NanoElectronics Roadmap for Europe: Identification and Dissemination

3rd General Workshop

Sardinia, June 14-15, 2018

WP4/Sub Task.4.2 Energy for autonomous systems

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HORIZON 2020

Outline

1. Introduction
2. Selection of the technologies and experts
3. Concepts (technologies) covered in NEREID roadmap
4. Application examples
5. Conclusion : Main recommendations

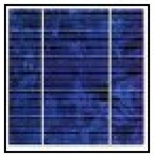
Introduction

Selection of technologies and experts

1. Introduction

- Market growth on connected devices - 8.4B (2017) +30%, 20.4B (2020): IoT, healthcare, wearables, home automation, WSN, etc.
- Energy supply is essential (<mW, tens of µW) → Energy harvesting

Photovoltaic (PV)

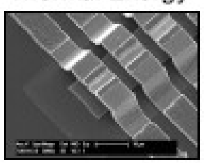


- ✓ Office
- ✓ Outdoor

Vibration/Motion

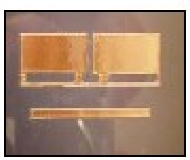
- ✓ Man
- ✓ Machine

Thermal Energy

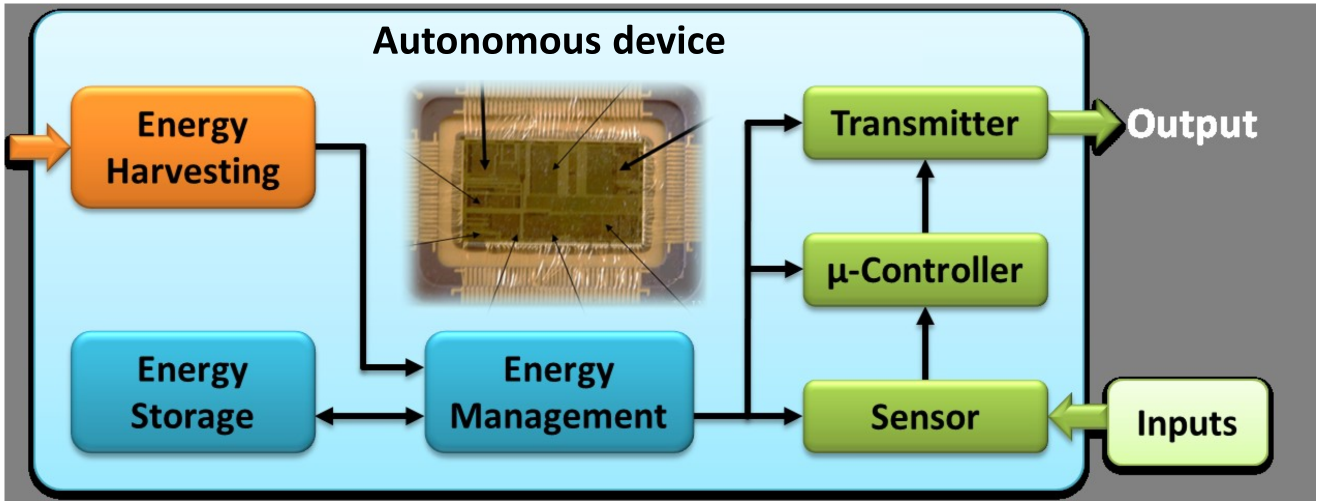


- ✓ Man
- ✓ Machine

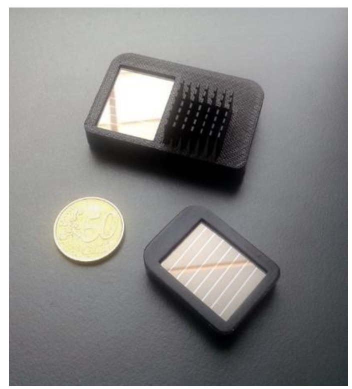
RF



- ✓ GSM 900/1800MHz
- ✓ WiFi 2.4GHz



Demonstration platform



Objective:

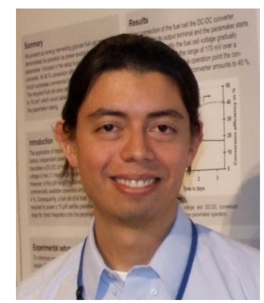
- Roadmap on energy harvesting technologies…
- Identify material and technological issues, challenges, applications…

2. Selection of Technologies and Experts (1/2)

- ST 4.2 was created after the 1st General Workshop (April 2016)
- Among the different EH technologies, 4 were selected for the initial roadmap:
  - Experts were selected coming from Industries and Universities:

