Industry Session 11: Energy Harvesting

3D Silicon Capacitive Interposer for RF Energy Harvesting device: Higher Efficiency, Higher Integration and Simplified Topology

Presented By –

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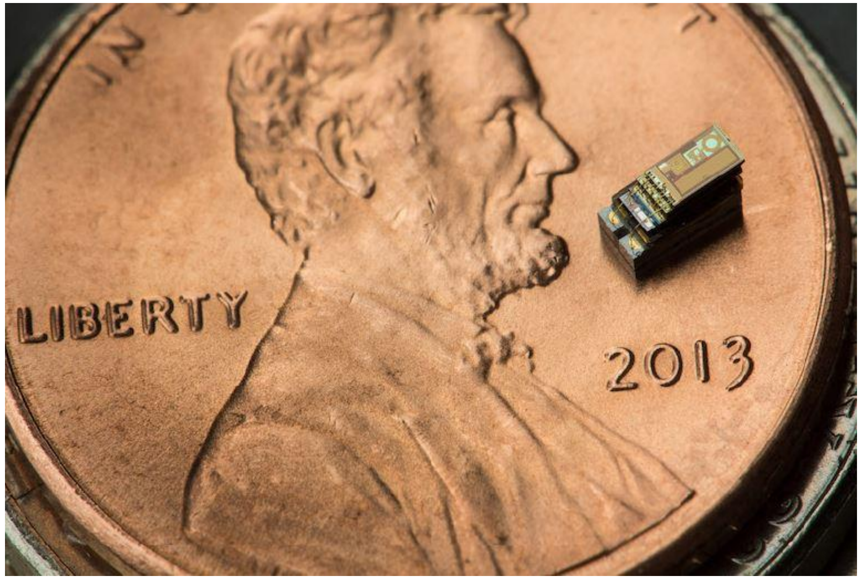
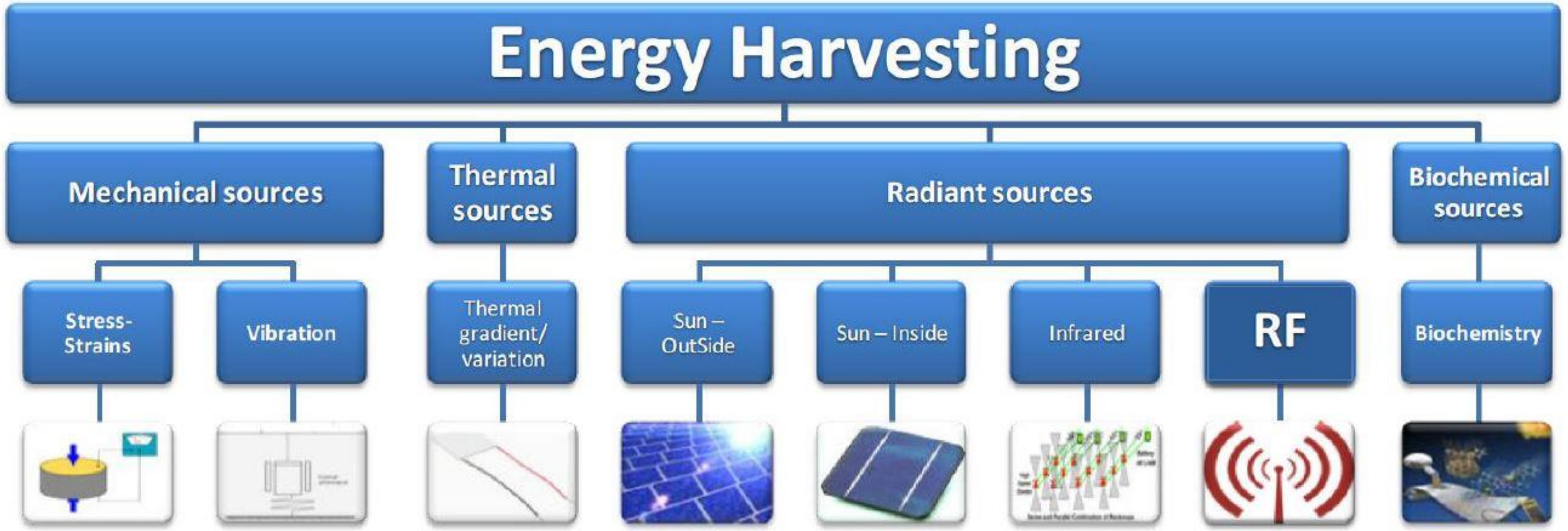
OVERVIEW

- **1- Introduction**
- **2- Concept and motivation**
- **3- 3D Silicon capacitive interposer: Performance enabler!**
- **4- Summary / Looking forward**

1- EH from surrounding environment



Smart dust developed by University of Michigan, sitting on a penny

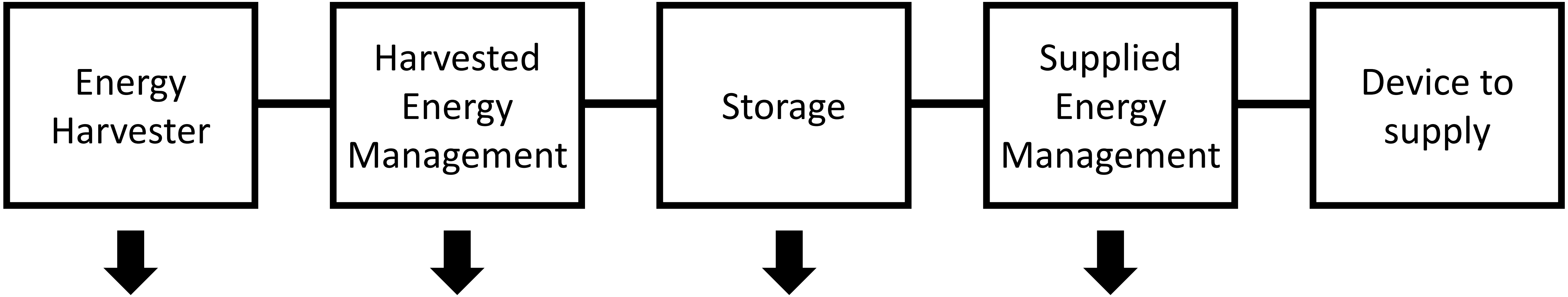


the smart dust can harvest energy from surrounding environment

Yu Luo &al.'RF Energy Harvesting Wireless Communications: RF Environment, Device Hardware and Practical Issues'; Sensors 2019, 19, 3010; doi:10.3390

Bruno Franciscatto. "Design and implementation of a new low-power consumption DSRC transponder Electronics". Université de Grenoble, 2014

1- Designing an EH supplying an electronic device



Different harvesters for different supplies:

- Antennas for RF
- Piezoelectric sensors for mechanical constraints
- Solar cells for solar energy
- …

Converts the harvested energy into a storable one. It requires an AC-DC converter (rectifier) and a DC-DC converter (step up)

Converts the harvested energy into a storable one.

