MEMS RESONATORS AS AN ENABLING TECHNOLOGY

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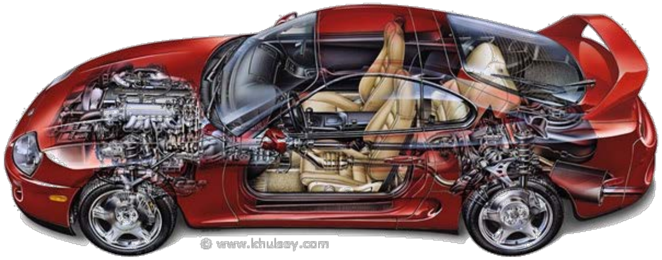
THE BROAD REACH OF MEMS

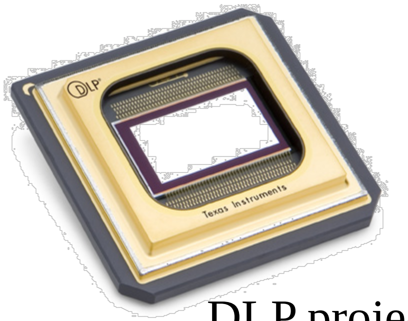
We are in an era of *deep* penetration of MEMS products into everyday life

There are products <u>everywhere</u>

- Pressure sensors in your car & body
- Accelerometers, gyros
- Ink-jet print heads
- Microphones
- TI DLP
- Etc.



Automotive: XL, gyro, pressure sensors, mm-wave imaging?



DLP projectors

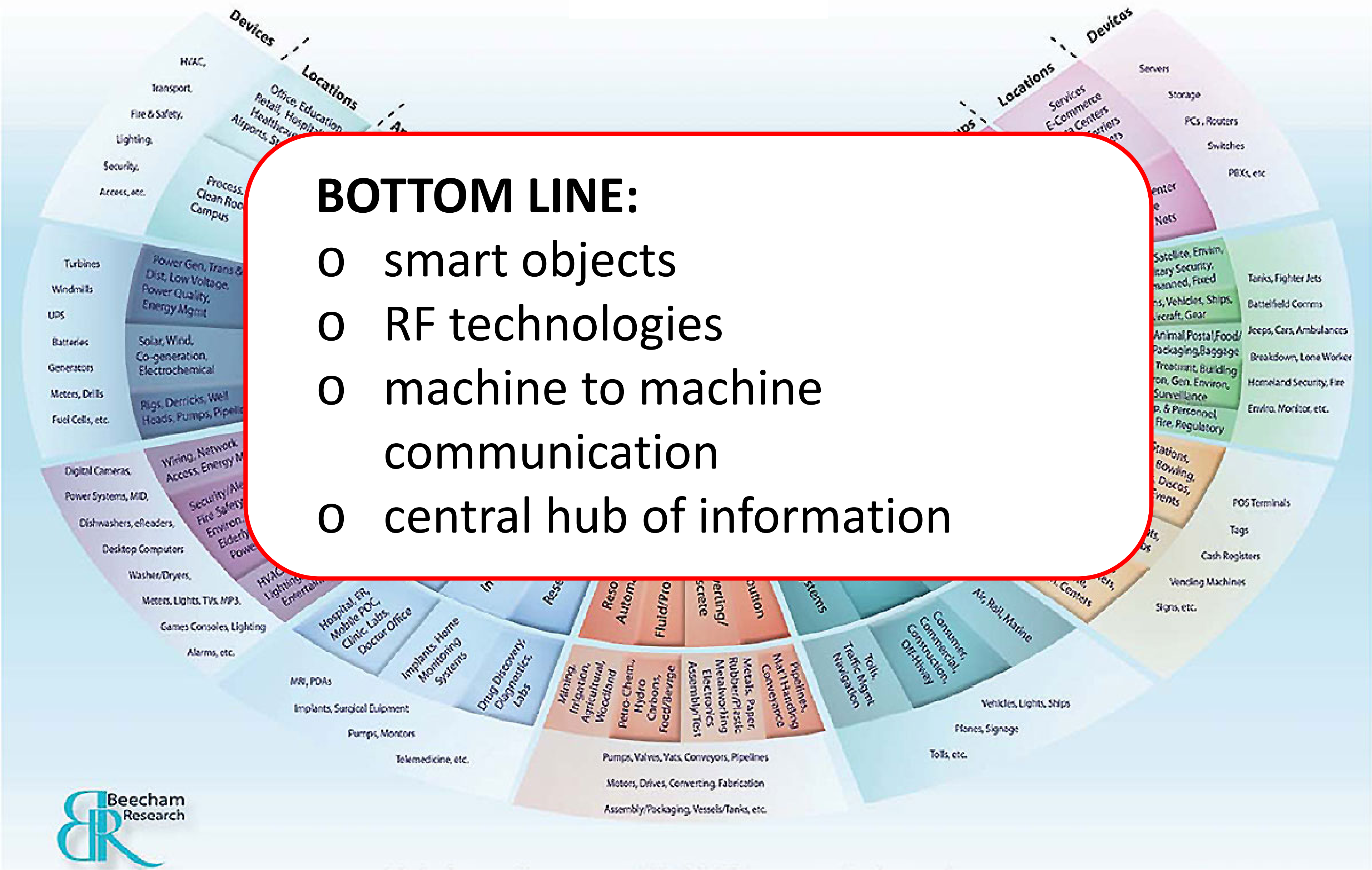
SLR camera stability

Mic, gyro, XL, FBAR filters

Sensors galore, health monitoring

HP inkjet printing (and now XLs)

THE INTERNET OF THINGS (IOT)

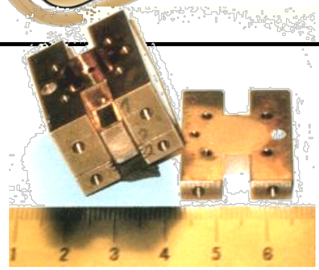
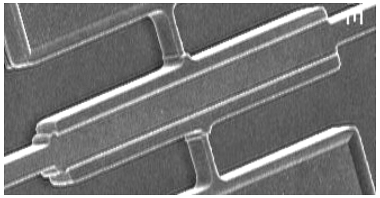


BOTTOM LINE:

- smart objects
- RF technologies
- machine to machine communication
- central hub of information

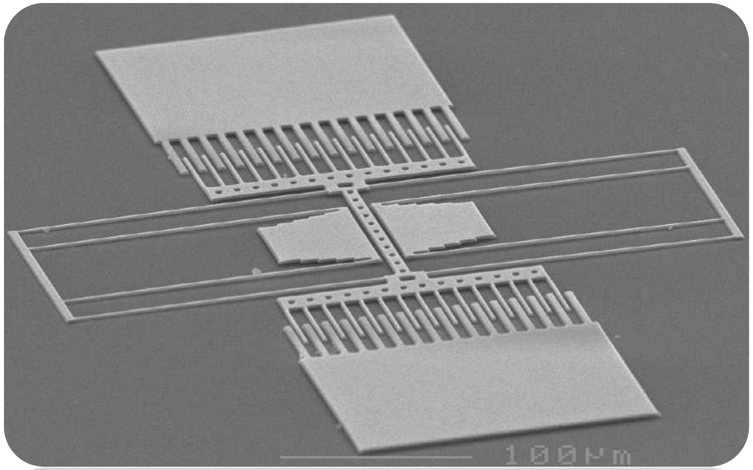
GHZ FREQUENCY RESONATORS

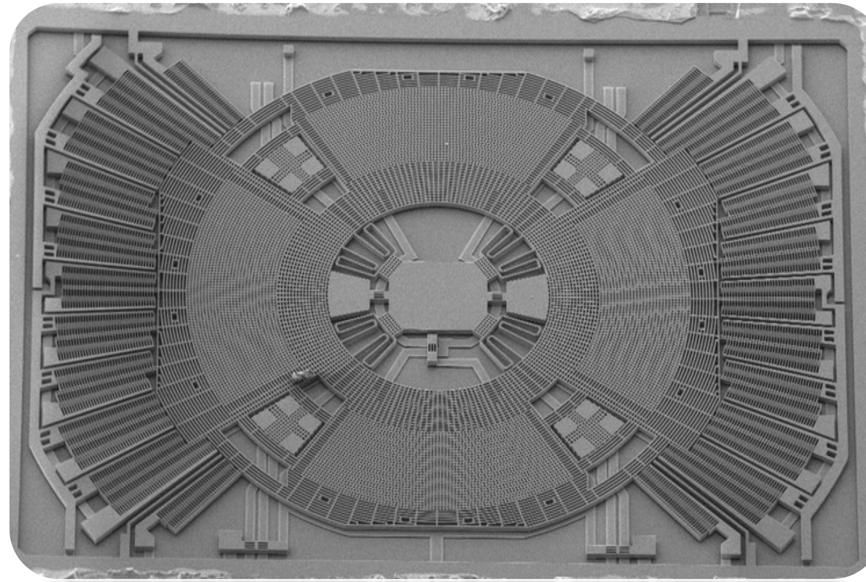
- Timing (oscillators)
- Wireless communication (frequency generation, filters, mixing, etc)
- Sensors (high Q = high SNR)

Resonator		**f_{res} $\lambda/2$**	**f_{res} $\lambda/2$**	**Comments**
air acoustic cavity		1 GHz 170 nm	60 GHz --	too small low-Q
EM cavity		1 GHz 15 cm	60 GHz 2.5 mm	too large @ 1GHz too $$ @ 60GHz
silicon acoustic resonator		1 GHz 4.3 µm	60 GHz 70 nm	perfect for µfabrication high-Q