- 4 technology experts :

  - **Stephane Monfray** – STMicroelectronics, Crolles, France
    Thermal energy harvesting → Electrostatic energy conversion
  - **Anne Kaminski-Cachopo** – Grenoble INP, France
    Solar Energy Harvesting
  - **Aldo Romani** – University of Bologna, Italy
    Circuits for energy management



  - **Gustavo Ardila** – Grenoble Alpes University / Grenoble INP, France
    Mechanical energy harvesting (piezoelectric materials)

↓

1st Domain workshop (Bertinoro, Italy, October 19th 2016)
- 40' presentations + discussions

Mid-term roadmap

2. Selection of Technologies and Experts (2/2)

- Inclusion of other missing technologies in the Roadmap

- New technology experts :
  - **Alessandra Costanzo** – University of Bologna, Italy
    RF energy harvesting/wireless power transfer

  - **Dhiman Mallick/Saibal Roy** – Tyndall Institute, Ireland
    Electromagnetic energy harvesters

2nd Domain workshop (Barcelona, Spain, December 15th 2017)
- 40' presentations + discussions

  - **James Rohan** – Tyndall Institute, Ireland
    Energy storage devices : microbatteries

  - **Androula Nassiopoulou** – IMEL/NCSR Demokritos, Greece
    Energy storage devices : micro capacitors

Final roadmap

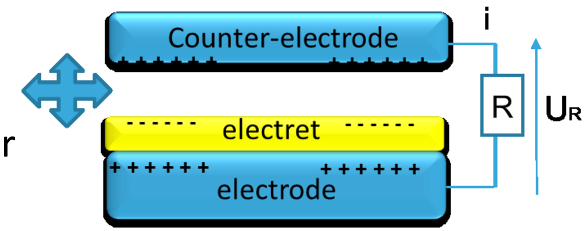
Concepts (technologies)

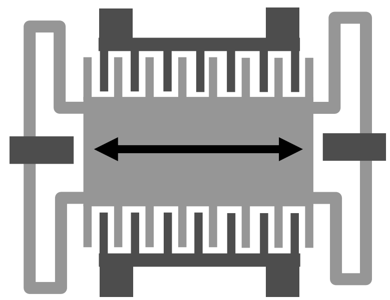
covered in NEREID roadmap

Concept #1: *« Electrostatic conversion » (1/2)*

- Principle

One electrode of the capacitor charged (electret, tribolelectricity…) and the relative movement between the two electrodes causes a variation of electric capacity
-> charges movement





- Applications are linked to mechanical vibrations harvesting (movements)
- Energy density is low at macro level but increases at micro scale (relative capacitor variation increases)
- Power is proportional to the surface potential
- Main challenge is related to the reliability of the material to keep the charges
- CMOS compatibility

❖ 1. Key research questions or issues

Improve efficiency, input bandwidth, reduce working frequency, increase reliability…

- ➢ Medium term: 5+: Fluorin polymers / surface texturation
- ➢ Long term: 10+ : Encapsulated SiO_2/triboelectric materials

❖ 2. Potential for application or Application needs and Impact for Europe

Autonomous sensors (IoT): Industrial / Infrastructures monitoring, transportation, wearable…

- ➢ Medium term: 5+ : Industrial machines/train, shoes
- ➢ Long term: 10+ : Cars, planes, medical patches

Concept #1: *« Electrostatic conversion » (2/2)*

3. Technology and design challenges

Develop low cost solutions, flexible approach, triboelectricity.

- Medium term: 5+ : Optimized polymers
- Long term: 10+ : Low cost polymers

4. Definition of FoMs (quantitive or qualitative) or planned evolution

FoMs	2023	2026	2029	2033
Volume power density (mW/cm^3) @1G and 100Hz	0.5 mW/cm^3	0.65	0.8	1 mW/cm^3
Volume energy per cycle ($\mu J/cm^3$) @1G	5$\mu J/cm^3$ per cycle	6.5	8	10$\mu J/cm^3$ per cycle

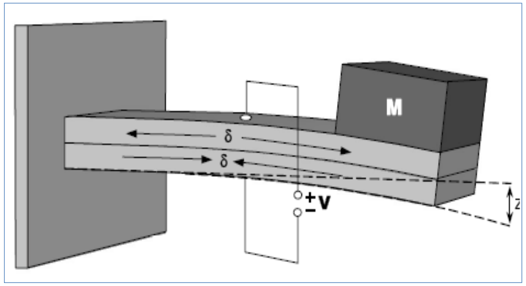
5. Some recommendations

- Enlarge frequency bandwidth (>50Hz) around low frequency target (<100Hz)
- Reliability of materials is key (maintain charges over 10 years)
- Develop flexible/low cost approaches (wearables)

