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Thin Film High Frequency Piezoelectric Resonators

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Outline

- Piezoelectric resonators for power regulation: background and motivation
- Aluminum nitride (AlN) resonators: fabrication, integration and performance
- Lithium niobate (LN) resonators: fabrication and performance
- Concluding remarks

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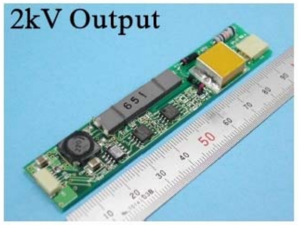
Piezoelectric Resonators for Power Regulation: Background and Motivation

Bulk Piezo-Transformers/Converters

- Early 90s, piezo-transformers offered solution to existing magnetic transformers for CCFL backlighting in LCD displays (laptops, PDAs, cameras, camcorders)
- Advantages
  - Inherent high open circuit gain → providing high lamp ignition voltage
  - Load dependent gain
  - Absence of leakage magnetic field
  - High Q factor
  - Small size and low weight
- ***Bulk piezo-transformers –> still too large for scales of interest***

Commercial DC-DC converters
Nihon Ceratec, Co, LTD., micromechatronics



	PPT04P2020XB1
Size	95×19×7mm
Input Voltage	8V - 14V
Output Voltage	0V - 2000V
Max. Output Power	4W
Max. Efficiency	> 80%
Control Voltage	0V - 10V
Ripple	Max. 0.1%

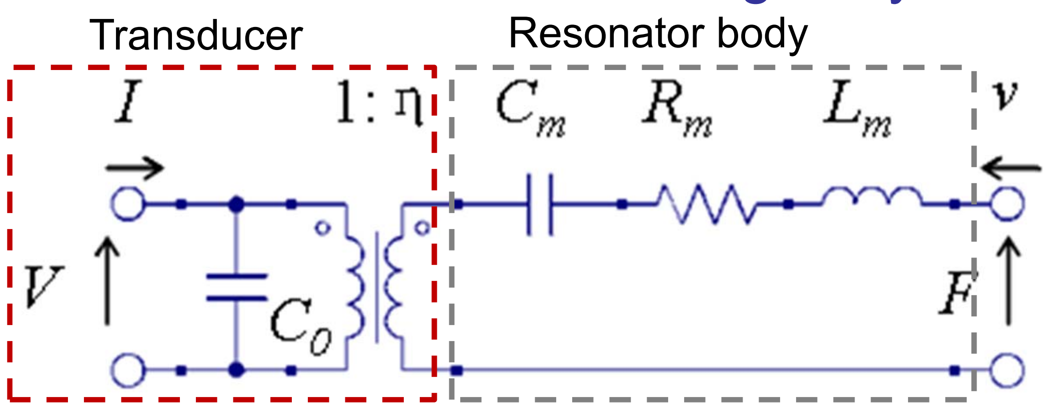
Commercial piezo-transformers
Micromechatronics

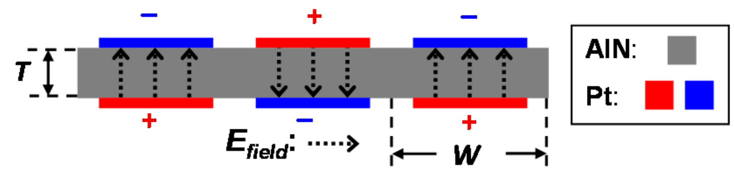
Step down, radial

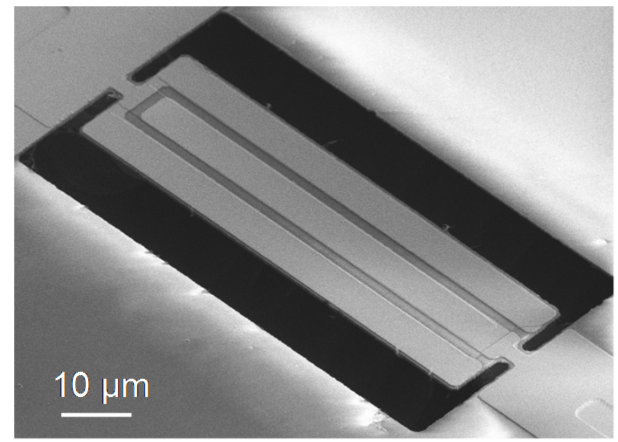
A. Carazo, "50 years of Piezoelectric Transformers: trends in the technology".

Resonator Design: Must Haves

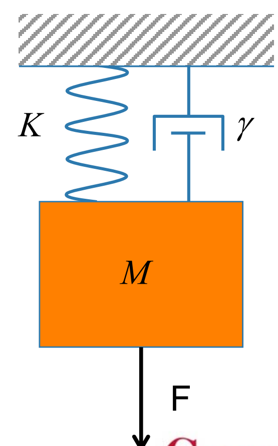
- A mechanical resonator can be seen as formed by a transducer and a resonating body





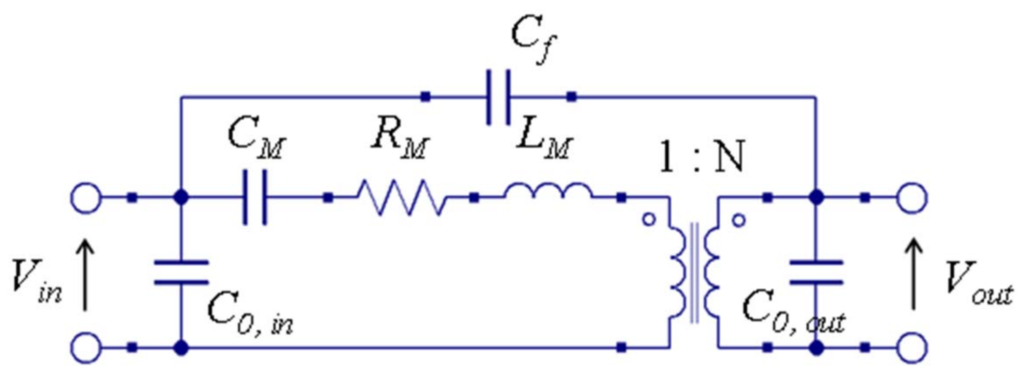


- The transducer converts electrical into mechanical energy and vice versa. Its performance are defined by the electromechanical coupling, $\mathbf{k_t^2}$
- The overall resonator layout, material stack and interfaces affect the energy loss in the resonator. An inverse measure of loss is **Q**.



Resonator Design: Must Haves

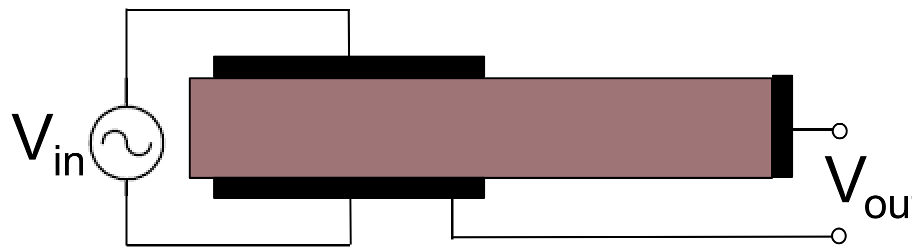
- For a piezoelectric transformer, a two-port model is generally used which takes into account the transformer ratio between input and output

