GHz CMOS-MEMS resonators

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Birck Faculty Seminar

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Motivation: Frequency Sources

Military & Aerospace

Communications
Navigation
IFF
Radar
Sensors
Guidance systems
Electronic warfare
Sonobouys

Research & Metrology

Atomic clocks
Instruments
Astronomy & geodesy
Space tracking
Celestial navigation

Consumer

Watches & clocks
Cellular & cordless phones, pagers
Radio & hi-fi equipment
TV & cable TV
Personal computers
Digital cameras
Video camera/recorder
CB & amateur radio
Toys & games
Pacemakers
Other medical devices
Other digital devices

Automotive

Engine control, stereo, clock, yaw stability control, trip computer, GPS

Industrial

Communications
Telecommunications
Mobile/cellular/portable radio, telephone & pager
Aviation
Marine
Navigation
Instrumentation
Computers
Digital systems
CRT displays
Disk drives
Modems
Tagging/ID
Utilities
Sensors

J.Vig, UFFC XO tutorial

Frequency Sources and Filters > 10GHz

- 10's GHz Filters/Oscillators:
  - Automotive
  - 5G
  - THz/mm-Wave imaging
  - THz spectroscopy
  - Infrastructure

everythingrf.com

comsol.com

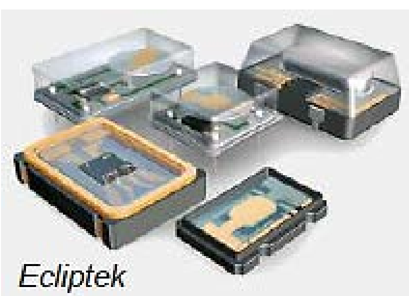

QinteQ

Toward monolithic frequency sources

MEMS Resonators for frequency sources:

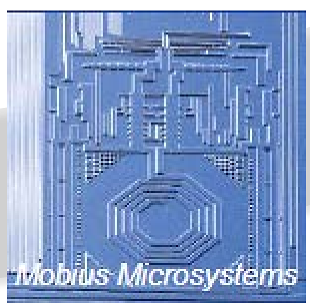
- High Q (f.Q ~ 10^{12}-10^{14}) for low noise oscillators
- Small footprint
- Wafer-level fabrication & packaging

Quartz XOs



up to 100s MHz
TCF < 0.1ppm

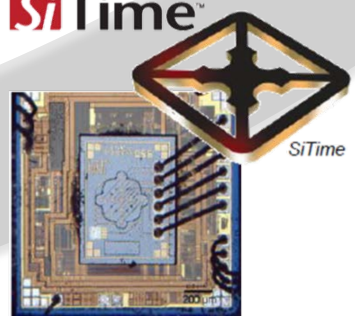
CMOS Osc.



up to 200 MHz
TCF ~150-15000ppm

Si MEMS

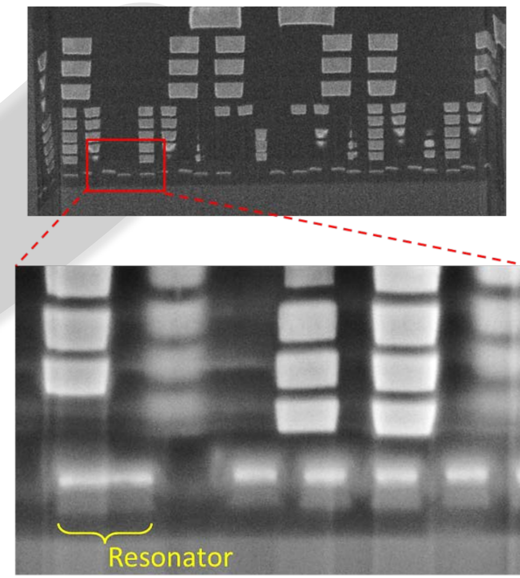
SiTime



up to 800 MHz
TCF ~.5-240ppm

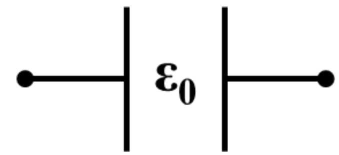
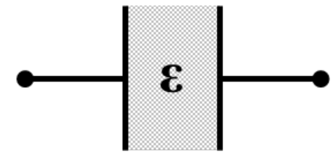
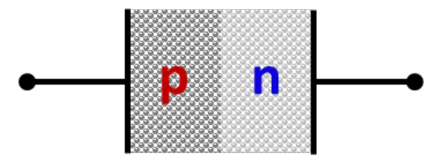
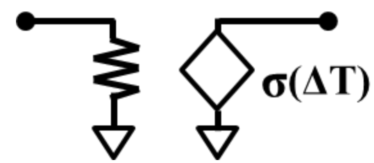
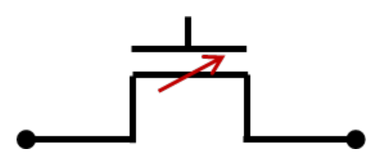
HybridMEMS

CMOS-MEMS resonators



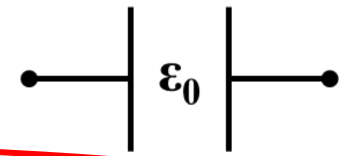
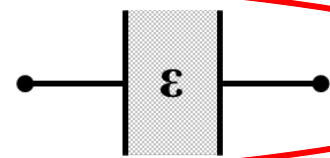
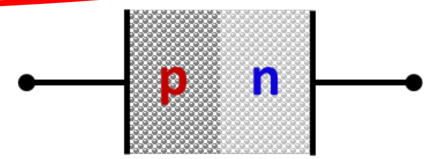
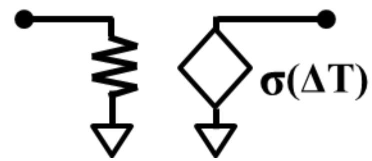
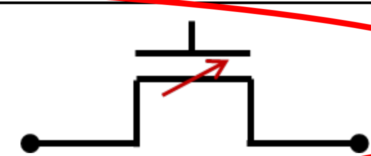
>10 GHz
TCF < 1ppm/K
In *standard* CMOS

CMOS-friendly resonator transduction

	Drive	Sense	
Capacitive – air gap	X	X	
Capacitive – solid dielectric	X	X	
Capacitive – solid-state	X	X	
Thermal	X		
Piezoresistive		X	
Transistor		X	

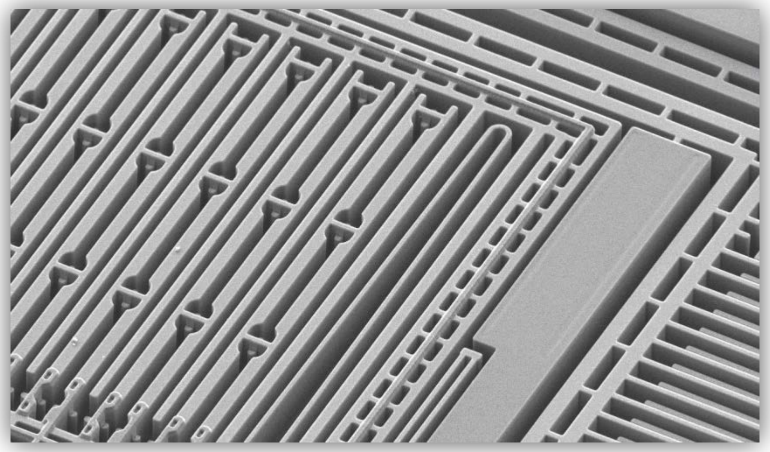
CMOS-friendly resonator transduction

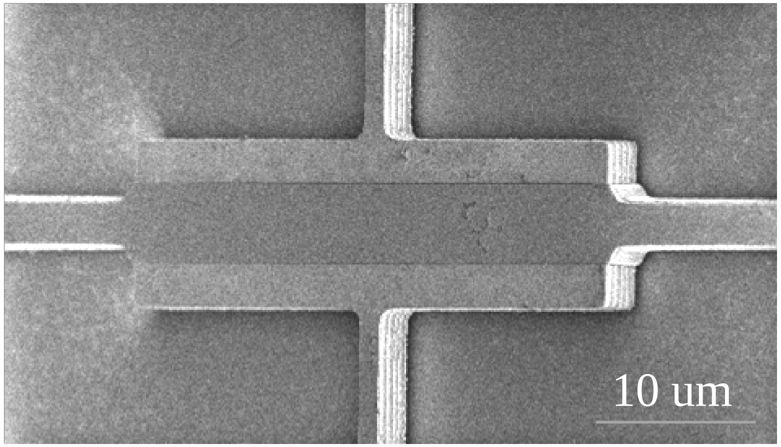
HYBRIDMEMS

	Drive	Sense	
Capacitive – air gap	X	X	
Capacitive – solid dielectric	X	X	
Capacitive – solid-state	X	X	
Thermomechanical	X		
Piezoresistive		X	
Transistor		X	

Dielectric transduction

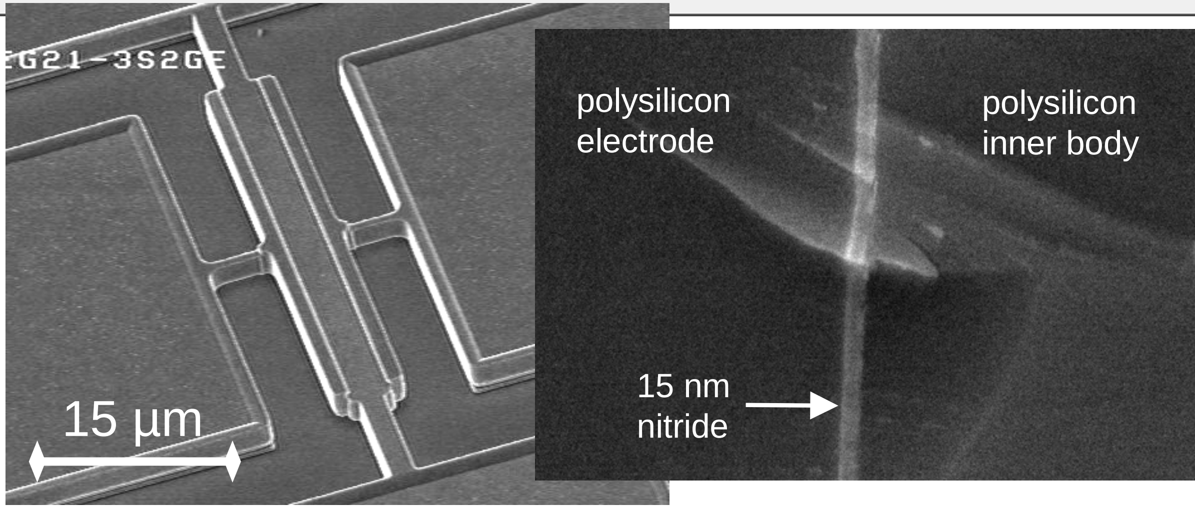
- Drawbacks of air-gap transducers
  - Fabrication complexity for release step
  - Low yield
    - Stiction
    - Particulates in gap
  - Costly packaging
- **Our approach**: dielectric film transducers
  - No stiction or particulate failure
  - Easier fabrication and integration
  - Improved performance at GHz frequencies





