



RDECOM



Integrated Micro-scale Power Conversion



TECHNOLOGY DRIVEN. WARFIGHTER FOCUSED.

Sarah Bedair, PhD

*Sensors & Electron Devices Directorate
U.S. Army Research Laboratory
Adelphi, MD 20783
sarah.s.bedair.civ@mail.mil*

Collaborators:

ARL:

Brian Morgan, Ph.D.
Christopher Meyer, Ph.D.
Iain Kierzewski
Jeffrey Pulskamp
Ronald Polcawich, Ph.D.

U. Florida:

Xue Lin
Chris Dougherty
Prof. David Arnold
Prof. Rizwan Bashirullah

Report Documentation Page				Form Approved OMB No. 0704-0188	
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE AUG 2012		2. REPORT TYPE		3. DATES COVERED 00-00-2012 to 00-00-2012	
4. TITLE AND SUBTITLE Integrated Micro-scale Power Conversion				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Army Research Laboratory,Sensors & Electron Devices Directorate,2800 Powder Mill Road,Adelphi,MD,20783-1197				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES Presented at the 2nd Multifunctional Materials for Defense Workshop in conjunction with the 2012 Annual Grantees'/Contractors' Meeting for AFOSR Program on Mechanics of Multifunctional Materials & Microsystems Held 30 July - 3 August 2012 in Arlington, VA. Sponsored by AFRL, AFOSR, ARO, NRL, ONR, and ARL.					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Same as Report (SAR)	18. NUMBER OF PAGES 38	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			



US ARMY
RDECOM

Autonomous System Technologies

ARL

Large-Scale Robotics



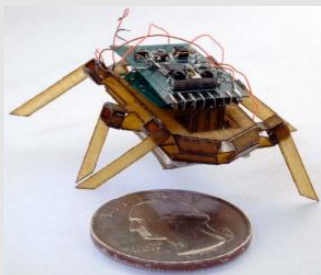
Man-Portable Systems



Micro-Autonomous System Technologies



MAST



Scale

- Miniature
- Multi-input / output
- Range of input voltages
- Output voltage, 1 V – 100's V
- < 1W

Missile health monitoring units



Lifetime

- Micro-watt saving adds weeks to battery life
- High efficiency w/ light loads
- μ W's continuous
- 10s of mW bursts
- 15-20 yrs operating lifetime

ARL Blue radio

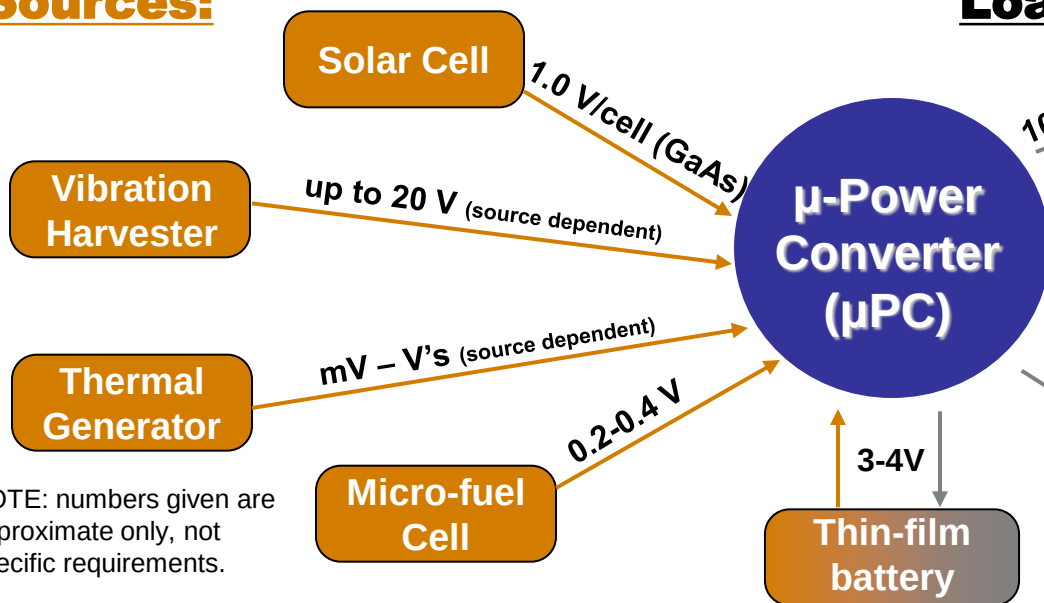


Lifetime & scale & speed

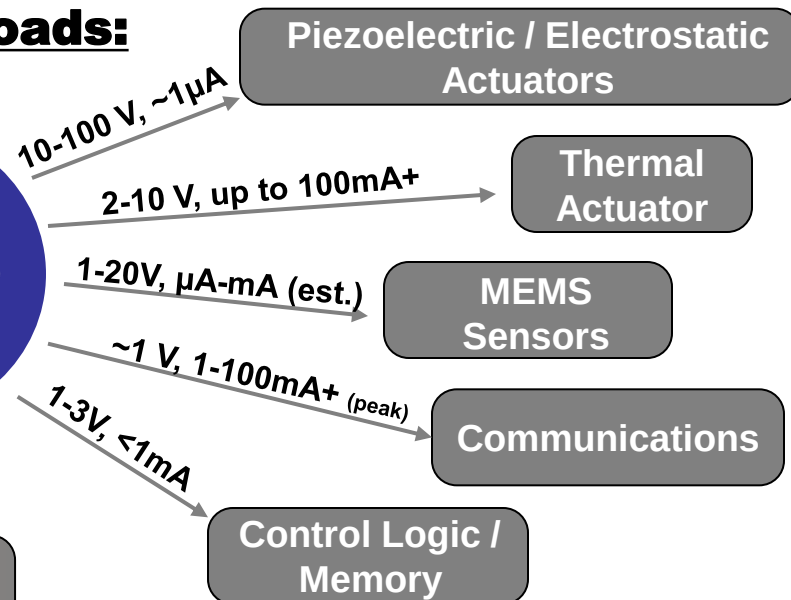
- "Power converters...one of biggest challenges"
- Moderate efficiency (>70%) w/ light loads
- Response time < 100usec
- Lots of outputs – e.g. 11.4V (5mA), 3.3 (50mA)

Many other applications or spin offs (missile prime power, soldier power managers, RF devices, TTL, etc)

Sources:



Loads:

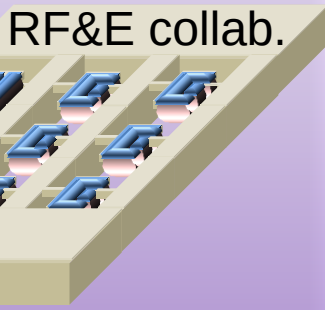


- Leverage CMOS to increase frequency and reduce passive size
- Hybrid integration with MEMS passives, particularly inductors

Integrated converters

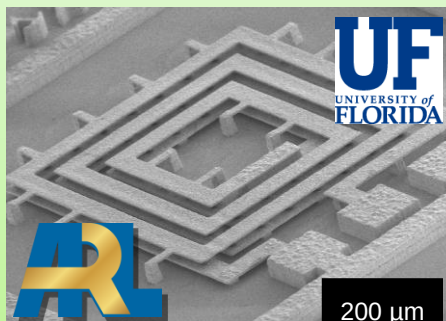
Piezo-transformers & capacitors

RF&E collab.



Magnetics

- ARL / UF Cu inductors

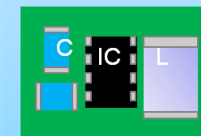


CMOS / control

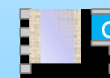
Prof. Rizwan Bashirullah

Switching frequency

4 MHz >20 MHz >100 MHz



~10's cm

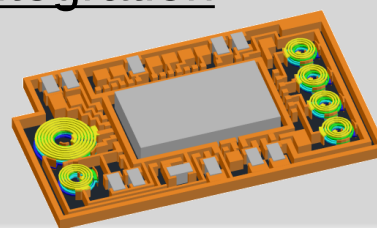
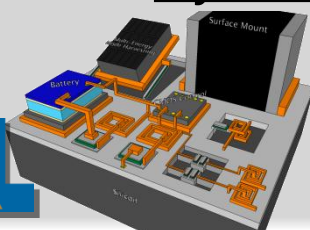


Stacked IC, L
Co-packaged C

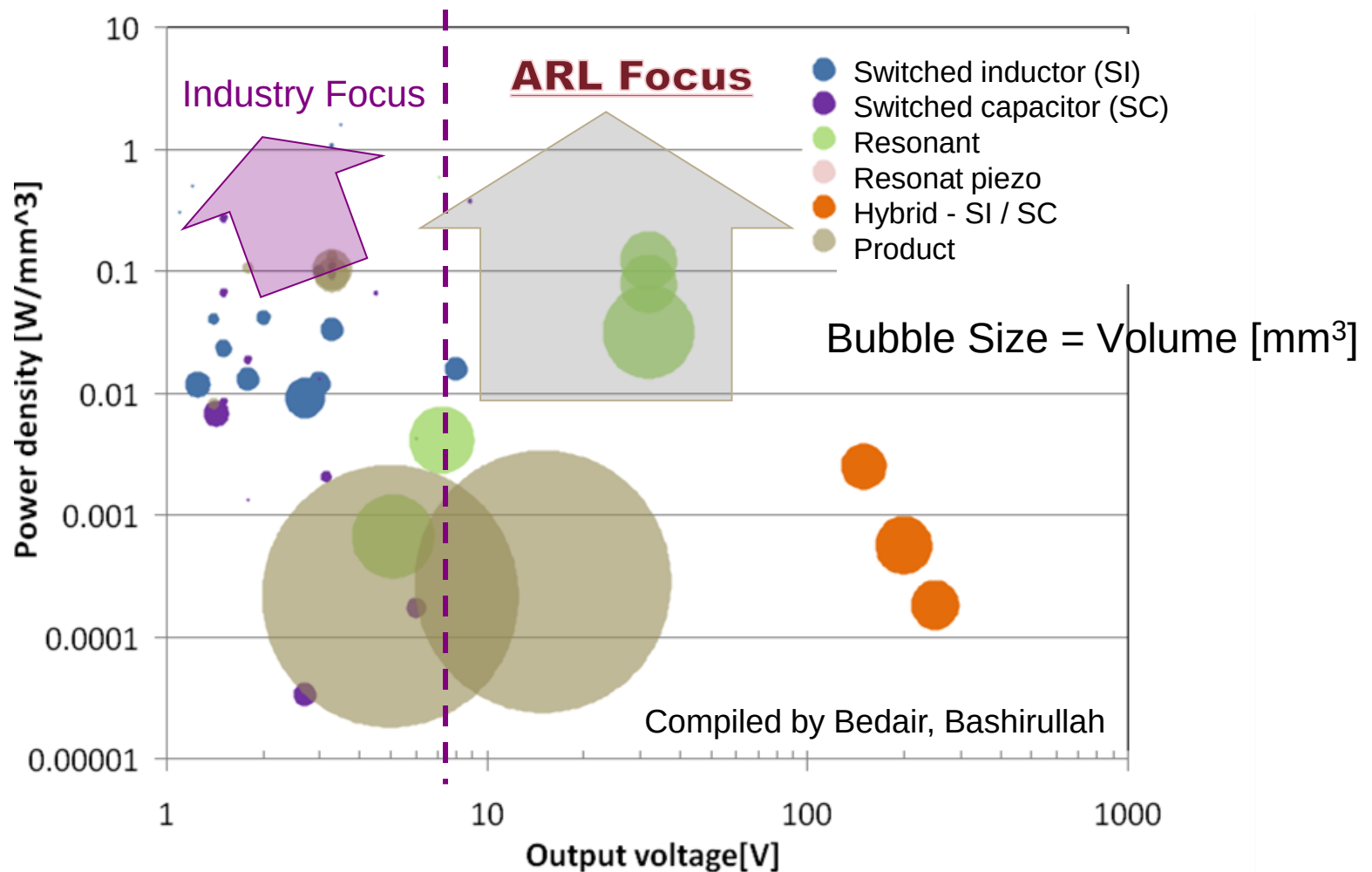


Dual die /
monolithic

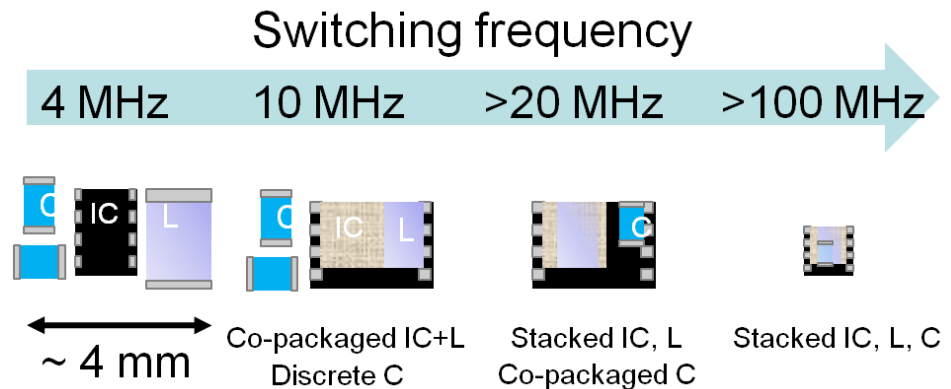
Hybrid integration



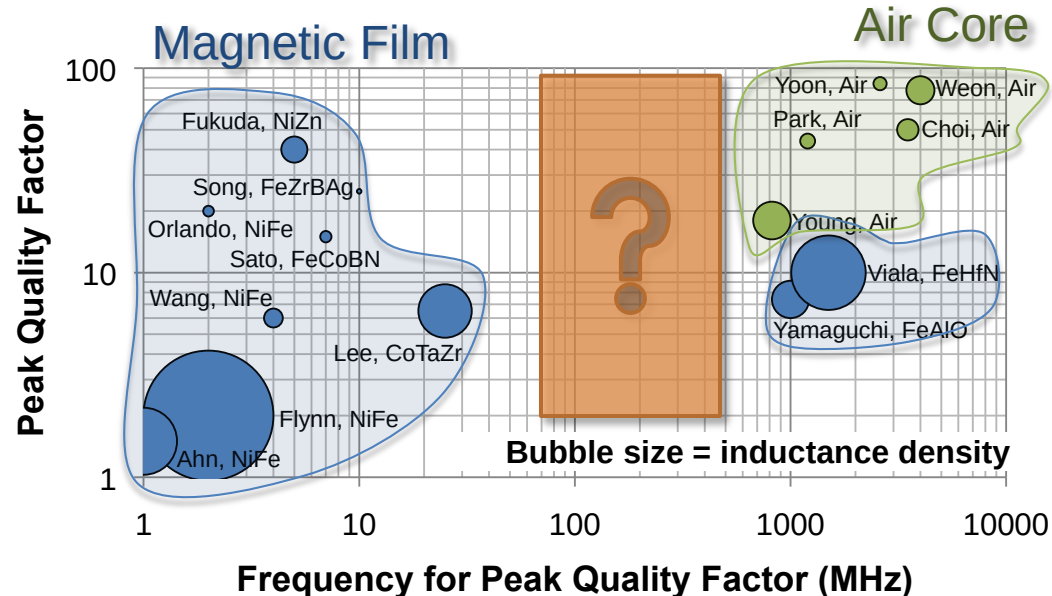
Power converters survey

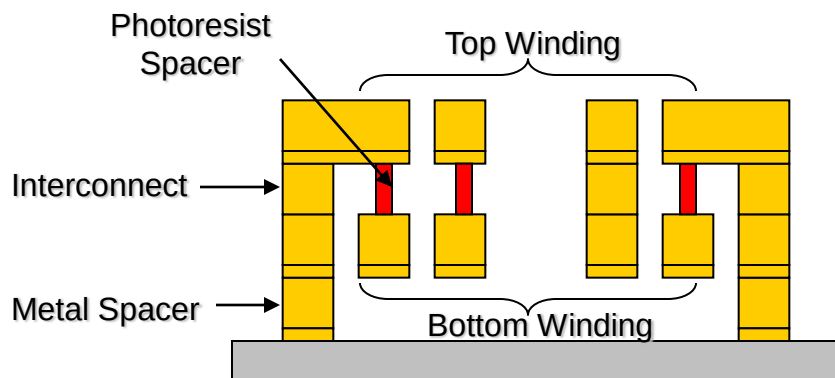


- **Increase switching frequency:**
 - Equivalent reactance with lower-valued passives.
- **Magnetic losses increase:**
 - Copper losses,
 - Skin and proximity effects;
 - Magnetic film losses;
 - Hysteresis,
 - Eddy currents,
 - Domain dynamics.
- **Increase magnetic switching frequency?**
 - Needs high bulk resistivity.
 - Needs fast moment reversal.
 - Needs to be compatible.
- **Air core?**
 - Needs higher inductance densities.
 - Needs greater quality factor at lower frequencies.