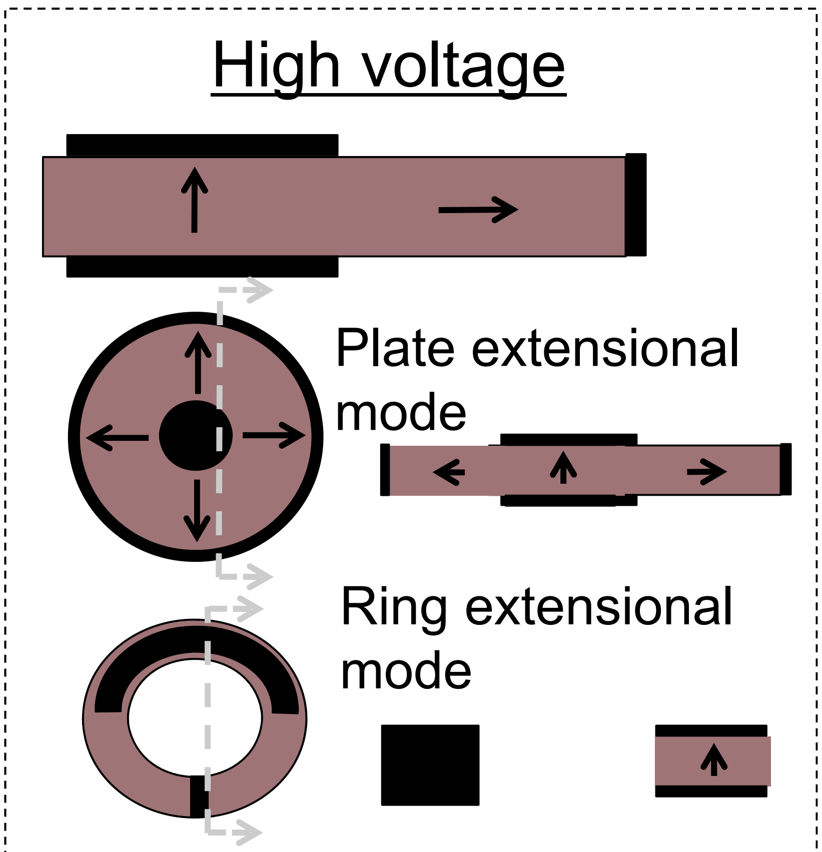


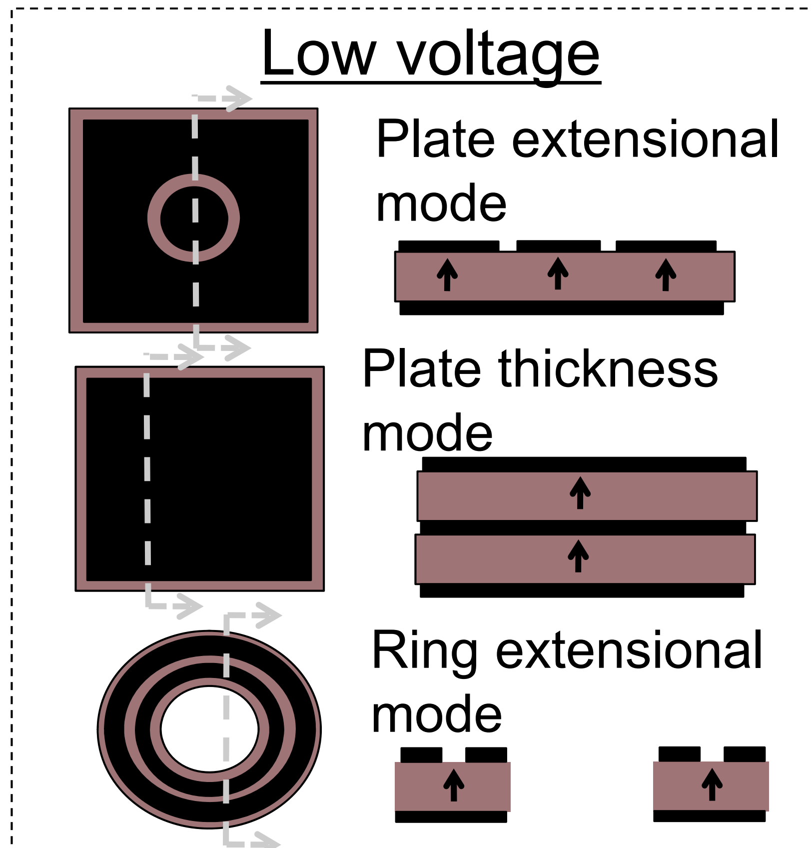
- The Figure Of Merit is given by $k_t^2 \cdot Q$
- k_t^2, and Q are crucial component in setting resonator performance:
  – Value of motional impedance: $R_M \propto \frac{1}{FOM}$
  – Power consumption and phase noise in an oscillator
  – Insertion loss and bandwidth of a filter
  – **Gain and efficiency** of a piezoelectric transformer