AIR-GAP MEMS RESONATORS

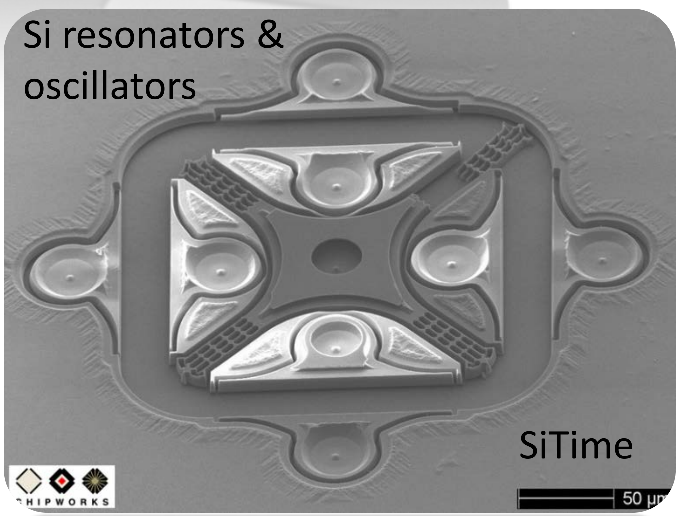
Comb-drive resonator, Tang, Howe 1989



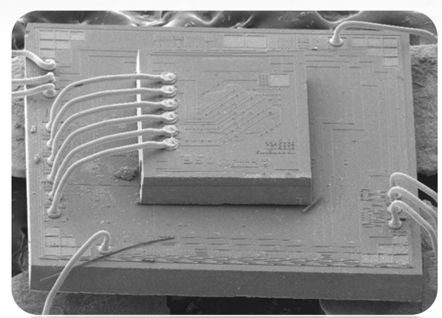


ST Microelectronics gyroscope

Si resonators & oscillators



SiTime



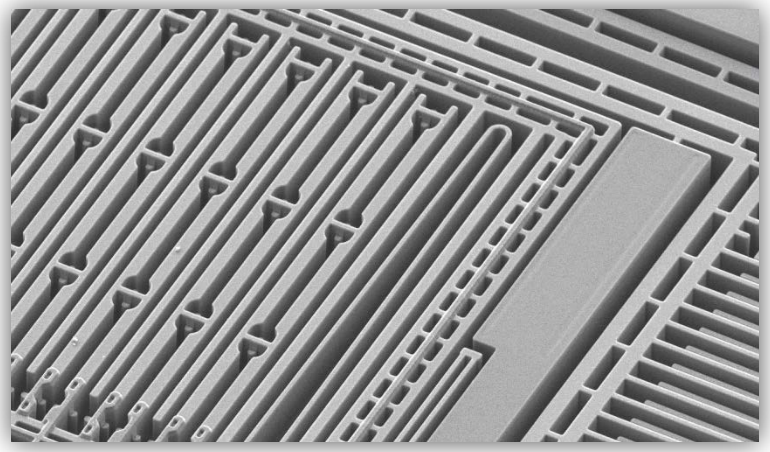
COMB DRIVE ACTUATOR

Sandia

DIELECTRIC TRANSDUCTION

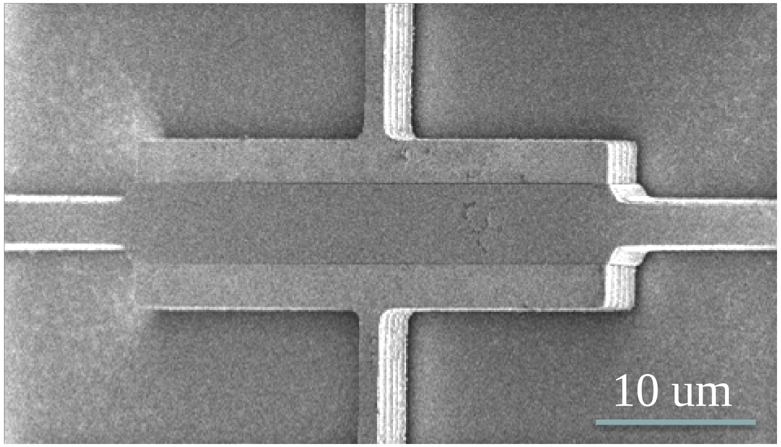
Drawbacks of air-gap transducers

- Fabrication complexity for release step
- Low yield
  - Stiction
  - Particulates in gap
- Costly packaging



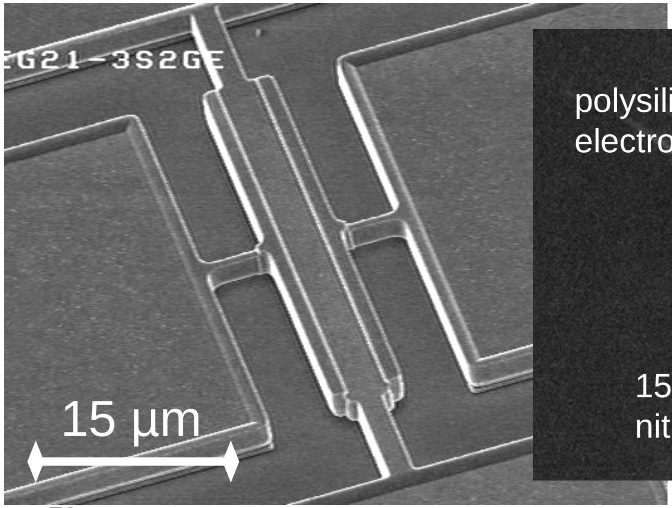
Our approach: dielectric film transducers

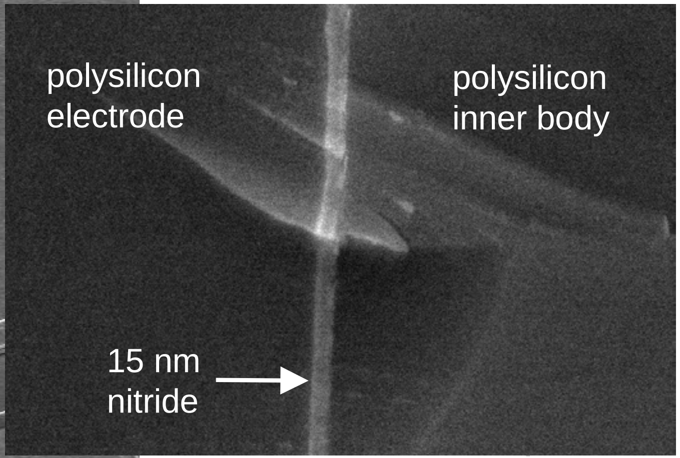
- No stiction or particulate failure
- Easier fabrication and integration
- Improved performance at GHz frequencies



Weinstein, IEDM 2007

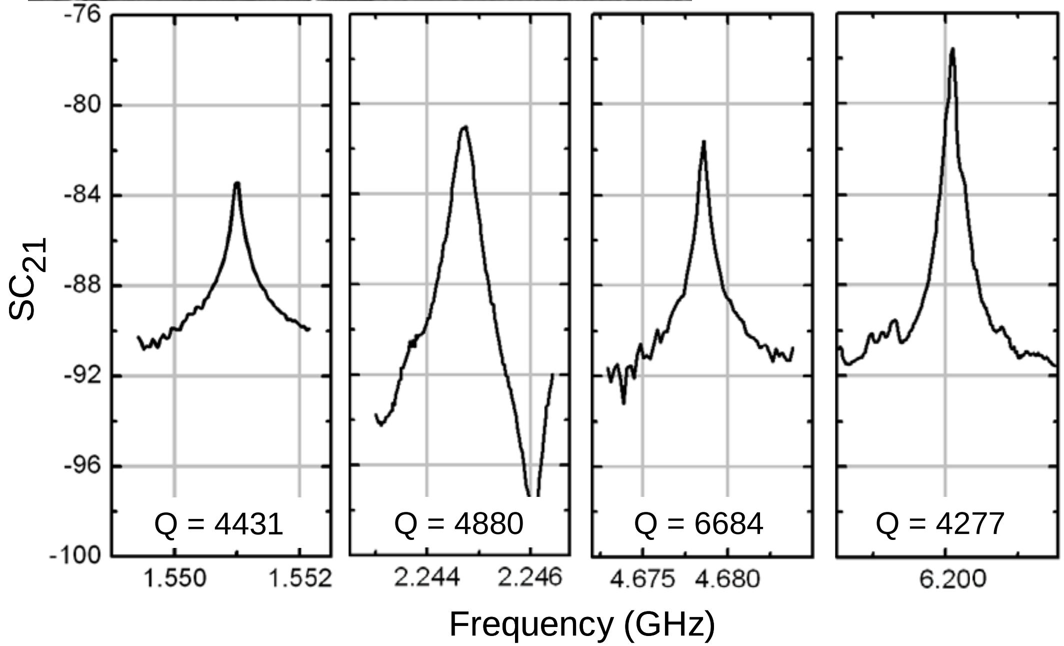
DIELECTRIC TRANSDUCTION

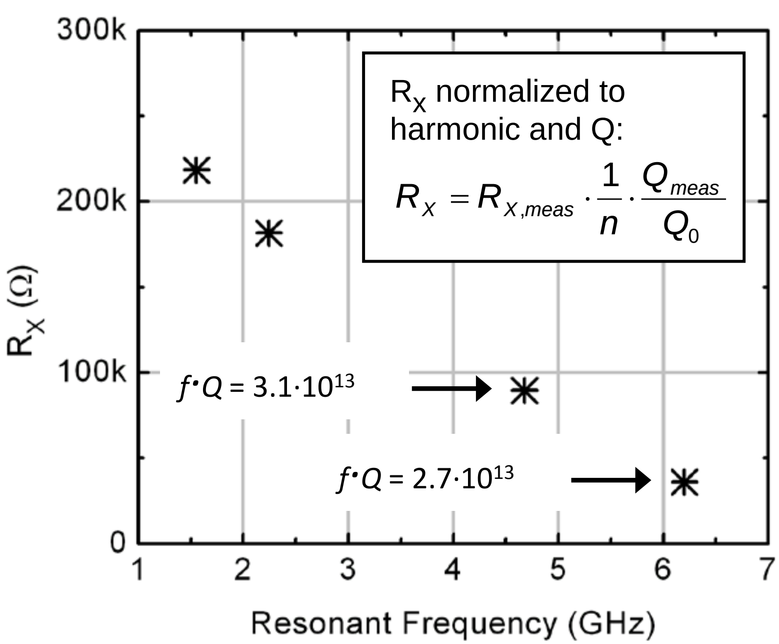




Silicon resonators demonstrated up to 6.2 GHz using dielectric transduction.

