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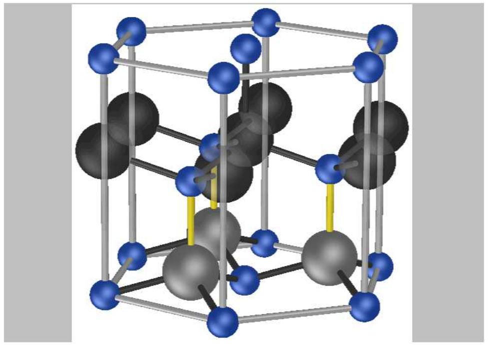

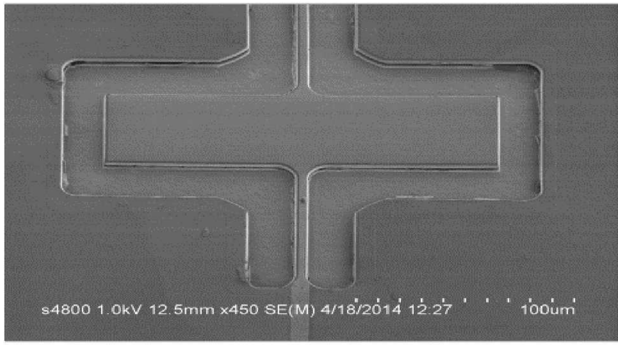

III-V Piezoelectric Sensors, Actuators, and Resonators

Giovanni Esteves, Michael D. Henry, Erica A. Douglas, Travis R. Young, Christopher D. Nordquist, Robert Reger, Adam Edstrand, and Benjamin A. Griffin

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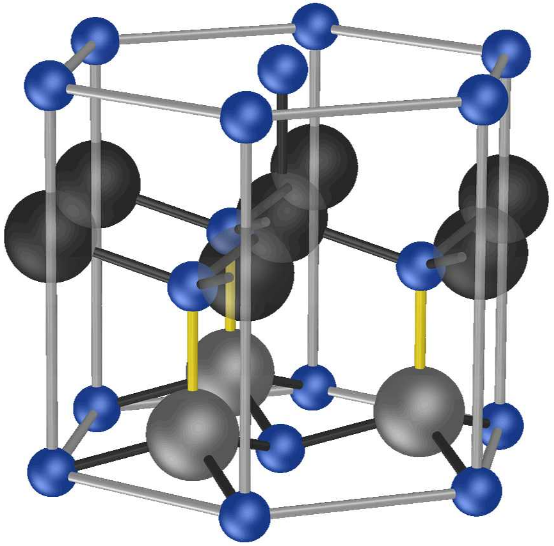
Outline

- **Piezoelectrics, AlN, and $Sc_xAl_{1-x}N$**
- **Texture Quality of AlN and ScAlN**
- Device Integration Challenges
- Microresonators
- XMEMS: MEMS for Extreme Environments
- Conclusion and Acknowledgements



Piezoelectric $Sc_xAl_{1-x}N$

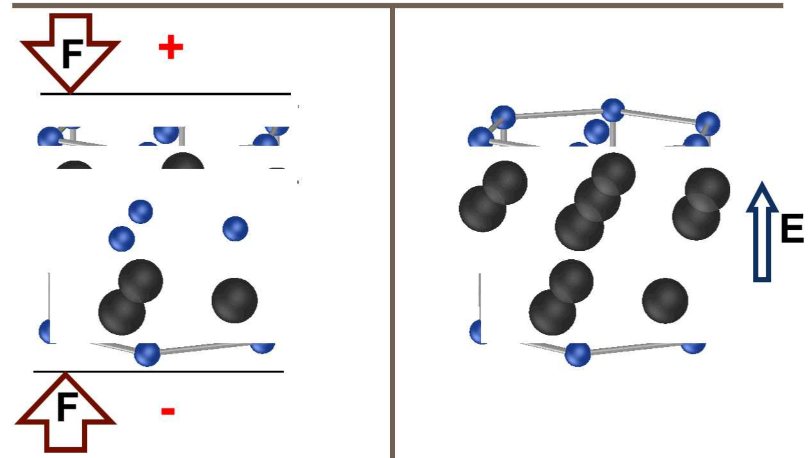
Piezoelectricity

- Material can couple electrical and mechanical energy
  - Direct effect
  - Converse effect
- Magnitude characterized by piezoelectric constant (d_{im})
- Efficiency characterized by electromechanical coupling coefficient (k_t^2)

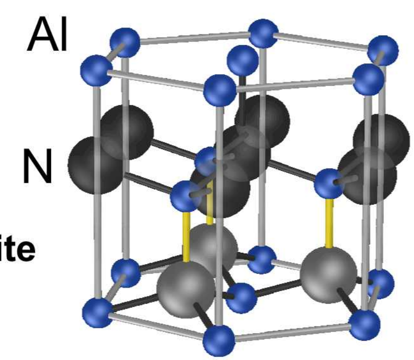
Aluminum Nitride (AlN)

- Reactively sputtered at low deposition temperatures ~350° C
- CMOS compatible
- Piezoelectric coefficients
  - d_{33}= 5 pC/N
  - d_{31}= -2 pC/N

Direct Effect	Converse Effect



Direct Effect	Converse Effect
Electrically polarize in response to an applied stress	Mechanically strain in response to an applied electric field
$P_i = d_{im} \cdot \sigma_m$	$\varepsilon_m = d_{im} \cdot E_i$



Hexagonal Wurtzite
a = 3.11 Å
c = 5 Å

AlN Commercial Success

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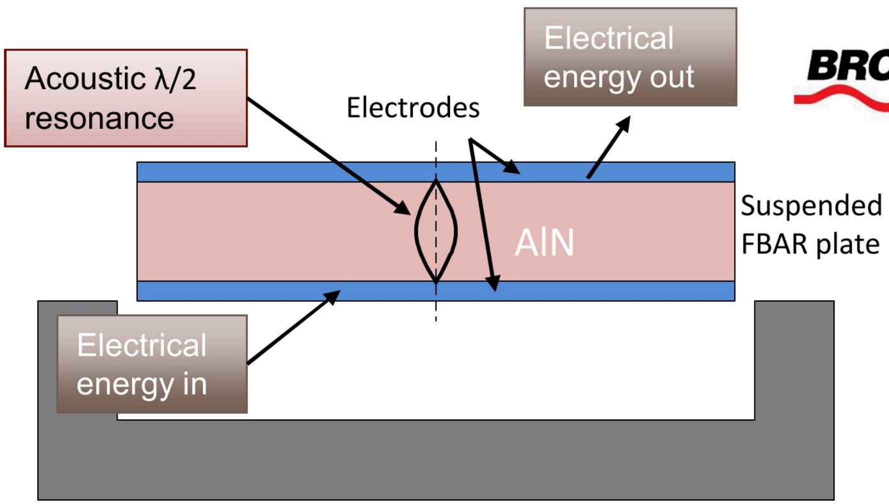
- Film Bulk Acoustic Resonator (FBAR) Filters
  - Half-wavelength, thickness mode resonators
  - Filter frequency is set by film thickness
  - Commercial success for AlN MEMS
    - >1 billion units produced per year from Avago Technologies
  - More than 40 discrete filter die in the modern smartphone
- Piezoelectric Micromachined Ultrasonic Transducer (PMUT) Applications
  - Proximity sensing
  - Short range communication
  - Extreme high sound pressure level microphones
  - Imaging
  - Chirp bought by TDK to create devices for gesture recognition



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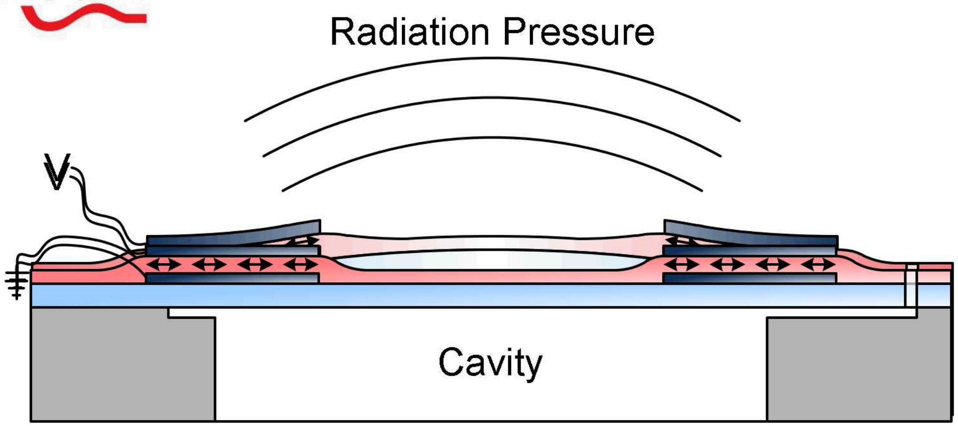
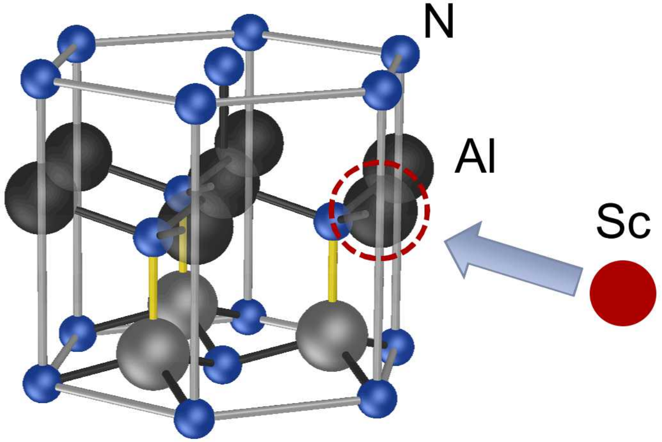
Chirp



Schematics courtesy of Ben Griffin

Influence of Sc Alloying in AlN

- $Sc_xAl_{1-x}N$ has the potential to replace current AlN technologies
- Sc doping into AlN increases piezoelectric response

