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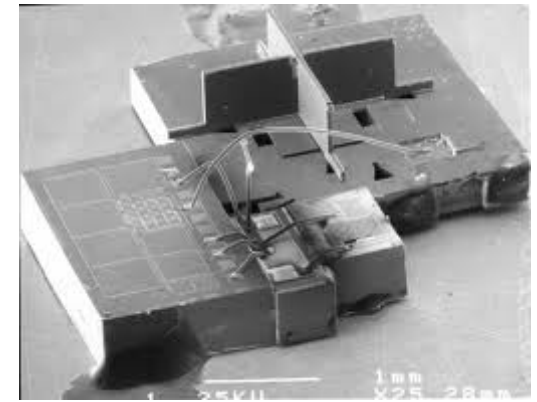
Energy & Smart Systems

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CNRS Research Director

EPoSS Annual Forum 2012, Paris (France), September 27, 2012



Smart Dust



- **Smart Dust:** DARPA-funded research proposal of the [University of California, Berkeley](#), in 1998.
- **Objective:** build wireless sensor nodes with a volume of one cubic millimeter.
- **Results:** working [mote](#) smaller than a grain of rice, and larger "COTS Dust" devices kicked off the [TinyOS](#) effort at Berkeley.



What does prevent a widespread adoption of wireless sensor networks?

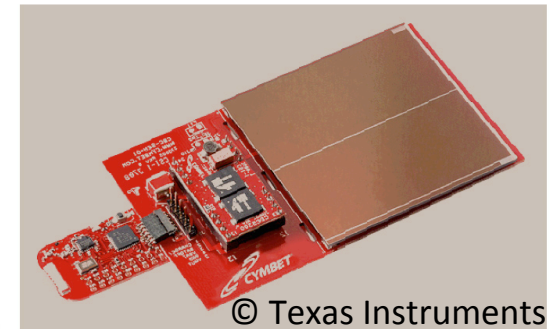
- *Reliability/robustness*
- *Cost*
- ***Energy autonomy***

Outline

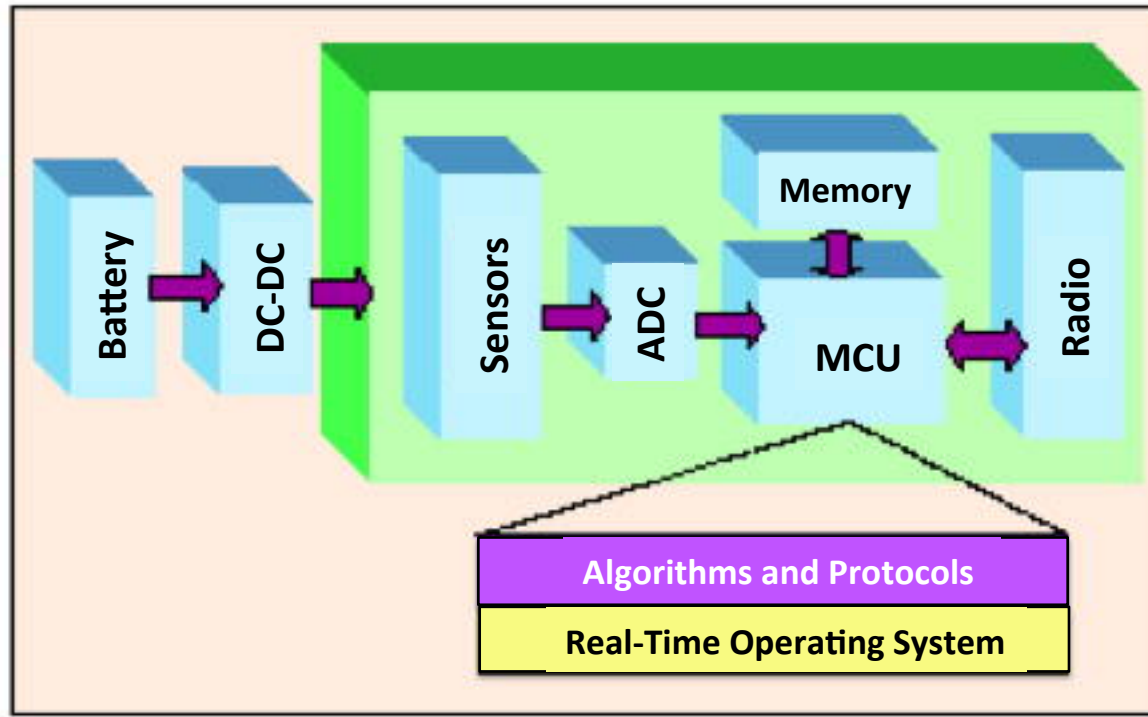
- Context
- The energy autonomy roadblock
- Research challenges :
 - Smart energy management
 - Low-power communication
 - Increasing energy density
 - Efficient energy harvesting
 - Green storage
- Conclusion

The energy autonomy roadblock

- Energy generation and storage devices are generally bulky
- Batteries have a limited lifetime
 - Prohibitive maintenance cost
 - Environmental issue
- Batteries can have safety issues
- Application dependent
- **MAIN CHALLENGES:**
 - Smart energy management
 - Increasing energy density
 - Efficient energy harvesting
 - Green storage



