Power harvesting towards autonomous RFIDs and wireless sensors

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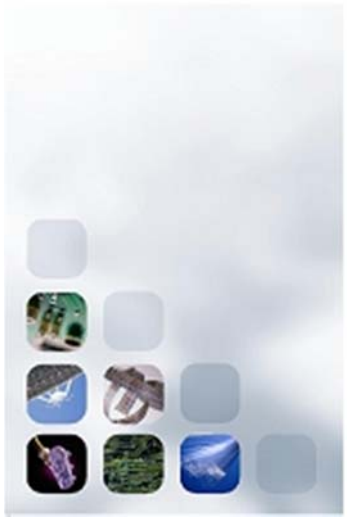
23 September 2010

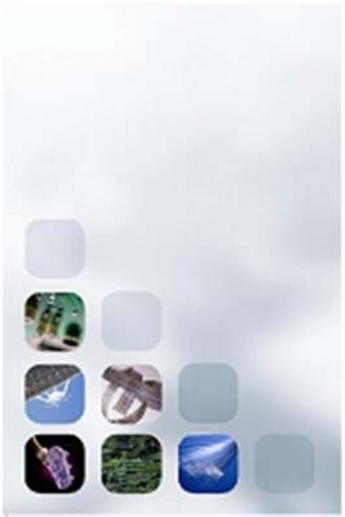
Outline

- Introduction
- Power scavenging / harvesting solutions
- Flexible Materials
- Integration of harvesting modules and sensors
- Electromagnetic / solar energy harvesting
- Summary



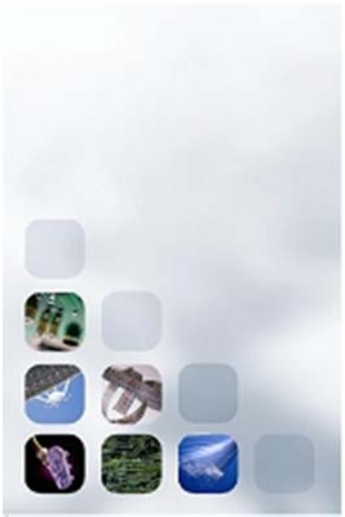
Introduction

- Ubiquitous sensor networks
  - Monitoring (environment, wild-life), security, health…
  - Conformal circuits
  - Low manufacturing / material / maintenance cost
- Independent - autonomous sensors
  - Optimize efficiency – minimize dissipated power / maximize harvested power
- Green networks
  - Environmental friendly



Power Harvesting

- Choice of harvesting module(s) is application dependent (in-door vs out-door , static vs. mobile, highly populated vs. rural), defined by intensity of available energy sources
- Hybrid harvesting modules required to guarantee sensor autonomy
- Efficiency depends on power density



Power Harvesting

- Energy sources:

Energy Sources	Harvested power	Conditions, Available power
Solar	10 mW/cm^2	Sunlight (100 mW/cm^2)
	< 0.1 mW/cm^2	Indoor light (< 1 mW/cm^2)
Kinetic (vibration)	1.3 mW (toes) / 8.4 mW (heel)	Piezoelectric Shoe mounted, standard walk (N.S. Shenck IEEE Micro 2005)
	85 uW	Piezoelectric MEMS harvester (IMEC 2010)
Thermal (Thermoelectric generators (TEG))	25 uW/cm^2	Wrist watch type TEG (IMEC 2007)
Acoustic	0.003-0.96 uW / cm^3	75-100 dB of noise
Electromagnetic	0.1-0.5 uW/cm^2	Harvesting, contrast to wireless power transmission

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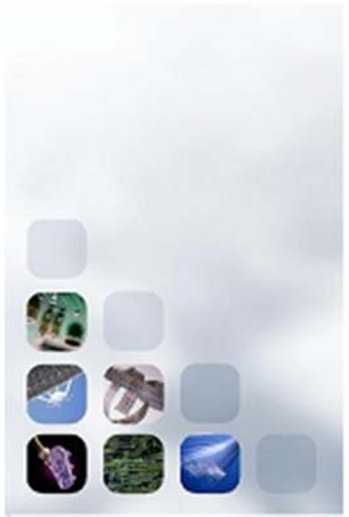

Power Harvesting

- Energy Sources

Human Body Sources	Total available power from body	Available power for harvesting
Body heat	2.8W - 4.8 W	0.2-0.32 W (neck brace)
Breathing band	0.83 W	0.42 W
Walking	67 W	5.0-8.3 W

Thad Starner, 'Human powered wearable computing', IBM systems journal, vol. 35, no. 3-4, 1996

Components / Materials

- Flexible substrates
  - Paper
  - Liquid crystalline polymer (LCP)
  - Textile
  - Metal coated PET (polyethylene terephthalate)

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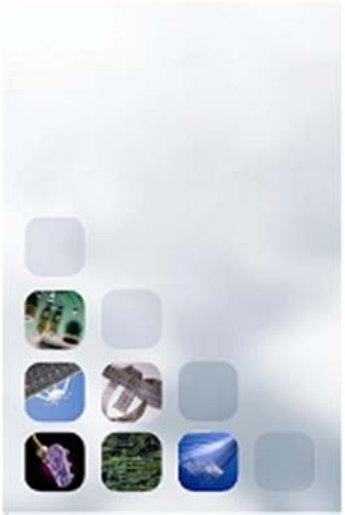
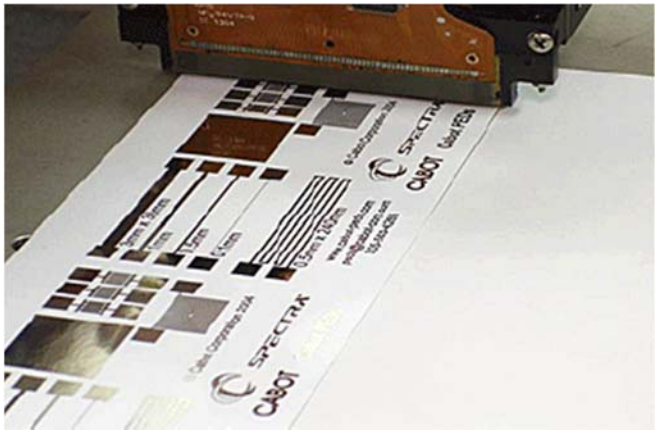
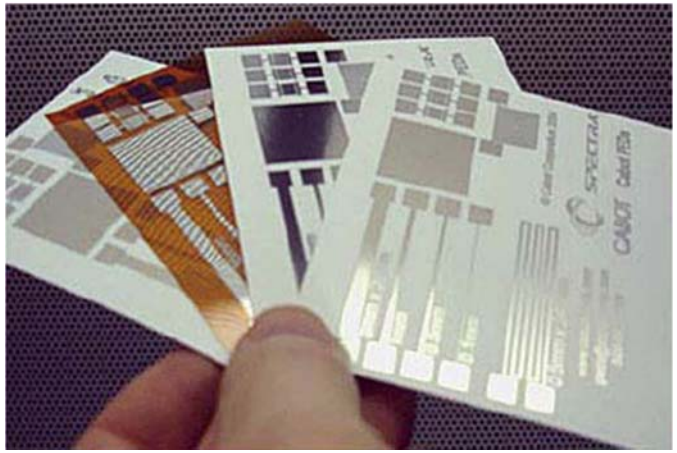