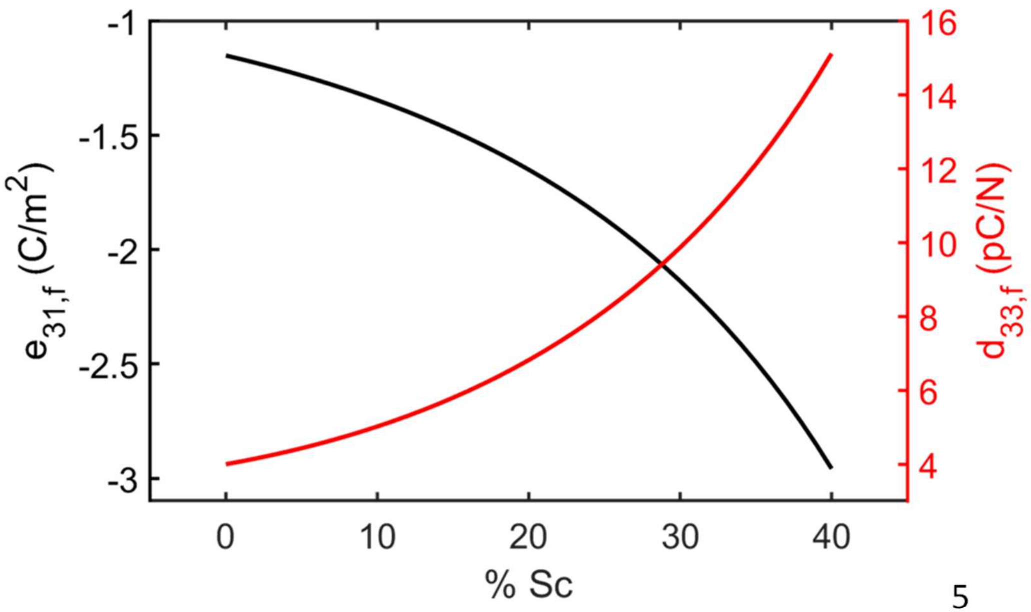


Device Performance Based on Properties

Resonators $$k_t^2 = \frac{e_{31}^2}{E_p \varepsilon_{33}}$$

Energy harvesting $$FOM = \frac{(e_{31,f})^2}{\varepsilon_{33,f}}$$

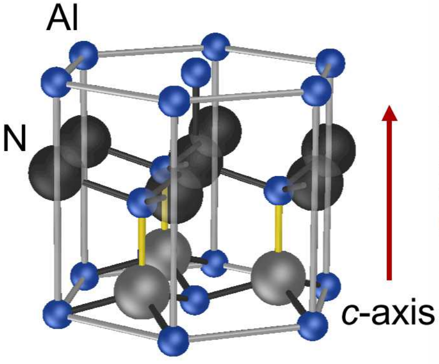
Sensors $$\frac{S}{N} = \frac{e_{31,f}}{\sqrt{\varepsilon_0 \varepsilon_{33,f} tan\delta}}$$



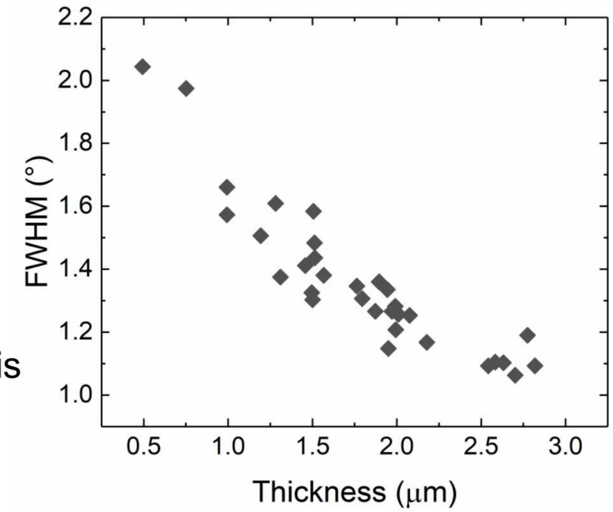
Caro et al., J Phys Condens Matter

Influence of Texture on Performance of AlN Films

- Target orientation for AlN is *c*-axis oriented
- Texture quality determined via X-ray diffraction (XRD) rocking curve measurements
  - Full-width half maximum (FWHM) describes how parallel the 002 plane of AlN is oriented with respect to film's surface
- Electromechanical coupling (k_t) increases as texture in AlN films improves
  - Growing thicker AlN films results in low FWHM
  - *Increasing thickness limits resonant frequency tuning in FBARS*



Recreated from S. Mishin et al., IEEE Symposium on Ultrasonics. (2003)



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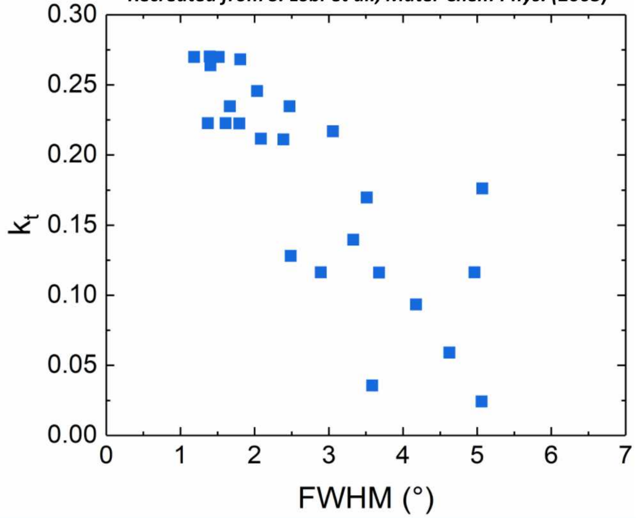
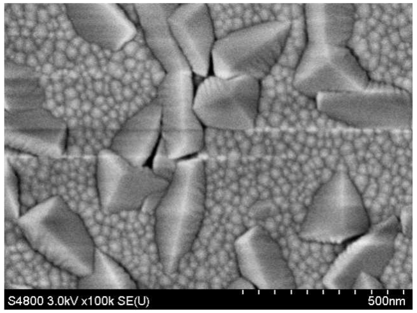
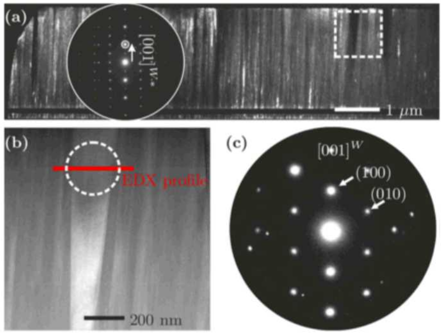


Challenges with Increasing % Sc and Recent Advances

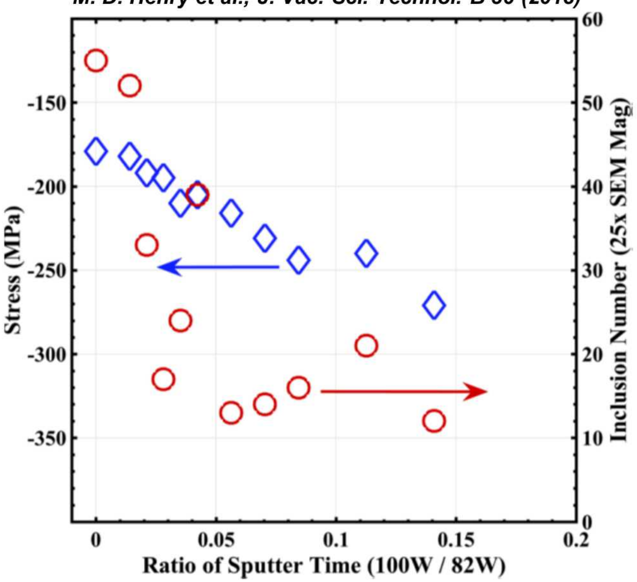
- Secondary grain growth (inclusions) in ScAlN
  - Increase with Sc concentrations
  - Density controlled by processing parameters
- Inclusions have a diffuse {100} orientation
  - Fichtner *et. al., 2017*
- Compressive stress suppresses inclusions
  - Henry *et. al.,* 2018
  - *Compressive stress not optimal for released MEMS*
- Platinum as a bottom electrode on 8" wafers
  - Mertin *et al.,* 2018
  - Full suppression of inclusions up to Sc 31%
  - High texture up to 42%
  - *Pt is not CMOS compatible and presents integration challenge*

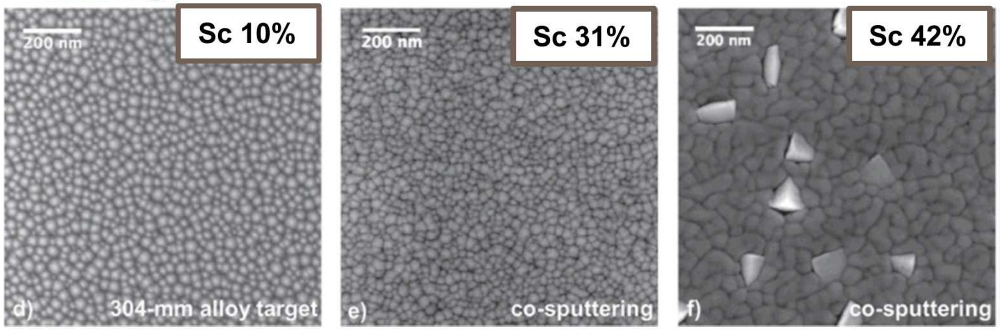


S. Fichtner et al., J. Appl. Phys. 122 (2017)



M. D. Henry et al., J. Vac. Sci. Technol. B 36 (2018)

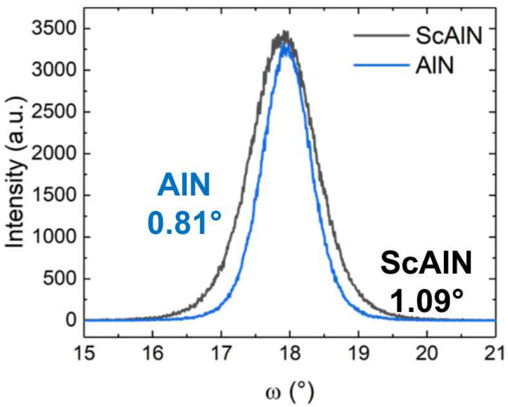


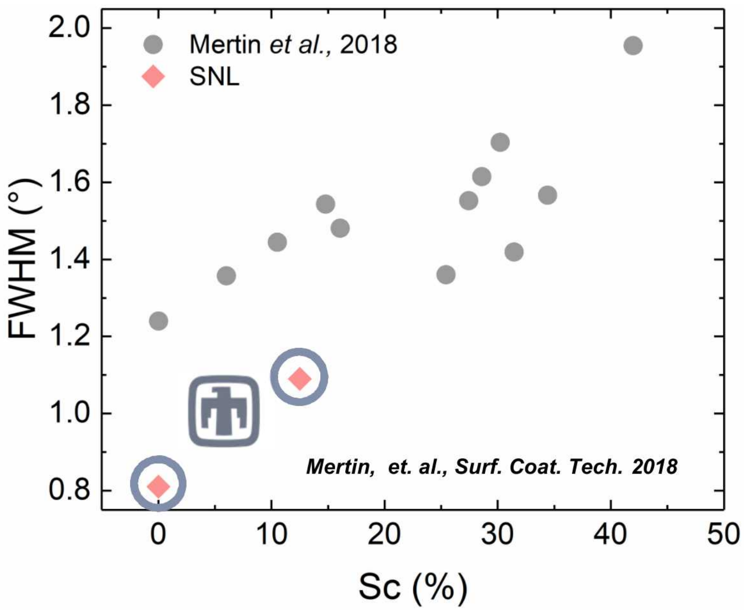


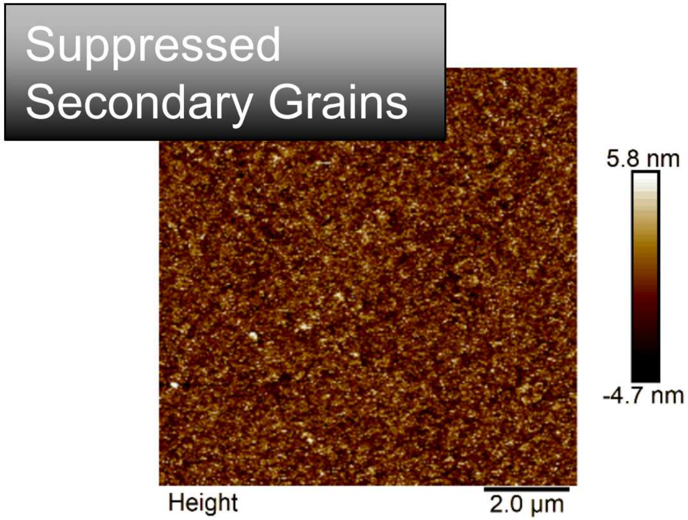
S. Mertin et al., Surf. Coat. Technol. (2018)

