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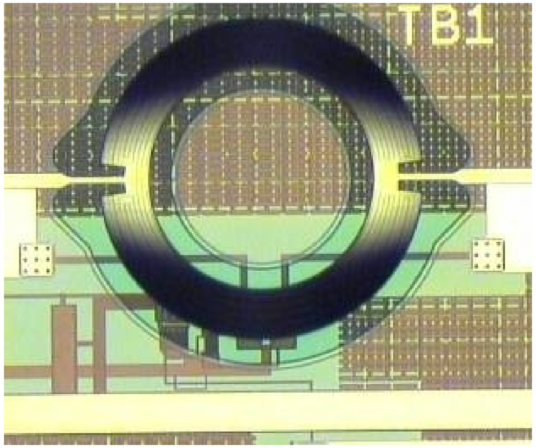


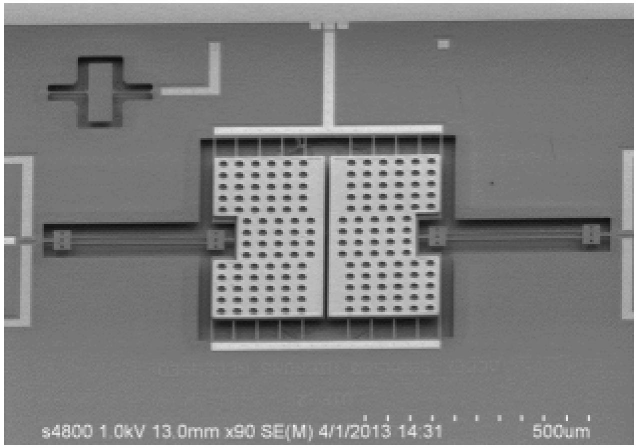


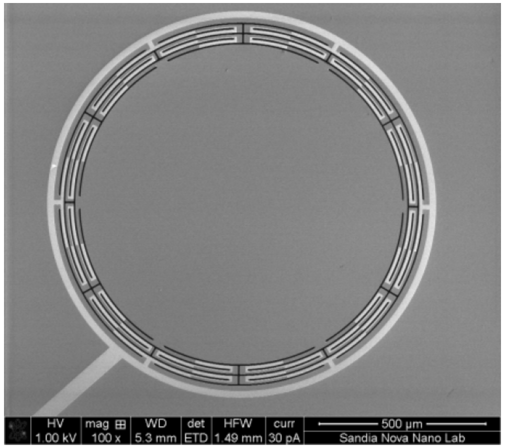


# Aluminum Nitride Based MEMS: Sensors, Actuators, and Resonators

Benjamin A. Griffin

5/24/16

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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# Sandia National Laboratory

Sandia National Laboratories


**Government Owned, Contractor Operated (GOCO)**




**Federally Funded Research and Development Center (FFRDC)**

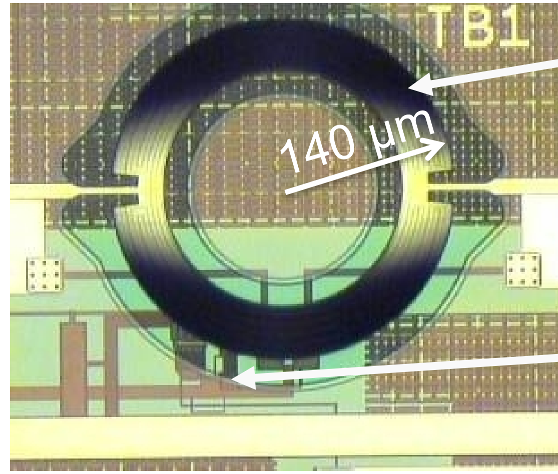
# Outline

- Aluminum Nitride
- RF Microresonators
- Double Ended Tuning Fork Acclerometers
- Microphones
- Piezoelectric Micromachined Ultrasonic Transducers
- XMEMS: MEMS for Extreme Environments

Sandia's Microsystems and Engineering Sciences Application (MESA) Facility

# Sandia's AlN MEMS Program

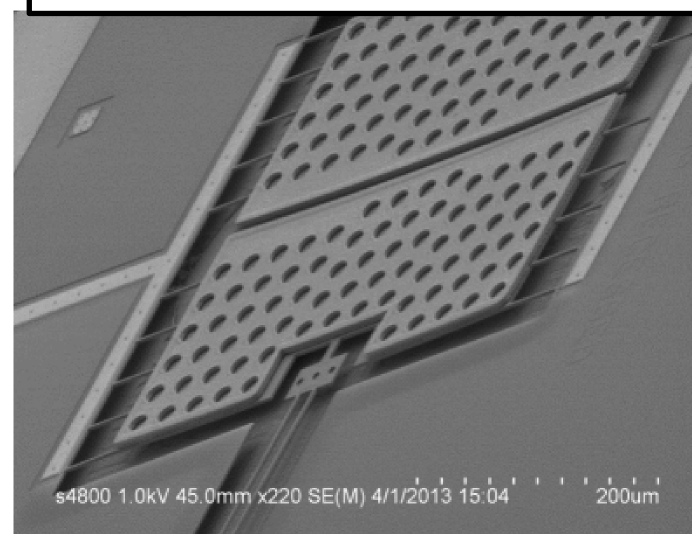
- RF Microresonators
- Accelerometers
- Ultrasonic Transducers
- Microphones
- XMEMS
- Phononic Crystals



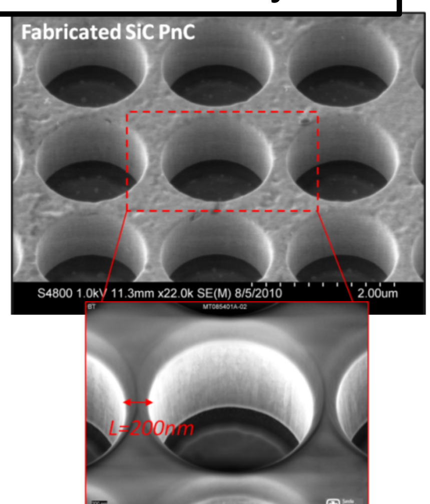

AlN Micro-Resonator

CMOS Circuit

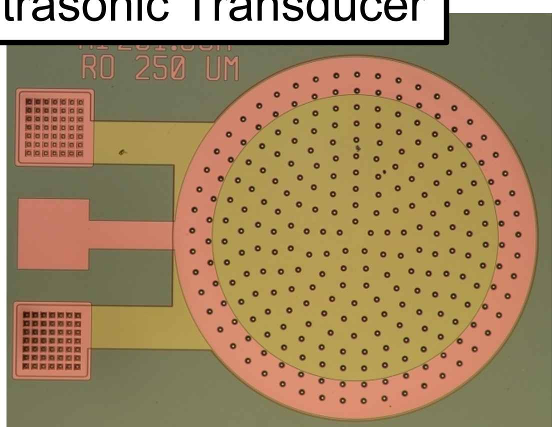
AlN Resonant Accelerometer




Phononic Crystal



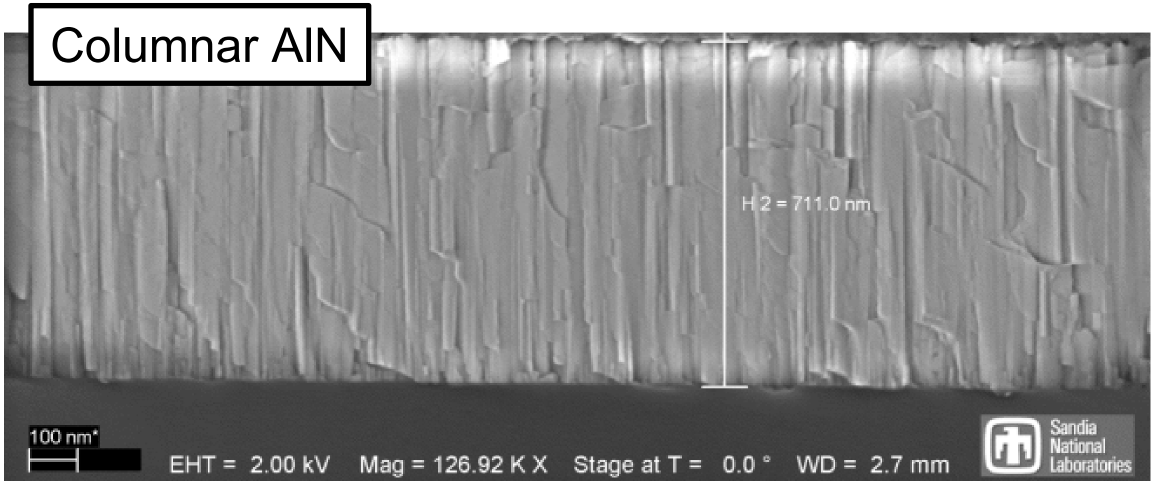

AlN:SiC XMEMS Ultrasonic Transducer



# Aluminum Nitride (AlN)

- Piezoelectric thin film
  - Physical vapor deposited
    - Low temperature deposition ~350˚C
  - CMOS compatible
  - Non-ferroelectric
    - No Curie temperature
    - Texture achieved during deposition
  - Large band-gap (6 eV)
  - High temperature capable
    - Melting point of 2,200˚C
    - Piezoelectric response has been measured at 1,150˚C

| Property | AlN |
|---|---|
| Low permittivity, $\varepsilon_{33}$ | 8.5 |
| High sensitivity, $g_{31}$ (V/m / Pa) | 0.027 |
| High signal-to-noise ratio (√Pa) | $21x10^5$ |
| Low loss tangent, $\tan\delta$ | 0.003 |
| Parallel piezo coefficient, $d_{33}$ (pm/V) | 5 |
| Transverse piezo coefficient, $d_{31}$ (pm/V) | 2 |



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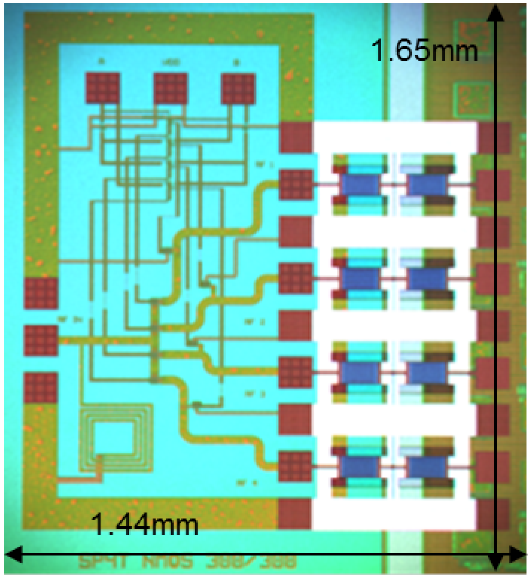
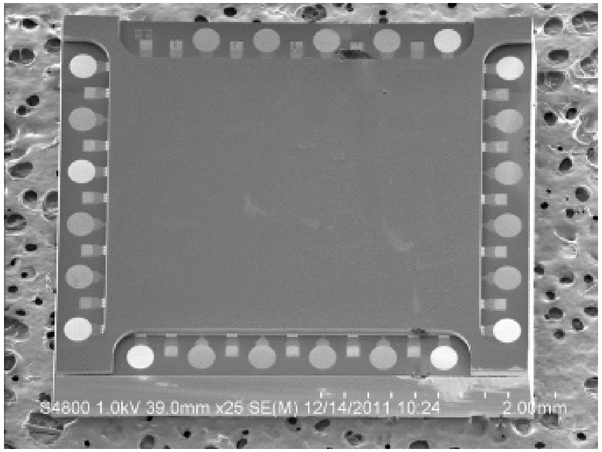
Switched Filter Array on CMOS



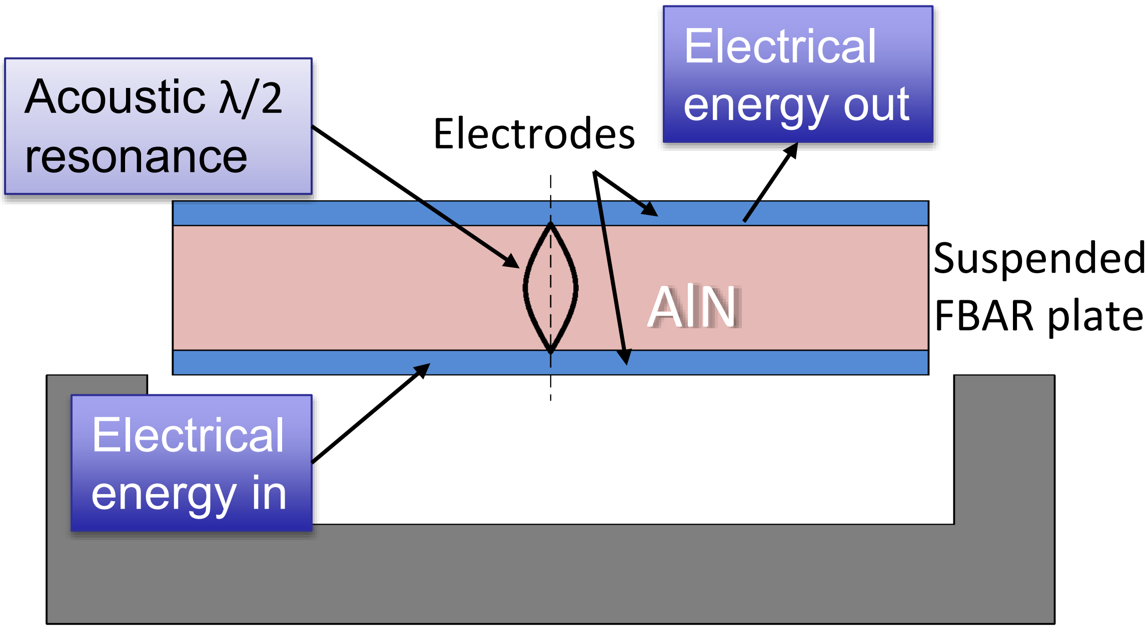




Wafer Level Packaged Microresonators

# AlN Commercial Success

- Film Bulk Acoustic Resonator (FBAR) Filters
  - Half-wavelength, thickness mode resonators
  - Filter frequency is set by film thickness
  - Commercial success for AlN MEMS
  - More than 60 RF filters in the modern smartphone*