Components / Materials

Paper

- Dielectric constant (*):
  3.3 (@ 2 GHz)
- Loss tangent (*):
  0.08 (@ 2 GHz)
- Can be made hydrophobic
- Inkjet printing
- Cost : very low
- Multilayer capability



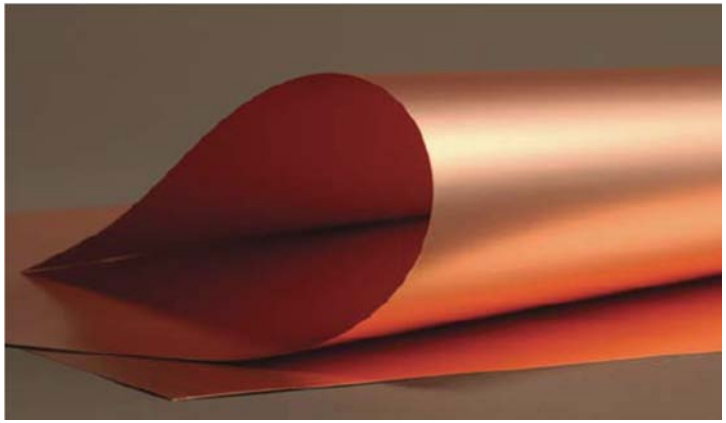


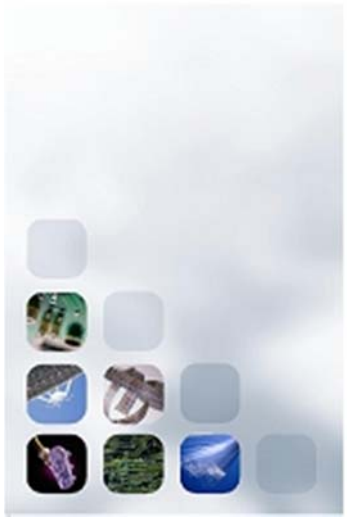
Li Yang, et. al, ‘ RFID Tag and RF Structures on a Paper Substrate Using Inkjet-printing Technology, IEEE Transactions on Microwave Theory and Techniques, vol. 55, no. 12, pp. 2894-2901, Dec, 2007.

Components / Materials

Liquid crystalline polymer (LCP)

- Dielectric constant: 2.9 (@ 10 GHz)
- Loss tangent: 0.0025 (@ 10 GHz)
- Water absorption < 0.04%
- Lamination < 282º C
- Multilayer capability
- Laser drilling (YAG, CO2)
- Low cost





Components / Materials

Textile materials

- Substrates: natural or man-made fibers [1]
- Synthetic fibers:

Textile	Aramid	Fleece	Upholstery fabric	Vellux	Cordura
Properties	Strong Heat resistant	Dries rapidly	Mixture of polyester and polyacryl	Synthetic fibre covered by thin layers of foam	Polyamide fiber
Dielectric constant	1,85	1,25			
Loss tangent	0,015	0,019			

[1] P. Salonen, et. al, 'Effect of Textile Materials on Wearable Antenna Performance: A Case Study of GPS Antennas,' IEEE AP-S, pp. 459-462, 2004.

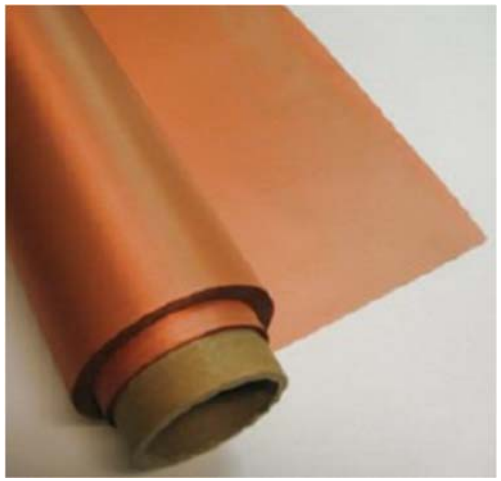
[2] C. Hertleer et. al. 'Aperture-Coupled Patch Antenna for Integration Into Wearable Textile Systems, IEEE AWPL vol. 6, p. 392-395, 2007.

[3] F. Declercq, et al. 'Permittivity and Loss Tangent Characterization for Garment Antennas Based on a New Matrix Pencil Two-Line Method,' IEEE T-AP vol. 56, no. 8, pp. 2548-2554, Aug. 2008

Components / Materials

Conductive Textiles

- FlecTron, Zelt, ShiedIt, Global EMC
- ShieldIt has adhesive backing (can be glued, stitched, sewn, ironed to substrate)
- Surface Resistivity (0.02-0.05 Ohm/sq)