AlN and ScAlN on $AlCu_{0.05}$

- High-quality ScAlN has been deposited on various CMOS compatible metal stacks
  - Depositing ScAlN on CMOS metal is valuable to industrial sector
  - Attractive to industry leaders and has sparked collaboration
- Optimal ScAlN film quality found in Ti, Ti/$AlCu_{0.05}$, and Ti/TiN/$AlCu_{0.05}$ metal stack
- Present results are ***state-of-the-art*** for their given thickness and Sc composition







$Sc_{12.5}Al_{87.5}N$ on Ti/TiN/$AlCu_{0.05}$

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- Microresonators
- XMEMS: MEMS for Extreme Environments
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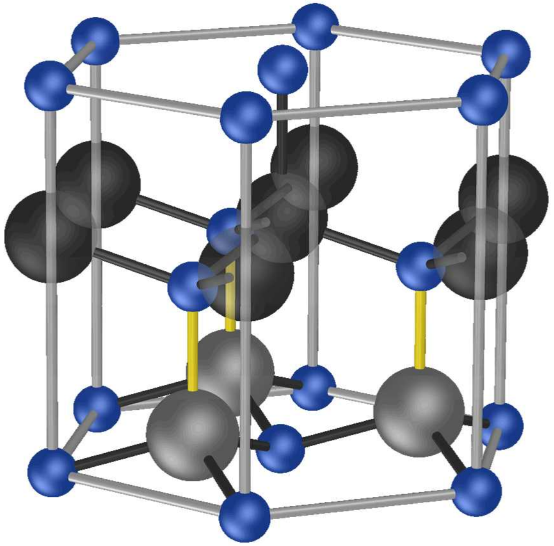
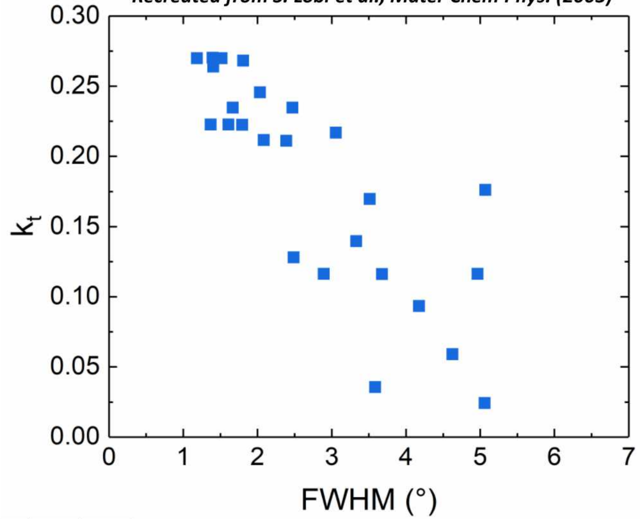
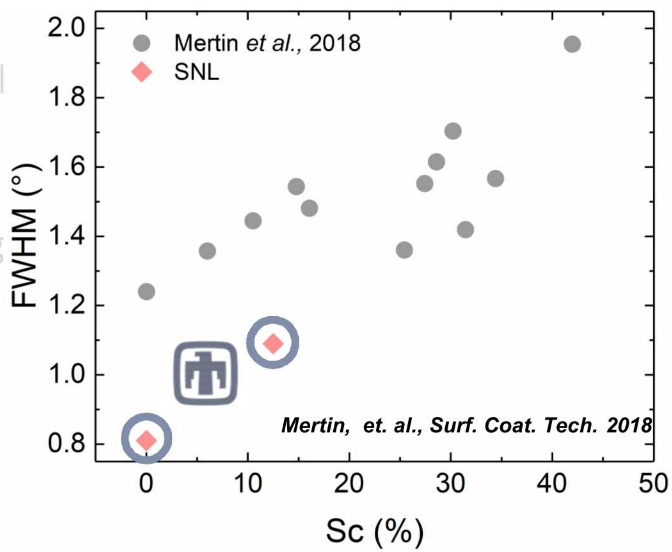


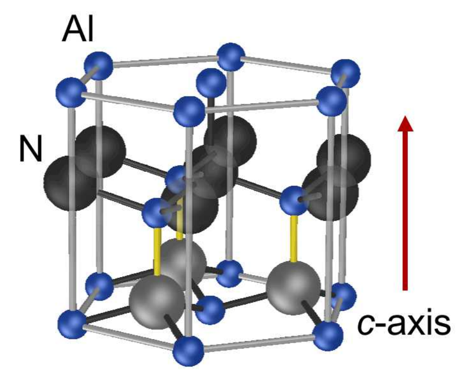
Device Integration Challenges

- Good film properties
- Film Stress
  - Shifts device performance
  - Stress uniformity across wafer can limit yield
  - Accurate local device stress knowledge is needed to improve modeling accuracy
- Etching
  - Pressure varied to control angl wall
  - $Sc_{12.5}Al_{87.5}N$ etches 3-4 times s and continues to reduce at hig %

Recreated from S. Löbl et al., Mater Chem Phys. (2003)







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  - Pressure varied to control angle side wall
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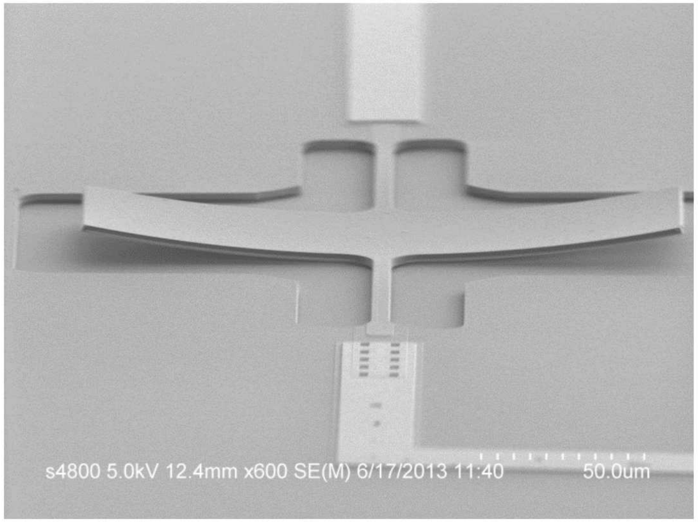

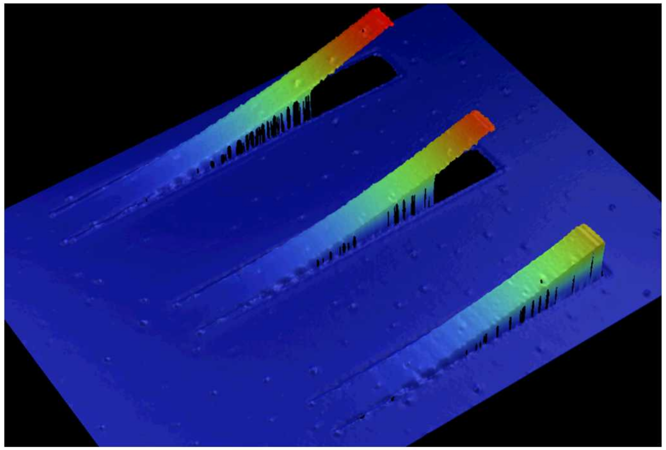

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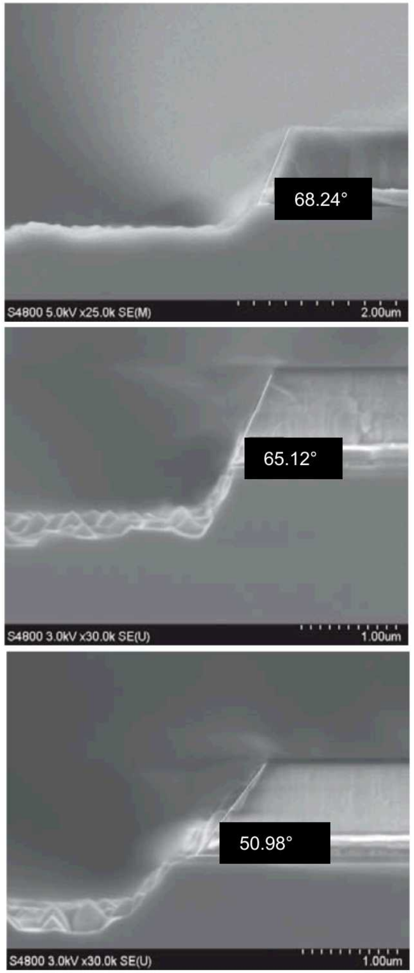
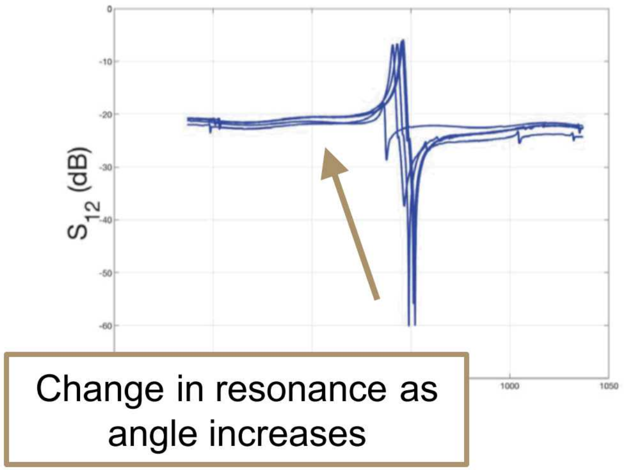
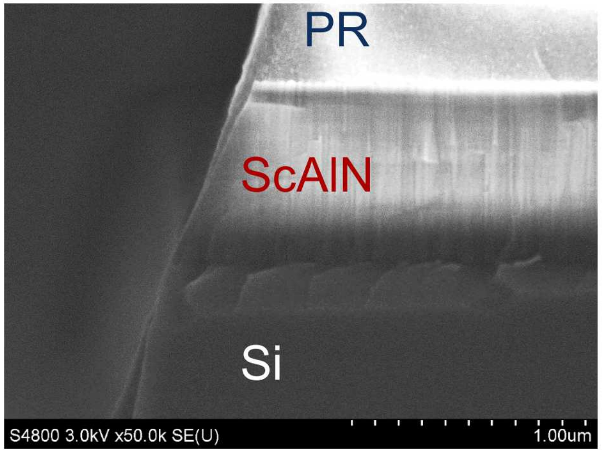
AlN with Resist Etch Mask