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

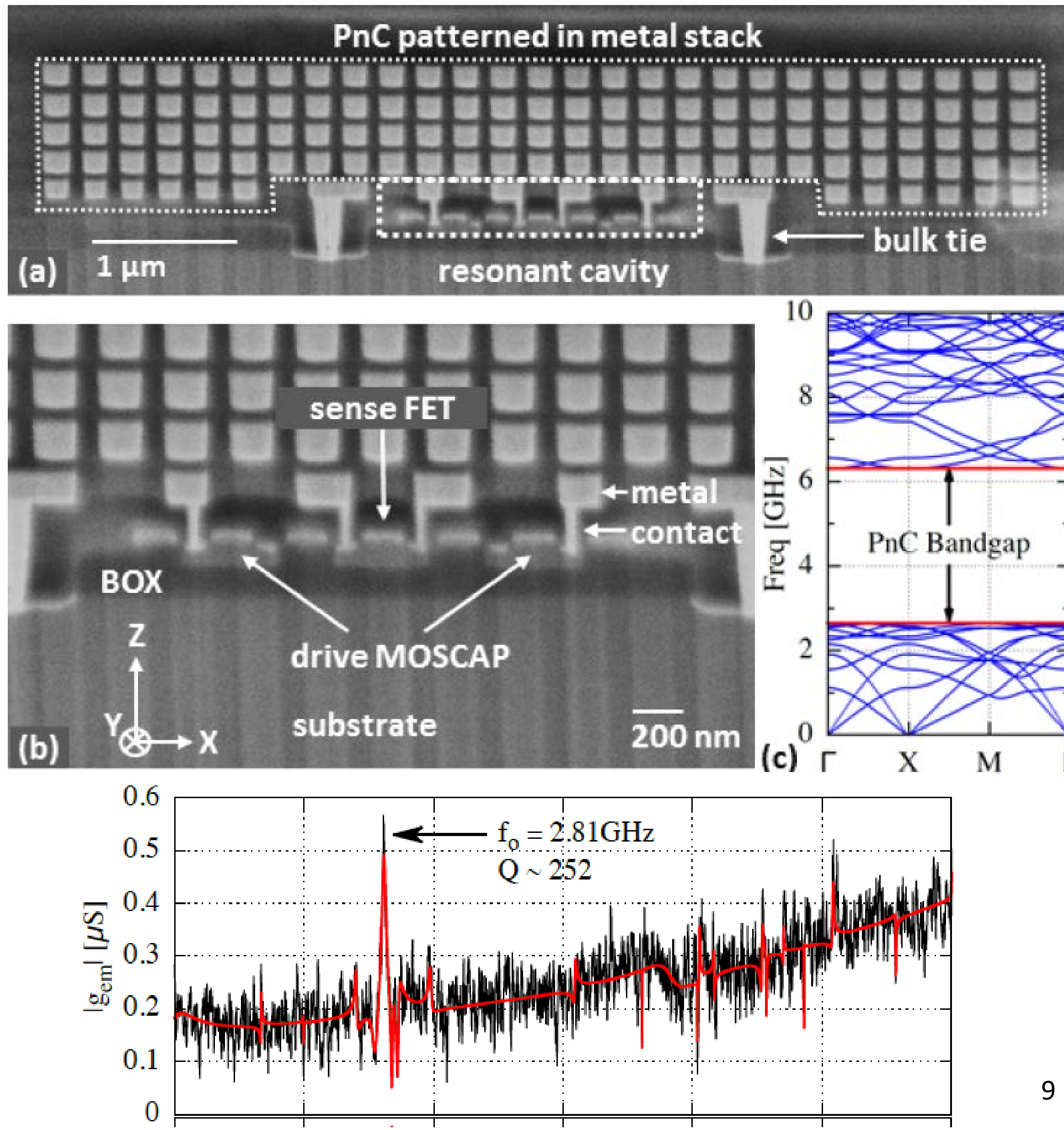




PHONONIC CRYSTAL BASED RBTS

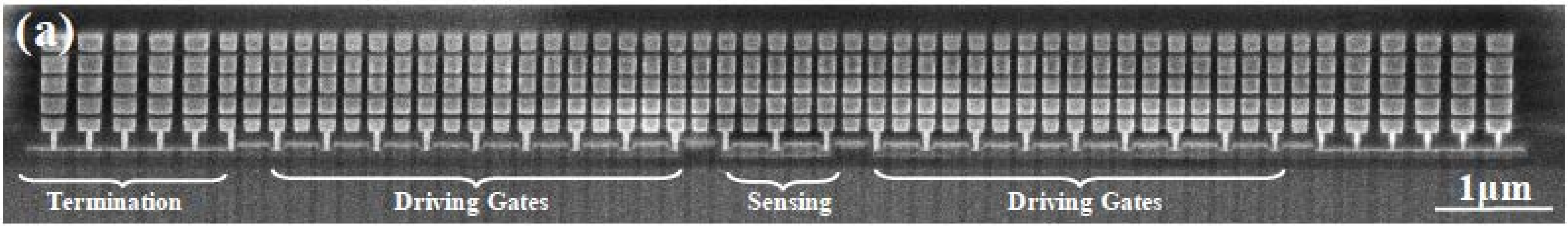
- 1st Phononic Crystals (**PnCs**) in a standard CMOS BEOL process
- Vertical acoustic confinement
- High-Q GHz-frequencies MEMS resonators
- No post-processing
- No special-packaging
- **GF 32SOI:**
    - High-fT
    - BOX: RF-feedthrough

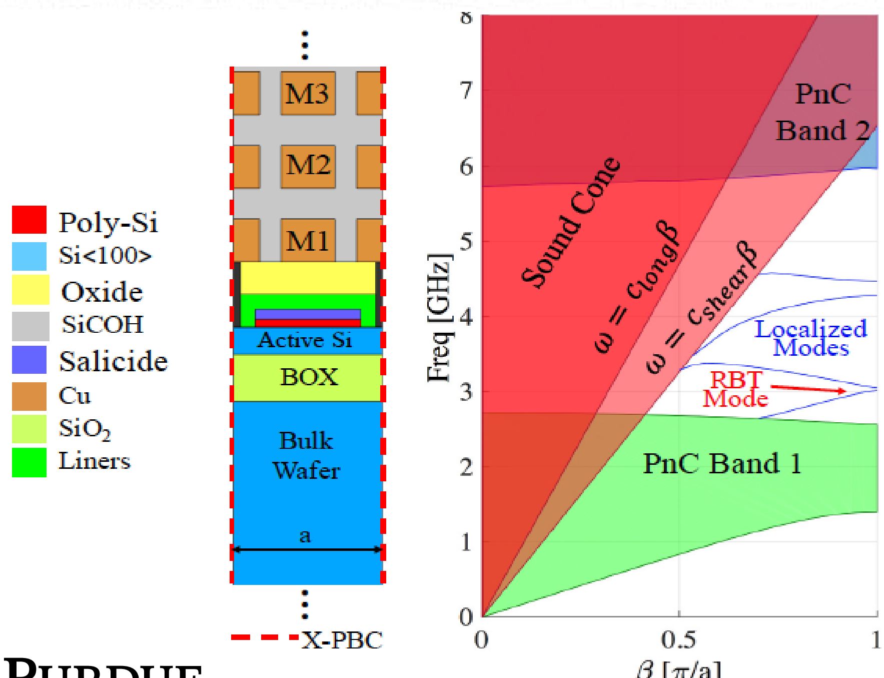
B. Bahr, R. Marathe, D. Weinstein IEEE IFCS14