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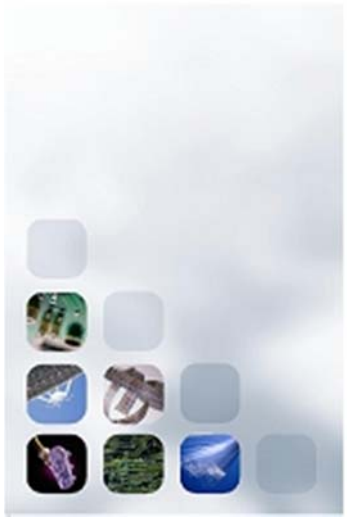
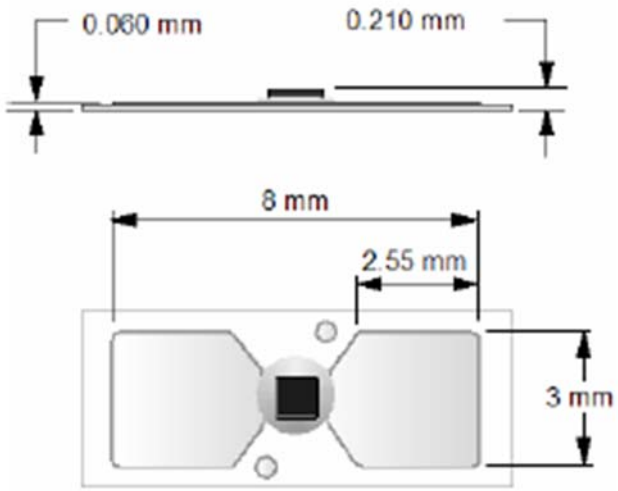
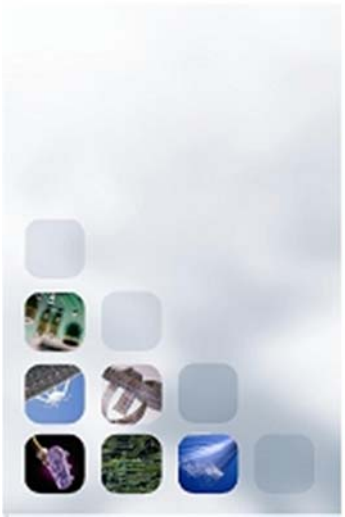


Components / Materials

PET (Polyethylene Terephthalate)

- Dielectric constant:
  3.3 (@ 0.9 GHz)
- Loss tangent:
  0.003 (@ 0.9 GHz)
- Thickness:
  50 um – 100 um





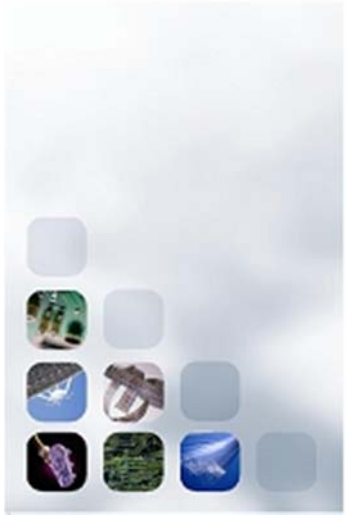
Integration

Possibilities

- Smart textiles
- MEMS
- Hybrid harvesting modules (Solar antennas)
- *Organic electronics*

Features

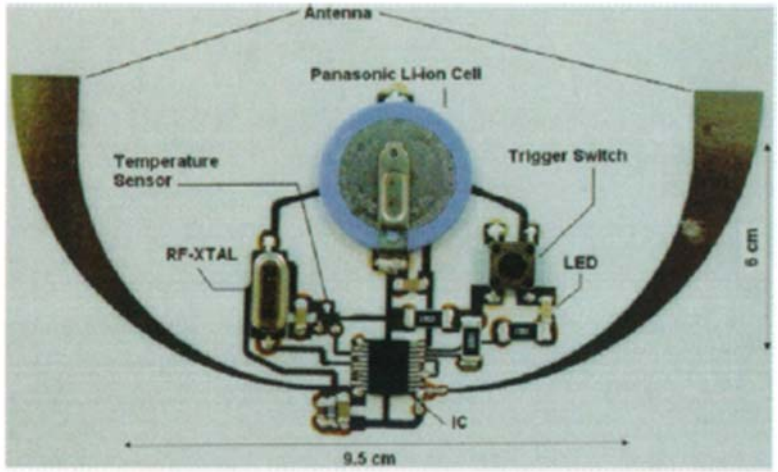
- Washability, Strechability, User comfort, Conformal shape

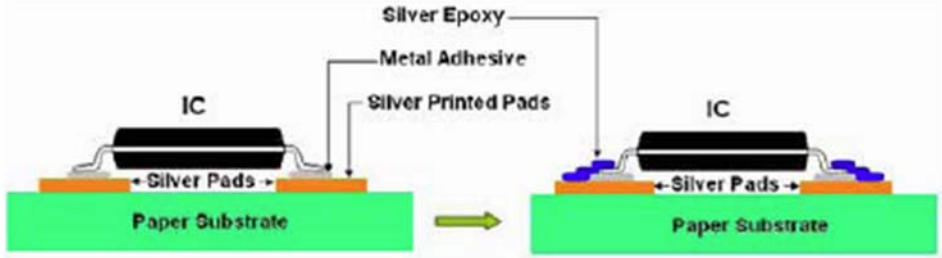


Integration

Paper substrates, ink-jet printing.

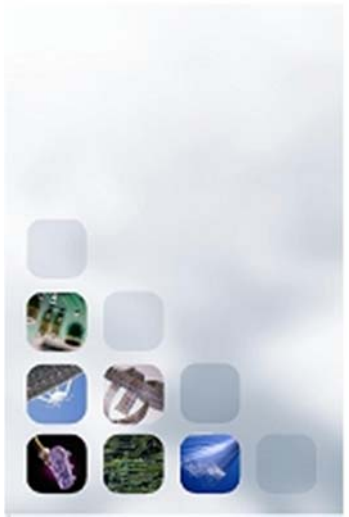
- Passive circuits (antennas, interconnects)
- Active components (temperature sensor, battery, microcontroller, crystal oscillator) mounted using silver conducting epoxy
- 9.5 x 5 cm
- Multilayer capability by laminating paper sheets





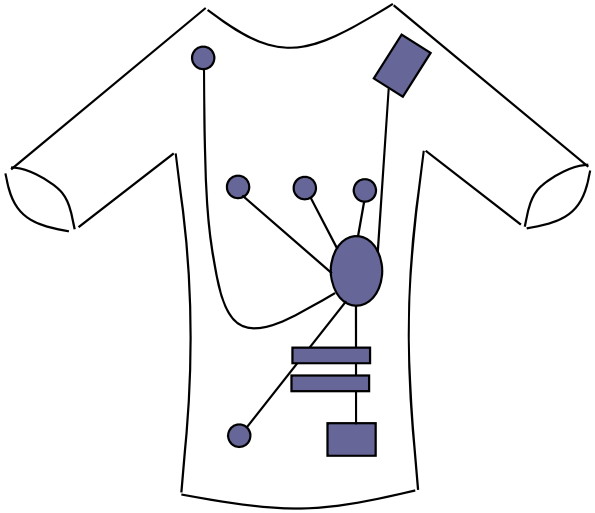
A. Rida, et al., “Conductive Inkjet-Printed Antennas on Flexible Low-Cost Paper-Based Substrates for RFID and WSN Applications ," *IEEE Antennas and Propagation Magazine,* pp.13-23, vol. 51, no. 3, June 2009.