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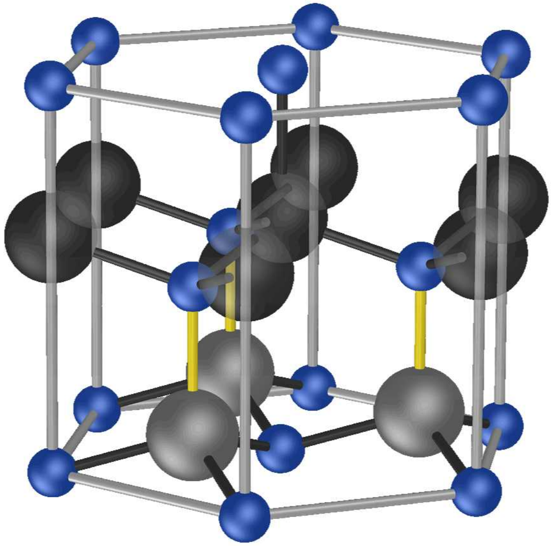
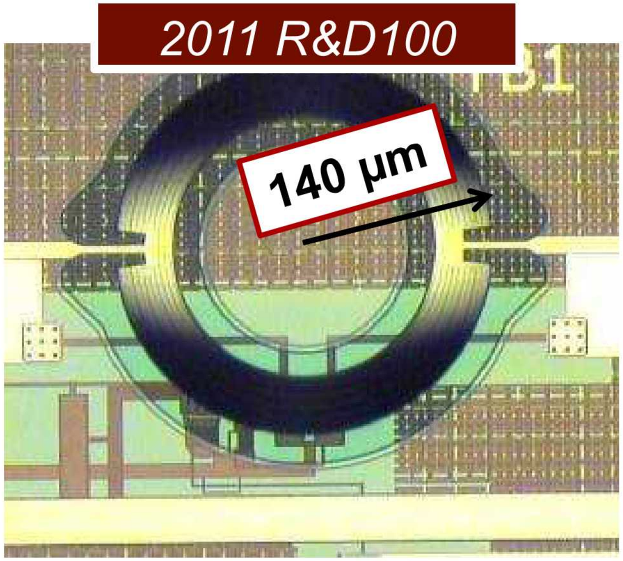
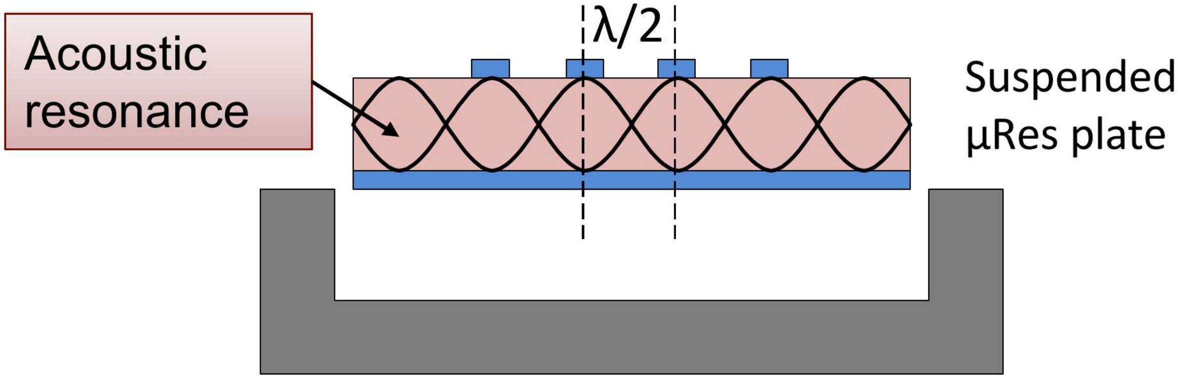


Aluminum Nitride Microresonators

- 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



µRes on CMOS



$$d_{31} = -2\,\mathrm{pm/V}$$

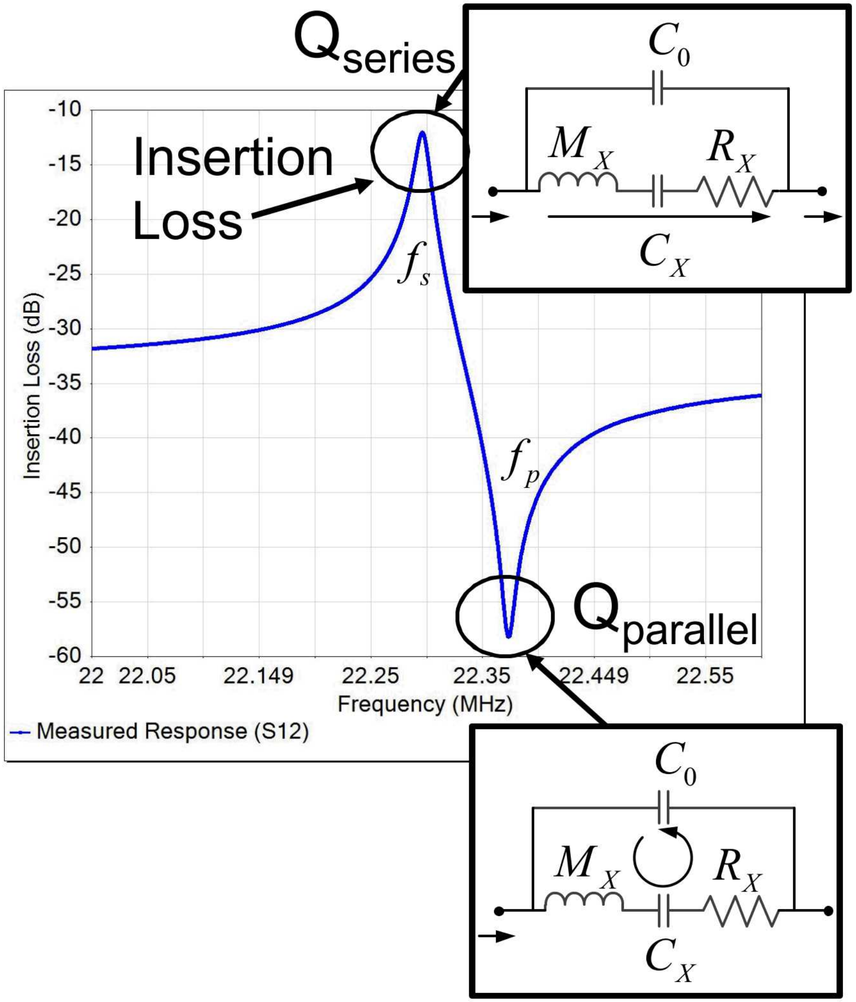
$$k_{31}^2 = 2\%\ (\mathrm{max})$$

Resonator Figure-of-Merit

- Insertion Loss
  - Proportional to FOM

$$FOM = k_t^2 Q$$

- Bandwidth
  - Minimum practical filter BW
    - Determined by Q
  - Maximum practical filter BW
    - Determined by k_t^2 ($BW = \frac{1}{2} k_t^2$)

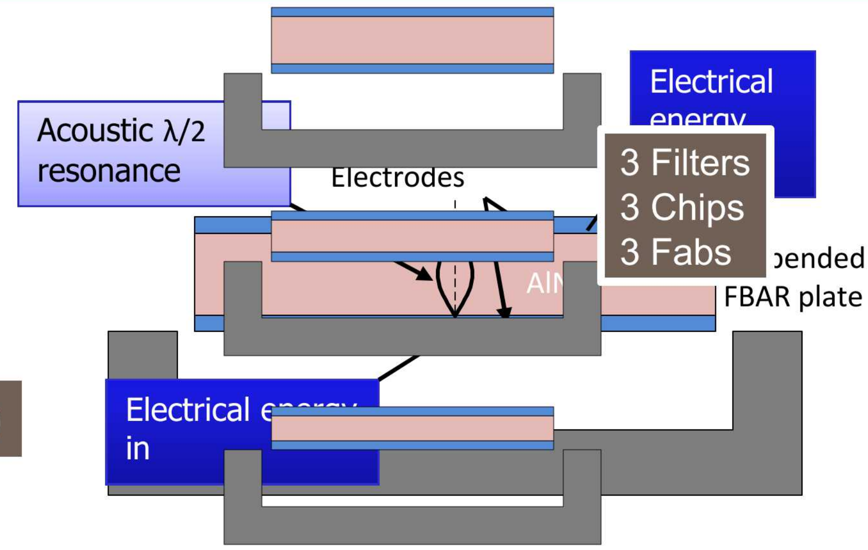


Current State-of-the-Art

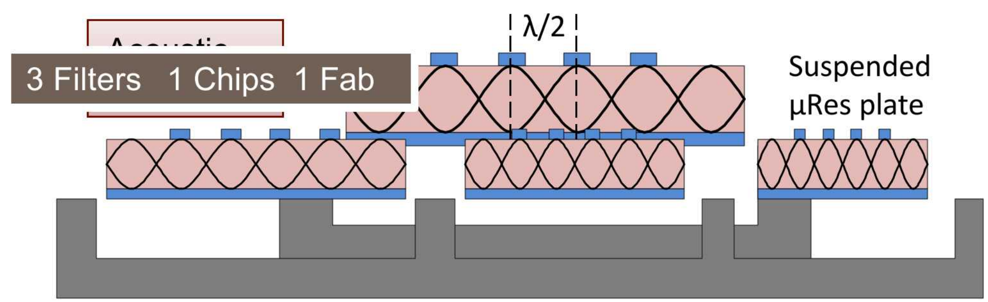
- **Film Bulk Acoustic Resonator (FBAR) Filters**
  - Commercial success for AlN MEMS
  - Filter frequency is set by film thickness

$$k_{t,33}^2 = \frac{d_{33}^2}{\varepsilon_{33} s_{33}^E}$$

~6% (AlN)