Avago FBAR




$$d_{31} \cong 5.4\,\text{pm}/\text{V}$$

$$k_{eff}^2 \cong 6\%$$

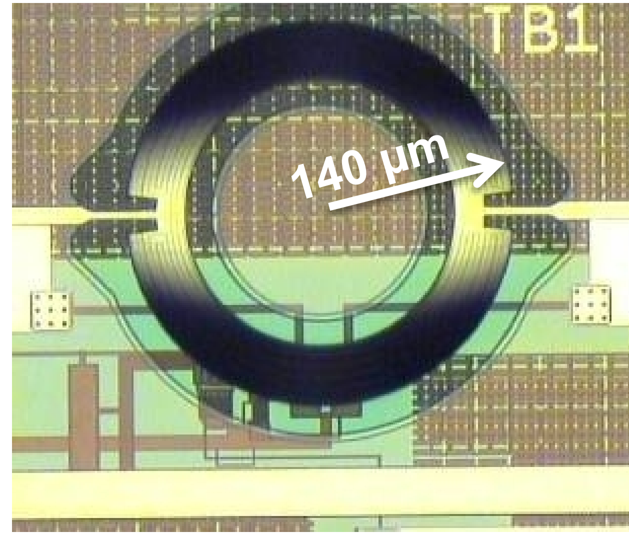
$$BW = \frac{k_{eff}^2}{2} \cong 3\%$$

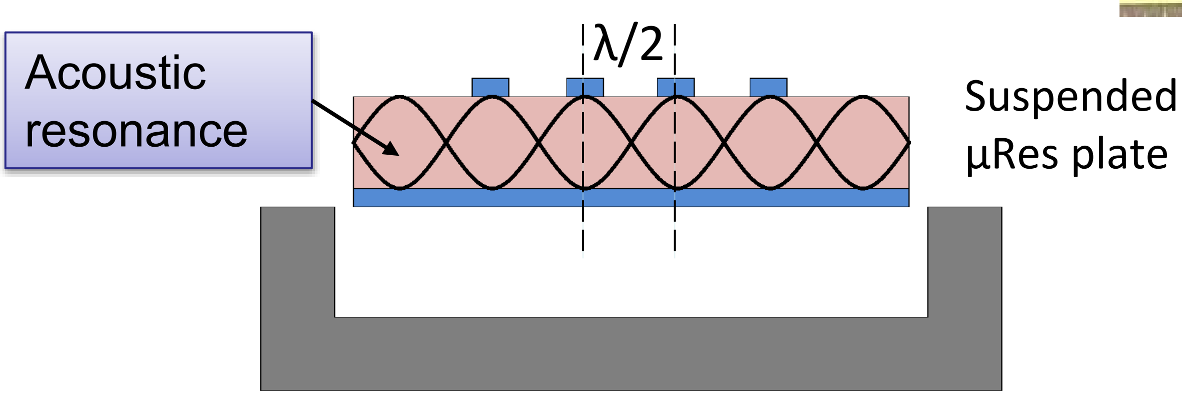
* 2015 Johnson, R. C., "Fabless RF Filters Cut Size, Share Same Die" http://www.eetimes.com/document.asp?doc_id=1327528

# Aluminum Nitride Microresonators

- Lateral mode devices
  - Wave propagation occurs in-plane
  - Frequencies are set by lithography
  - Single chip: 32 kHz to 10 GHz
- Applications
  - Miniature High-Selectivity Filters
  - Filter Banks for Spectrum Analysis and Spectrally Aware Radios
  - Miniature Low Power Oscillators

**Monolithic Integration of Microresonator and CMOS**



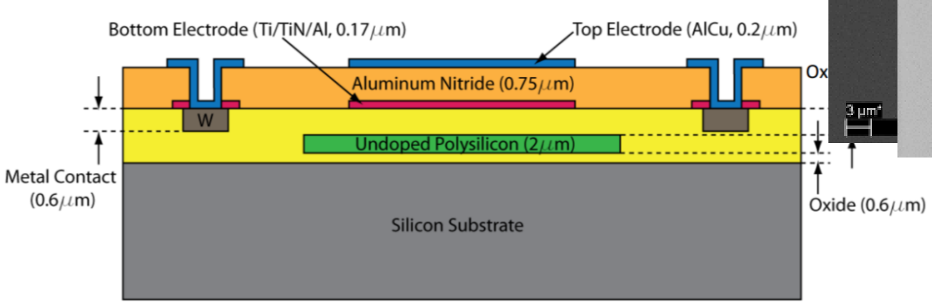

$$d_{31} \cong -2.2\,\mathrm{pm/V}$$

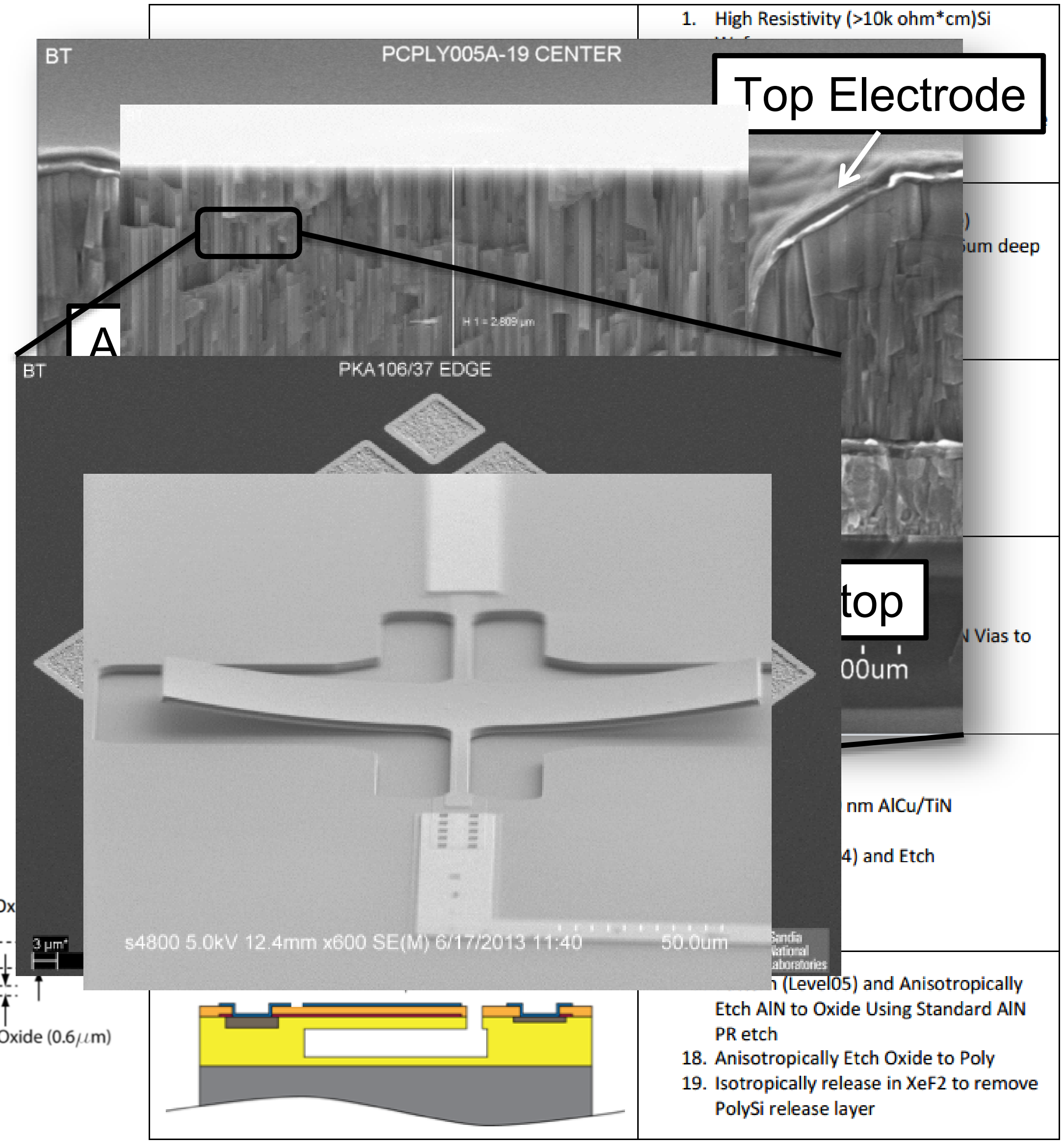
$$k_{eff}^2 < 2\%$$

$$BW < 1\%$$

# AlN Microresonator Fabrication

- 6-Masks To Form Basic AlN Device:
  - Si Release Layer Definition
  - Tungsten Contact Stops
  - Bottom Metal
  - AlN Via Etch
  - Top Metal
  - Release Trench
- Additional Optional Masks
  - 1 µm Thick Metal and Spacer (2)
  - Wafer-Level Packaging (2)
  - Gold Plating (2)



# MonolithiAlN On CMOS Fabrication

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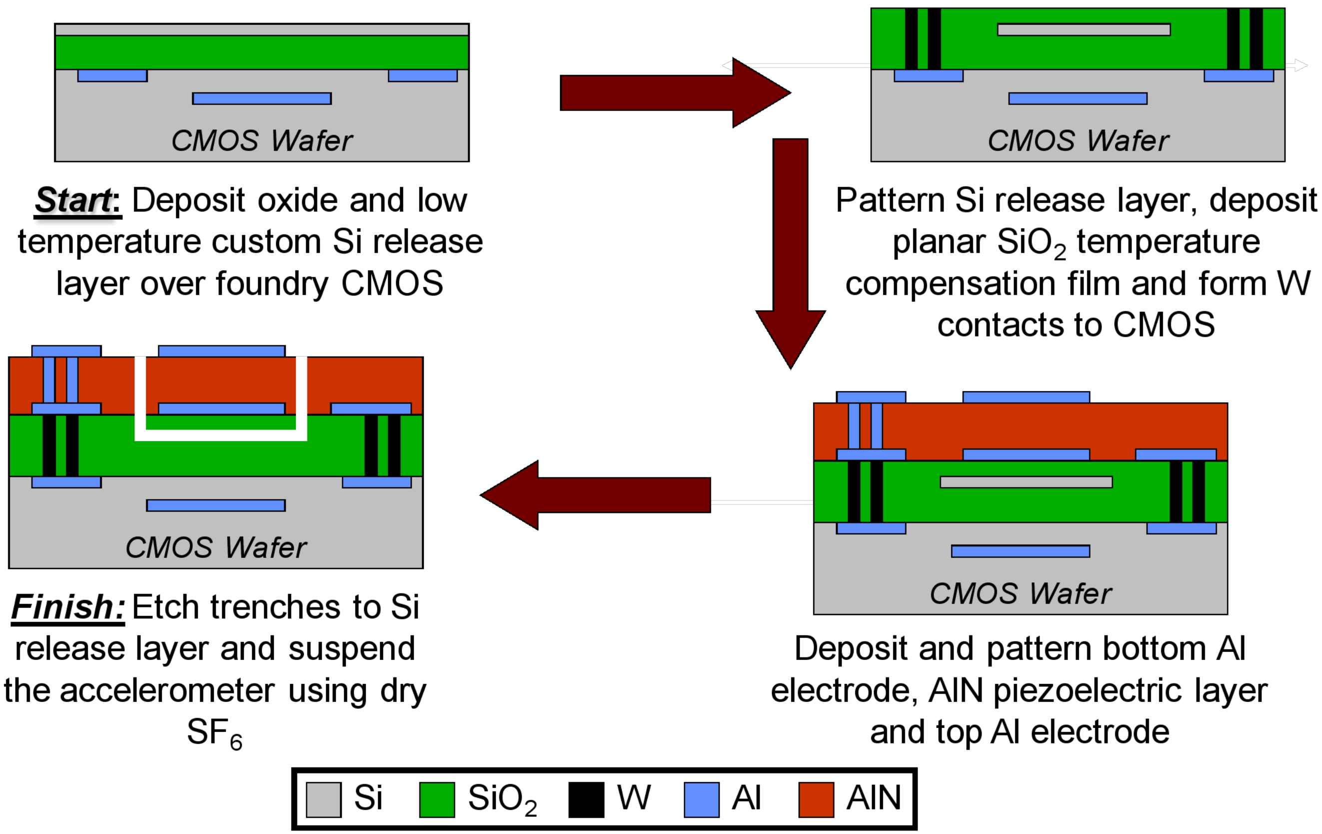
- Same 6-Masks
- AlN Piezoelectric Layer
- Maximum Process Temperature of 350 to 400°C
- Processing on Standard CMOS After Back End of Line
- CMOS Transistors for Configuration and Tuning
- CMOS Metals for RF Routing and Passives





K. E. Wojciechowski, R. H. Olsson, T. A. Hill, M. R. Tuck and E. Roherty-Osmun, “Single-Chip Precision Oscillators Based on Multi-Frequency, High-Q Aluminum Nitride MEMS Resonators,” *IEEE International Solid-State Sensors, Actuators and Microsystems Conference*, pp. 2126-2130, June, 2009.

