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Integrated Components for Chip Scale Power Management

Christopher D. Meyer[1], Sarah S. Bedair[1], Jeffrey S. Pulskamp[1], Ronald G. Polcawich[1], Nathan S. Lazarus[1], Iain M. Kierzewski[1], Xue Lin[2], Christopher Dougherty[2], and Rizwan Bashirullah[2]

[1]U.S. Army Research Laboratory
[2]University of Florida

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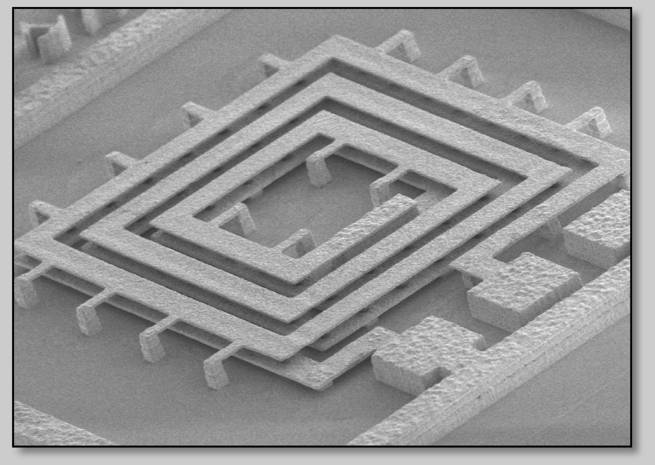
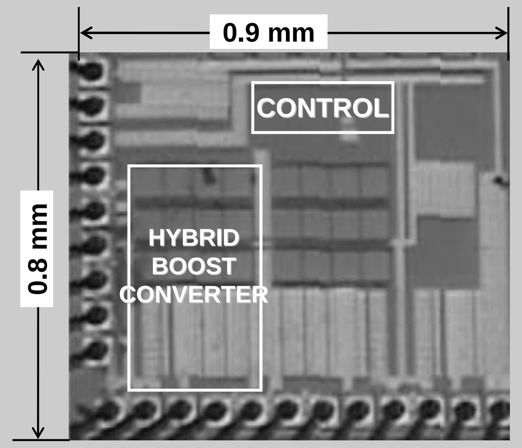
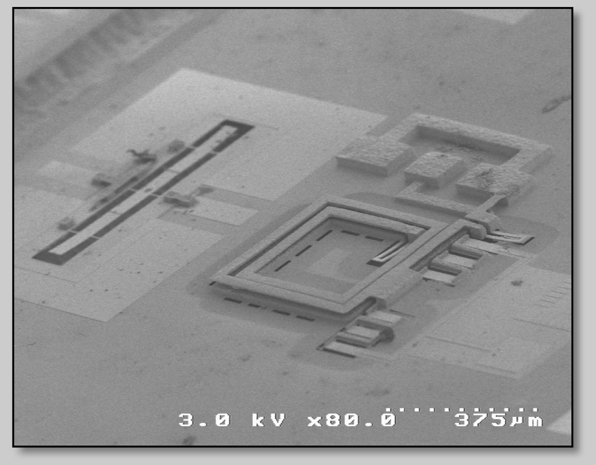
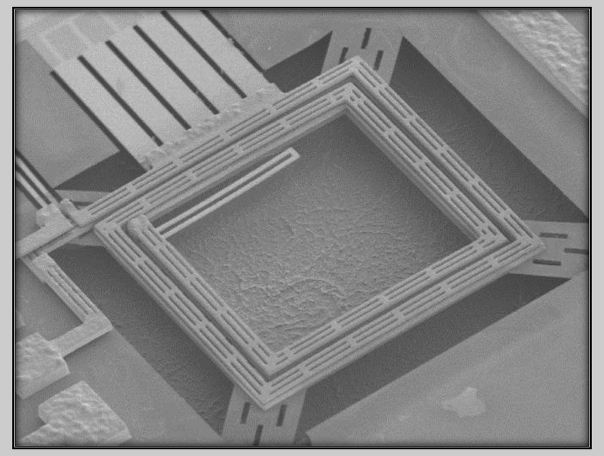
Miniature power converters