- **Lateral mode devices**
  - Wave propagation occurs in-plane
  - Frequencies are set by lithography
  - Frequencies from 32 kHz to 10 GHz realized on a single chip
  - Current niche in intermediate frequency (IF) filters

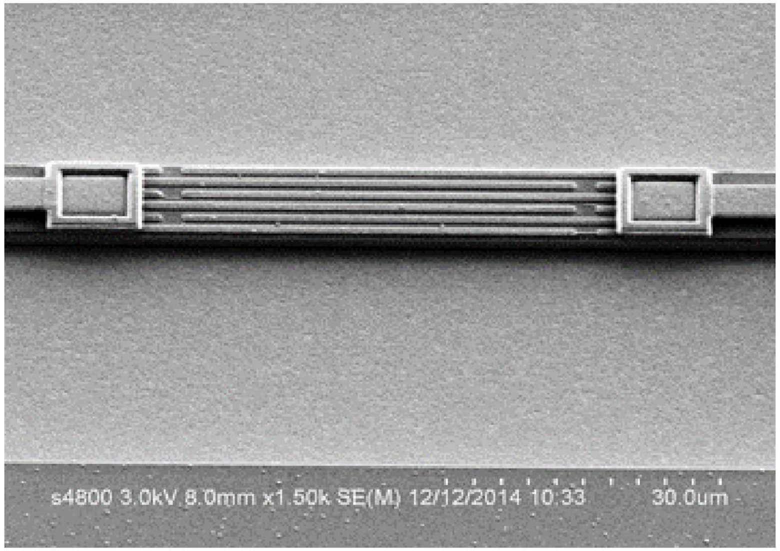


$$k_{t,31}^2 = \frac{d_{31}^2}{\varepsilon_{33} s_{11}^E}$$

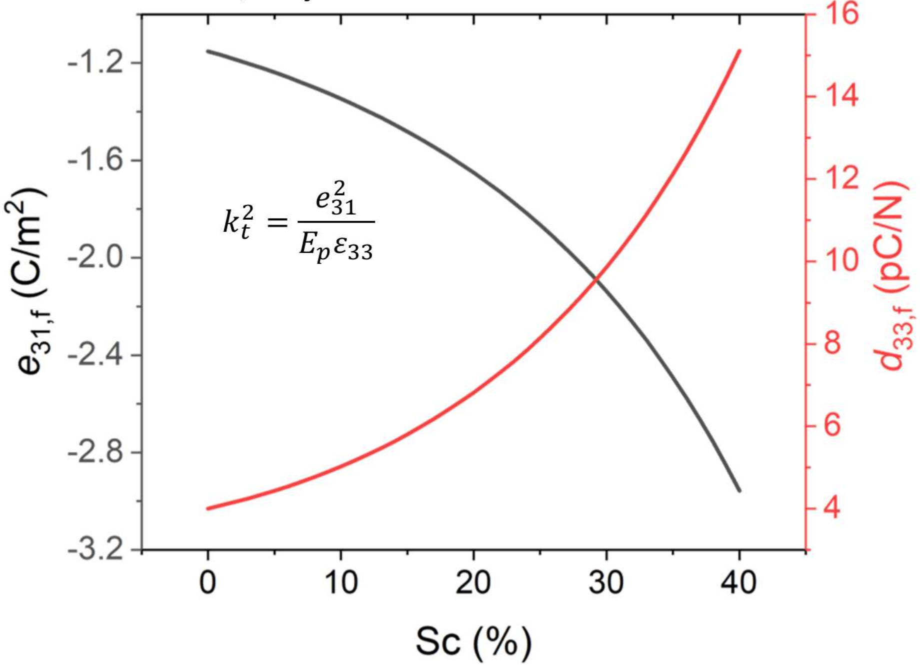
~2% (AlN)

Improving Piezoelectric Performance

- Widespread adoption limited by coupling coefficient (2%)
- FBARs have coupling coefficient of 6%
- Alloying Sc into AlN increases piezoelectric performance
- Investigate the material through device performance

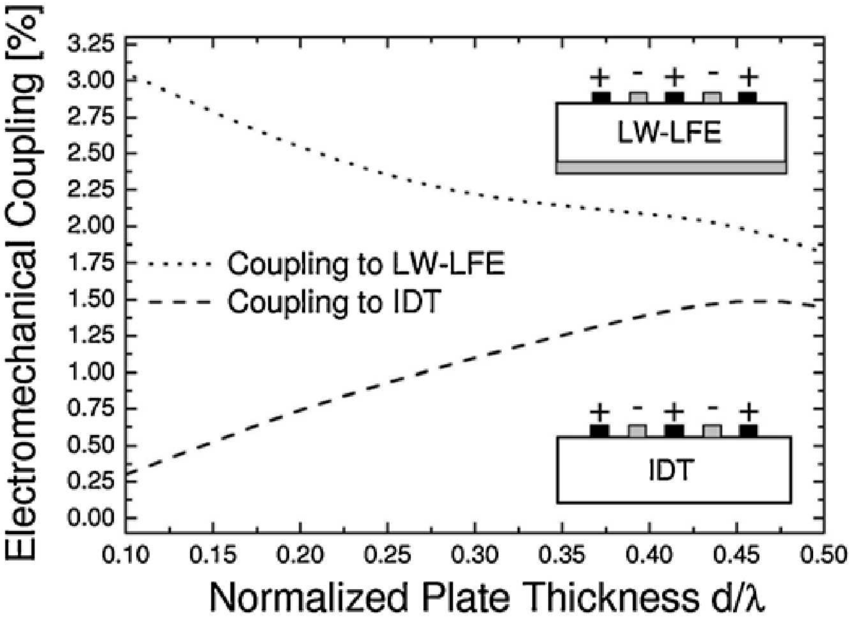


Caro et al., J Phys Condens Matter 2015

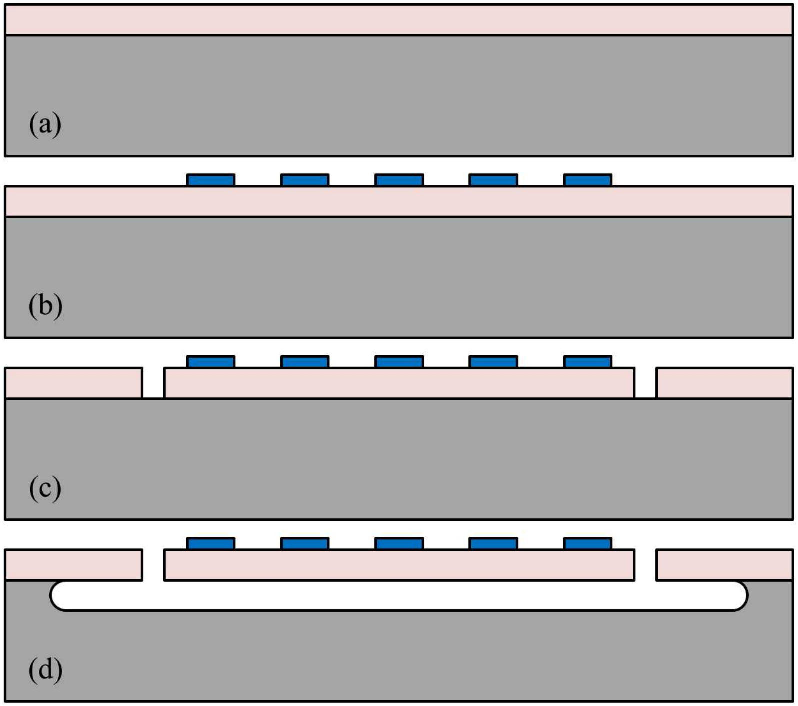


Sandia ScAlN Lateral Mode Device

- Investigating film growth affects on resonator figure of merit
  - Coupling coefficient
  - Quality factor



Minimum Integration Resonator Fabrication



$Sc_{12.5}Al_{87.5}N$ Contour-Mode Resonators

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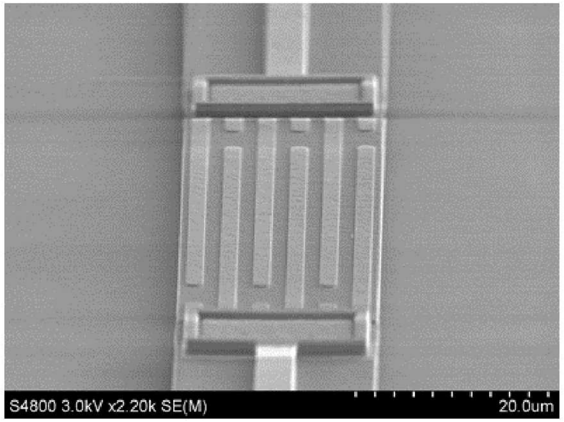
M. D. Henry et al., J. Vac. Sci. Technol. B 36 (2018)



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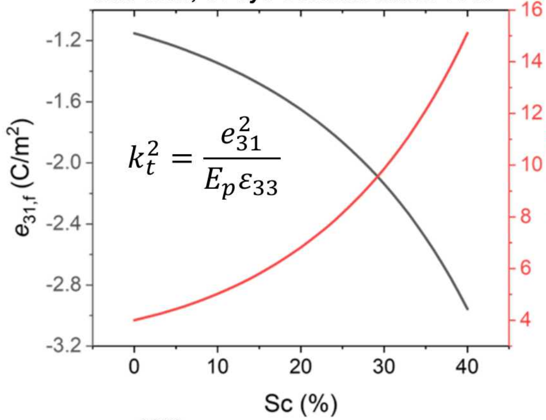

