Smart MEMS Piezo Based Energy Harvesting with Integrated Supercapacitor and Packaging

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Abstract. The smart-MEMPHIS project (H2020 RIA) has the ambition to combine new features of energy harvesting, energy storage and power management by miniaturization and innovative packaging technology to produce leadless pacemakers and structural health monitoring applications. The project will integrate several multi-functional technologies and nanomaterials; MEMS-based energy harvester, ultra-low-power ASIC, miniaturized energy storing supercapacitor, all heterogeneously integrated for cost effective 3D integration. The presentation will cover various aspects and requirements as well as the considered solutions for each module.

1. Introduction

IoT is one of the main drivers for technology development related to the main challenge of all smart devices-self-powering: a trillion sensors need power. A big percentage of IoT opportunities will not realise if batteries need to be changed often, they are placed in inaccessible places (*e.g.* inside bridges or building walls as for Structural Health Monitoring applications) or large quantities are required. However, energy harvester to be of any advantage, the applications would run on ultra-low power, low data rate and low duty cycle. For these applications, miniaturization and low cost fabrication are needed.

Vibration piezoelectric energy harvesters convert mechanical strain into electrical energy. They have received much attention in the last 15 years, due to the simple configuration and high conversion efficiency as comparing to electrostatic and electromagnetic harvesters [1]. Utilization of Micro Electro Mechanical Systems (MEMS) technologies allows for a totally integrated system containing sensor, electronics, communication and energy source.

The International Technology Roadmap for Semiconductors has recognized energy efficient electronics as a key enabler for addressing the potential of spatially distributed and connected sensors [2]. We are interested in exploring and developing novel smart energy enabling technologies via MEMS-based energy harvesting technologies with a final goal of a system-on-chip or integrated component solutions. In particularly, designing novel structures in combination with piezoelectric MEMS technology for more energy efficient small-size electronic systems using autonomous power supply through new innovative technologies. However, the scaling remains an issue and the unfavourable scaling of power with miniaturization needs to be solved.

2. Energy Harvester System and Applications

A standard energy harvester system for a wireless sensor network consists of five main components: harvester, energy storage, microcontroller, sensor(s) and transceiver (Fig. 1).

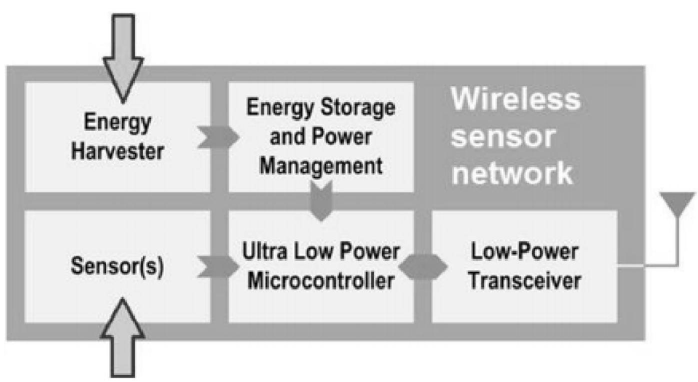


Fig. 1. Typical architecture of wireless sensor network.

Similar architecture is used also for the energy harvesting system developed within the Smart-MEMPHIS project [3] with focus on implantable pacemakers and aircrafts (Fig. 2).

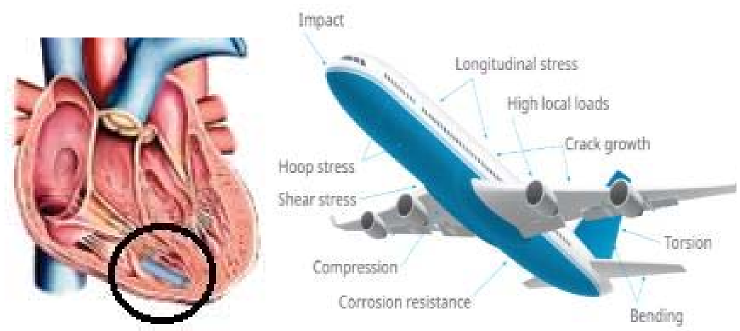


Fig. 2. (Color on line) Leadless pacemaker (left, © LivaNova, reproduced with permission) and Structural Health Monitoring (SHM) for aeronautical application (right).