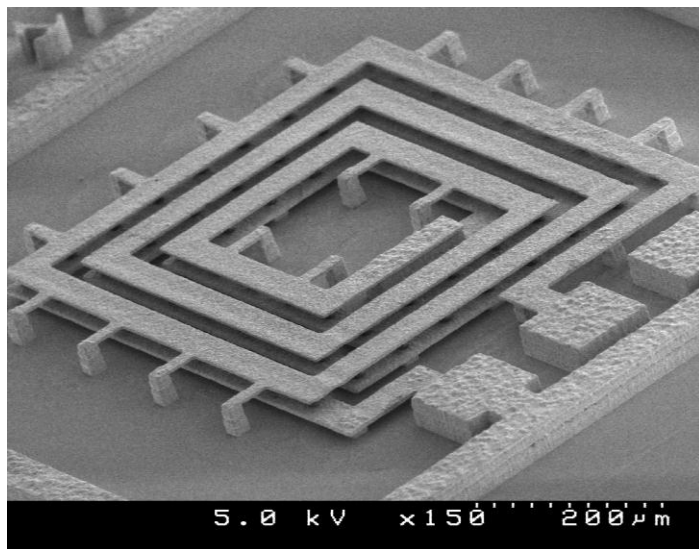


**Adapted from Tyndall Institute*



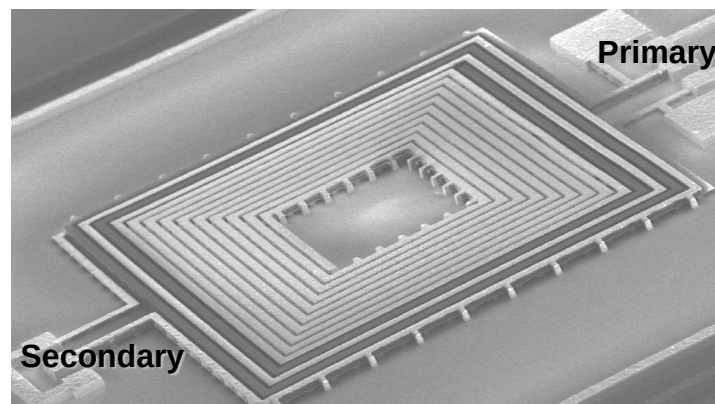


Inductor Cross Section



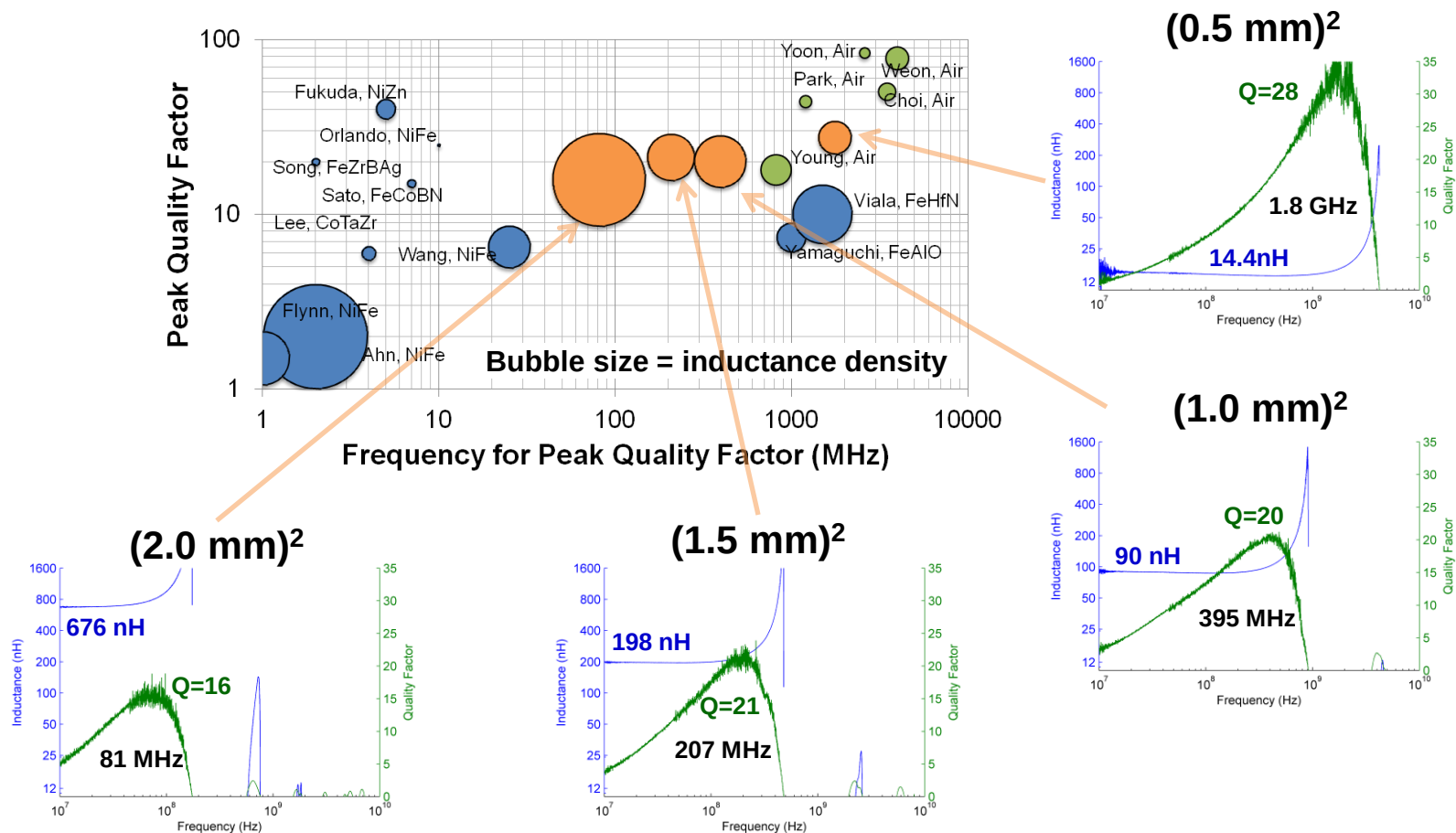
Air core MEMS Inductor

- **Process: electroplate copper through selectively exposed photoresist molds**
 - Four independent copper layers, 10-30μm per layer.
 - Ability to create polymer parts from remnant photoresist.
- **Vertical spacing off substrate to reduce coupling/interference**
- **Identical process flow for inductors or transformers**



Air core MEMS Transformer

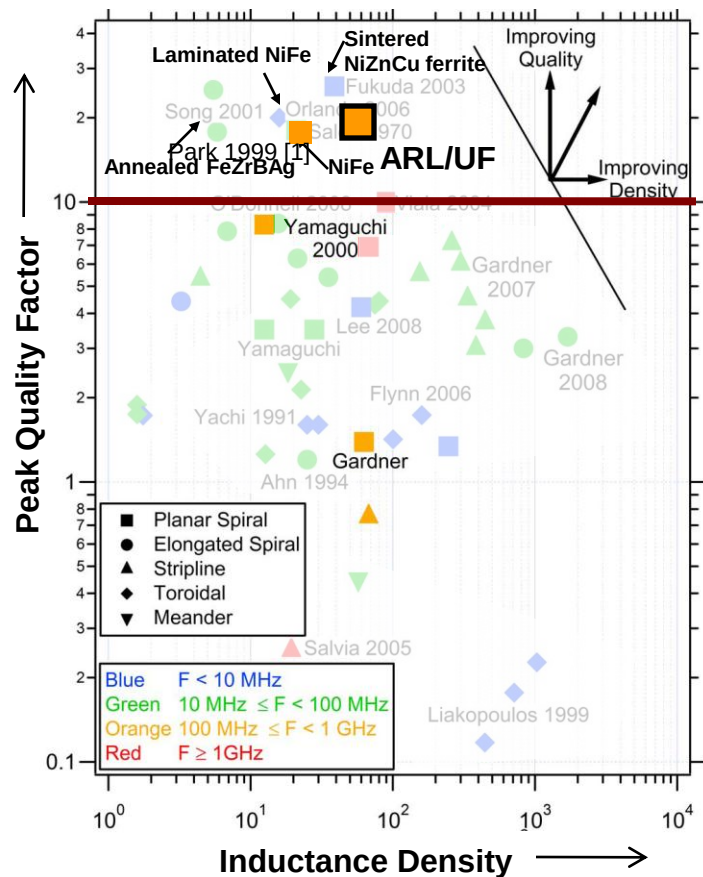
- Various size inductors on Pyrex.
- RF characterization with VNA.
- Peak Q's > 20, inductance densities > 100 nH/mm².



*Meyer et al., IEEE Trans on Magnetics 2010

*Meyer et al., ECS 2011

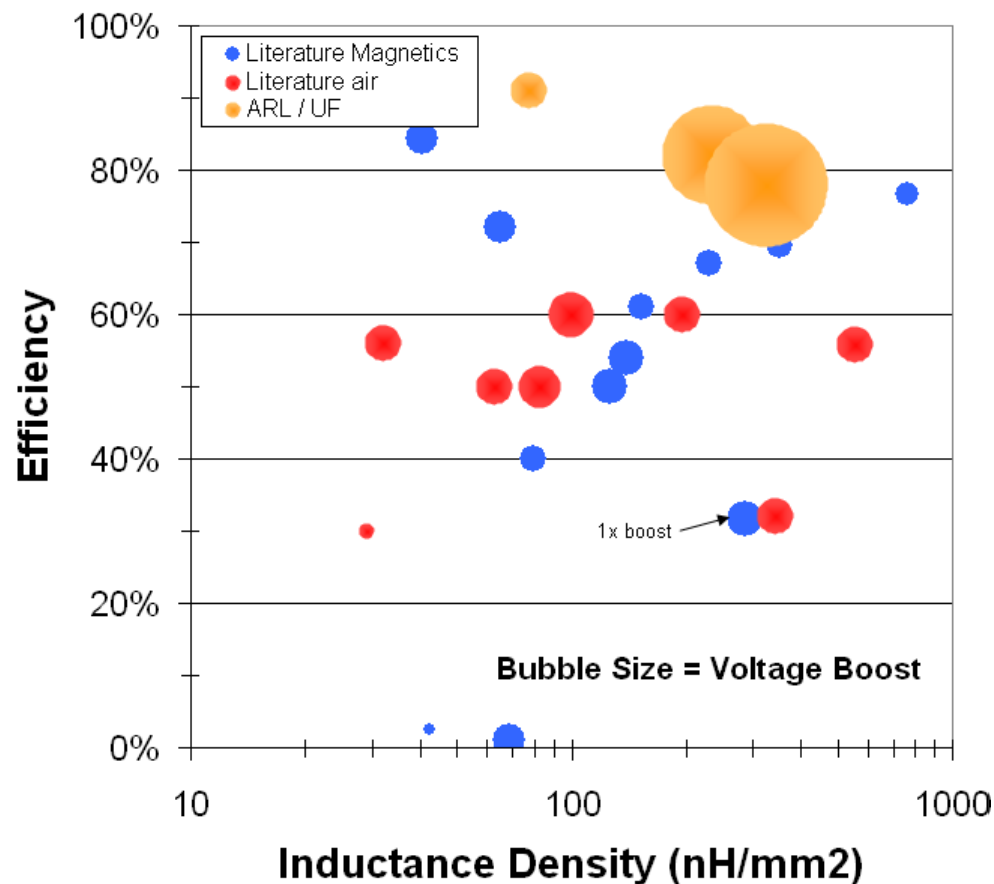
Micro-Inductors (mostly magnetic film)



Gardner, et al., "Review of On-Chip Inductor Structures with Magnetic Films," *IEEE TMAG*, 2009.

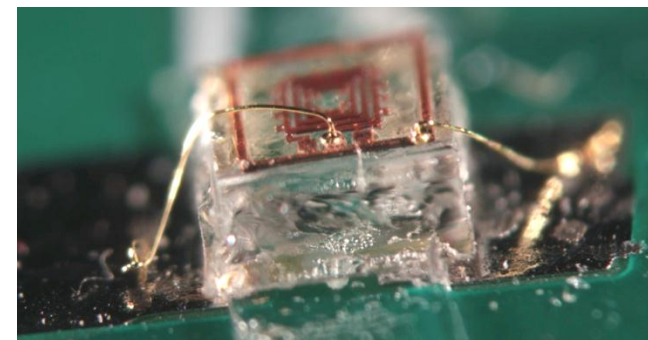
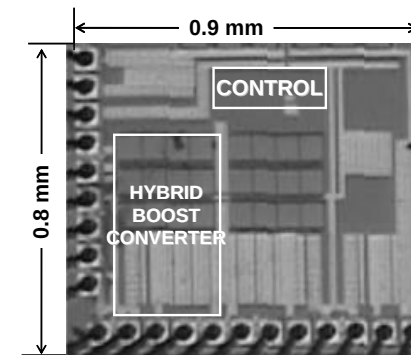
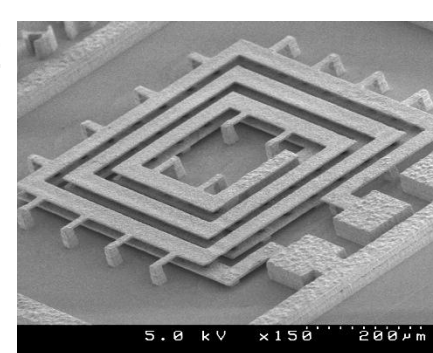
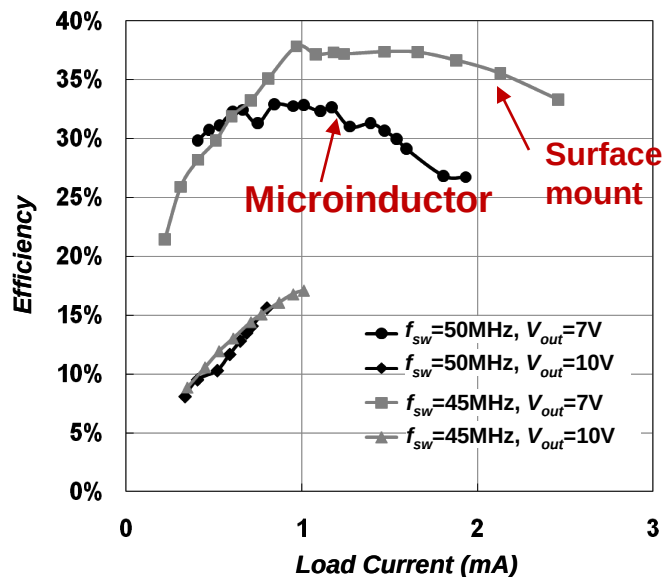
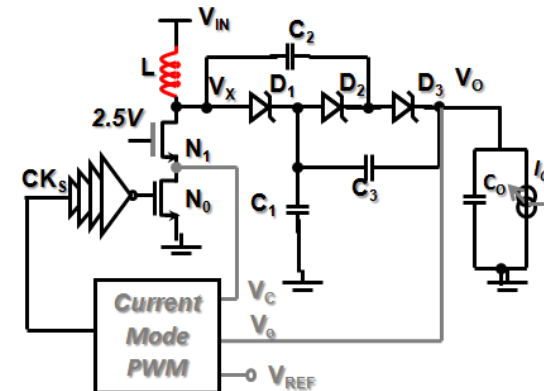
[1] J. Y. Park and M. G. Allen, "High Q Spiral-Type Microinductors on Silicon Substrates," *IEEE TMAG*, 1999.