# Performance of Mature Acoustic Resonator Technologies

| Technology/ Metric | $K^2$ Theory | $K^2$ Experiment | Q @ ~ 1 GHz | ~FOM Measured | CMOS Integration | Multiple Frequencies on a Substrate |
|---|---|---|---|---|---|---|
| AlN BAW/FBAR | 5.3% | 5.7% | 3000 | 170 | Yes | High Cost |
| Standard $LiTaO_3$ SAW | 5.3% | 5.3% | 600 | 32 | No | Yes |
| Electrostatic Resonators | < 0.1% | << 0.1% | ~10,000 | < 1 | Some | Yes |
| AlN Microresonator | 1.6% | 1.5% | 2350 | 35 | Yes | Yes |

More about this at the end…

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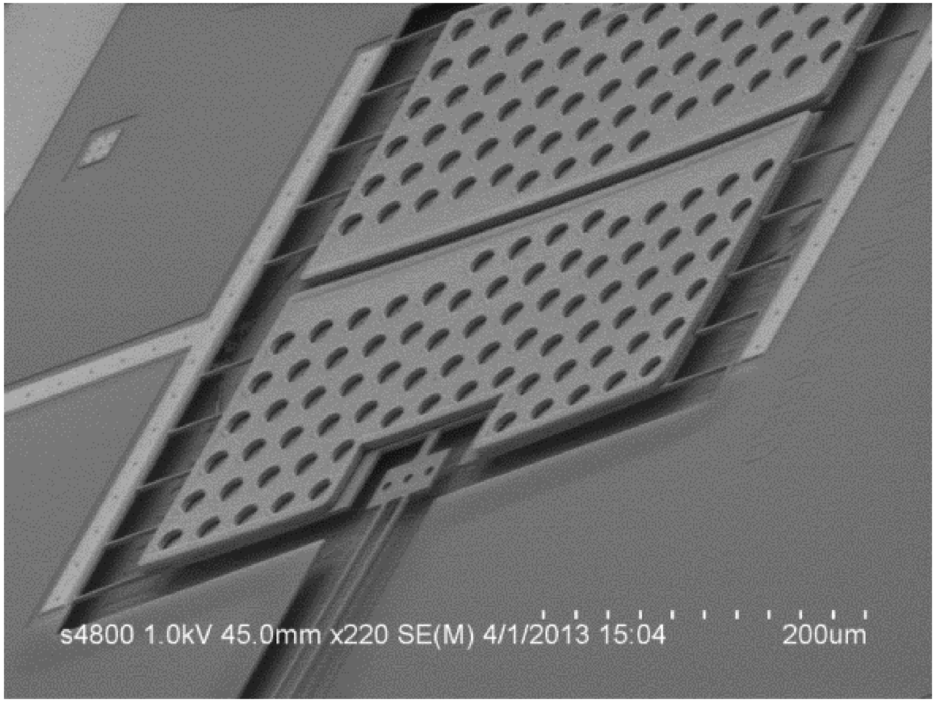
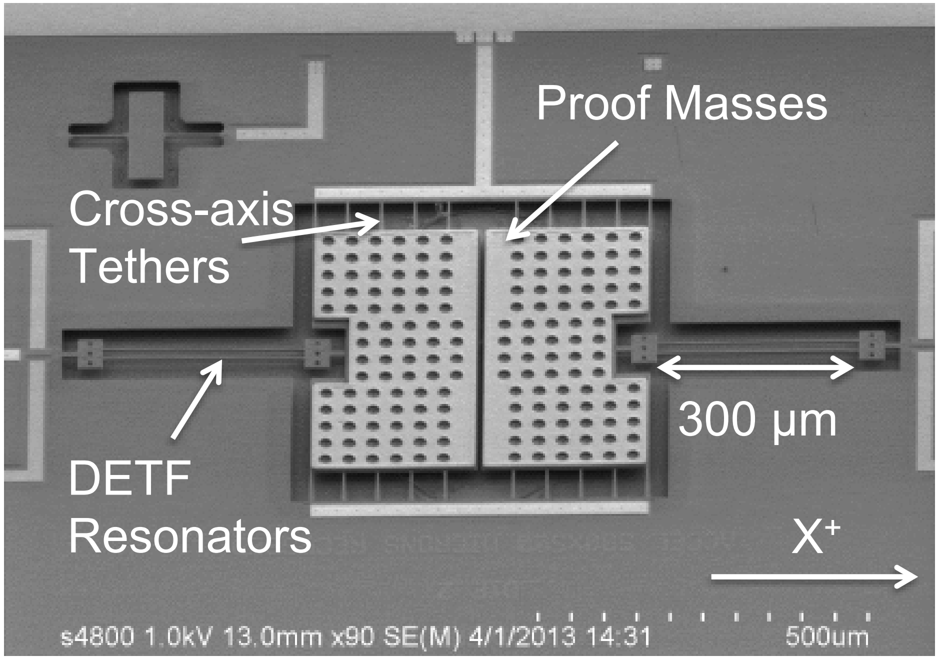


# AlN Resonant Accelerometers Based on Microresonator Process

- Aluminum nitride
  - Low temperature
  - CMOS compatible
- Piezoelectric
  - Lower impedance
  - Higher power handling
  - Lower noise
- Resonant sensing
  - High sensitivity
  - Low power circuit interface
  - High dynamic range for open loop operation

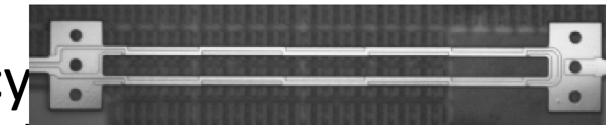


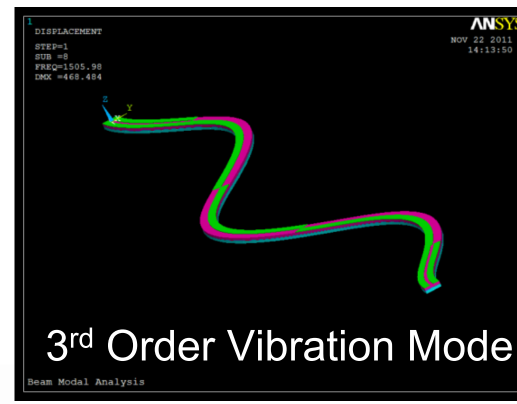

Aluminum Nitride Resonant Accelerometer

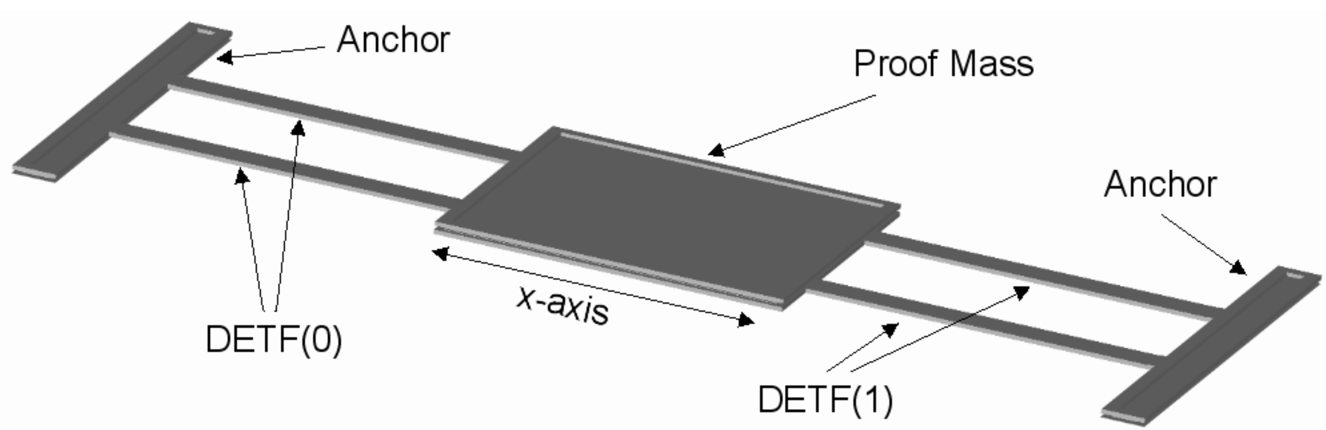
# Resonant Accelerometer Operation

- Double-ended tuning forks (DETF) placed in oscillation loop
- Positive x acceleration increases frequency of DETF(0), decreases frequency of DETF(1)
  - Accel = frequency[DETF(0)] – frequency[DETF(1)]
  - Subtraction reduces effects due to temperature, drift, and cross-axis accelerations
  - Temperature and cross-axis rejection are dependent on DETF matching

Double Ended Tuning Fork (DETF)



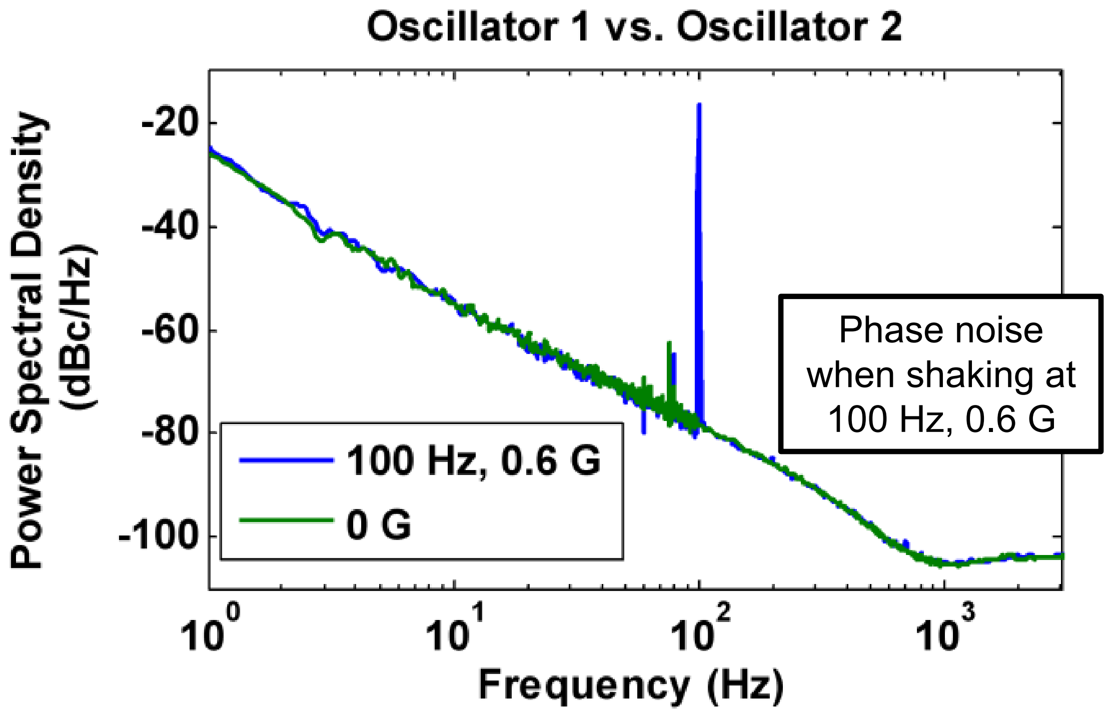


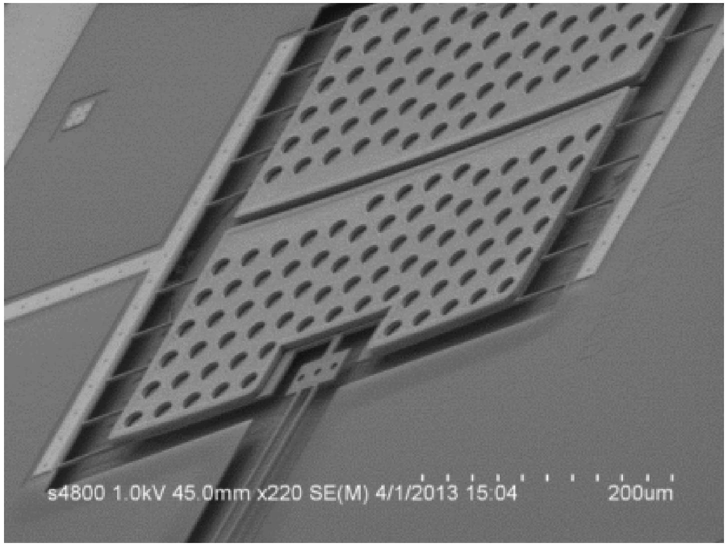




Resonant Accelerometer Model

# DETF Accelerometer Specifications

- Minimum detectable signal is 0.50 mG/√Hz
- Bandwidth > 200 Hz
- Cross-axis sensitivity of 2.8% and 1.2%