Modes of operation

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

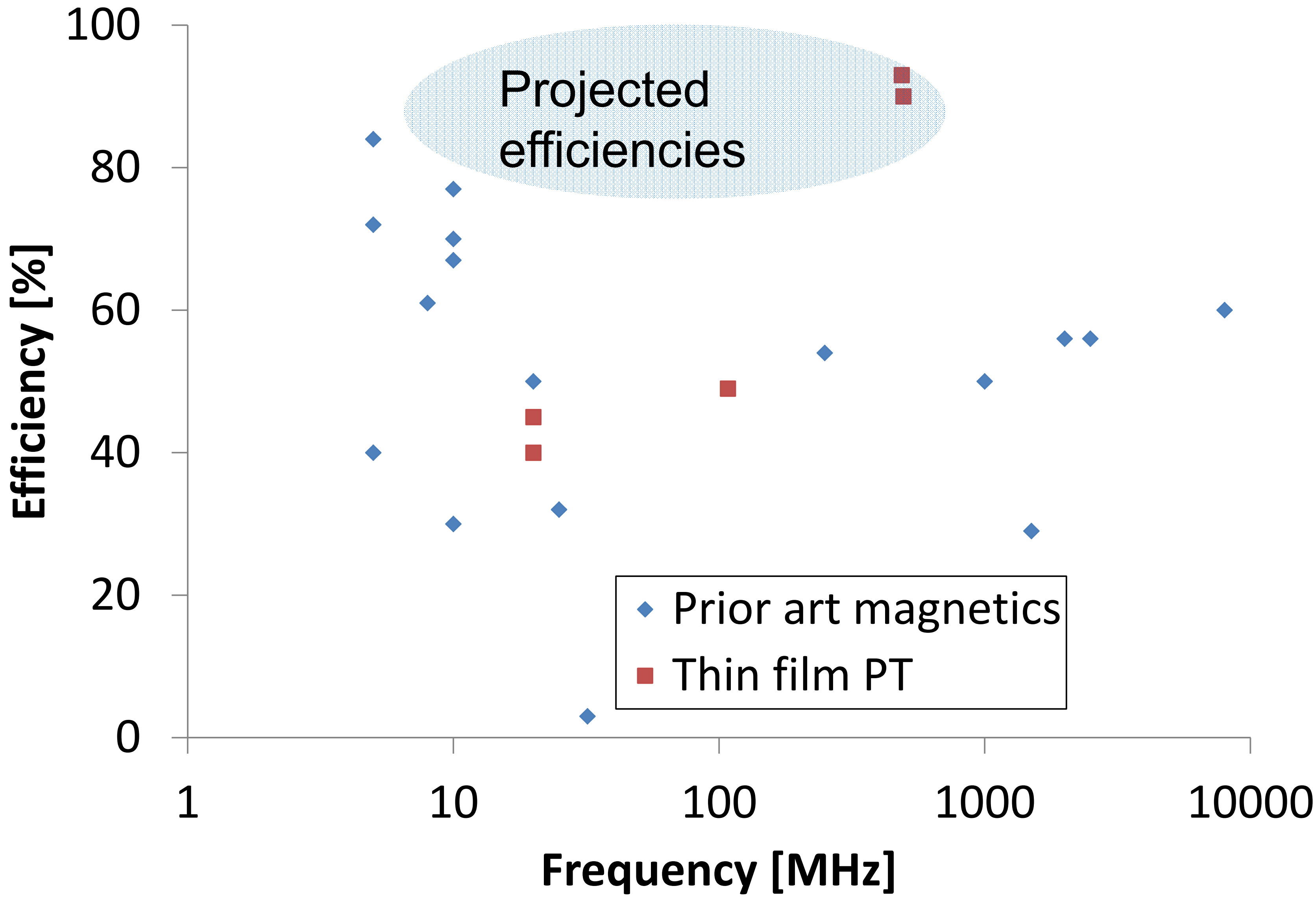






J. Yang, *IEEE TUFFC*, 2007.

Efficiency and Size Advantage



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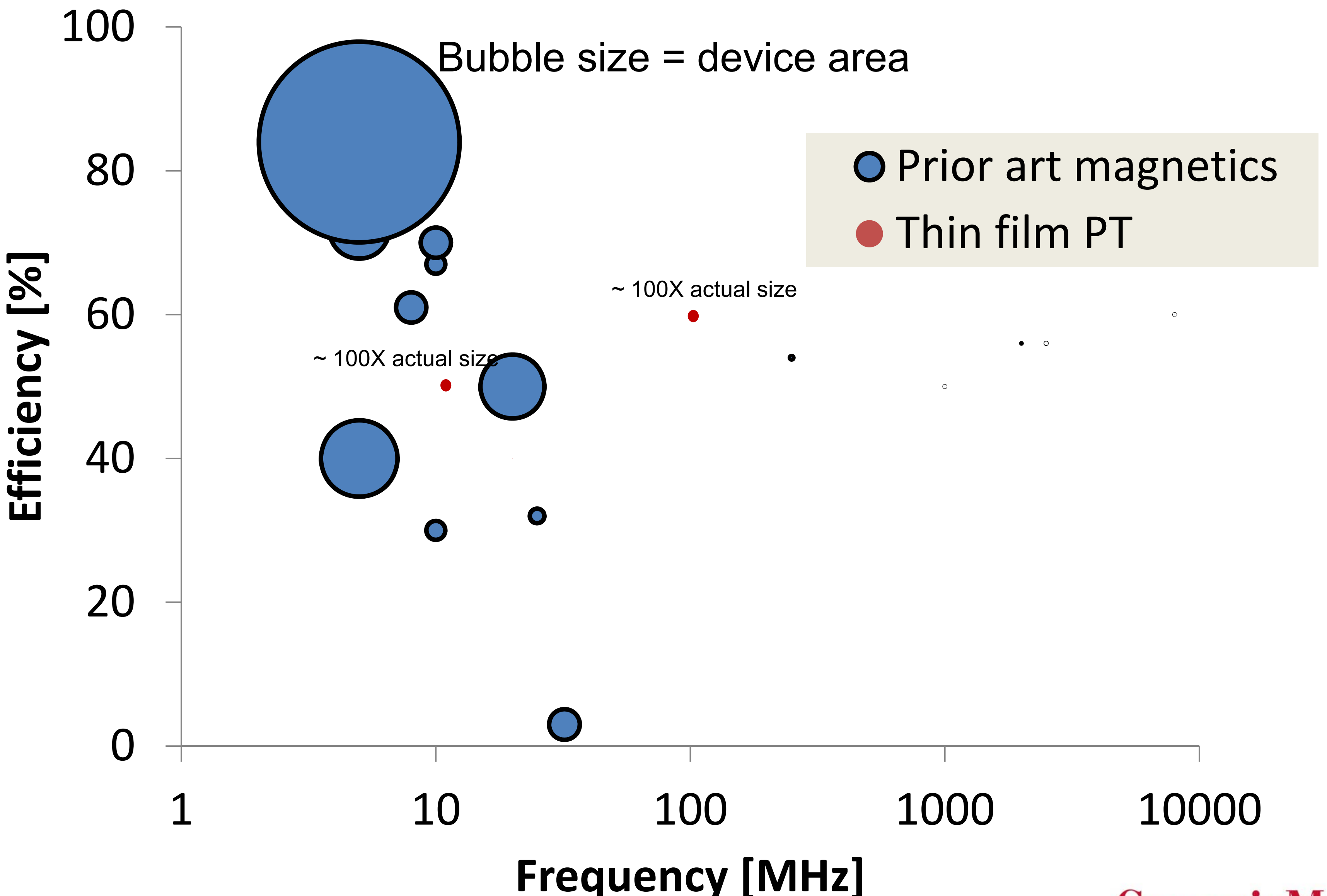
Efficiency and Size Advantage



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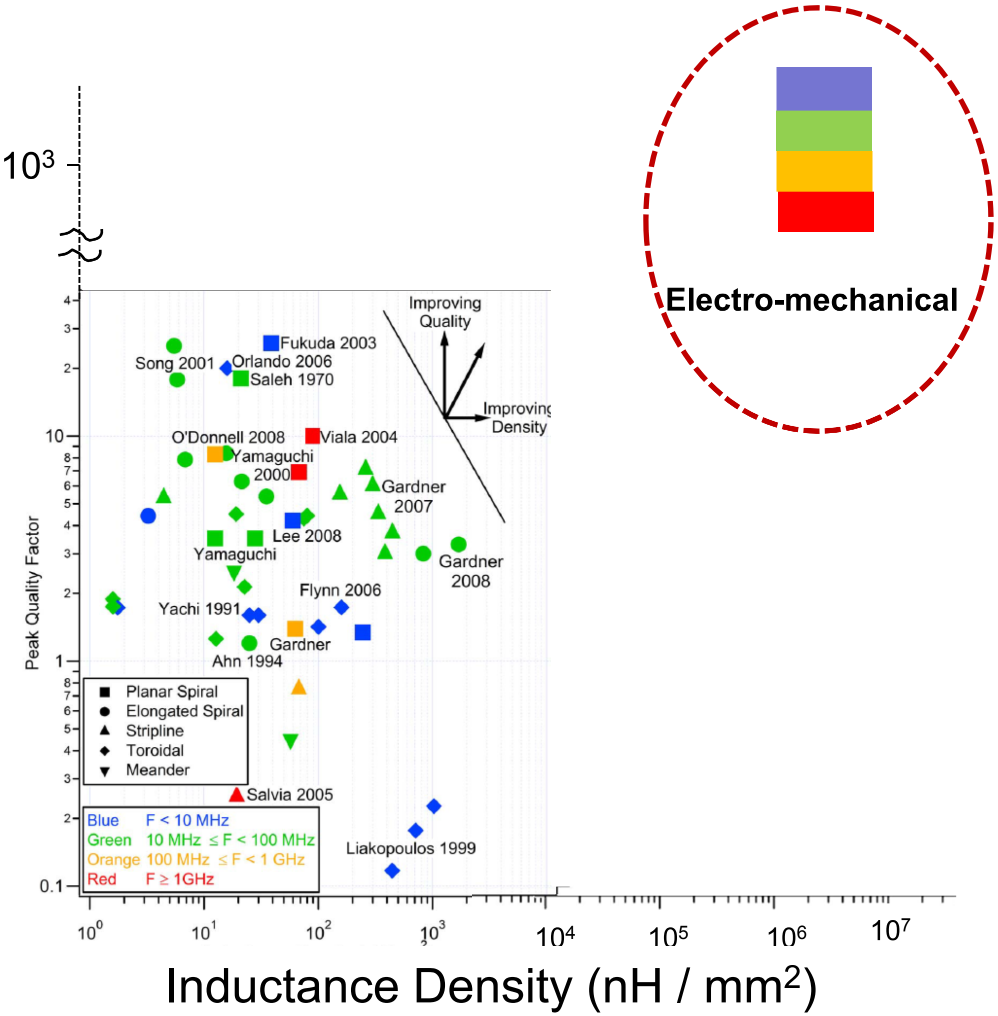
One Port Resonator Inductance Density

- Thin-film piezoelectrics implemented as one-port resonators
- Resonant inverters & resonant gate-drive applications
- Very high inductance densities (>10^6 nH / mm^2) when compared with thin-film, lumped element L's
- Inductances ranging from few nH to several μH with Qs > 1,000 can be easily synthesized