Converts the storage energy into a supplied one. It may require a step down DC-DC converter and a LDO

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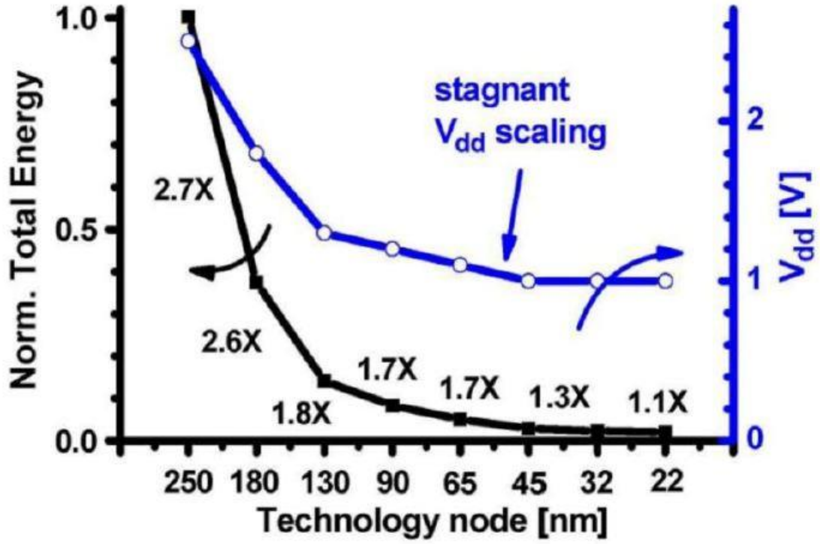
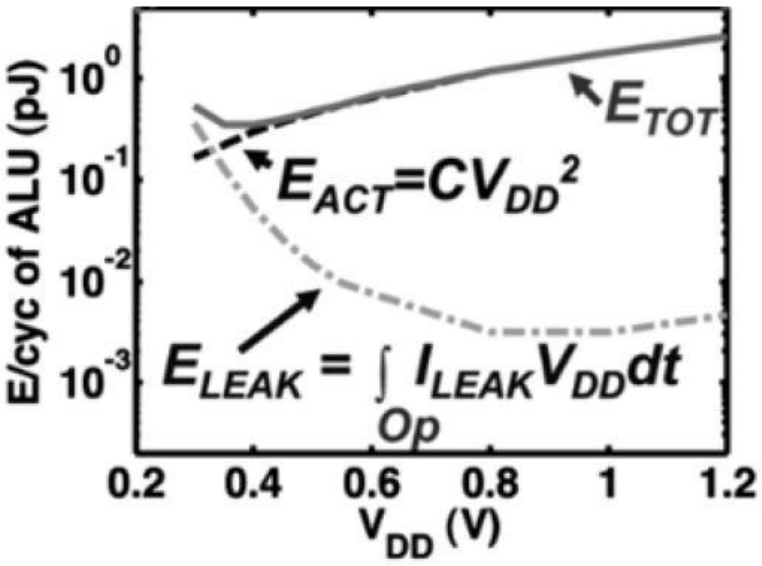
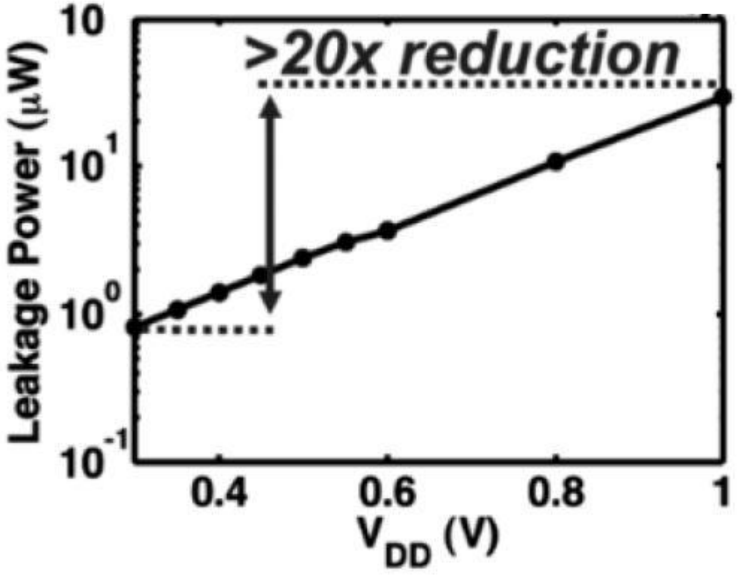
1- Electronic devices consume less

Reduction of energy per operating cycle and leakage power for a microcontroller type system consisting of a processor and an SRAM memory







→ *RF harvesting is possible*

1- Various frequency bands for RF harvesting

Comparison of Various frequency bands for RF charging

Parameter[1]	Cellular bands									
Band	850 MHz		1.7 GHz		2.1 GHz		1.9 GHz		2.5 GHz	
Wavelength, m	0.35		0.18		0.14		0.16		0.12	
Array size,[2] m	0.35 × 0.35		0.18 × 0.18		0.14 × 0.14		0.16 × 0.16		0.12 × 0.12	
	Omni	Direct.	Omni	Direct.	Omni	Direct.	Omni	Direct.	Omni	Direct.
Energy radius, m	11.38	37.51	5.69	18.76	4.60	15.18	5.09	16.78	3.87	12.75
$P_{harvested}$,[3] μW	12.94	140.73	3.24	35.18	2.12	23.06	2.59	28.16	1.50	16.27
Replenishment rate,[4] %	159	2715	–35	604	–58	361	–48	463	–70	225
Energy positive range,[5] m	16.09	53.05	8.04	26.53	6.51	21.47	7.20	23.73	5.47	18.04
Support time,[6] min	6.30	0.37	N/A	1.66	N/A	2.77	N/A	2.16	N/A	4.44

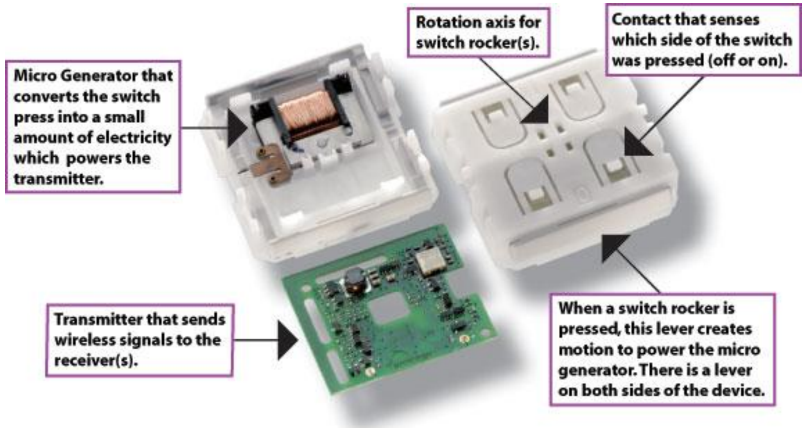
Parameter[1]	ISM (industrial, scientific and medical) bands					
Band	915 MHz		2.4 GHz		5.8 GHz	
Wavelength, m	0.33		0.12		0.05	
Array size,[2] m	0.33 × 0.33		0.12 × 0.12		0.05 × 0.05	
	Omni	Direct.	Omni	Direct.	Omni	Direct.
Energy radius, m	10.57	34.85	3.95	13.01	1.67	5.50
$P_{harvested}$,[3] μW	11.17	121.44	1.56	16.94	0.28	3.02
Replenishment rate,[4] %	123	2329	–69	242	–94	–40
Energy positive range,[5] m	14.95	49.28	5.58	18.41	2.36	7.77
Support time,[6] min	8.11	0.43	N/A[7]	4.19	N/A	N/A