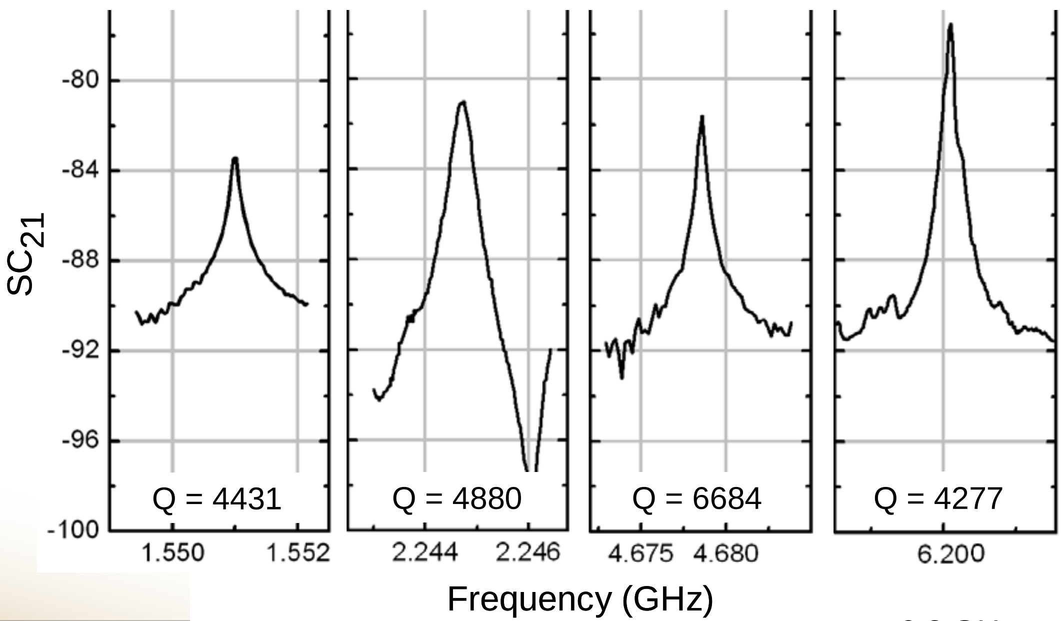
Weinstein, IEDM 2007

Dielectric transduction

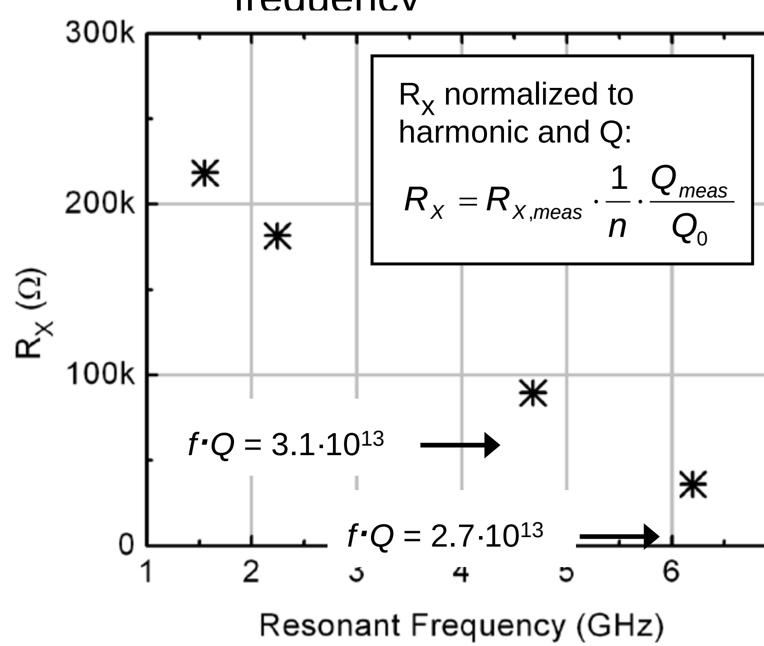


Silicon resonators demonstrated up to 6.2 GHz using dielectric transduction.

- High Q ($f.Q$ ~ 2-3 x 10^{13})
- Highest frequency in Si to date
- CMOS-ready materials
- Transduction efficiency improves with increasing frequency

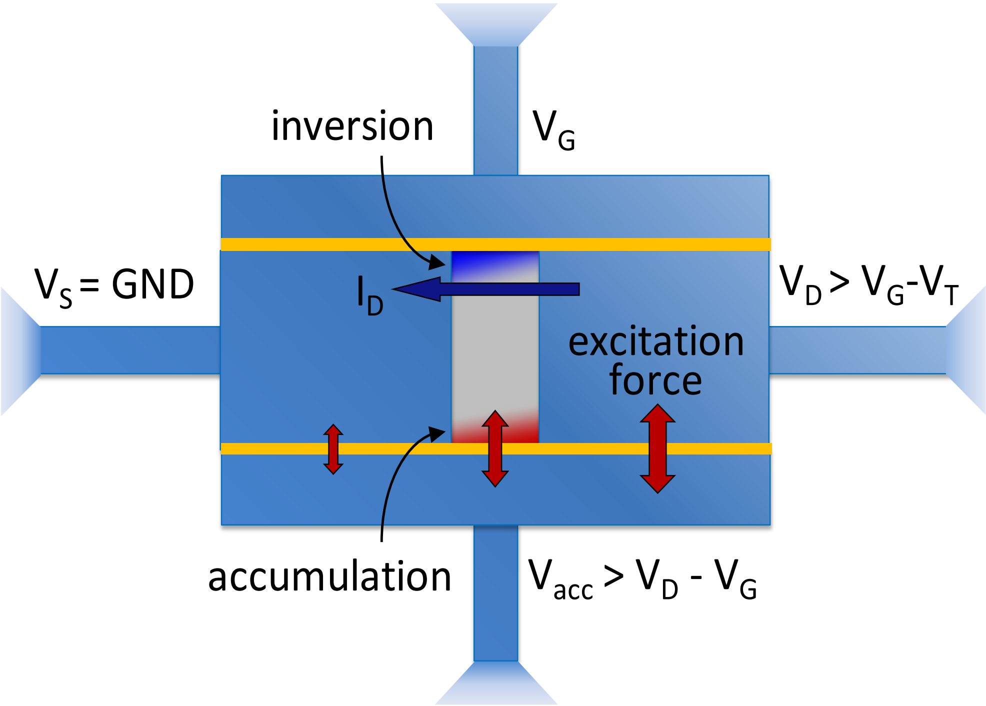


6.2 GHz



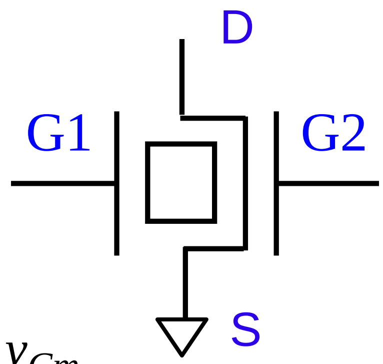
Freq (GHz)

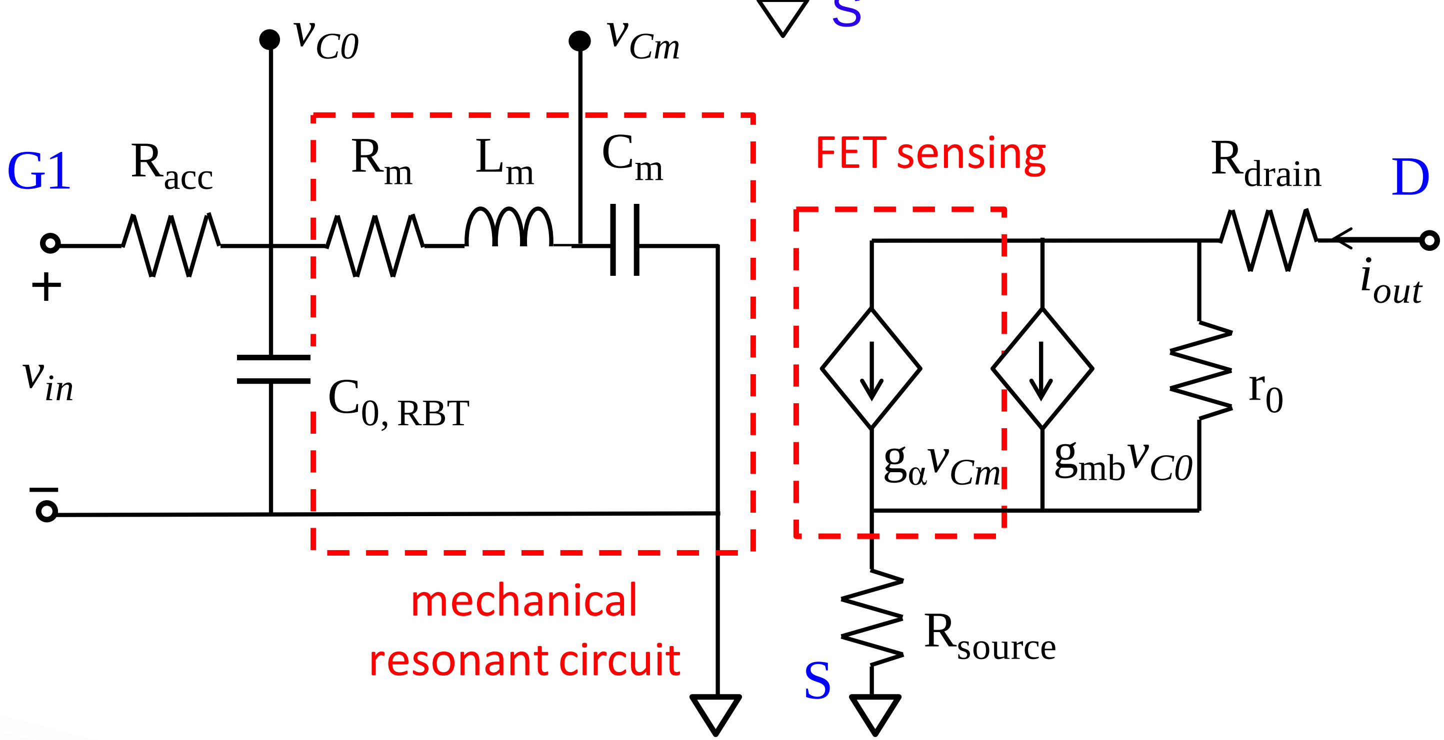
Resonant Body Transistor (RBT)



1. Drive gate in accumulation ($V_{acc} + v_{in}$). No current flows, but capacitive force drives resonant motion.
2. Elastic waves at driving frequency form a standing wave in the body at resonance.
3. Sense gate biased to strong inversion (V_G). As the fin vibrates, elastic waves modulate the drain current I_D piezoresistively.