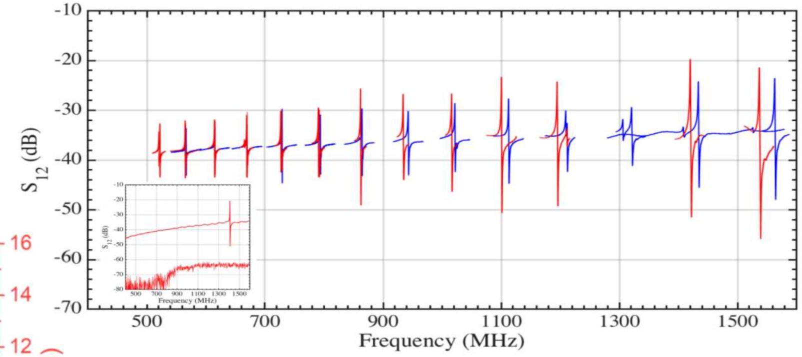

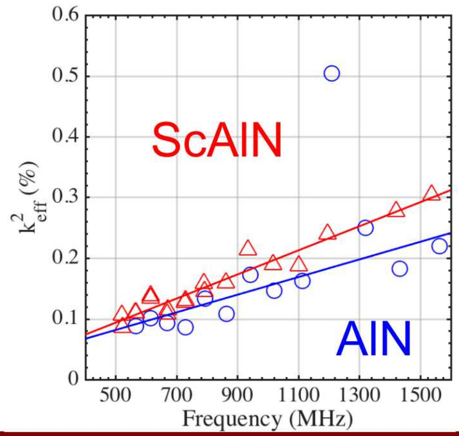

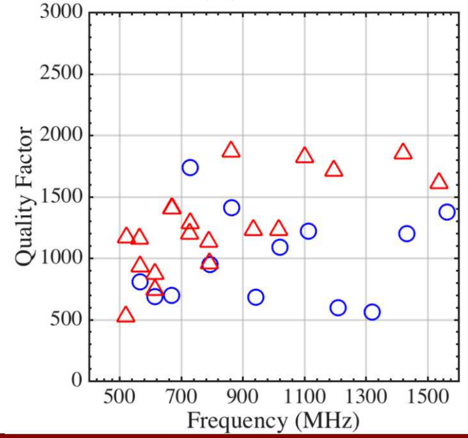

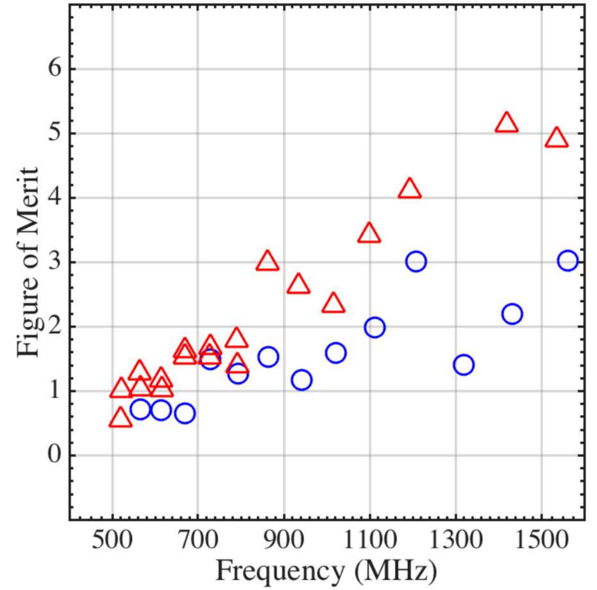

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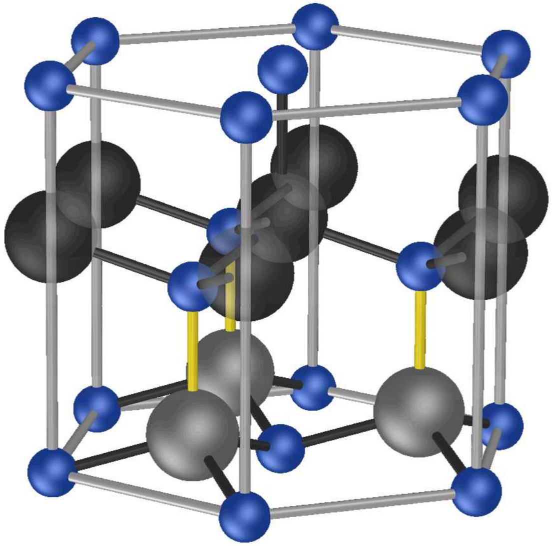
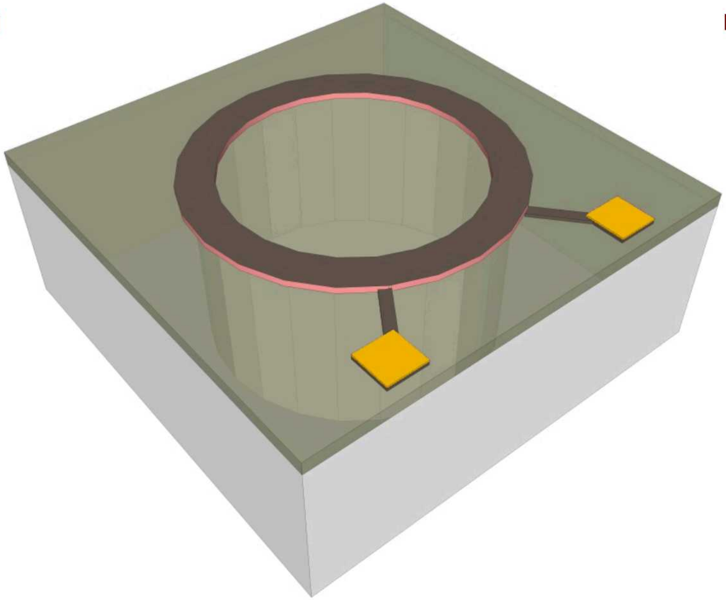


Objective and Program Relevance

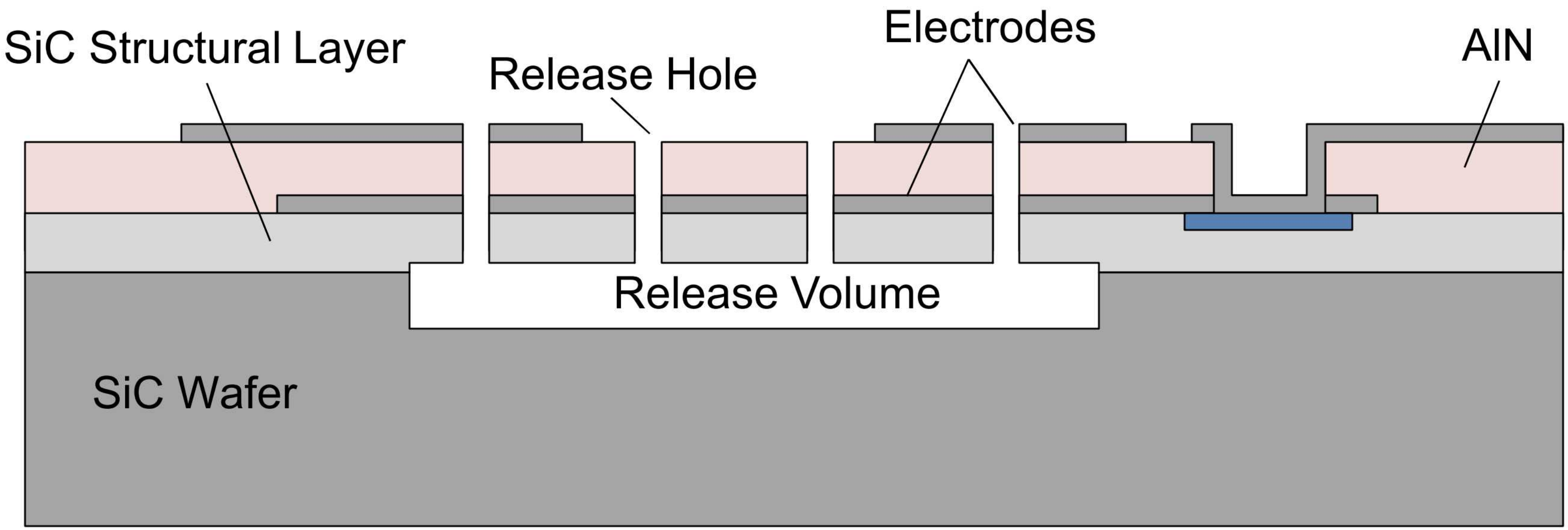
- Develop material set to enable development of extreme temperature capable transducers
- Applications for transducers that can withstand extreme temperatures
  - Gas turbines (1250˚C)
  - Hypersonic flight research (755˚C)
  - Automotive engines (300-1000˚C)
  - Nuclear power plant (300˚C)
  - Coal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



*grc.nasa.gov

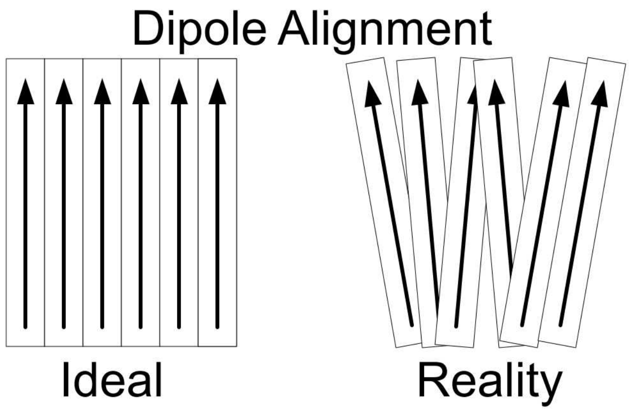
Proposed Technology

- 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)

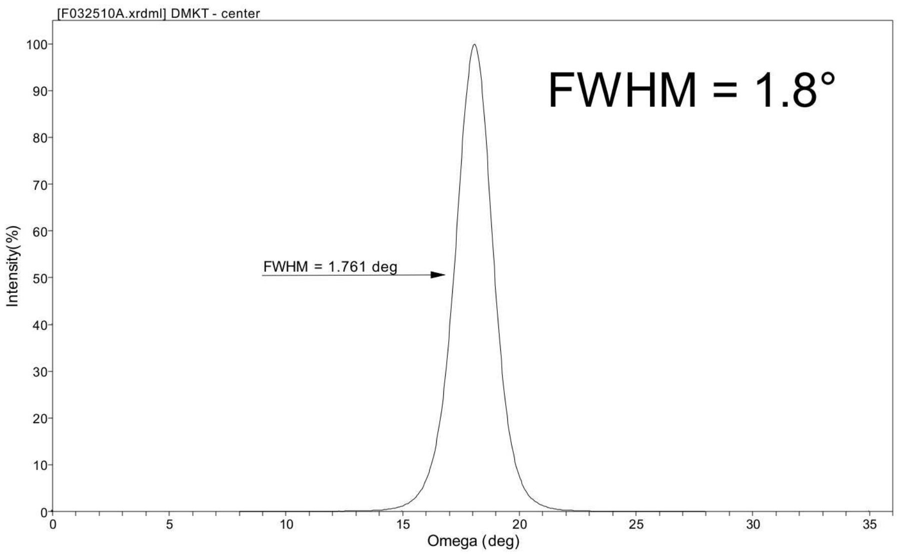


Annealed AlN Alignment

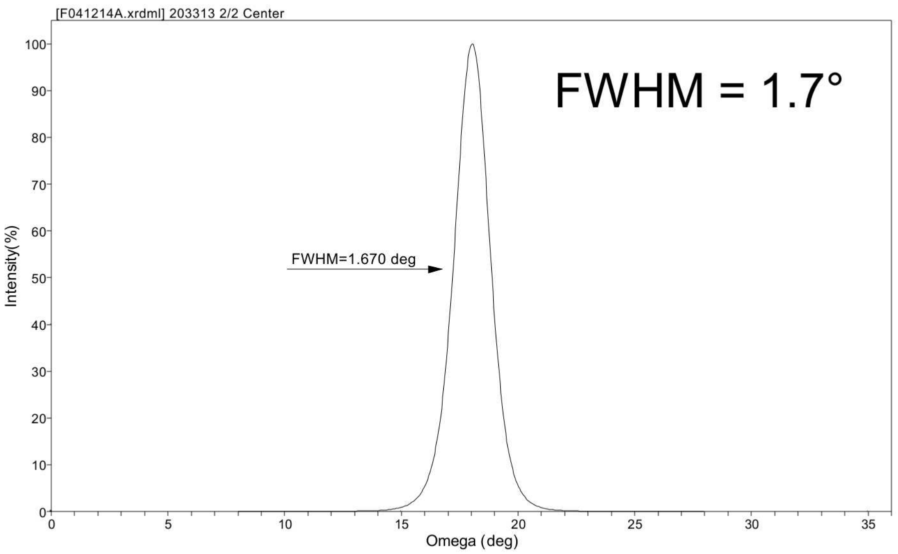
- Anneal of AlN on titanium / titanium nitride bottom metal electrode at 950˚C for 3 hr
  - XRD measurements to determine if AlN is still columnar
  - In general, the goal is <2˚