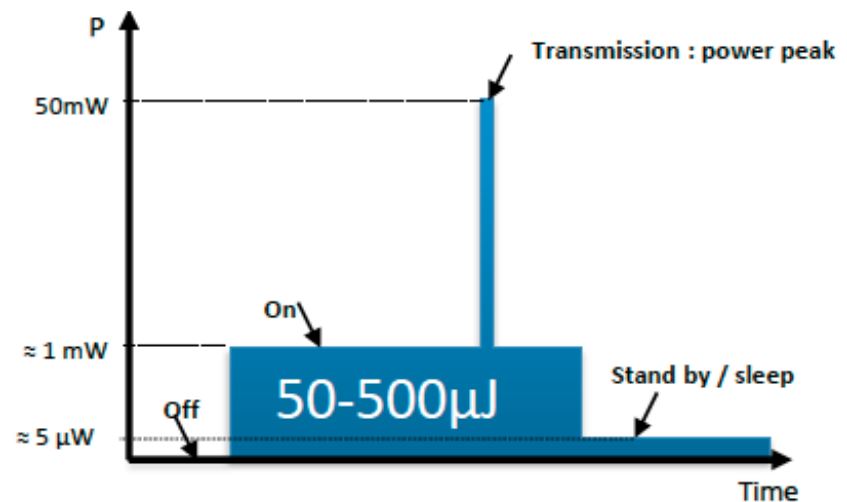
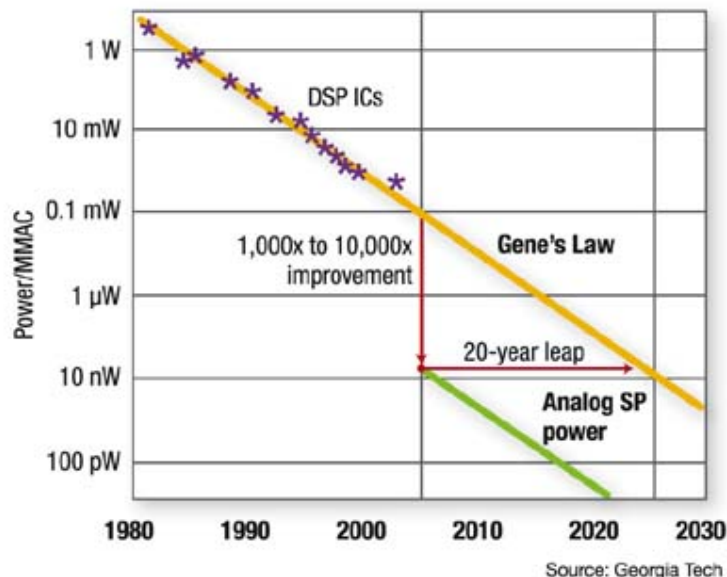
Where does the energy go?



- Processing
 - excluding low-level processing for radio, sensors
- **Radio**
- **Sensors**
- Power supply

Smart energy management

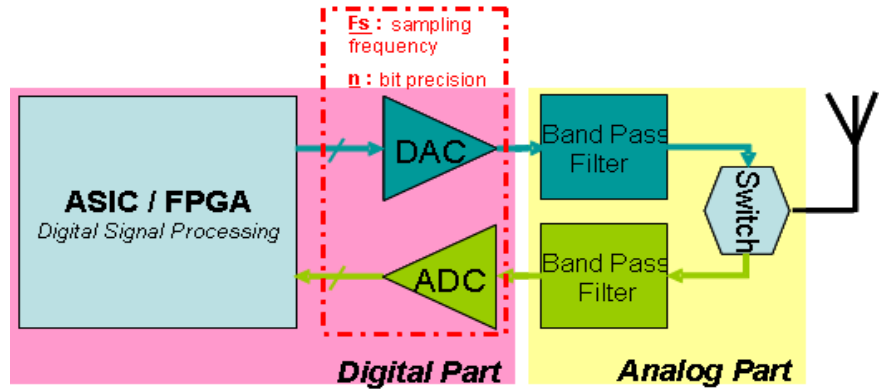
- Energy-driven architecture: *No “one-fit-all” solution*
- Low-power design techniques (multi-VT, multi-voltage, VDD cut-off during sleep, sub-threshold logic, asynchronous logic, dark silicon, etc)
- Efficient conversion of supply voltages
- Duty cycle adapted to the available energy
- Low-power protocols



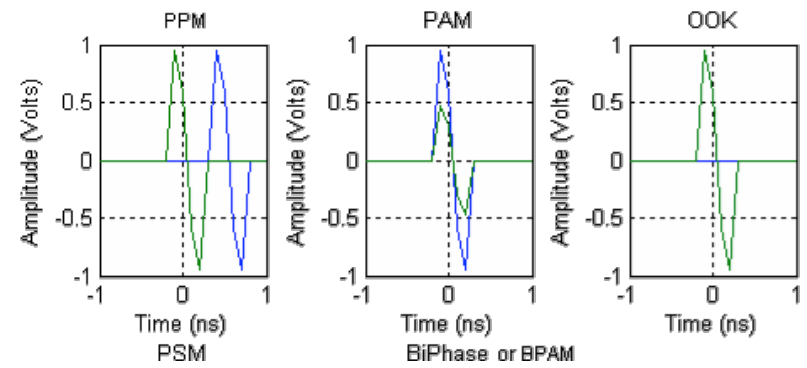
Advantages of IR-UWB* communication

- Low-energy impulse transmission
- Large frequency band
- Very short pulse
- Lower interference probability
- Small size antenna
- Geo-localization