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

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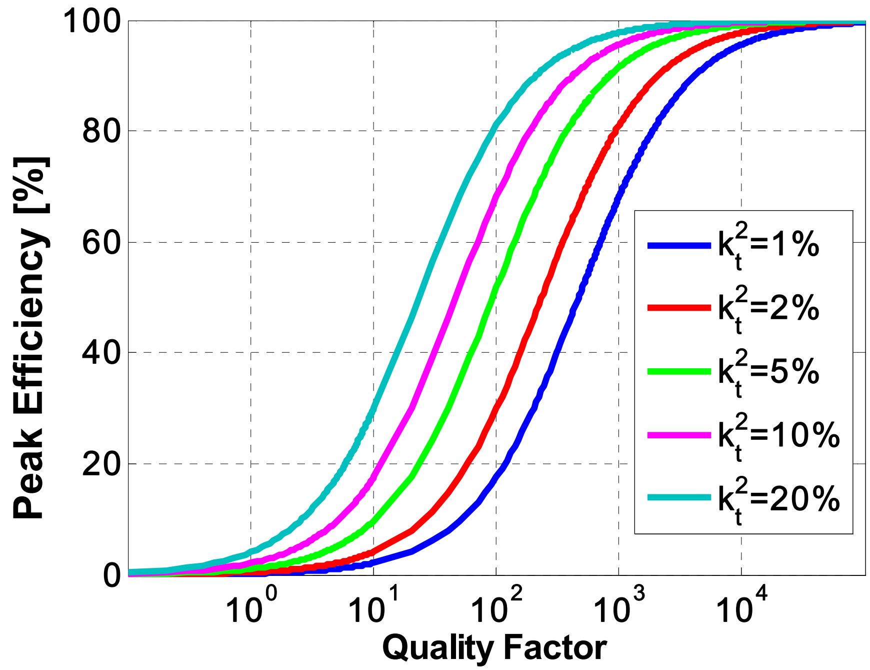
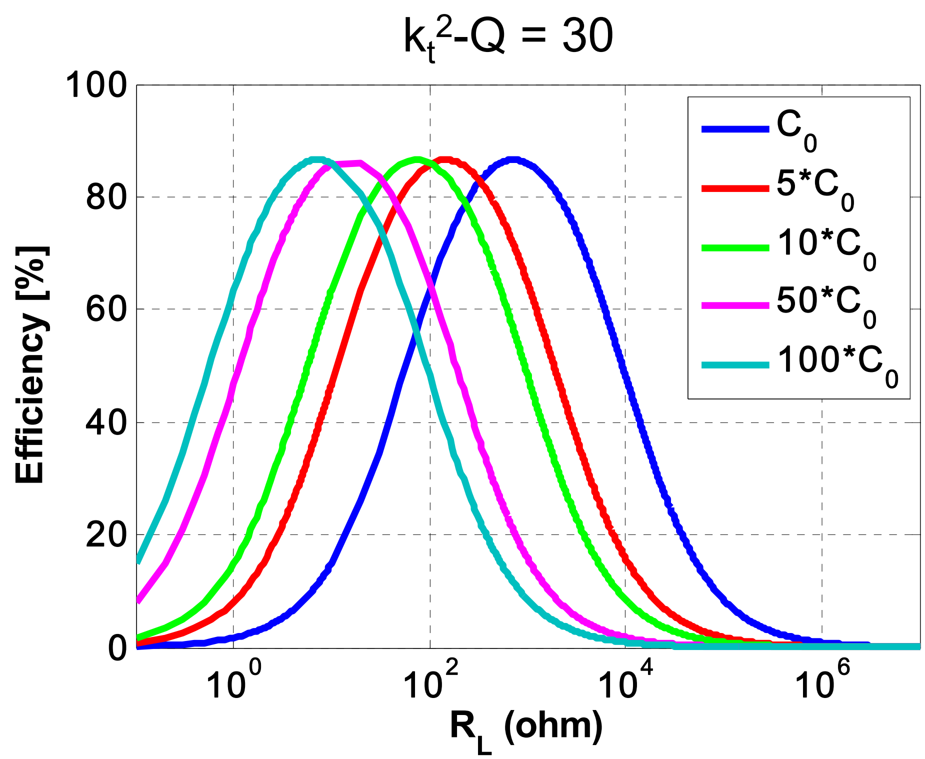
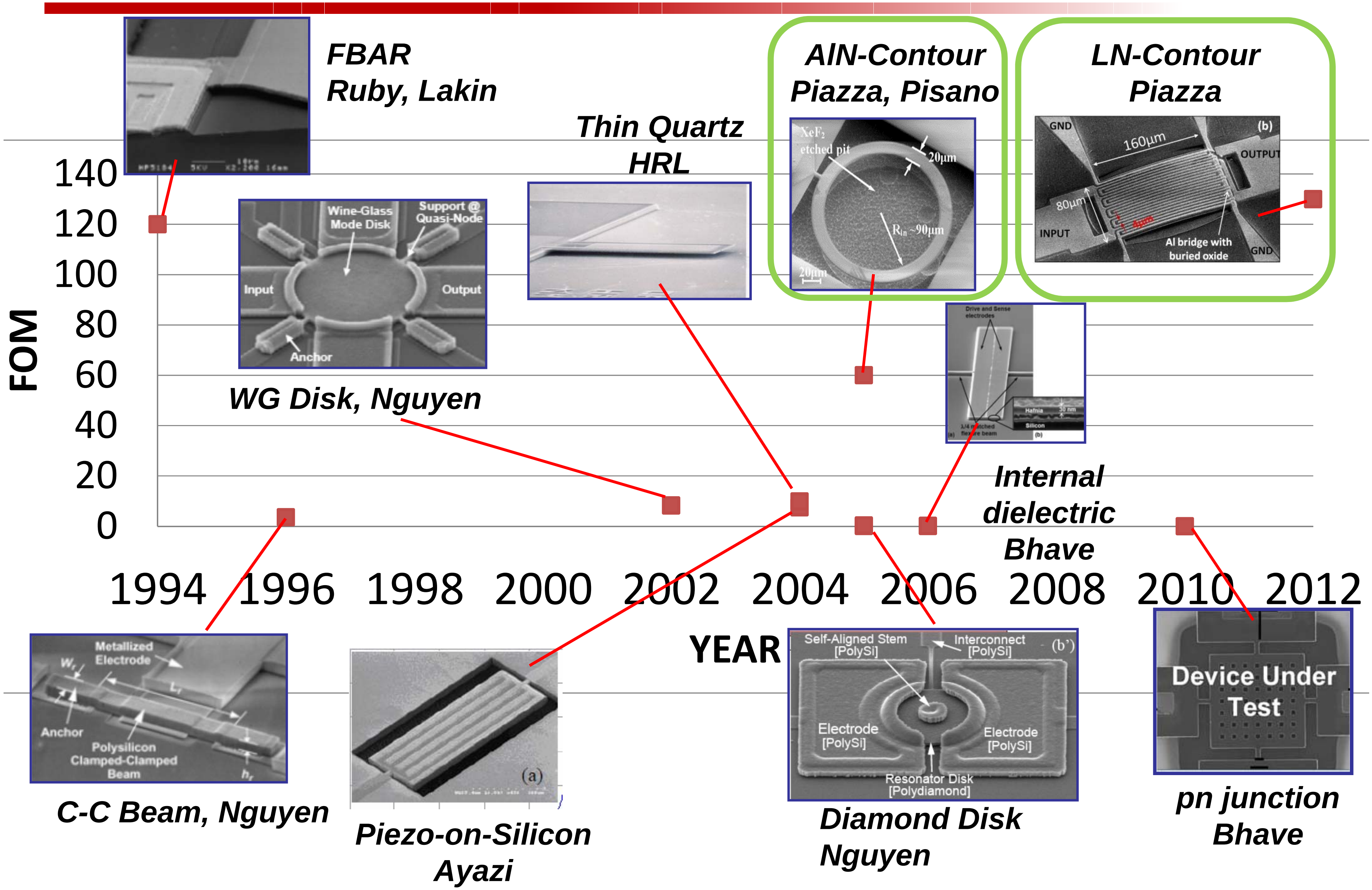
Efficiency vs. Resonator Performance

- Thin film PT efficiency vs. resonator FoM
- Efficiency vs. load can be designed for by changing the resonator characteristic impedance (device sizing)





FOM Comparison



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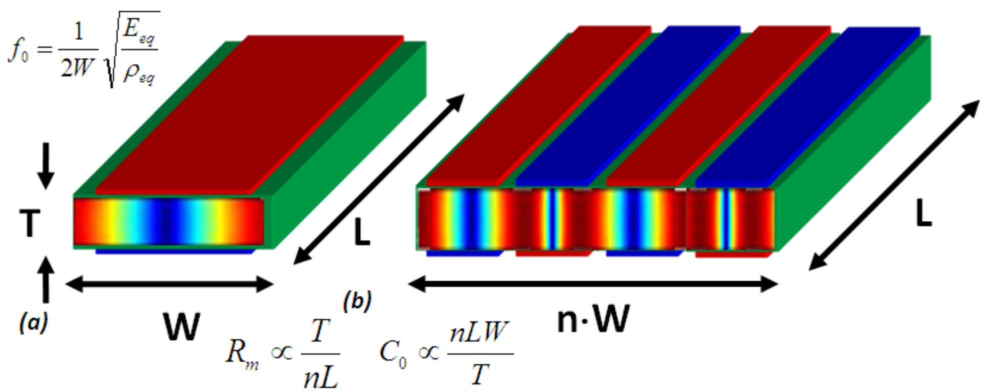
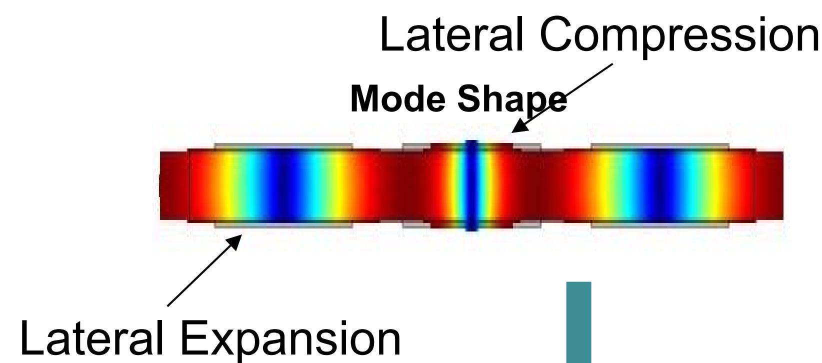
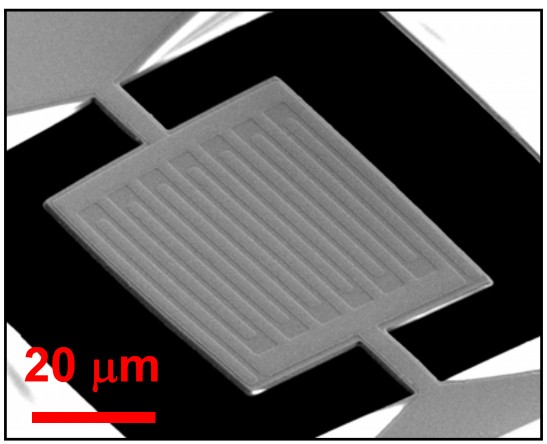
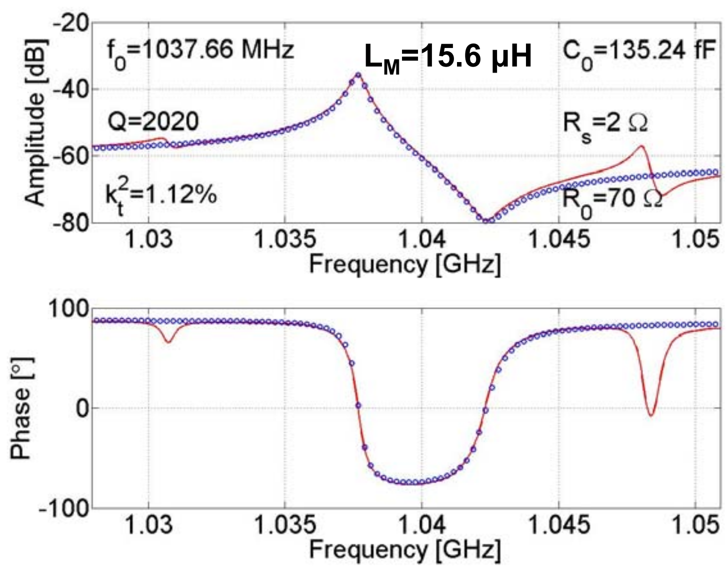
Aluminum Nitride Resonators