High frequency RF power inductors

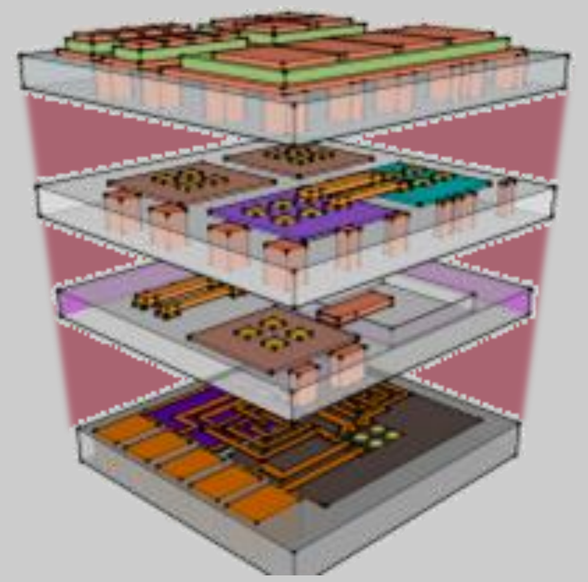


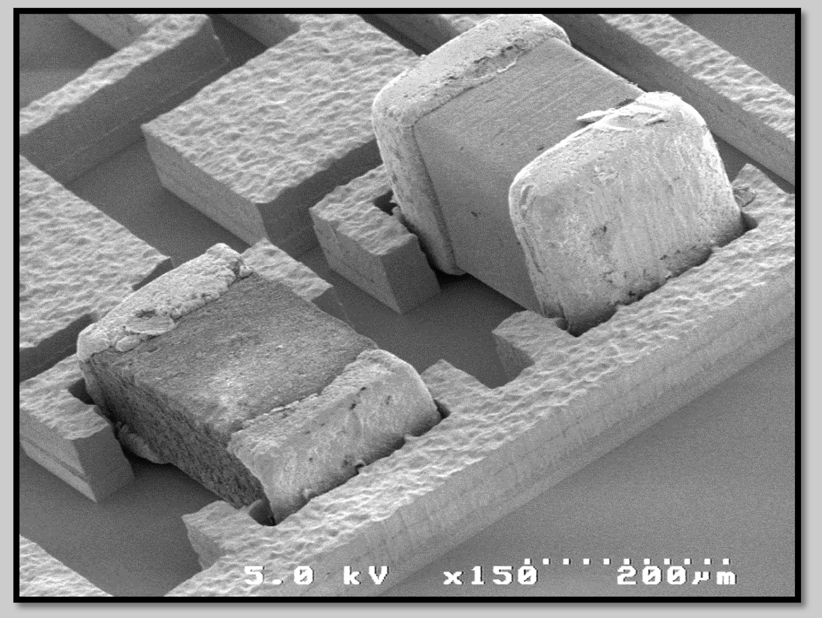
CMOS switching / control

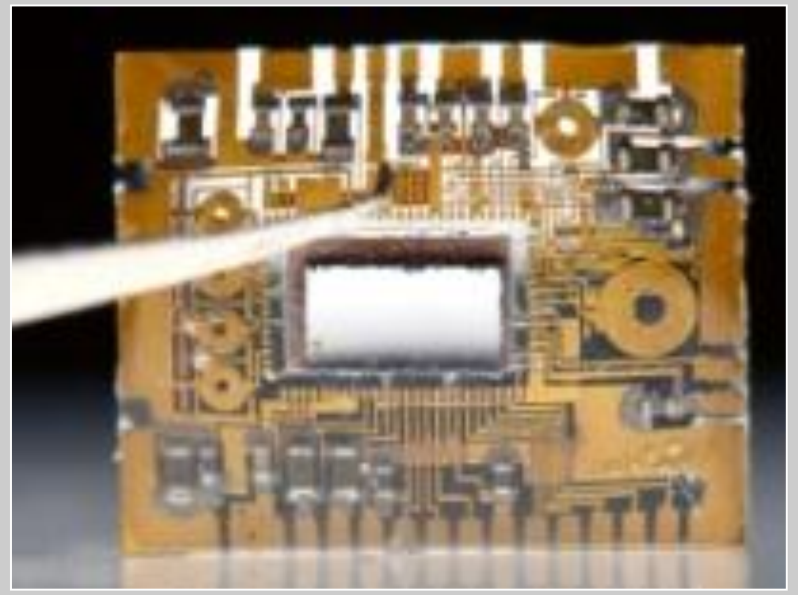

Tunable components


Mechanical transformers

Monolithic / hybrid integration


3D integration for SWAP constrained systems


Hybrid component integration



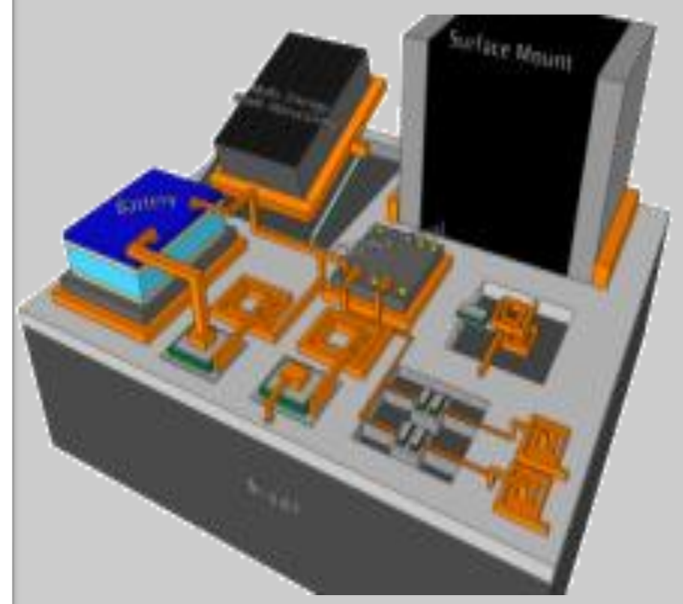
Wearable power components


Stretchable power inductor and components


Wireless attachment points

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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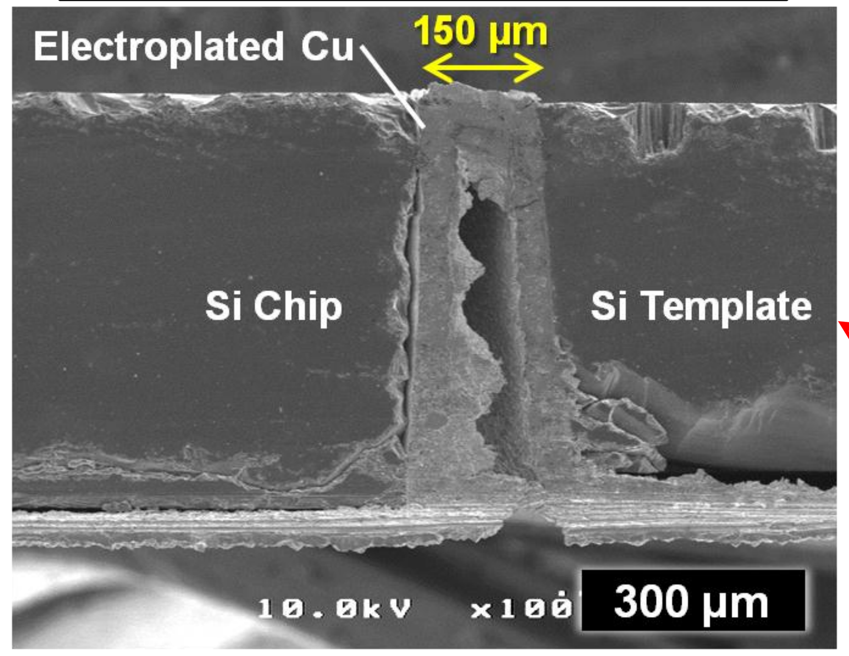
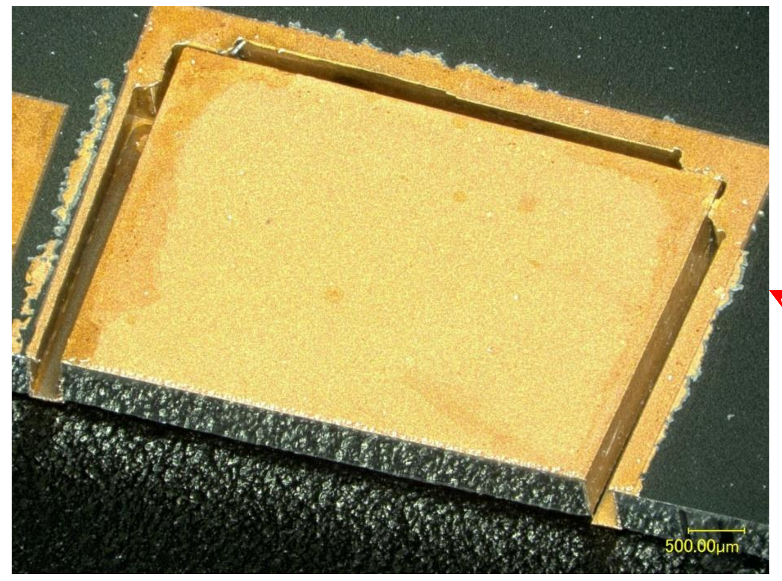
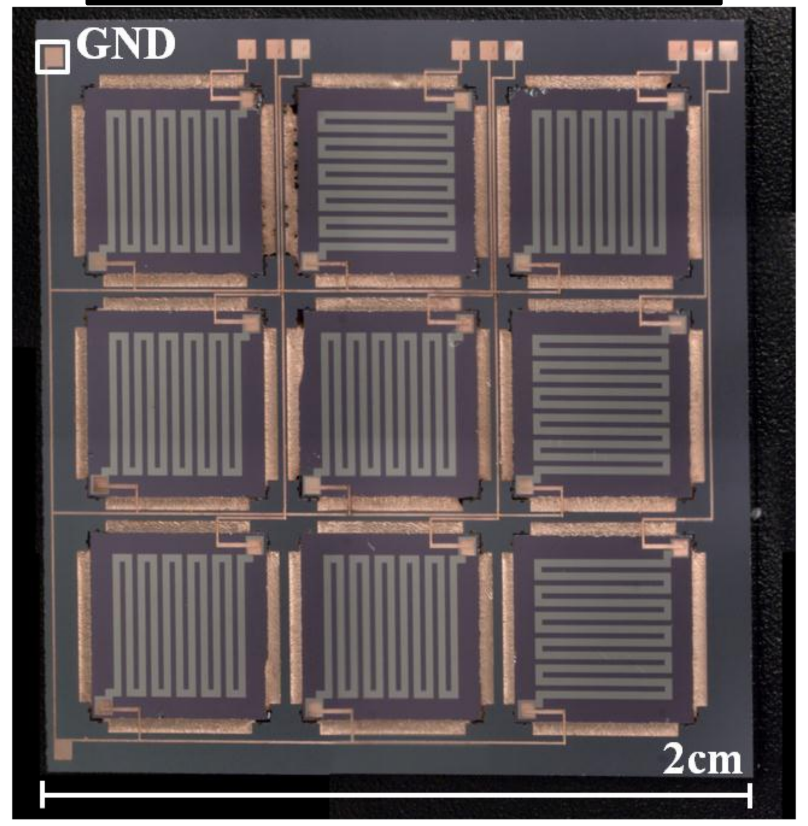
Hollow Trench Vias



Backside Copper



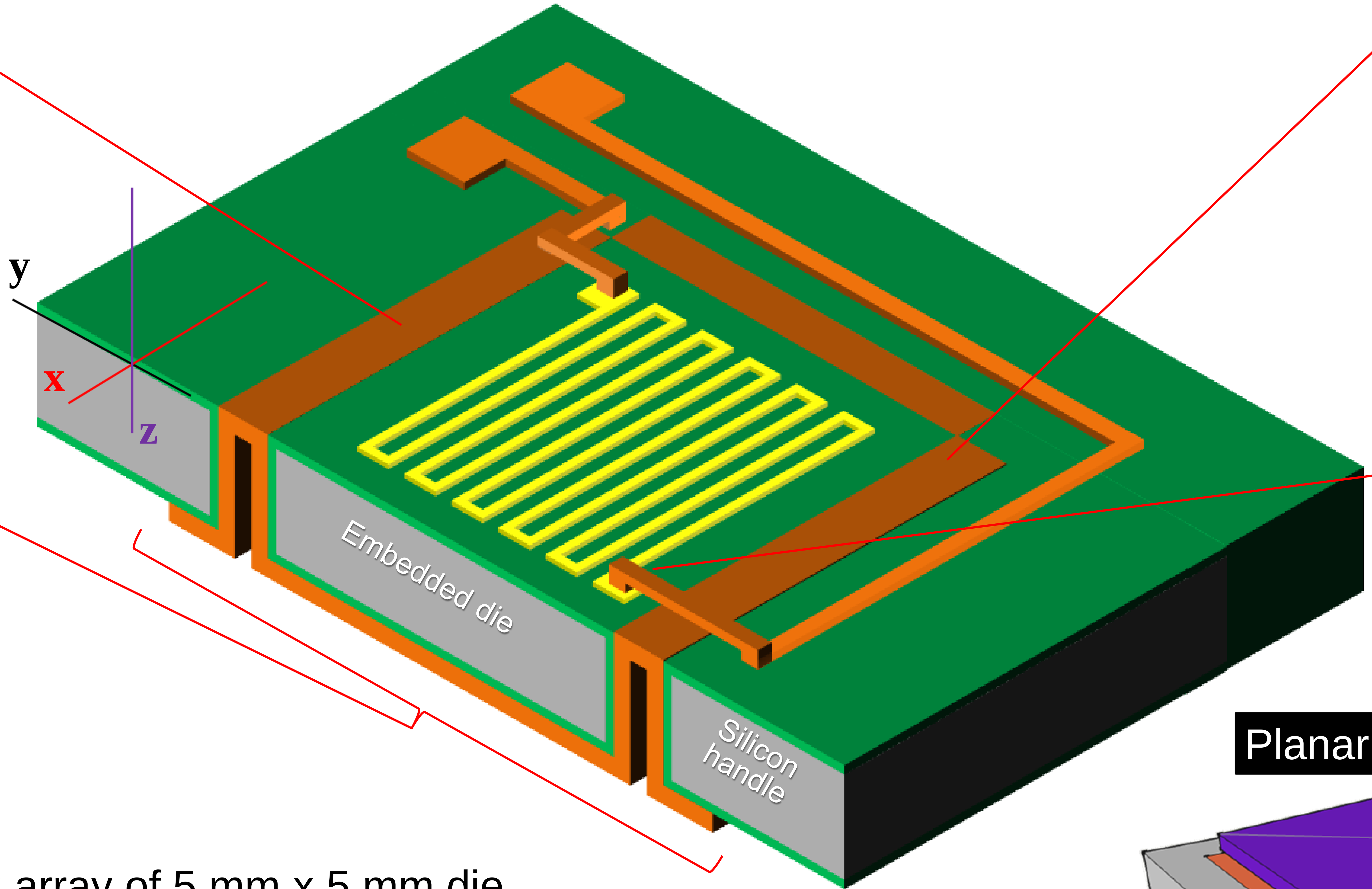
Heater Die Array



- 3x3 array of 5 mm x 5 mm die
- 200 Ω surface heaters
- 280 µm inter-die spacing

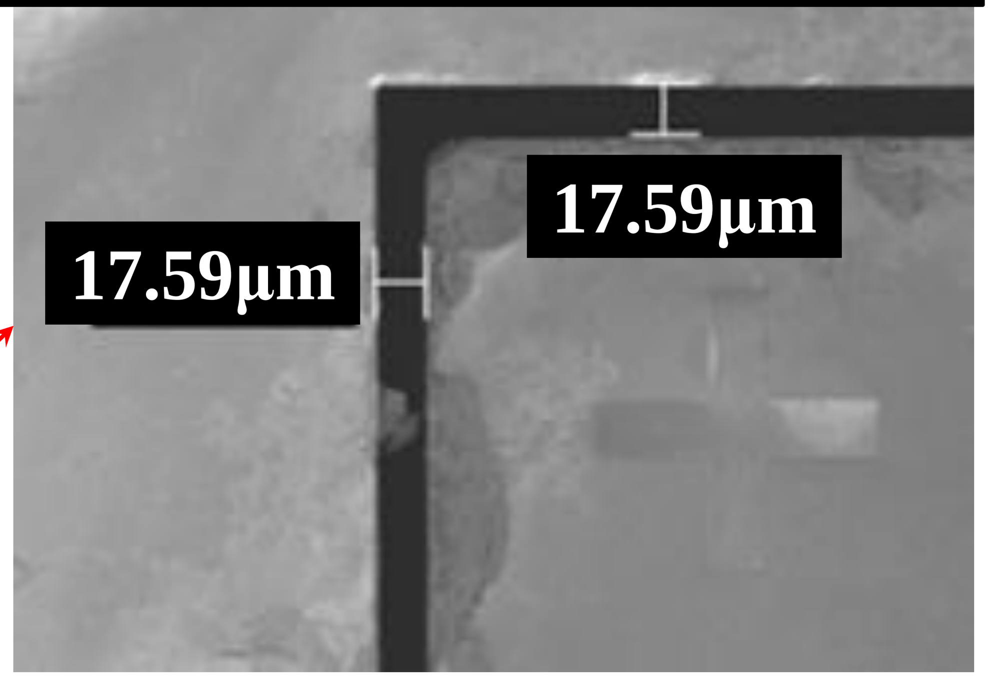
Heterogeneous Die Integration Process

- Electroplated copper holds die in place in silicon wafer
- Simultaneously yields electrical vias with 125-326 µΩ resistance through 525 µm thick silicon handling wafer



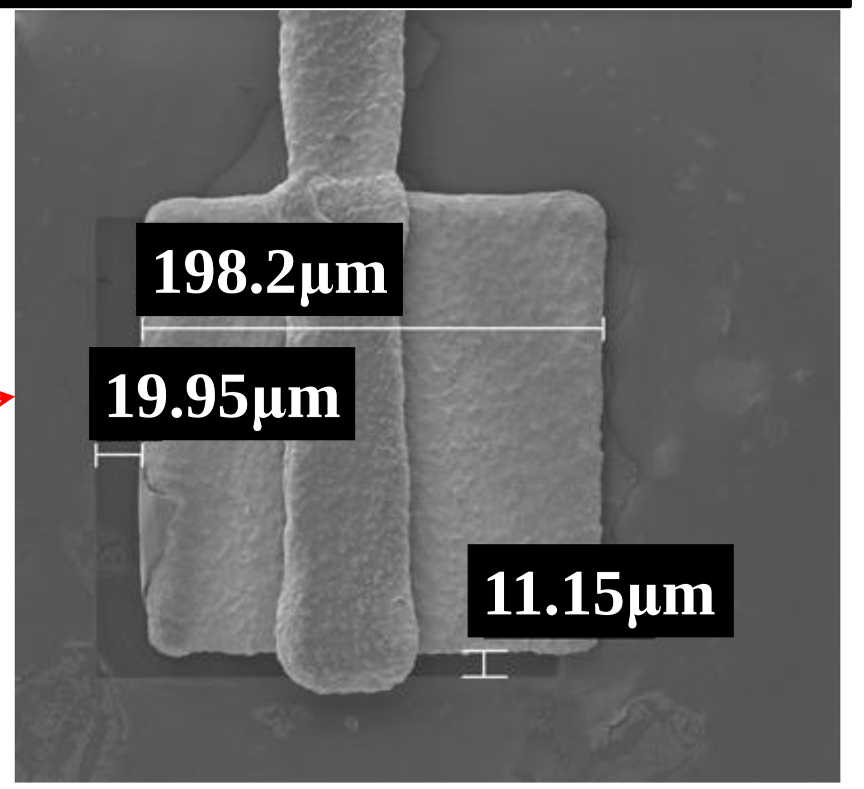
CD Meyer et al., "Heterogeneous Chip Integration into Silicon Templates by Through-Wafer Copper Electroplating," in *ECS Transactions*, vol. 45, no. 6, pp. 163-169, 2012.