- **Main challenges :**
 - Fast DAC/ADC
 - Reception synchronization
 - 1 pJ/bit

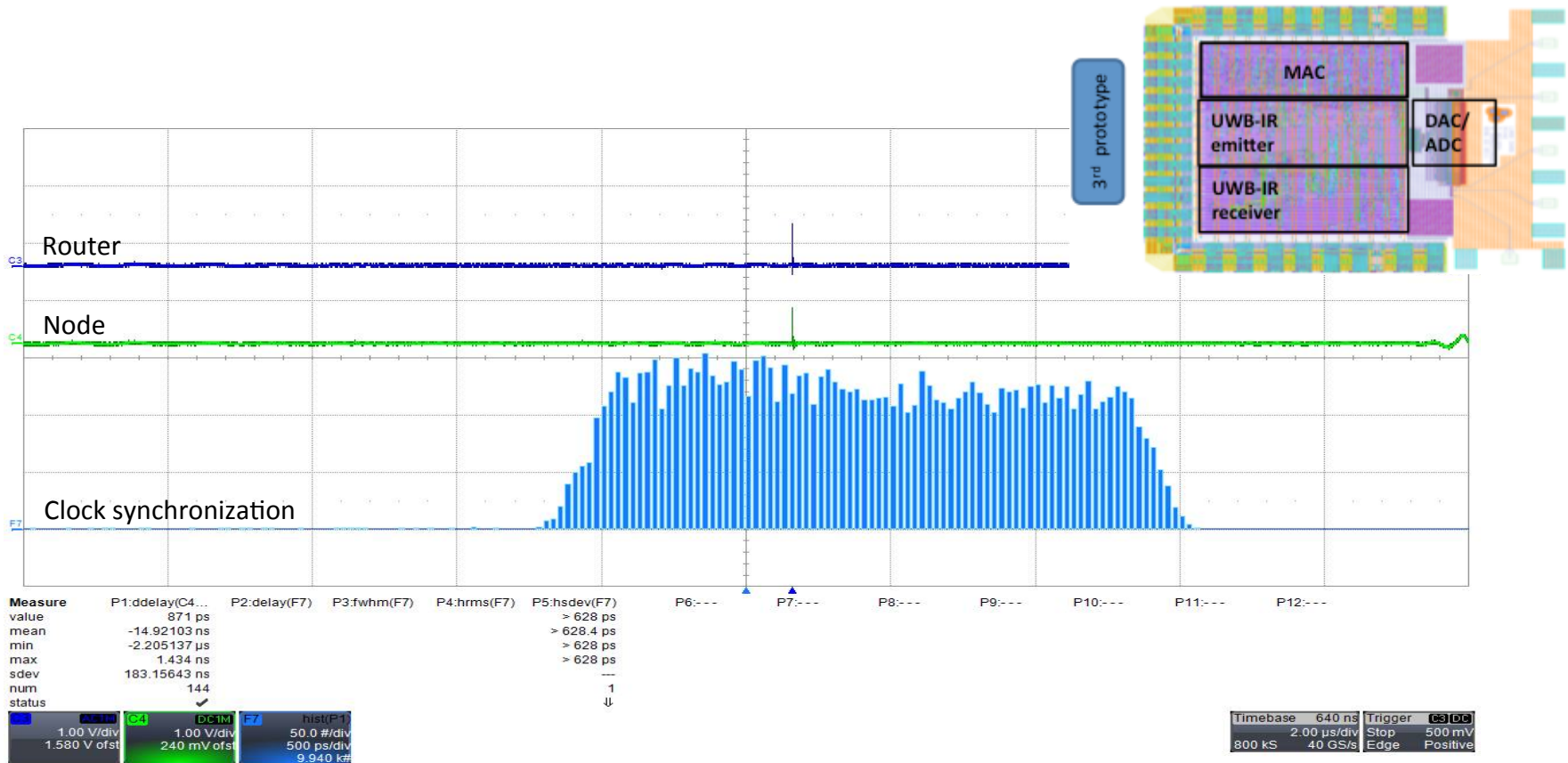


→ Emission
← Reception
Mostly Digital Radio Architecture



* Impulse Radio-Ultra Wide Band

Low power IR-UWB emitter/receiver



$P_{\text{consumption}} = 50 \text{ mW}$

Max data-rate : 500Mbps

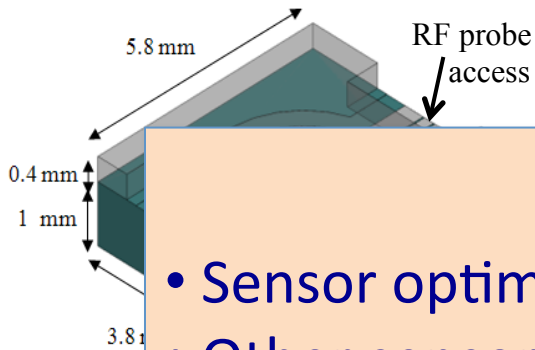
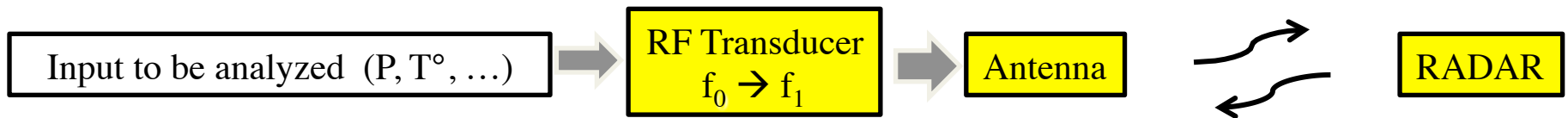
Energy/bit: 100pJ/bit (best case)

Clock synchronization precision $\sim 10 \text{ ns}$

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Is there a way to avoid the energy issue?