M. Tentzeris, “Inkjet-Printed paper/polymer based RFID and Wireless Sensor Nodes: the final step to cognitive intelligence?, Invited presentation, COST IC0803 RF/Microwave Communication Subsystems for Emerging Wireless Technologies Working Group Meeting, Athens, Oct. 8, 2010.



Integration

- **Textile passive and active circuit and sensor integration.**
- Wearable smart fabric with sensing and communication (transmission) capabilities.

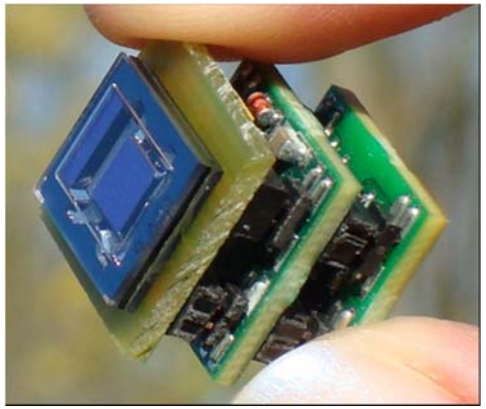


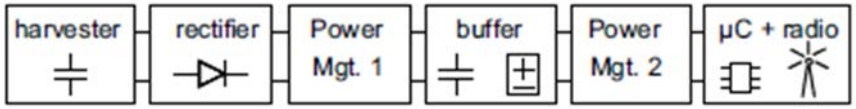
F.Declercq, et al, 'A Textile antenna based on high-performance fabrics,' EuCAP, Edinburgh, Nov. 11-16 2007.

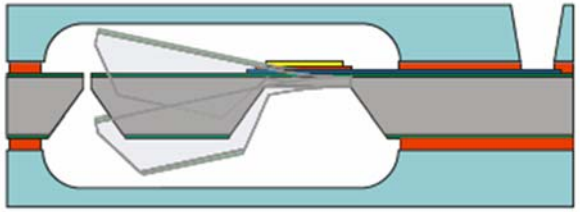
PROETEX, FP6-2004-IST-4-026987, Advanced e-textiles for firefighters and civilian victims, http://www.proetex.org/

Integration

- **MEMS Piezoelectric energy harvester**
- IMEC developed piezoelectric energy harvesters capable of generating up to 85µW of power (unpackaged)
- CMOS compatible MEMS processes on 6’ silicon and SOI wafers.
- Piezoelectric material: Aluminium Nitride (AlN)
- Size: 1cm^3
- Resonance: 150-1200Hz
- Vacuum package
- 220 uF capacitor for energy storage





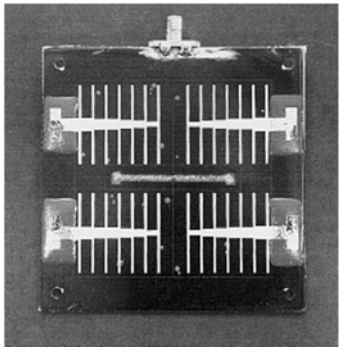


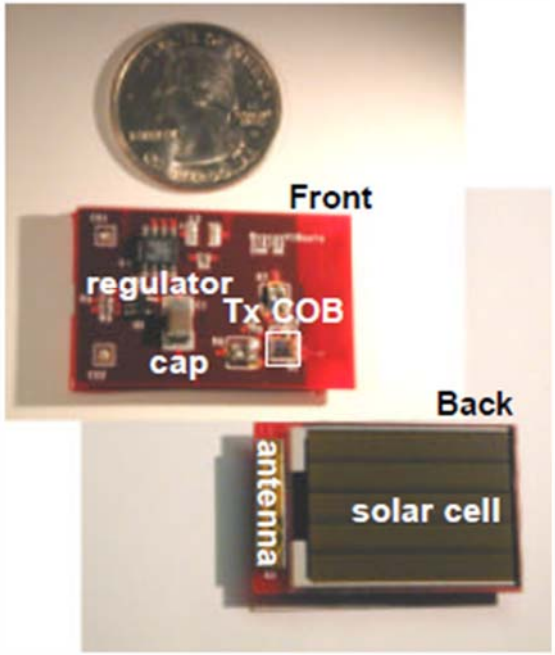
R. Elfrink, et al., "First autonomous wireless sensor node powered by a vacuum-packaged piezoelectric MEMS energy harvester," *IEEE International Electron Devices Meeting (IEDM)*, pp.1-4, 7-9 Dec. 2009

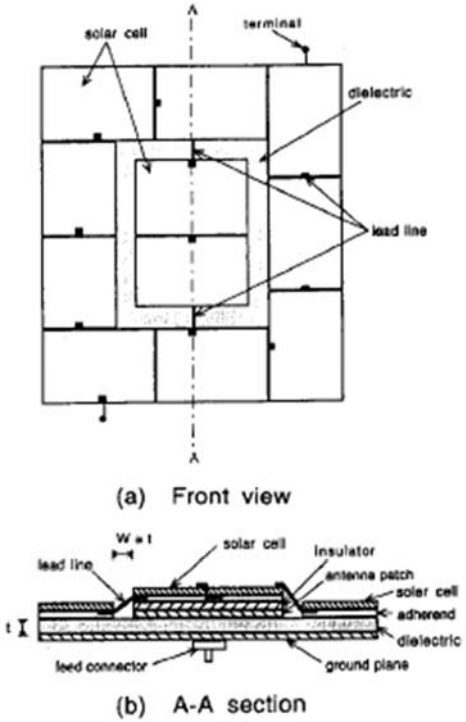
Integration

Solar / Electromagnetic harvester

- 1.9GHz/-1.5 dBm Transmitter 2.4x3.9 cm^2







Shad Roundy, Brian P. Otis, Yuen-Hui Chee, Jan M. Rabaey, Paul Wright, A 1.9GHz RF Transmit Beacon using Environmentally Scavenged Energy *IEEE Int. Symposium on Low Power Elec. and Devices*, 2003, Seoul, Korea.

M. Tanaka, R. Suzuki, Y. Suzuki, K. Araki, "Microstrip antenna with solar cells for microsatellites," *IEEE International Symposium on Antennas and Propagation (AP-S), vol. 2, pp. 786-789, 20-24* June 1994.