Concept #2: *« Piezoelectric conversion » (1/2)*

- Principle

Resonant cantilever covered by a piezoelectric layer and a inertial mass attached. As the cantilever is bent, strain is transferred to the piezo layer -> asymmetric charge distribution (Voltage)



- Applications are linked to mechanical Vibrations harvesting (movements)
- Devices tuned at a specific vibration frequency
- Devices are easy to fabricate
- CMOS compatibility
- Macro-devices and MEMS (new) are actually on the market

1. Key research questions or issues

Improve efficiency, performance of piezo, input bandwidth, reduce working frequency

- Medium term: 5+: Higher density seismic masses, packaging (vacuum), non-linearities…
- Long term: 10+ : Small scale hybrid devices, nanocomposites (nanotechnology) …

2. Potential for application or Application needs and Impact for Europe

Autonomous sensors (IoT): Industrial/Infrastructures monitoring, transportation, wearable…

- Medium term: 5+ : Industrial machines/train, shoes
- Long term: 10+ : Cars, planes, medical patches

Concept #2: *« Piezoelectric conversion » (2/2)*

3. Technology and design challenges

Bio-compatibility, Low temperature fabrication process (integration on flexible substrates)

- Medium term: 5+ : Piezo-electret, composites without lead
- Long term: 10+ : Nanocomposites (nanotechnology)

4. Definition of FoMs (quantitive or qualitative) or planned evolution

Surface/volume power density (µW/cm² or µW/cm³)

MEMS devices (research) (f < 300Hz, G<0.5)

FoMs	2023	2026	2029	2033
FoM1: Volume power density (mW/cm^3)	1	1.15	1.3	1.5
FoM2: Surface power density (mW/cm^2)	0.15	0.165	0.18	0.2

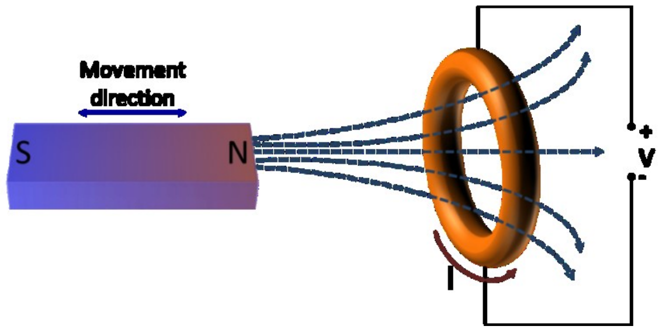
5. Some recommendations

- Consider new sustainable materials to avoid lead based piezoelectrics
- Develop micro/nano piezo-composites could be a key for performance improvement

Concept #3: *« Electromagnetic transduction »*

- Principle: Faraday's Law

Relative motion – magnetic field & coil (or change in the flux linkage) -> Electromo force



- Applications are linked to mechanical Vibrations harvesting (movements)
- Devices tuned at a specific vibration frequency
- Macro-devices are vastly developed and are on the market
- MEMS devices less explored due to drastic drop in performance

1. Key research questions or issues

Increase power density with miniaturization, high performance micro/nano magnets (MEMS)

- Medium term: 5+: Integration techniques (magnets, coils), thick polymer bonded powdered magnets
- Long term: 10+ : rare-earth free, nano-composites, MEMS compatible coil fabrication

2. Potential for application or Application needs and Impact for Europe

Railroad monitoring, automotive sensors powering, IoT, human wearable devices…

- Medium term: 5+ : SHM from industrial machines, train, cars, aircrafts…
- Long term: 10+ : Monitoring automated process manufacturing, enabling smart sensing for automated transportation

Concept #3: *« Electromagnetic transduction »*

3. Technology and design challenges

Magnet coil interaction (most imporant factor -> EM coupling), CMOS compatible permanent magnets (MEMS applications)

- Medium term: 5+ : Optimized patterned magnets, avoid rare-earth magnets, multi-nano-layers
- Long term: 10+ : Suitable micro-coil topology (aligned magnet array), hard-nanostructured magnets

4. Definition of FoMs (quantitive or qualitative) or planned evolution

Surface/volume power density (mW/cm^2 or mW/cm^3)