Corner Alignment Notches



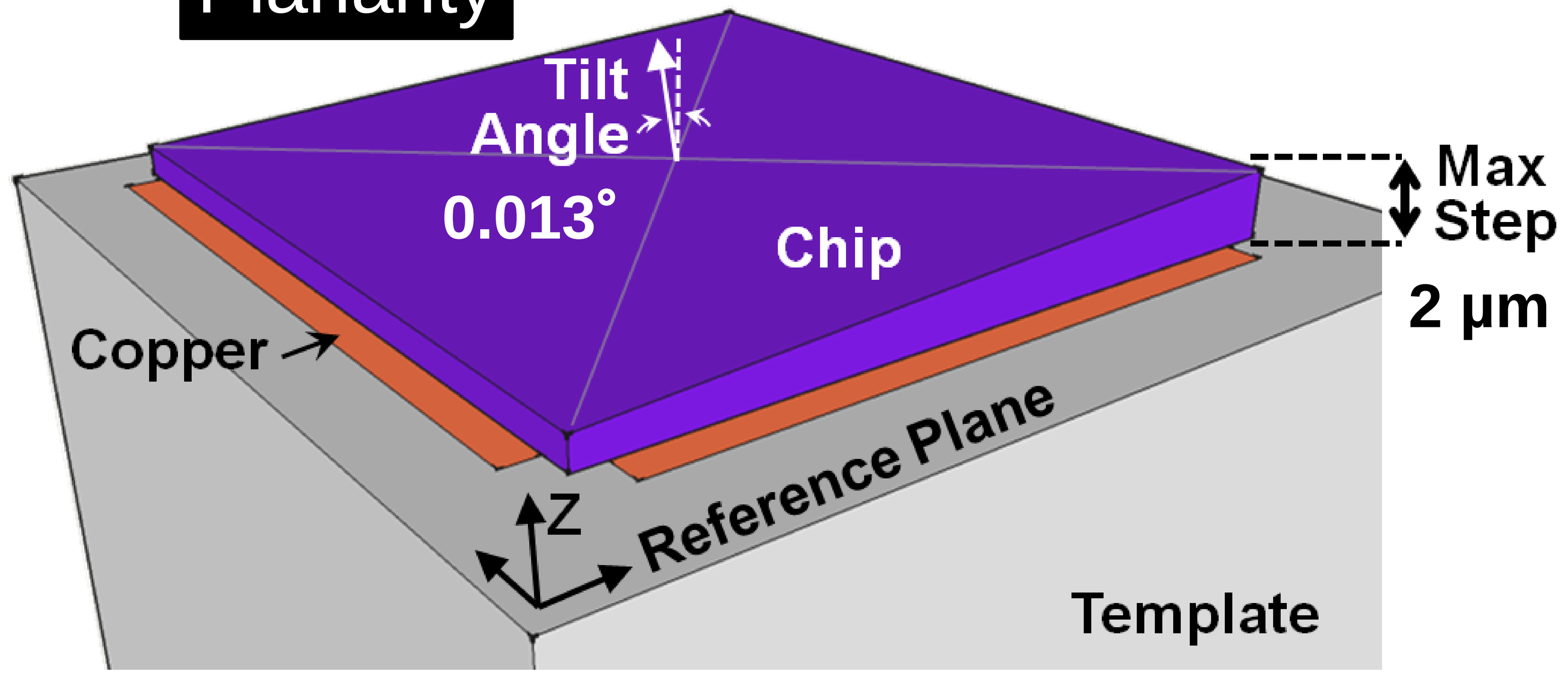
- Corner notches give hand-placed lateral alignment within 20 µm

Topside Pad Alignment



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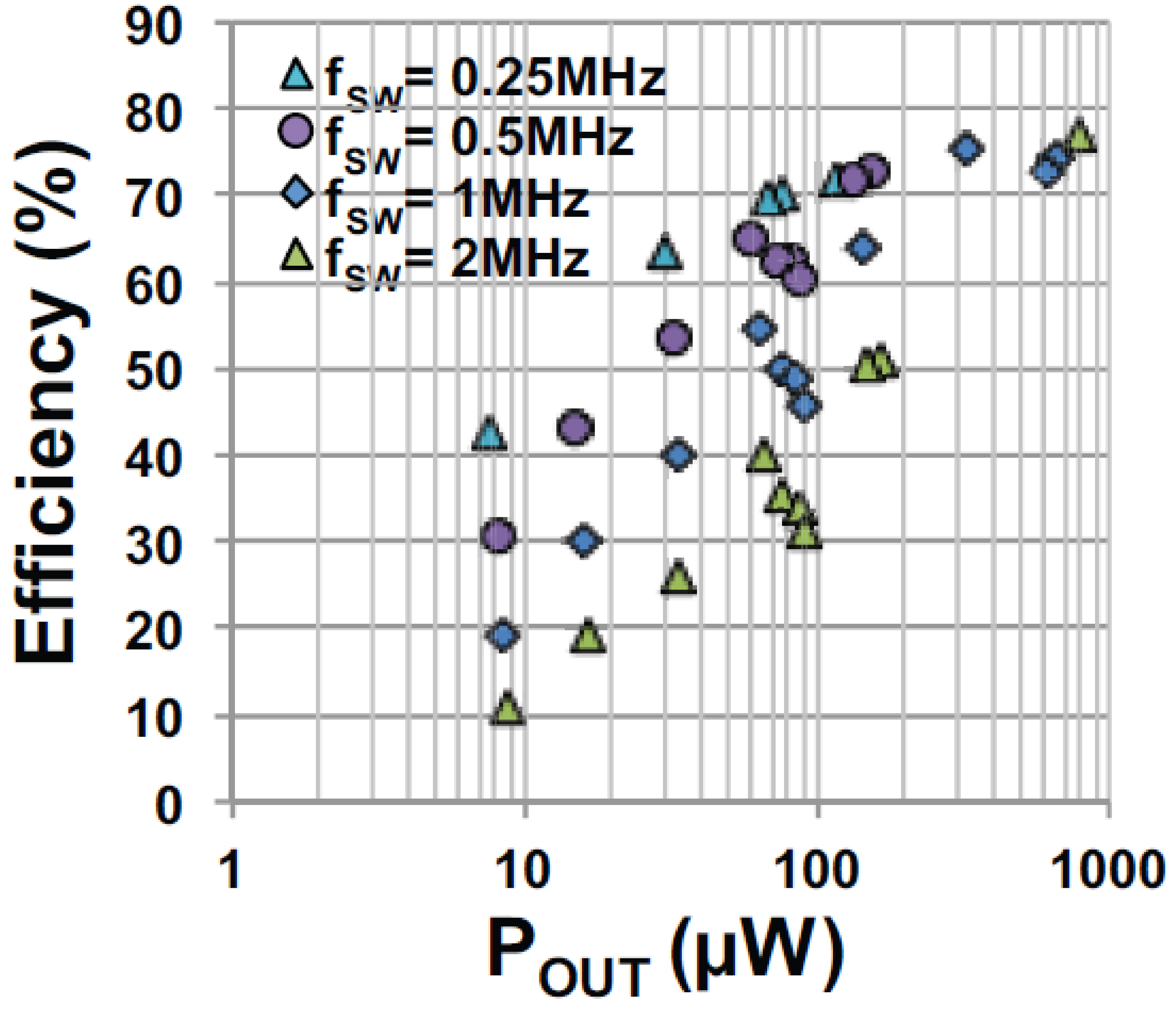
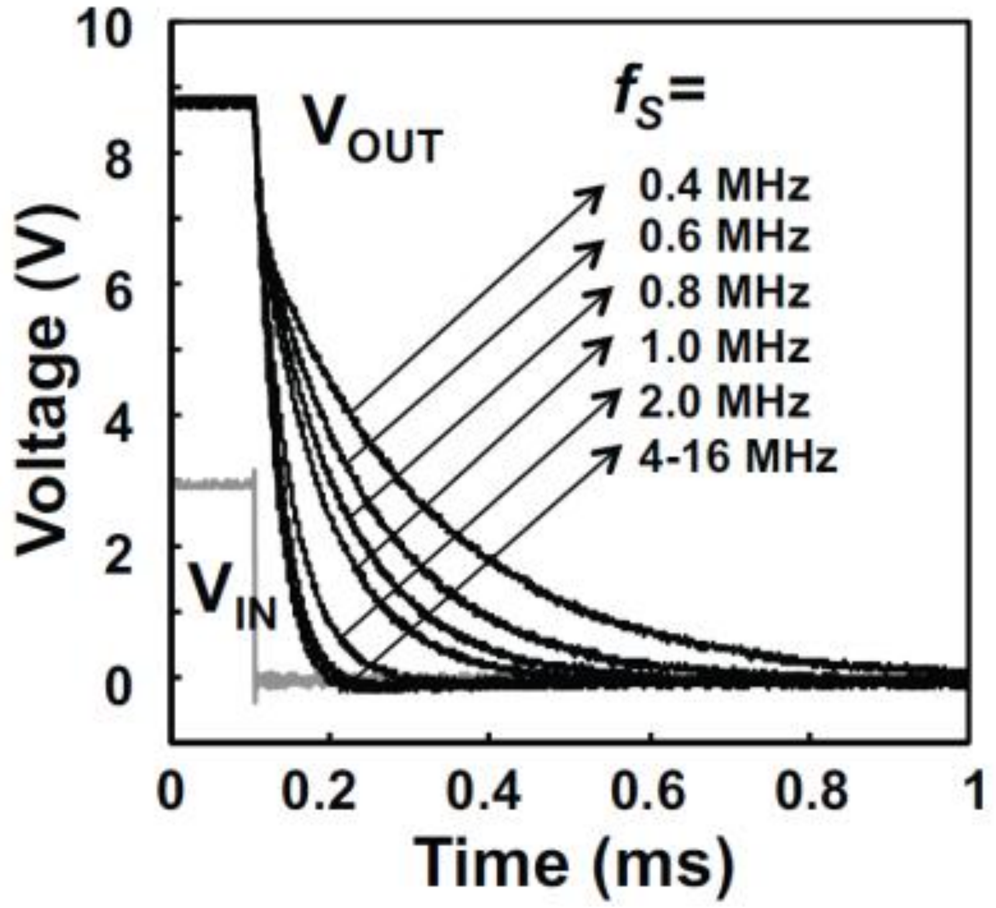
- Fully-integrated (mm^3) bi-directional converter driving ARL mm-scale robot wing
  - PZT actuated, 10 V, DC-500 Hz, CL=2-5 nF
- Design, model & test of switched-capacitor ladder converter w/ new voltage distributed nested bootstrap technique
- Fabricated in 0.13 µm 1.2/3.3V triple-well CMOS
- Demonstrated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