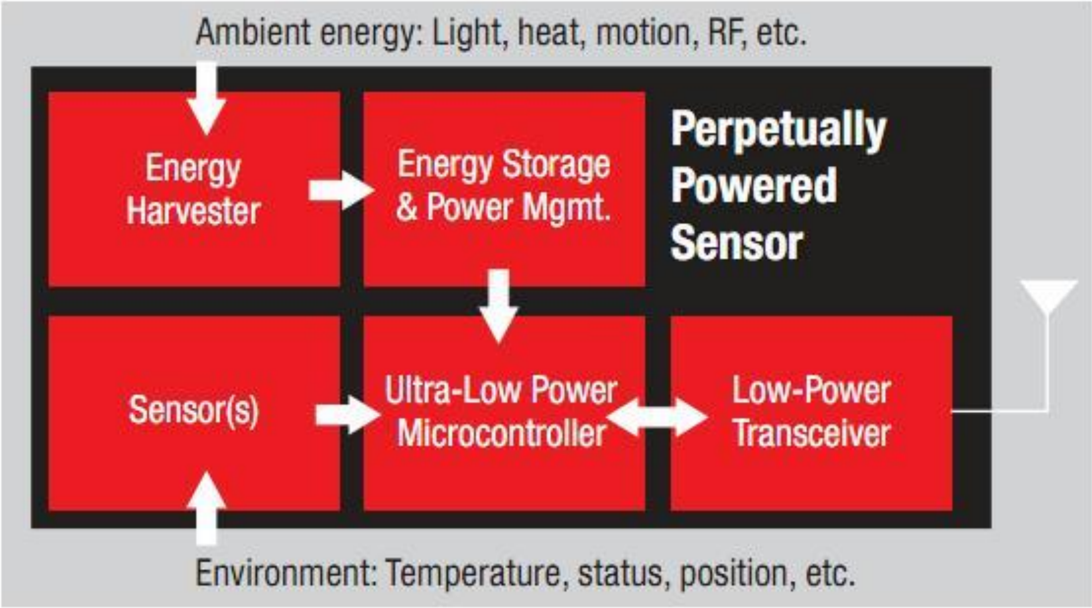
[1] Parameters used for estimation are: transmitter antenna gain (omni-directional/directional) 2.15/14.51dBi, receiver gain 0dBi, WET efficiency 50 percent, sensitivity = –20dB, consumed power (discharge rate) 5μW, radiated power 1/0.63W (omni-directional/directional).
[2] Assuming 3 × 3 square transmitter array with 1/2 wavelength separation.
[3] Harvested power at reference distance 10m.
[4] Energy replenishment rate at 10m = (harvested power/consumed power –1) · 100 percent.
[5] Maximum distance where harvested power ≥ consumed power.
[6] Time of harvesting to support N = 10 min of autonomous work at 10m.
[7] Not available due to feasibility constraints.

'On feasibility of 5G-grade dedicated RF charging technology for wireless-powered wearables'

2- New Trends_Battery-Free devices

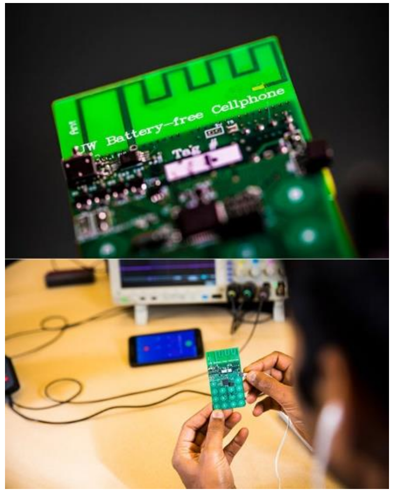
They consist of low power energy harvesters that supply power, while the Super Capacitors store the energy and provide the high current pulses.

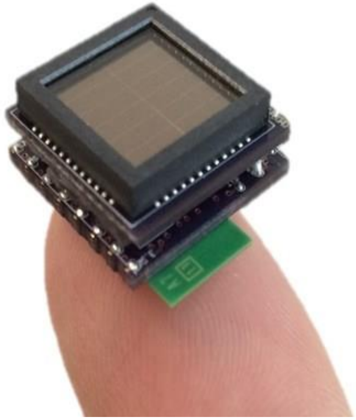




Stephen Evanczuk. 'Energy Harvesting Wireless Sensors'

first battery-free cellphone that can send and receive calls using only a few microwatts of power.Mark Stone/University of Washington

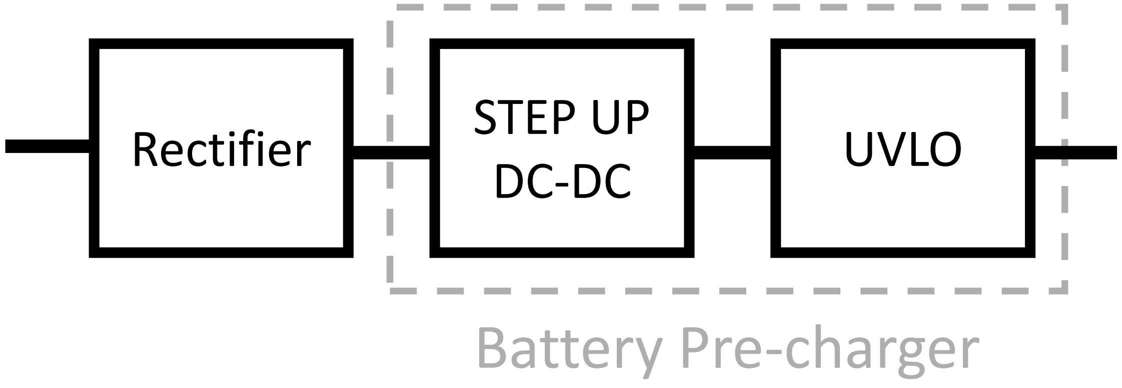




→ **What will be the impact from a functional point of view ?**

2- Harvested Energy Management strategy

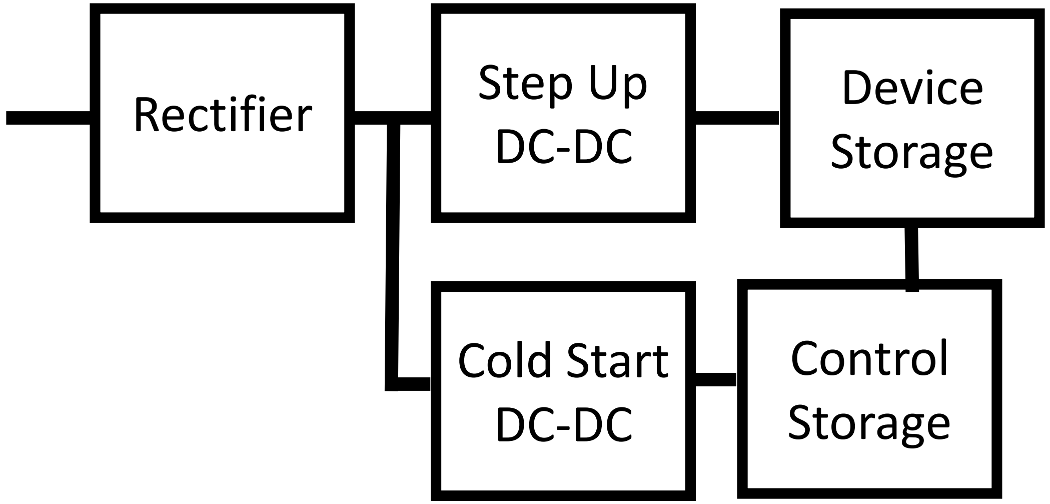
Battery



As the battery can only be charged with its nominal voltage, the energy harvester output voltage has to be increased to this value. The battery can be charged only when the correct voltage has been reached thanks to the UVLO.

➡ These 2 blocks need control signals, thus the battery has to be charged before the harvester could work.

SuperCapacitor

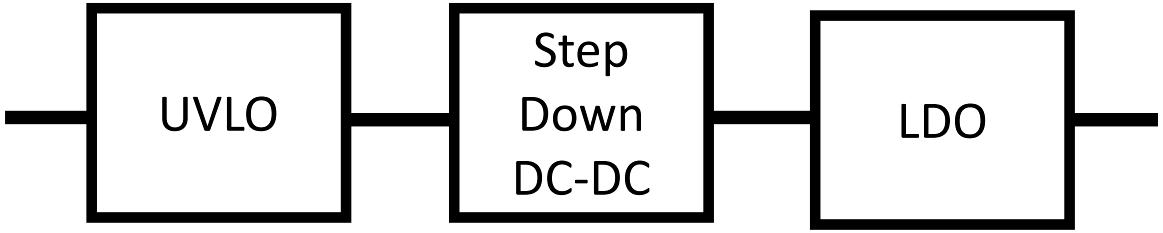


There is no need for UVLO, the supercapacitor can be charged with different voltages. Thus, we can add a cold start DC-DC which needs no control signal. Once the control storage capacitor is charged at a minimal voltage value, the cold start DC-DC is turning off and the step-up DC-DC is turning on. The device storage capacitor is charged and it also supplied the control storage capacitor.