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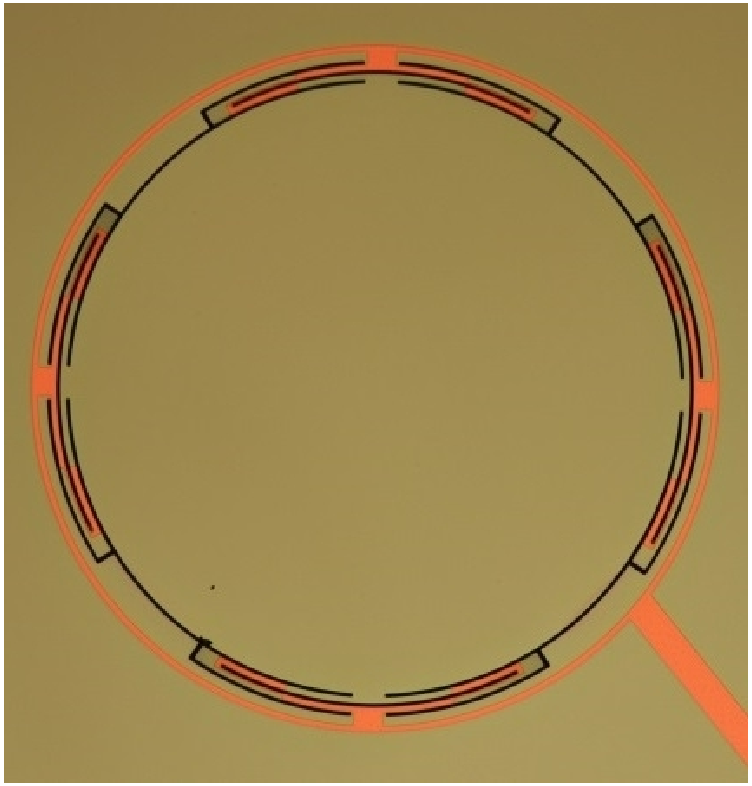
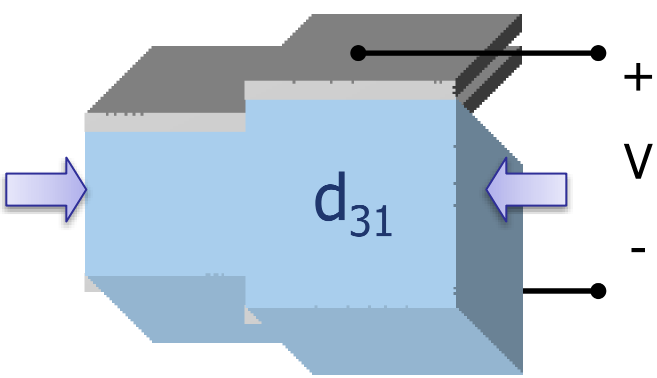
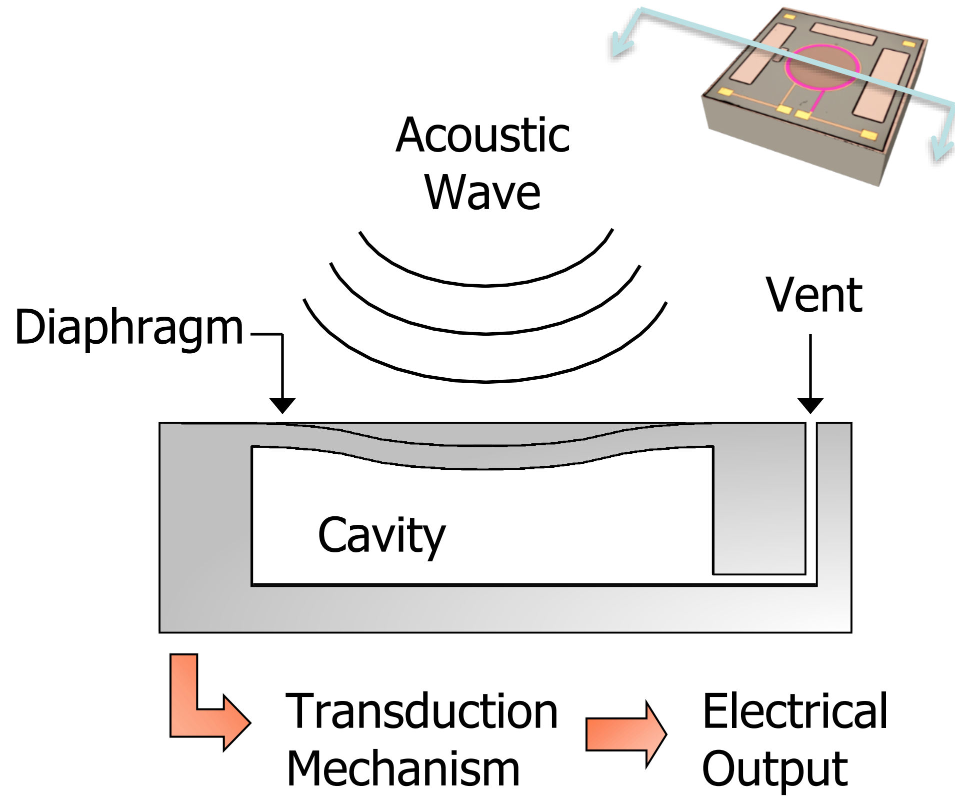
Resonant Microphone for Low Power Wakeup



# Microphone Operation

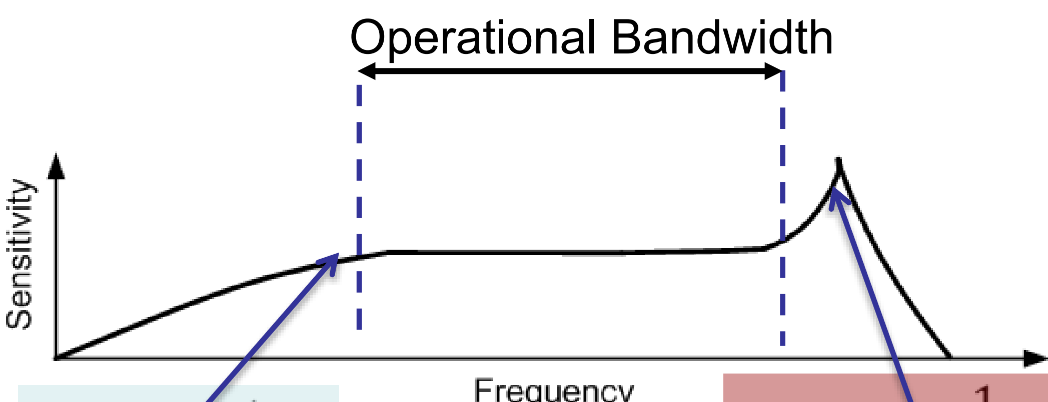
- Microphone
  - Device that converts input acoustic energy to output electrical energy
  - Diaphragm, cavity, vent



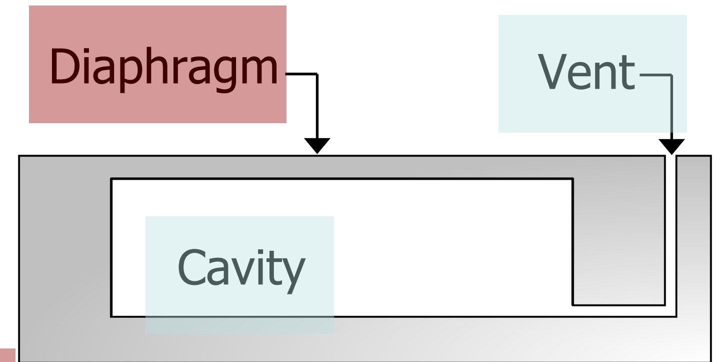
# Conventional Microphone Operation

- Operational Bandwidth
  - Frequency range over which sensitivity remains constant to within specification (ex: ±1 dB)
- Lower Limit
  - Cut-on frequency set by the RC time constant of the vent and cavity
- Upper Limit
  - Resonant frequency and quality factor (Q)

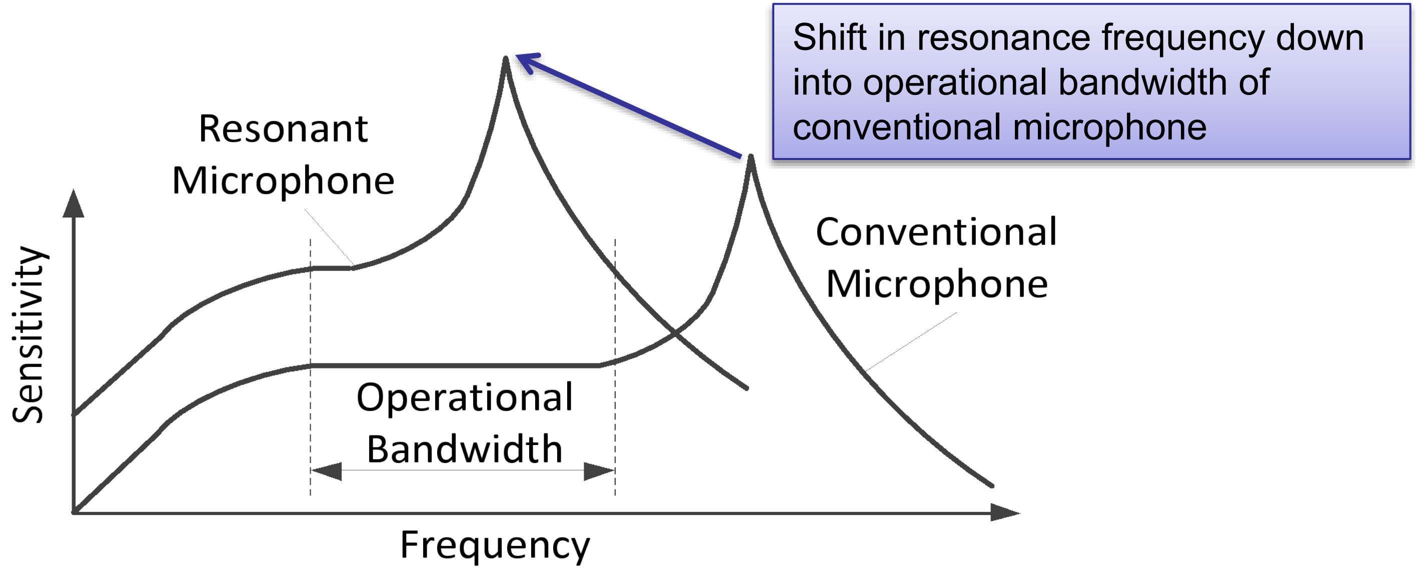



$$f_{co} = \frac{1}{2\pi R_v C_C}$$

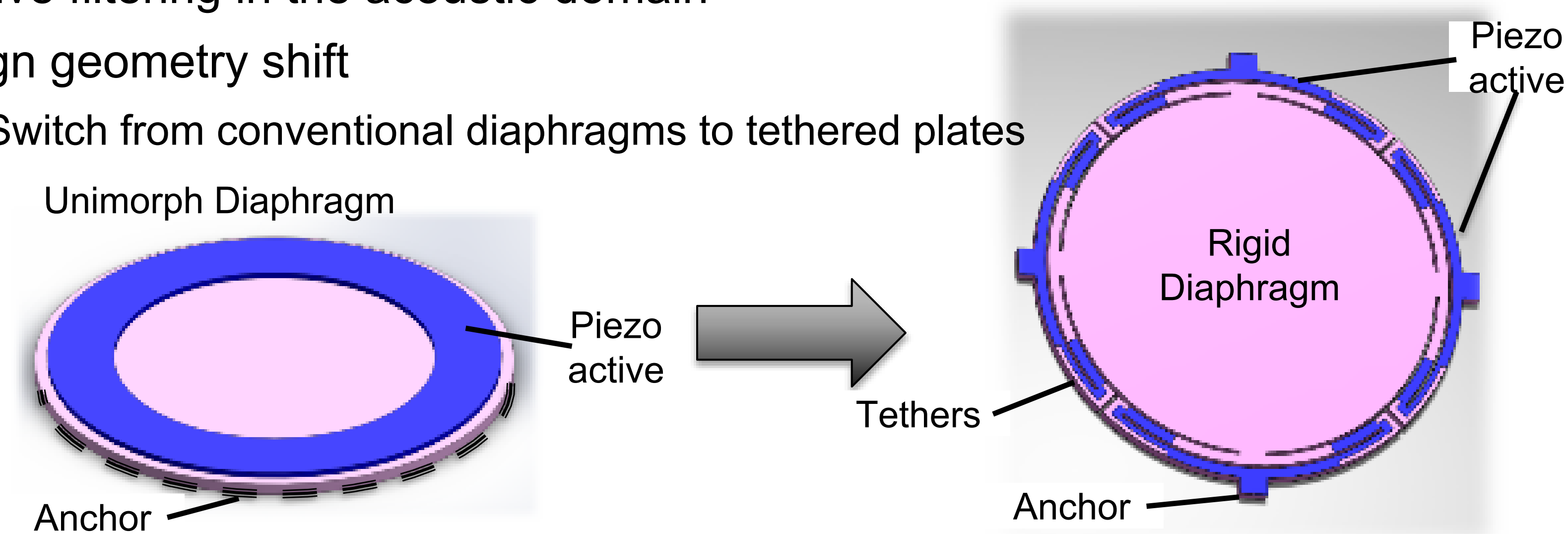
$$f_{res} = \frac{1}{2\pi\sqrt{M_D C_D}}$$