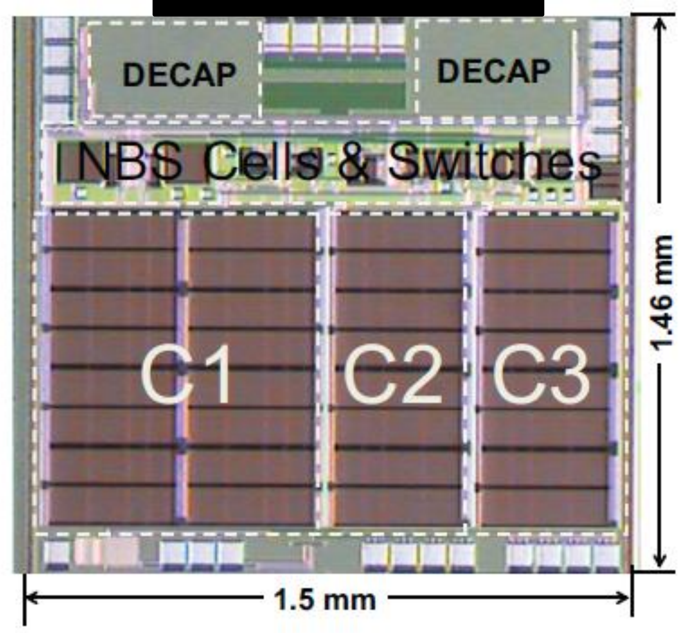
Measured Efficiency



Step Response to 5 nF

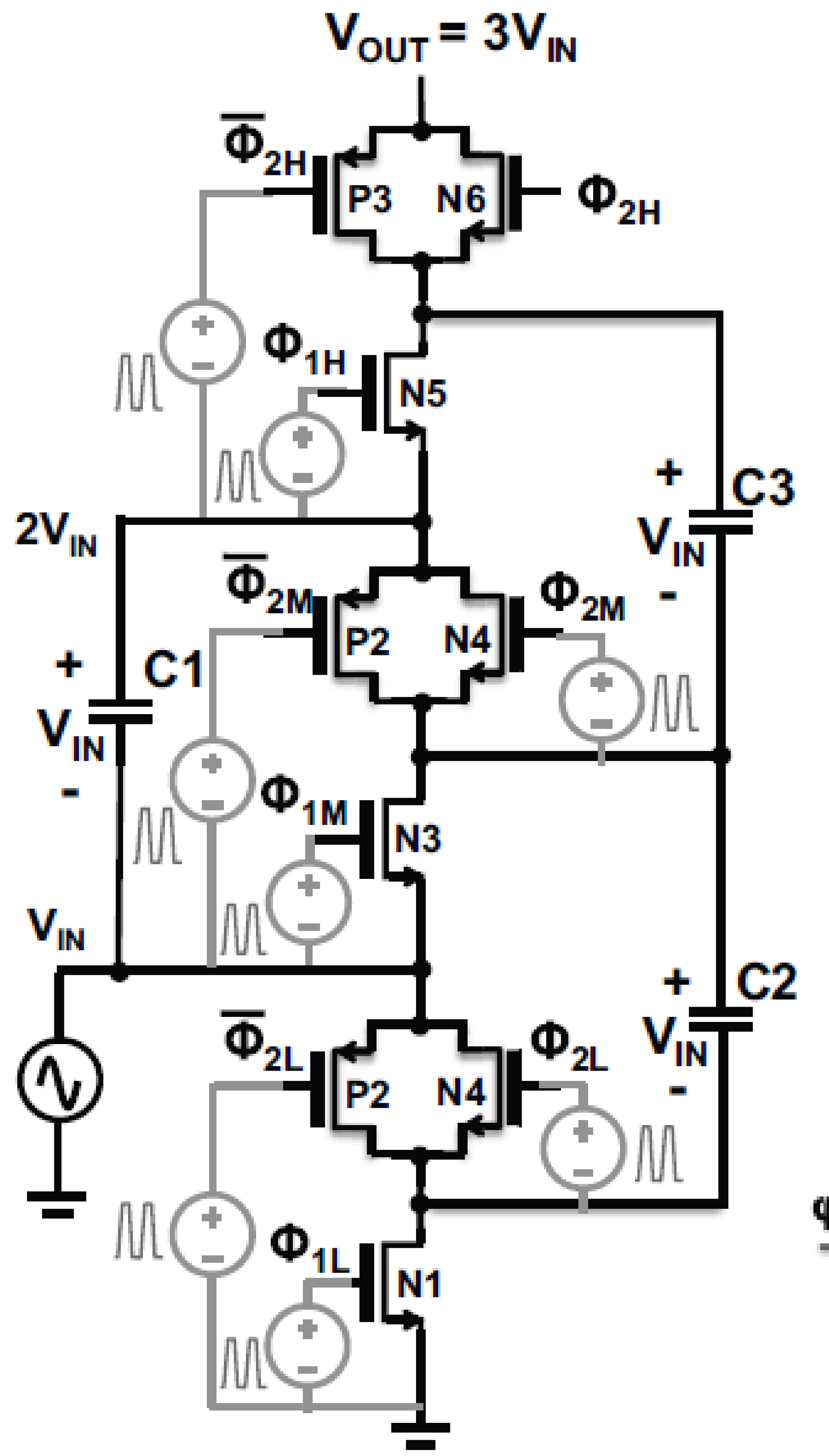


Die Photo

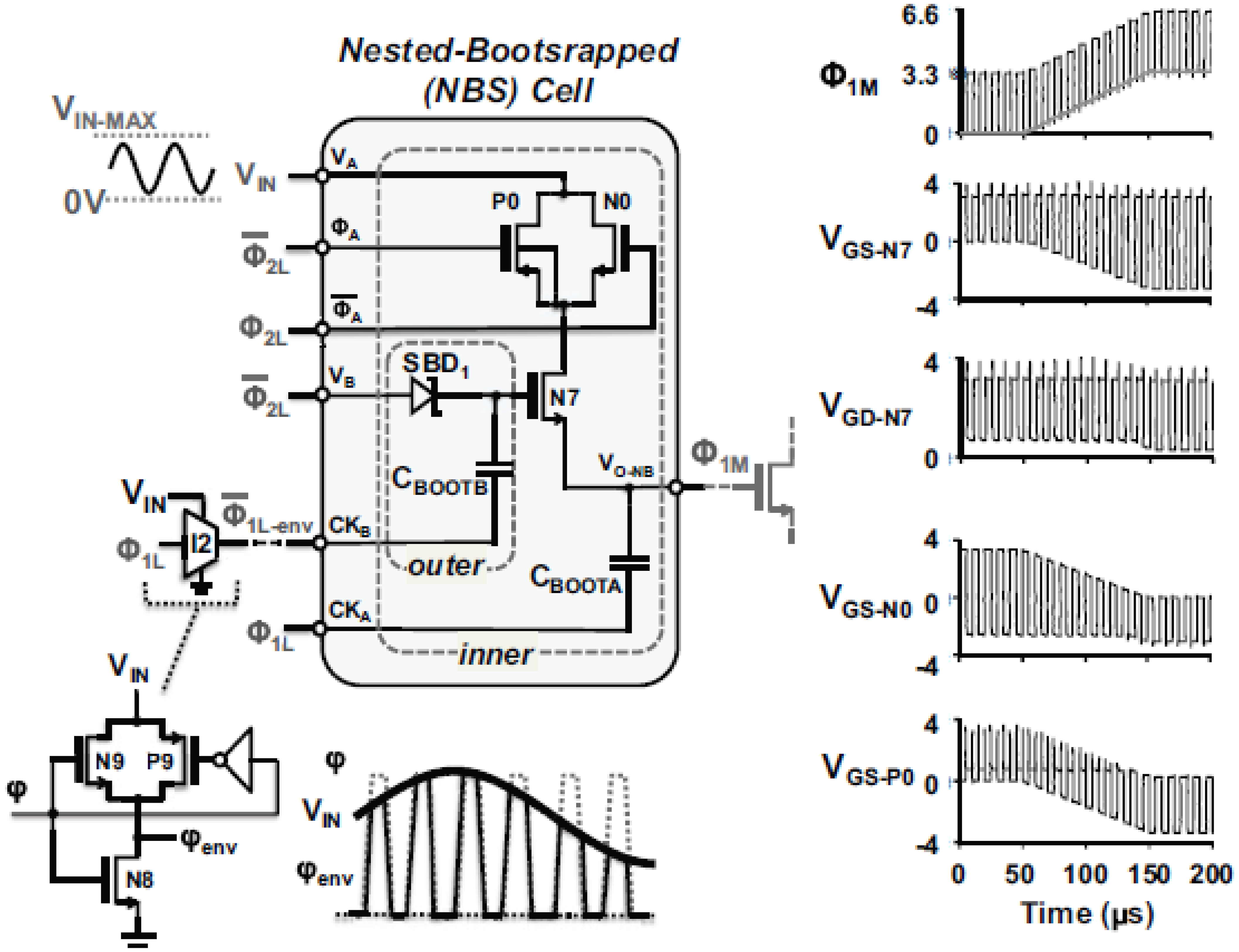


CM Dougherty, et al., "A 10V Fully-Integrated Bidirectional SC Ladder Converter in 0.13µm CMOS using Nested-Bootstrapped Switch Cells," in Symposium on VLSI Circuits Digest of Technical Papers, 2013.