➡ The supercapacitor can be discharged and there is no minimal harvested power required in order to be able to charge the capacitor.

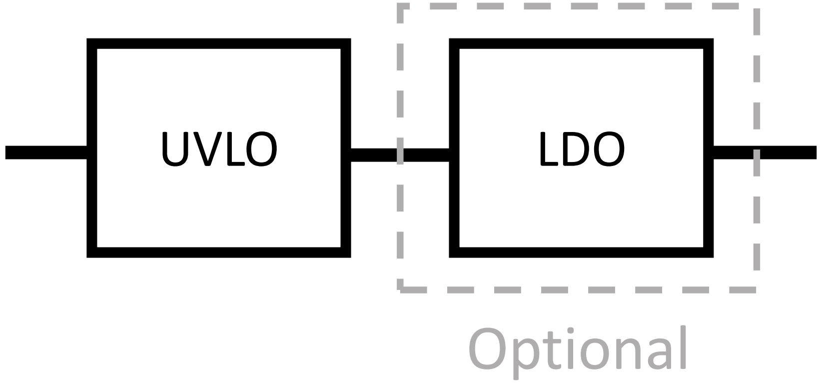
2- Supplied Energy Management strategy

Battery



For IOTs, nominal voltage is lower than battery nominal voltage which is 3.65V, a step down DC-DC has to be added. If only a LDO is added, the efficiency, 49% at best, would have a critical impact on the overall efficiency.

SuperCapacitor



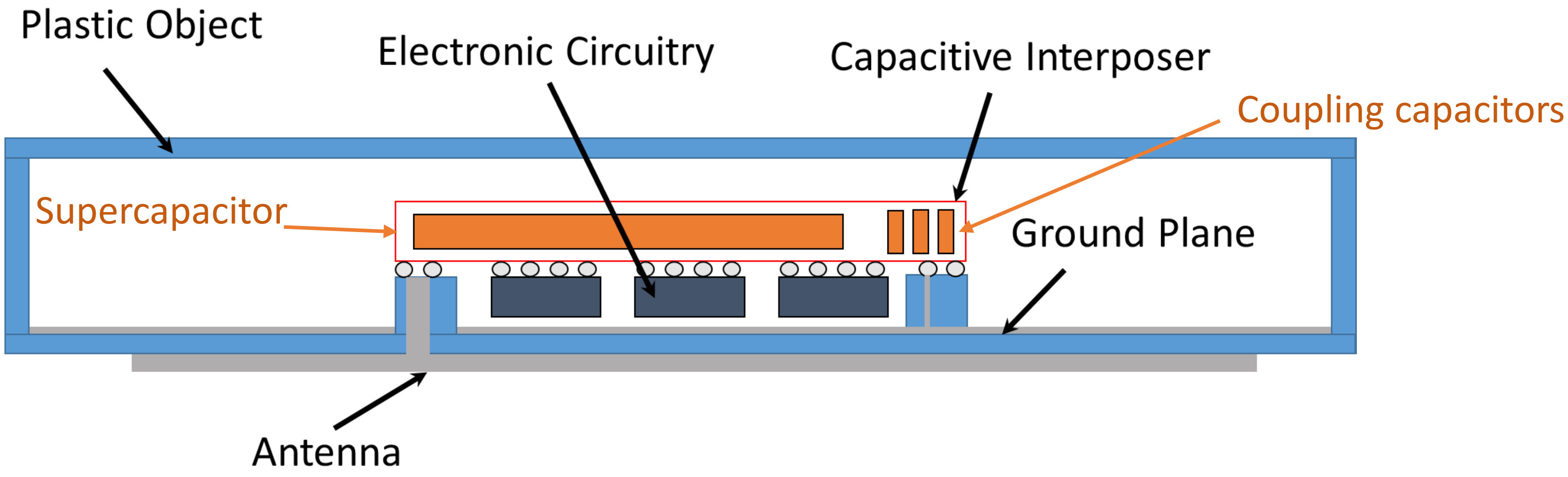
As we can tune the storage voltage, there is no need of step down DC-DC. The supercapacitor will be sized to have the output voltage into the spec limitations. As the supercapacitor is accepting an highest peak current, the LDO is optional.

➡ The battery energy management needs one or two additional functional blocks, which leads to more energy dissipation. The device can be activated more often with a supercapacitor based energy management.