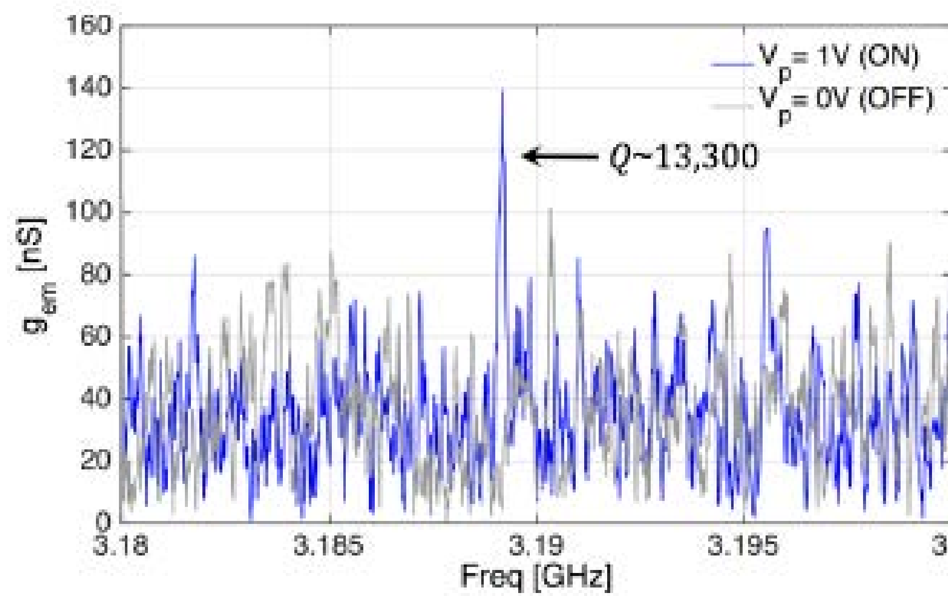


PNC WAVEGUIDED MODES

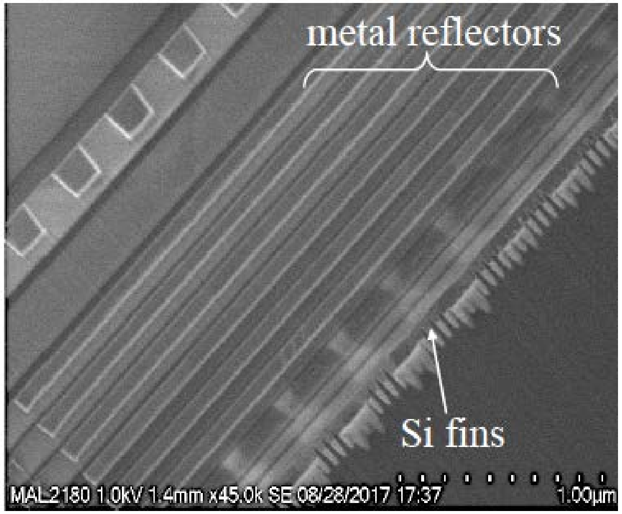
- Quality factors ranging from 8000 to 15000
- Improved spurious mode suppression
- Poor transduction efficiency resulting in low g_{em} (nS)







RESONANT FIN TRANSISTORS

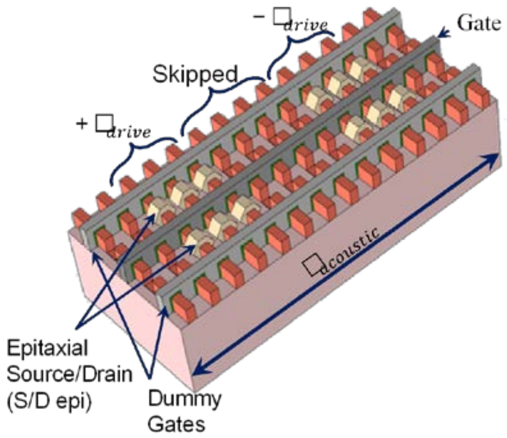


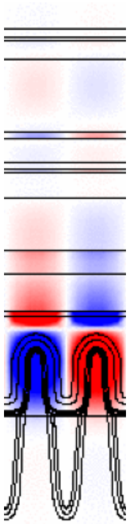
Resonators fabricated in GF 14nm FinFET process (14LPP)

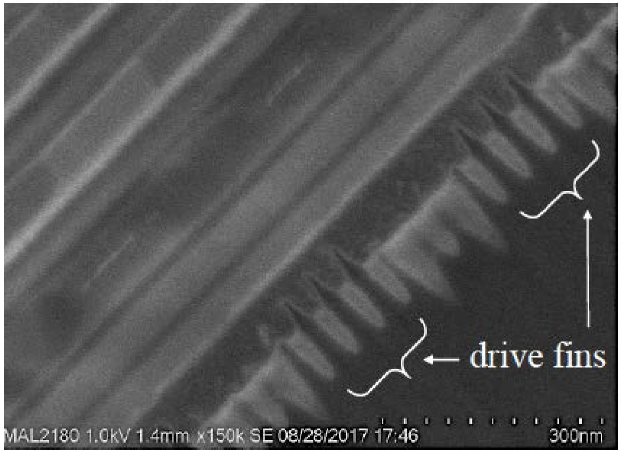
- Footprint: 300nm x 7um

Compared to IBM 32nm RBT

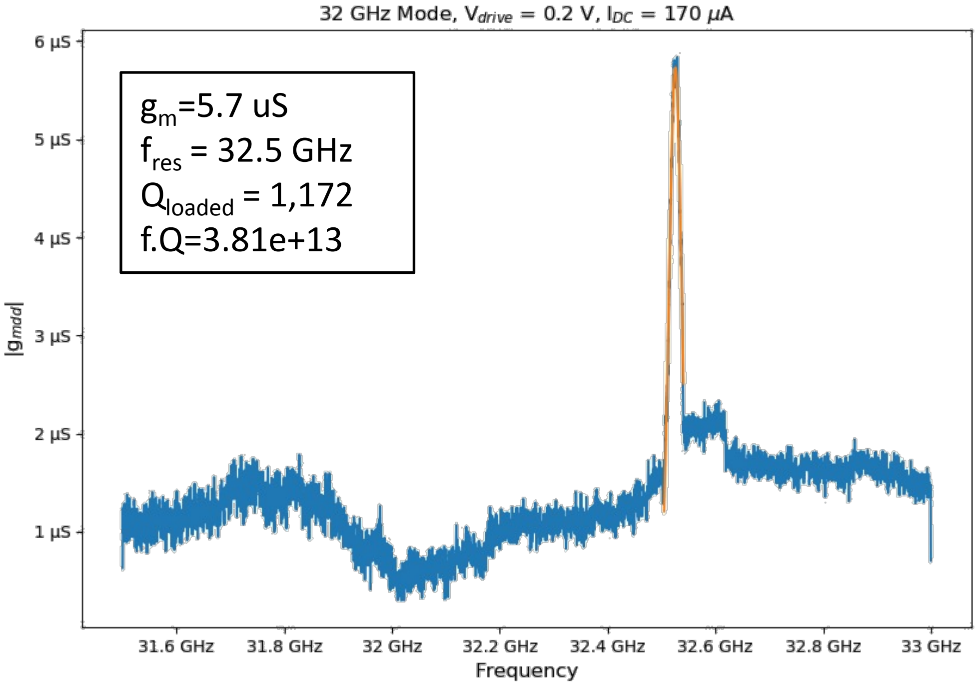
- 10x higher frequency
- 100x higher g_{mech}







B. Bahr, Y. He, D. Weinstein, ISSCC'18



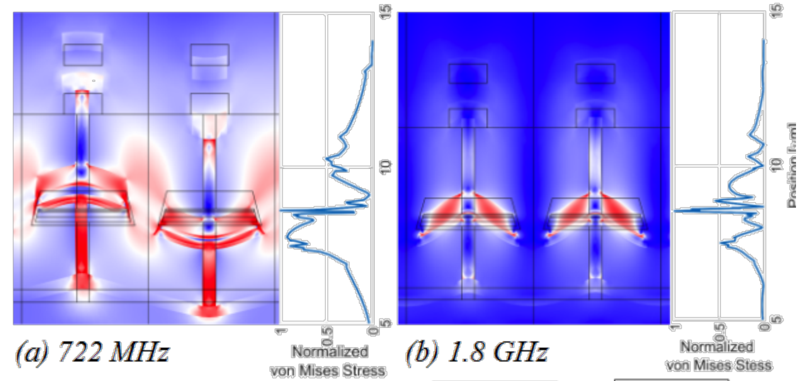
FERROELECTRIC TRANSDUCTION

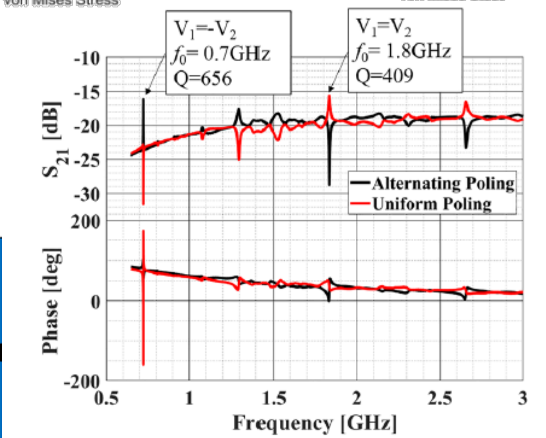
Ferroelectric materials are being introduced in planar CMOS technologies as **FeFETs and FeCAPs** for RAM applications.

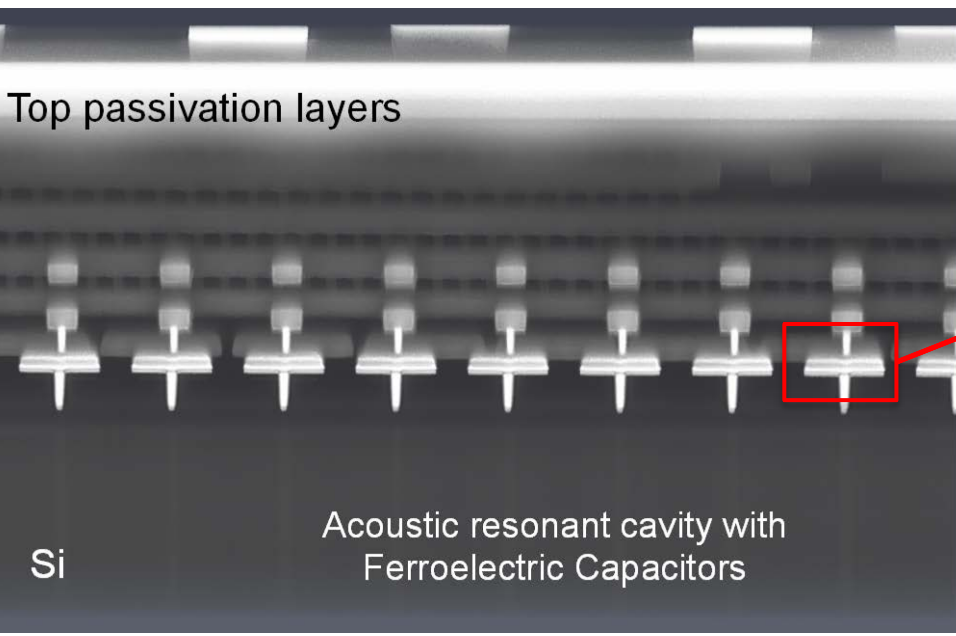
Piezoelectric

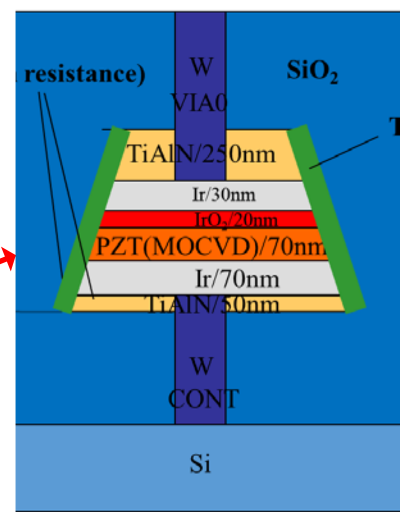
- → generate high stresses for driving
- → High readout sensitivity