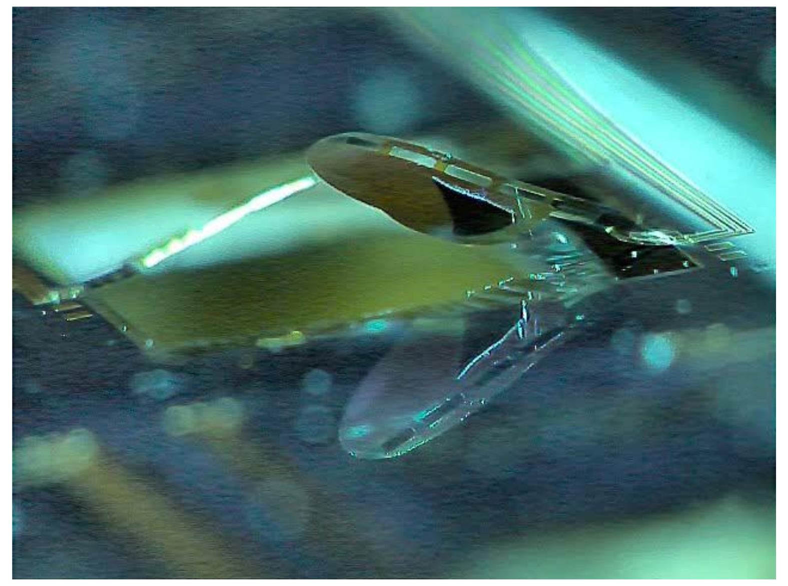
SC Ladder

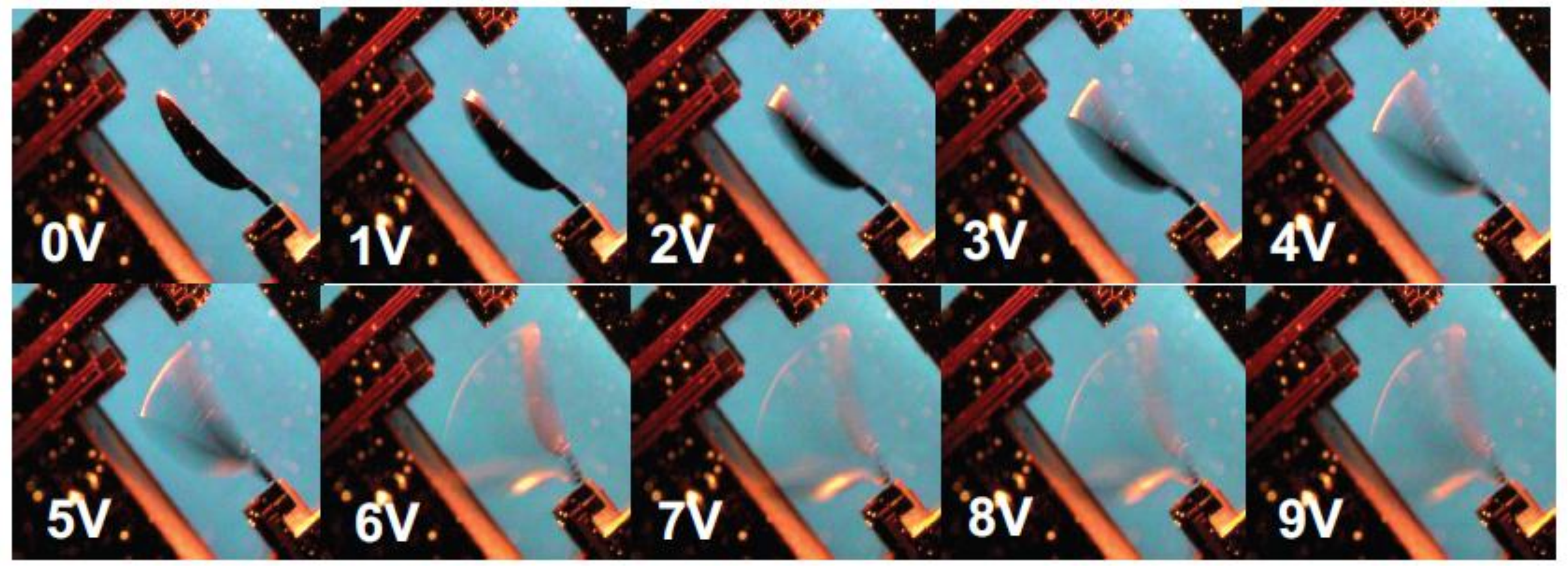


Nested-Bootstrapped Switch (NBS) Cells



mm³ Converter Driving ARL's Micro-flyer





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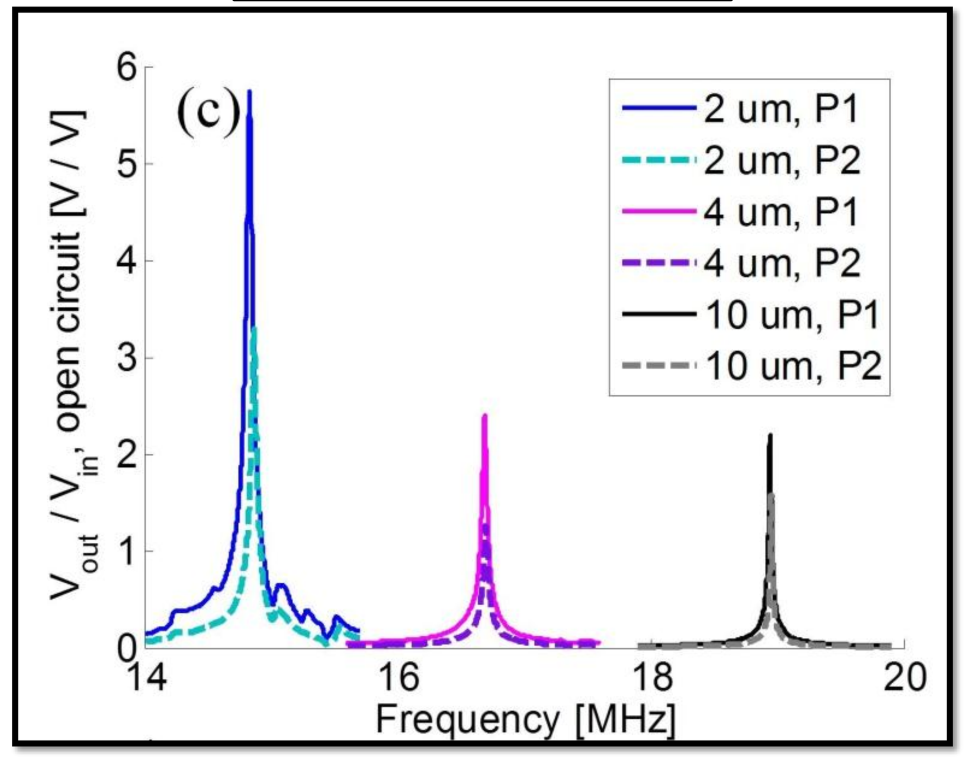
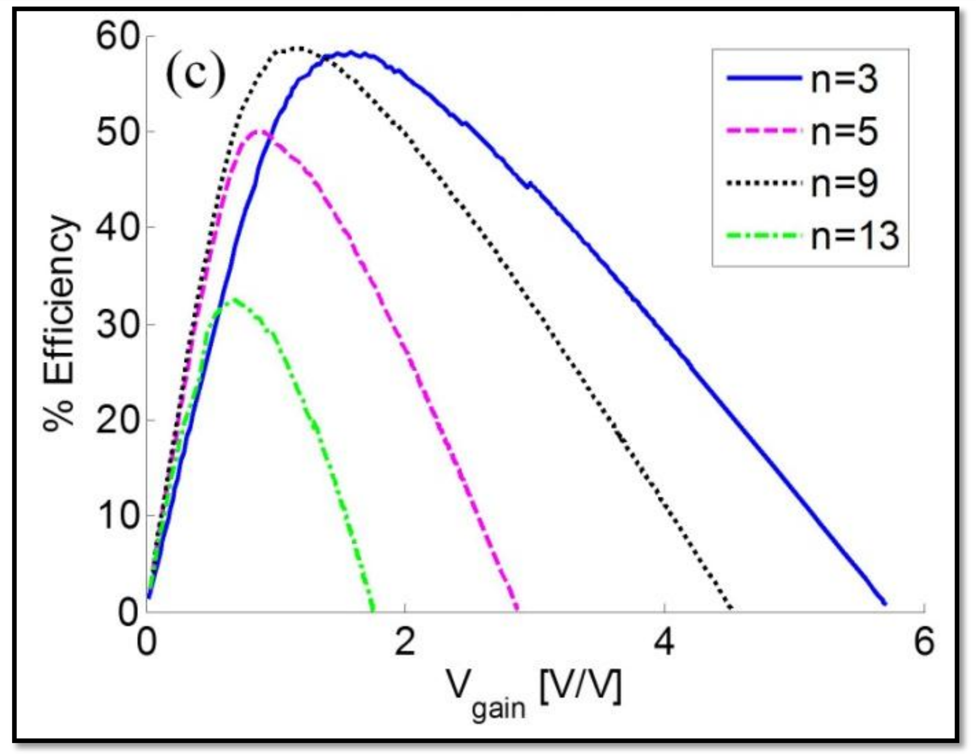
Thin Film Piezo Transformers