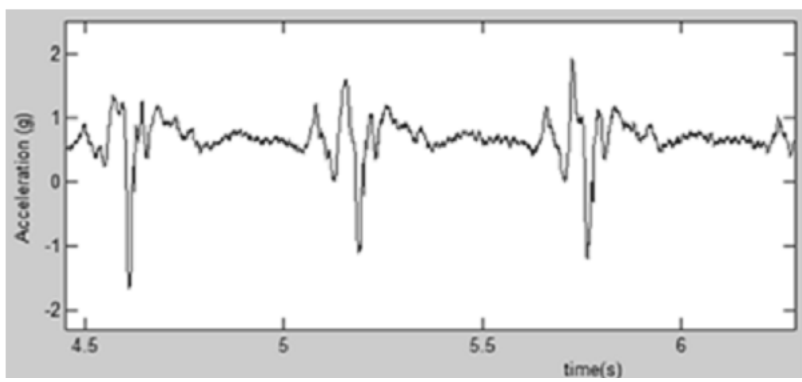


Fig. 3. Heartbeat waveform.

Smart implantable medical devices will require a solution to the problem of device longevity. While for SHM, the monitoring of the changes in material complex structures (*e.g.* micro-cracks in aircraft wings), requires at present many various sensors to collect data. So, there is a need for smart autonomous wireless acoustic sensors for aeronautical SHM applications.

For the leadless pacemaker, the energy sources inside the body, near the heart looks as shown in Fig. 3. For the harvester we are using the heart’s mechanical vibration as transduction.

The smart-Memphis energy harvester is based on MicroElectroMechanical systems (MEMS)-based thin-film piezoelectric mechanism that is more attractive for converting mechanical energy into electrical energy at small dimensions (mm^3 scale).

3. Piezoelectric Material Deposition

PZT (Lead Zirconate Titanate) is a piezoelectric 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

There are two main ways of depositing PZT films: sol-gel and sputtering. For smart-Memphis we use sol-gel deposition (Fig. 4) because it is a low-cost technology, has high deposition rate, allows for excellent thickness uniformity, has less defects and high breakdown voltage. SEM images of typical PZT layers deposited by Silex are shown in Fig. 5 and Fig. 6.

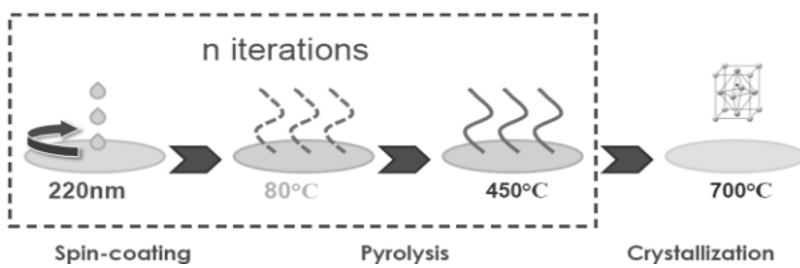


Fig. 4. Schematic of PZT sol-gel deposition.

Industry-benchmark levels for figure of merit of Silex PZT are:

– Piezoelectric effect e_{31}: -15 C/m^2 with high wafer Uniformity
– Young's modulus: 75GPa
– Relative permittivity ε_r: 1200 (tunable from 700 to >1400)
– Breakdown voltage: 80–130 V/µm depending on PZT type
– Leakage current: < 200 nA/cm^2
– Reliability testing evaluation in progress with good preliminary results.

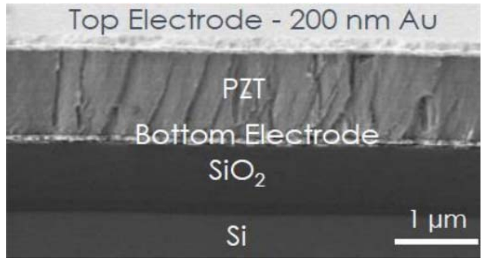


Fig. 5. 1.2 µm <100> PZT with only 6 layers.

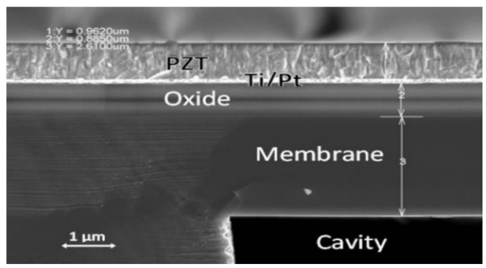


Fig. 6. PZT on Cavity SOI substrate.

4. Piezoelectric Material Characterization & Poling

A poling setup has been designed by AixACCT Systems Gmbh allowing for non-destructive poling and testing on wafer level (Fig. 7) as well as on device level. A poling set-up for fast heating and cooling of 1inch samples with integrated measurement for deflection measurement of MEMS structure has been also developed. These allow for enhanced characterization of thin film and device by determination of e_{31} on wafer level, also heating systems for piezoelectric thin film test systems and implementing of in-situ e_{31} measurements during poling.