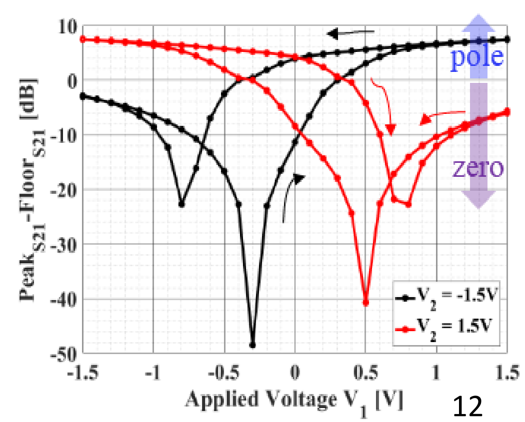
Texas Instruments (TI) FeCAPs process for acoustic waveguiding



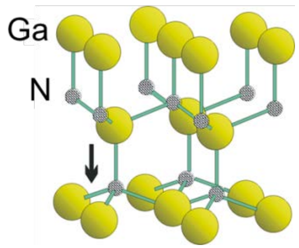


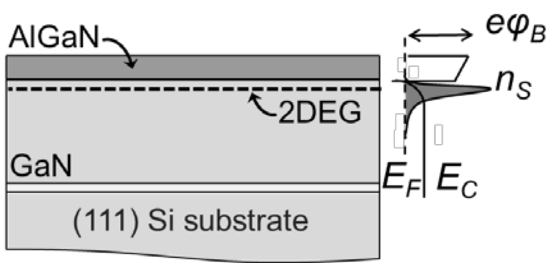


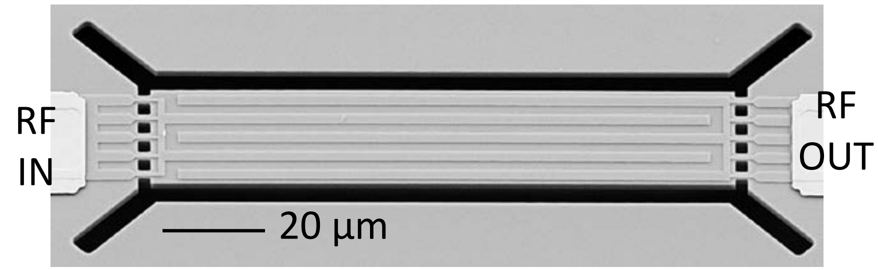




GALLIUM NITRIDE TECHNOLOGY







High Electron Mobility Transistors

- high charge density (10^{13} cm^{-2})
- high mobility (2000 cm^2/V s)

High Power Applications

- wide bandgap (3.4 eV)
- high breakdown field (3.3 MV/cm)

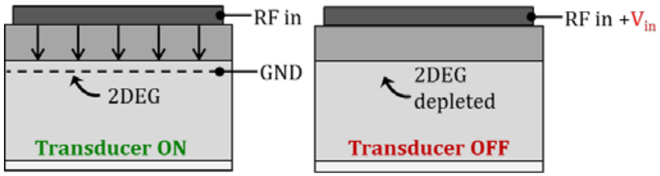
Monolithic Microwave ICs

- high saturation velocity (3 10^7 cm/s)

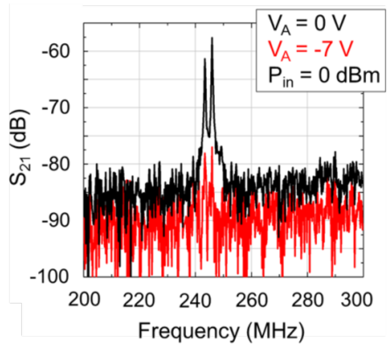
Electromechanical Benefits

- PE Coupling: k_T^2 of 2%
- Low acoustic loss (f.Q > 1e13 at 1 GHz in GaN-on-Si)
- Intimate integration with HEMTs/MMIC technology
- Use of 2DEG for tuning and programmability

MEMS resonators in GaN MMICs



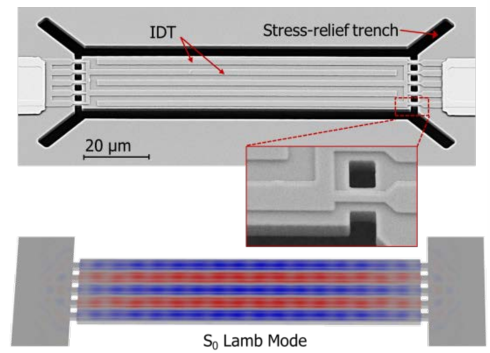
- First DC-switchable piezoelectric transducer
- Depletes transduction capacitor in the “OFF” state by >10x, ideal for filter banks loading an antenna
- 20 dB suppression by each of drive or sense transducers

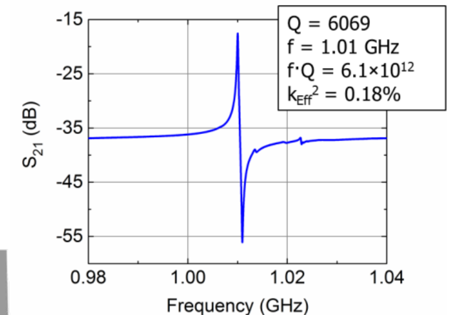


Popa, Weinstein, Transducers ‘13

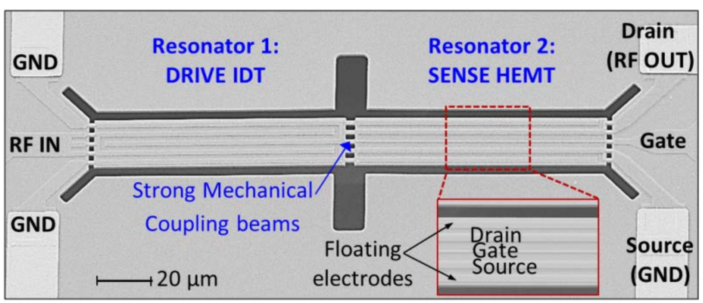
Contour mode resonators to achieve multiple frequencies on a single chip

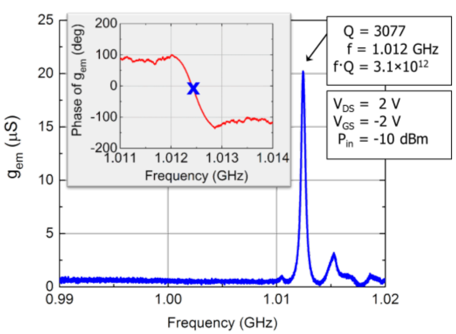
- Highest f.Q product in GaN contour mode resonators
- Highest keff2 in GaN contour mode resonators





Popa, Weinstein, IFCS ‘14





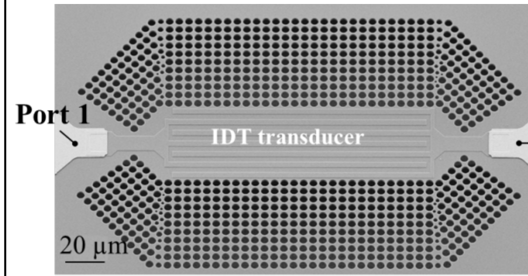
Mechanically coupled resonators with PE drive and HEMT sensing

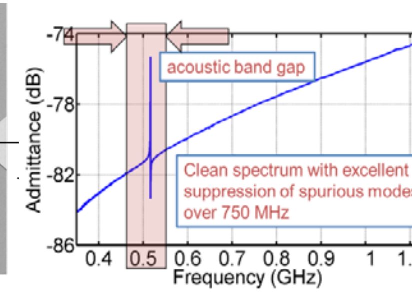
- 10x improvement in broad-band floor
- 100x improvement in SNR relative to previous designs

Popa, Weinstein, Hilton Head ‘14

Phononic crystals used to define frequency-dependent boundary conditions

- Achieved spurious-free frequency range over 750 MHz
- Power handling: IIP3>27dBm due to improved thermal paths