Miniaturized devices (f < 100Hz, G<0.5)

FoMs	2023	2026	2029	2033
FoM1: Volume power density (mW/cm^3)	5	6.5	8	10
FoM2: Surface power density (mW/cm^2)	0.15	0.18	0.21	0.25

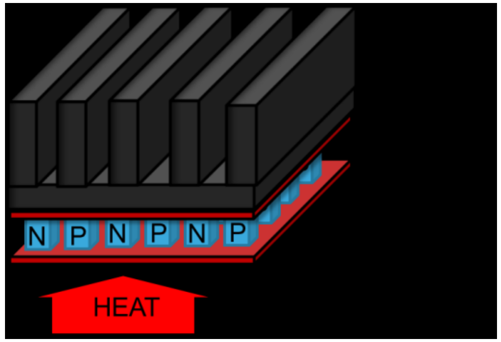
5. Some recommendations

- CMOS compatible integration technique for rare-earth free (e.g. NdFeB - neodymium).
- 3D coil integration/development having low resistive loss/enhanced turn numbers.

Concept #4: « Thermal EH » (1/2)

- Principle

Seebeck effect: generation of a voltage along a conductor when it is subjected to a temperature difference
Low voltage : elevator circuit needed (working at Vteg>75mV)



- Fast thermalization (need for a big heat sink)
- Non-flexible
- Bi_2Te_3 Expensive/rare/toxic material
- Low output voltage
- Power proportionnal to available temperature gradient

❖ 1. Key research questions or issues

Improve efficiency of thermal to electricity transformation , Develop “green” solutions (not based on Bi_2Te_3)…

- ➢ Medium term: 5+: Nanostructured materials / SiGe, TiSi nanodots based solutions
- ➢ Long term: 10+ : Nanostructured materials / Si based solutions

❖ 2. Potential for application or Application needs and Impact for Europe

Autonomous sensors for security monitoring

- ➢ Medium term: 5+ : Hot pipelines, electrical installations, Pipe leaks, electrical lines, Heating systems control, sensors in cars (exhaust), trains…
- ➢ Long term: 10+ : Sensors in cars (motor), planes

Concept #4: *« Thermal EH » (2/2)*

3. Technology and design challenges

Develop new material for improved efficiency without Bi_2Te_3 near room temperature,
Maintain the thermal gradient on thin devices / reduce size of heat sink

- Medium term: 5+ : Nano structured materials / SiGe based solutions
- Long term: 10+ : Phonon engineering / Si based solutions

4. Definition of FoMs (quantitive or qualitative) or planned evolution

ZT, output power vs available temperature difference (mW/K²/cm²)

FoMs	2023	2026	2029	2033
ZT	>2.5	2.65	2.8	>3
Output power (mW/K²/cm²)	>0.15	0.165	0.18	>0.2 (+30%)

5. Some recommendations

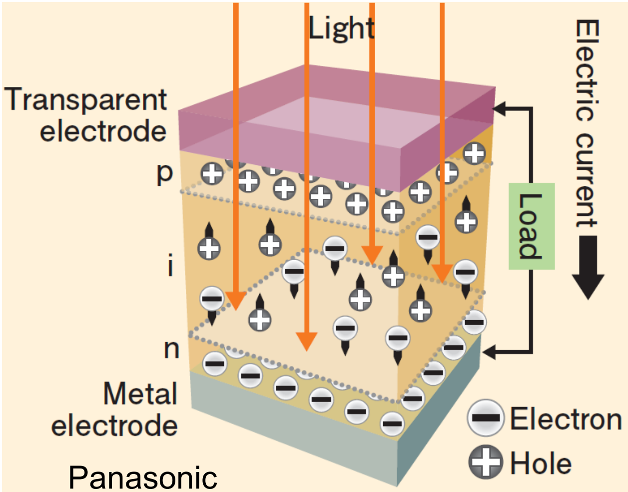
- Consider new sustainable materials to avoid Bi_2Te_3.
- Develop new thermal energy approaches (non Seebeck): Phase change, thermomechanical…

Concept #5: « Photovoltaic EH » (1/2)

Principle :

Photovoltaic effect:

- Absorption of light by the semiconductor
- Electron-hole pair generation, separation and collection
- Power delivered



- A market dominated by the Si (mature technology):
  - For *outdoor* applications, crystalline Si solar cells
  - For *indoor* applications, amorphous Si photovoltaic cells
- Solar cells spectral sensitivity and efficiency differ depending on the light spectrum which is very different for artificial and sun light
- Indoor standard characterization procedures and norms are not defined