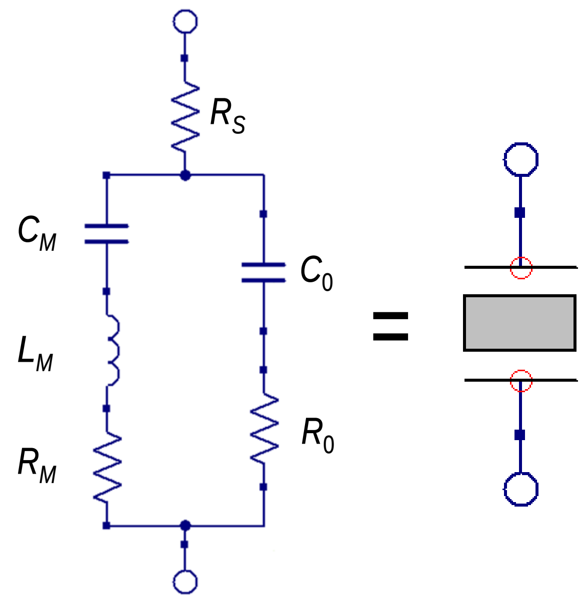
AlN Contour-Mode Resonator (CMR)











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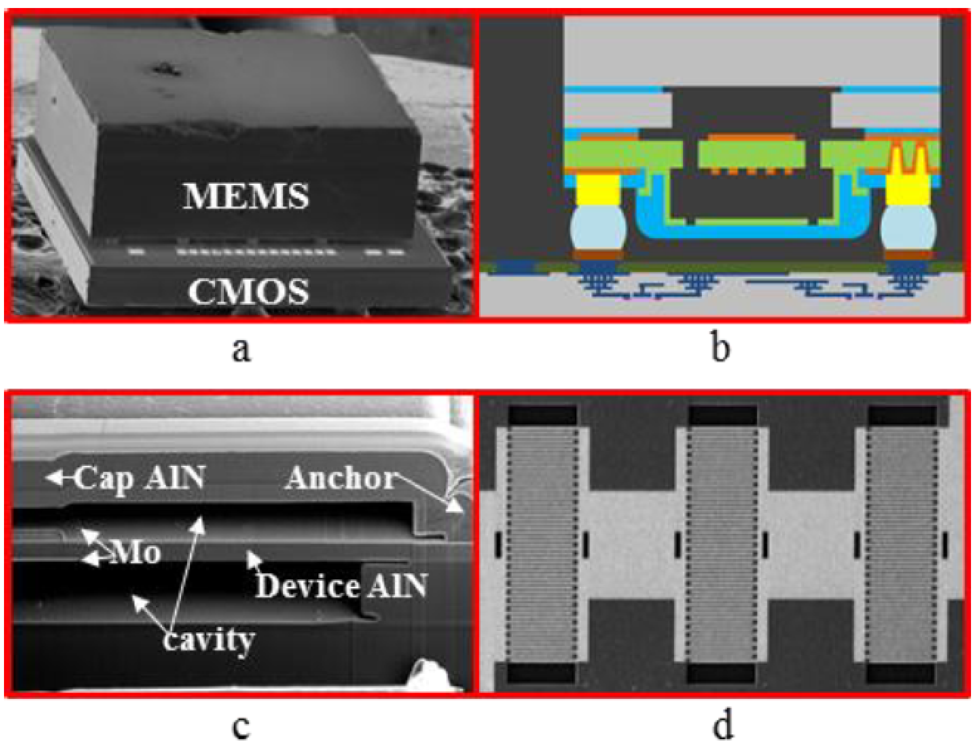
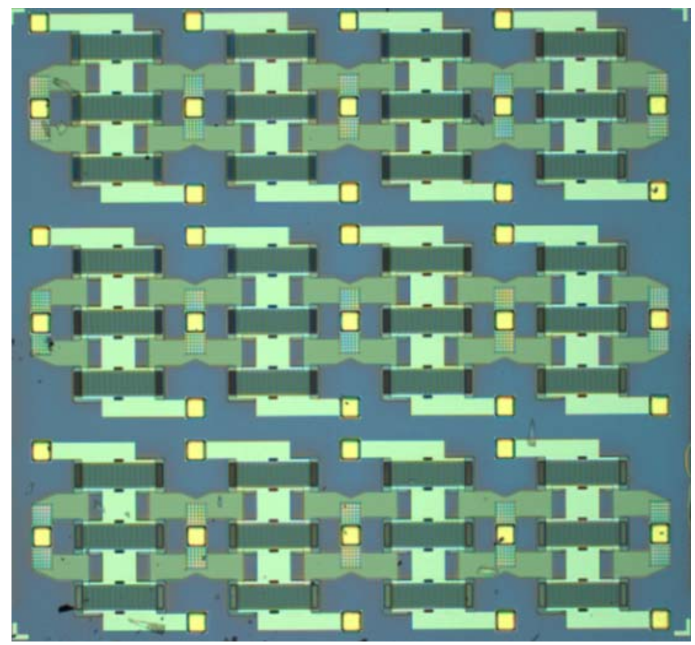
AlN CMR Fabrication

- Process is intrinsically CMOS-compatible as it uses low temperature AlN sputtering and metals
- Currently working with Institute of MicroElectronics (IME) in Singapore to transfer process on 8” wafers and enable heterogeneous integration with CMOS (funded by IARPA)





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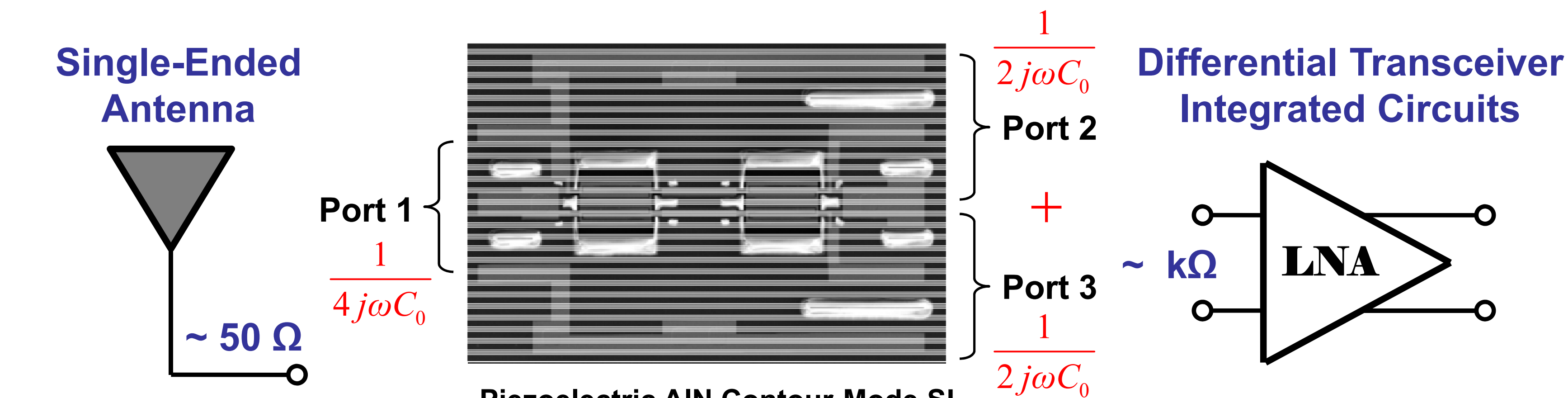
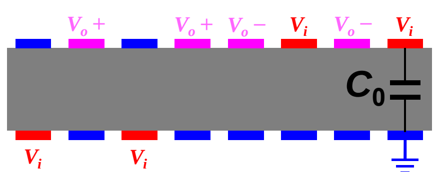
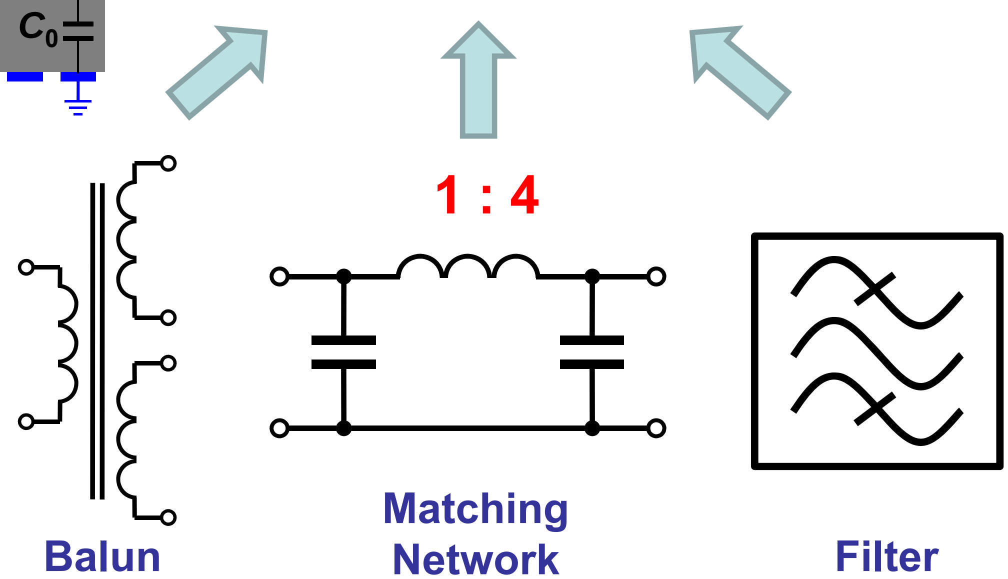
High Frequency Impedance Transformation