- 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 / mm^3

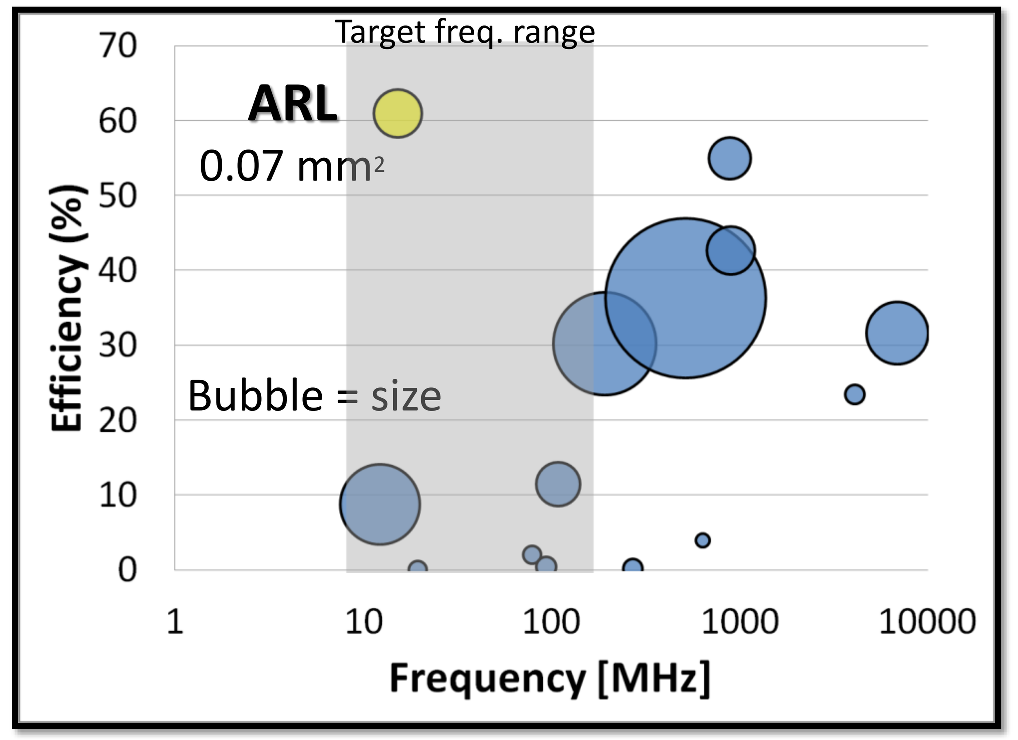
Voltage Gain



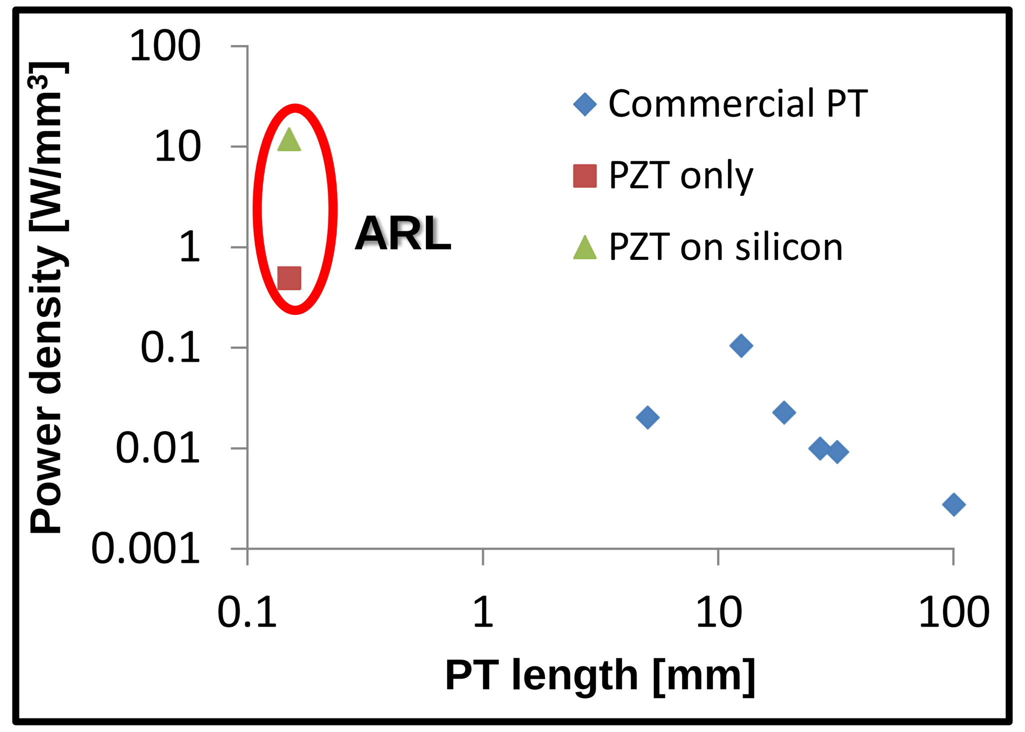
Voltage Gain vs. Efficiency



Comparison to MEMS resonators

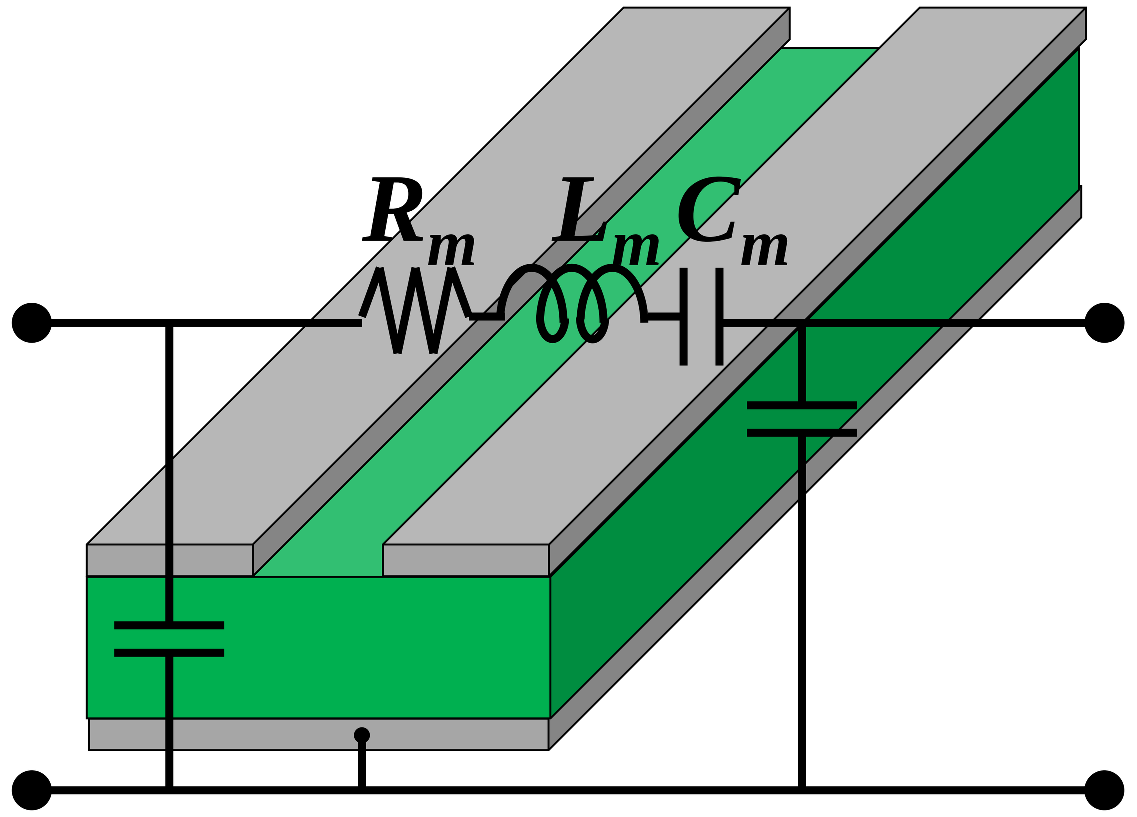


Comparison to commercial PT's

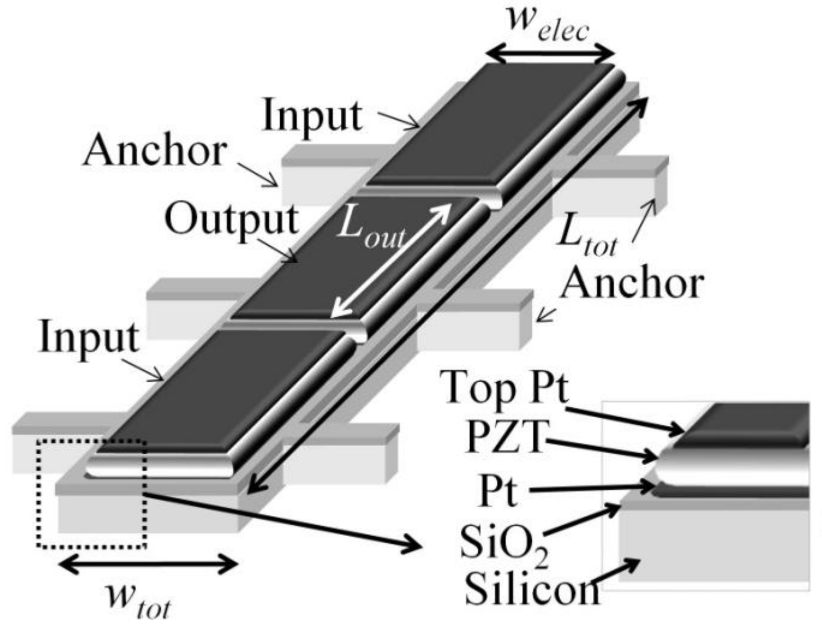


SS Bedair, et al., "Thin-Film Piezoelectric-on-Silicon Resonant Transformers," *IEEE J. MEMS*, vol. 22, no. 6, pp. 1383-1394, 2013.

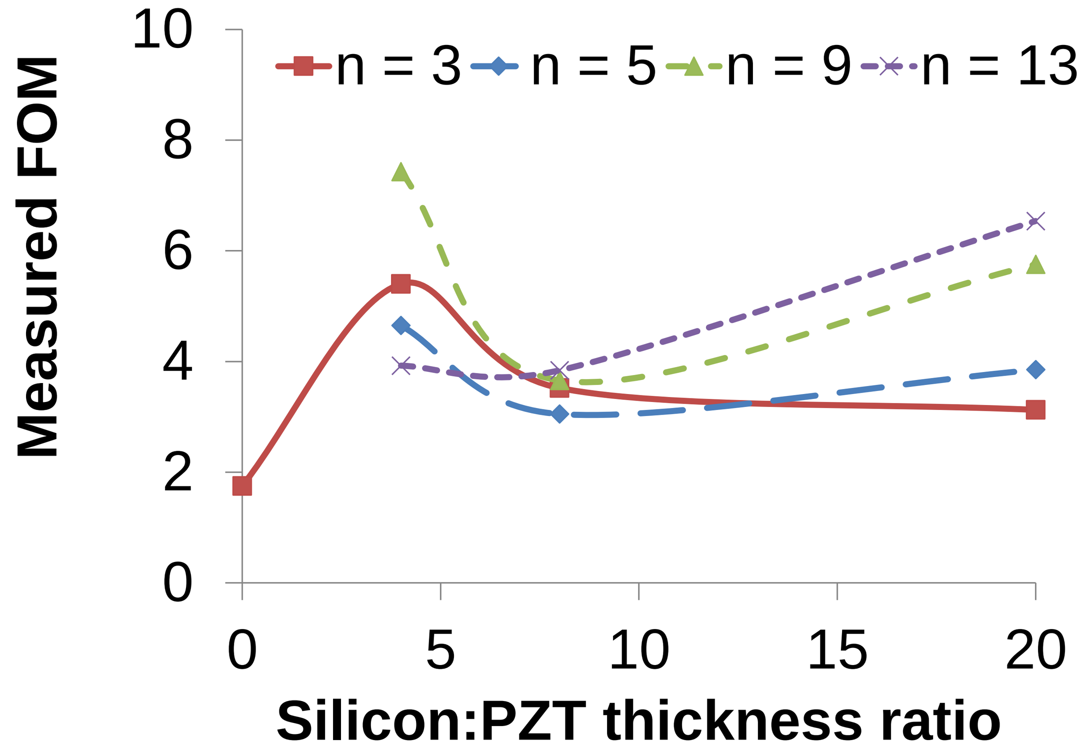
Principle



Piezo-on-silicon transformer



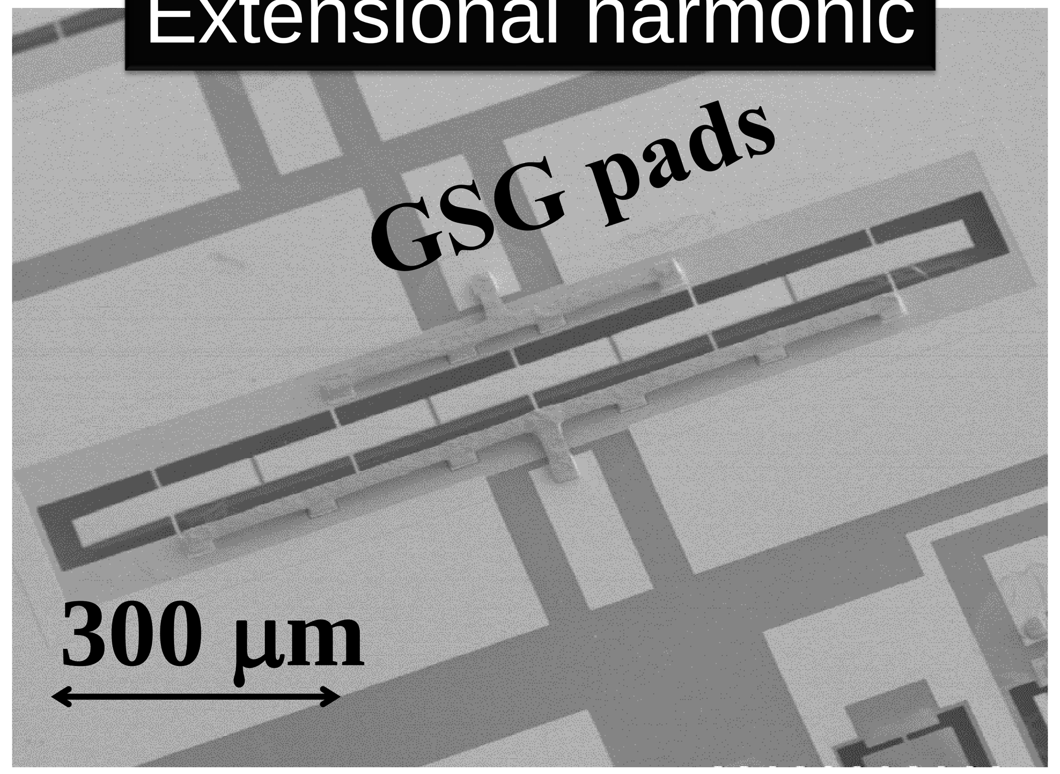
FOM = keff² Q



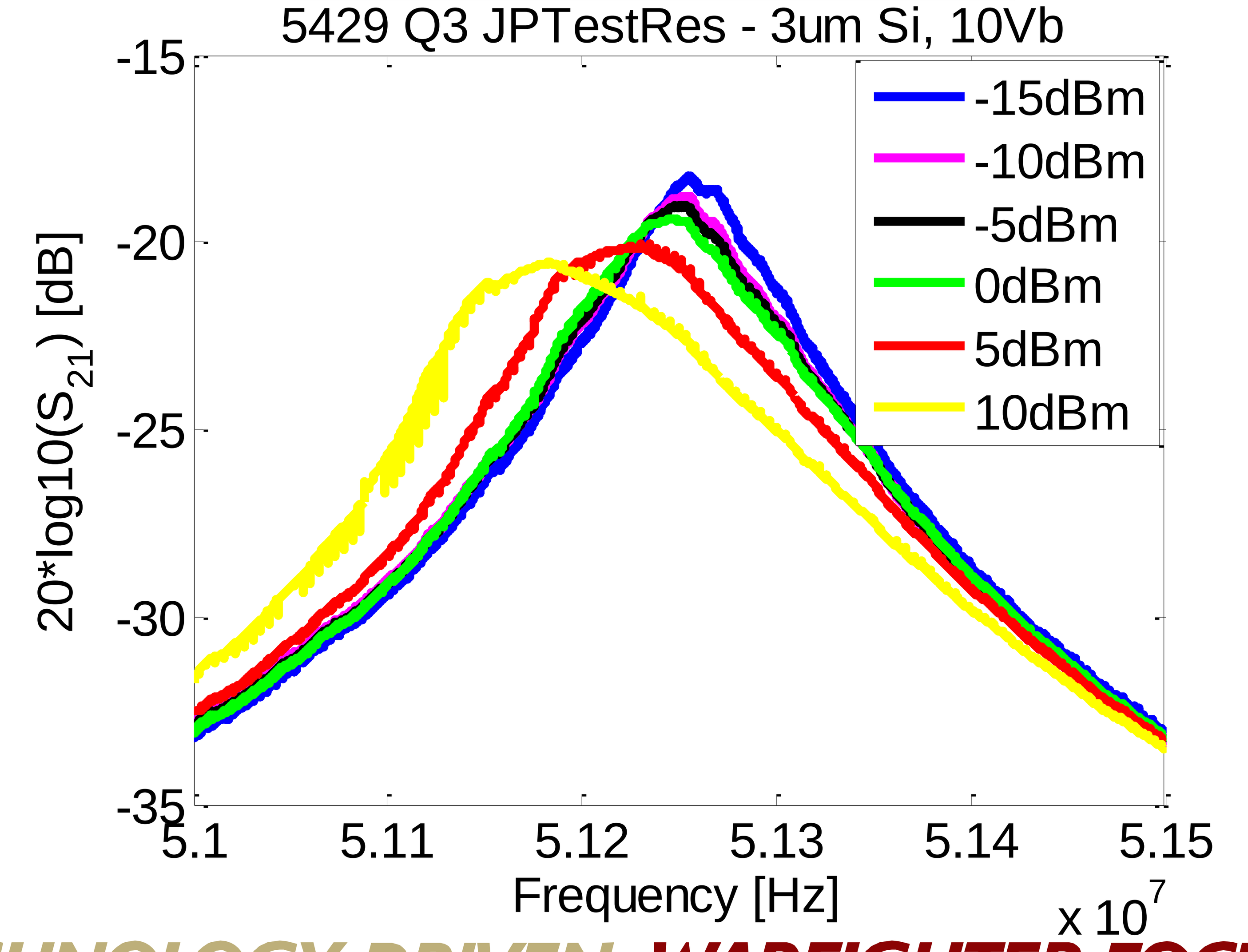
Electromechanical vs. Magnetic

Energy Storage	Energy density	Limits	Theor. Limit
Magnetic field	~μH^2	Magnetic saturation	~10^4 J/m^3
Strain	~$Y\varepsilon^2$	Fracture	~10^7 J/m^3