Micro-Transformers



→ *Significantly less transformer work in literature*

- **0.27 mm² inductor w/in hybrid boost converter.**
 - SI boost followed by 2 SC stages.
 - 130 nm, 1.2 V CMOS, $f_{sw} = 100$ MHz.
 - $V_{out} = 7$ V from 1.2 V input (6x conversion).
- **Inductor wirebonded to PCB.**
- **Performance limited at higher current levels by winding resistance.**



• Challenge

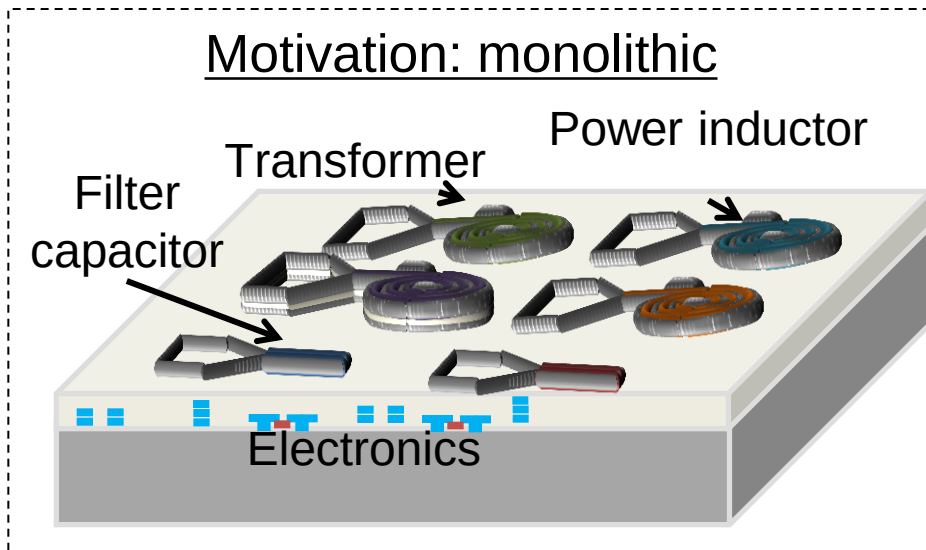
- Single chip integration of CMOS with dielectrics & magnetic materials
- Temperature / fabrication incompatibility

• Approach

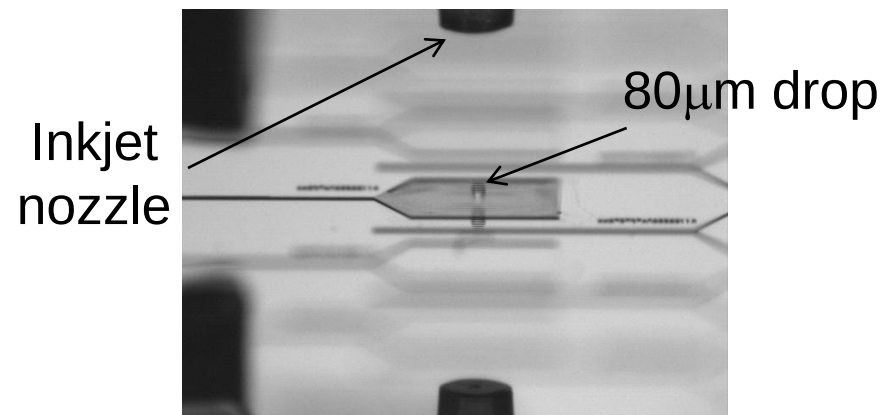
- Well and capillary delivery system
- Dissolve or suspend nanoparticles
- Dose structures with appropriate nanoparticles:
 - High-k dielectrics for capacitors
 - Magnetics for inductors

• Advantages

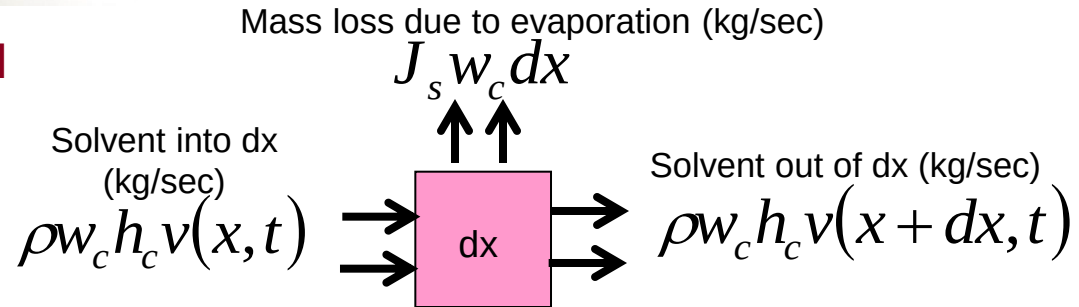
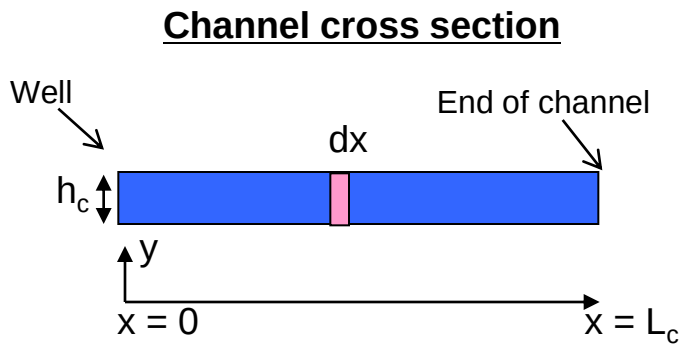
- Room temperature
- Material flexibility
- Complex 3-D geometries



Deposit using inkjet printing



- Evaporated solvent in channel is replenished by the well

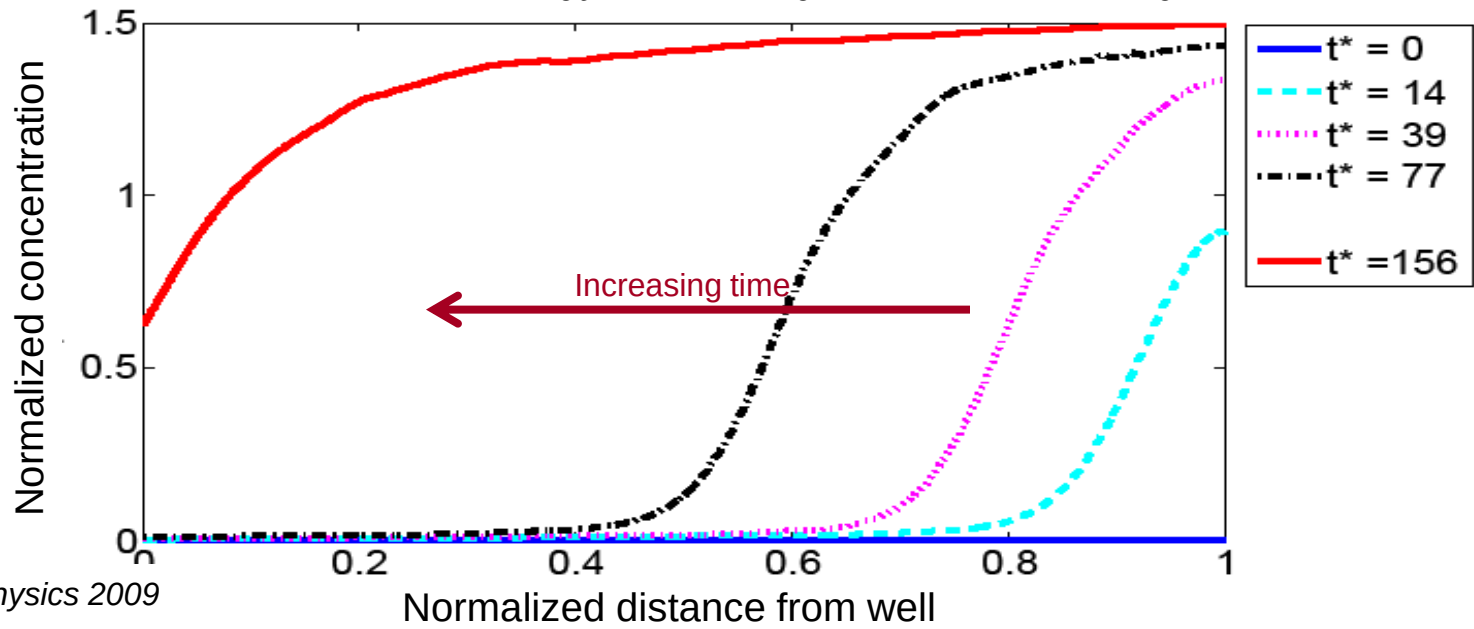


Total solvent mass rate of change

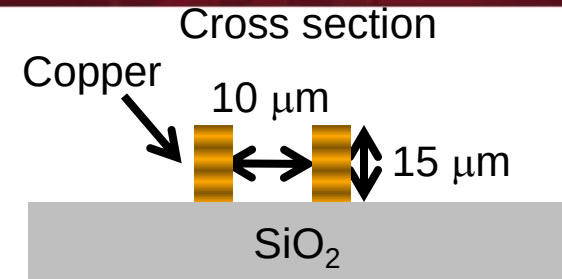
$$\rho \frac{\partial h_c}{\partial t} dx \cdot w_c = \rho w_c h_c dv(x, t) - \rho w_c h_c dv(x + dx, t) - J_s w_c dx$$

Rate of change of solute (kg/sec)

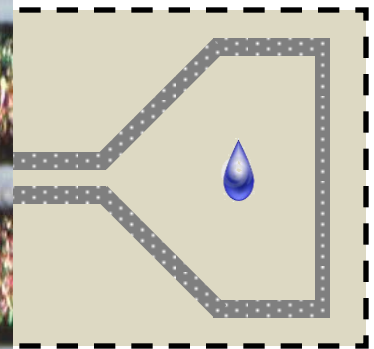
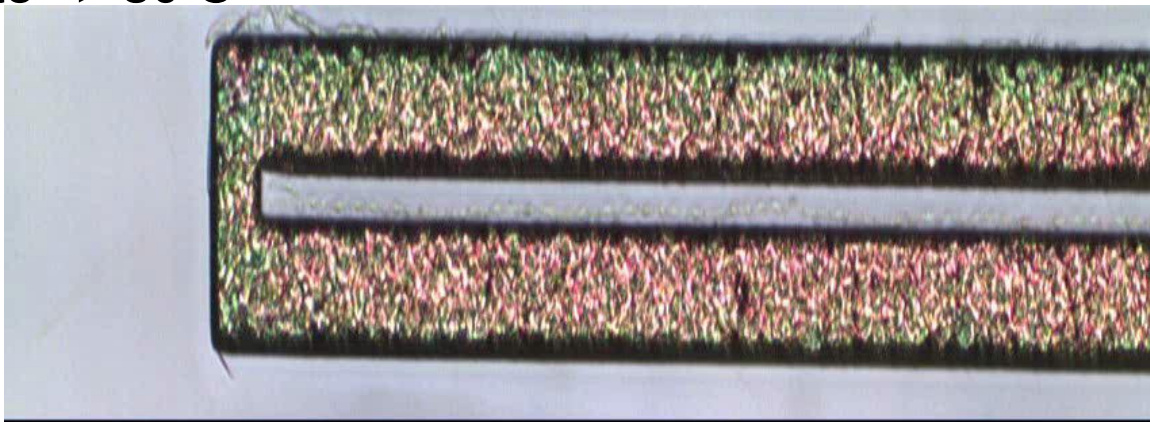
$$\frac{\partial}{\partial t} (c(x, t)) = - \frac{\partial}{\partial x} (c(x, t) \cdot v(x, t)) + D \frac{\partial^2}{\partial x^2} c(x, t)$$



- 30 nm NiFe_2O_4 in methanol suspension
- 2 mm long, 10 μm wide, 15 μm tall channel
- Drop *by hand* $\sim 1 \mu\text{L}$ from a 10 μL syringe, substrate $\rightarrow 30^\circ\text{C}$

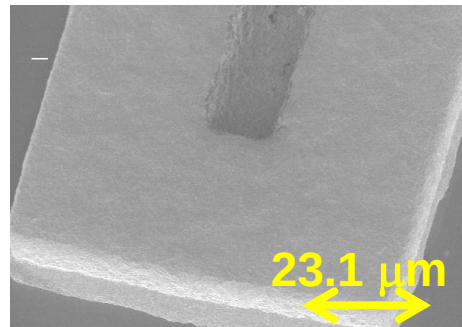
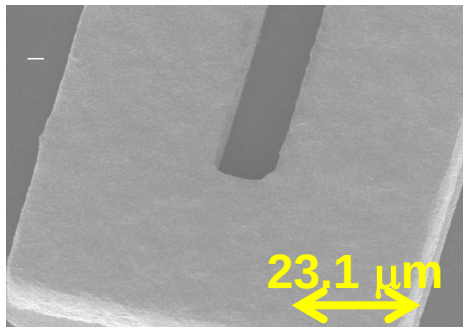


$\sim 70\mu\text{m}$

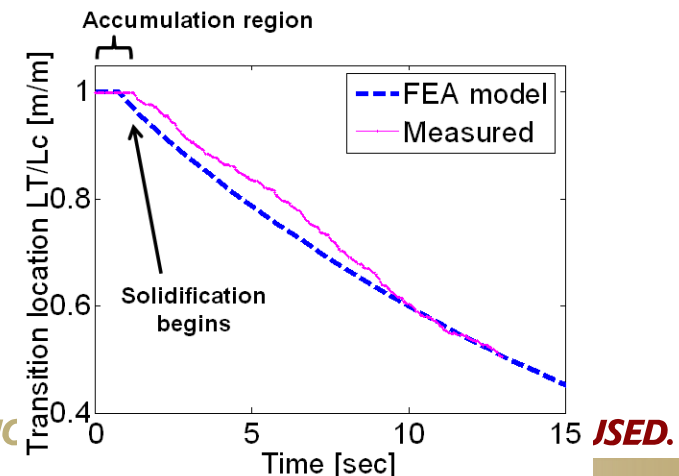


Before

After

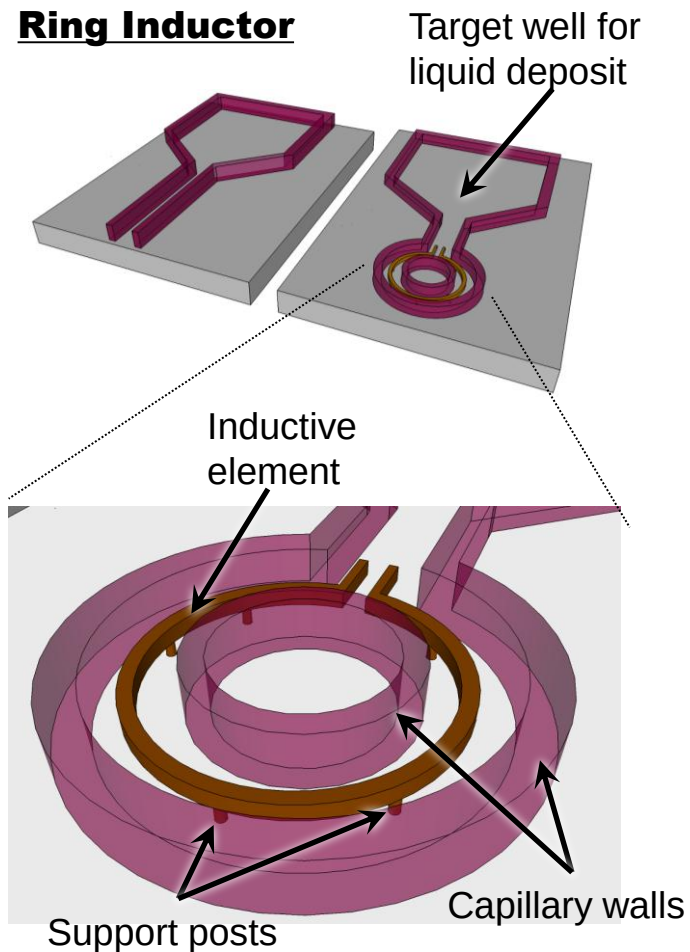


Comparison w/ Theory



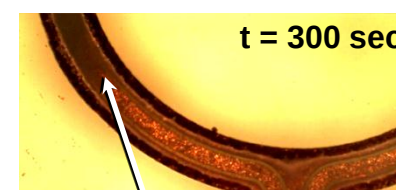
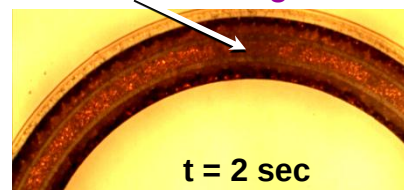
- Trace suspended within circular channel.
- Magnetic NPs deposited fully around trace in single step.