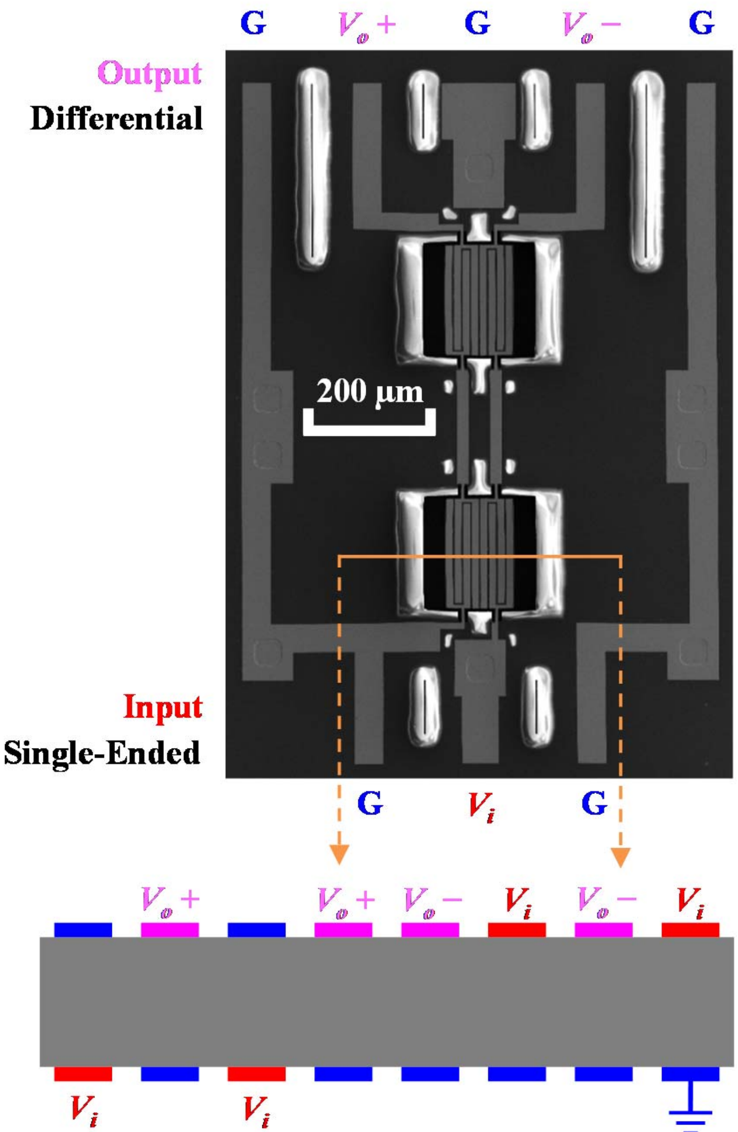
Piezoelectric AlN Contour-Mode SL Single-Ended-to-Differential Filter

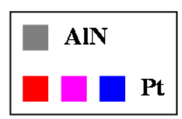




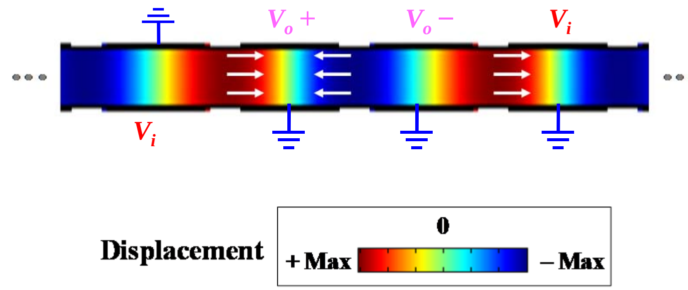
- Multi-Frequency: **272 MHz – 947 MHz**
- Low Insertion Loss: **1.9 dB for 1st order** **2.5 dB for 2nd order**
- High Rejection: **53 dB for 2nd order**
- High CM Suppression **33 dB for 2nd order**

High Frequency Impedance Transformation





All blue electrodes are grounded



- Electrodes are patterned and routed so as to ensure optimal coupling and single-ended to differential operation
- Single-ended to differential output enables 1:4 impedance transformation
- Single-ended to single-ended configuration can be easily implemented if more amenable to power converters

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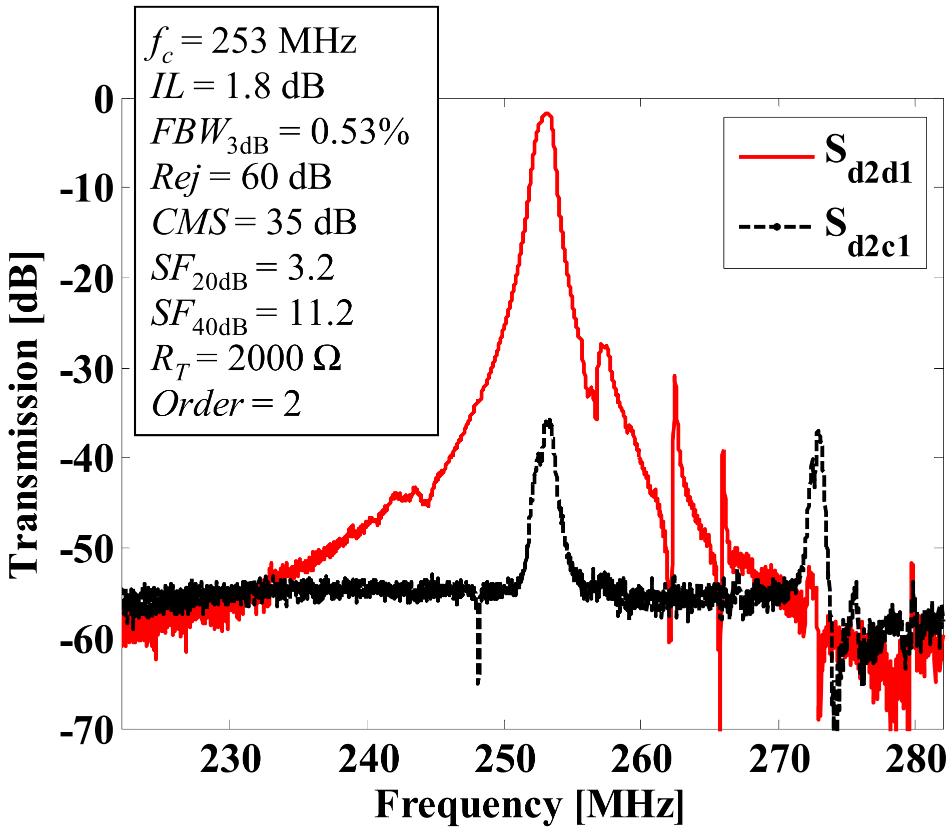
High Frequency Impedance Transformation



- Low loss transformation with properly matched load
- This device exhibited a FoM around 60 (typical value for this class of resonators).
- Impedance transformation demo'ed at 253 MHz, but individual resonators have been shown to work with the same performance up to few GHz