RBT equivalent circuit

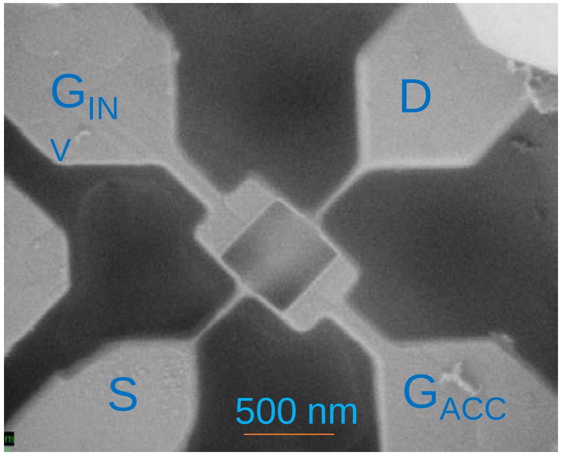




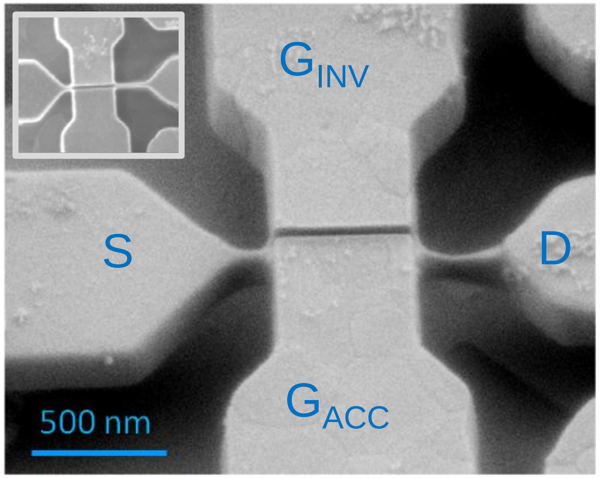
Amplification of mechanical signal before presence of parasitics