1. Key research questions or issues

Improve indoor/outdoor solar cell efficiency with adapted materials, flexibility, low cost, stability

- Medium term: 5+: Organic, dye sensitized, perovskite, III-V compounds solar cells, tandem on Si solar cells
- Long term: 10+ : Nanostructured solar cells, multi-junction solar cells, quantum dots…

2. Potential for application or Application needs and Impact for Europe

Autonomous systems : portable devices, IoT, …

- Medium term: 5+ : Sensors, IoT, portable electronic devices, home automation, security systems…
- Long term: 10+ : IoT, health applications, factory automation…

Concept #5: « *Photovoltaic EH* » *(2/2)*

❖ 3. Technology and design challenges

Use materials with adapted bandgap for performance improvement

Optimized solar cells structures and low cost technologies

- Medium term: 5+ : Commercialized organic and inorganic solar cells (III-V compounds, DSSC…) with improved efficiency for outdoor/indoor
- Long term: 10+ : Increased stability (when needed) and efficiency for indoor and outdoor.

❖ 4. Definition of FoMs (quantitive or qualitative) or planned evolution (Commercialized)

FoMs	2023	2026	2029	2033
Output power (W/cm²) and efficiency under standard output sunlight conditions (AM1.5G, 1kW/m², 25°C)	>23mW/cm² (eff. : 23%) c-Si cells	>23.6mW/cm² (eff. : 23.6%) c-Si cells	>24.2mW/cm² (eff. : 24.2%) c-Si cells	>25mW/cm² (eff. : 25%) c-Si cells
Output power (W/cm²) for indoor modern artificial light conditions (200lux, LED…)	>20µW/cm²	>21.5µW/cm²	>23µW/cm²	>25µW/cm² (+25%)

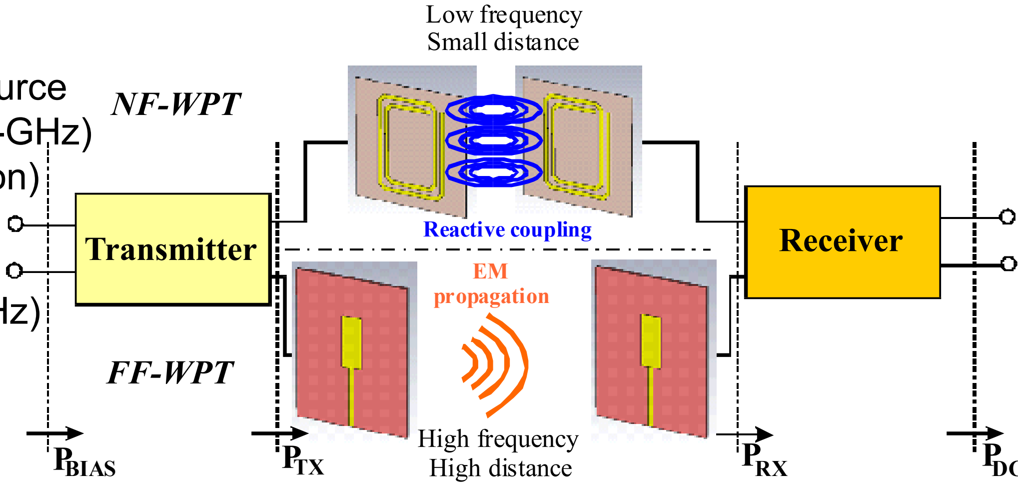
❖ 5. Some recommendations

- Define standard procedures for indoor photovoltaic cells characterization
- Design and optimize structures for outdoor or/and indoor light (sensitivity to light sources, flexibility if necessary, cost…)

Concept #6: « RF energy harvesting/wireless power transfer » (1/2)

2 Principles :

- Radiated far field RF source (High frequency 300MHz-GHz) -> Antennas (no interaction)
- Near EM field – Capacitive coupling (low frequency 30kHz-MHz) ->coils, electrodes (strong interaction)



- Far field : Used for low/ultra low power (~µW-mW) applications (harvesting)
Low efficiency
No commercial applications
- Near Field : medium to high power app. (~mW-W-kW).
Medium to high efficiency
Commercial applications

1. Key research questions or issues

Rectifiers with high dynamic range, compact receiving antennas with non-conventional materials

- Medium term: 5+: Rectifying topologies (CMOS based), flexible antennas (wearables)
- Long term: 10+ : Miniature integrated systems (Antenna + rectifier – CMOS tech.), implanted mini-antennas (medical)