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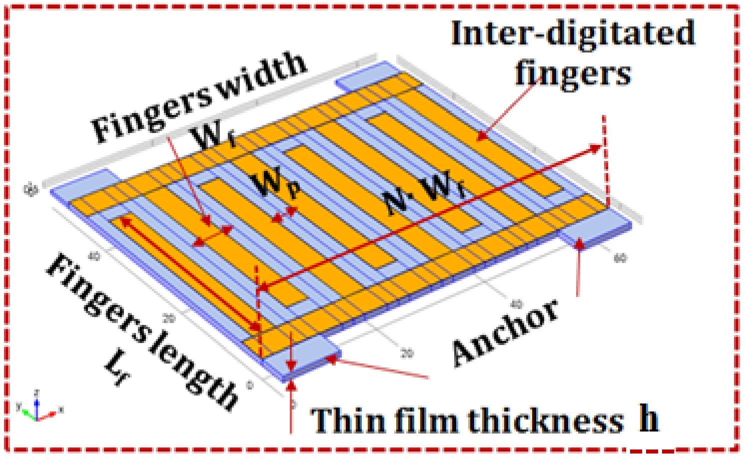
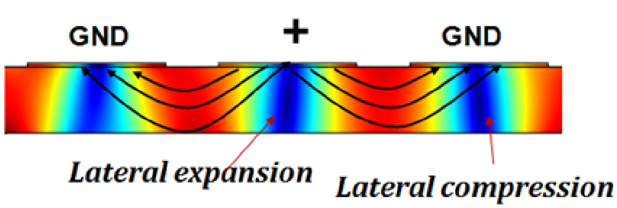
Lithium Niobate Resonators

$LiNbO_3$ Resonator: Device Design

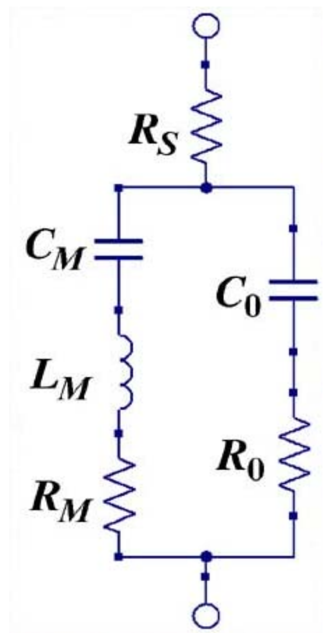
3D drawing of a typical LFE micro-resonator

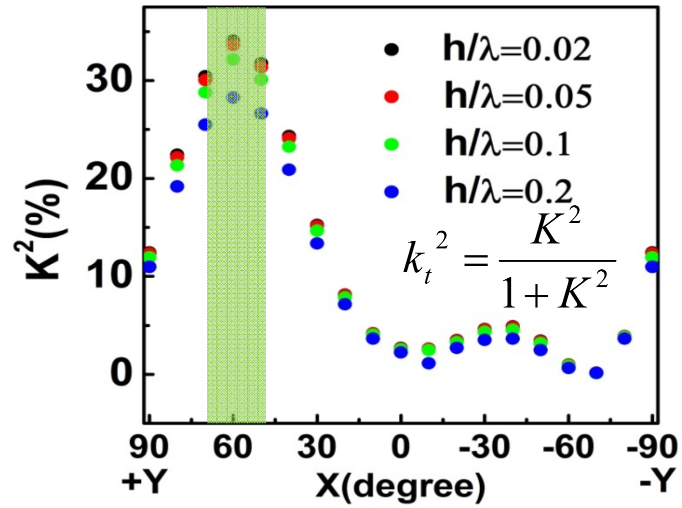


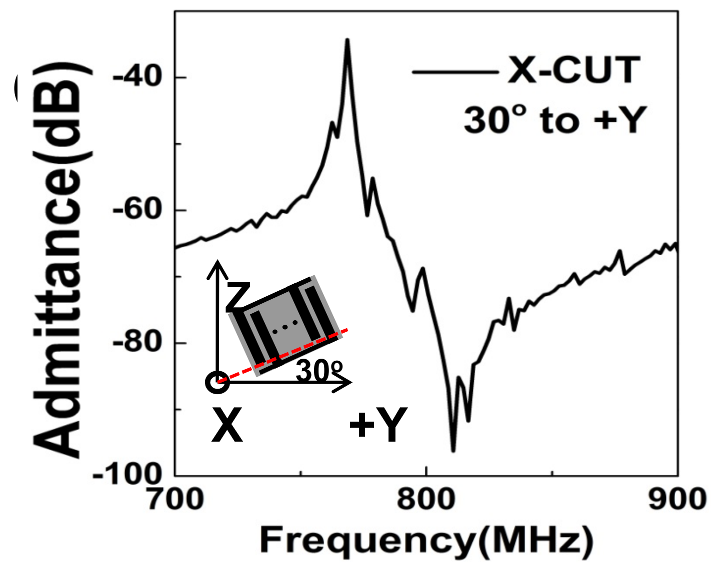
Vibration mode shapes



MBVD Model

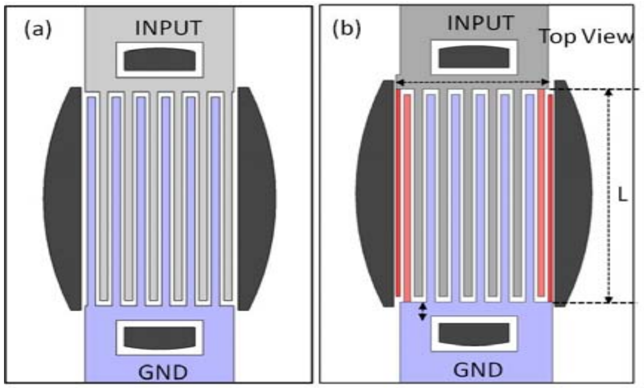


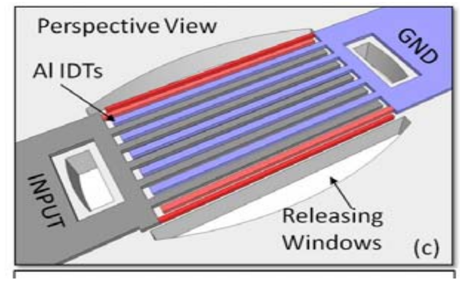


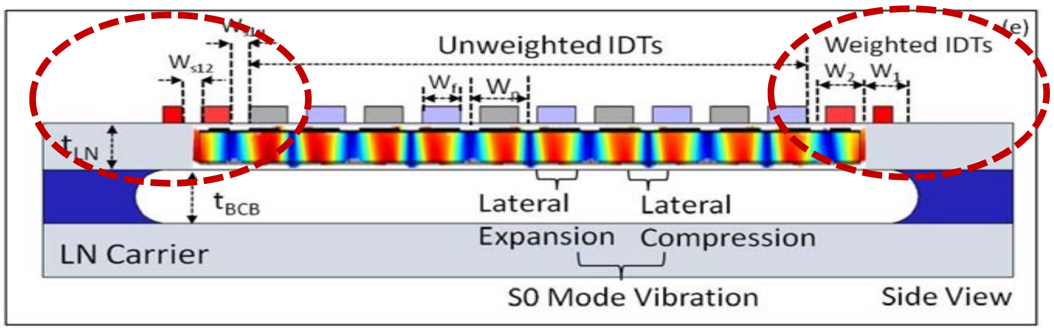


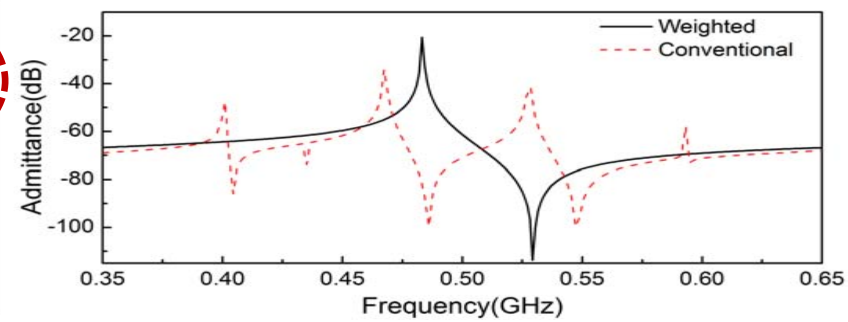
$$f_0 = \frac{1}{2W}\sqrt{\frac{E_{eq}}{\rho_{eq}}} \qquad C_0 \propto f(W_f, L_f, W_p) \qquad R_m \propto \frac{1}{k_t^2 \cdot Q \cdot C_0}$$

Weighted Finger Design









- Electric and acoustic boundary conditions define maximum energy coupling in the main mode of vibration
- A weighted finger design is used to improve device tolerances to process variations