Resonant Body Transistors

Nano Letters '10

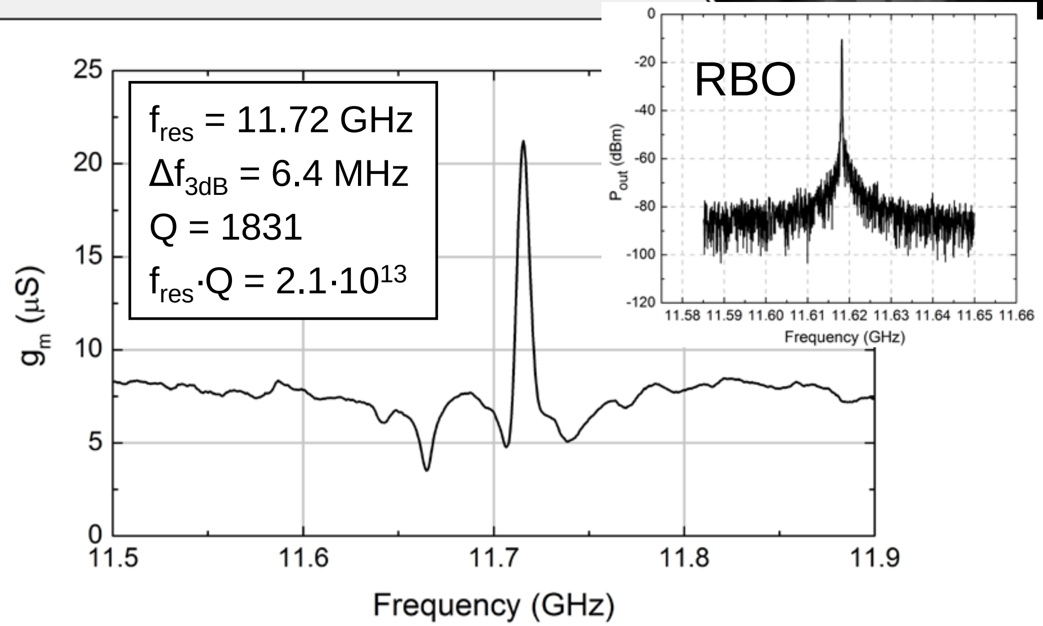


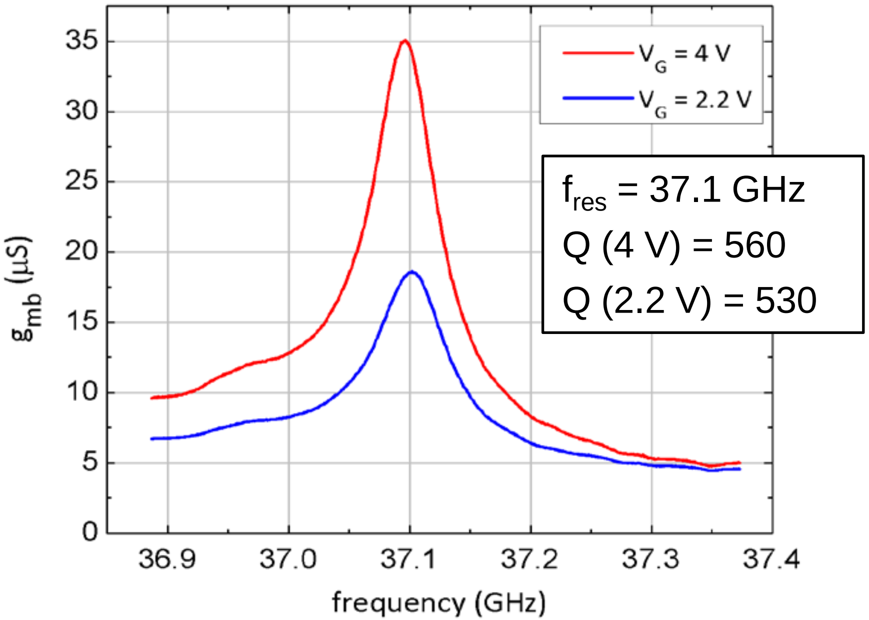
Hilton Head '10



First harmonic 114 nm fin width

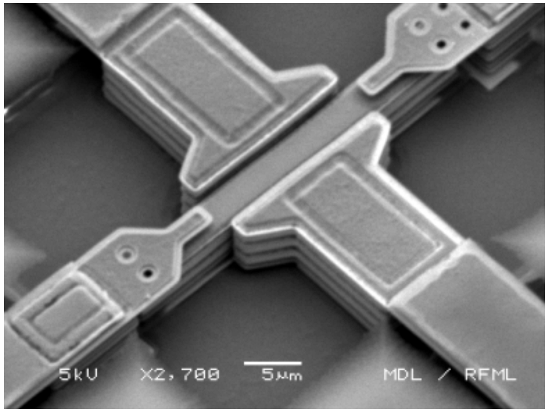
15 nm Si_3N_4 dielectric films





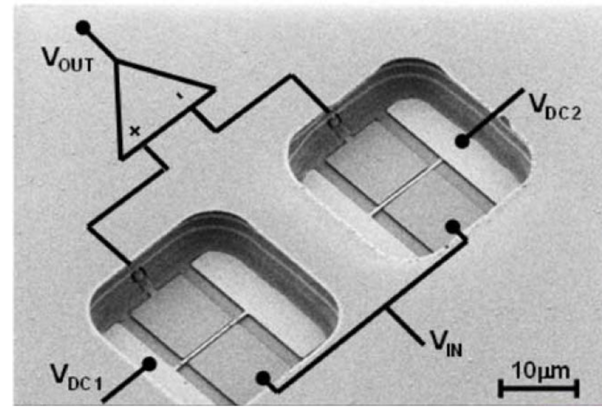
CMOS Integration of Si MEMS

Back-end-of-line post-processing



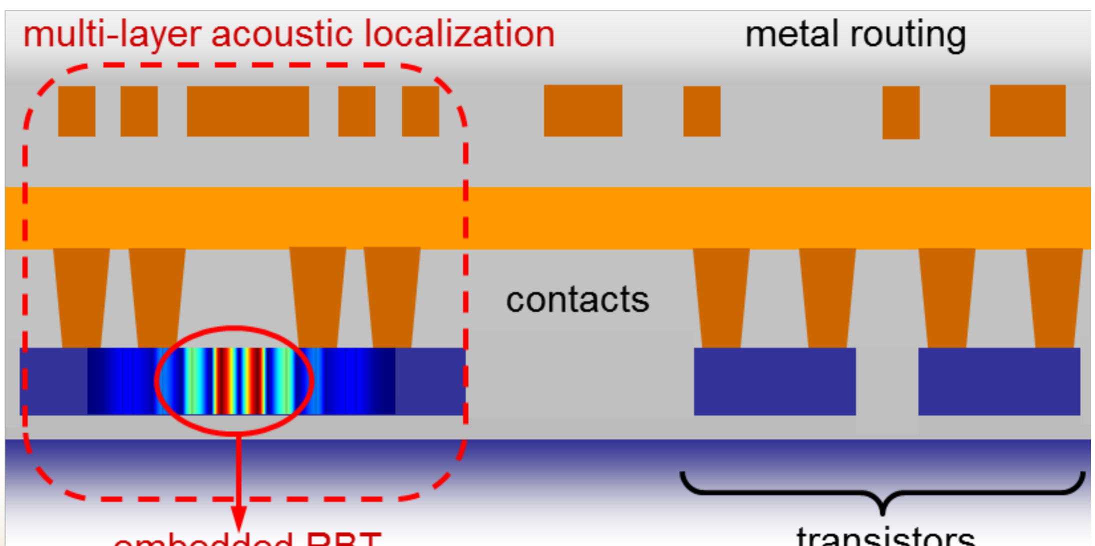
W.-C. Chen, *JMM,* 2011

Front-end-of-line post-processing



J.-L. Lopez, *EDL,* 2009

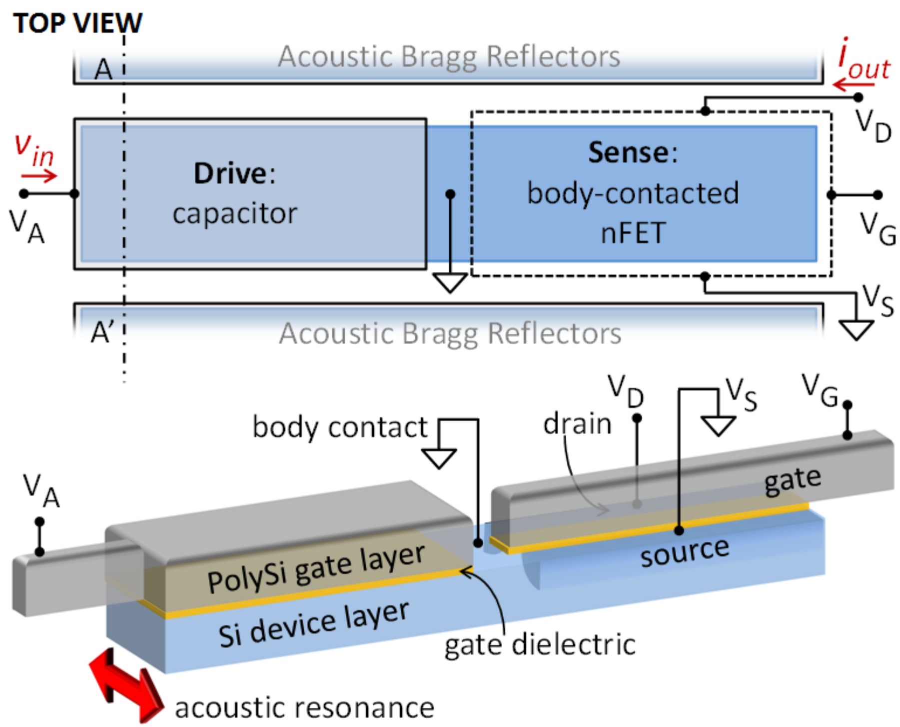
Our approach: solid-state MEMS

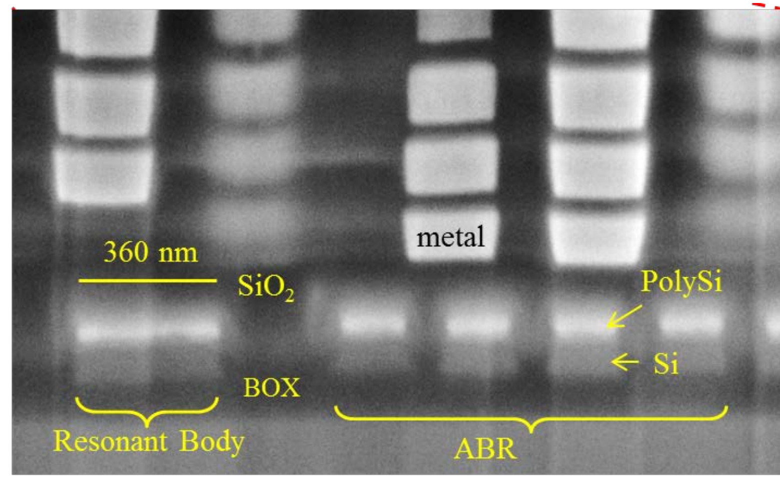


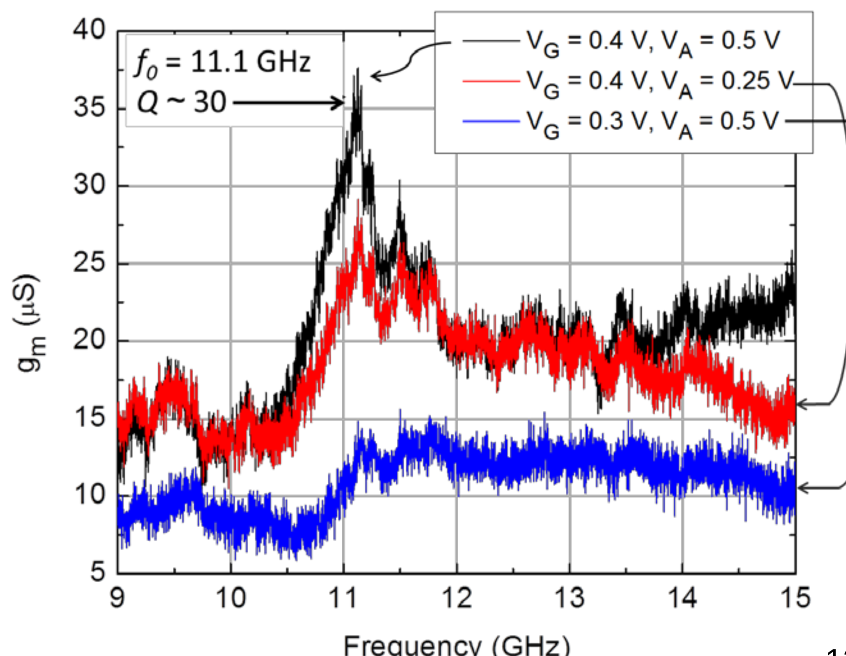
Unreleased RBTs in 32SOI CMOS

First generation CMOS-MEMS resonators

Single FET for both drive and sense.
Acoustic Bragg Reflectors in Si (FEOL)



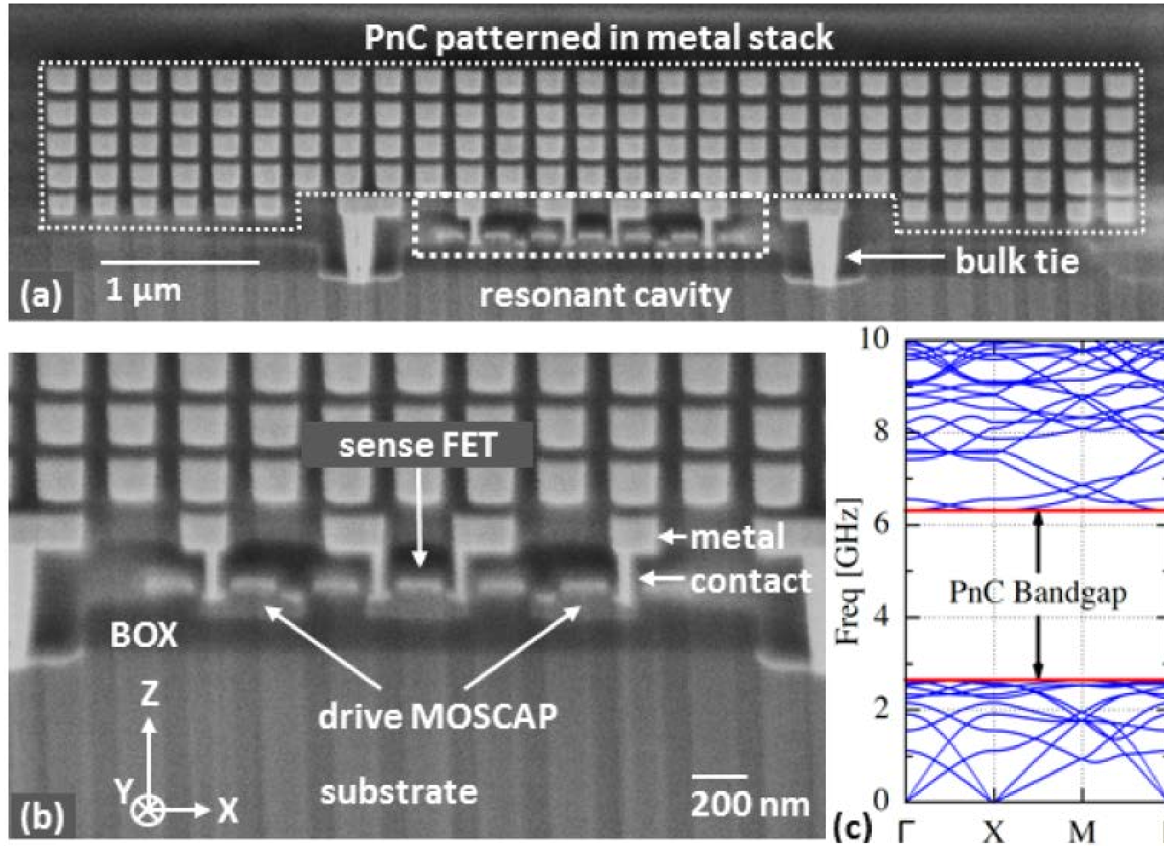


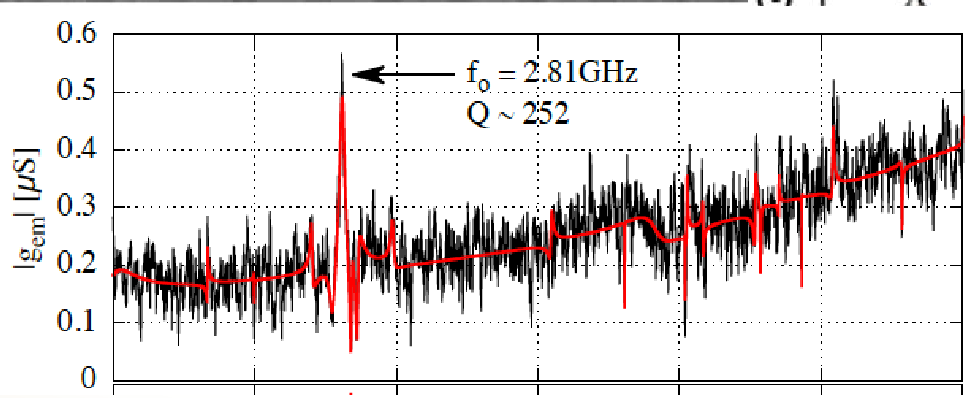


Phononic Crystal based RBTs

- 1st Phononic Crystals (**PnCs**) in a standard CMOS BEOL process
- Vertical acoustic confinement
- High-Q GHz-frequencies MEMS resonators
- No post-processing
- No special-packaging
- **GF 32SOI:**
    - High-fT
    - BOX: RF-feedthrough

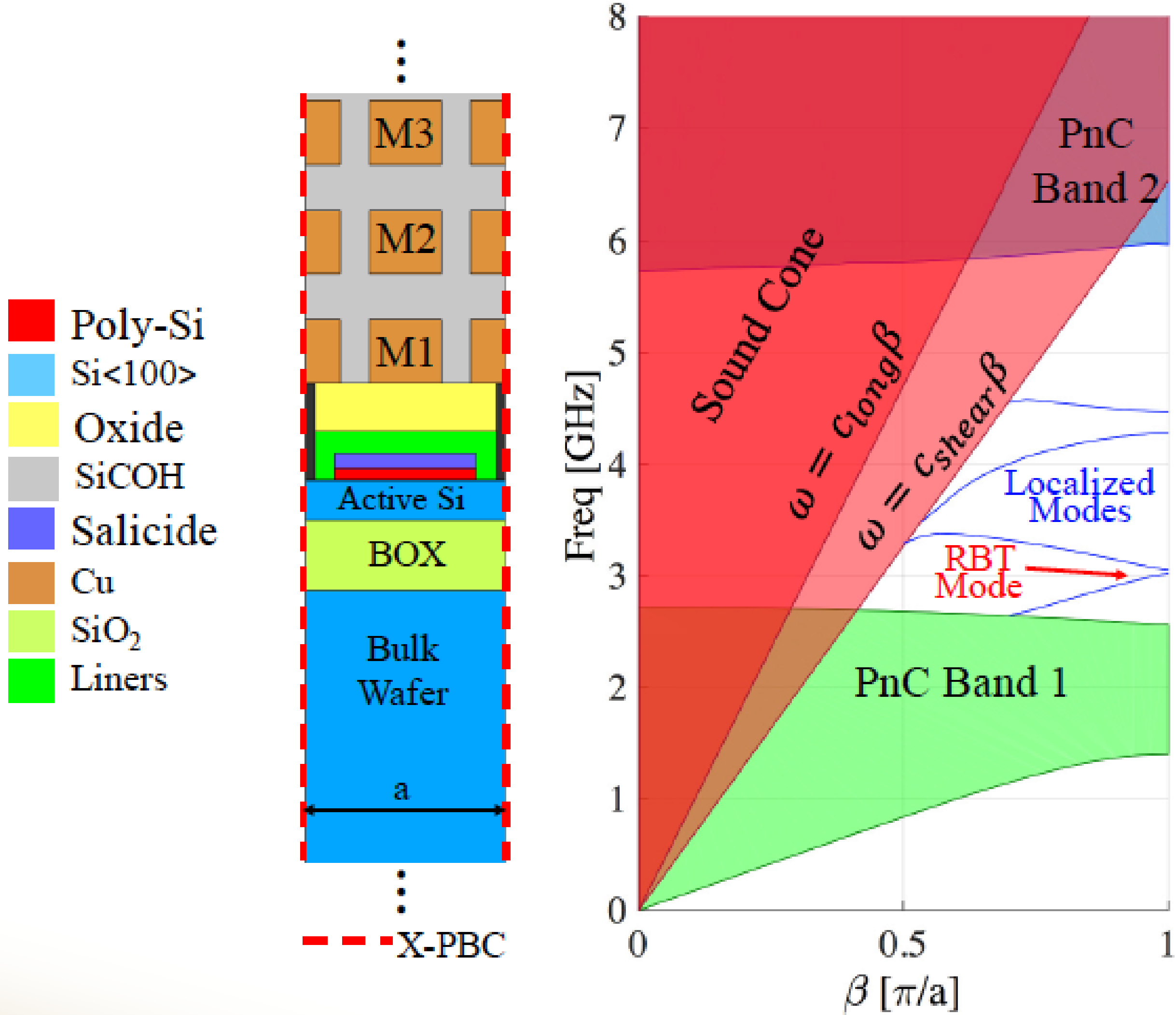
B. Bahr, R. Marathe, D. Weinstein IEEE IFCS14