Fabricated device Extensional harmonic



Power Handling on Si



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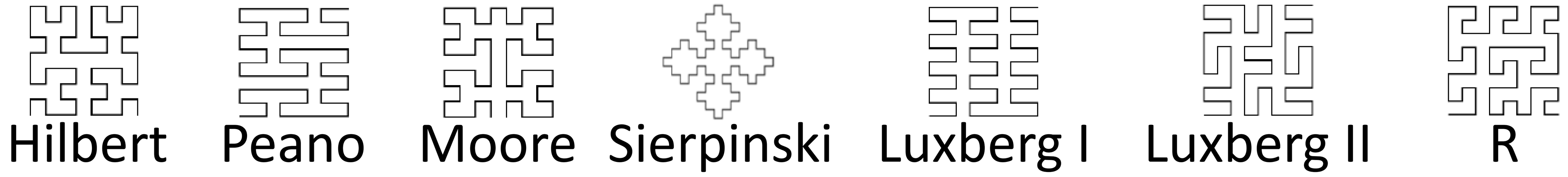
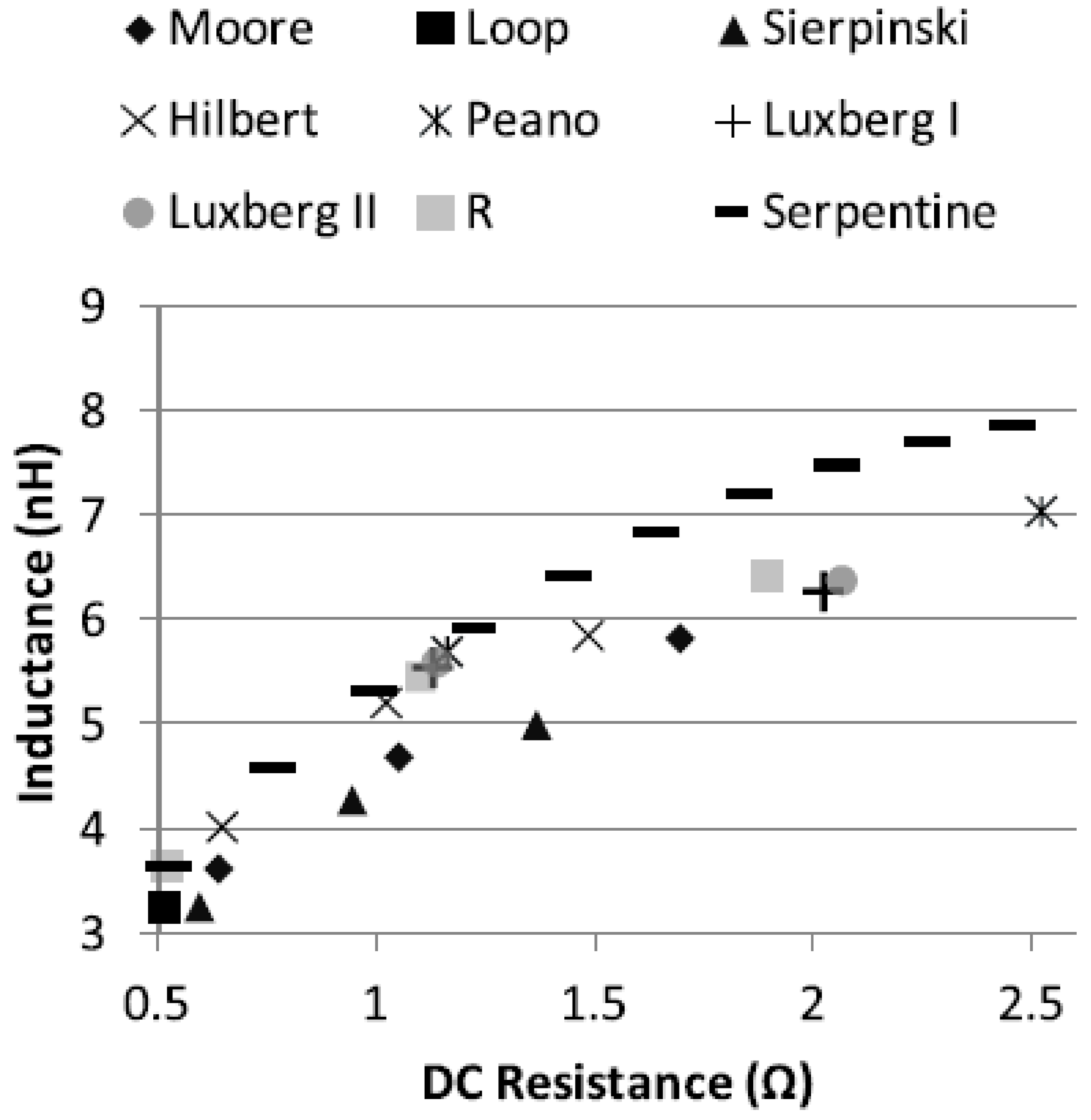
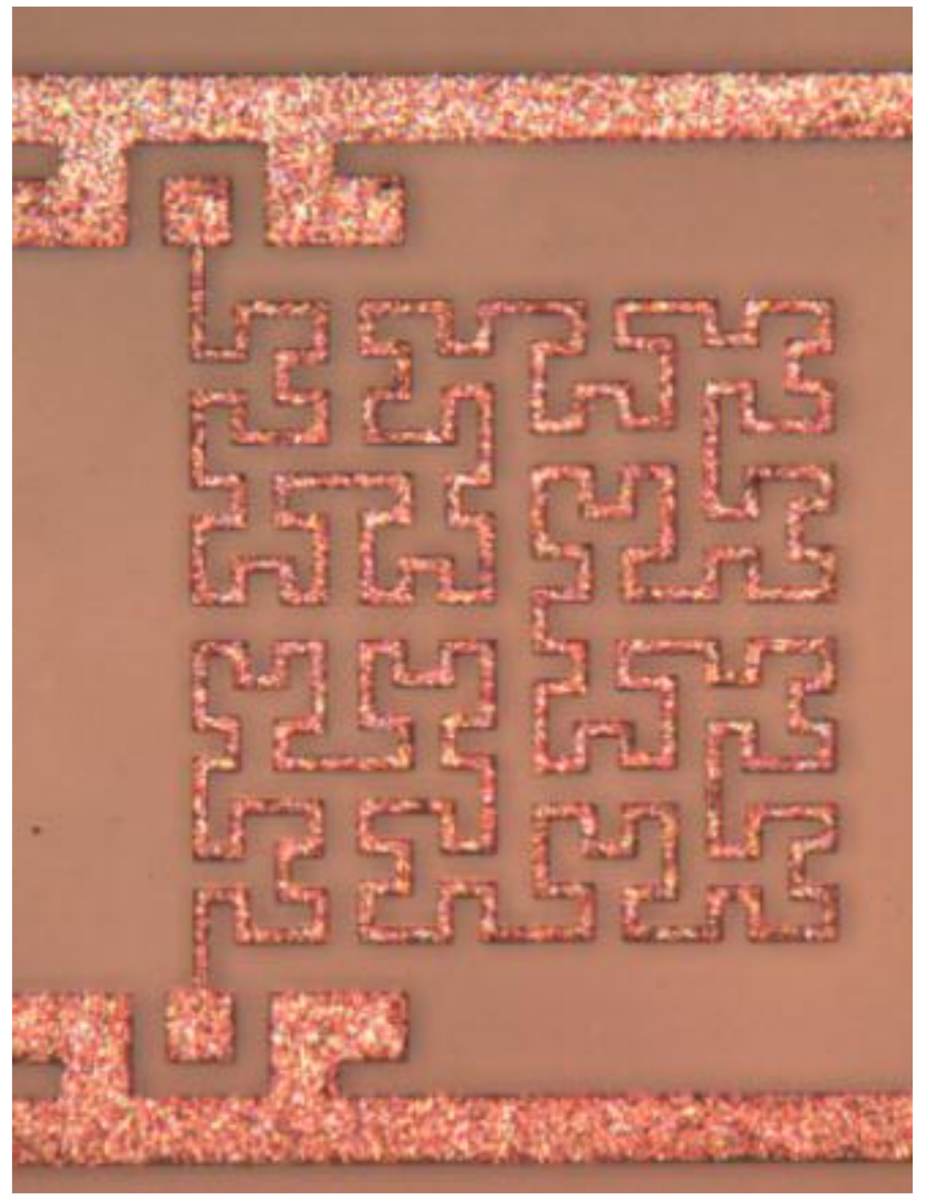
- Develop power systems to allow highly efficient wireless power of stretchable systems
- Multilayer inductors based on liquid metal galinstan for 150%+ strain
  - 250 nH stacked spiral and 55 nH solenoid
- Characterization of space-filling fractal inductors with solid metal traces
  - Lower order fractals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