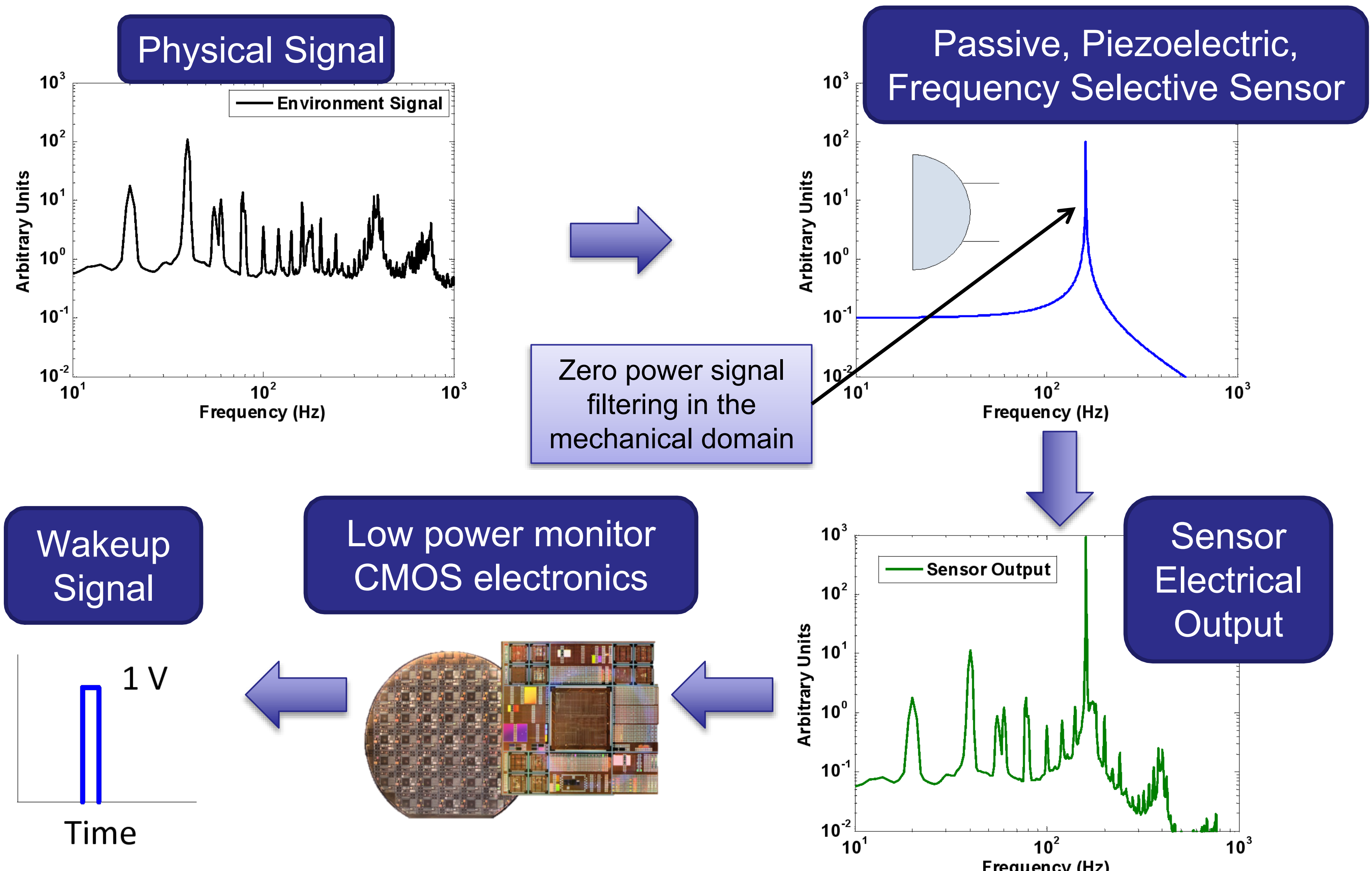
# Resonant Acoustic Sensor




- Passive filtering in the acoustic domain
- Design geometry shift
  - Switch from conventional diaphragms to tethered plates

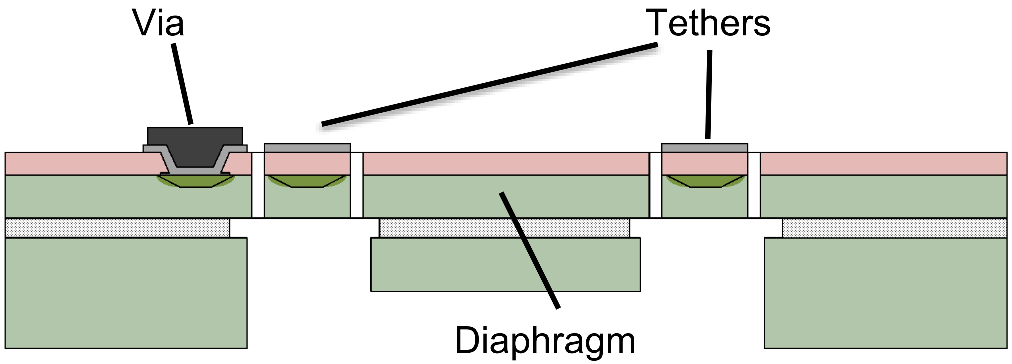


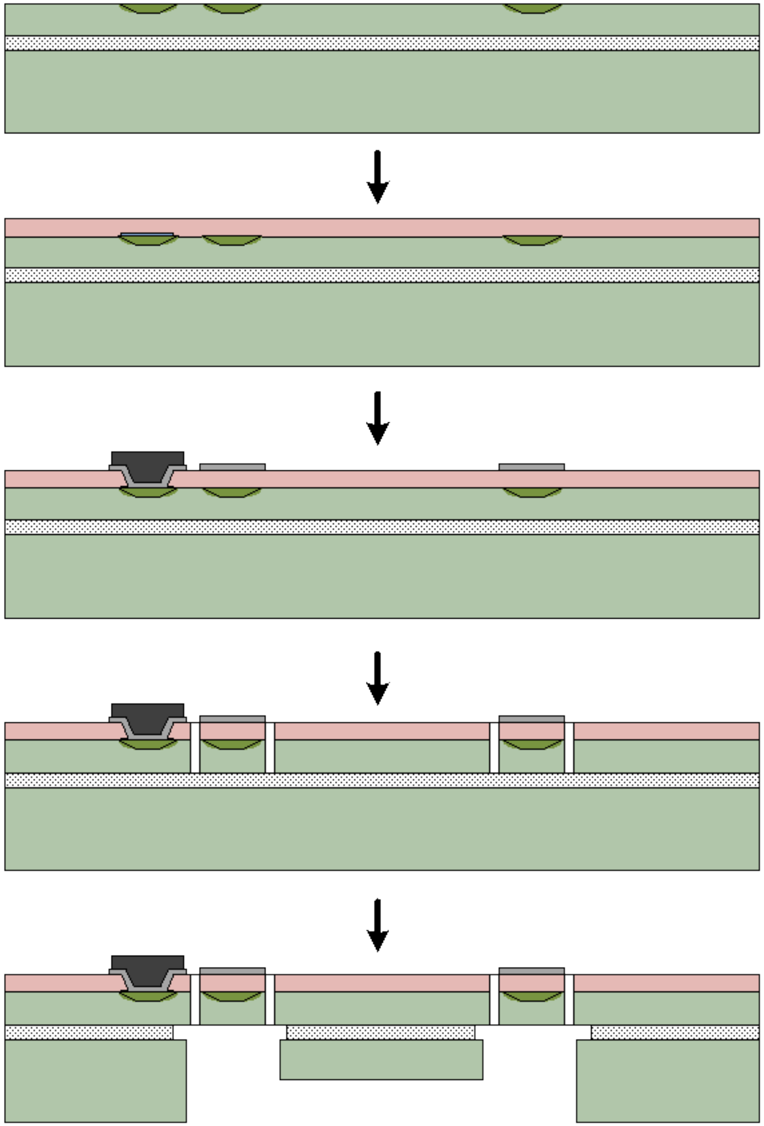
# Low Power Wakeup Systems



# AlN Microphone Fabrication

- 10-Mask Microphone Process:
  - Bottom Electrode Implant (2)
  - Via Etch and Etch Stop (2)
  - Top Metal
  - Via Integrity Thick Metal (2)
  - Tether Etch
  - Nested Backside DRIE (2)
- Additional Optional Masks
  - Plating for Frequency Tuning (2)



# Resonant Microphone Results

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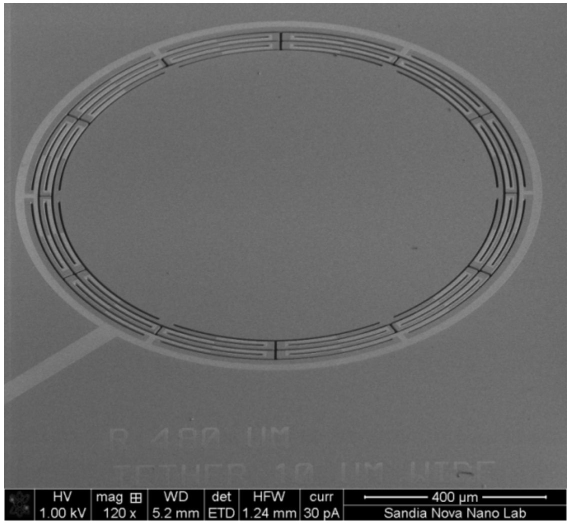