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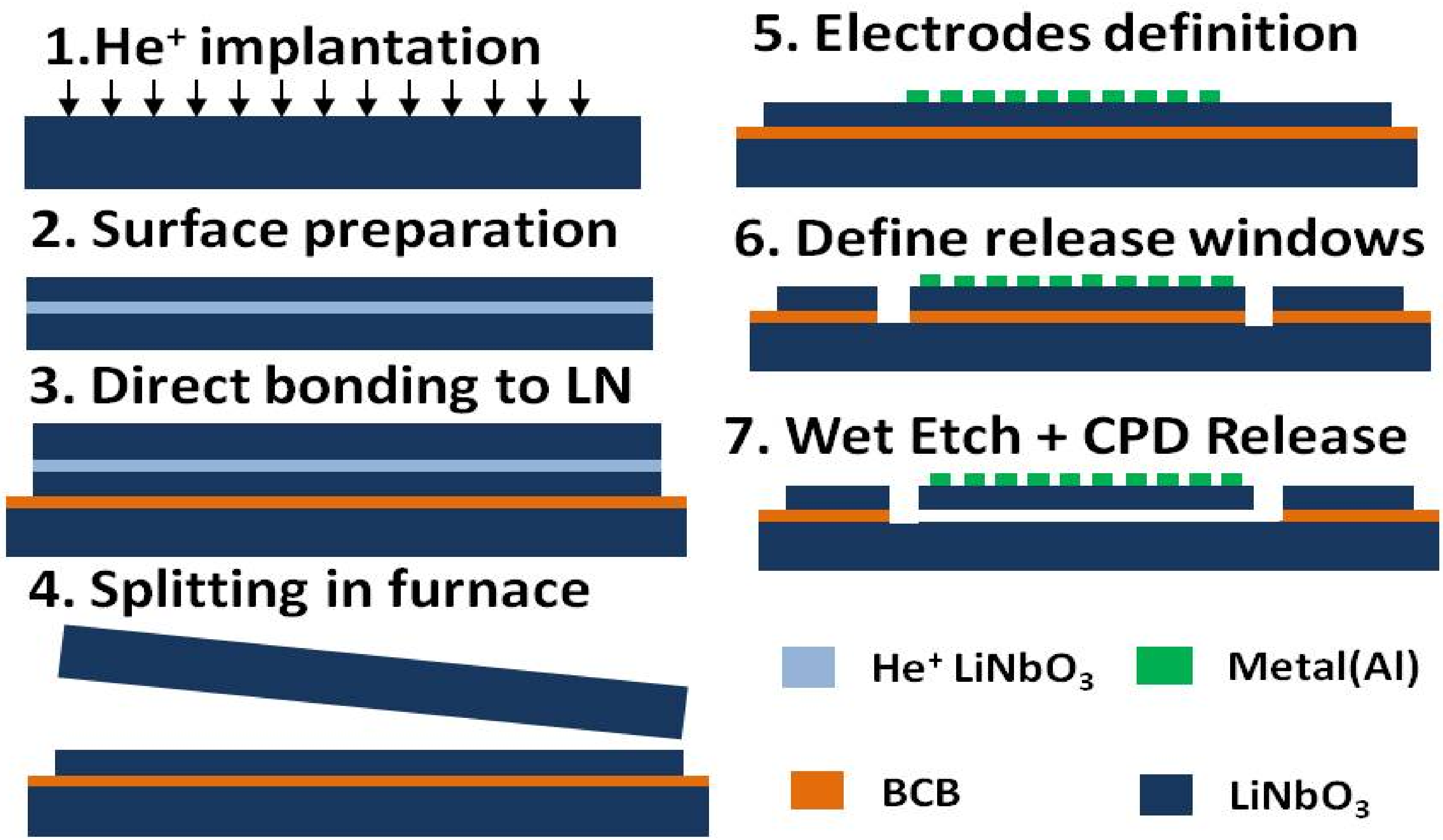
LN Laterally Vibrating Resonators



- Based on ion slicing technique (as SOI)
- Attains films of bulk quality

- Low temp process
- Leverages conventional micromachining techniques

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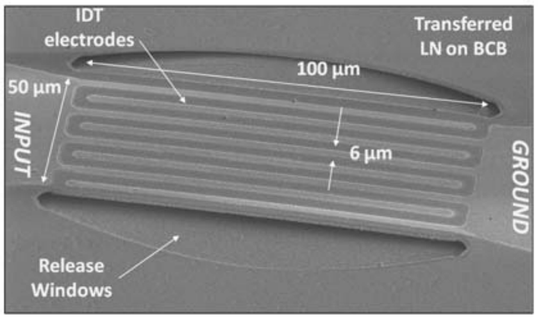
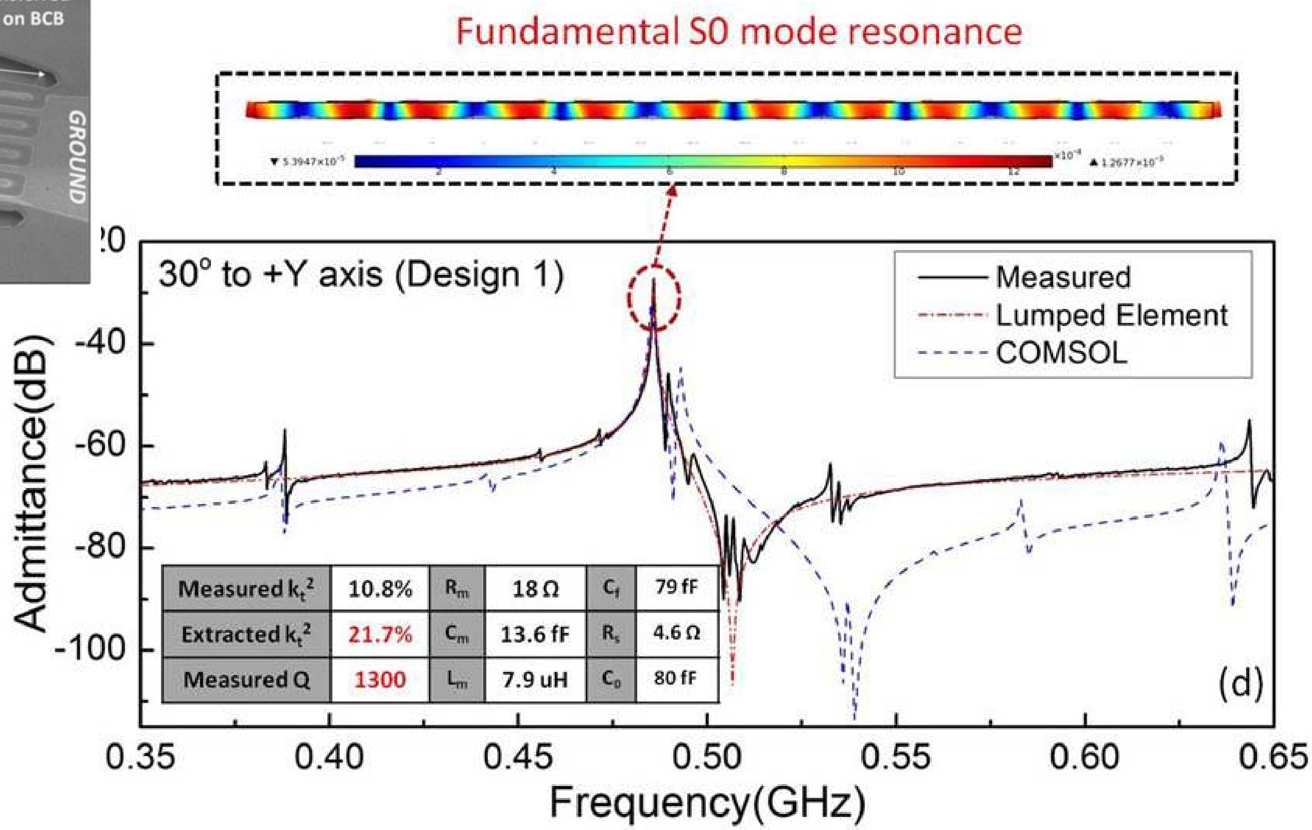
One-Port LN Resonators





- k_t^2 of 21.7% and Q of 1300
- High FoM of 282 demonstrated – One of the highest for MEMS resonators!

Concluding Remarks

- AlN MEMS resonators are becoming a commercial reality for timing applications
- High frequency operation and large scale integration of resonators will ultimately enable new applications that take advantage of high Q passives – Power regulation is one of them.
- Challenges for deployment of AlN PT are in the system level implementation. LN resonator development requires further efforts at the device and process flow standardization before it becomes mainstream.
- The development of piezoelectric AlN and LN M/NEMS platforms will also enable the deployment of other high-performance sensors and actuators

Acknowledgments

- **PhD Students:**
  - Enes Calayir, Cristian Cassella, Sid Ghosh, Nick Kuo (now at QCOM), Mohammed Mahmoud, Matteo Rinaldi (now Prof. at NEU), Jeronimo Segovia, Lisha Shi, Nipun Sinha (now at INTEL), Changting Xu, Chengjie Zuo (now at QCOM)
- **Post-Docs/Research Scientists**
  - Augusto Tazzoli (now at Maxim), Nick Miller (now at SiTime), Songbin Gong (now Prof. at UIUC), Usama Zaghloul (now at Avago), Nancy Saldhana (now at GTRI)
- **Collaborators**
  - Fedder (CMU), Mukherjee (CMU), Pileggi (CMU), Van der Spiegel (Penn), Otis (UW), Turner (UCSB), Carpick (Penn), De Boer (CMU).
- Funding from DARPA, IARPA, NSF, Qualcomm and Northrop Grumman

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