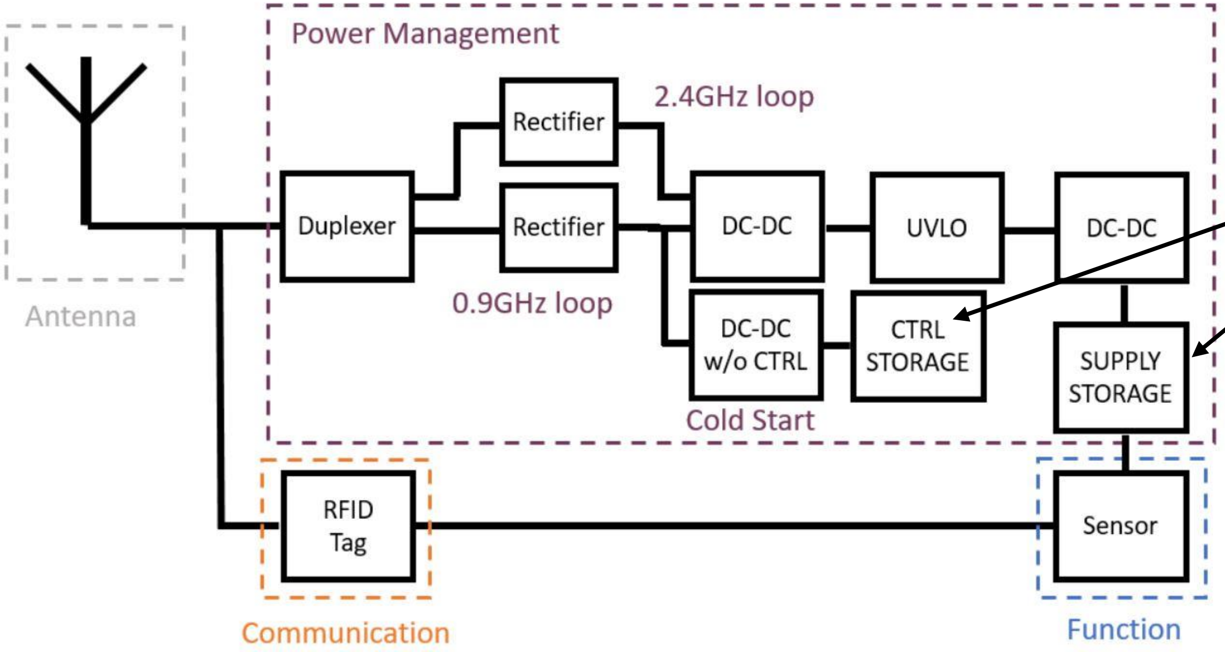
2- INCA project: 3D SiP for EH

3 key elements: Heterogeneous integration

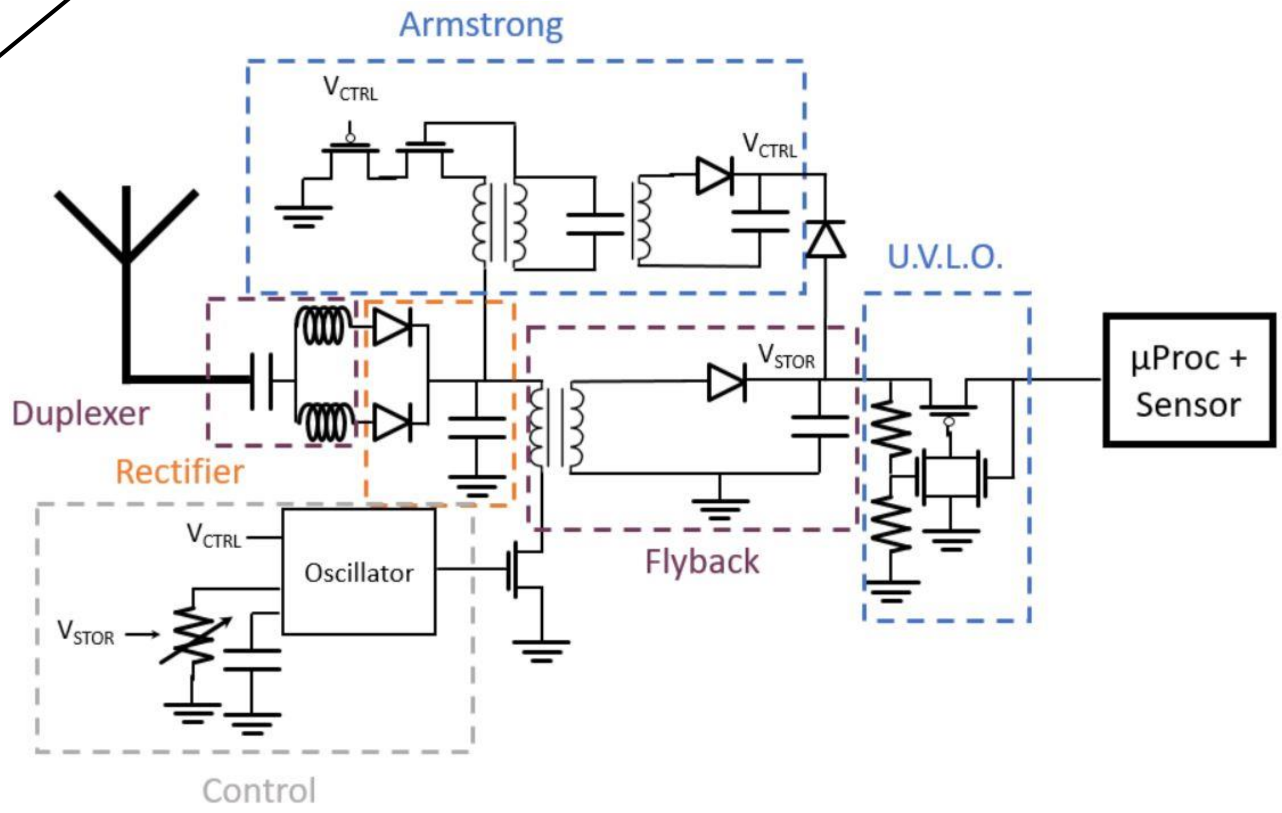
- Antenna will be designed using Plastronics
- Capacitors will be buried inside a simple face interposer
- The power management circuitry will be designed in FDSOI 28nm



2- Block Diagram

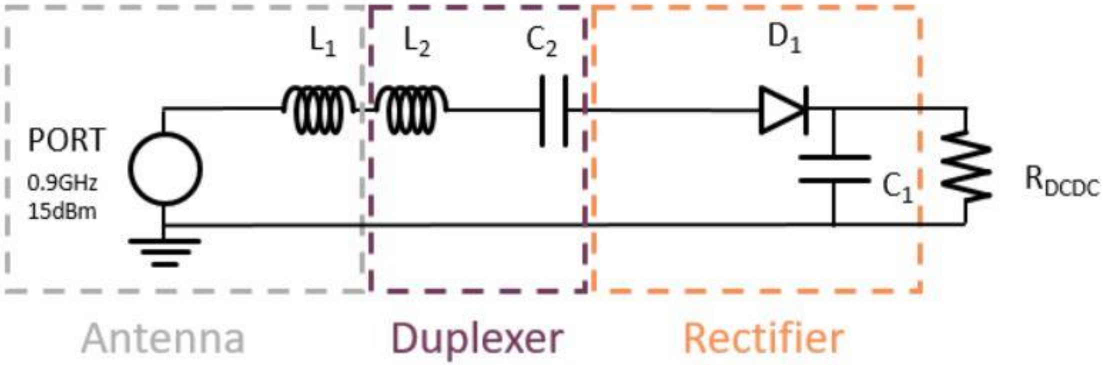


- Multiple storage devices
- Specific for each functional block
- Optimal energy management



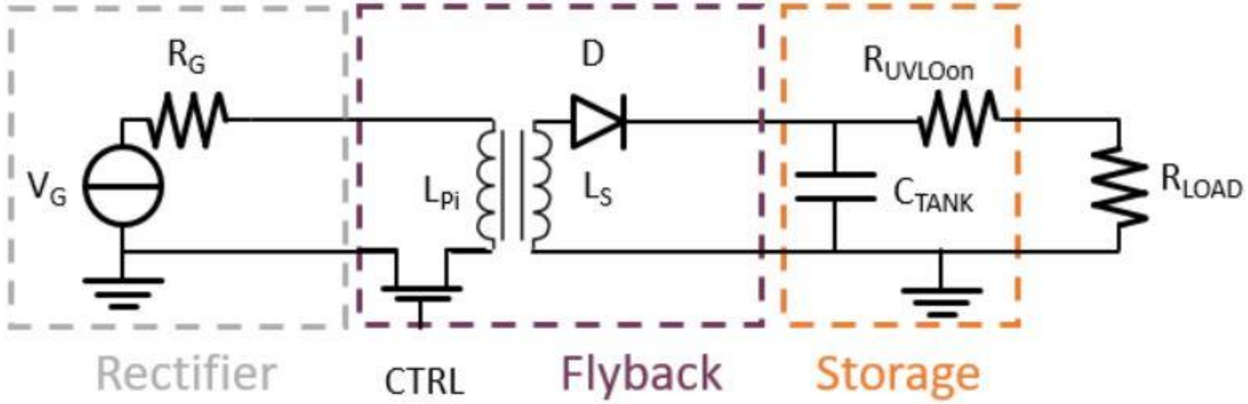
➡ Take advantage of capacitors integration capability

2- Block Diagram- How does it work



Rectifier

Ensuring the energy conversion from 150mV (depends of the rectenna) to 1V



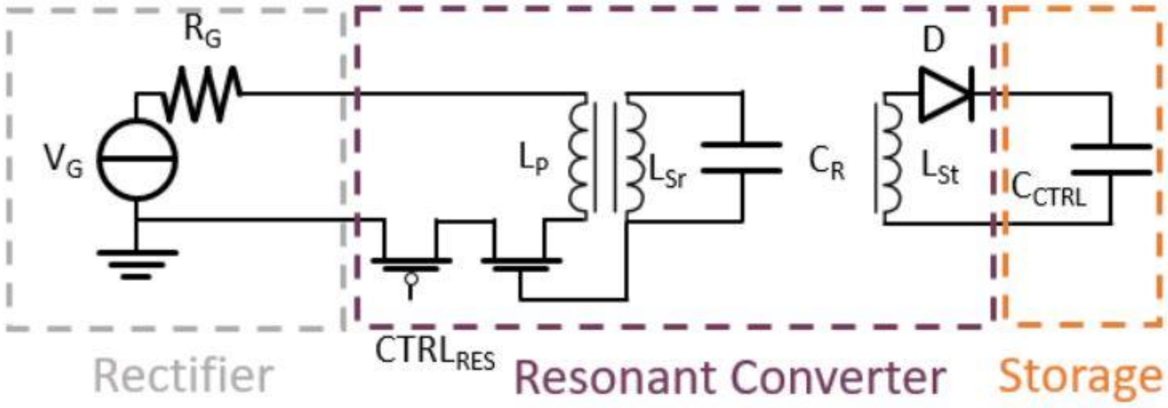
Rectifier DC to Storage DC: a Fly-back converter

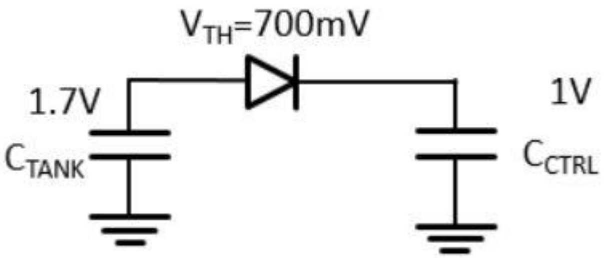
Fly-back needs a control block (an oscillator), which has to be supplied. The supply voltage has to come from the storage capacitor → We need another way to start the charge of the storage capacitor.