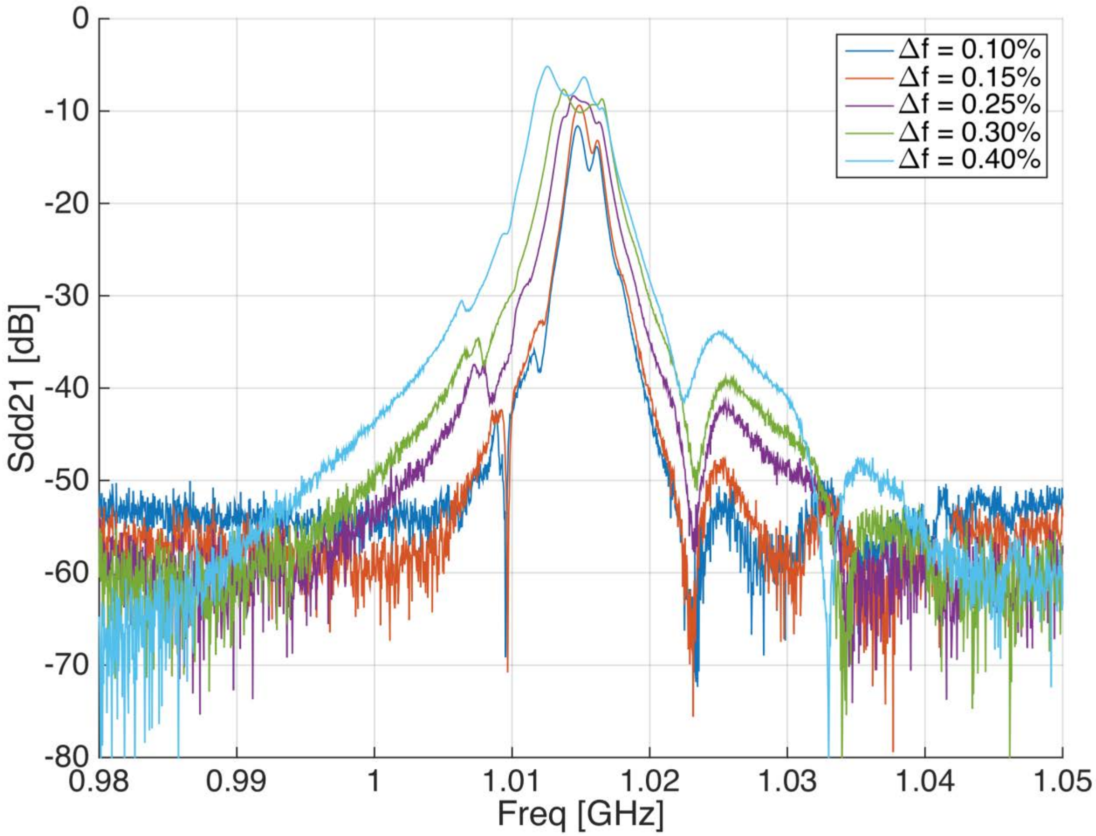


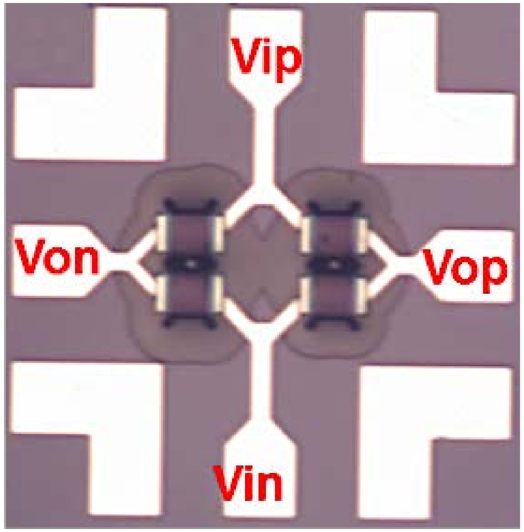


Wang, Weinstein, Hilton Head ‘14

RF FILTERS

- Small footprint RF lattice filters using Lamb mode resonators

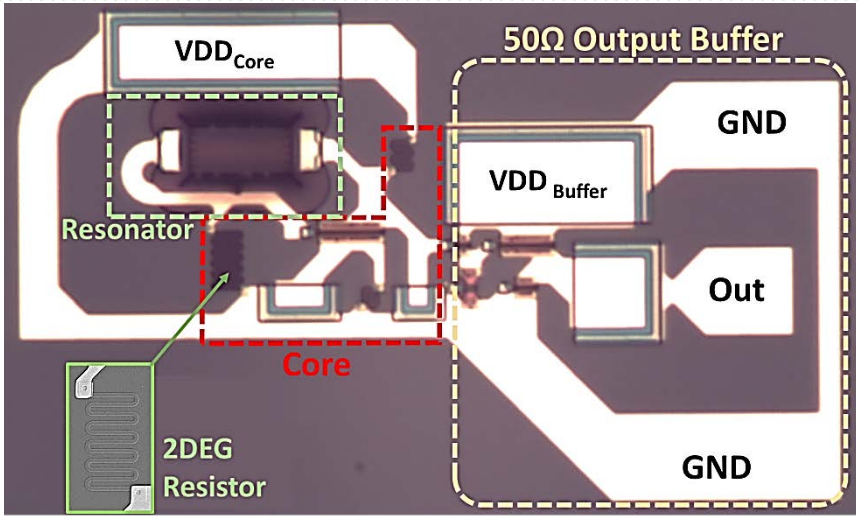


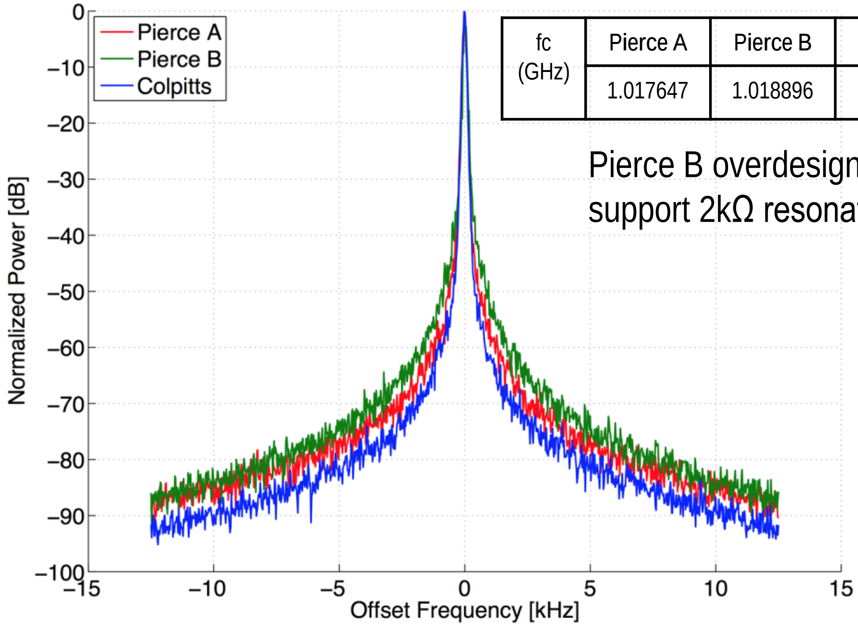


Δf (%)	f (GHz)	BW_{3dB} (%)	IL (dB)
0.10	1.015	0.19	11.6
0.15	1.015	0.11	9.38
0.25	1.015	0.28	8.36
0.30	1.015	0.38	7.65
0.4	1.014	0.39	5.16

GAN MEMS OSCILLATORS

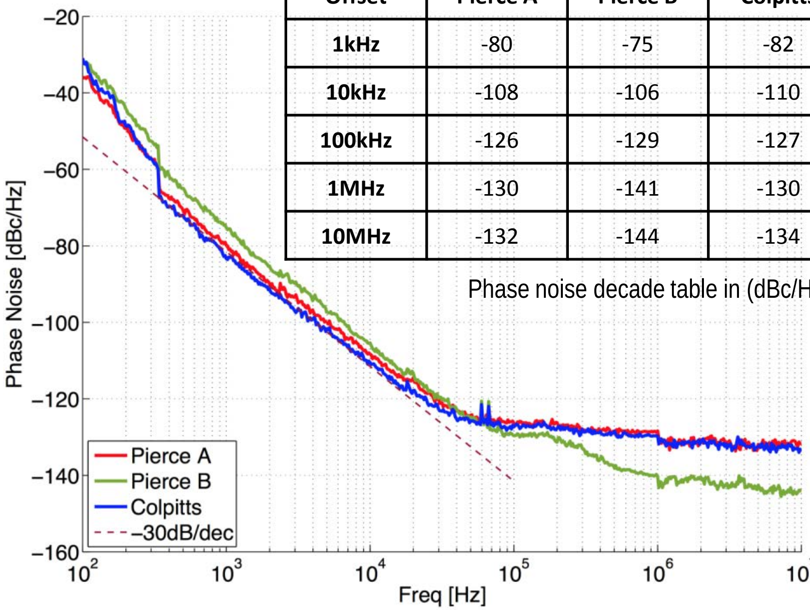
- First demonstration of monolithic MEMS oscillators in GaN.
- Pierce and Colpitts topologies implemented with Lamb-mode resonators in GaN at 1GHz.
- Passive and active devices in DAHI GaN HEMT+MEMS technology on 111 Si.





fc (GHz)	Pierce A	Pierce B	Colpitts
	1.017647	1.018896	1.015505

Pierce B overdesigned to support 2kΩ resonator



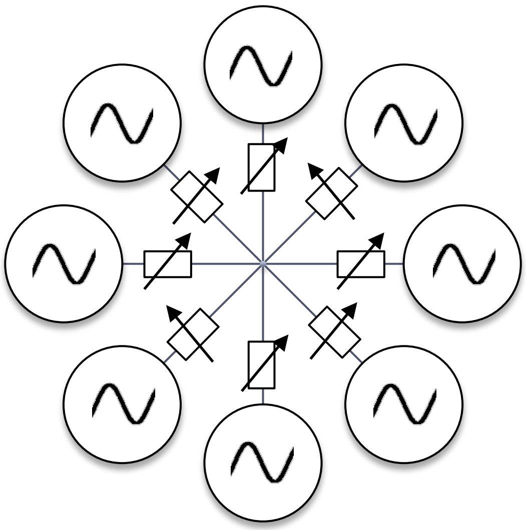
Offset	Pierce A	Pierce B	Colpitts
1kHz	-80	-75	-82
10kHz	-108	-106	-110
100kHz	-126	-129	-127
1MHz	-130	-141	-130
10MHz	-132	-144	-134