2. Potential for application or Application needs and Impact for Europe

Wearables, implantable electronics, biomedical devices, logistics, tracking goods

- Medium term: 5+ : Body sensors, wearable monitoring (physiological), pace-maker, smarter RFID
- Long term: 10+ : Smart textile, implantable chips for monitoring (smart prosthesis)

Concept #6: «RF energy harvesting/wireless power transfer» (2/2)

❖ 3. Technology and design challenges

Integrated design (antenna/rectifier) -> large dynamic range, design of dedicated signals (enhanced power transfer)

- Medium term: 5+ : Auto-adjusting solutions (sensing RF power & exploiting self bias mechanism of ultra low power transistor), dynamical variation of power transmission (proof of concept)
- Long term: 10+ : High dynamic range rectennas, power shaping sources adjustable in real-time

❖ 4. Definition of FoMs (quantitive or qualitative) or planned evolution

FoMs	2023	2026	2029	2033
Miniaturized Antenna radiation efficiency	> 50 %	> 56 %	> 62 %	> 70 %
Increase RF-to-DC conversion efficiency at low-power levels (1µW)	> 20%	> 26%	> 32%	> 40%

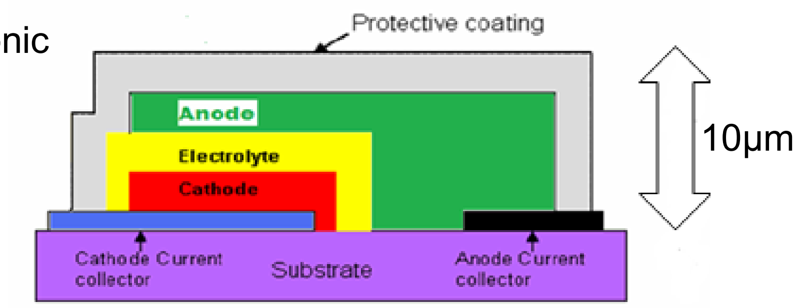
❖ 5. Some recommendations

- Optimize rectenna components (minimize losses, maximize power transfer)
- Design high efficient receiving antennas with miniaturization constraints (maximize received power)

Concept #7: *« Energy storage - Microbatteries » (1/2)*

Principle :

- Electrolyte : high ion conductivity, low electronic conductivity
- Replacement of the classical Liquide electrolyte -> thin film



- Si integrated
- Lithium based thin films: ~1 mWh/cm^2, capacity retention -> 1000 cycles
- Electrode thickness limit < ~µm
- Ionic conductivity of solid elecrolyte << liquid based (commercial)
- Size reduction, safer

1. Key research questions or issues

Improve capacity (reduced surface, volume), increase power capability (portable applications), increase peformance of electrode/electrolyte

- Medium term: 5+: Multilayer structure, 3D structuring, higher conductivity materials
- Long term: 10+ : New lithium based elecrolyte, new materials, interface engineering

2. Potential for application or Application needs and Impact for Europe

Internal, external autonomous sensors, healthcare systems

- Medium term: 5+ : Factory, environment, medical patches
- Long term: 10+ : Home, agriculture, implantable

Concept #7: *« Energy storage - Microbatteries » (2/2)*

3. Technology and design challenges

Patterning active materials, low temperature integration, packaging

- Medium term: 5+ : Integration on silicon, reliability (packaging)
- Long term: 10+ : Integration on flexible, low cost (packaging)

4. Definition of FoMs (quantitive or qualitative) or planned evolution

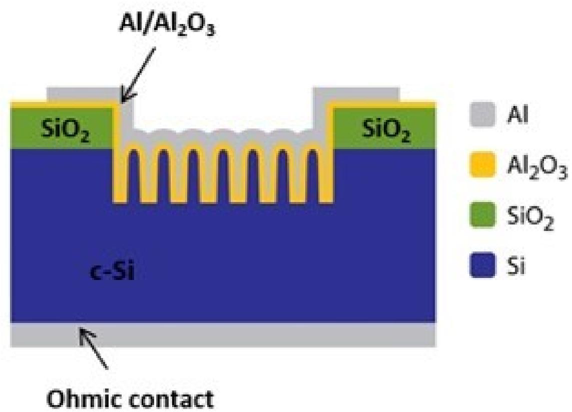
FoMs	2023	2026	2029	2033
FoM1: Surface energy density (mWh/cm^2)	5	6.5	8	10
FoM2: Surface power density (mW/cm^2)	10	13	16	20
FoM3: Cycle life	10,000	13,000	16,000	20,000

