Integrated Components for Chip Scale Power Management

Miniature power converters
- High frequency RF power inductors
- CMOS switching / control
- Tunable components
- Mechanical transformers

Monolithic / hybrid integration
- 3D integration for SWAP constrained systems
- Hybrid component integration

Wearable power components
- Stretchable power inductor and components
- Wireless power coupling for integrated soldier power

Power supply on chip

ARMY Applications
- Microrobotics
- Small munitions
- Radios
- Portable electronics
- Soldier power

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Integrated Components for Chip Scale Power Management

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Heterogeneous Die Integration Process

- Electroplated copper holds die in place in silicon wafer
- Simultaneously yields electrical vias with 125-326 $\mu$Ω resistance through 525 $\mu$m thick silicon handling wafer

Corner Alignment Notches

- Corner notches give hand-placed lateral alignment within 20 $\mu$m

Topside Pad Alignment

- Frontside 3 layer 10 $\mu$m copper with spray-coated AZ4999 for interconnects and passives

Planarity

- Frontside alignment against photoresist-coated wafer for micron-level planarity over mm-scale die

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- Fully-integrated (mm$^3$) bi-directional converter driving ARL mm-scale robot wing
  - PZT actuated, 10 V, DC-500 Hz, CL=2-5 nF
- Design, model & test of switched-capacitor ladder converter w/ new voltage distributed nested bootstrap technique
- Fabricated in 0.13 µm 1.2/3.3V triple-well CMOS
- Demonstrated 3x voltage boost
- Achieved 77% efficiency with 800 µW load

**Measured Efficiency**

**Step Response to 5 nF**


**Die Photo**

**Nested-Bootstrapped Switch (NBS) Cells**

**mm$^3$ Converter Driving ARL's Micro-flyer**
Developed analytical models describing both efficiency & voltage gain for piezo-on-silicon (composite) transformers

Measured 6:1 voltage gain and 60% efficiency

~100 mW power through 30 x 70 x 4 µm thick (3 µm SOI) device, leading to > 10 Watts / mm³

Comparison to MEMS resonators

Comparison to commercial PT's

Voltage Gain vs. Efficiency

Voltage Gain

Piezo-on-silicon transformer

Principle

Energy Storage Energy density Limits Theor. Limit
Magnetic field $\sim \mu T$ Magnetic saturation $\sim 10^4$ J/m³
Strain $\sim Y_e$ Fracture $\sim 10^7$ J/m³

Fabricated device

Extensional harmonic

GSG pads

300 µm

Power Handling on Si

5429 Q3 JPTestRes - 3um Si, 10Vb

-15dBm
-10dBm
-5dBm
0dBm
5dBm
10dBm

-35 -30 -25 -20 -15
20*log10(S21) [dB]
Frequency [Hz]

Power density [W/mm³]
PT length [mm]
Commercial PT
PZT only
PZT on silicon
ARL

FOM = k_eff² Q

-15 -10 0 5 10 15
20*log10(S21) [dB]
Frequency [Hz]

Comparison to commercial PT's

• Develop power systems to allow highly efficient wireless power of stretchable systems
• Multilayer inductors based on liquid metal galinstan for 150%+ strain
  – 250 nH stacked spiral and 55 nH solenoid
• Characterization of space-filling fractal inductors with solid metal traces
  – Lower order fractals similar performance to serpentine, higher order worse
  – 10x lower peak stress than serpentine

Fractal Inductors

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<tr>
<th>Hilbert</th>
<th>Peano</th>
<th>Moore</th>
<th>Sierpinski</th>
<th>Luxberg I</th>
<th>Luxberg II</th>
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Silicone molding process

1. Top mold
2. Cured silicone
3. Botton mold
4. Un-cured silicone

Multilayer Inductors