2- Block Diagram- How does it work

How to start the energy conversion without any energy?

Armstrong converter in order to charge the storage capacitor when it is empty

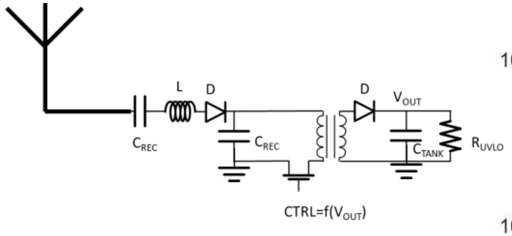


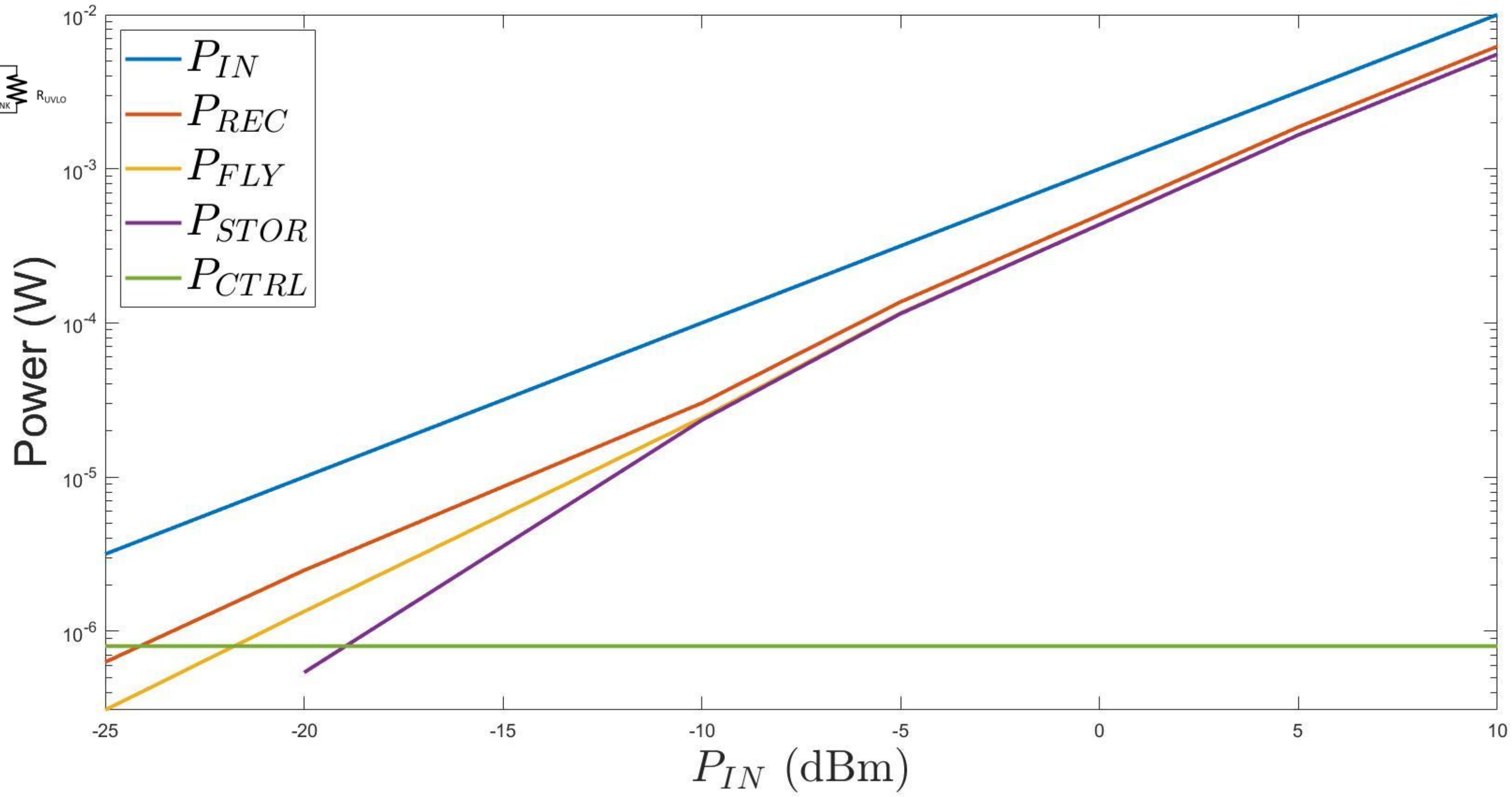


Cold start process:

1. Armstrong on. It charges the control storage capacitor C_{CTRL}
2. V_{CTRL} reaches 1V, Armstrong is turning off, flyback is turning on
3. Flyback charges the tank capacitor C_{TANK}
4. C_{CTRL} charges C_{CTRL} through a diode.

2- Harvested power as a function of Pin





➡ In order to harvest energy, we can turn on the flyback for a minimal P_{IN} of -20dBM. Otherwise, the Armstrong should stay on.

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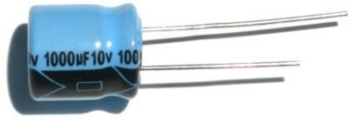
3- Energy storage devices

Capacitor



- Low Energy (stores a **small** amount of energy as **static electricity**)
- Very High Power (releases it **very quickly**)

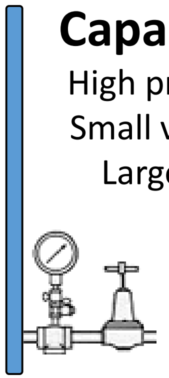
Ultracapacitor

- Moderate Energy (stores a **medium** amount of energy as **static electricity**)
- High Power (releases it **quickly**)

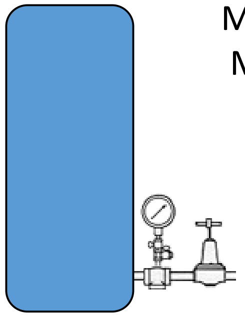
Battery

- High Energy (stores a **large** amount of energy as a **chemical reaction**)
- Low Power (releases it **slowly**)