S. Vaccaro, J.R. Mosig, P. de Maagt , Two Advanced Solar Antenna “SOLANT” Designs for Satellite and Terrestrial Communications, IEEE Transactions on Antennas and Propagation, vol. 51, no. 8, Aug. 2003, p. 2028-2034

Electromagnetic Energy Harvesting

- Rectenna elements and arrays have been optimized achieving good RF-to-DC efficiency in directive, wireless power transmission applications.

- Recent interest for low profile, energy efficient, self-sustainable sensor networks, focuses on optimizing RF-to-DC efficiency for low power densities corresponding to ambient EM fields.

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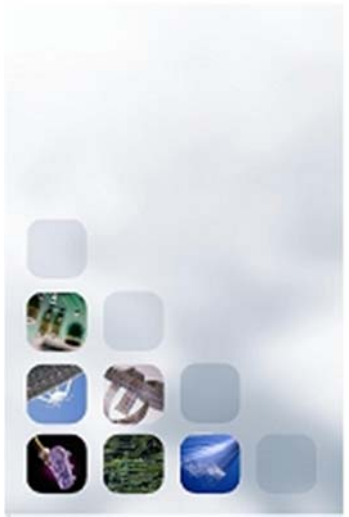
Electromagnetic Energy Harvesting

Design poses several challenges:

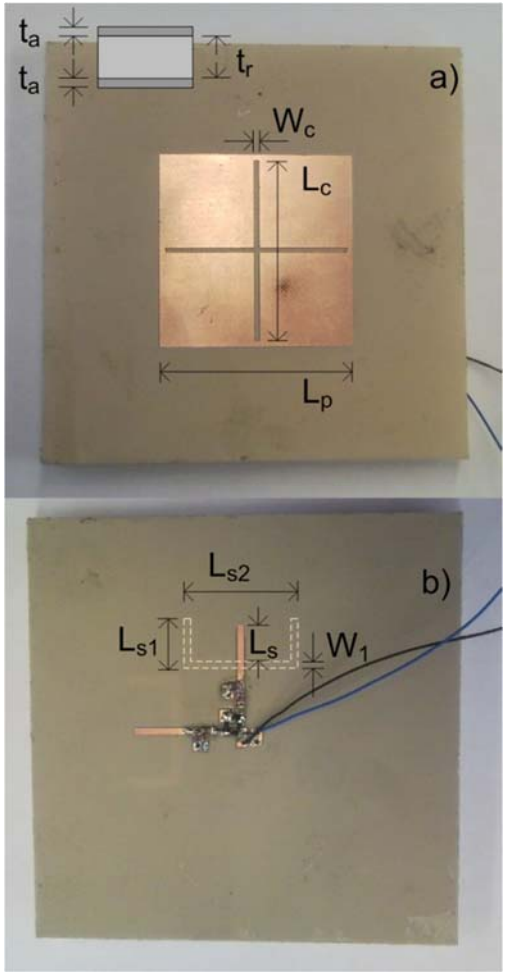
- Compact antenna elements, Arbitrary polarization, broadband, multi-band designs
- EM simulation to model radiating element.
- Nonlinear optimization to model rectenna circuit and optimize rectifier taking into account the antenna properties.
- Antenna in receiving mode (Norton, Thevenin equivalent)



Electromagnetic Energy Harvesting

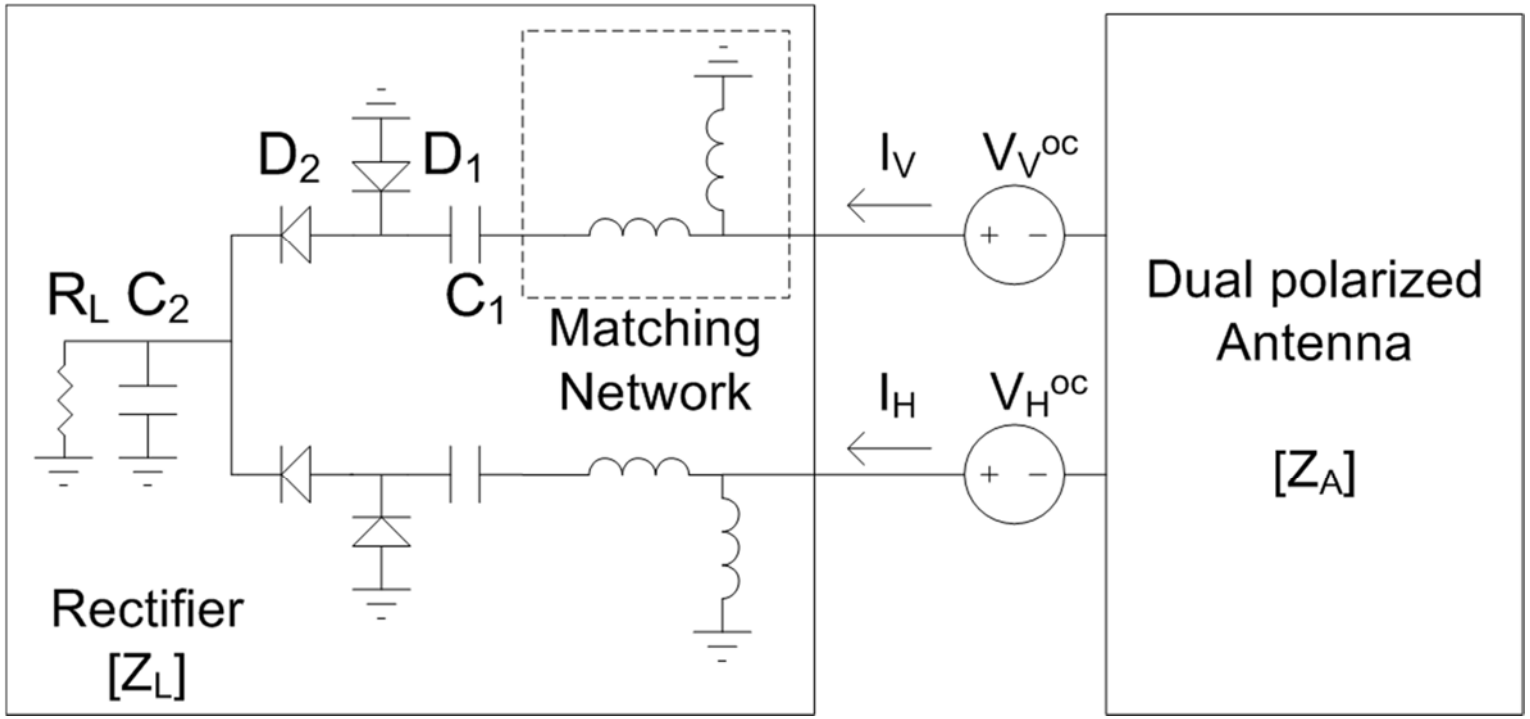
Rectenna design example

- 2.40GHz - 2.48GHz ISM band
- Aperture coupled patch topology:
- Circuit and radiator layers are made of Arlon A25N 20mil thick
- Separated by a Rohacell51 layer of 6mm in order to achieve the desired bandwidth.