Fractal Inductors

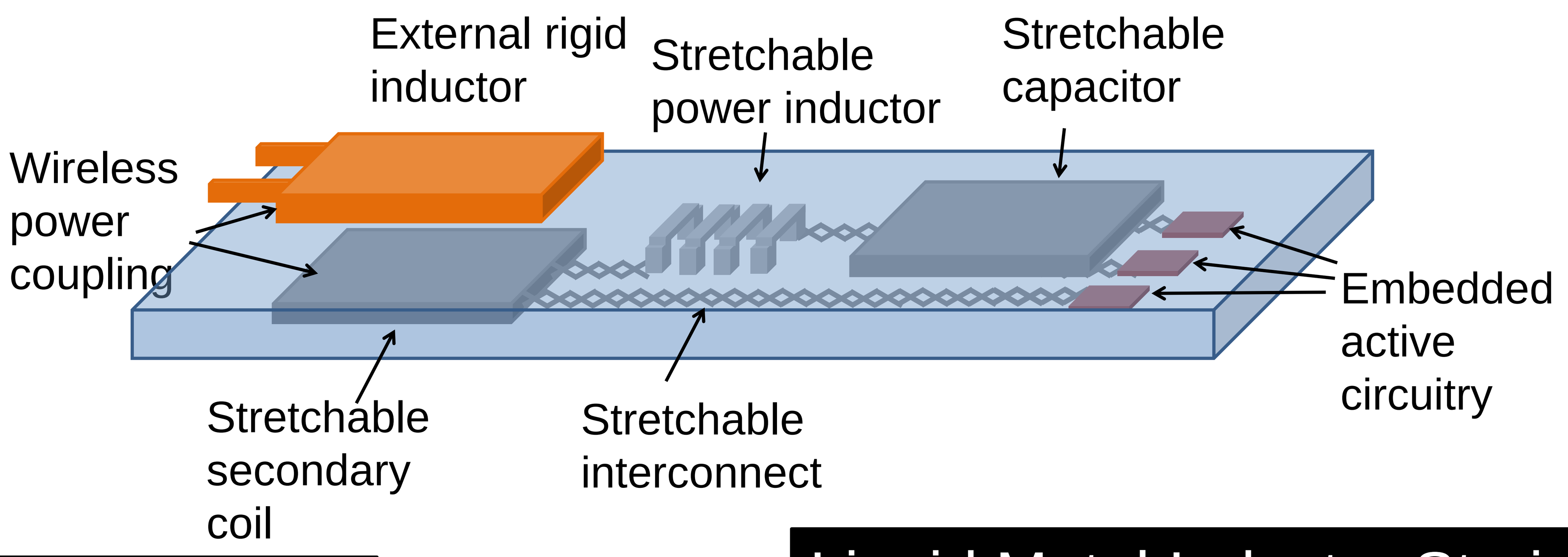




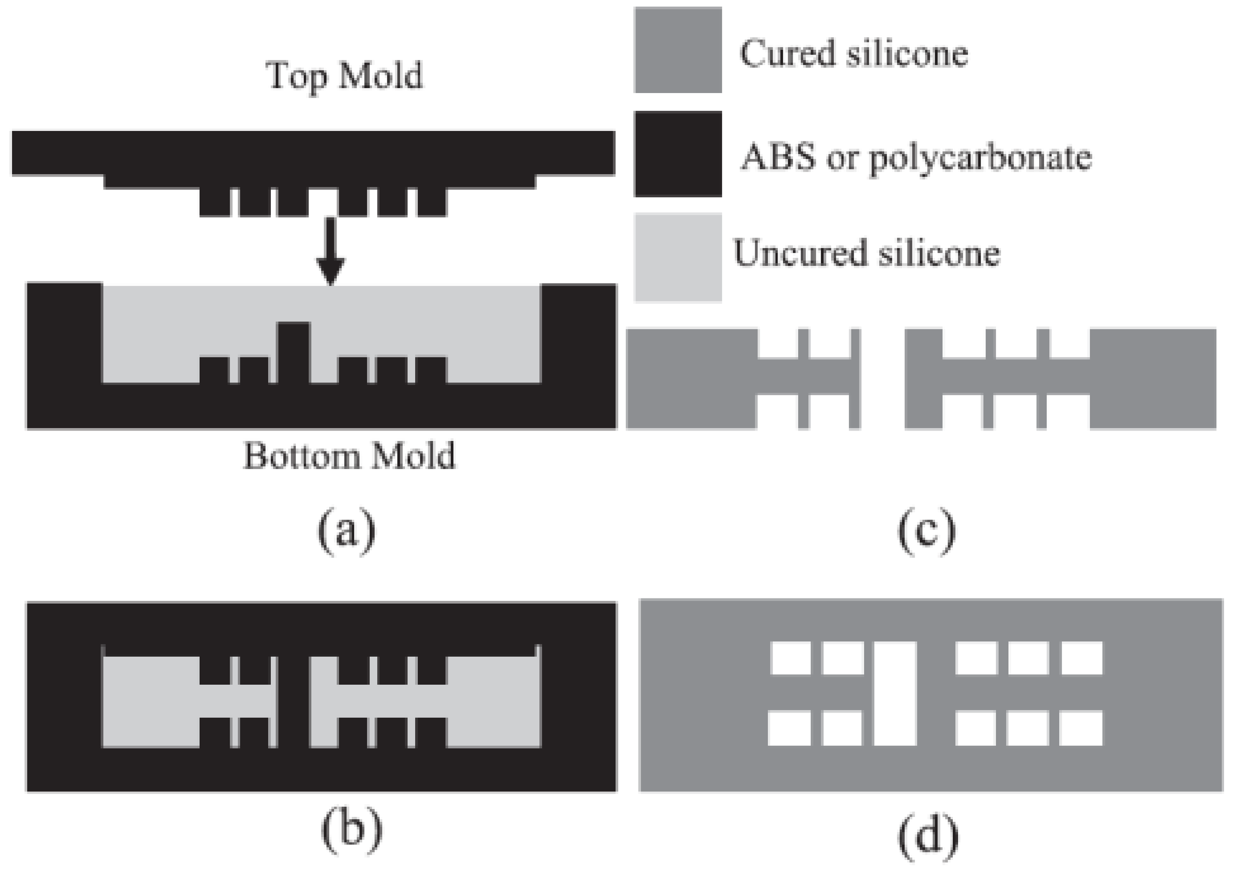


N Lazarus et al., "Fractal Inductors," *IEEE Trans. Magnetics*, vol. 50, no. 4, pp. 1-8, 2014.

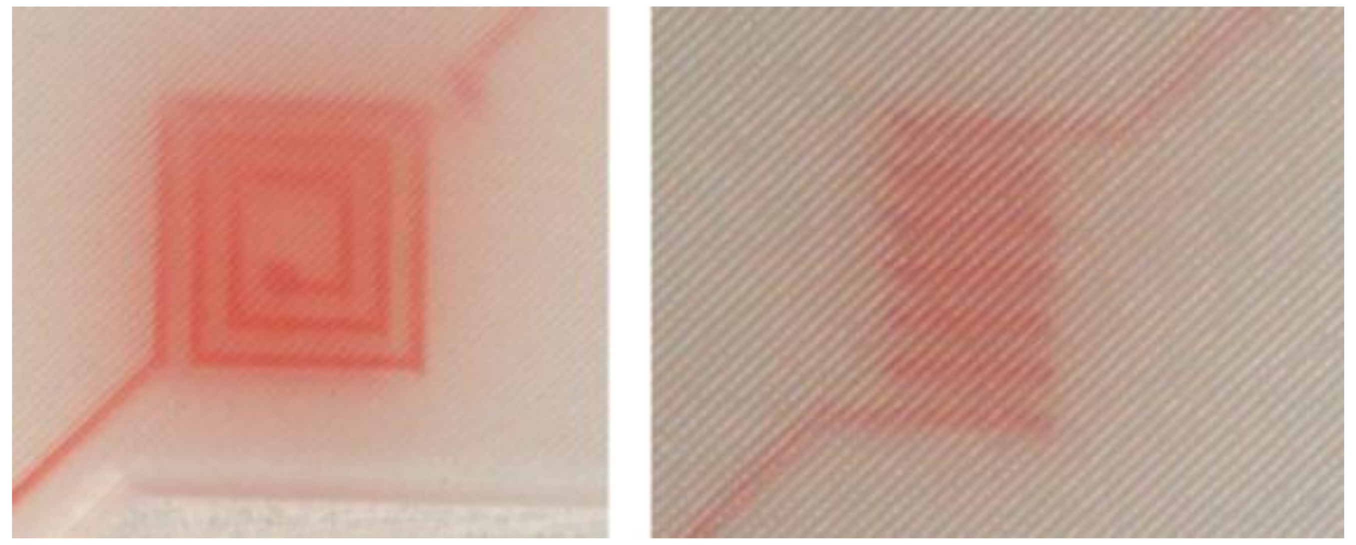
Stretchable Power System



Silicone molding process

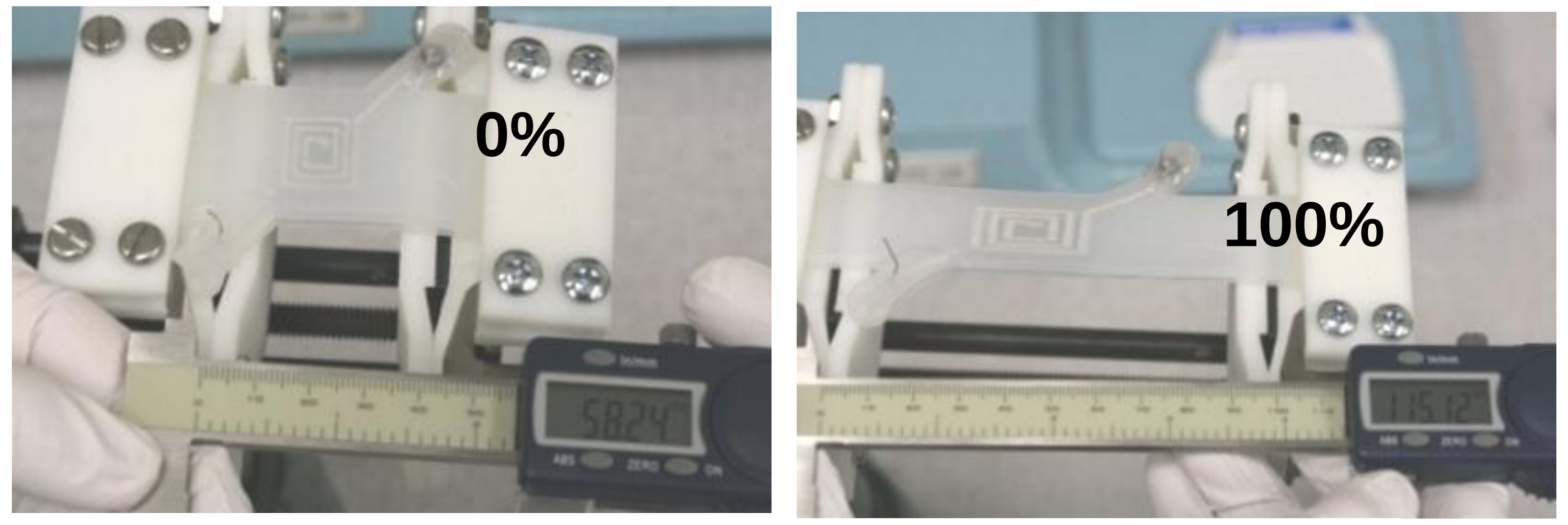


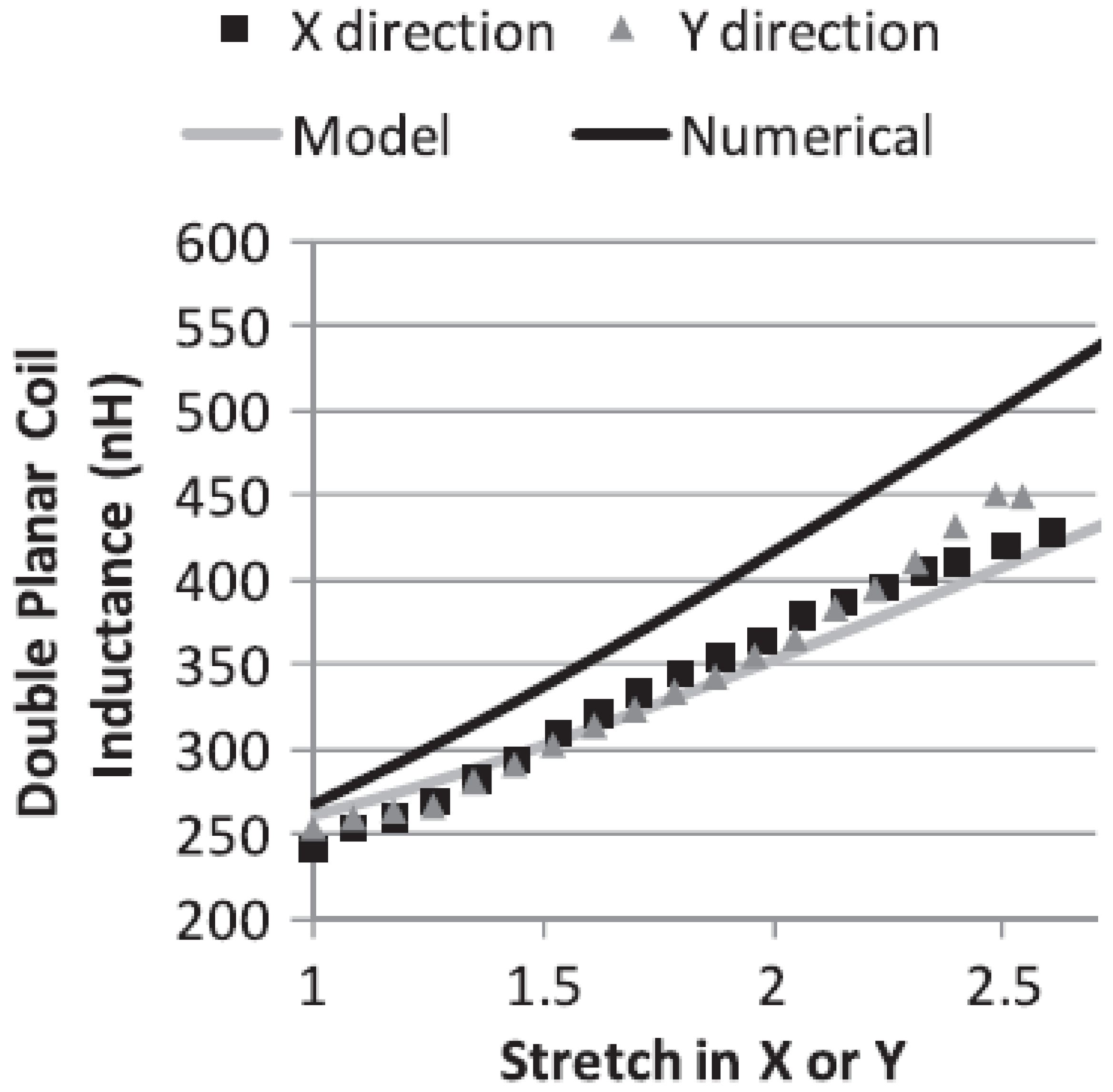
Multilayer Inductors



N Lazarus et al., "Multilayer liquid metal stretchable inductors," *Smart Materials and Structures*, vol. 23, no. 8, 2014.

Liquid Metal Inductor Strain Testing





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