The water tank analogy



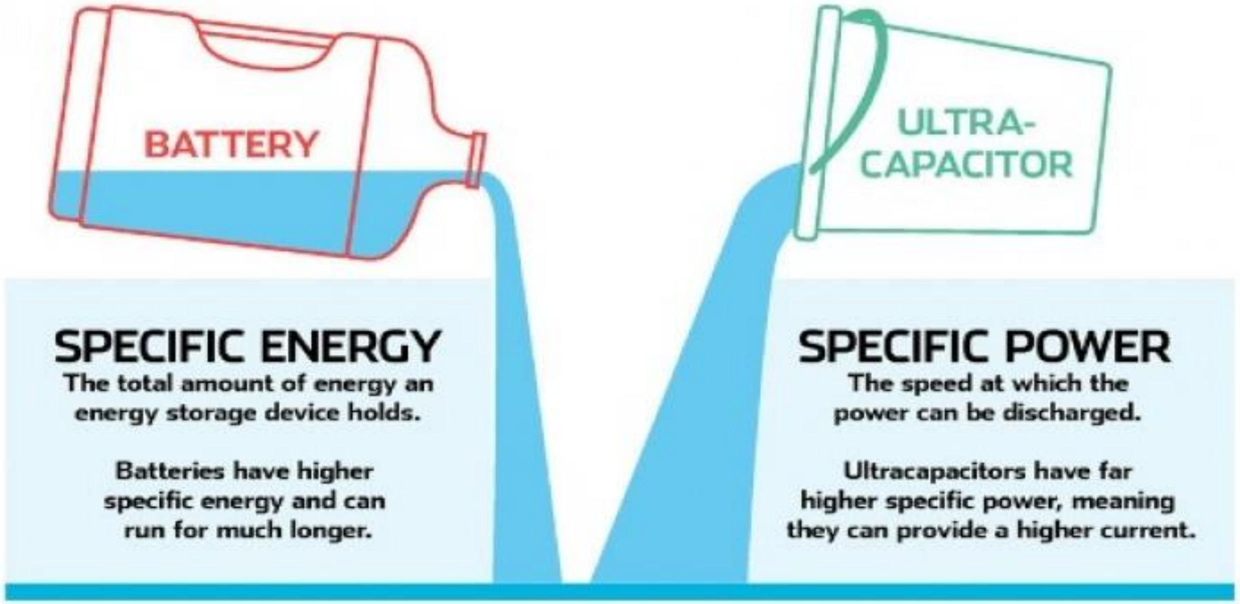
Capacitor:
High pressure
Small volume
Large tap



Ultracapacitors:
Moderate pressure
Moderate volume
Moderate tap

Battery:
Low pressure
Large volume
Small tap

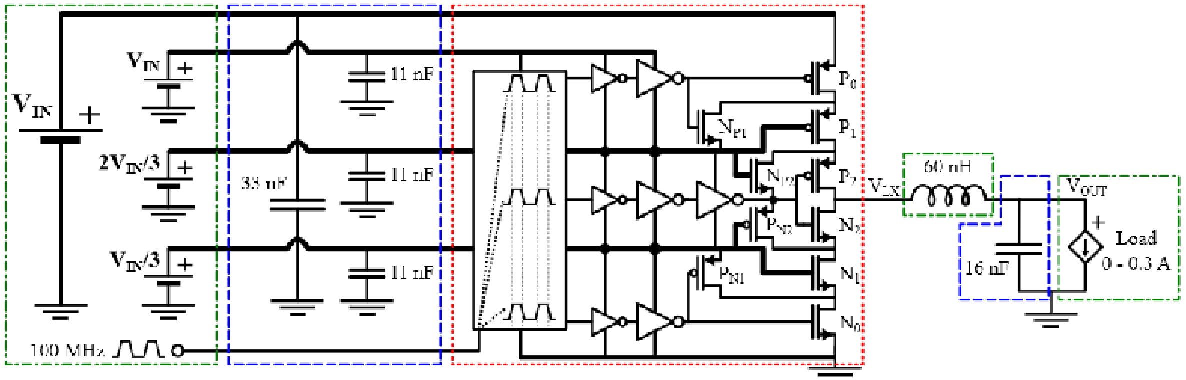
3- Energy / Power Quantities



Sensors need a small amount of energy with high activation rate → Supercapacitors are better suited for such application (no energy waste)

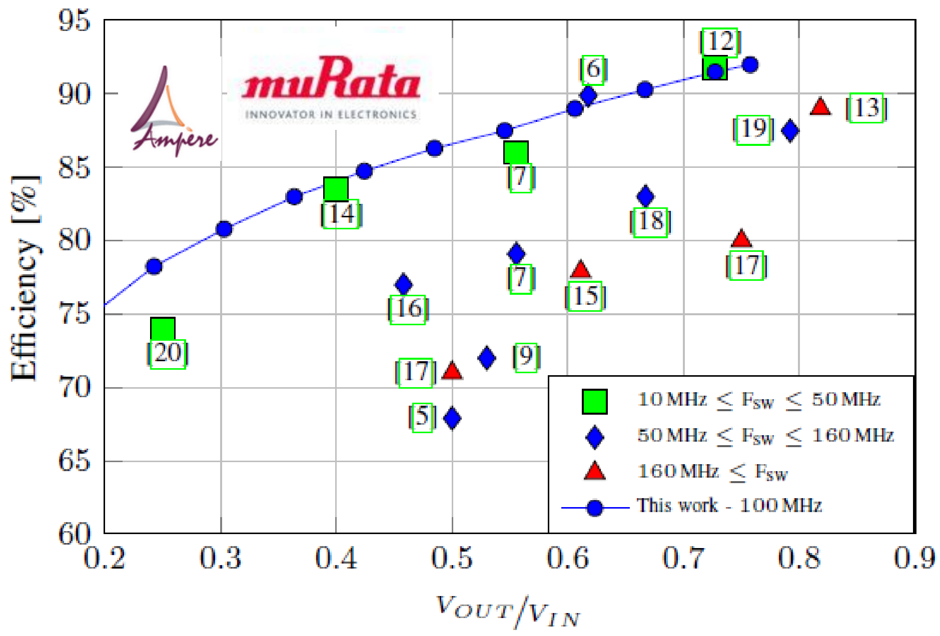
3- Silicon Interposer with integrated DTC

HF integrated VRM sub-block demonstrator

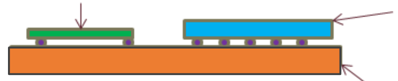


Schematic of the circuit designed in 40 nm CMOS and experimentally verified

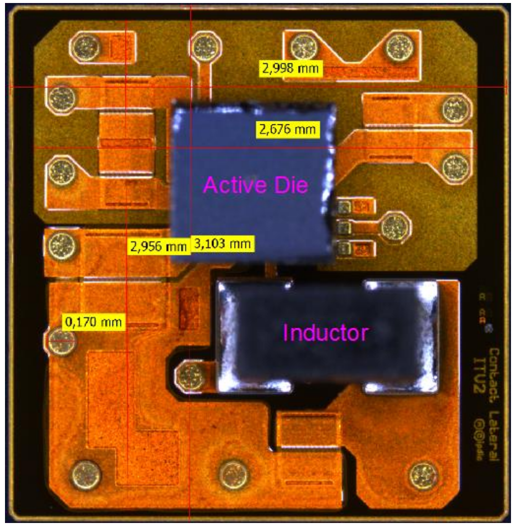
Peak efficiency

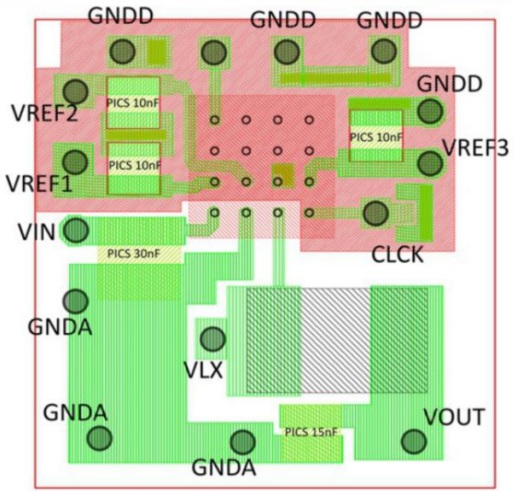


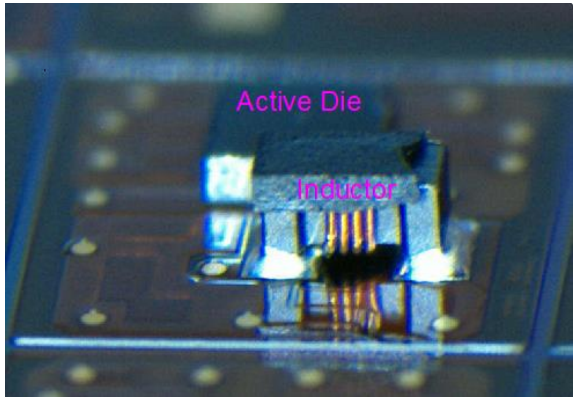
A 100 MHz, 91.5% Peak Efficiency Integrated Buck Converter With a three-MOSFETs Cascode Bridge
Florian Neveu & Al., IEEE TRANSACTION ON POWER ELECTRONICS