5. MEMS Harvester Structure Design & Characterization

Energy flow of piezoelectric harvester has tree primary steps: capturing the mechanical stress from the available source, converting the mechanical energy into electrical energy with the piezoelectric transducer, and processing and storing the generated electrical energy. For each of these steps, there are losses involved; for mechanical excitation, mechanical to electrical conversion, and electrical conversion. The harvester design (by Acreo Swedish ICT) aims to decrease these losses via harvester geometry and its packaging, via proper modelling of the physical-mechanical to electrical transduction using analytical models and finite element simulation (Comsol, Ansys). The MEMS harvester works in d_{31} mode where the electric field is perpendicular to the strain direction (Fig. 9).

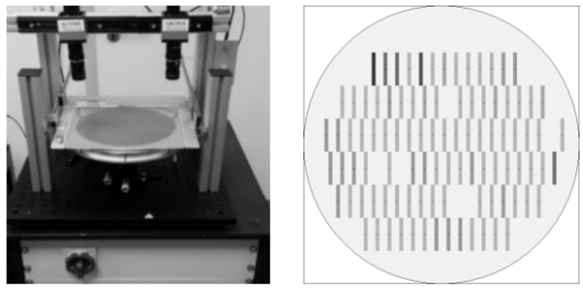


Fig. 7. Prototype full wafer poling (left) and Non-destructive poling and testing on wafer level (right).

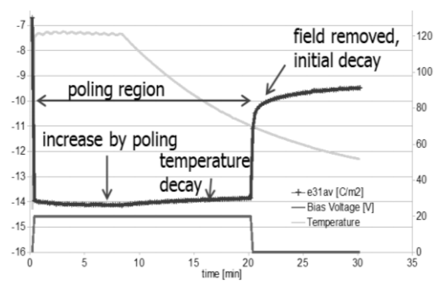


Fig. 8. *In-situ* measurement of e_{31} during temperature poling.

For the harvester characterization, Acreo uses a combination of Laser Doppler vibrometer, shaker and vacuum chamber to obtain information on mechanical characteristics, piezo-mechanical coupling, damping and losses (air and vacuum) and verification of harvester model.

5. Super Capacitor

The supercapacitor is a storage device for the harvested energy and consists of electrodes, separators and electrolytes. Novel materials are explored for the different parts of the supercapacitor. Material requirements for electrodes are porosity, surface area, mechanical stability, electrical conductivity, electrochemical stability. For the electrodes, especially carbon nanostructures synthesized by CVD (chemical vapor deposition) and electrospun cellulose carbonized by pyrolysis are developed. Specifically, 3D structured carbon nanofiber / MnO_2 composite material (NCNF / MnO_2) exhibits the best performance with high specific capacitance (108.6 F/g @ 0.5A/g) and excellent power capability (84.3 F/g @ 15 A/g).

The separator uses glass fiber with high thermal stability up to 600°C, excellent mechanical property and high uptake of different electrolytes. The electrolyte is a high temperature ionic liquid (EMIM Ac) enables high working voltage window up to 1.5 V and increases the energy density to 21.1 Wh/kg. Temperature durable PVA / H_3PO_4 gel electrolyte with reduced leakage risk and high package capability. The device with gel electrolyte can deliver 82 mF after high temperature exposure.

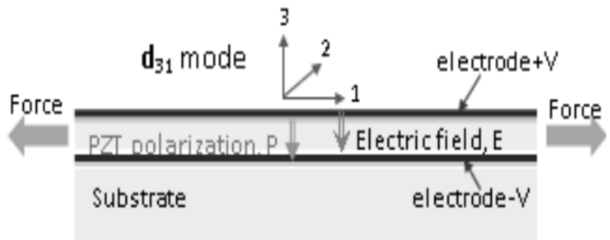
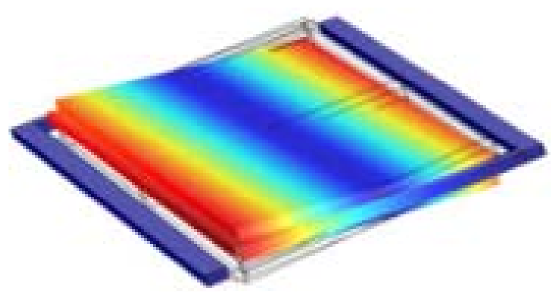
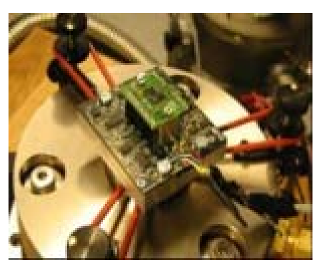


Fig. 9. Applied force, strain, electric field and polarization for the d_{31} mode of operation.