Phase noise decade table in (dBc/Hz)

B. Bahr, L.C. Popa, D. Weinstein, ISSCC'15

NON-BOOLEAN INFORMATION PROCESSING

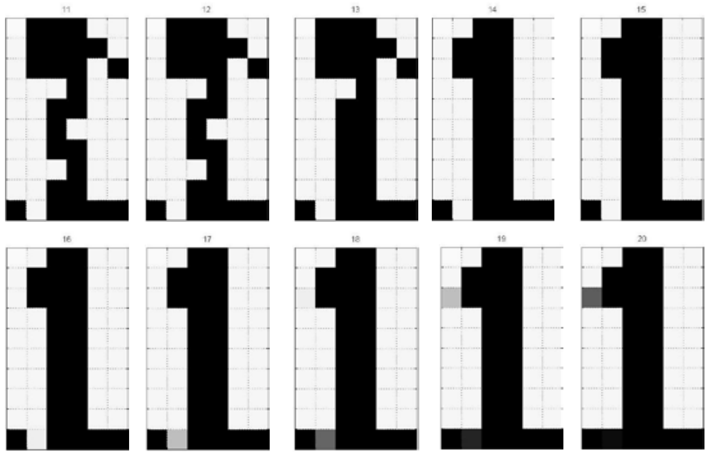
Coupled arrays of Resonant Body Oscillators



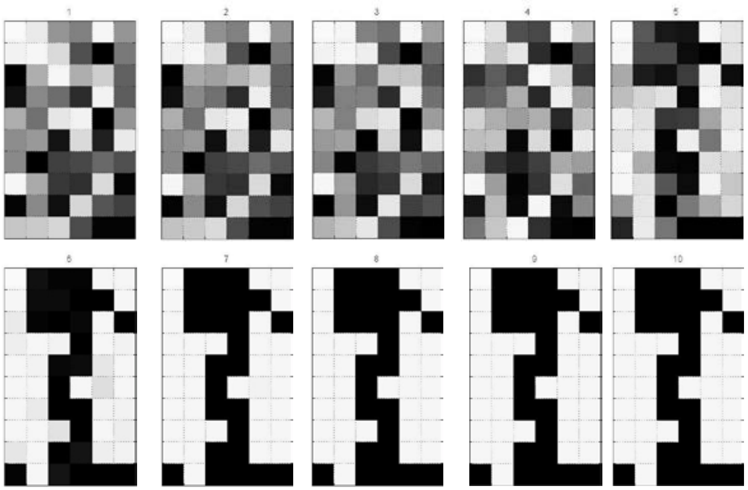
Phase patterns in nonlinear coupled oscillator arrays.

Efficient processing/memory for imaging and other large-scale systems

Recognition



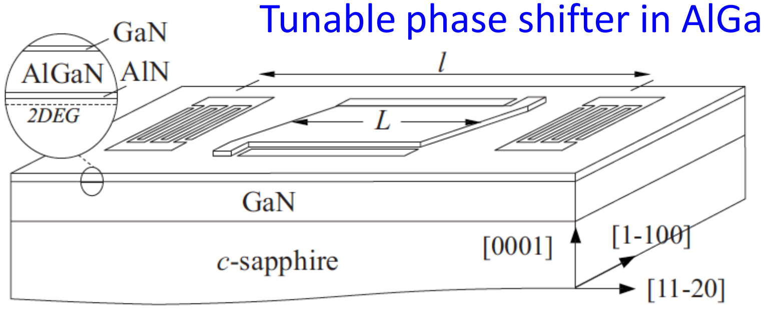
Learning



ACOUSTOELECTRIC EFFECT

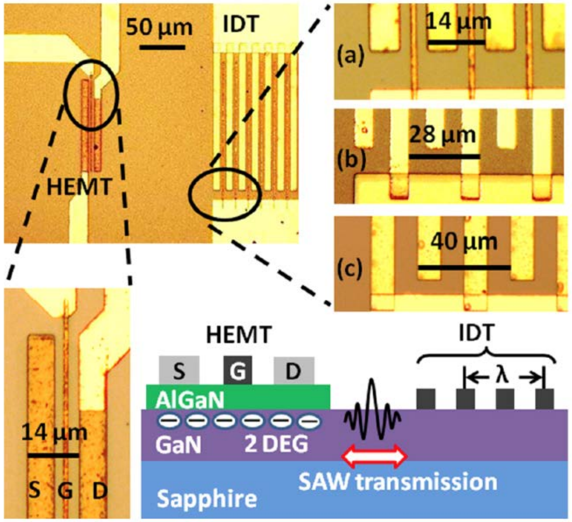
- Energy exchange between free carriers and elastic wave in piezoelectric semiconductor
- Wave can be **attenuated** or **amplified** by DC electric field
- First posited by Parmenter in 1953

Tunable phase shifter in AlGaN/GaN



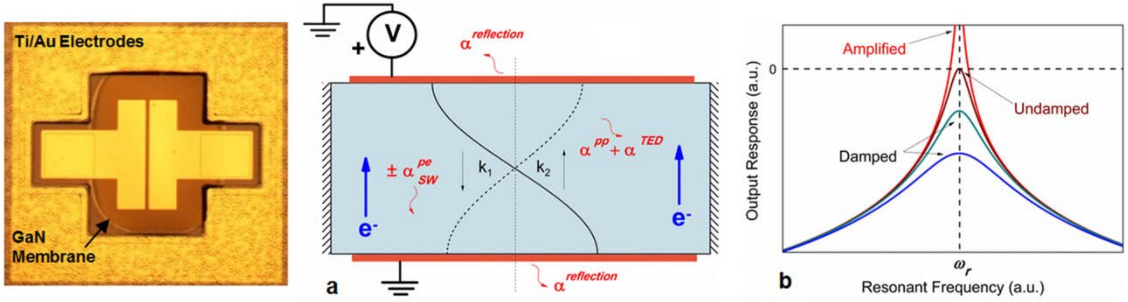
Pedros, Bougrioua et al, APL 96, 123505 (2010)

SAW generation by HEMT



Shao, Pipe et al, APL 99, 243507 (2011)

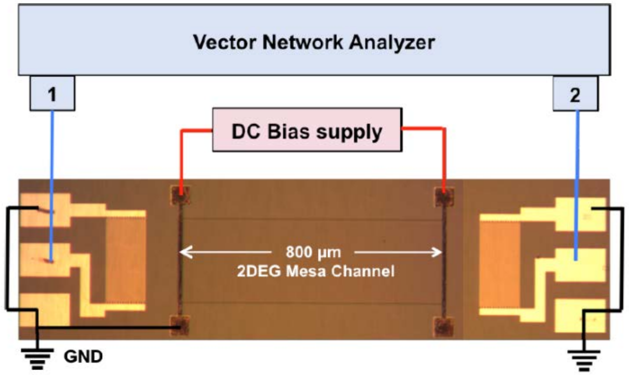
Increased Q in GaN FBAR

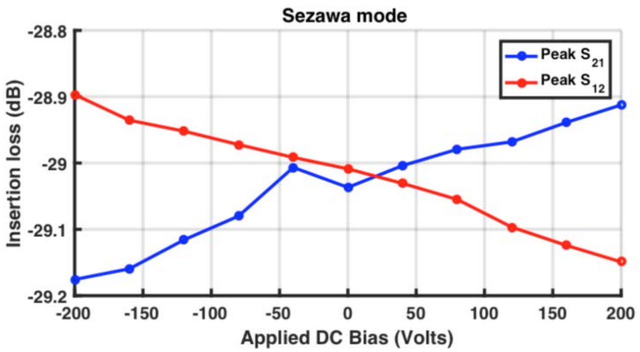


Gokahle, Rais-Zadeh, Nat. Sci. Rep 4,5617 (2014)

NON-RECIPROCAL DEVICES

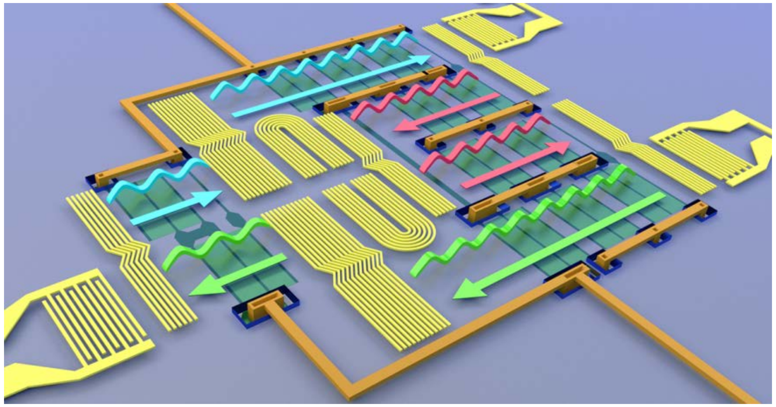
- Acoustoelectric effect is inherently non-reciprocal