Before

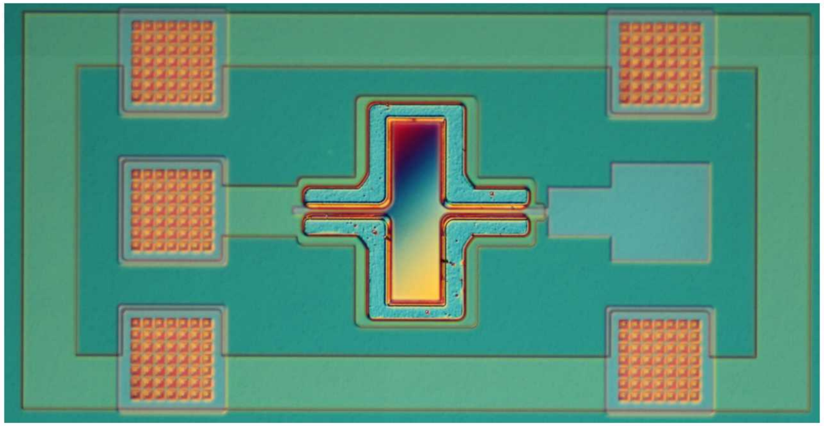


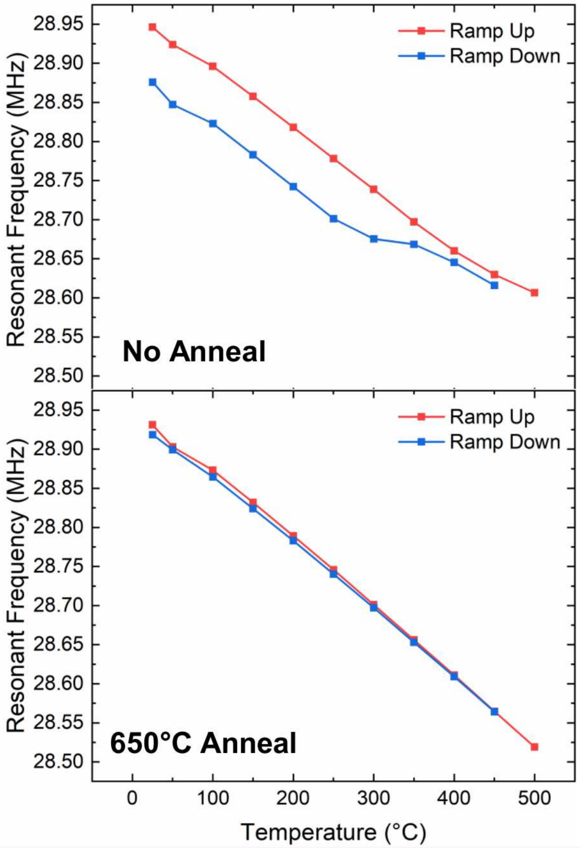
After

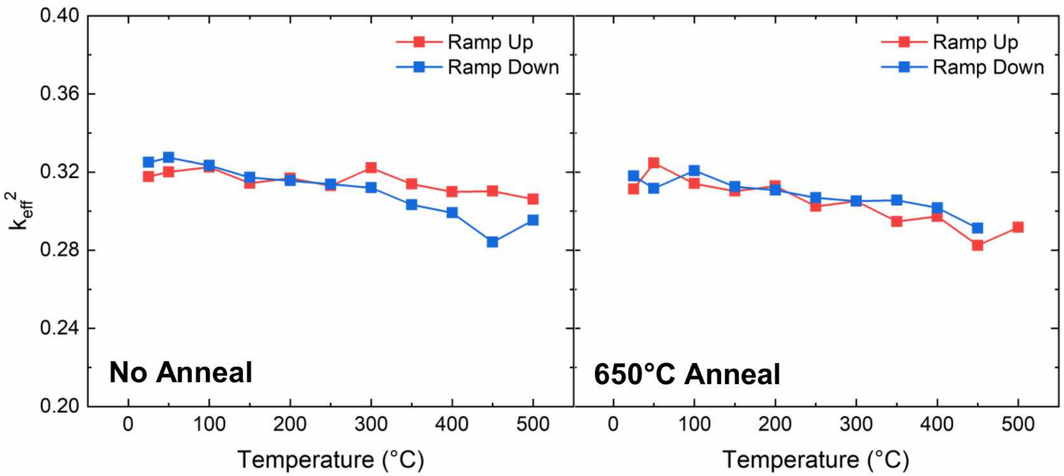


In Air Temperature Testing

- Heated chuck from to 500˚C in steps of 50˚C
- Temperature hysteresis loop results in permanent frequency shift of 2,400 ppm



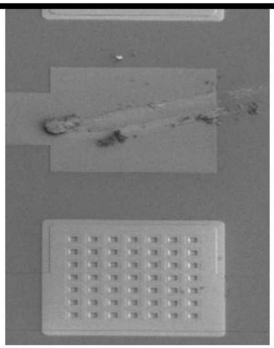


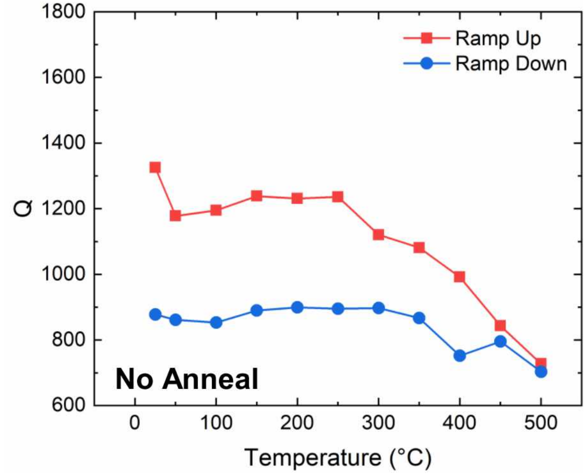


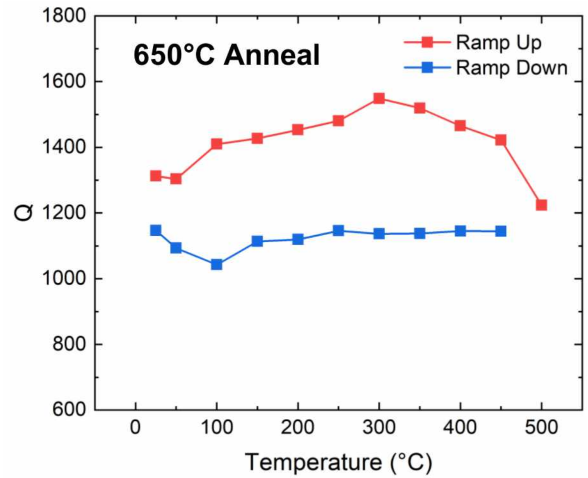
Quality Factor

- 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

Conclusion

Materials Science Research

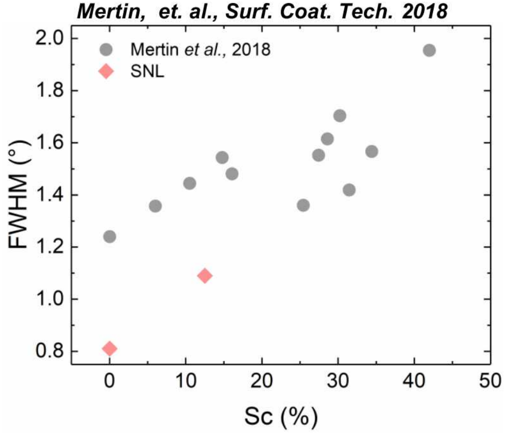
- Ti/Ti/$AlCu_{0.05}$ allows for growth of $Sc_{12.5}Al_{87.5}N$ films with a high-quality microstructure and texture
    - Suppressed secondary grains ScAlN
    - CMOS compatible metal and allows for commercialization of ScAlN technologies

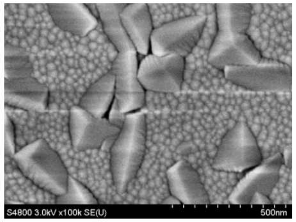
Devices: pMUTS and Microresonator

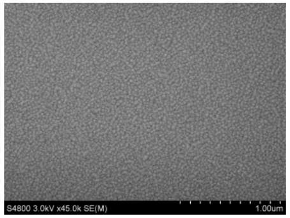
- Can fabricate AlN and ScAlN CMR with competitive metrics
- pMUTS are currently being used for sensing applications

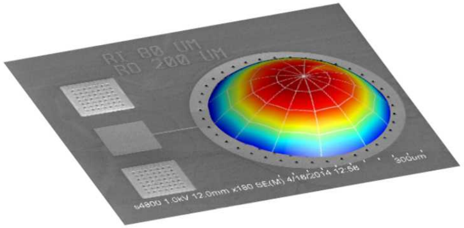
XMEMS

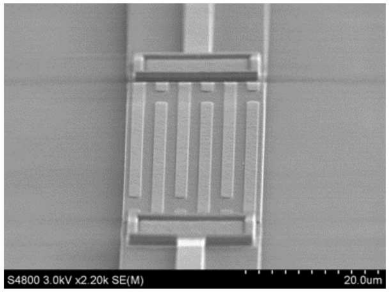
- Successfully tested microresonator *in situ* up to 500˚C
- pMUTs and microresonators can withstand 950˚C anneals
- AlN temperature limit >1000˚C