Passive Sensors With EM Transduction

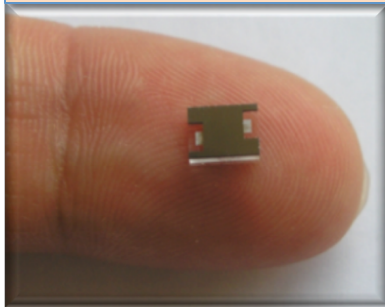


• Principle:

Future challenges:

- Sensor optimization and integration
- Other sensors: temperature, radiation dosimetry, gas
- Localization/identification

to

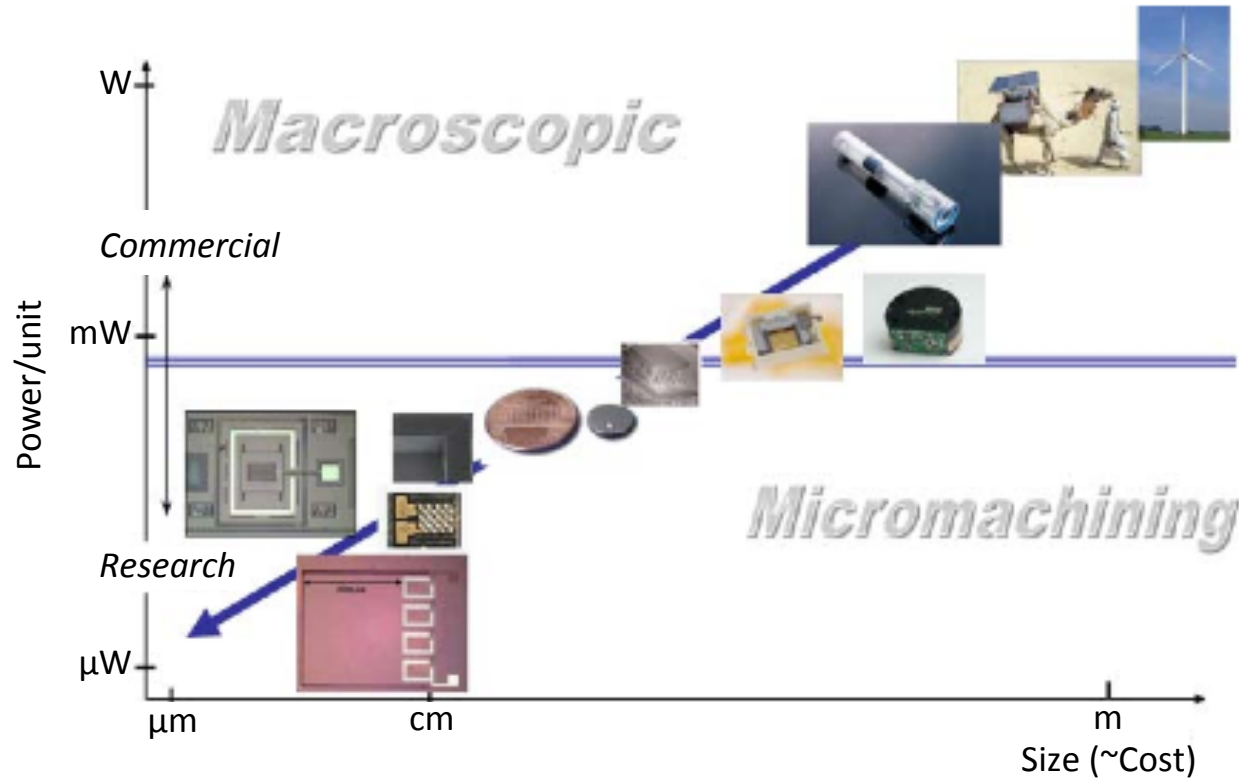


Passive Pressure Sensor

- Zero consumption
- Compatible with harsh environment
- No EM wave conversion losses: increased interrogation distance

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Effect of downscaling



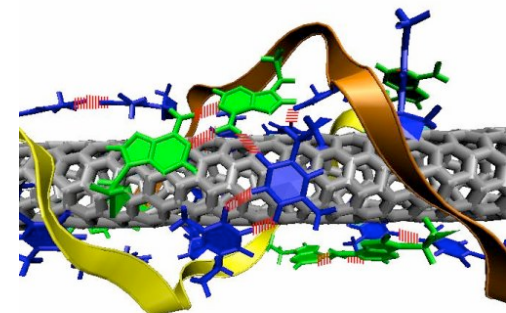
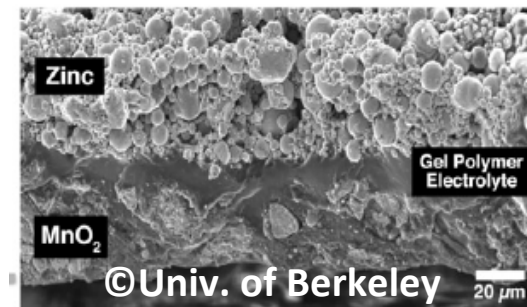
- Reducing size also decreases the output power

Increasing Energy density

- Take advantage of *micro & nano-technologies*
- Integration: 3D, SoC, SiP, TSV, advanced assembly techniques...
- Take advantage of *new materials*: flexible substrate, macrofiber composite, nano-material & *metamaterial* synthesis, etc
- Take advantage of *nanoscale, mesoscale effects*

Microbatteries

- High energy density ($>300\text{Wh/l}$)
 - 3D architectures
 - Air cathodes
- Low-cost
 - Self-assembly, inkjet printing...
- High power density
 - **Nanomaterials** as electrodes
- Low toxicity (ex: Zn, graphene)
- No use of strategic materials
- Safe devices
 - Polymer or glass electrolytes
- Improved lifetime: ≥ 10 years, up to 10000 cycles