Ring Inductor

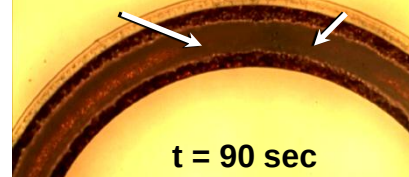


Top View During Deposition

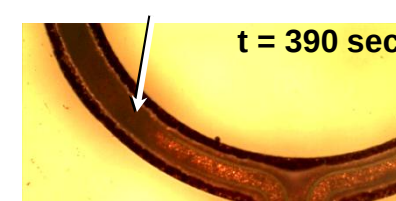
Accumulation Region



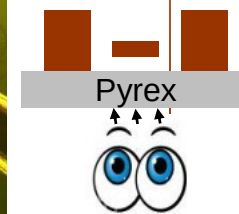
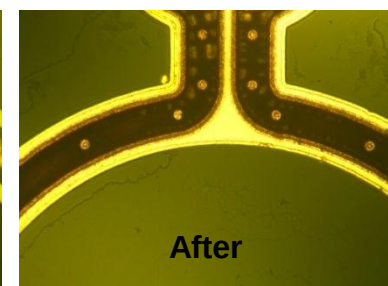
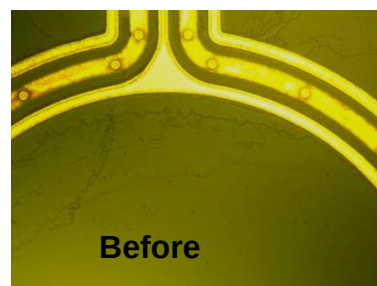
Two Solidification Fronts



Left Solidification front

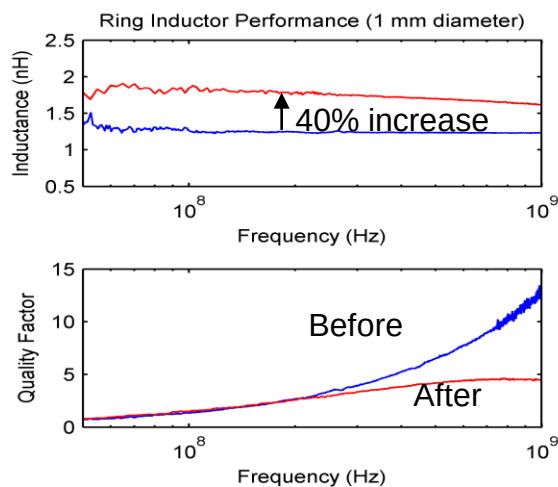
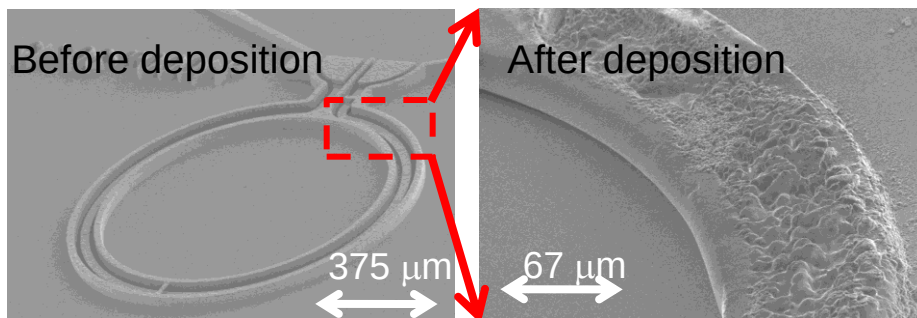


Backside View



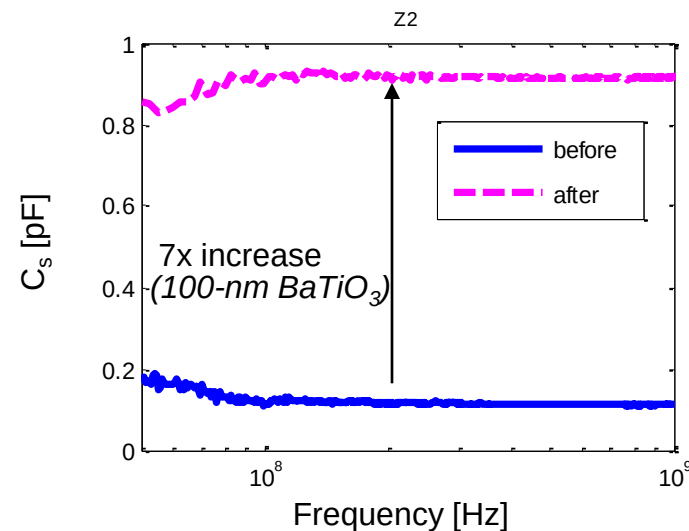
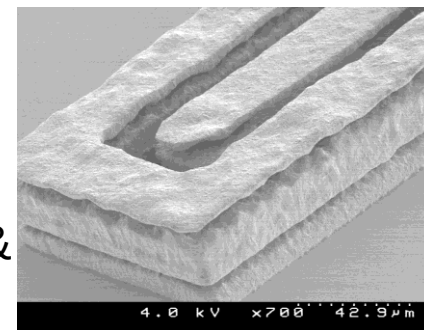
Ring Inductor

- Wicked ring inductors w/ Ni-ferrite nanoparticles (30 nm)



Parallel plate capacitors

- Dual channel parallel plate capacitor
- Measured capacitance before / after solution wicking & complete solvent evaporation



Why piezoelectric transformers (PT)?

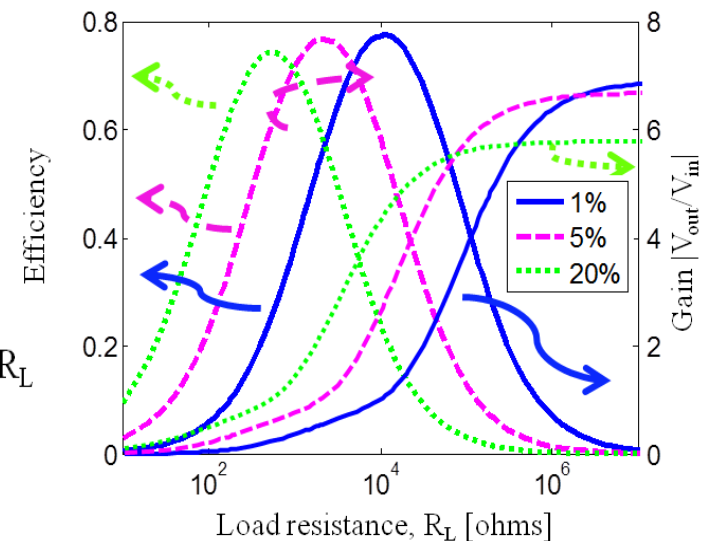
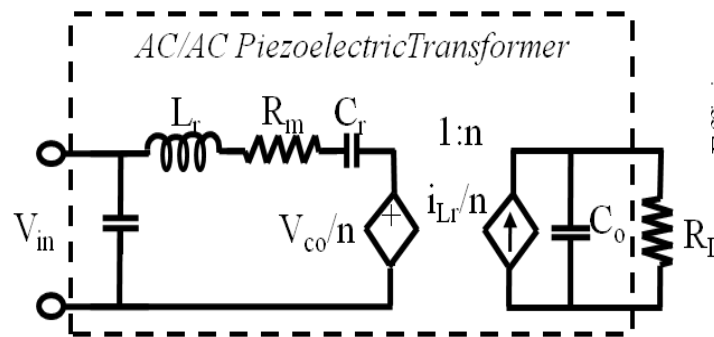
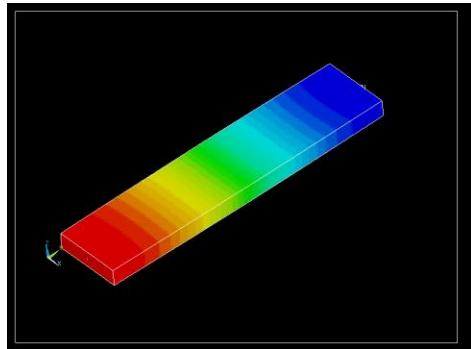
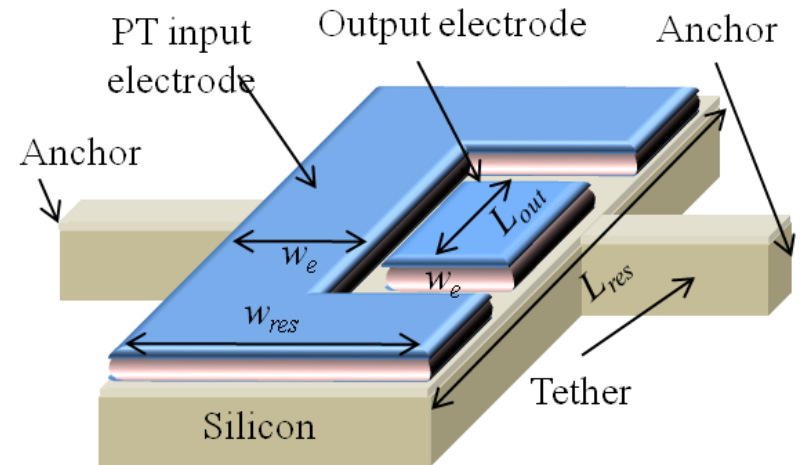
- Bulk PT's used for small size, high voltage isolation, low EM noise

Challenges?

- AC/AC performance (efficiency, gain, power) depends heavily on R_L

Current work:

- Leverage ARL expertise in thin-film PZT-MEMS
- Characterizing power handling & load dependence of gain and efficiency



Potentially 2-orders of magnitude smaller than traditional converters



Piezo MEMS Transformers

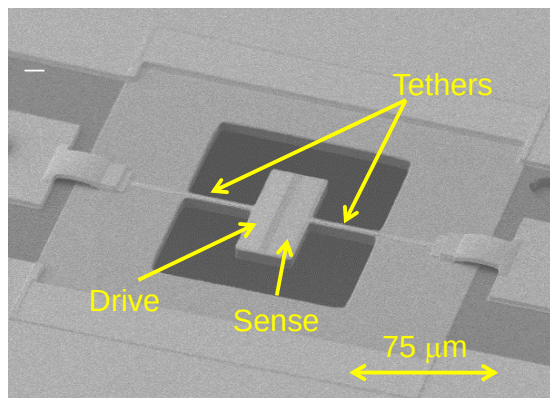
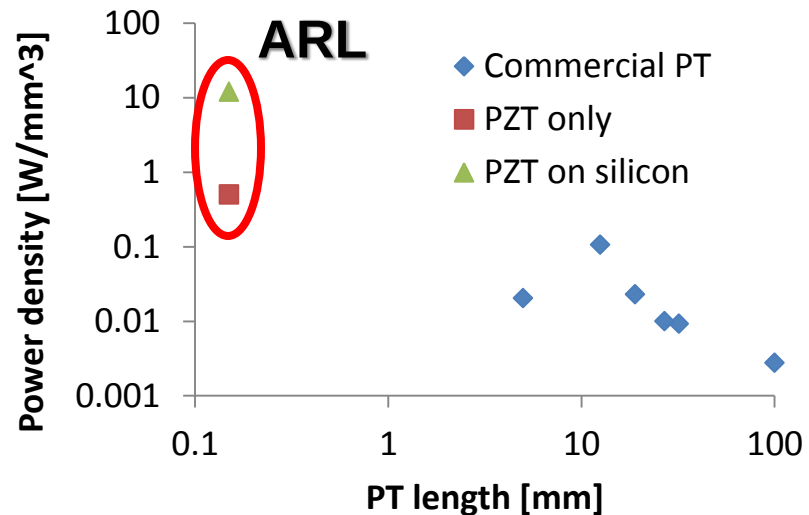


PZT on SiO₂ vs PZT on Si

- Stiffer support increases power handling
- Early results:
 - PZT on Si exhibits >20X power handling
 - AC voltage boost >2X demonstrated

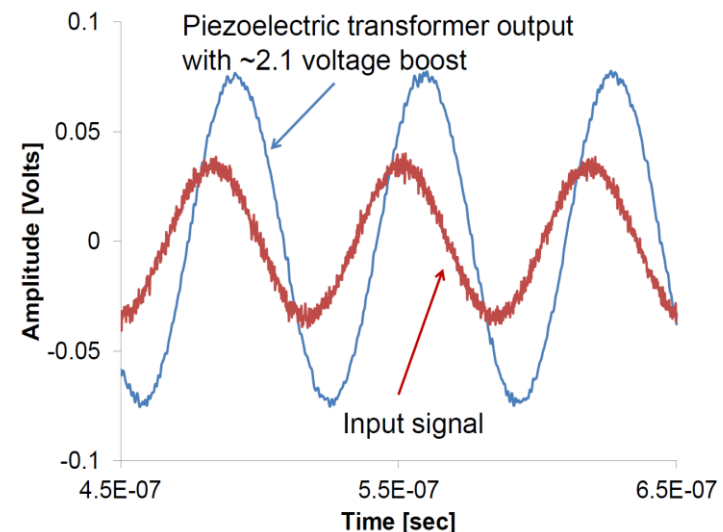
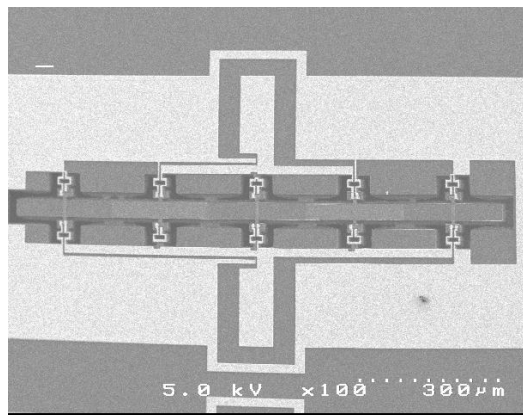
Future work:

- Further characterize power, efficiency, gain characteristics for new designs
- Modify process for multi-layer PZT (voltage buck or boost)