Eigenfrequency = 1115.7 Surface: Total displacement (μm)

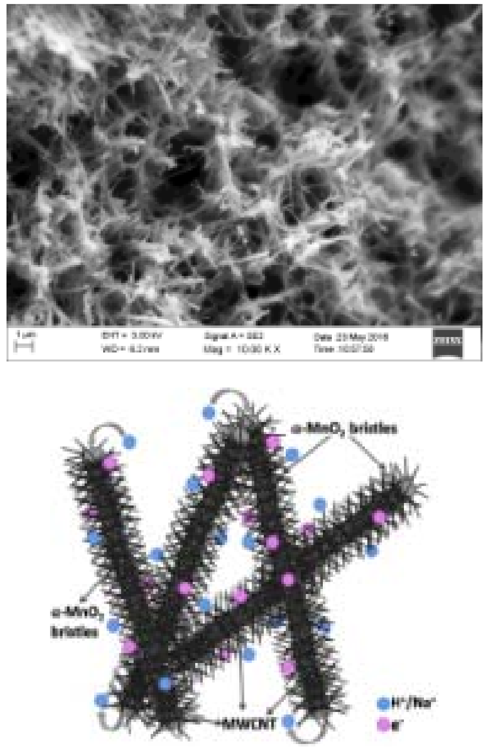


(a)



(b)

Fig. 10. (Color on line). MEMS harvester simulation (a) and image of shaker (b).



(a)

(b)

Fig. 11. (Color on line). MnO_2 growth on Carbon Nano Fiber matrix; (a) SEM image, (b) schematic.

7. Power Management Unit

Ultra-low-power integrated power management unit (PMU) for the leadless pacemaker (Fig. 12) contains the piezoelectric-harvester interface circuits (rectifier) for power-transfer, DC-DC power conversion, voltage regulation and control circuitry. The key goals and challenges are the efficient extraction of very low power-levels (in the μW range) and also ultra-low-power / low-voltage IC design.

The energy consumption bottlenecks are the Communication unit (RF standard, protocols), Memory unit (low-voltage RAM), Sensor interfaces (ADCs and drivers), Power management unit (efficiency) and Controller unit. The first generation test chip in 0.18μm CMOS technology with high-voltage option including reconfigurable rectifier and DC/DC conversion is under characterization.

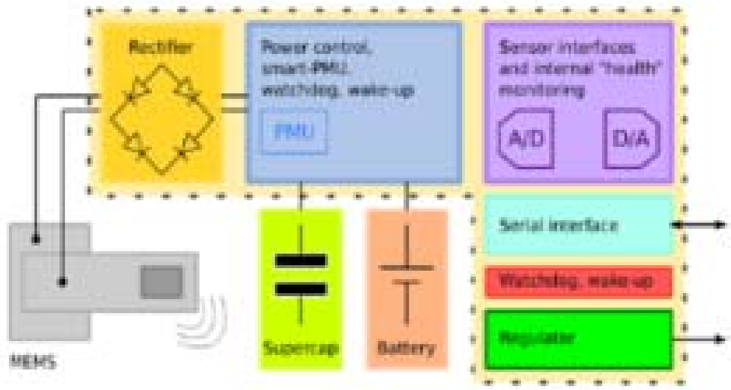
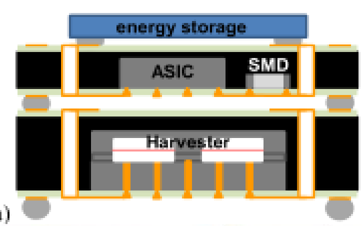


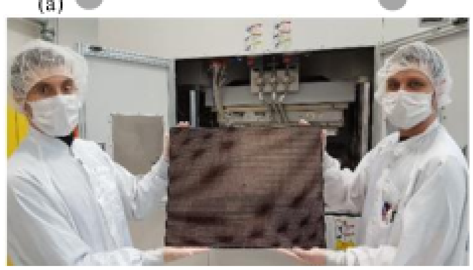
Fig. 12. Schematic of ultra-low-power integrated power management unit for energy harvesting.

8. Packaging Concept

The above components; the stress sensitive MEMS harvester, the PMU / ASIC and the energy storage need to be packaged (Fig. 13a) and integrated into the leadless pacemaker and structure health monitoring. The highly miniaturized packaging technology is based on Fan-out Panel Level Packaging (Fig. 13b) and Package-on Package (PoP).



(a)



(b)

Fig. 13. (a) Schematic of smart-Memphis packaging concept and (b) Fan-out Panel Level Packaging processing on 24“x18“

9. Conclusion

The smart-Memphis project has many challenges for all components of the system:

- Energy harvesting from vibrations (TRL2 → TRL5) Challenge: Low frequency (10Hz), small movements, and small size Approach: sol-gel PZT process and smart harvester design.
- Energy storage (TRL2 → TRL4-6) Challenge: Rechargeable, energy density, maturity Approach: Functionalisation of electrode materials.
- Tailored ASICs (TRL2 → TRL6) Challenge; Low energy consumption and small size Approach: Efficiency and very low static energy consumption.
- Packaging (TRL3 → TRL6-7) Challenge: Size and reliability Approach: Flat panel packaging, either 2D / 3D.

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References

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