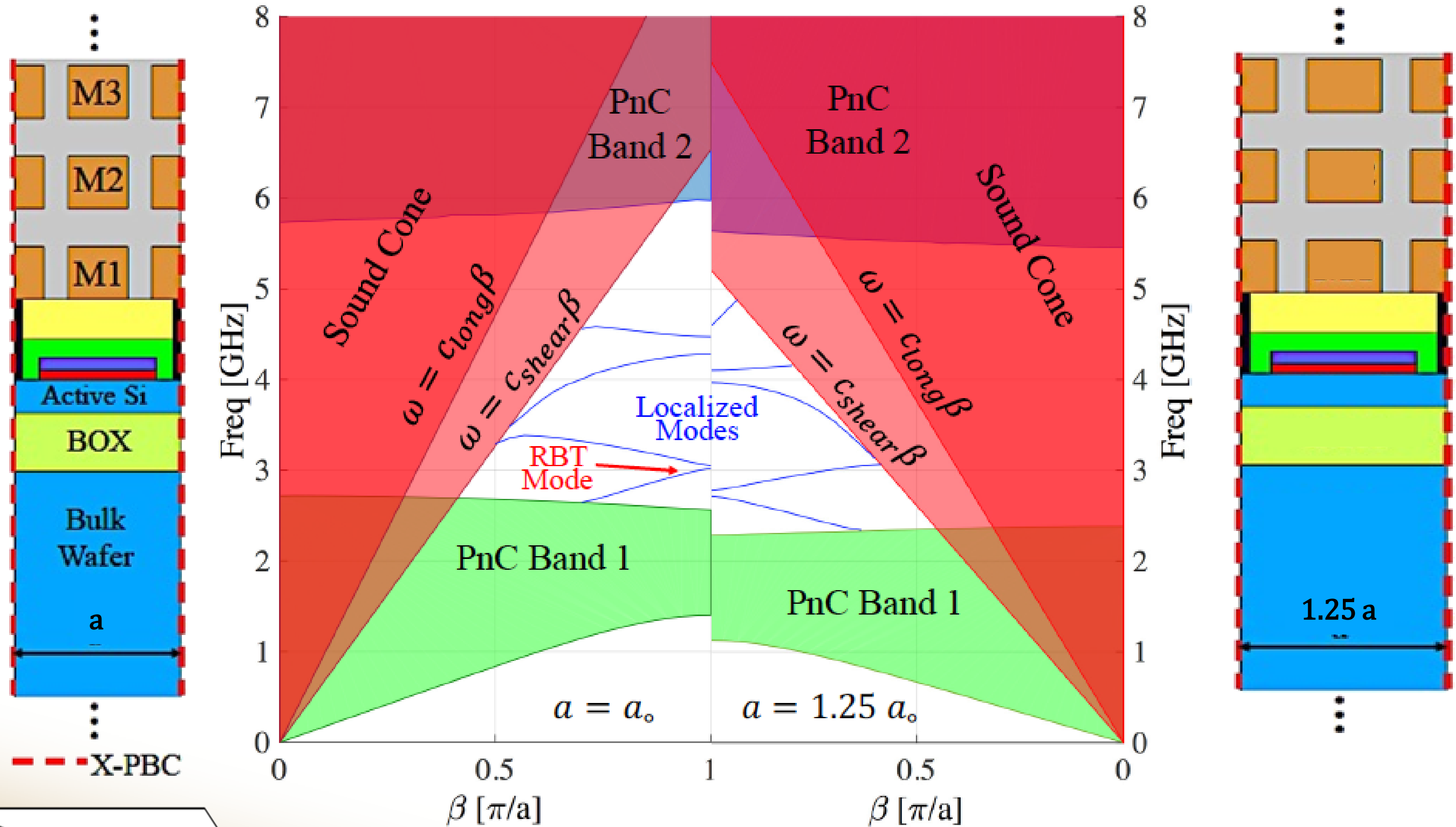
PnC Waveguided Modes

True vertical confinement – laterally waveguided modes in FEOL CMOS



PnC Waveguided Modes

Termination of waveguided modes to form high Q resonator



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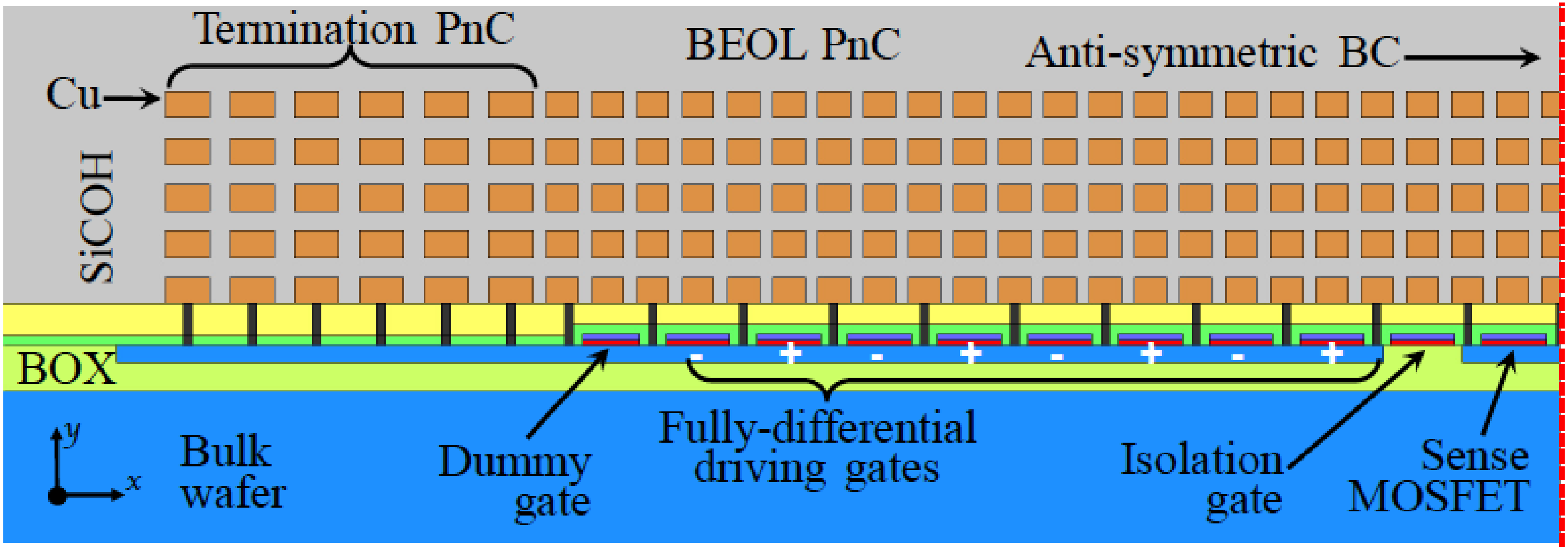
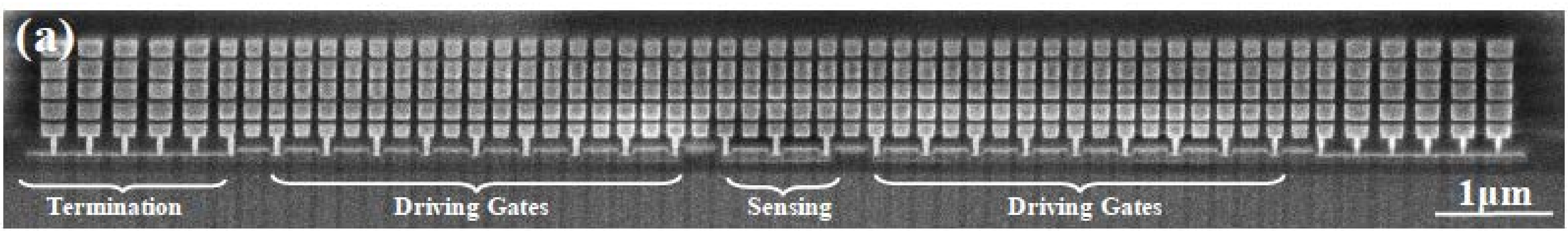
Waveguided RBT

Geometry of RBT

- Differential drive and sense using multiple MOSCAPs/MOSFETs
- Termination PnC to laterally confine resonance mode