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Energy harvesting

Mechanical



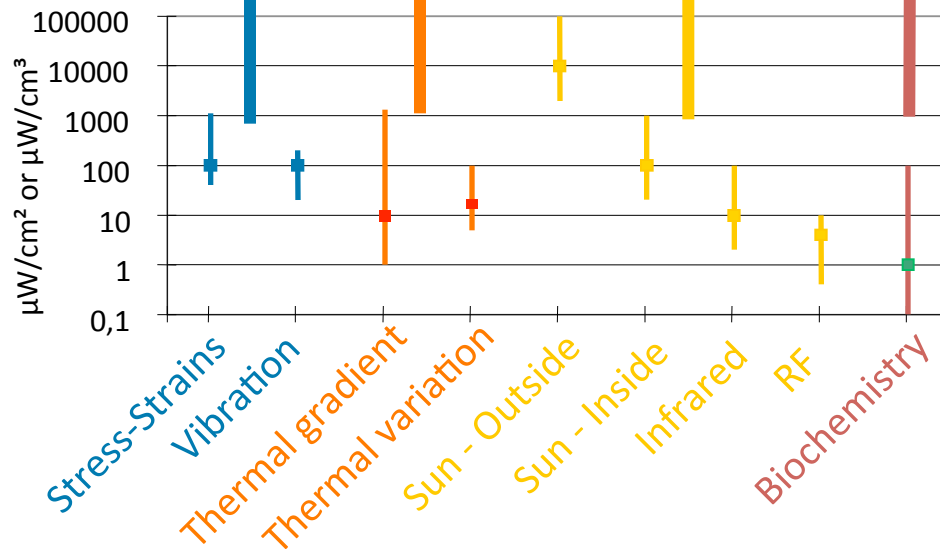
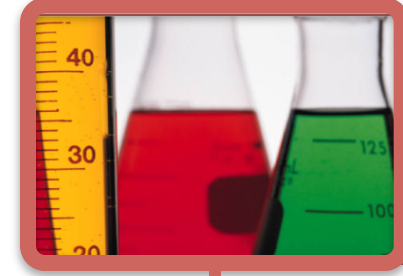
Thermal



Radiant



Chemical

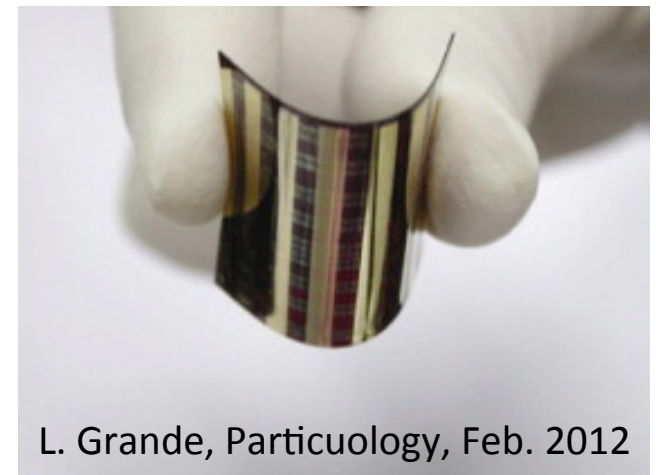
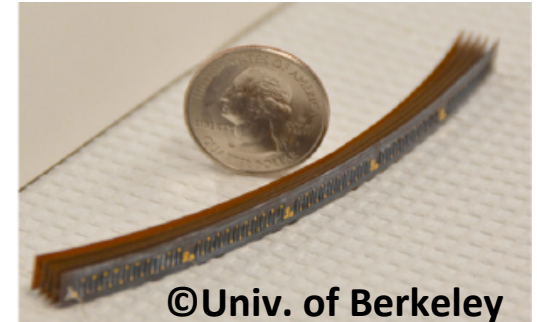


Power density of sources **available** in the environment

- No universal source of ambient energy
- Choice of the best source is application dependent
- *Multisources*
- *Use of multifunctional devices*

Energy harvesting

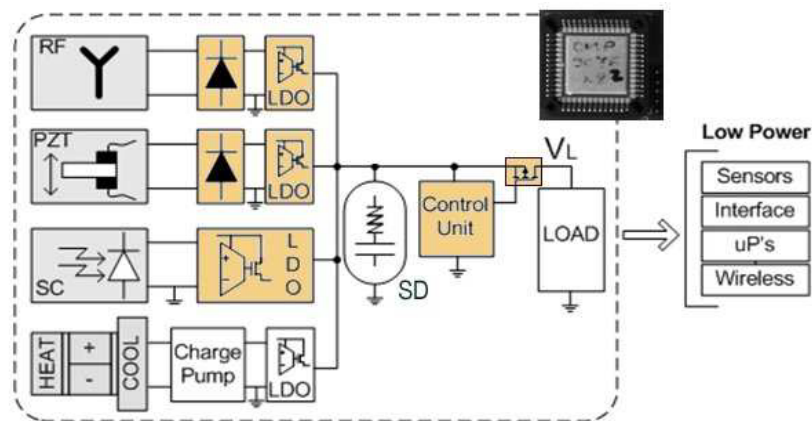
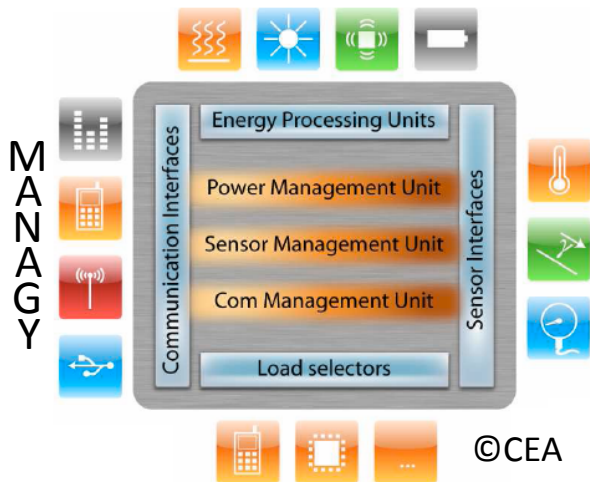
- Thermogeneration
 - New materials for improved Z
 - Efficient power management (MPPT, self-starting...)
- Photovoltaic
 - Improve energy conversion efficiency $\gg 10\%$
 - Indoor applications
- Vibrational
 - Increase bandwidth
 - Efficient AC-DC conversion
- RF
 - Efficient AC-DC conversion



Graphene properties are very promising ...