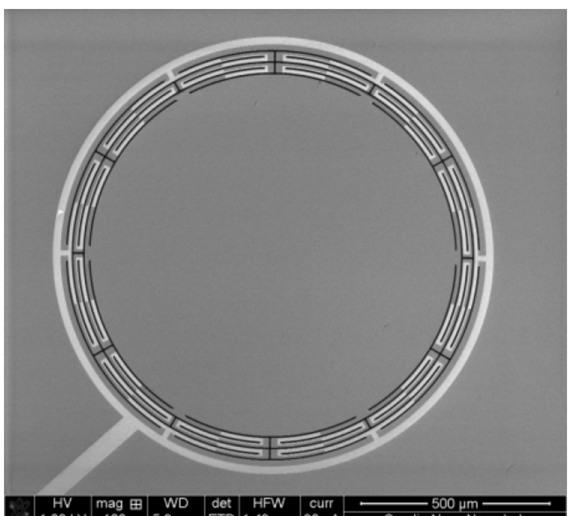


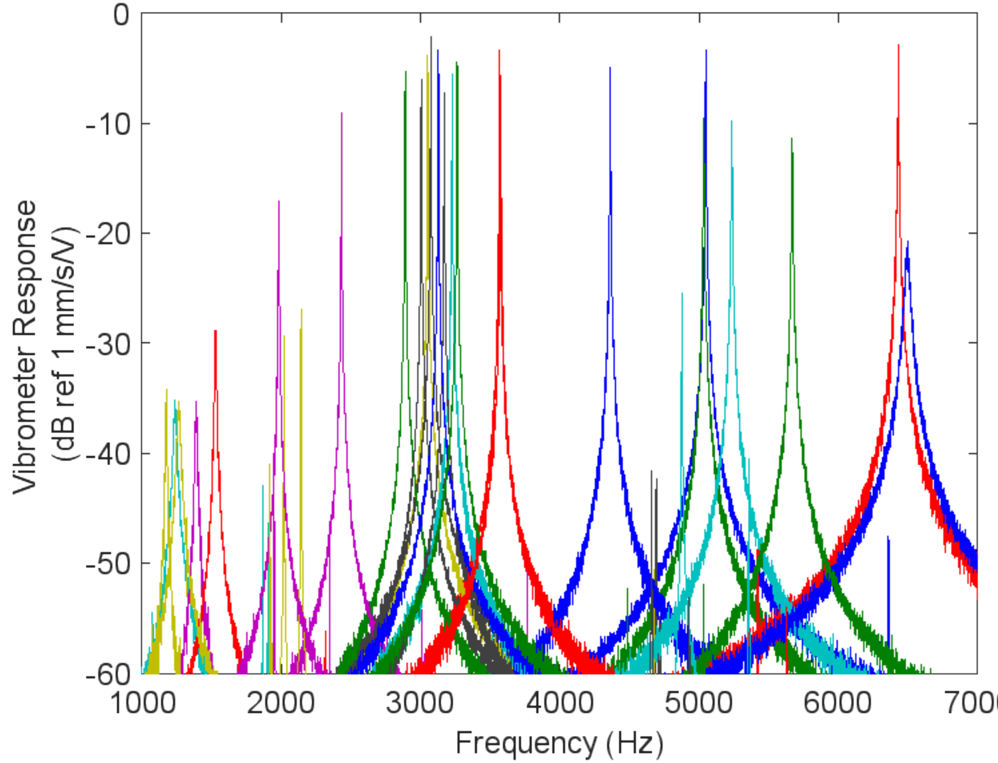


- $f_{res}$ from 400 Hz to > 10 kHz
- $Q$ up to 3,000

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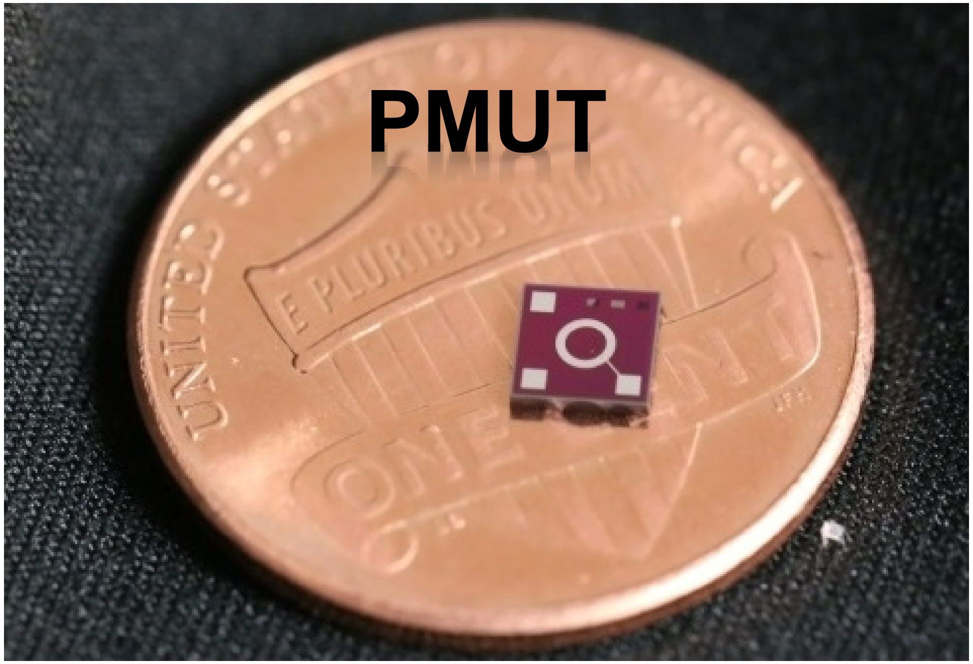
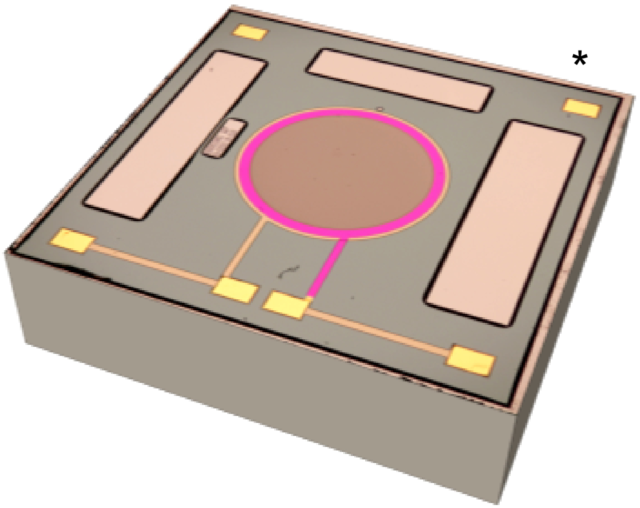


# Piezoelectric Micromachined Ultrasonic Transducers

- Transmitters or Microphones
- Air-Coupled PMUT Applications
  - Proximity sensing
  - Short range communication
  - Extreme high sound pressure level microphones
  - Imaging
  - Gesture recognition
  - Flow metering



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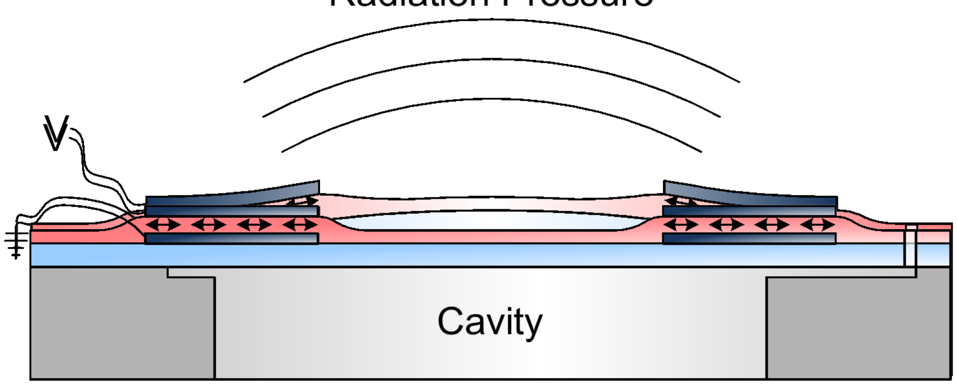
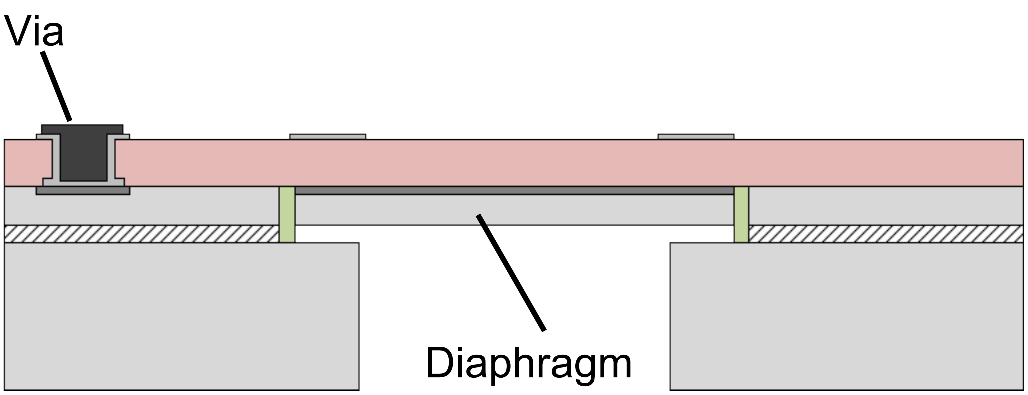
†fabricated by
Avago Technologies

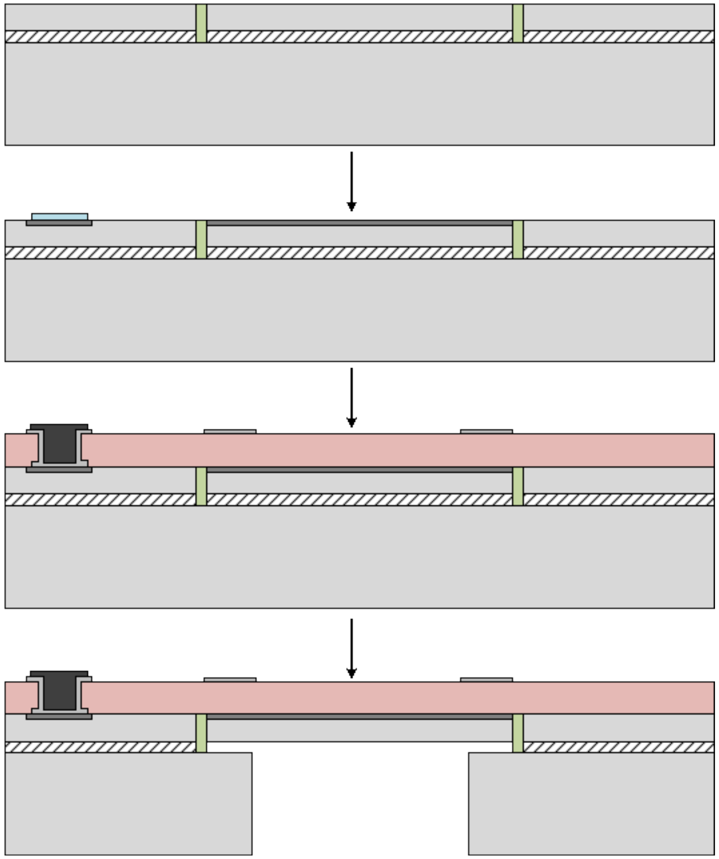



*B. A. Griffin, M. D. Williams, C. S. Coffman, and M. Sheplak, "Aluminum Nitride Ultrasonic Air-Coupled Actuator ", JMEMS, vol. 20, no. 2, pp. 476-486, 04/2011.

# PMUT Fabrication

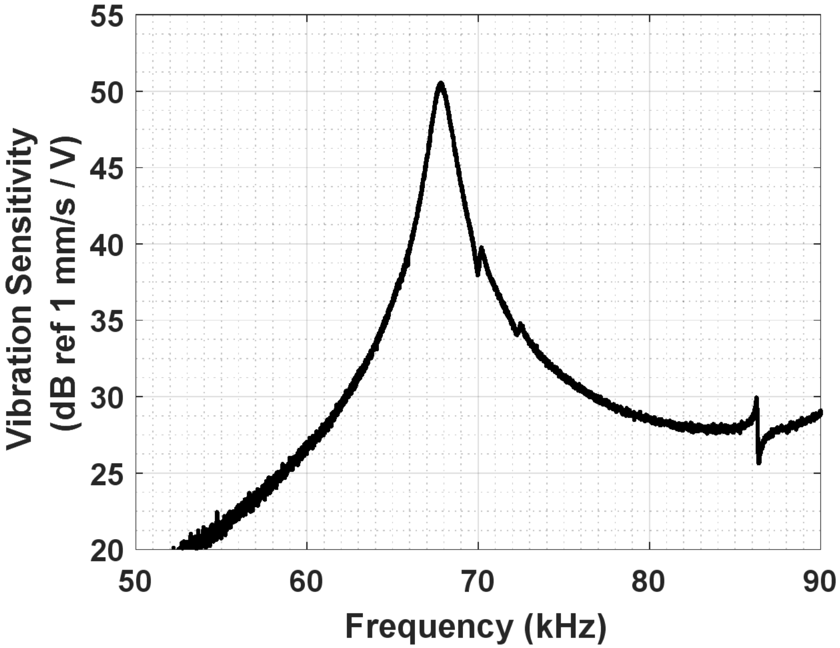
- 8-Mask PMUT Process:
  - Polysilicon Release Etch Stop
  - Bottom Electrode Implant
  - Via Etch and Etch Stop (2)
  - Top Metal
  - Via Integrity Thick Metal (2)
  - Backside DRIE



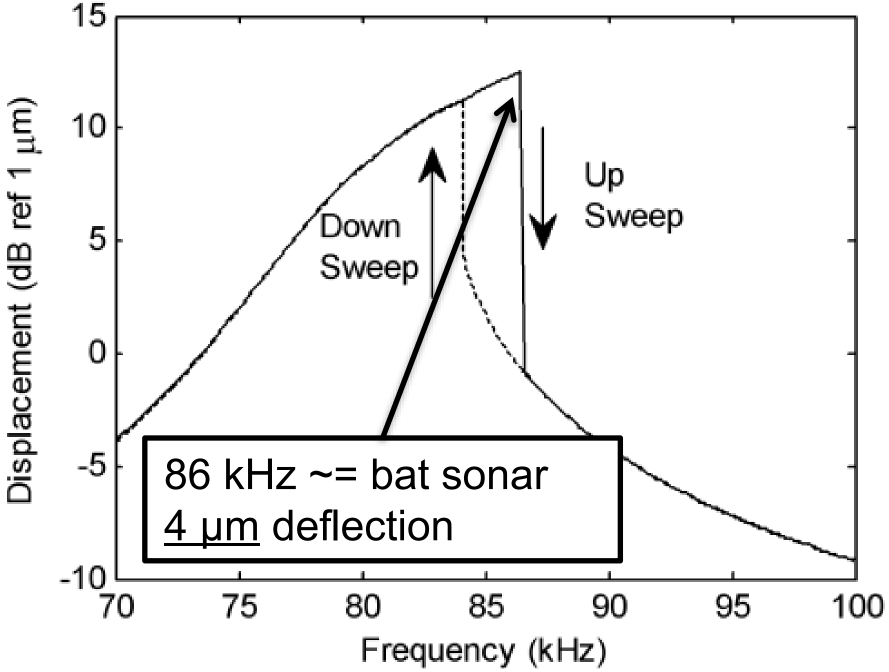



# PMUT Measurements

Example PMUT Response




Duffing Behavior at 50 V Drive Amplitude



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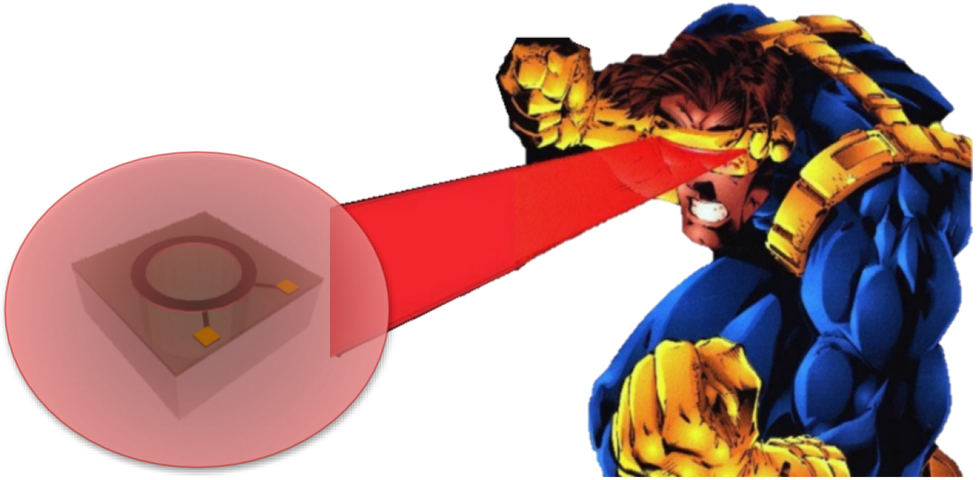