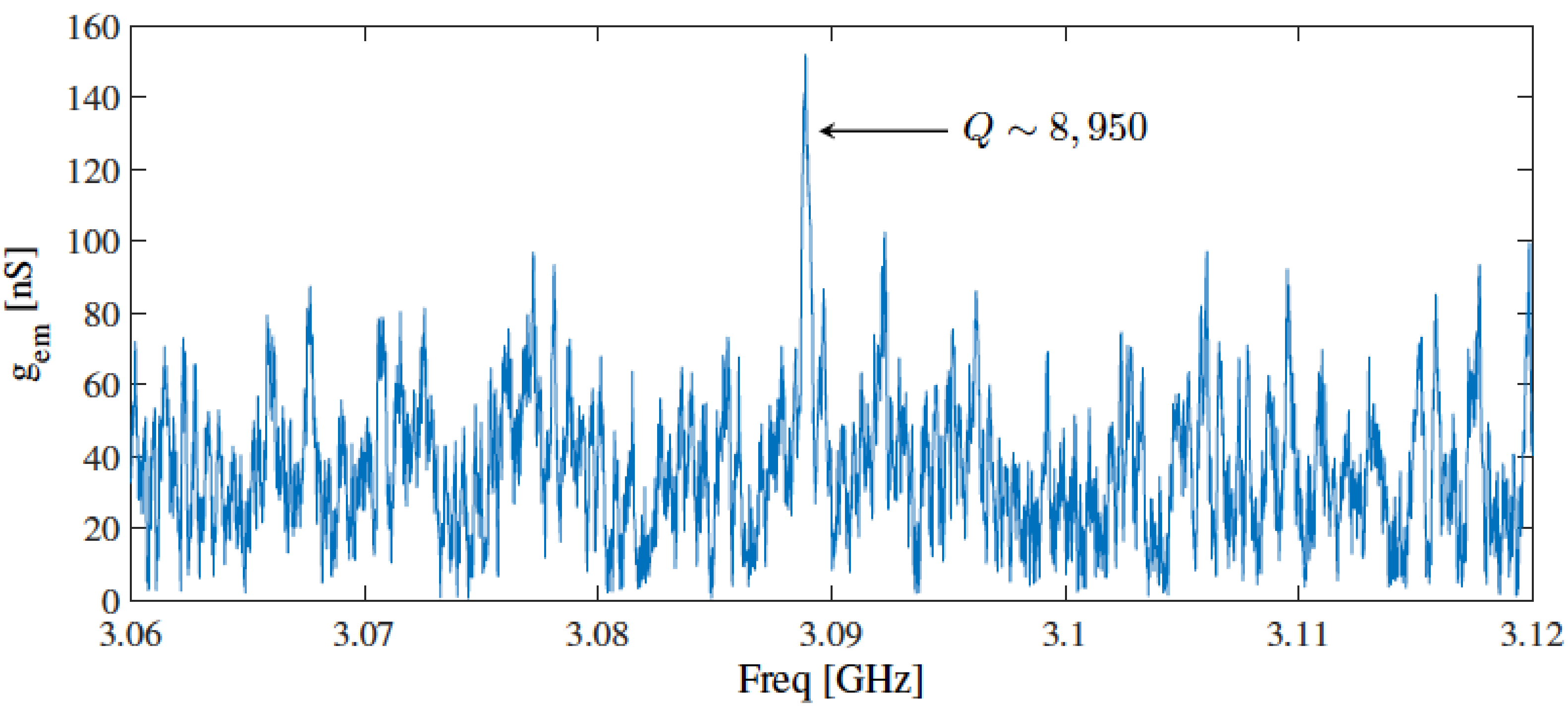




Waveguided RBT

Measured frequency response

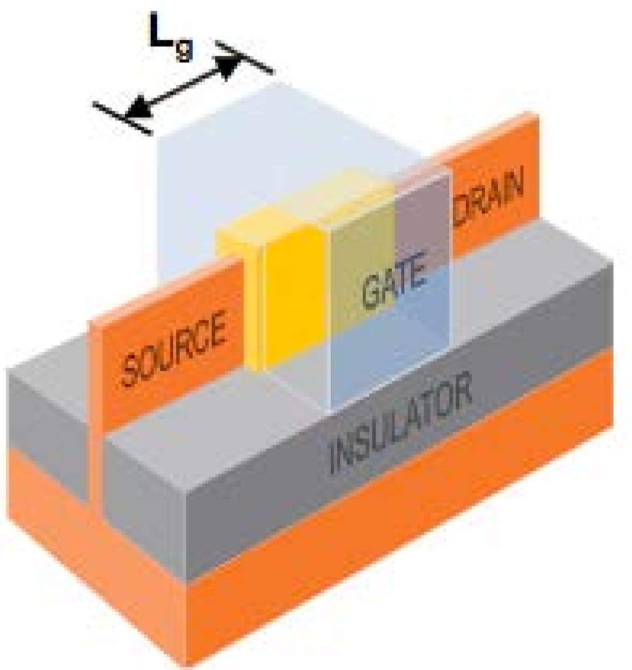
- Quality factors ranging from 8000 to 15000
- Improved spurious mode suppression
- Poor transduction efficiency resulting in low g_{em} (nS)