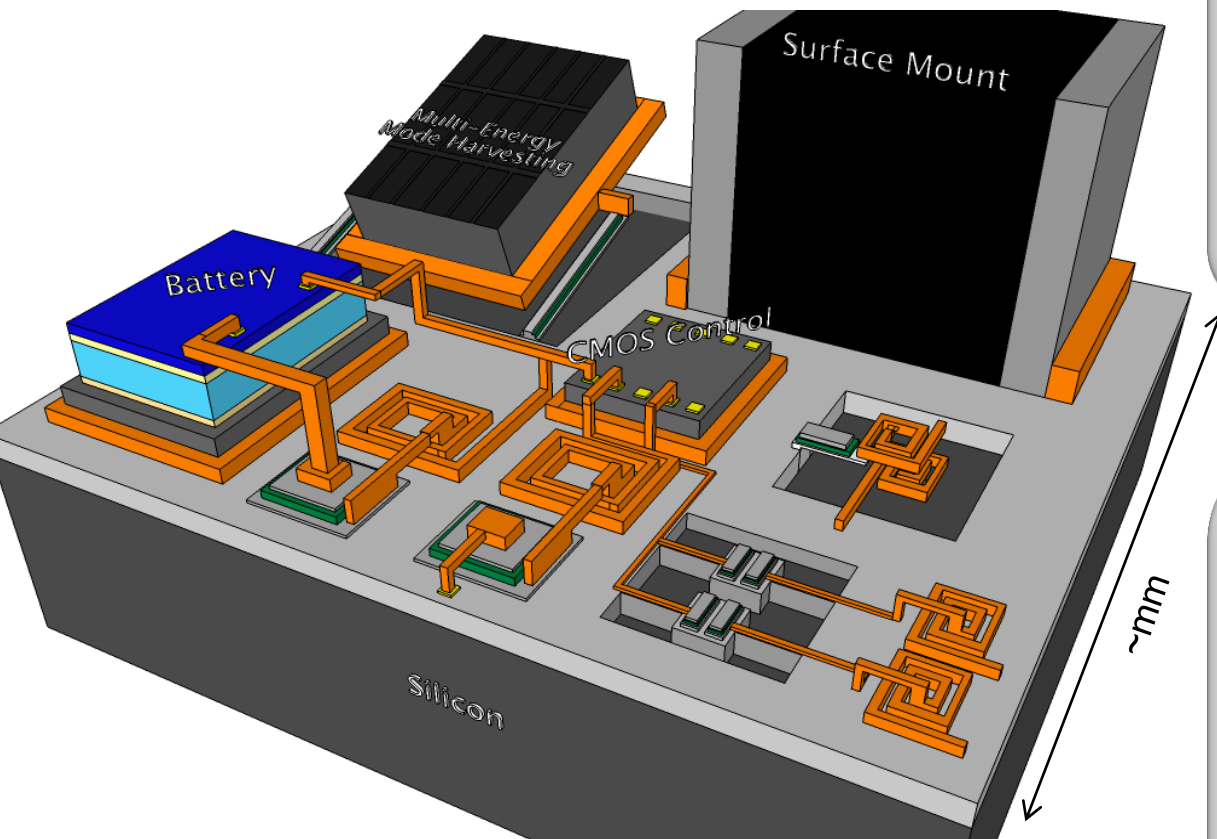
Gen 1 → fundamental mode, ~10% efficient

Gen 3 → 9th order mode, ~60% efficient

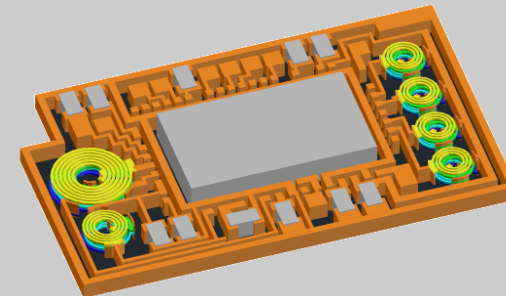


1st Demo of Voltage Gain (15MHz)

Single-chip power scavenging and control



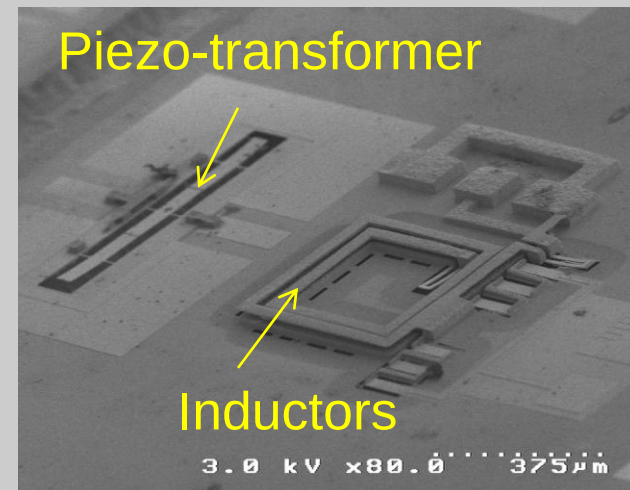
Heterogeneous Integration



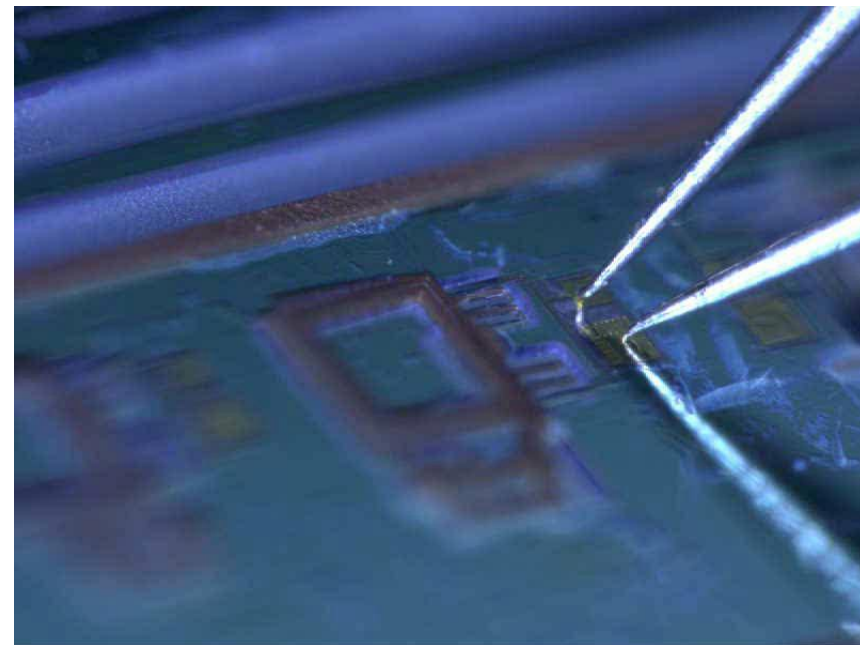
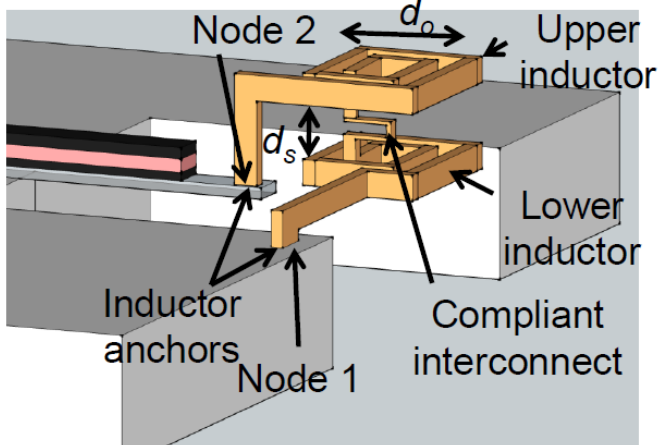
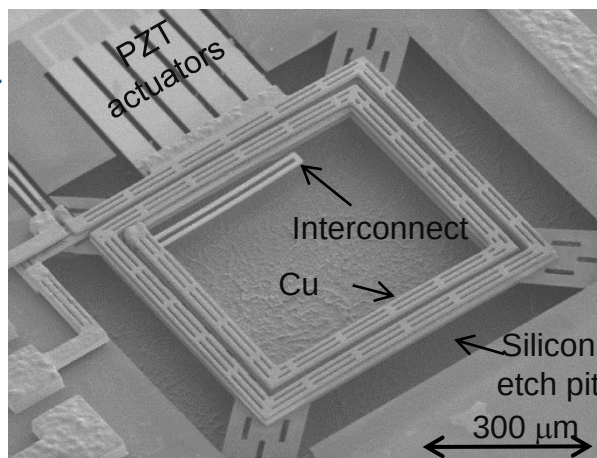
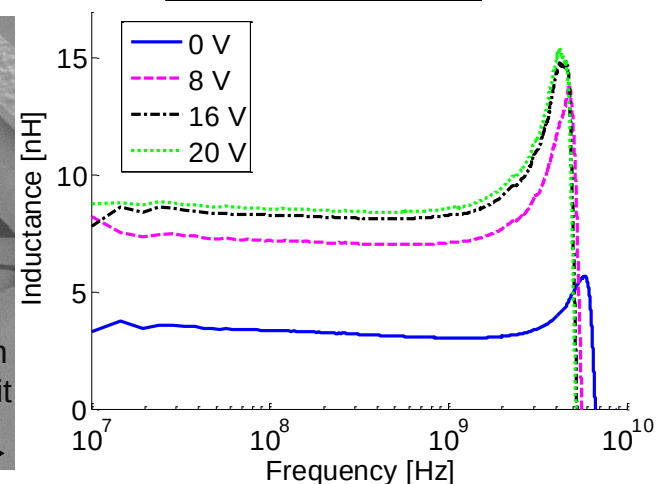
Monolithic Integration

Piezo-transformer

Inductors

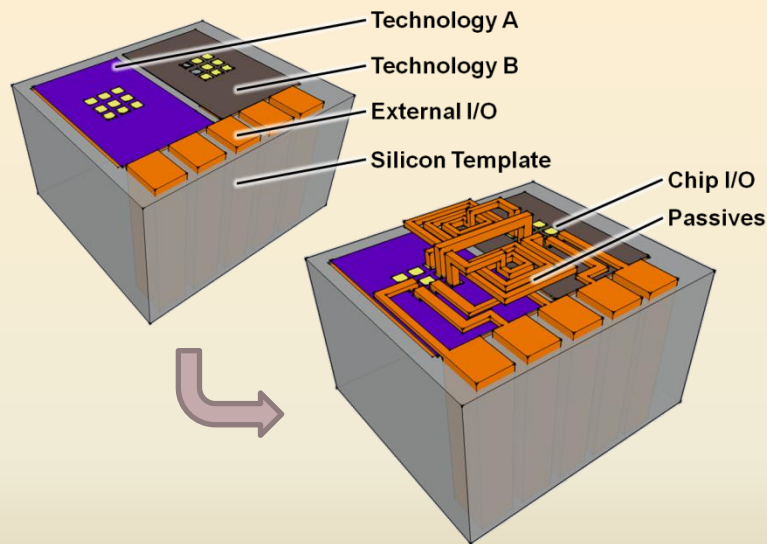


- **Combine inductor process with PZT MEMS actuator process to create tunable passive components**
 - Control for power electronics
 - Tunable RF components
- **Demonstrated high performance, tunable inductors**
 - Tuning ratio $\sim 2.7:1$
 - Q 's > 10

Device conceptFabricated deviceMeasurements

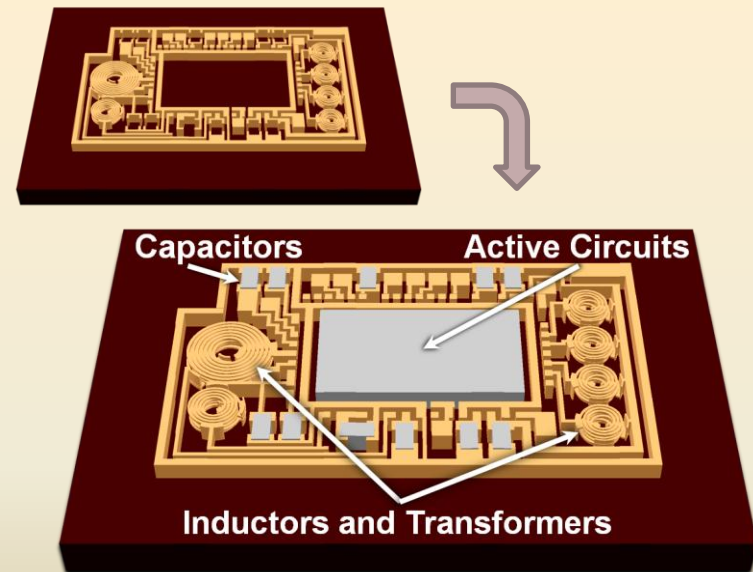
Heterogeneous Integration Strategies

Chip-First



- Embed chips w/in **template wafer**
- Fabricate passives and **routing last**.

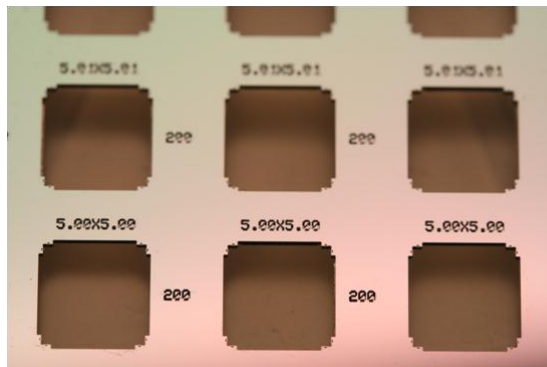
Chip-Last



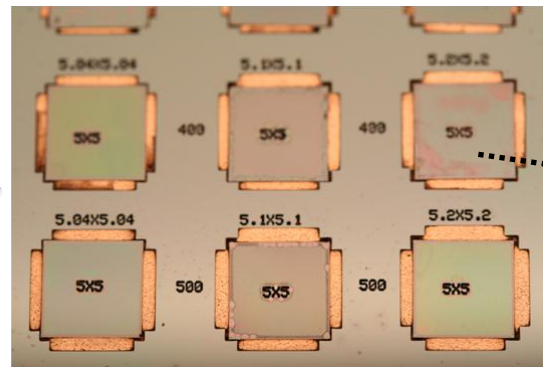
- Fabricate passives and **routing first**.
- Embed chips w/in **3D copper scaffolding**.

- Microfabricated silicon template by DRIE.
- Template and chips mounted co-planar.
 - Measured planarity w/in $\sim 5 \mu\text{m}$
- Aligned chips using template corners.
 - Maximum lateral offset $< 40 \mu\text{m}$.
- Electroplated $60 \mu\text{m}$ thick copper to embed.
- Planar surface to be post-processed to form passives and interconnects.

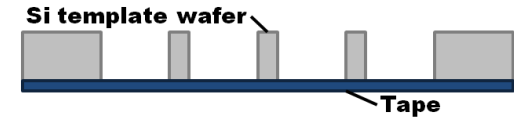
Silicon template



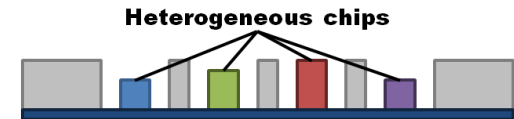
Embedded chips



1. Attach template wafer to taut tape.



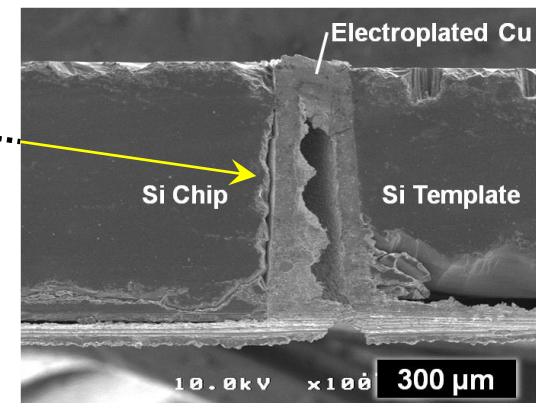
2. Place chips in openings and attach to tape.