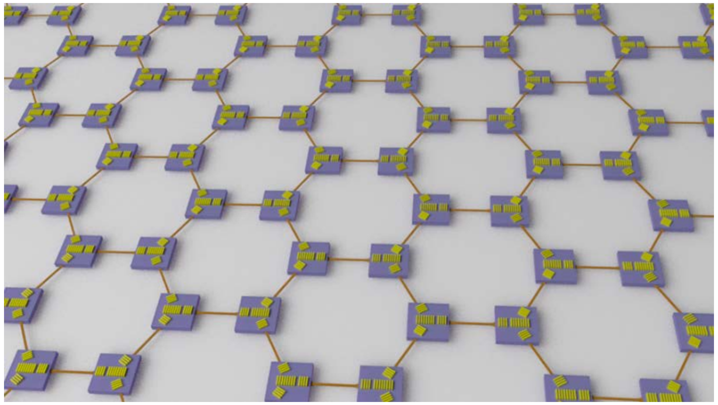




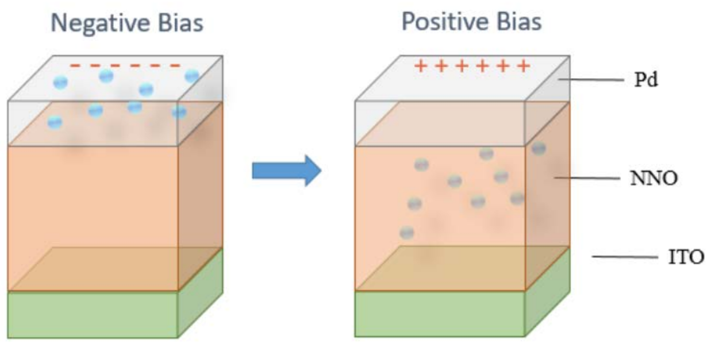
S. Ghosh et al., Transducers'17

- Traveling wave amplifiers, isolators, circulators, correlators
- Topological insulators, topomechanics for quantum computing

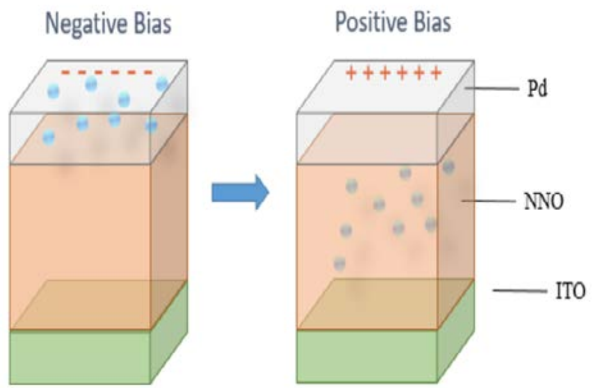




NICKELATE ACTUATORS

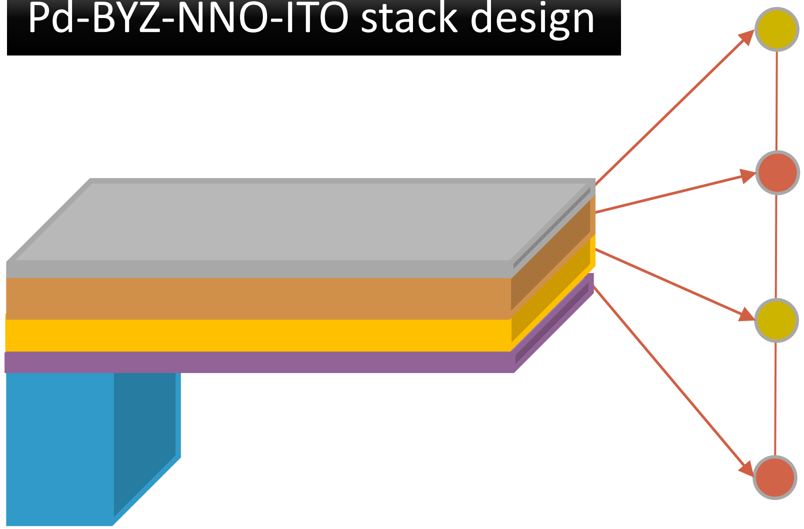


Voltage-driven transition. Ions diffuse into or out of the Nickelate to induce the MIT with an applied bias voltage, which need not be maintained on the electrode once the transition occurs.



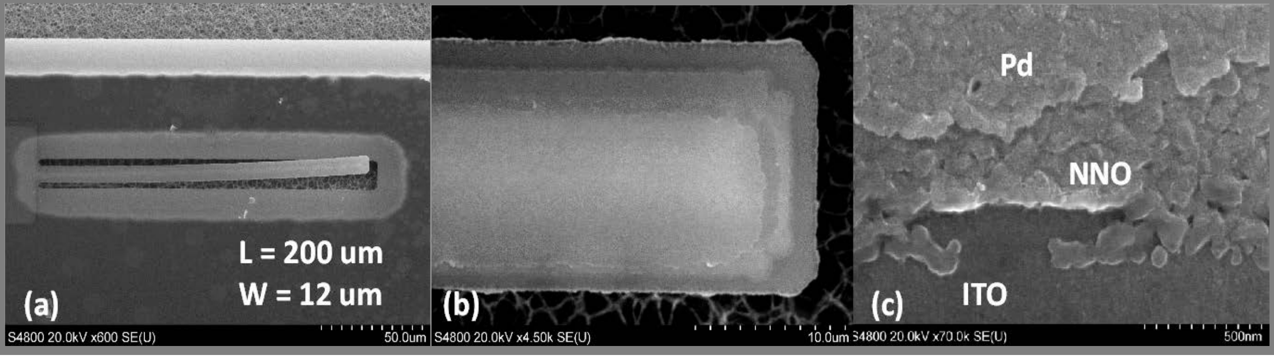
Insulator-to-Metal transition temperature shown experimentally below room temperature for NNO.

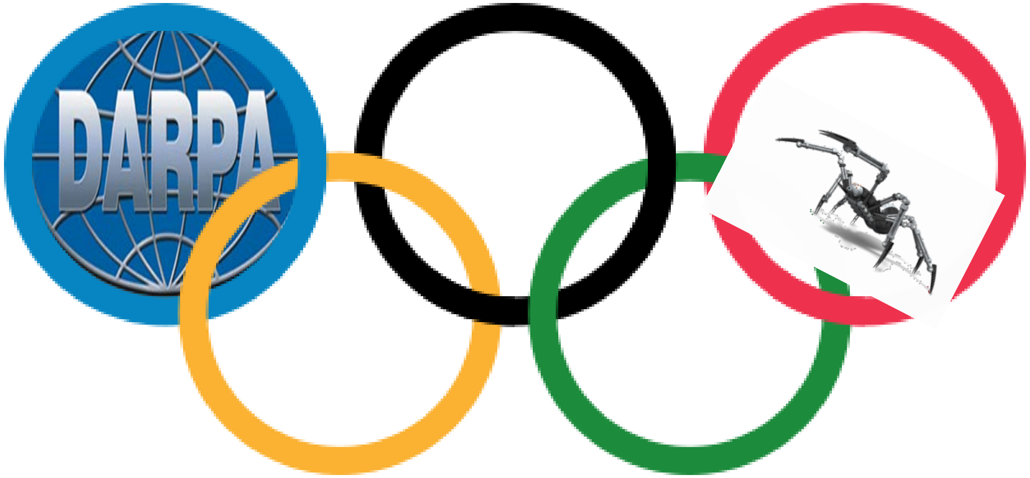
Pd-BYZ-NNO-ITO stack design

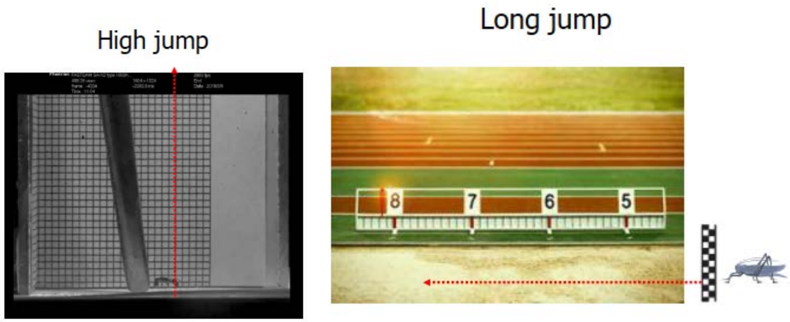


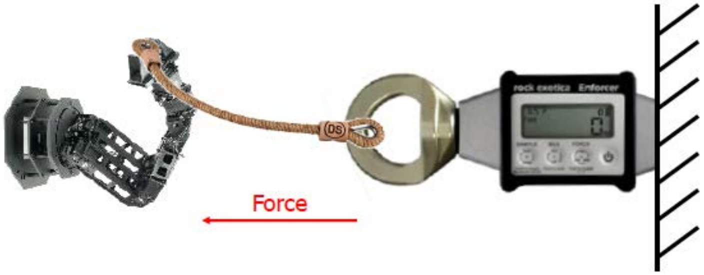
- Pd, top electrode, catalyst of H_2 split into protons and electrons
- BYZ, dielectric layer to provide electric field to drive protons. Store protons as well
- NNO, provide strain during proton doping
- ITO, bottom electrode, resistant to rigorous annealing process of NNO

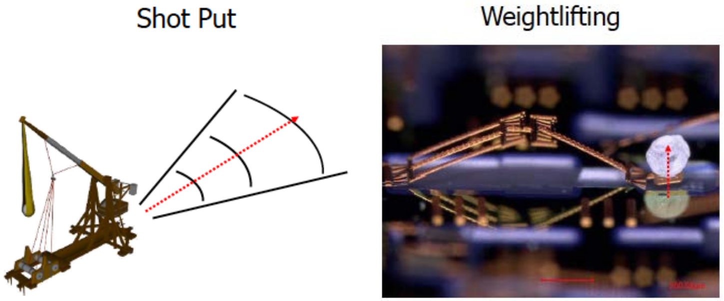
NOMAD: UNTETHERED MICROROBOTS











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