# XMEMS:  MEMS for Extreme Environments

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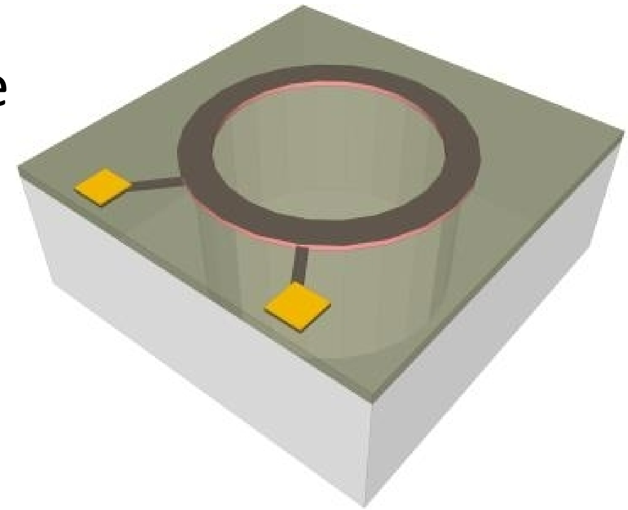
- Objective: develop material set to enable development of extreme temperature capable transducers
- Applications for transducers that can withstand extreme temperatures
  - Gas turbines (1250˚C)
  - Hypersonic flight research (755˚C)
  - Automotive engines (300-1000˚C)
  - Nuclear power plant (300˚C)
  - Coal power plants (700˚C)

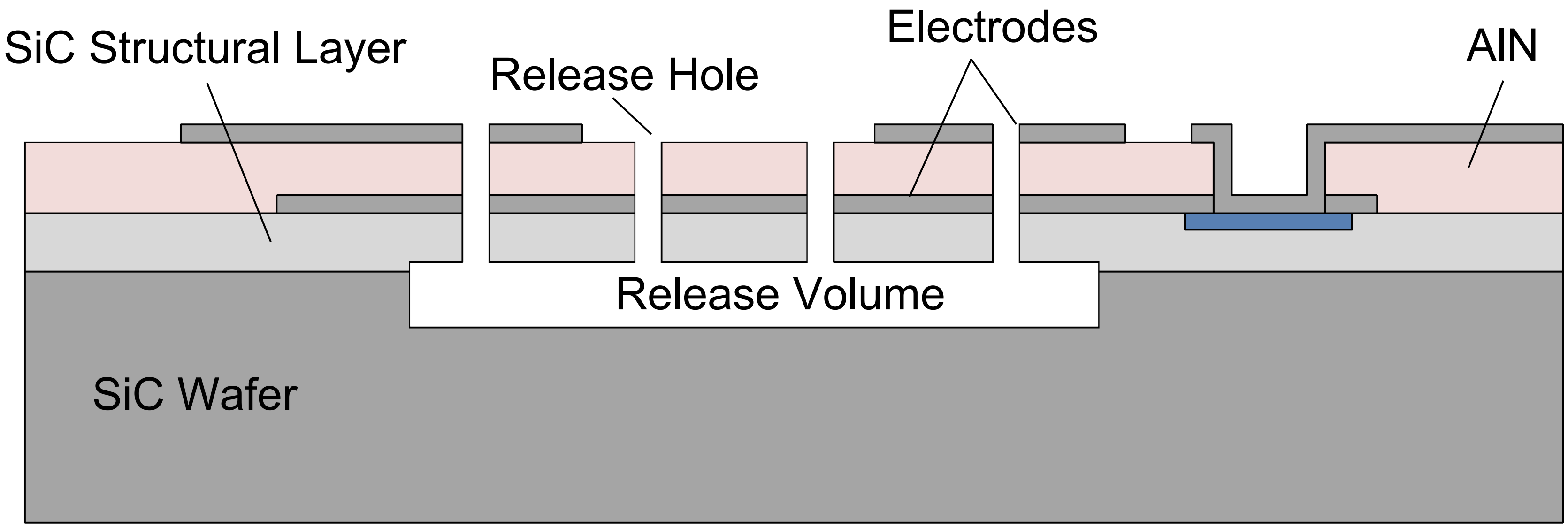




*grc.nasa.gov

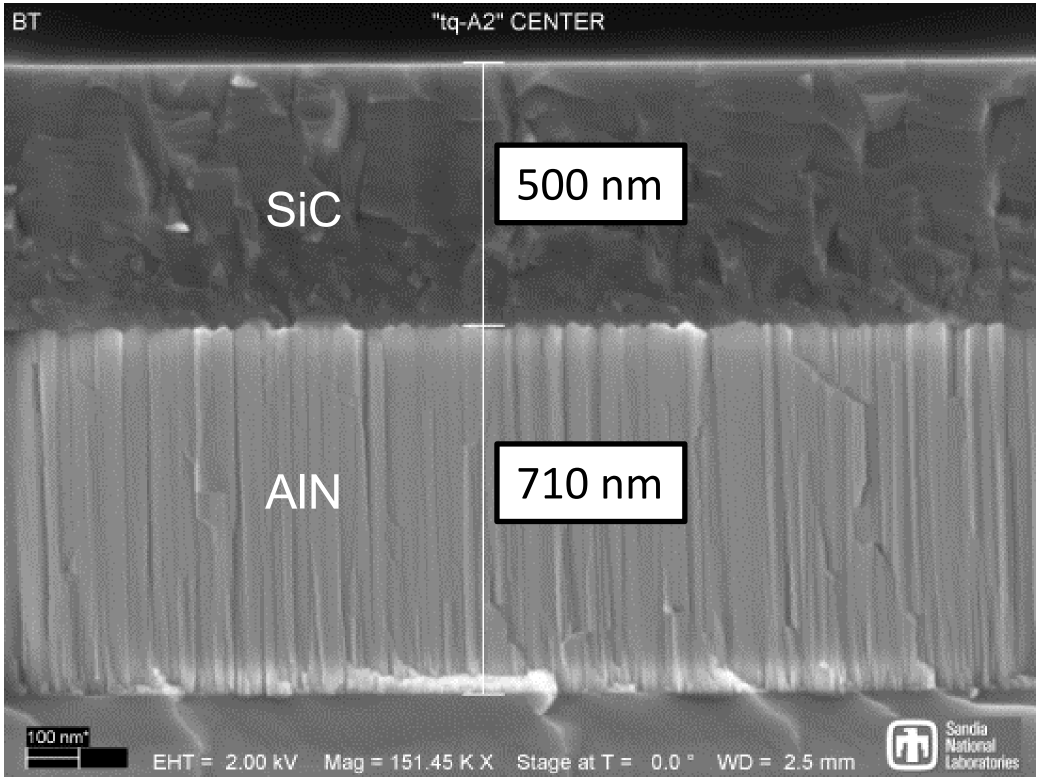
# Proposed Technology

- Developing a MEMS material set that combines
  - Aluminum nitride (AlN) piezoelectric thin film
  - Silicon carbide (SiC) structural film and wafer
  - High temperature capable electrodes
    - Titanium/Titanium nitride (Ti/TiN)
    - Nitrogen doped SiC (SiC:N)

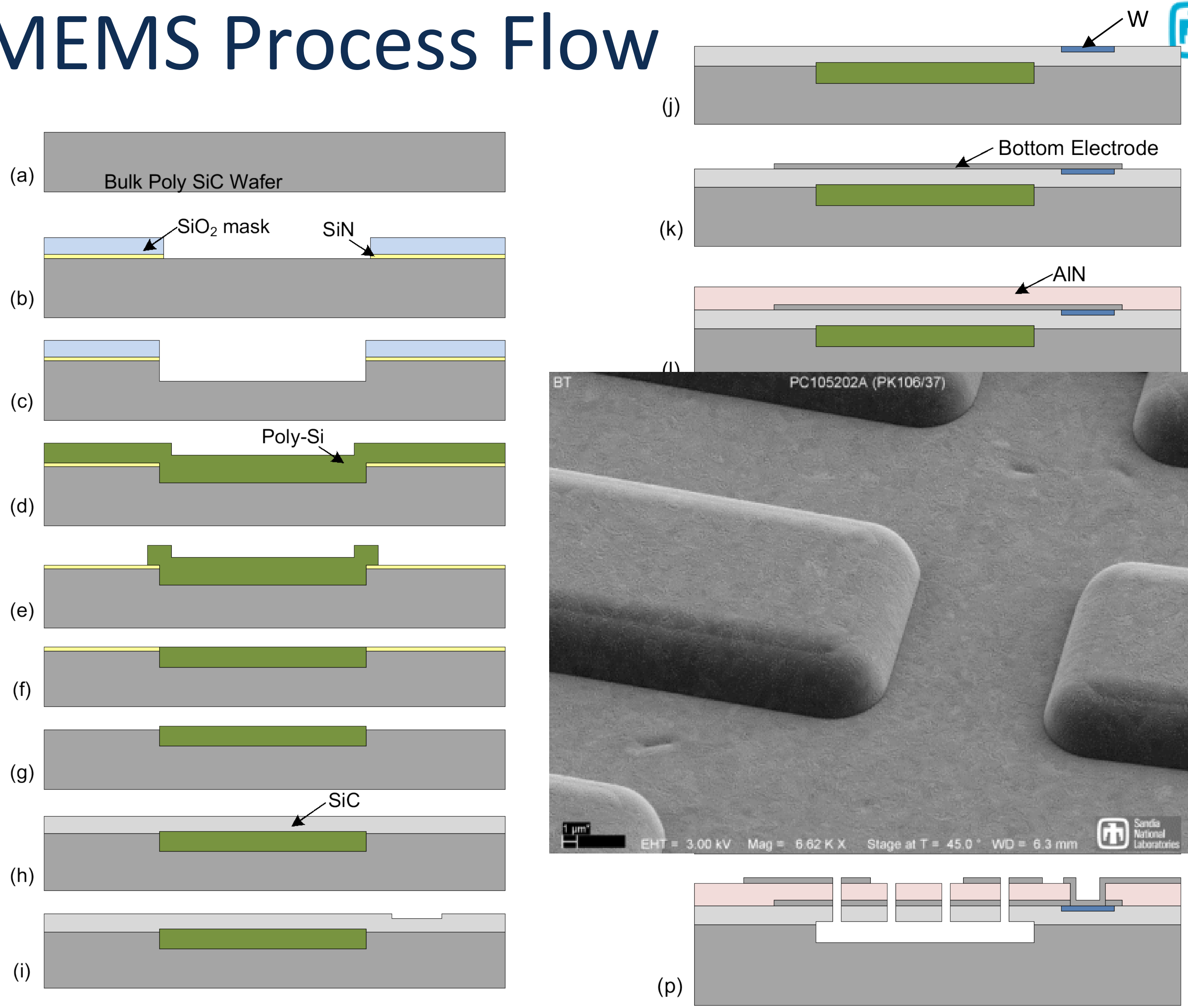


# High Temperature Capable Materials

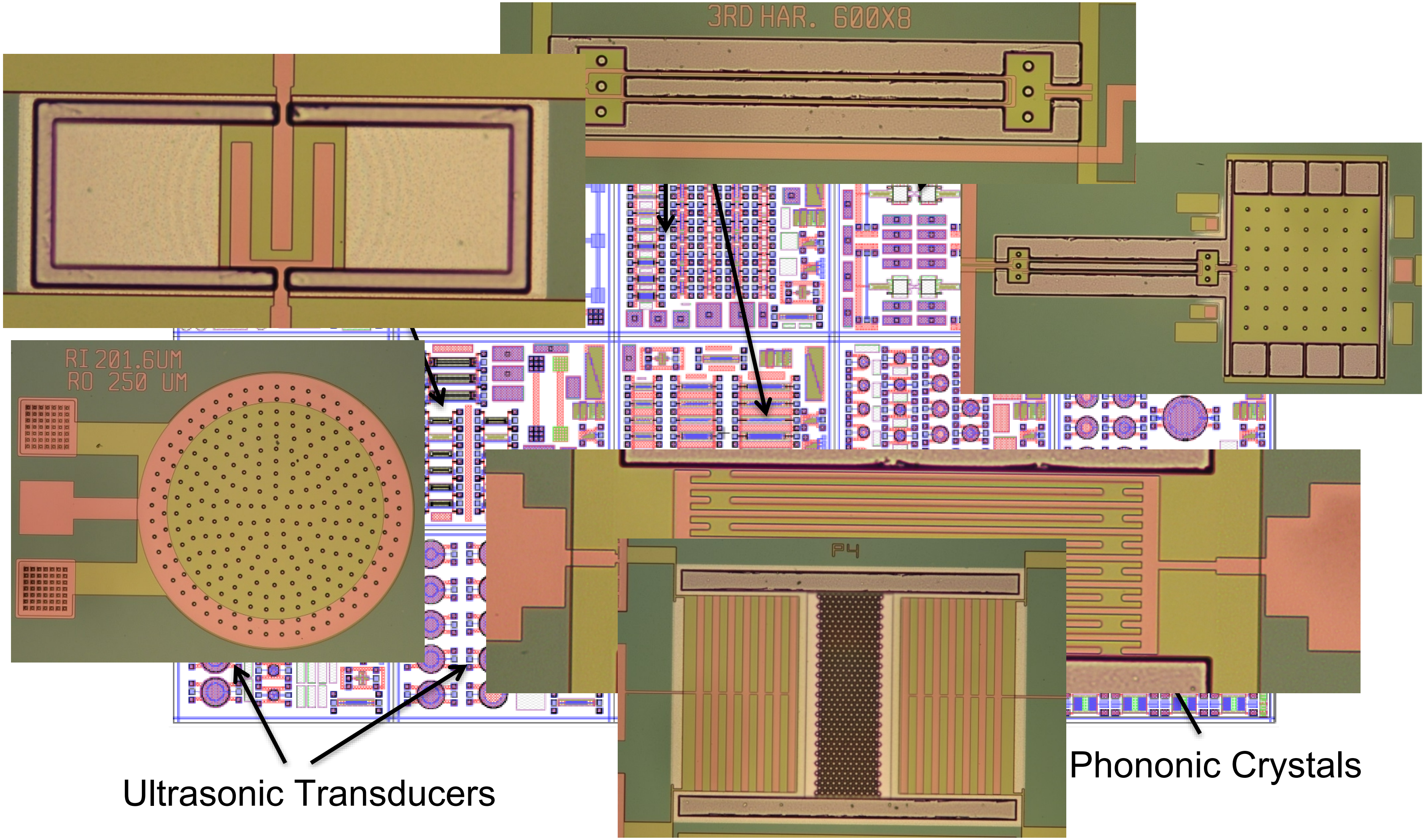
- Silicon Carbide
  - Sublimates at >2500˚C
  - High mechanical strength
  - Coefficient of thermal expansion nearly matched to AlN
- LPCVD Silicon Carbide
  - 850-950˚C
  - Mainly hexagonal 6H-SiC
  - Surface roughness ~50 nm