3. Electroplate copper over surface and in trenches.



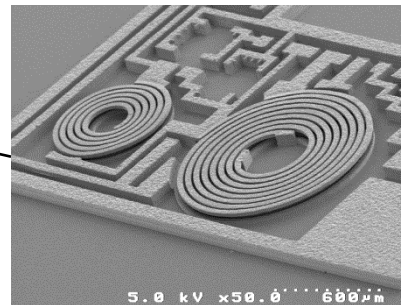
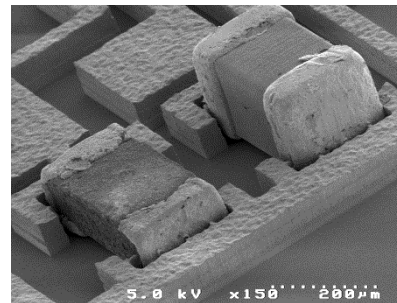
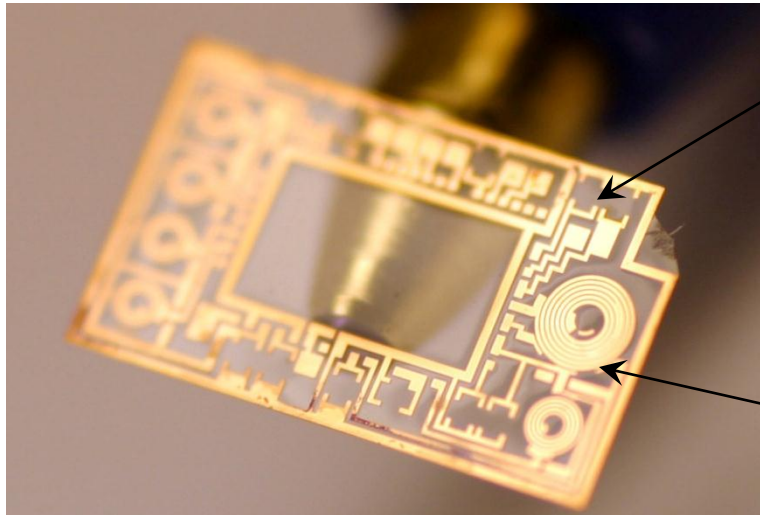
4. Pull tape from embedded wafer.



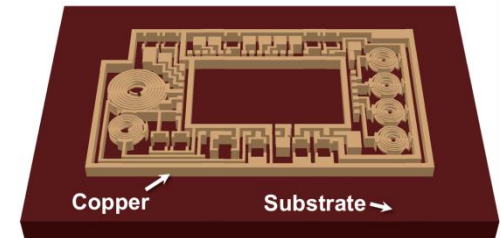
*C. Meyer, et al. ECS 2012.

TECHNOLOGY DRIVEN. WARFIGHTER FOCUSED.

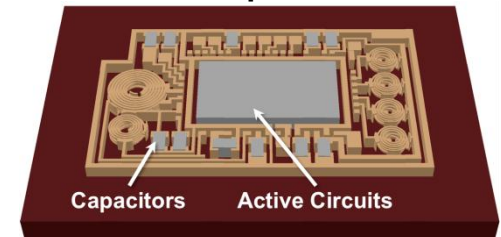
- **Scaffolding fabricated by 3D copper process.**
 - Total thickness 90 μm .
 - High aspect ratio >10:1 for dense routing and passives.
- **Deformable sockets for press-fit integration.**
 - Alignment & prevents tombstoning of parts.
- **Will be demonstrated w/ 3-in-1 VHF CMOS converter die.**



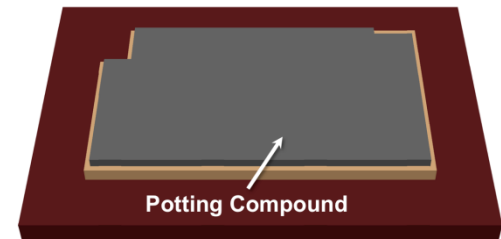
1. Scaffold.



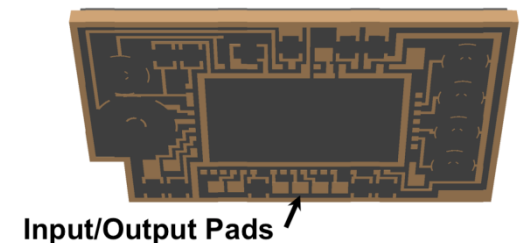
2. Populate.



3. Back Fill.

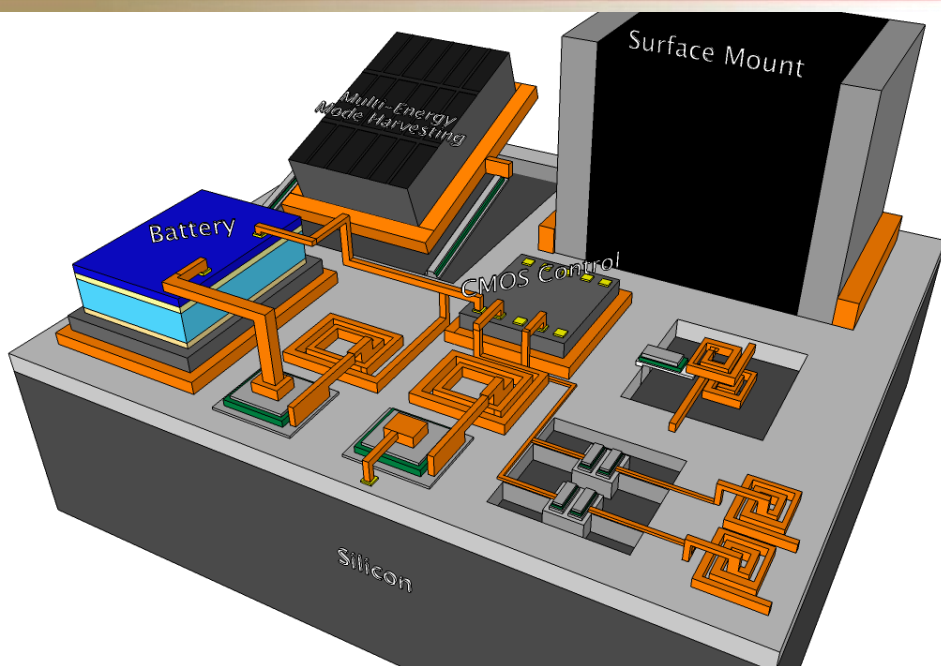


4. Detach.



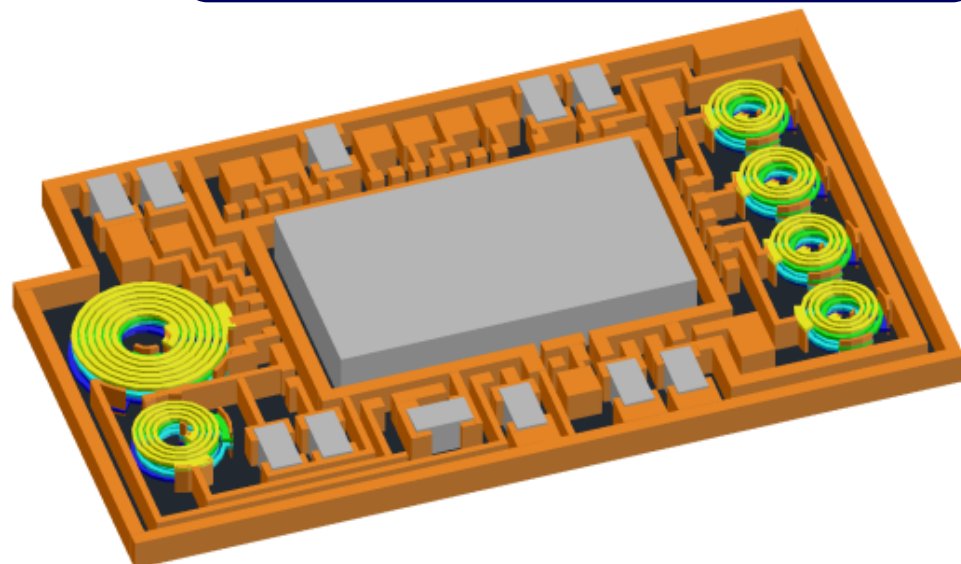
*C. Meyer, et al. *Hilton Head 2012*.

Questions?



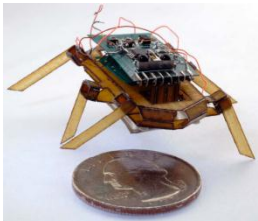
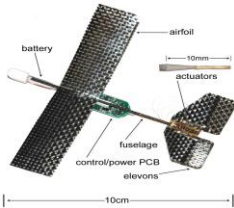
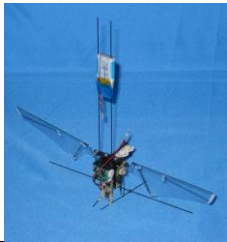
Single-chip multi-modal power
scavenging and control

Inductors holding chips instead
of chips holding inductors



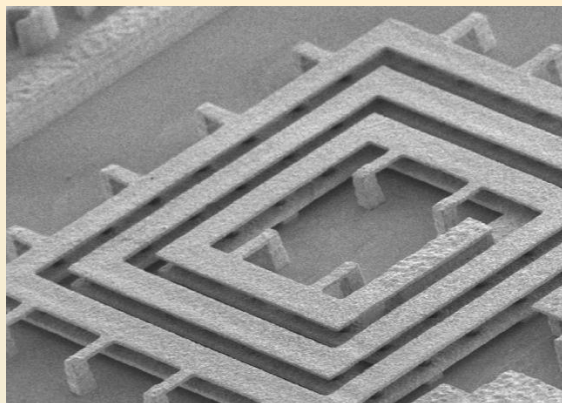
TECHNOLOGY DRIVEN. WARFIGHTER FOCUSED.



System	Total Mass	Battery	Other Power Components (motors, controllers, etc)
Harvard Micro Fly (projected) 	0.12g	42%	38%
Berkeley RoACH 	3g	23%	24%
Berkeley Glider 	2g	32%	19%
Daedalus Flapper 	11.8g	22%	27%

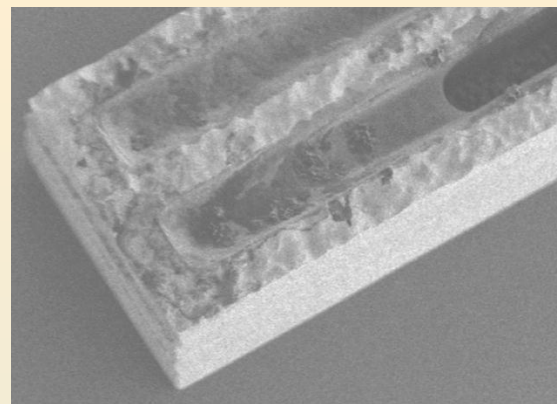
3D Copper Micromachining

Air-Core Magnetics



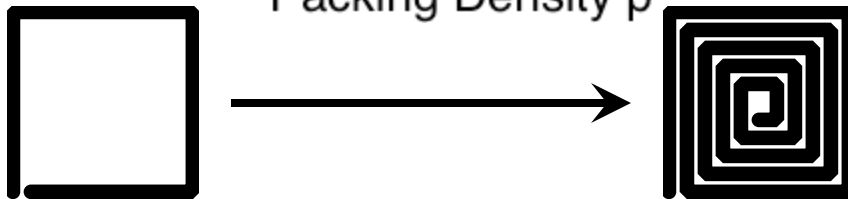
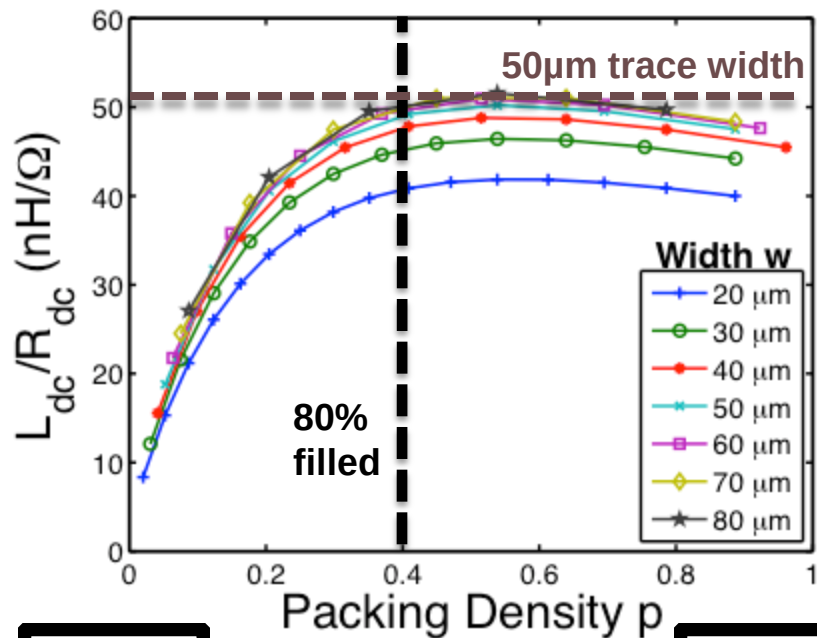
- Optimize coil for 50-500 **MHz** switching.
- Vertical **stacking**.
- **Thick copper** traces.
- **Air gaps** around traces.
- Inductance densities > **100 nH/mm²**.
- Quality factors > 20.

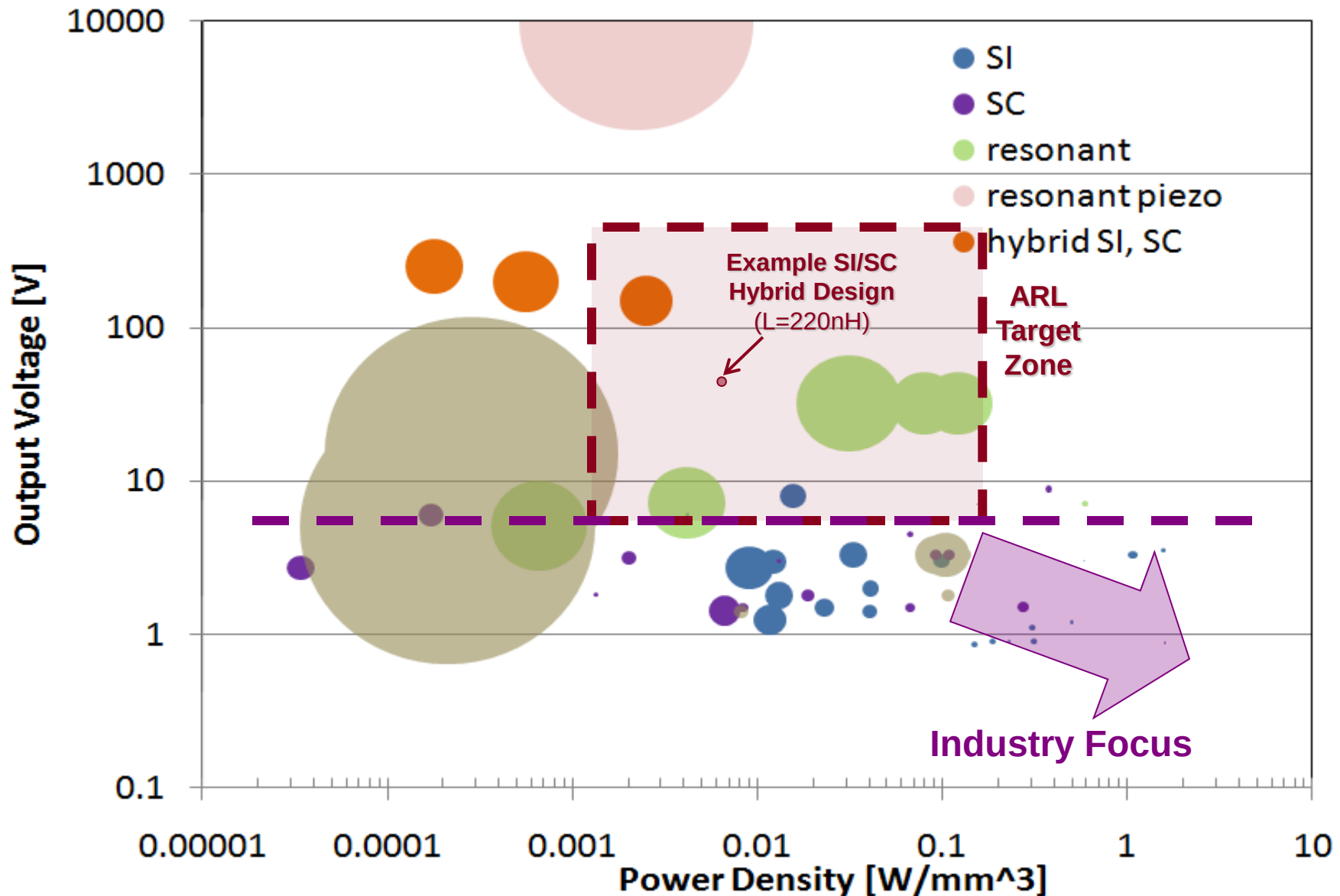
Capillaries for Nanoparticle Deposition



- Nanoparticles with **low loss at MHz**.
- **Fluidic, capillary-driven** packing into mold.
- **Single-step** deposition and patterning.
- Full **encapsulation** of floating structures.
- All **room temperature** process.
- Compatible w/ **any nanoparticle** material.