Electromagnetic Energy Harvesting

- Joint antenna and rectifier optimization using Thevenin equivalent of antenna in receive mode.



Electromagnetic Energy Harvesting

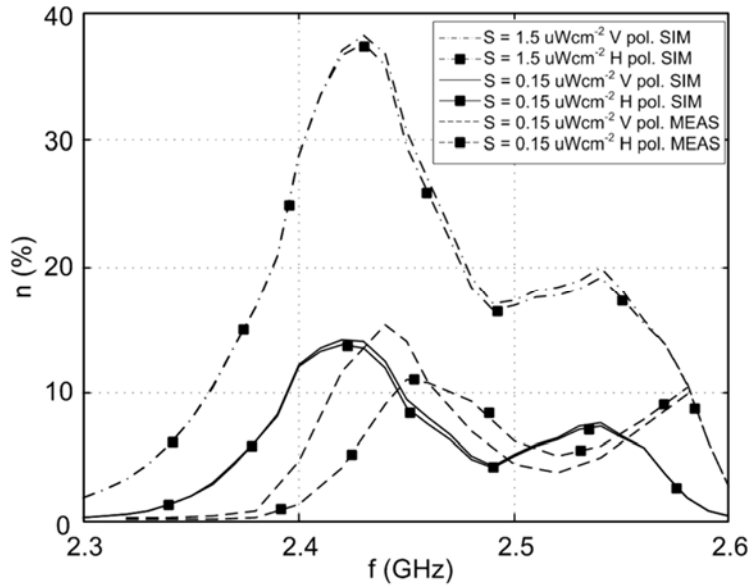
- Open circuit voltage maybe calculated using reciprocity theory

$$\eta = \frac{P_{DC}}{P_{RF,av}} = \frac{V_{DC}^2}{P_{RF,av} R_L}$$

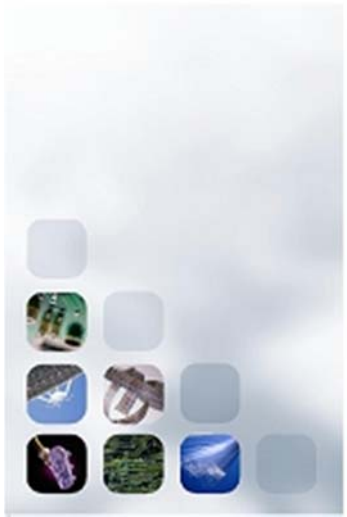
$$V_{V,H}^{oc}(\theta_o, \phi_o, S) = \frac{4\pi}{jk\eta_o} F_{V,H}(\theta_o, \phi_o) E_o$$

$$P_{av} = \frac{1}{4} V^{oc\,*} [Z_A + Z_A^*]^{-1} V^{oc}$$

$$E_o = \sqrt{2\eta_o S} \qquad \eta_o = 120\pi$$

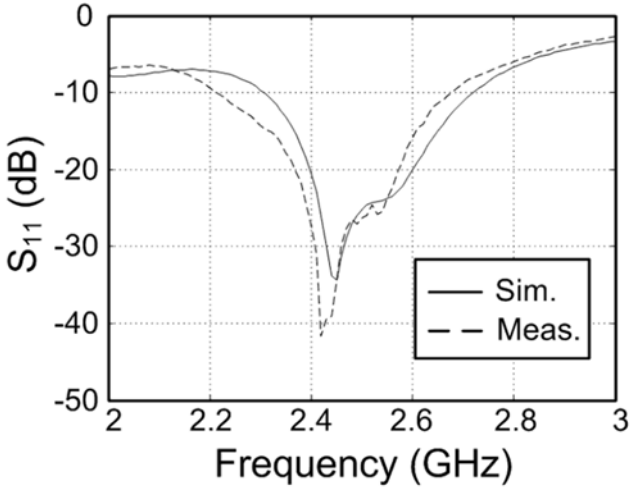


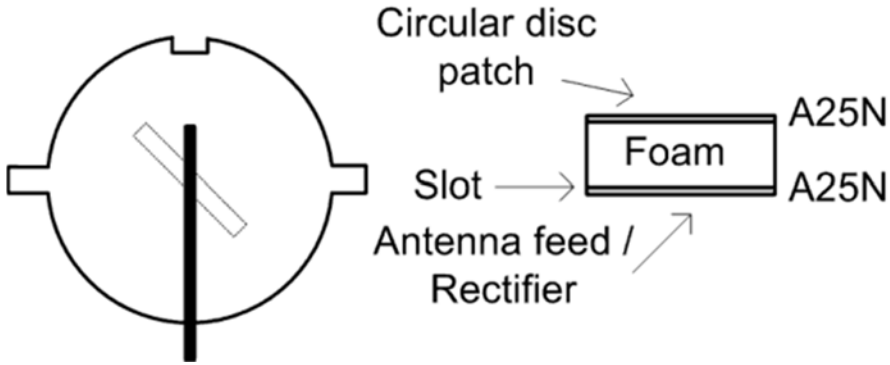
- One may optimize in harmonic balance the input power density at the desired direction of arrival.