5. Some recommendations

- Multilayer materials processing -> increase capacity/unit footprint
- New materials: increase ionic (electrolyte) and electronic (electrodes) conductivity

Concept #8: « *Energy storage - Microcapacitors* » *(1/2)*

3 Parameters :
- Capacitance density (Energy stored)
- Leakage current (Operation voltage, energy stored, retention)
- Series resistance (Charging, discharging time thus power)



- Si integrated (integration compatibility)
- Robustness of operation (lack of electrolyte)
- Higher voltage operation (lower leakage current)
- Environmental, health friendly materials
- Disadvantage : lower capacitance density -> energy storage

1. Key research questions or issues

Improve capacity density, reduce leakage current, reduction of series resistance

- Medium term: 5+: 3D structuring + high-K, optimized dielectrics, thicker electrodes
- Long term: 10+ : 3D structuring + new materials, higher conductivity materials

2. Potential for application or Application needs and Impact for Europe

Internal, external autonomous sensors, healthcare systems

- Medium term: 5+ : Factory, environment, medical patches
- Long term: 10+ : Home, agriculture, implantable

Concept #8: *« Energy storage - Microcapacitors » (2/2)*

3. Technology and design challenges

3D structuring, uniform high-K deposition, integration with on-chip harvesters

- Medium term: 5+ : Nanotechnology, known high-K materials, design
- Long term: 10+ : Nanotechnology, new materials, implementation

4. Definition of FoMs (quantitive or qualitative) or planned evolution

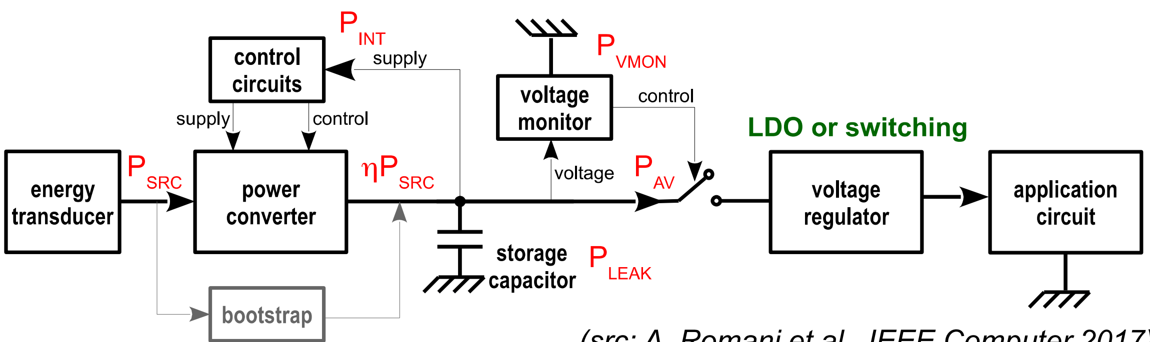
FoMs	2023	2026	2029	2033
FoM1: Capacitance density (µF/cm²)	10	22	34	50
FoM2: Series resistance (Ω)	1	0.73	0.46	0.1
FoM3: Vmax (V)	5	6.5	8	10

5. Some recommendations

- Research on uniform thin high-k dielectrics with reduced leakage currents
- 3D structures for high capacitance density
- New electrode materials for decrease series resistance

Concept #9: *« Micro-power management » (1/2)*

- Principle



(src: A. Romani et al., IEEE Computer 2017)

- Essential to store and deliver the harvested energy to circuits
- Must consume less than the input power
- Efficiency must be traded with self-consumption
- Should keep sources in the MPP

1. Key research questions or issues

Improve the minimum sustainable input power and voltage, reduce power consumption

- Medium term: 5+: Miniaturization of inductors, Inductor-less converters, MOSFETS with low Vth...
- Long term: 10+ : Miniature systems, MEMS piezoelectric transformers, adaptive MPPT…

2. Potential for application or Application needs and Impact for Europe

Autonomous sensors..