- Analytical expressions to determine geometry.
 - Mohan, et al, "Simple accurate expressions for planar spiral inductances," *IEEE JSSC*, 1999.
- Stacking for increased density.

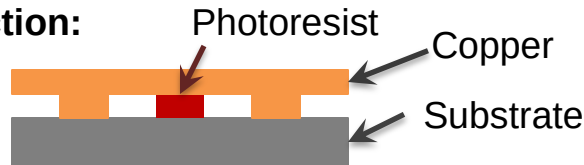




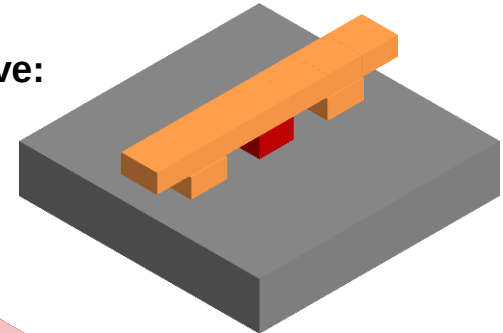


- **Example: Form a copper beam with photoresist support post.**

Cross section:



Perspective:



Sputter Cu seed.

Spin photoresist.

Expose.

Develop.

Expose.

Electroplate.

Sputter Cu seed.

Spin photoresist.

Expose.

Develop.

Expose.

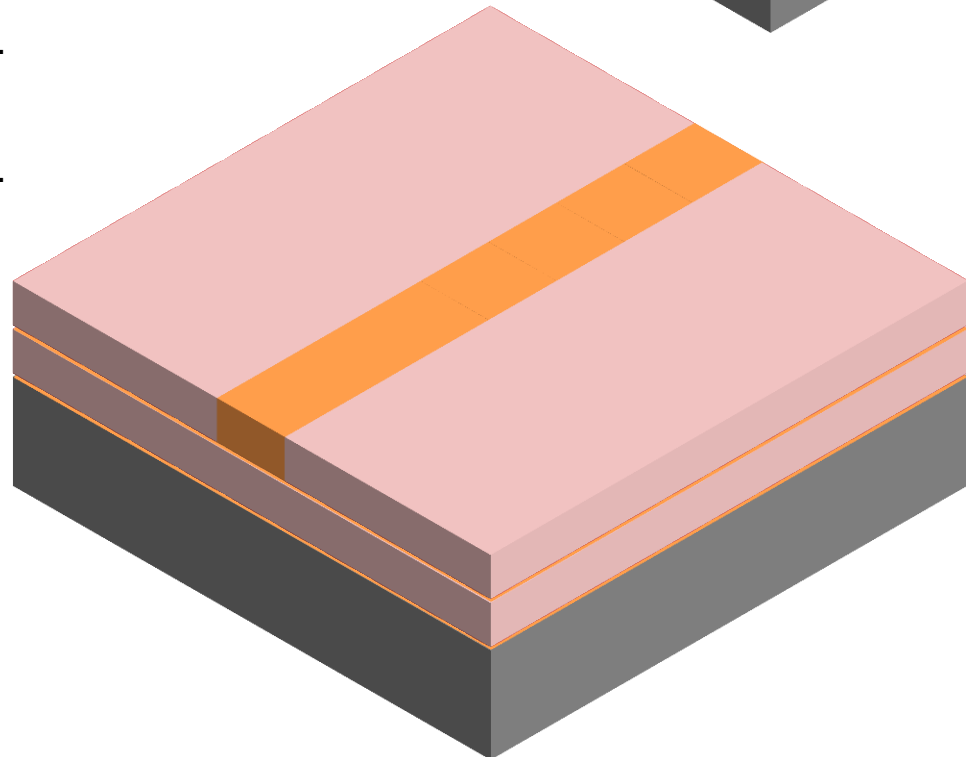
Electroplate.

→ Develop.

Etch seed.

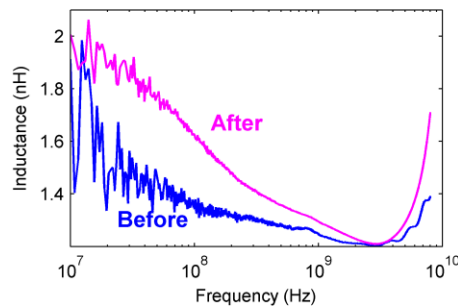
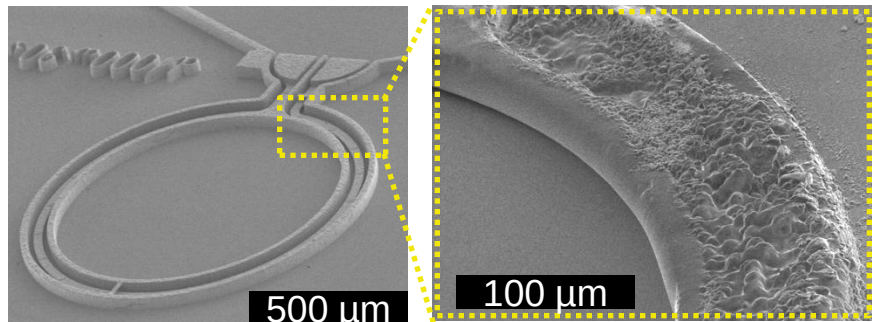
Develop.

Etch seed.



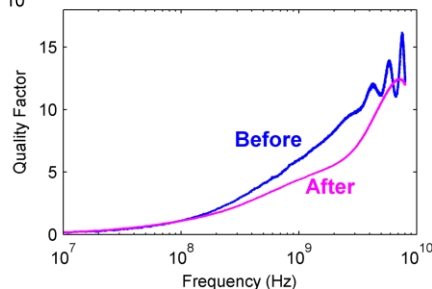
Ring Inductor

- 30 nm NiFe_2O_4 ferrite mixed into IPA, *n*-butanol, diacetone alcohol and B-79 PVB.



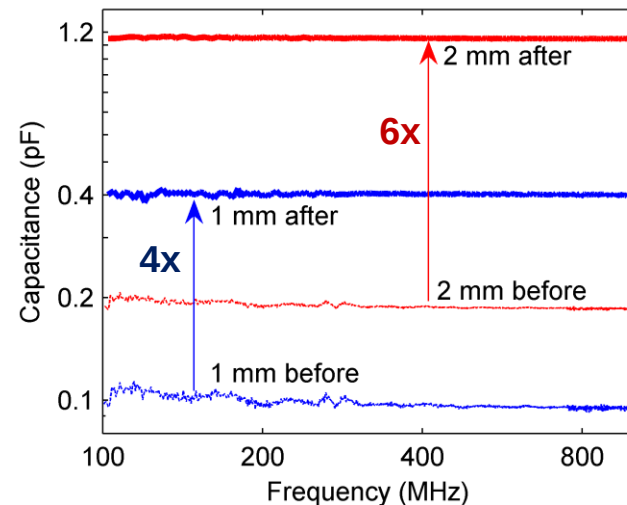
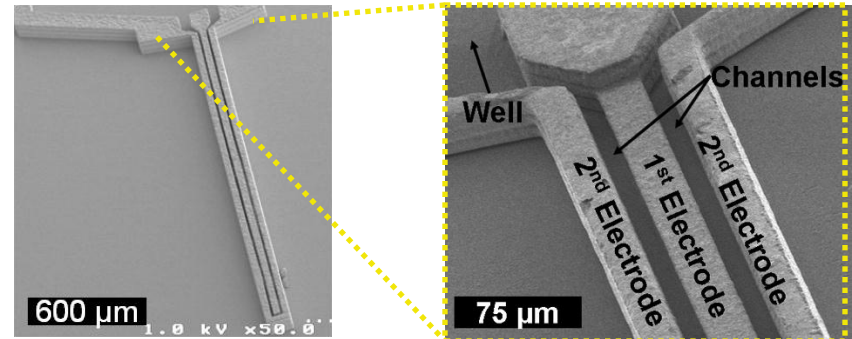
- ~25% inductance boost.

- No detriment to Q up to 100 MHz.



Dual-Channel Parallel Plate Capacitors

- 100 nm BaTiO_3 dielectric mixed into IPA, *n*-butanol, diacetone alcohol and B-79 PVB.



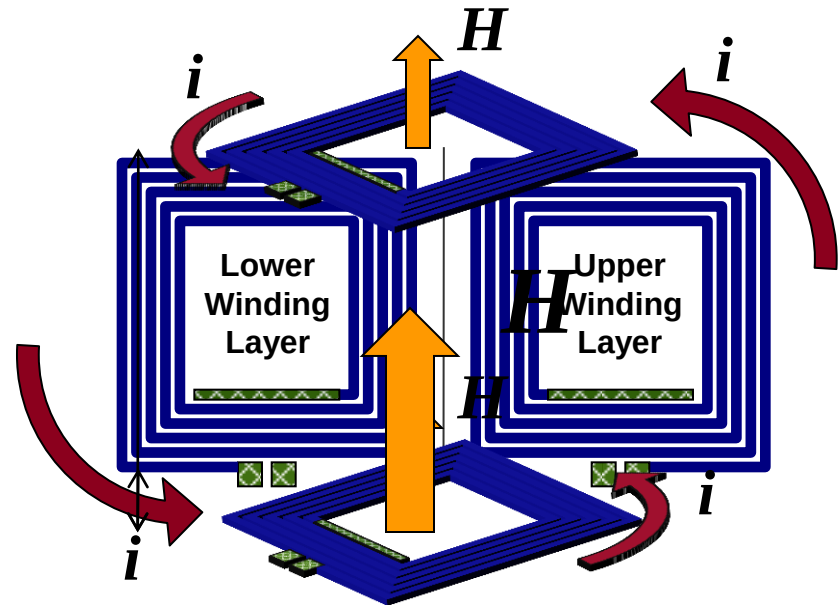
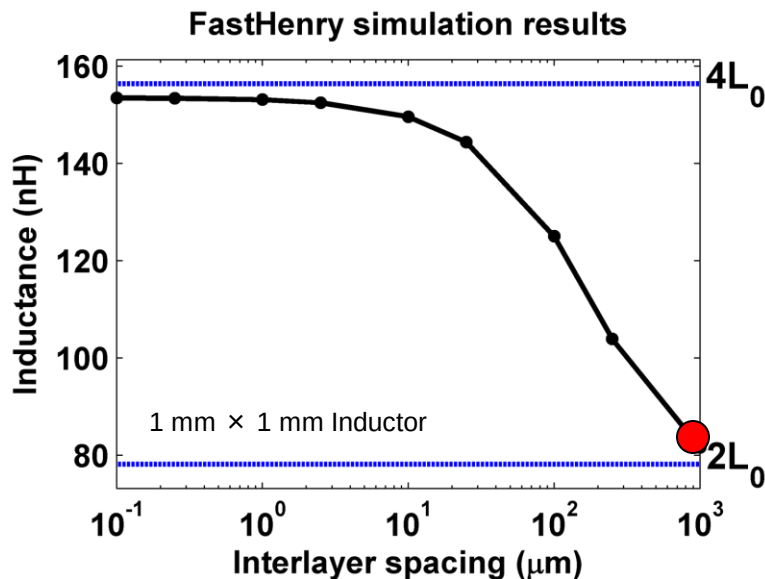
Approach for high Q (>20):