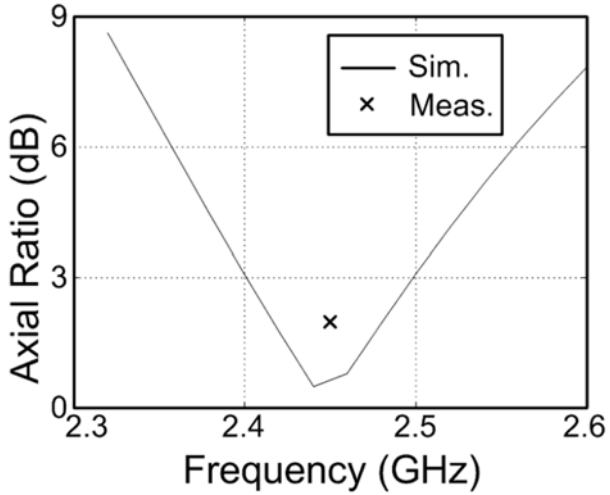


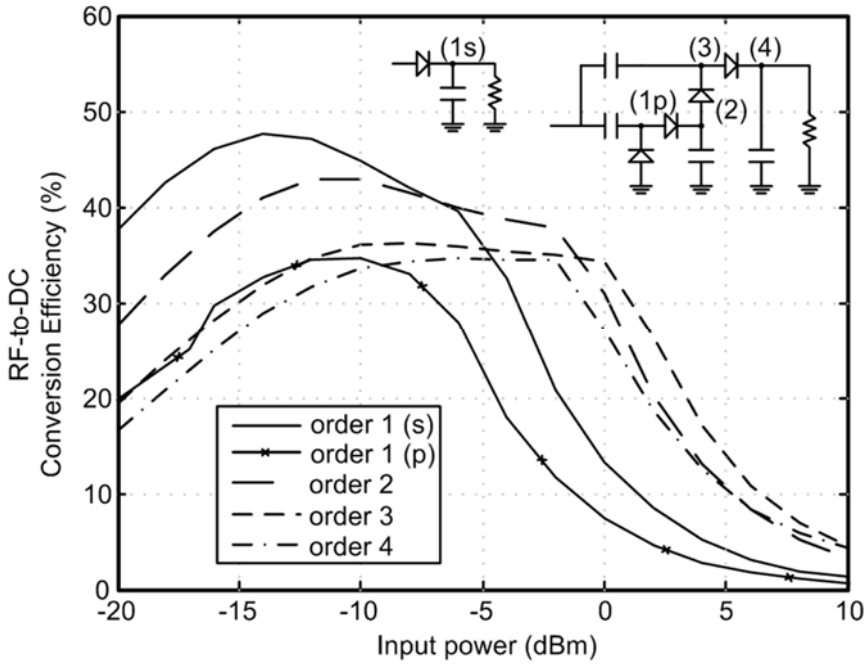
Electromagnetic Energy Harvesting

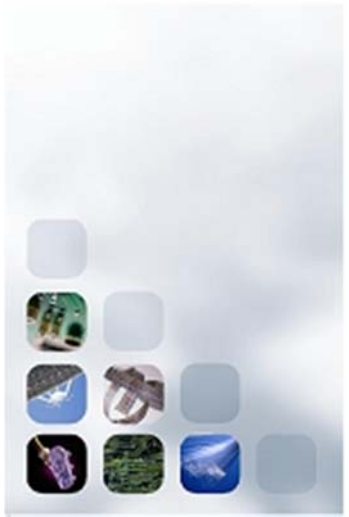
- Circularly polarized rectenna











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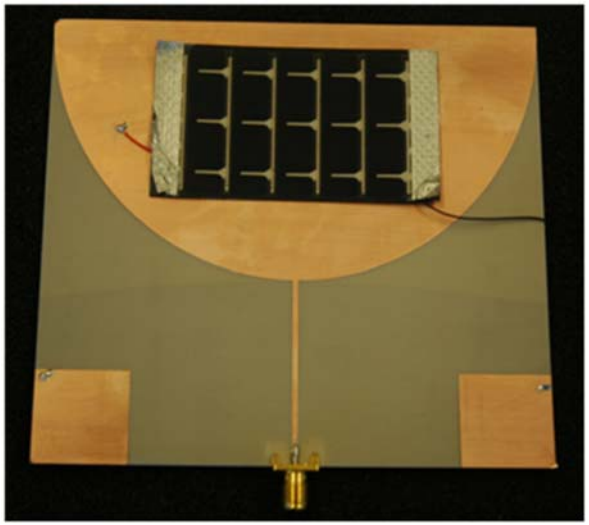
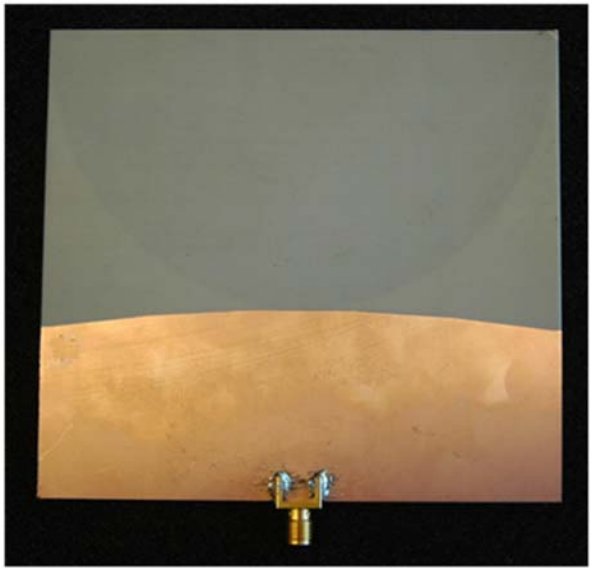
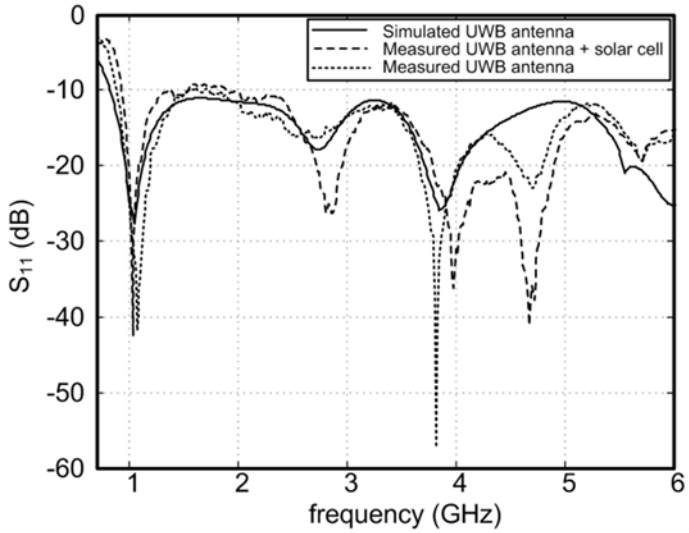
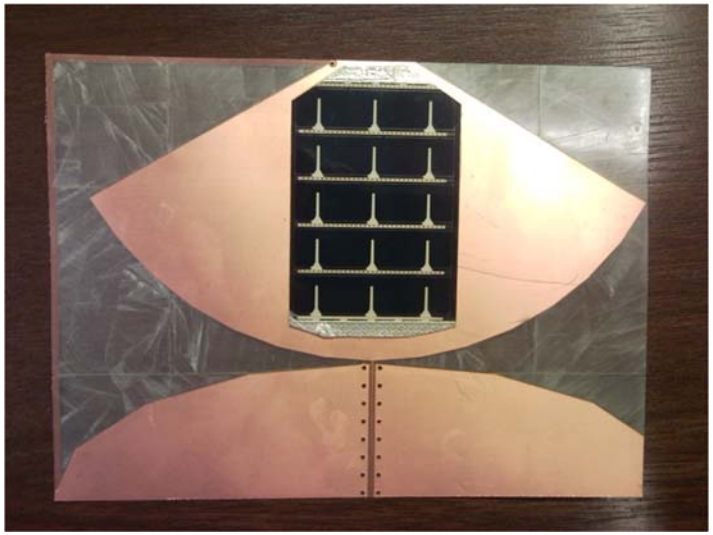
Electromagnetic Energy Harvesting