- The active die is 1mm² and the primary designed-for-validation interposer is 3mm by 3mm but is subject to 40% gain in space.
- The inductor is an 0402 SMD standard package soldered next to the active die.
- The active circuit is designed using a 40nm bulk CMOS technology





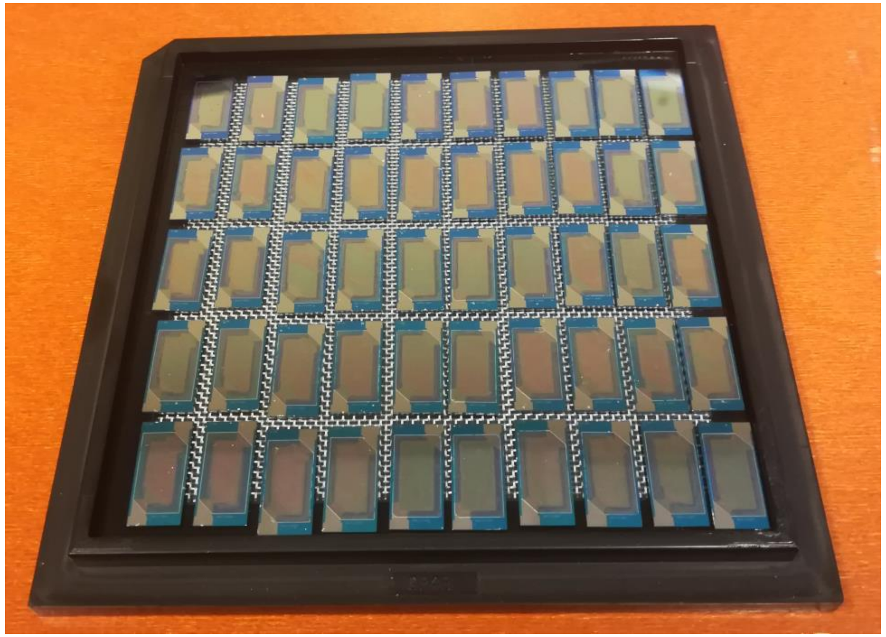


3- Key Benefits

Integrated DTC

- Trench Capacitors placed as close as possible to the I/Os
- High density capacitors / Very low profile
- No derating versus Temperature / voltage / Frequency
- Higher reliability
- Higher efficiency compared to PCB solution
- Increased power Density / Parasitic (ESR/ESL) reduction
- Compatible with assembly standards

3- Solid-state Supercapacitor



50 Supercapacitors

Supercapacitor

- High Power Function / Rapid Charge & Discharge < 0.1s
- 1mF-10 mF capacitance / 3.5V op voltage
- Very Low profile (key differentiator for many applications)
- Low impedance (enhance pulse current handling)
- Safety (no danger of overcharge)
- Easy Assembly (stacking, interconnect, …)
- Long life time (little degradation over 100K of cycles)

3- Key Benefits

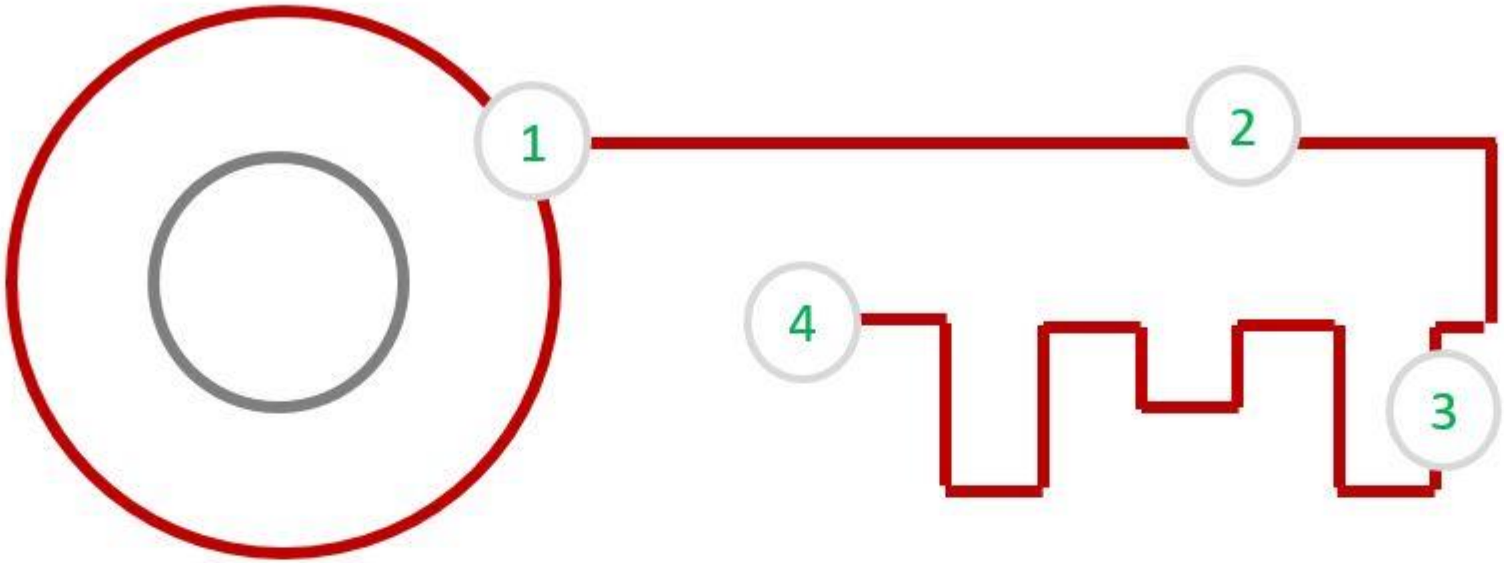
SuperCapacitor

- Reduces voltage drop (better energy and power management)
- High current pulses
- Extended operation temperature range
- No chemical reaction (low heating levels, slower aging and degradation)
- Improved safety (do not explode, no full-charge detection is needed)
- Fewer battery replacements in some applications
- Cost-effective energy storage (Low cost per cycle)

4- Summary / Looking forward

1. Smart dust concept
Sensors are consuming less
Low power harvesting from surrounding environment
RF harvesting is possible

2. Supercapacitors as storage device
<u>Simplified topology</u>
Better energy management (no energy waste)
INCA project: 3D SiP Harvester
<u>Higher Integration</u>



3. 3D Silicon capacitive interposer
<u>Higher efficiency</u>
Integrating Trench capacitors + supercapacitors
Key component to reduce power consumption

4. Next
RF Energy harvester Demonstrator

Acknowledgment

- Special Thanks to:

  - Prof. **Bruno Allard** : *Head of Ampere laboratory; INSA de Lyon - Institut national des Sciences appliquées de Lyon*
  - Dr. **Nicolas Jeanniot** : *Researcher Ampere laboratory ; INSA de Lyon - Institut national des Sciences appliquées de Lyon*
  - Dr. **Frederic Voiron** : *Principal Chief Scientist; MuRata Integrated Passive Solutions*

Q & A

Thanks a lot for your time and attention!

Any questions and/or comments?

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- *Florian Neveu & Al. 'A 100 MHz, 91.5% Peak Efficiency Integrated Buck Converter With a three-MOSFETs Cascode Bridge', IEEE TRANSACTION ON POWER ELECTRONICS*