soldering/ wire-bonding several components on a single substrate
  - Custom package (e.g. steel), no integration

- **In near future:**
  - WLP (consumer), encapsulated (automotive)
  - 3D common with TSV´s, interposers.
  - In some case it could be possible to remove the package (i.e. WLP); in some case it is mandatory to keep it
  - Standard MID packages or over molding on PCB, 2-4 sensors on same package (single dies)

- **In the long run:**
  - CMOS ready wafers where MEMS can be processed; MEMS above CMOS
  - WLP will prevail
19. Interconnect technologies

• Today:
  – Soldering (lead frames and flip-chip)
  – Wire-bonding
  – Adhesive
  – TSV’s and interposers

• In the future:
  – Soldering (lead frames and flip-chip)
  – Wire-bonding
  – Adhesive
  – TSV

• In the long run:
  – In 2020 already new interconnects (CNT or other)
  – TSV’s and new interposers
20. Environmental requirements

- Today
  - High temperature / RH / pressure
  - Mechanical shocks
  - Corrosion

- In the future no changes to current requirements