- Ultra-wideband rectenna / solar harvester



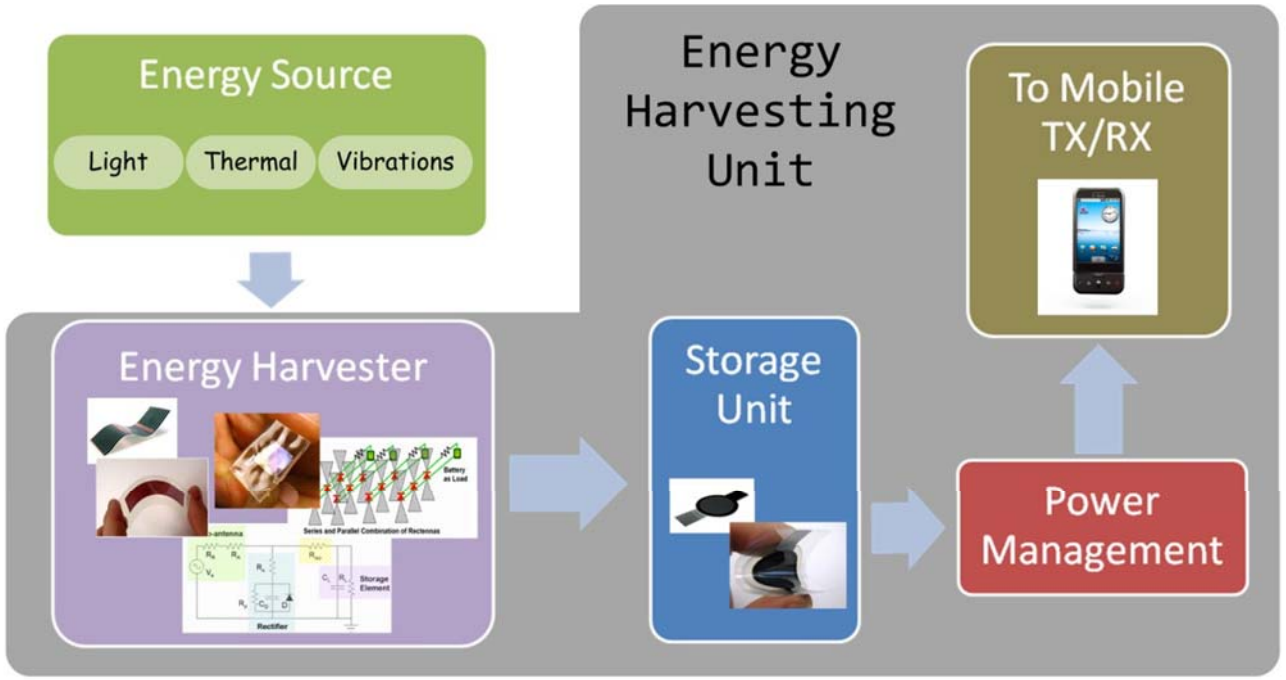






Power Harvesting

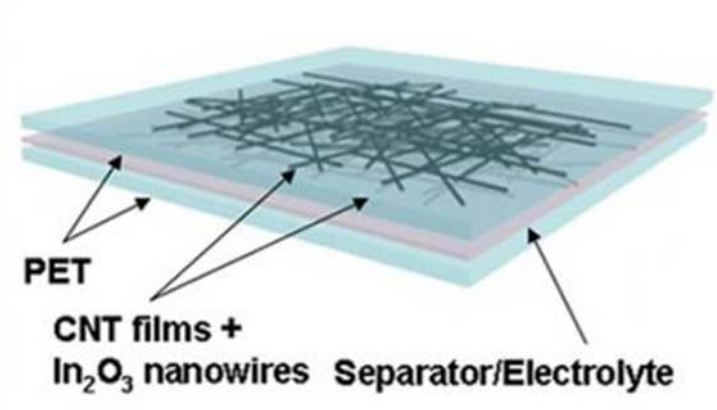
- Harvesting and Storage modules must be considered



Flexible Storage Modules

Flexible Storage devices / modules

- Flexible super-capacitors
- Stores an energy density of 1.29 Watt-hour/kilogram with a specific capacitance of 64 Farad/gram
- Conventional capacitors: energy density < 0.1 Wh/kg and storage capacitance of several tenth millifarads.



Chongwu Zhou et al. Flexible and Transparent Supercapacitor based on Indium Nanowire / Carbon Nanotube Heterogeneous Films. *Applied Physics Letters*, Vol.94, Issue 4, Page 043113, 2009

Summary

- Hybrid harvesting systems
- Low cost materials and fabrication techniques
- Embedding electronics on flexible substrates
- Stretchability, Washability, Interconnects
- Storage modules
- Autonomous Sensors

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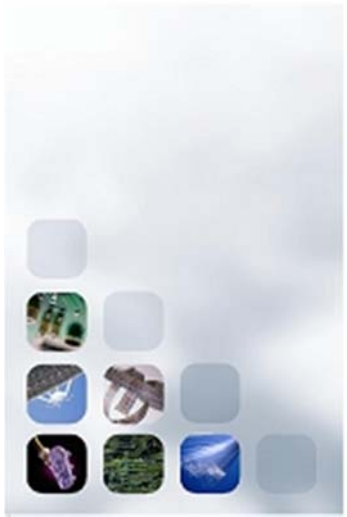

Related Events / Contacts

- http://www.cost-ic0803.org/
- Upcoming meeting, Lausanne Nov. 8-9, 2010

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Related Events / Contacts

- http://ewtw.cttc.es/
- September 15-16, 2011, Sitges - Barcelona

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Thank you for your attention!

- Questions?

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