- Medium term: 5+ : Environmental monitoring & automation, healthcare
- Long term: 10+ : Embedded nodes for implantable/wearables

Concept #9: « *Micro-power management* » *(2/2)*

3. Technology and design challenges

Design of energy-aware circuits with reduced leakage & active currents, Development of dedicated microelectronic processes (options/devices)

- Medium term: 5+ : Energy-aware design (power converters)< 100nA, MOSFETS with low Vth
- Long term: 10+ : Energy-aware design (all system parts), more efficient power switches (reduced control voltage, low leakage)

4. Definition of FoMs (quantitive or qualitative) or planned evolution

FoMs	2023	2026	2029	2033
Minimum input voltage and power for cold-start-up	< 100 mV, <1 µW	< 73 mV, < 730 nW	< 46 mV, < 460 nW	< 10 mV, < 100 nW
Minimum Conversion efficiency	70%	73%	76%	80%

5. Some recommendations

- Define trade-offs (intrinsic power consumption, efficiency, performance): energy-aware power design of circuits.
- Size reduction of inductors, planar alternatives (piezoMEMS), quality of switches

Application examples

Application examples: *(1/2)*

❖ Application 1: Transports (automotive, railroad)

Example of use-case	Technology	Ambient Conditions	FoM 2023 +5 ans	FoM 2026	FoM 2029	FoM 2033 +10 ans
Sensor on freight wagon	Outdoor solar (commercial devices c-Si cells)	AM 1.5G (1000W/m²)	>23mW/cm²	>23.6mW/cm²	>24.2mW/cm²	>25mW/cm²
Sensor near car engine	Thermal Harvesting /small heatsink (~mm thick)	Hot source=125°C Cold 60°C	>0.25mW/cm²	>0.28mW/cm²	>0.31mW/cm²	>0.35mW/cm²
Sensor near car engine	Thermal Harvesting / large heatsink (~cm thick)	Hot source=125°C Cold 60°C	>25mW/cm²	>27.4mW/cm²	>29.8mW/cm²	>33mW/cm²
Sensor on truck trailer	Piezoelectricity with mechanical harvesting (Commercial)	Freq=200Hz Acc=1G	>0.1mW/cm²	>0.115mW/cm²	>0.13mW/cm²	>0.15mW/cm²
	Miniaturized electromagnetic harvesters		>0.3mW/cm²	>0.36mW/cm²	>0.42mW/cm²	>0.5mW/cm²

- Power management circuits : 40-80% (<10µW), 90% (~100µW)

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Application examples: (2/2)

- Application 2: IoT for domotic applications

Example of use-case	Technology	Ambient Conditions	FoM 2023 +5 ans	FoM 2026	FoM 2029	FoM 2033 +10 ans
Wireless sensors to control heaters, lights, occupancy…	Indoor Solar	150lux (bedroom)	>15µW/cm²	>15.9µW/cm²	>16.8µW/cm²	>18µW/cm²
	Indoor Solar	300lux (living room)	>30µW/cm²	>32.1µW/cm²	>34.2µW/cm²	>37µW/cm²
Sensors for Heat control & Heat Meters	Indoor Thermal Harvesting on Heaters / large heatsink	Hot source=45°C Cold 20°C	>3.8mW/cm²	>4.16mW/cm²	>4.52mW/cm²	>5mW/cm²
	Indoor Thermal Harvesting on Heaters / small heatsink	Hot source=45°C Cold 20°C	>37µW/cm²	>40.9µW/cm²	>44.8µW/cm²	>50µW/cm²

- Power management circuits : 40-80% (<10µW), 90% (~100µW)

Conclusions: Main recommendations

Conclusion: Main recommendations (1/2)

- Projects should mainly focus on the development and optimization of a complete application as a whole (from harvesting to the use case).
- The improvement of the EH performance/efficiency is as important as the development of "green" materials. Replacing toxic/rare materials used nowadays (lead based piezoelectrics, Bi_2Te_3 for thermoelectrics, NdFeB - neodymium, for electromagnetic conversion).
- The use of nanotechnologies is foreseen to increase the performance of all the concepts in general.
- Flexible and low cost approaches for wearable applications should be developed as well.

Conclusion: Main recommendations (2/2)

- Increasing the bandwidth at low frequency target (below 100Hz) will help to fit applications for vibration mechanical EH.
- Indoor PV: Define standard procedures for indoor PV cells characterization
- Exploit the mm-wave band (30 GHz – 300 GHz) for intentional Far-field RF Wireless Power Transfer (WPT) for enhancing rectenna miniaturization and focusing of the energy transfer.
- Energy storage is required as a hybrid device with the EH options to alleviate any transient effects and assist with higher power operation: nanotechnologies, high-K, new materials, 3D structuring…
- Power Management: size reduction of inductors, planar alternative to inductors, reduce leakages and allow low input powers.

Thank you for your attention!