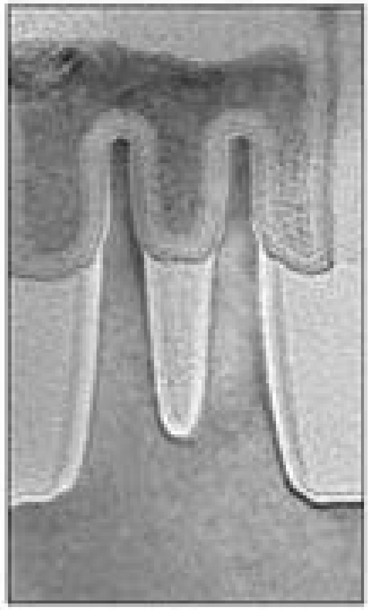


B. Bahr, D. Weinstein
Hilton Head '16, IFCS16

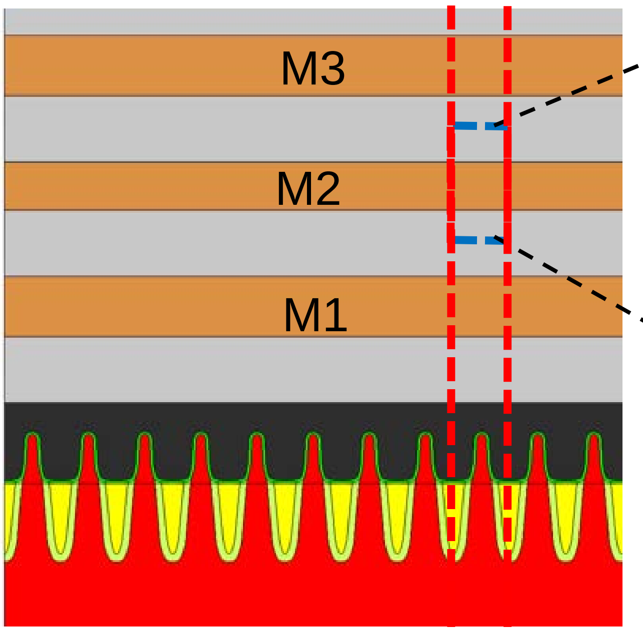
Resonant Fin Transistors

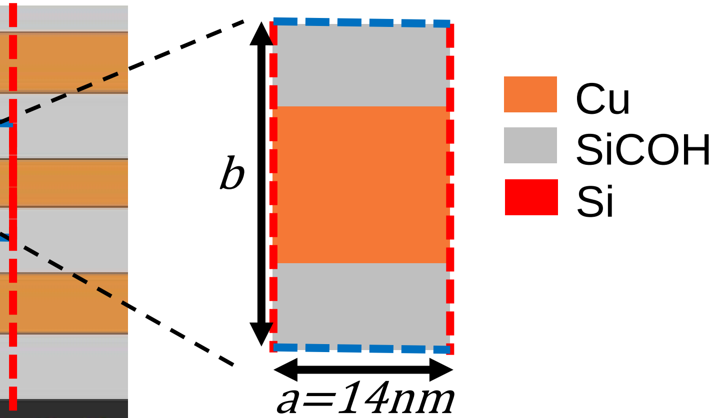
GLOBAL FOUNDRIES 14LLP TECHNOLOGY

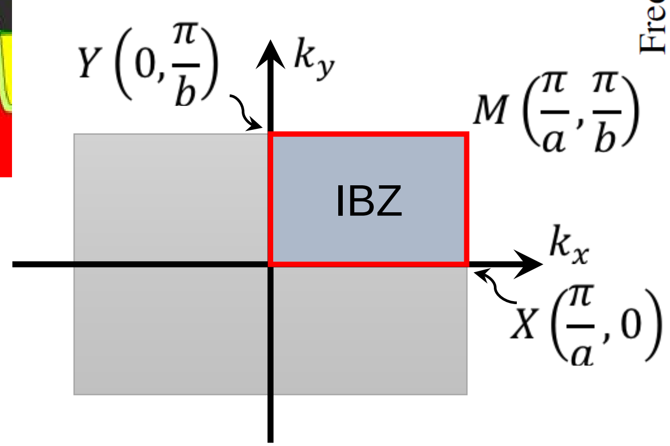


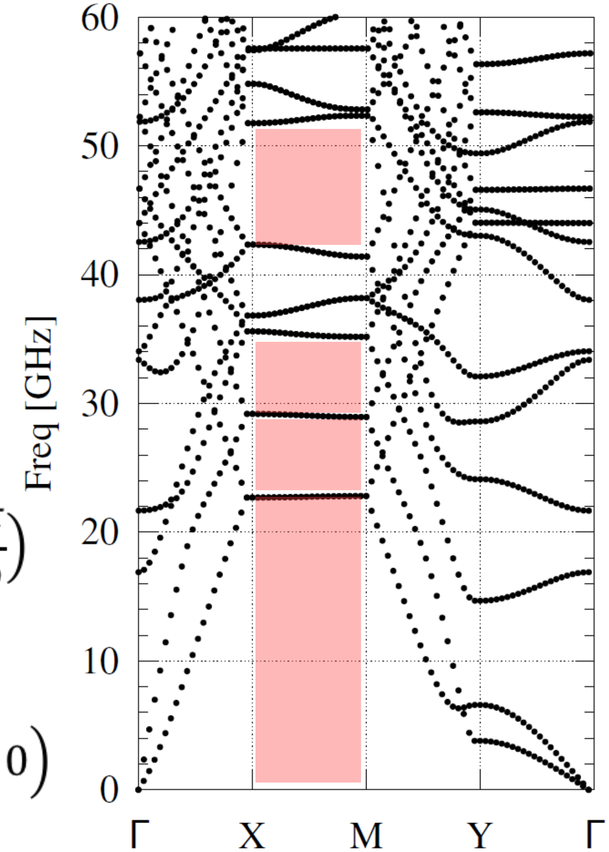


BEOL Reflector in GF 14nm FinFET Technology





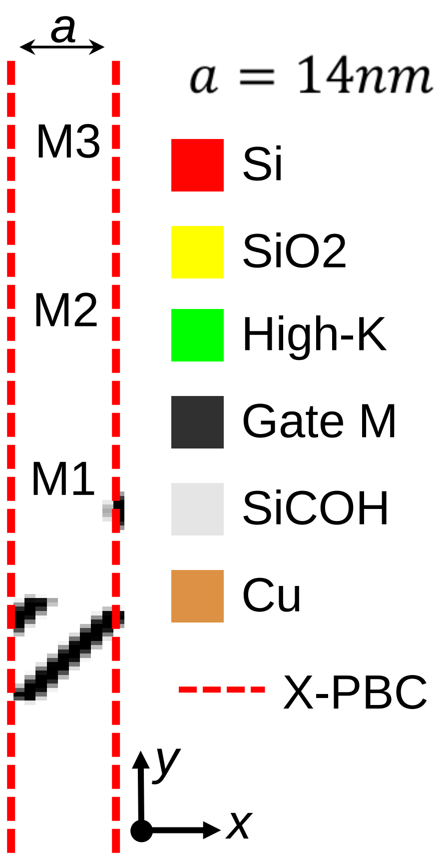


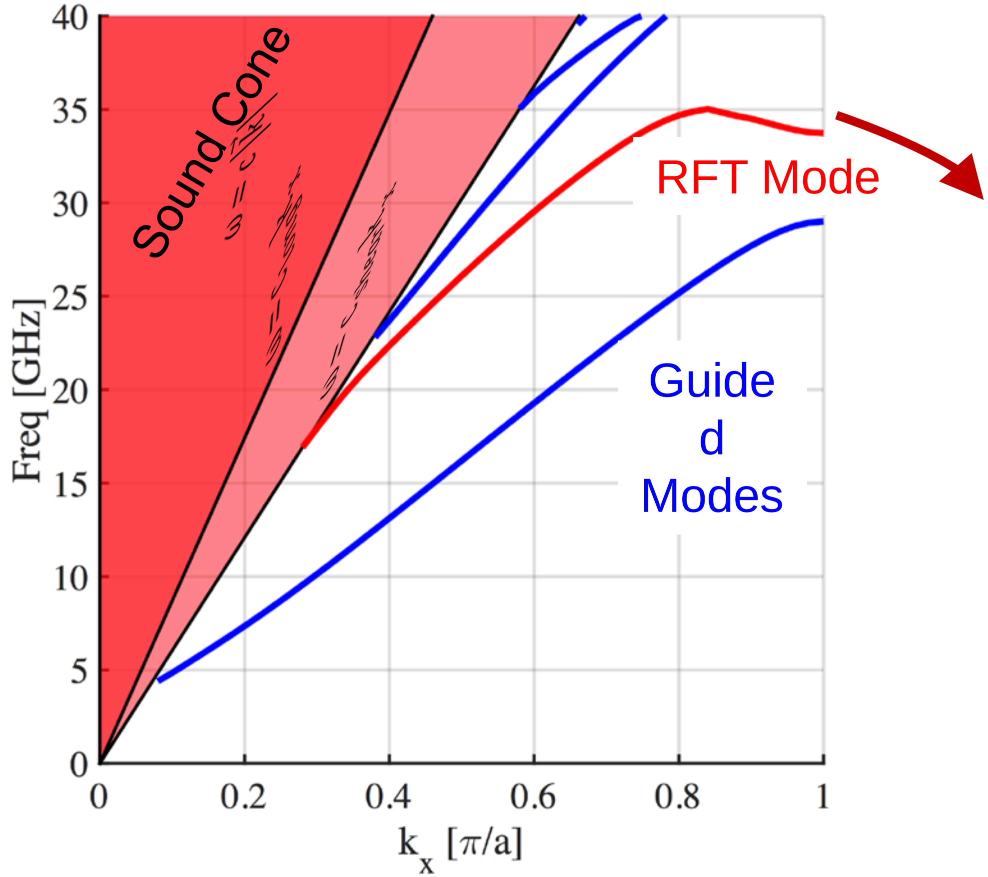


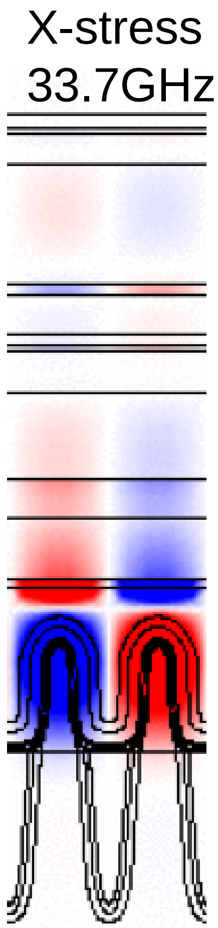
Bloch Waves:

$$|\psi(\vec{r})\rangle = e^{i\,\vec{k}.\vec{r}}\,|u_{\vec{k}}(\vec{r})\rangle$$

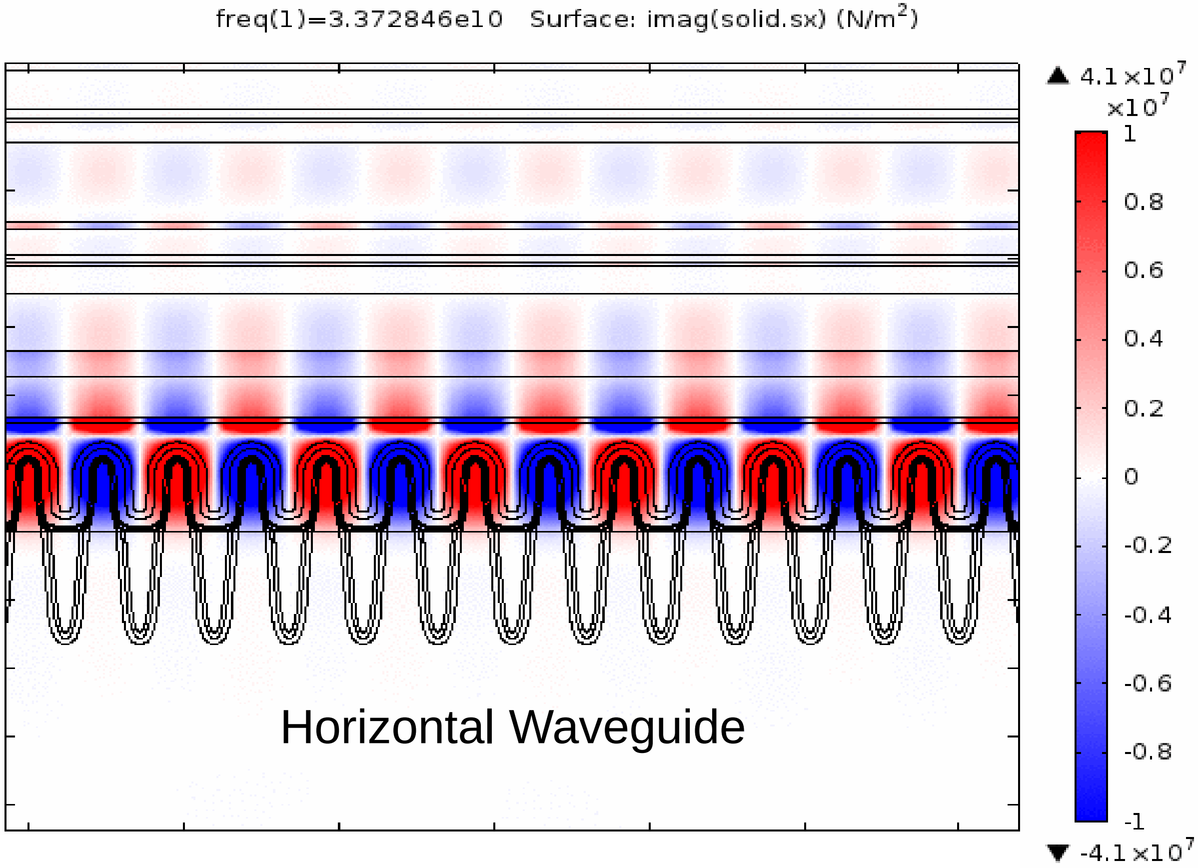
Bottom Confinement & Dispersion Characteristics





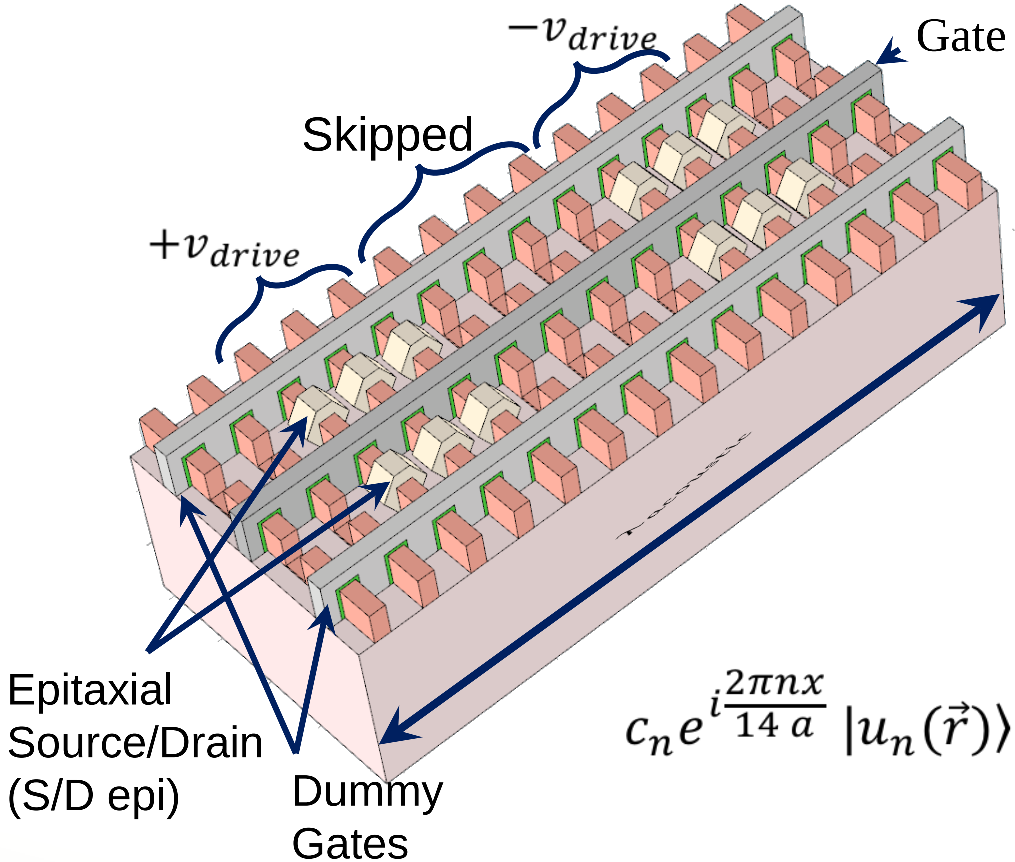


Mode Shape & RFT Structure



- Electrostatic Drive
  - MOS Caps
- Active FET Sensing
- Gate is Common
  - Signal on S/D
- Fully-differential fins
- Abrupt Horizontal termination

