Industry Session 11: Energy Harvesting

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

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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


1- Designing an EH supplying an electronic device

- Energy Harvester
- Harvested Energy Management
- Storage
- Supplied Energy Management
- Device to supply

Different harvesters for different supplies:

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

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

Converting the harvested energy into a storable one.

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

<table>
<thead>
<tr>
<th>Parameter(^1)</th>
<th>Cellular bands</th>
<th>ISM (industrial, scientific and medical) bands</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>850 MHz</td>
<td>1.7 GHz</td>
</tr>
<tr>
<td>Band</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wavelength, m</td>
<td>0.35</td>
<td>0.18</td>
</tr>
<tr>
<td>Array size, (^2) m</td>
<td>0.35 × 0.35</td>
<td>0.18 × 0.18</td>
</tr>
<tr>
<td>Omni</td>
<td>11.38</td>
<td>15.71</td>
</tr>
<tr>
<td>Direct.</td>
<td>37.51</td>
<td>35.18</td>
</tr>
<tr>
<td>Omni</td>
<td>12.94</td>
<td>14.07</td>
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<tr>
<td>Direct.</td>
<td>140.73</td>
<td>32.47</td>
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<tr>
<td>Omni</td>
<td>159</td>
<td>604</td>
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<tr>
<td>Direct.</td>
<td>2715</td>
<td>12.59</td>
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<tr>
<td>Omni</td>
<td>16.09</td>
<td>26.53</td>
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<tr>
<td>Direct.</td>
<td>53.05</td>
<td>7.20</td>
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<tr>
<td>Omni</td>
<td>6.30</td>
<td>1.66</td>
</tr>
<tr>
<td>Direct.</td>
<td>0.37</td>
<td>N/A</td>
</tr>
</tbody>
</table>

\(^1\) 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) 3µW, 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.

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

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.

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

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.

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

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

The Power of the Future. Today / Tecate PowerBurst Overview
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

- 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.

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

- 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

- 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

- 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
   **Simplified topology**
   Better energy management (no energy waste)
   INCA project: 3D SiP Harvester
   **Higher Integration**

3. 3D Silicon capacitive interposer
   **Higher efficiency**
   Integrating Trench capacitors + supercapacitors
   Key component to reduce power consumption

4. Next
   RF Energy harvester Demonstrator
Acknowledgment

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  ▪ Dr. Frederic Voiron: Principal Chief Scientist; MuRata Integrated Passive Solutions
Thanks a lot for your time and attention!

Any questions and/or comments?
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