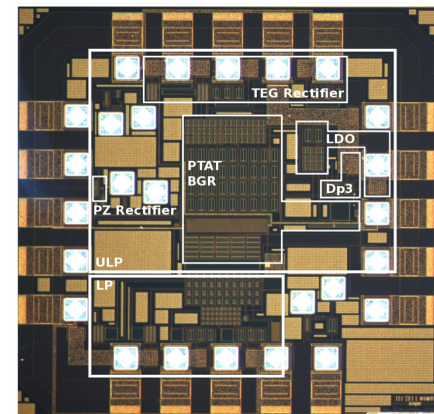
Energy Harvesting Power Management

- Generic power management circuit almost impossible: AC, DC, high voltage/low current or low voltage/high current...
- Availability of source over time: *multisource*
- High efficiency/low-power



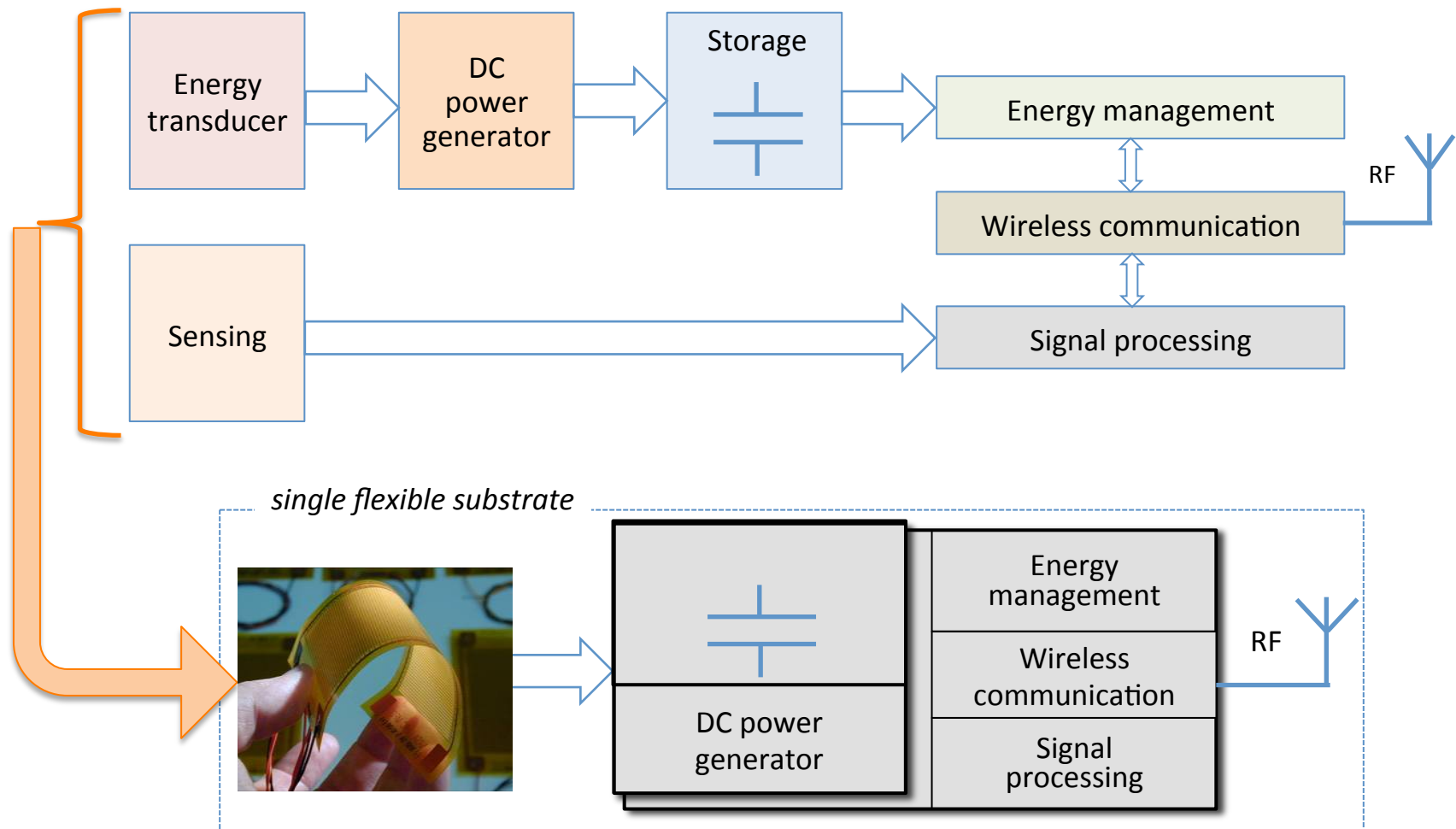
J.Colomer-Farrarons, P. Miribel-Catala, Springer 2011