# XMEMS Process Flow

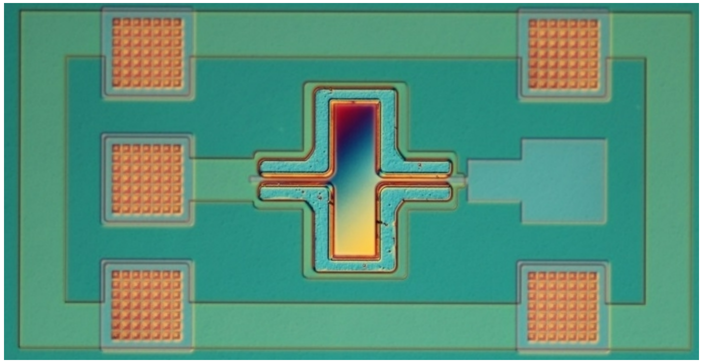


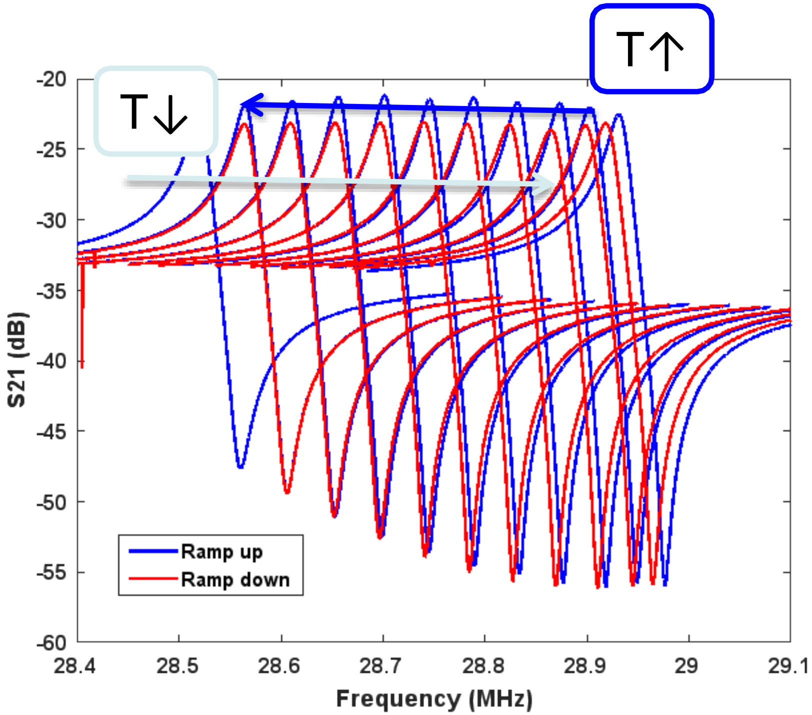
# Devices Fabricated

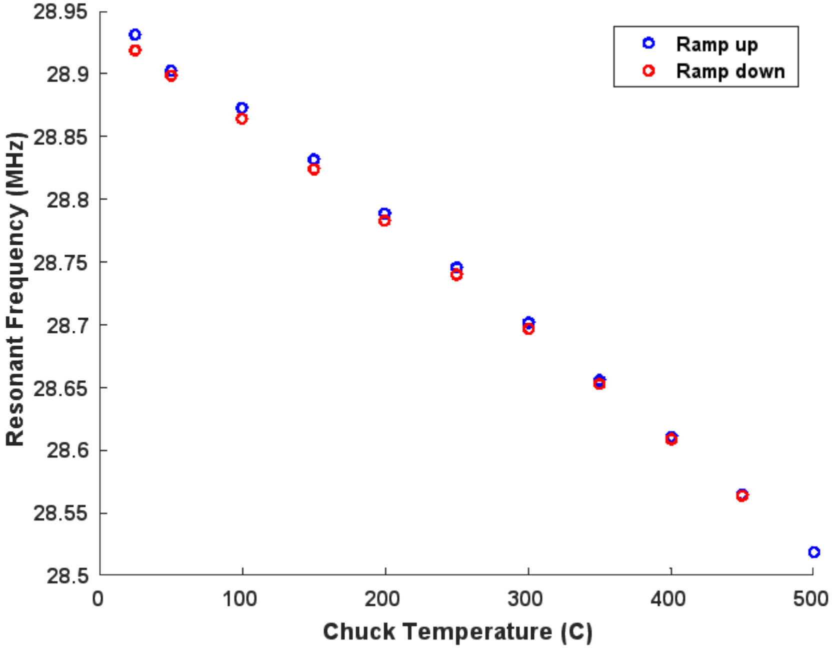


# Pre-anneal Results

- RTA at 650˚C, <1 Torr Argon, for 5 minutes before heated chuck testing
- Frequency shift decreases from 2,400 to 400 ppm



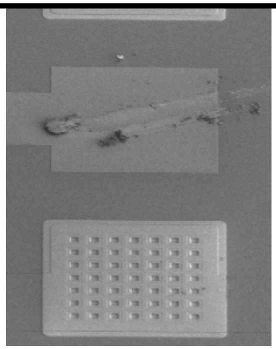


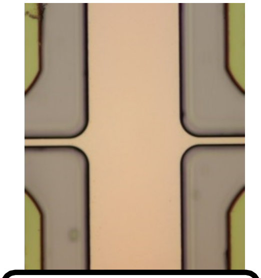
# Quality Factor

- Quality factor degradation observed over temperature ramps
- Potential sources
  - TiN oxidation
  - Probe contact issues
  - Via degradation
  - Carbon contamination

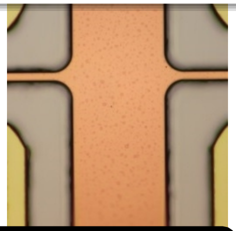
Probe tip shift from thermal expansion



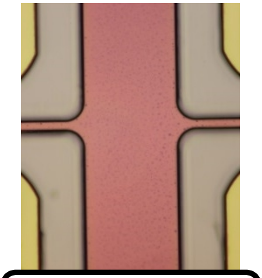
TiN Surface



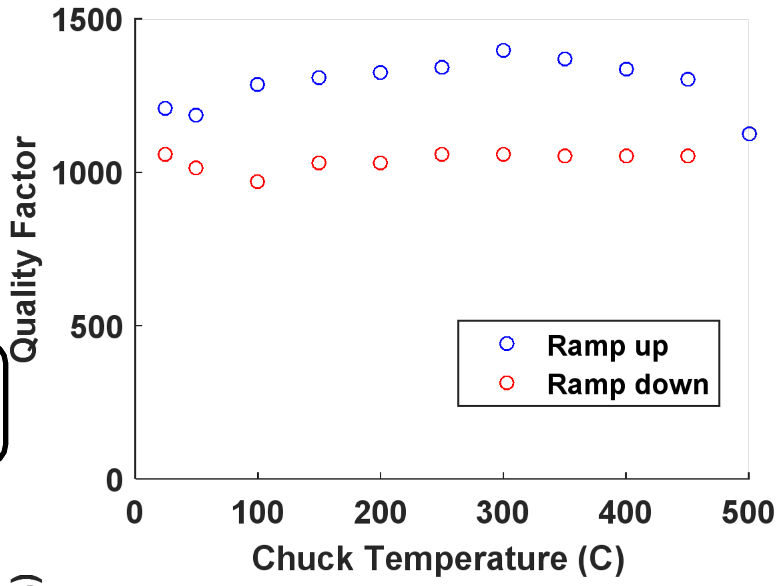
Post-release

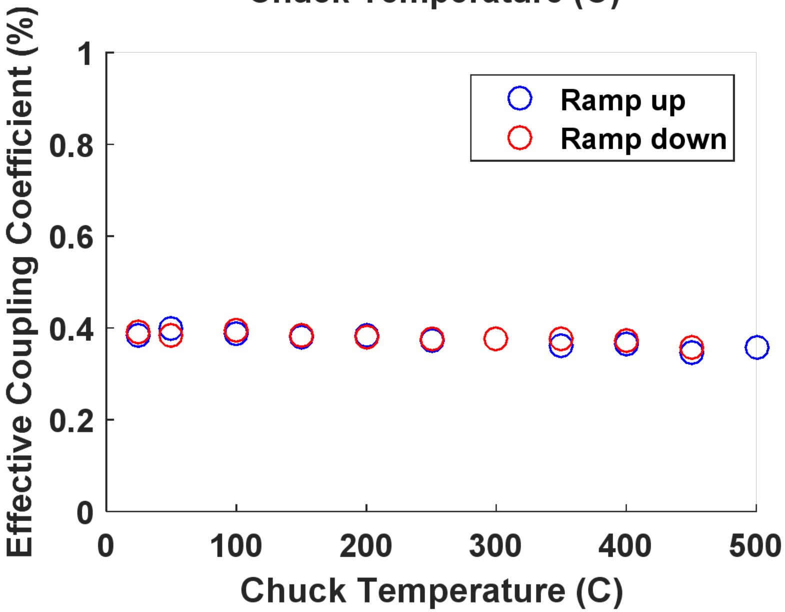


Post-Anneal



Post-Air Test



# Sandia's AlN Team

Sandia National Laboratories

- Current: Ben Griffin, Chris Nordquist, Matt Eichenfield, David Henry, Tammy Pluym, Katherine Knisely, Travis Young, Alex Grine, Ian Young, Aleem Siddiqui, Paul Stanfield, Michael Satches, Ihab El-Kady, Charles Reinke, Jeremy Moore, Sasha Summers, Kenneth Douglas, Adrian Schiess, Mark Balance, Emily Crispin

- Former: Troy Olsson, Ken Wojciechowski, Peggy Clews, Jim Stevens, Bongsang Kim, James Fleming, Janet Nguyen, Melanie Tuck, Maryam Ziaei-Moayyed

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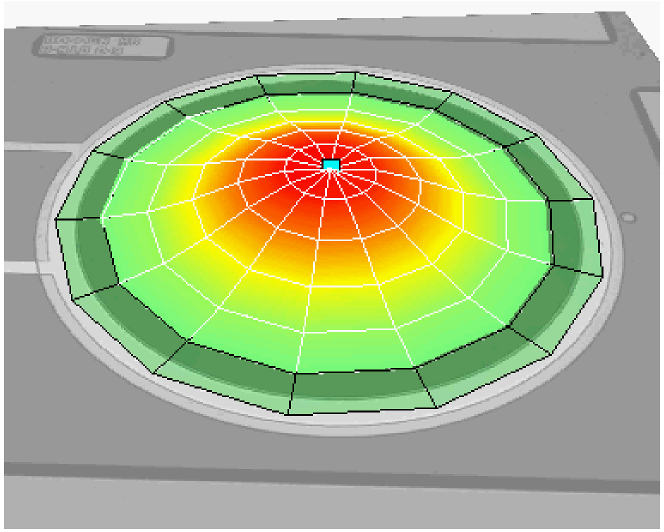

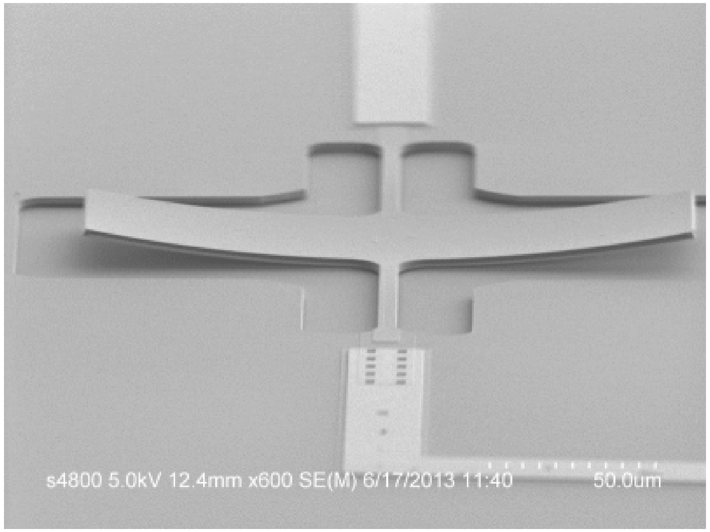


# Questions?