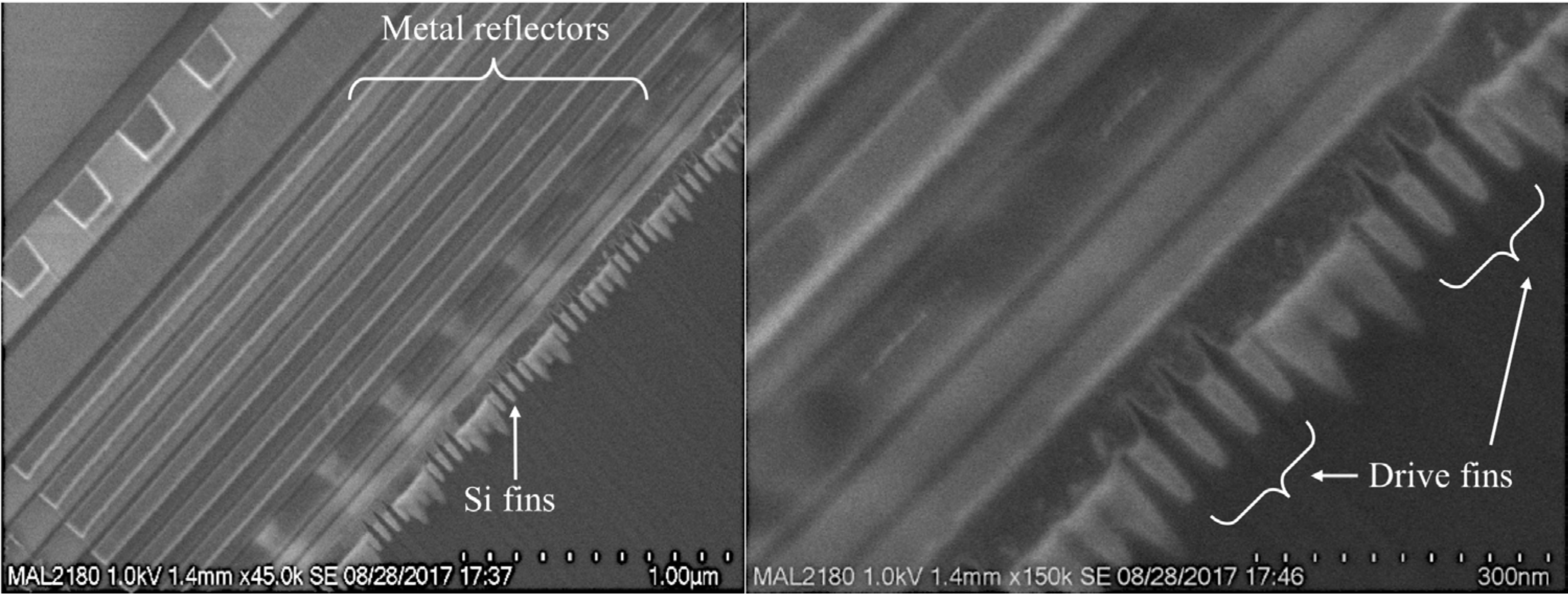
Resonant Fin Transistor Unit Cell



$$c_n e^{i\frac{2\pi n x}{14\,a}} |u_n(\vec{r})\rangle$$

- Epitaxial S/D Contacts
- DRC restrictions
- 3-Skip-4 Fin Configuration
  - 14 fins / unit cell
  - 7th Spatial harmonic $k_x = \pi/a$
- RFT:
  - 1 Sense Unit
  - 10 Drive Units
  - Full device has 154 fins
  - 6.8µm x 200nm

SEM Micrograph



Circuit Configuration of the RFT

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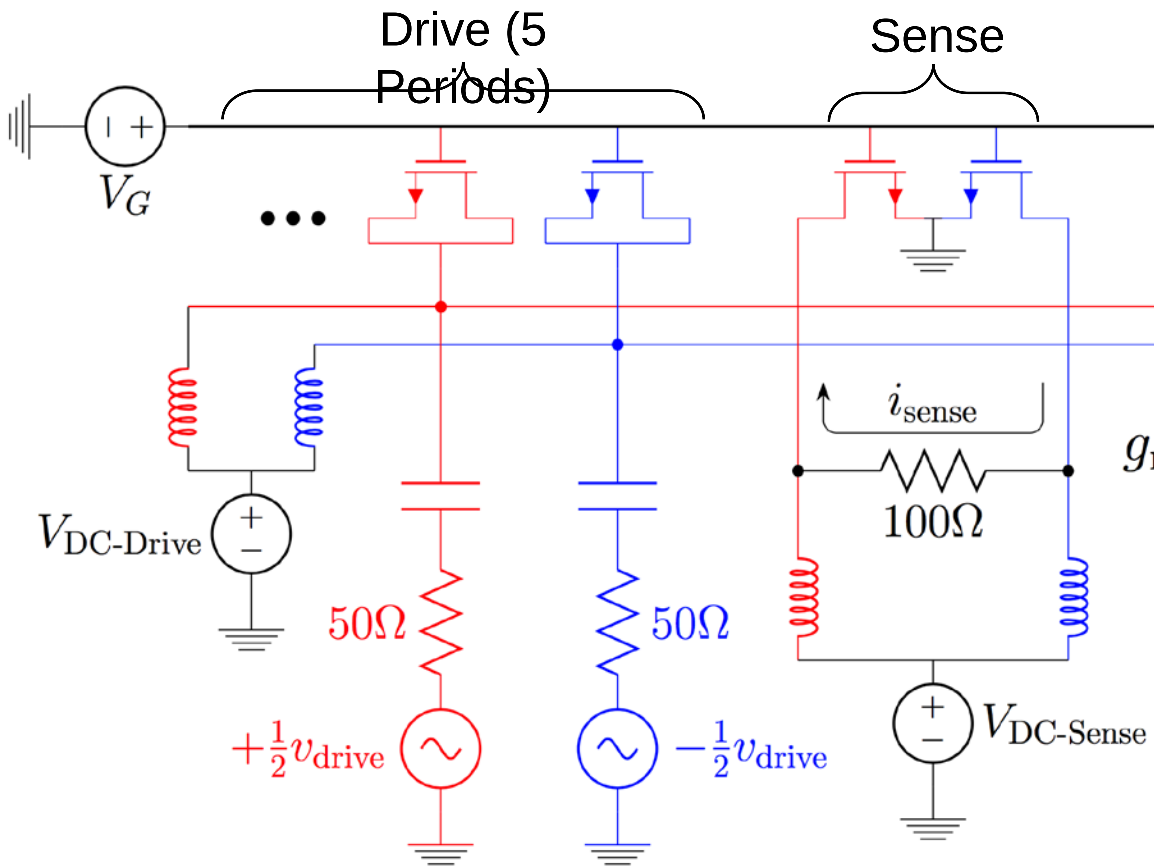
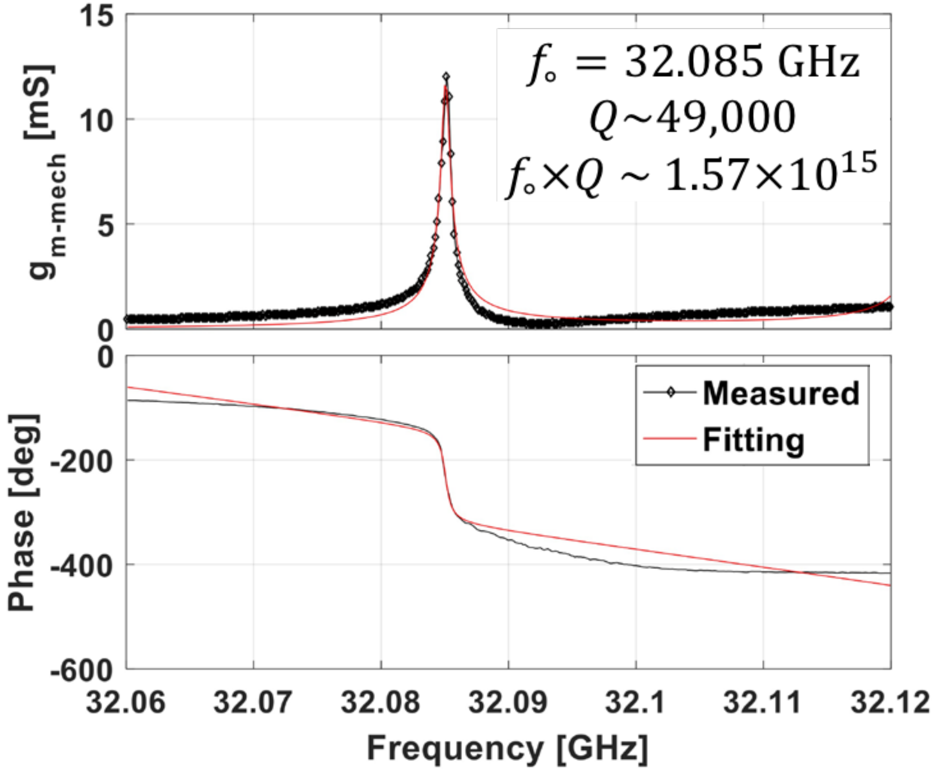
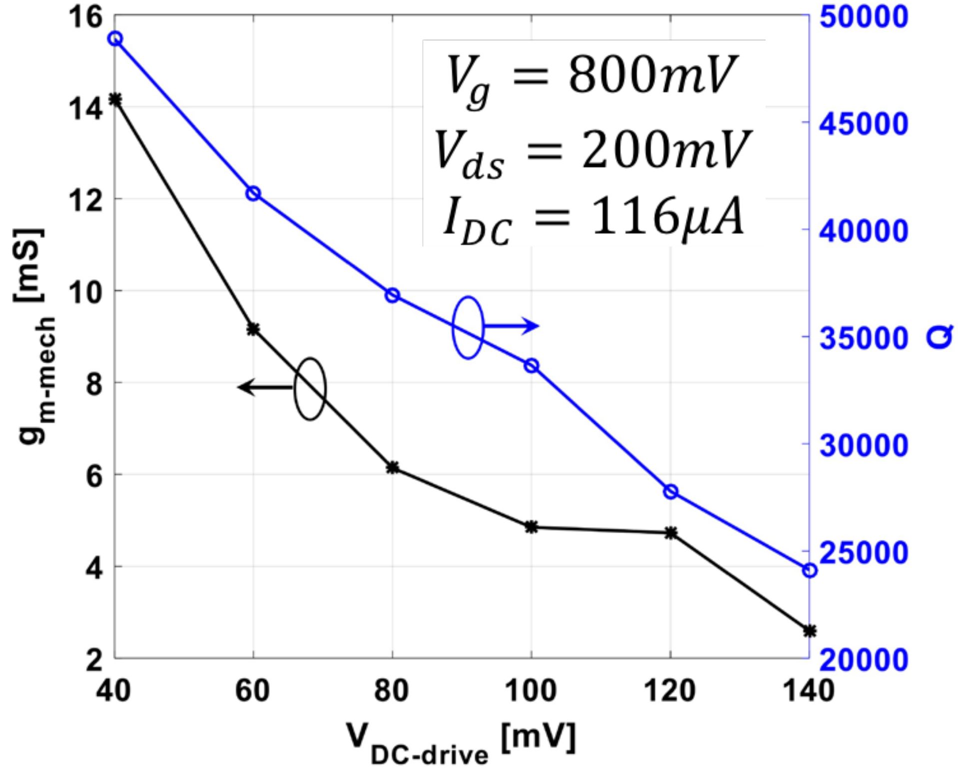


$$g_{\text{m-mech}} = \frac{i_{\text{sense}}}{v_{\text{drive}}} = Y_{21dd} - Y_{12dd}$$

RF Measurement Results





- $f_o = 32.0GHz$ (10x)
- $Q \sim 49{,}000$ (3.6x)
- Highest FOM: $f_\circ \times Q \sim 1.57 \times 10^{15}$ (36x)
- $g_{m-mech} \sim 14mS$ (10^5x)

Conclusion

- Phononic MEMS resonators now enable clocks and filters at GHz frequencies embedded in standard CMOS processes
- Technologically poised for large scale implementation in ICs
  - Unreleased resonators
  - Solid-state transduction
  - Si CMOS (FinFET, FeRAM), GaN MMIC
- We can now leverage these high Q systems for computation as well
  - Non-boolean logic (neural inspired inference)
  - Boolean phase-based logic

Acknowledgements

- Funding
  - DARPA YFA, NSF CAREER, Intel Early Career Award, DARPA UPSIDE
- Students
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  - Bichoy Bahr
  - Radhika Marathe
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  - TI: Dennis Buss, Bichoy Bahr