Multisource (TEG/PZ) converter
I_{ddq}=200nA



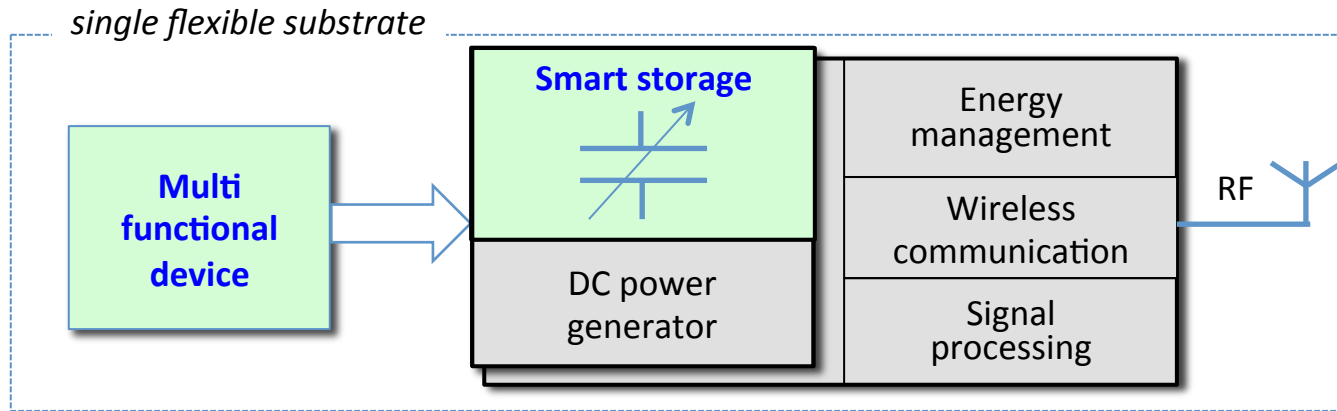
Multifunctional device

Application: SHM scenario



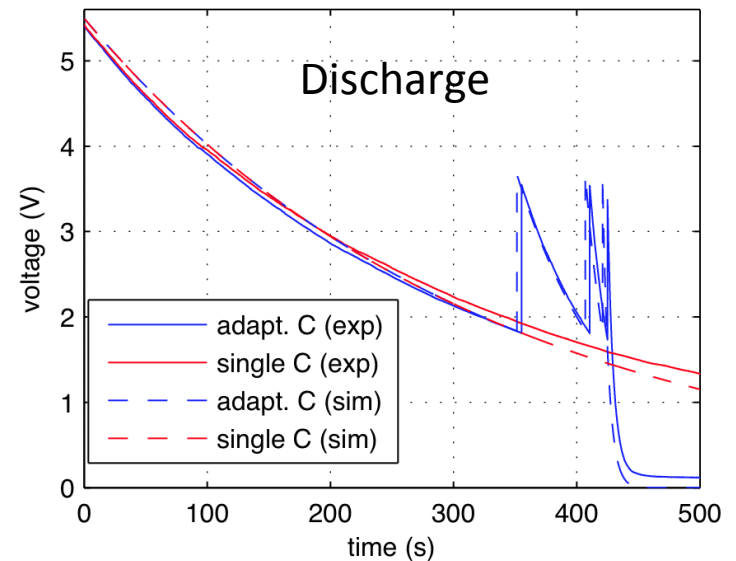
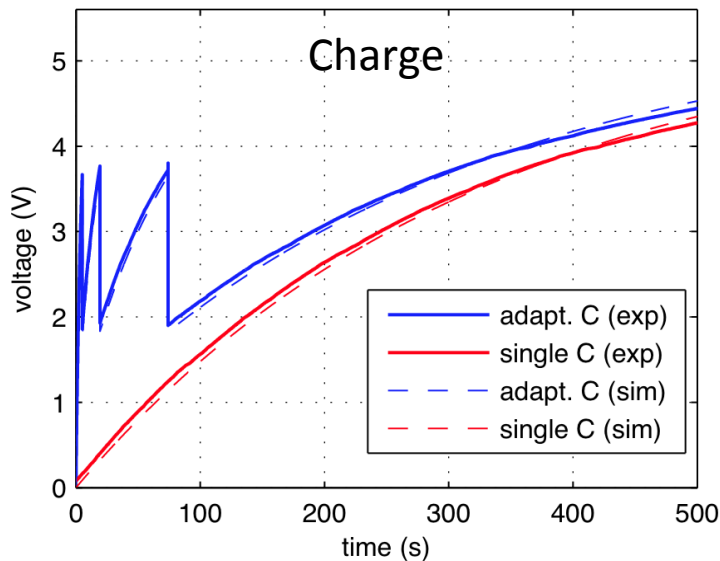
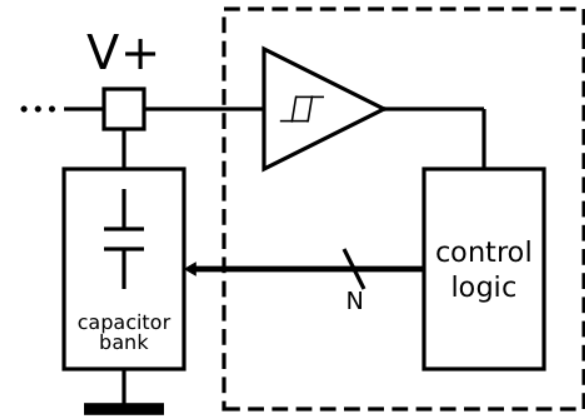
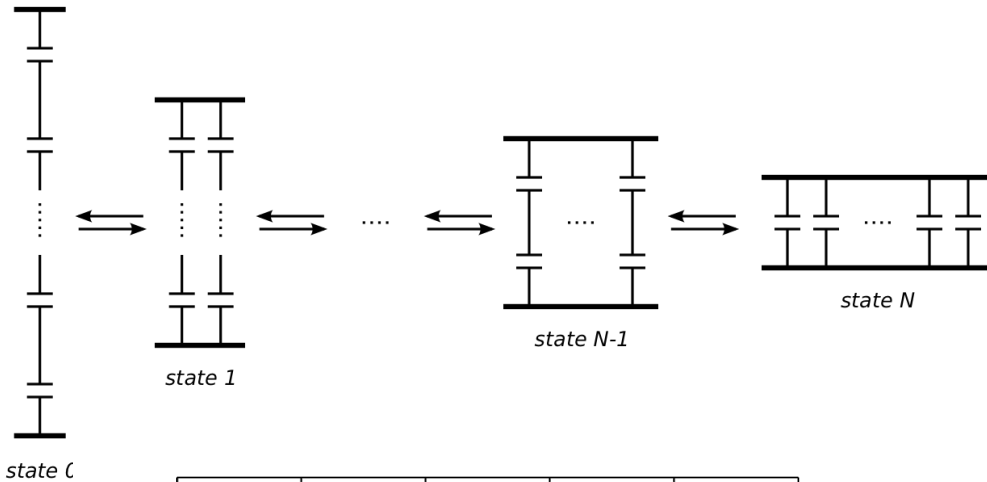
Smart integrated storage