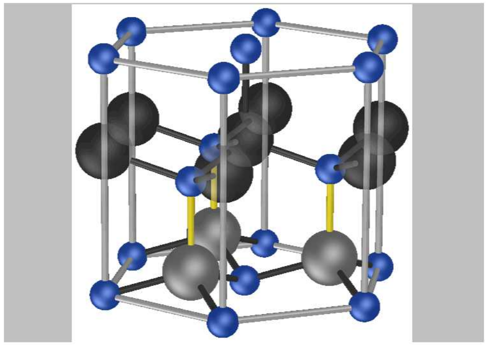
Sandia's PiezoMEMS Team

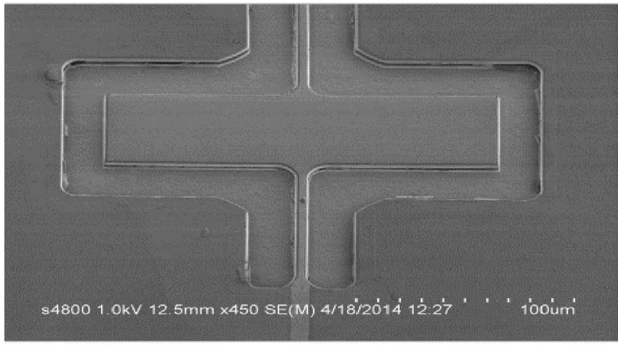
- Current: Benjamin Griffin, Giovanni Esteves, Chris Nordquist, Matt Eichenfield, M. David Henry, Tammy Pluym, Darren Branch, Travis Young, Mike Wiwi, Erica Douglas, Robert Reger, Adam Edstrand, Sean Yen, Alex Grine, Tom Friedmann, Ian Young, Aleem Siddiqui, Paul Stanfield, Michael Satches, Ihab El-Kady, Charles Reinke, Katherine Kinsely, Sasha Summers, Kenneth Douglas, Stefan Lepkowski, Adrian Schiess, Mark Balance, Emily Crispin, Andrew Leenheer, Matt Delaney, Larry Koch, Todd Bauer, Sara Jensen, Garth Kraus, Vince Hietala

- Former: Troy Olsson, Ken Wojciechowski, Janet Nguyen, Peggy Clews, Mike Baker, Jim Stevens, Bongsang Kim, James Fleming, Vic Yarberry, Sukwon Choi, Jeremy Moore, Sean Scott, Melanie Tuck, Maryam Ziaei-Moayyed, Jeremy Moore, Camille Padilla, Rajen Chanchani, Tracy Peterson, Randy Shul, Catalina Ahlers, Chris Dyck, Chris Rodenbeck

DARPA

LABORATORY DIRECTED RESEARCH & DEVELOPMENT





III-V Piezoelectric Sensors, Actuators, and Resonators

<u>Giovanni Esteves</u>, Michael D. Henry, Erica A. Douglas, Travis R. Young, Christopher D. Nordquist, Robert Reger, Adam Edstrand, and Benjamin A. Griffin

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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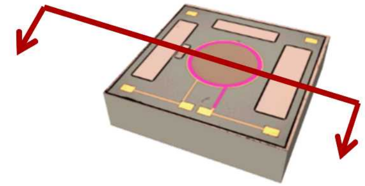
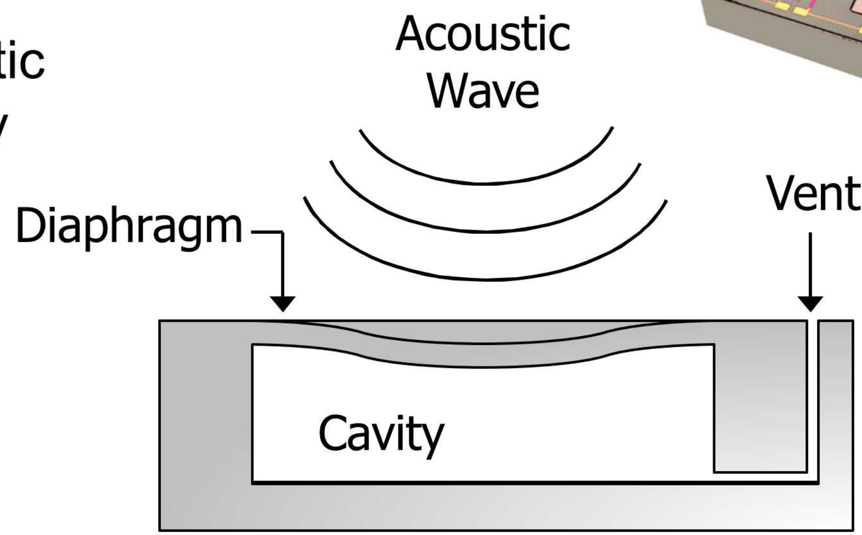
Piezoelectric Micromachined Ultrasonic Transducers (pMUTs) Operation

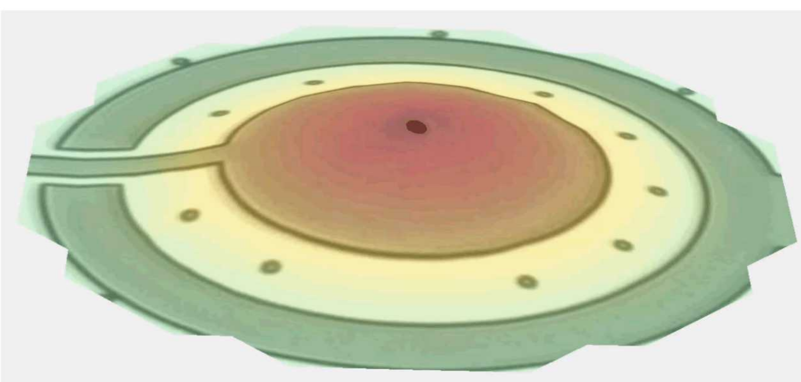
- Microphone
  - Device that converts input acoustic energy to output electrical energy
  - Diaphragm, cavity, vent

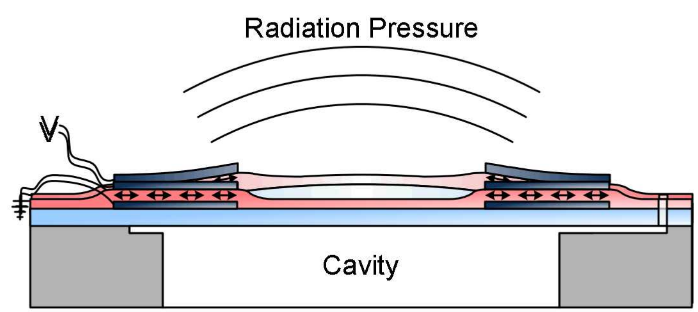




Transduction Mechanism → Electrical Output

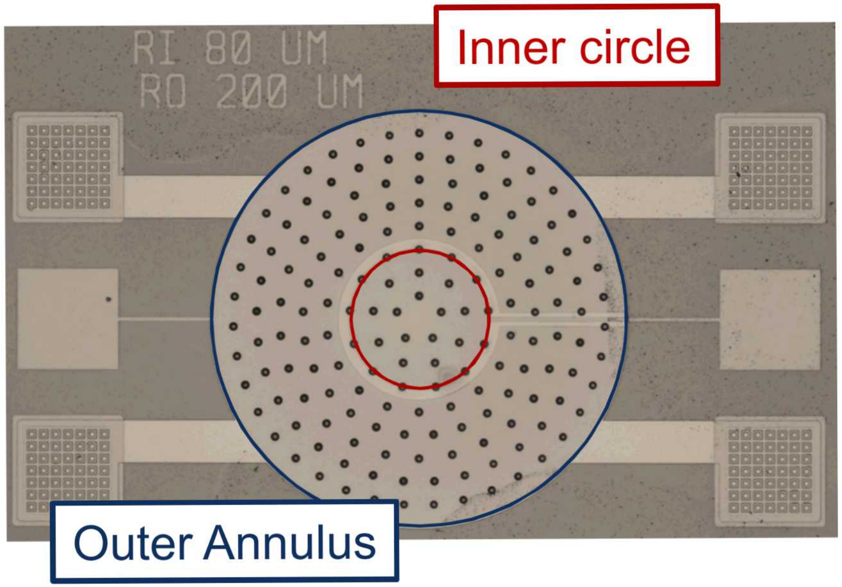
PMUT Pixel

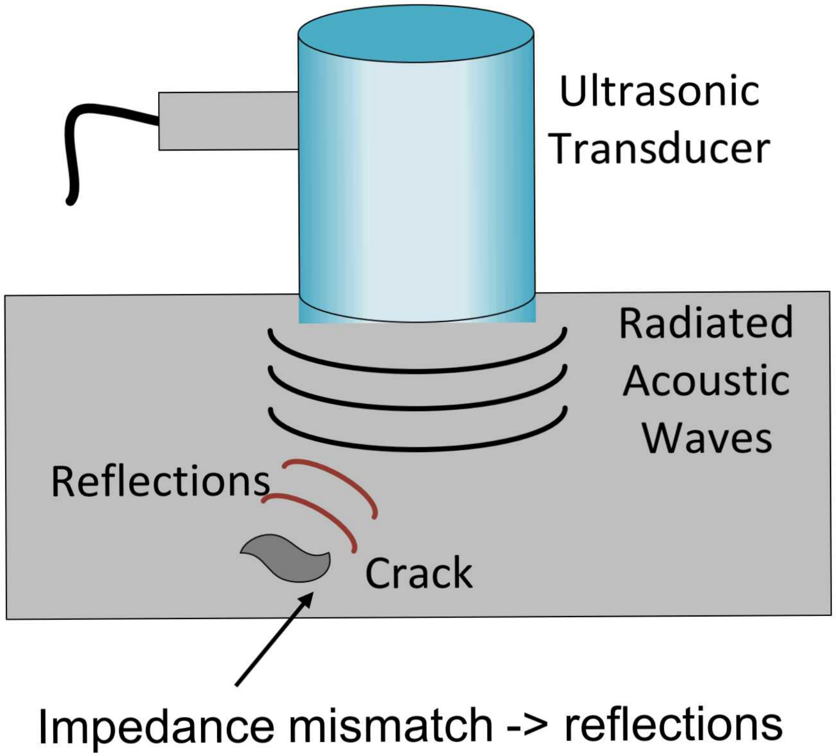




Imaging Application

- Sensing
- Pulse signal in outer annulus
- Inner circle senses the reflection





High Temperature Capable pMUT

- Rapid Thermal Anneals
  - Argon purged
  - Vacuum of 1 Torr
  - Temperature held for 2-7 minutes