1. Air-core stacked spirals

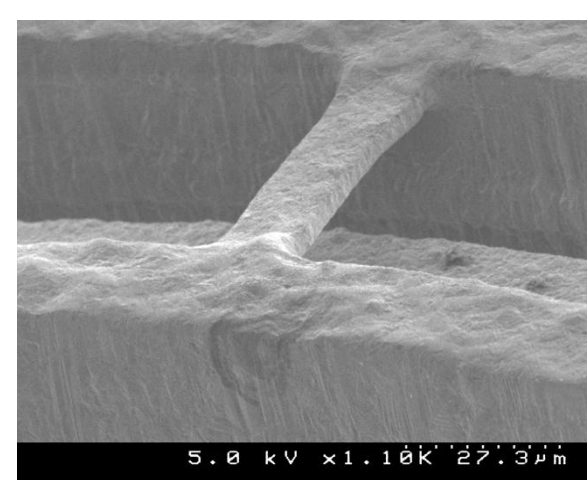
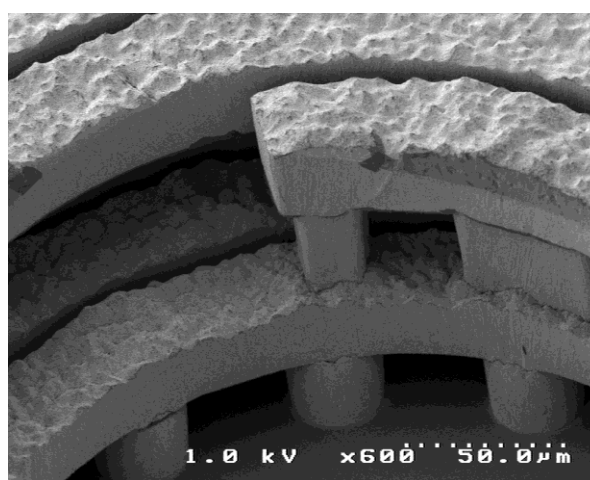
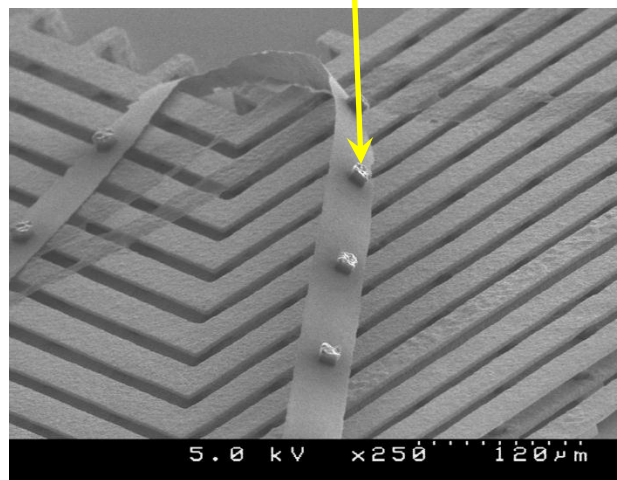
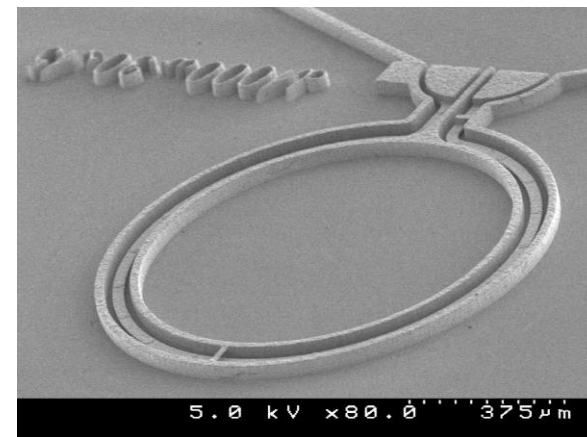
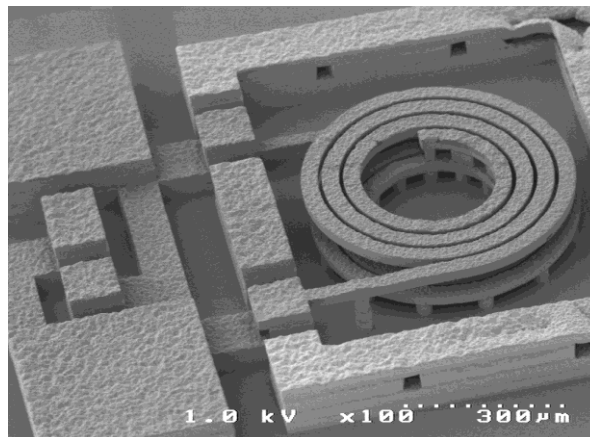
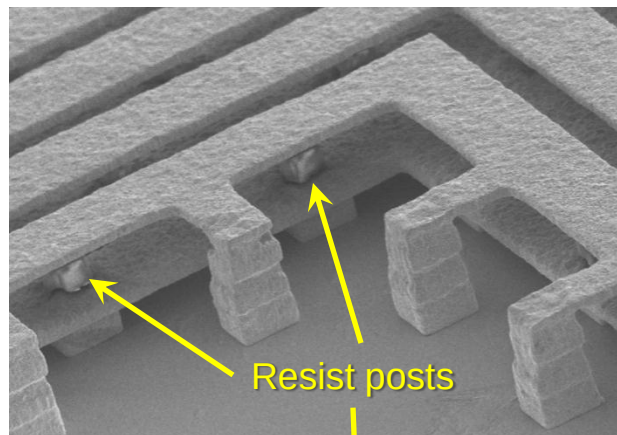
- Eliminates high frequency magnetic losses & magnetic fabrication complexity
- Stacked windings for 4X inductance over single layer [1]

2. Thick Cu traces for low resistance

3. Patterned inter-layer dielectric for low capacitance



[1] Geen, et al., "Miniature Multilayer Spiral Inductors for GaAs MMICs," GaAs IC, 1989.



10um Cu,
Resist posts

30um Cu,
no posts

10um Cu,
microfluidic channels

Advantages

- High piezoelectric coefficients
- Piezoelectricity scales well with thinner films
- High electromechanical coupling coefficients

Disadvantages

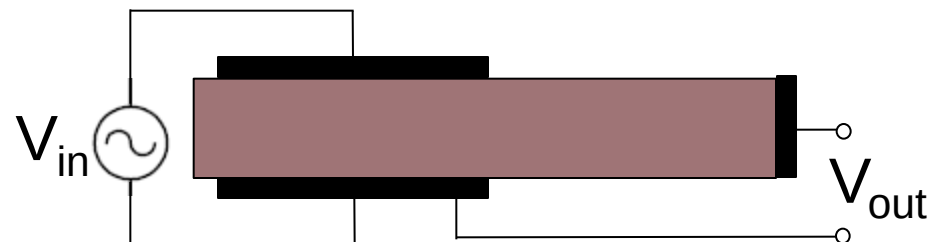
- New materials set for many clean rooms (both piezoelectric and electrode)
- Few foundries for ferroelectric films
- Comparatively high processing temperatures

	ZnO	AlN	PZT 52/48
$\epsilon_{33, f}$	8 - 12	10.4	900 - 1300
$d_{33, f}$ (pC/N)	10 - 12	3.4 - 3.9	90- 110
$e_{31, f}$ (C/m ²)	-0.43 to -0.8	-0.9 to -1.0	-10 to -18
$k^2_{p, f}$	0.06 - 0.085	0.065 - 0.11	0.1-0.20

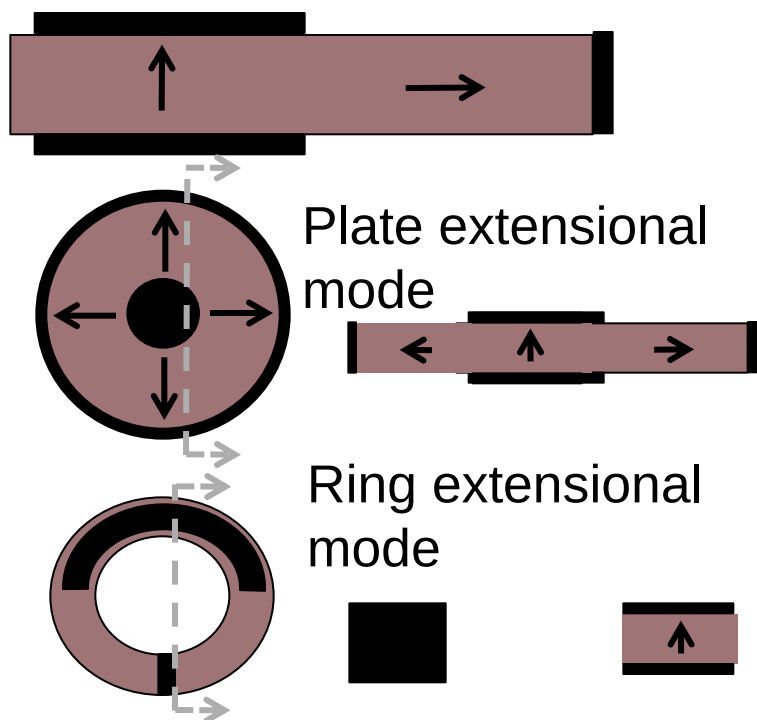
P. Muralt, IEEE Trans. UFFC 903 (2000)

$$k^2 = \frac{\text{Mechanical Stored Energy}}{\text{Electrical Input Energy}}$$

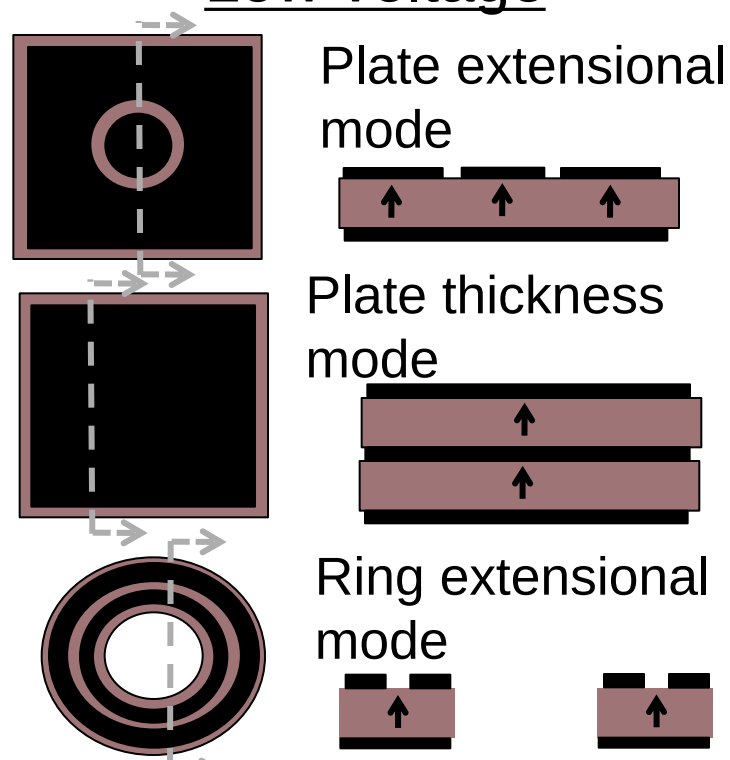
- Wide variety of modes
- Rosen, traditional type, but difficult to realize using traditional fabrication



High voltage



Low voltage

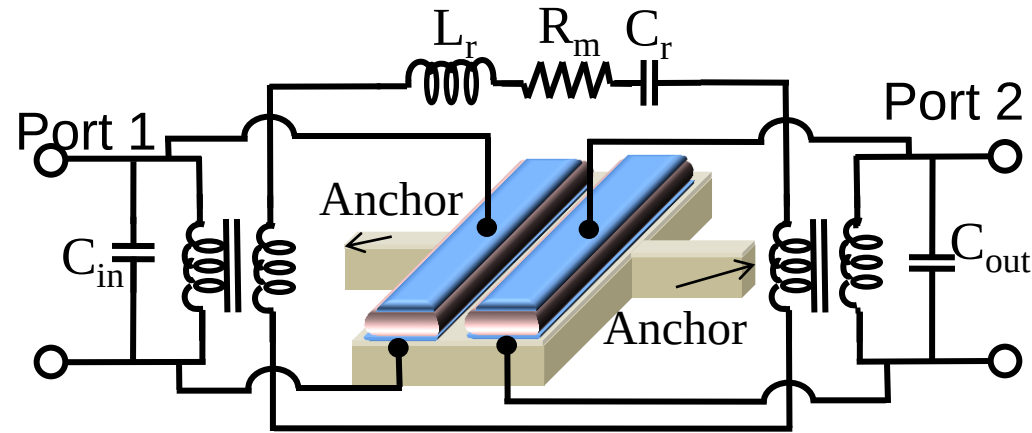


Modal force

$$F_1 \propto e_{31} V_1 A_{in}$$

Charge on output

$$Q_2 \propto e_{31} \bar{Z} A_{out}$$



Electromechanical coupling coefficient – input & output

$$\eta_{in} \propto e_{31} A_{in}$$

$$\eta_{out} \propto e_{31} A_{out}$$

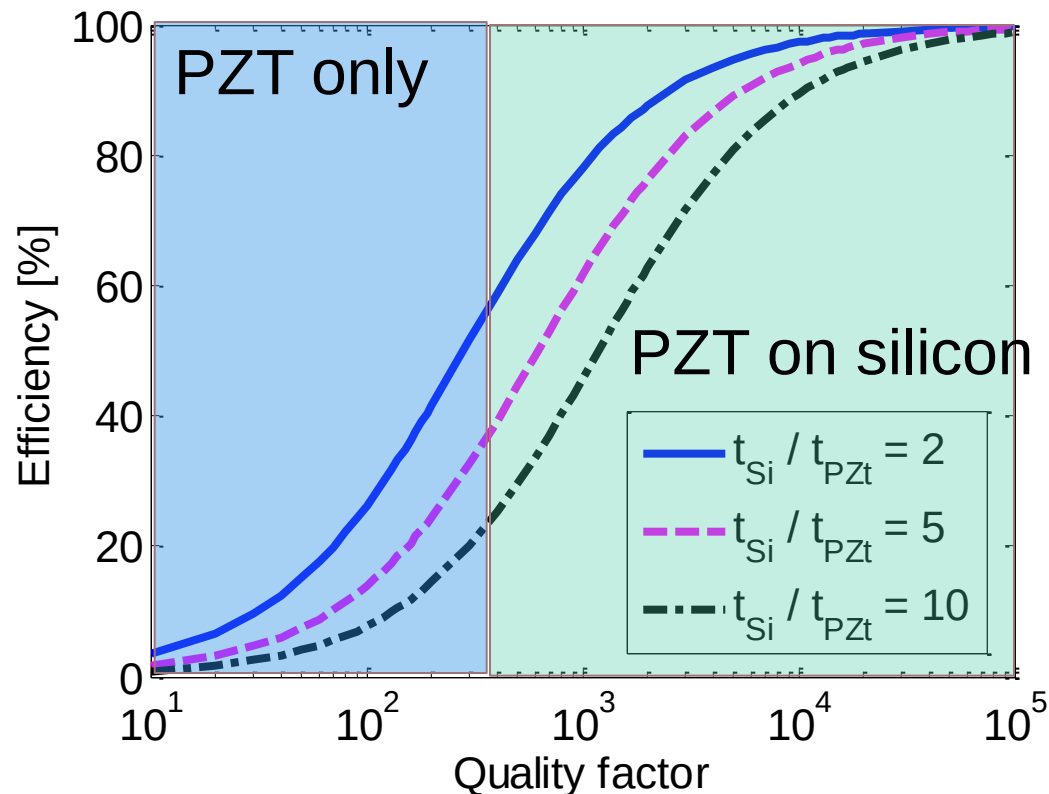
R, L, C equivalence

$$L_r = \frac{mass}{\eta_{in} \eta_{out}} \quad C_r = \frac{\eta_{in} \eta_{out}}{k_n}$$

$$R_m = \frac{n \pi A_x \sqrt{E_i \rho_m}}{2Q} \frac{1}{\eta_{in} \eta_{out}}$$

- Efficiency versus Q factor, $k_{31} = 0.3$
- PZT only $Q < 400$
- With silicon, trade Q for effective electromechanical coupling factor

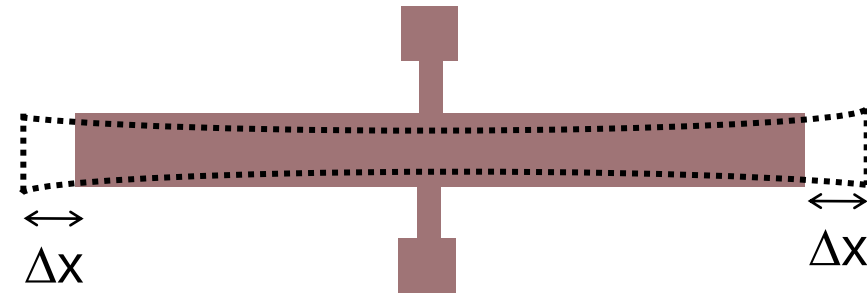
$$\eta = \frac{R_o''}{R_o'' + R_m} = \frac{1}{1 + \frac{n^2 \pi^2}{2Q} \frac{1}{k_{31}^2} \left(1 + \frac{t_{Si}}{t_{PZT}} \frac{E_{Si}}{E_{PZT}} \right)}$$



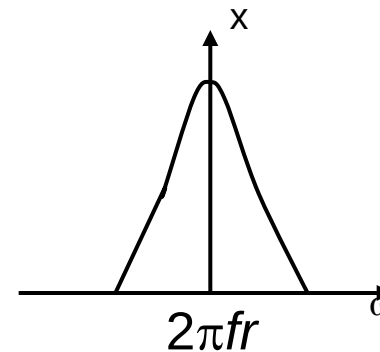
- Critical vibration amplitude, x_{cr} , from a critical strain, ε_{cr}
- Mechanical energy stored per cycle

$$E_m = \frac{1}{2} k_o x_{cr}^2 \propto E_c A_c x_{cr}^2$$

- With silicon, composite elastic constant, $E_c \gg E_{pzt}$
- Power $\sim E_m * f_r$
- Fundamental tradeoff of efficiency & voltage gain vs. power handling vs. Q
- Lower thermal resistance to thermal ground
- Non-linearities manifest as spring softening or spring stiffening terms in the frequency response



Linear response



Spring softening
 $k_1 < 1$

$$k = k_o (1 + k_1 x + \dots)$$