Battery-free system: storage on ultracapacitors



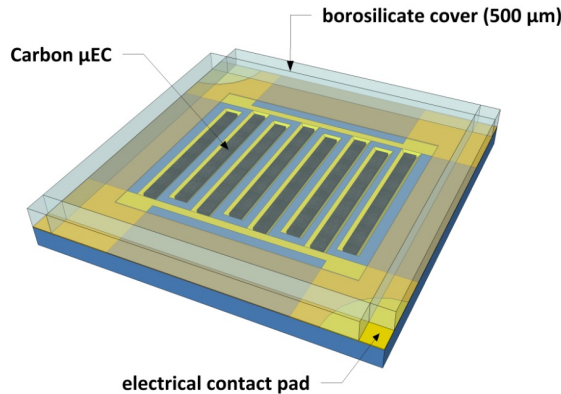
- **Advantages over batteries :**
 - Much longer lifetime ~ million cycles
 - Safer operation
 - Environment friendly
- **Main drawbacks :**
 - Lower energy density
 - Self-discharge
- **Integration on silicon**
 - lower self-discharge
 - co-integration with power management
 - smart adaptive storage

Smart adaptive storage



Micro-storage on chip

Carbon-based micro-supercapacitor on silicon with liquid organic electrolyte

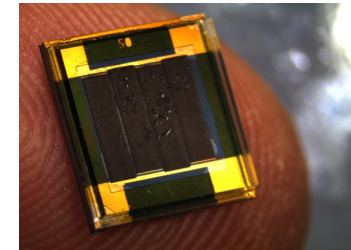
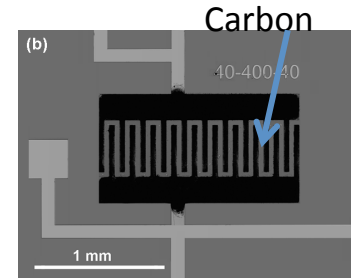


- **ACTIVE MATERIAL DEPOSITION**

- Inkjet printing -> high resolution
- Electrophoretic deposition -> collective
- Screen printing -> high thickness

- **ENCAPSULATION**

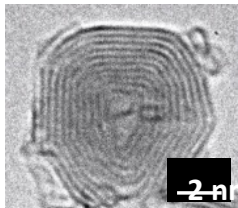
- Wafer-level packaging
- Low temperature process (< 150°C)
- Hermetical (humidity free)



- **RESULTS (without encapsulation):**

Carbon Onions by electrophoresis

Project Partner University Fund: Drexel University (USA), CIRIMAT, LAAS



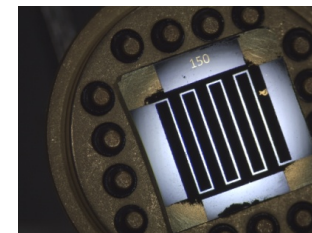
$$C = 1,7 \text{ mF.cm}^{-2}$$

$$E = 7,7 \text{ mJ.cm}^{-2}$$

$$P = 700 \text{ mW.cm}^{-2}$$

Very high specific power

Activated carbon by screen printing



$$C = 82 \text{ mF.cm}^{-2}$$

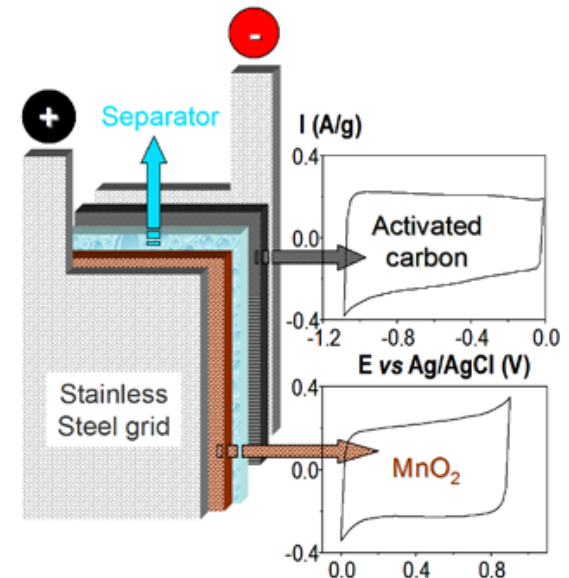
$$E = 257 \text{ mJ.cm}^{-2}$$

High specific energy

Future micro-storage challenges

– More Power, More Energy → $1\text{F}/\text{cm}^2$

- Enhanced materials:
 - Carbons: OLC, CDC, MWCNT... }
 - Pseudo: RuO_2 } + Nanostructuration
- New electrolytes:
 - Protic Ionic Liquid, Ionogel, Hygrogel
- Improved configurations:
 - down to nanoscale
- Efficient *encapsulation*
- *Hybrid* micro-devices
 - Capacitive / pseudo capacitive



Conclusion

Energy autonomy of smart systems is still a big challenge:

- Global *energy-driven* system design approach
 - Modeling/simulation
 - Low-power sub-systems
- Energy density increase
 - *Micro & nano-technologies* are key enablers
 - Metamaterials such as *graphene* are very promising
- Energy *harvesting* is essential
- *Green & low-cost* technologies
- *Reliability & robustness* need to be addressed

We have ADREAM*...

*Architectures for **D**ynamic **R**esilient **E**MBEDDED **A**utonomous and **M**obile Systems



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