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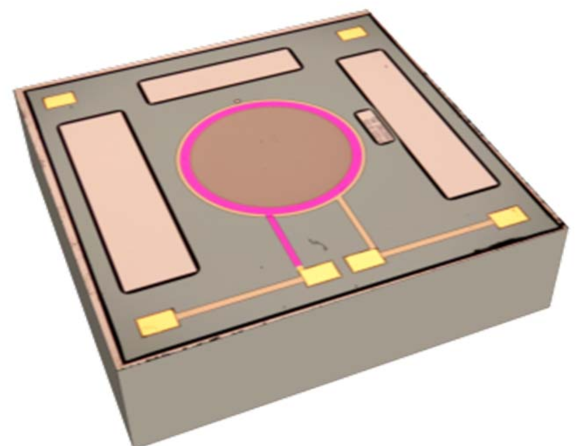

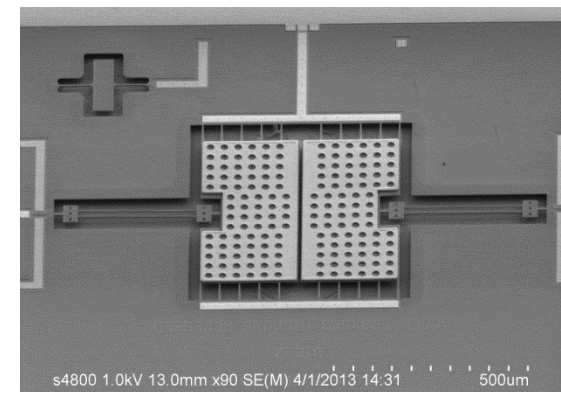

Piezoelectric MEMS Based on Aluminum Nitride

Benjamin A. Griffin

1/22/14

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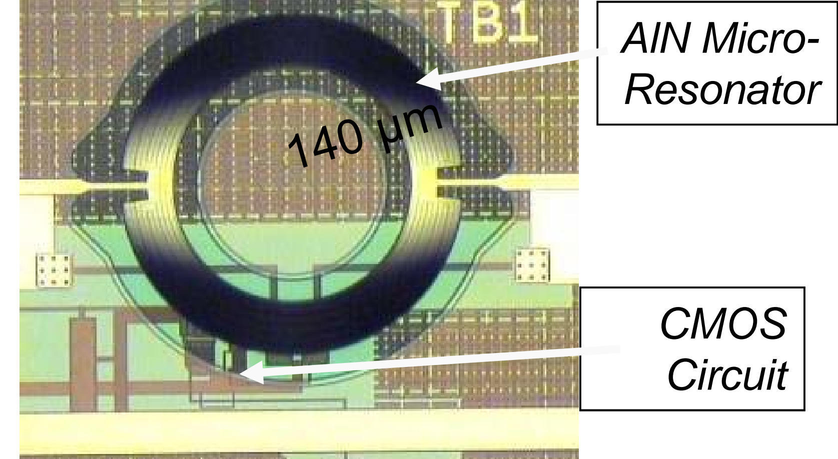
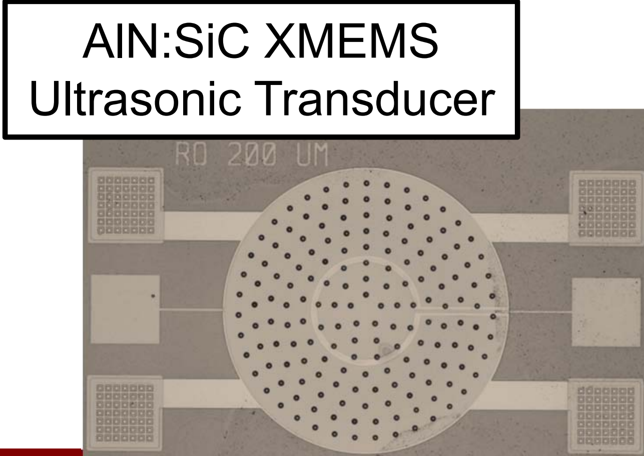
Outline

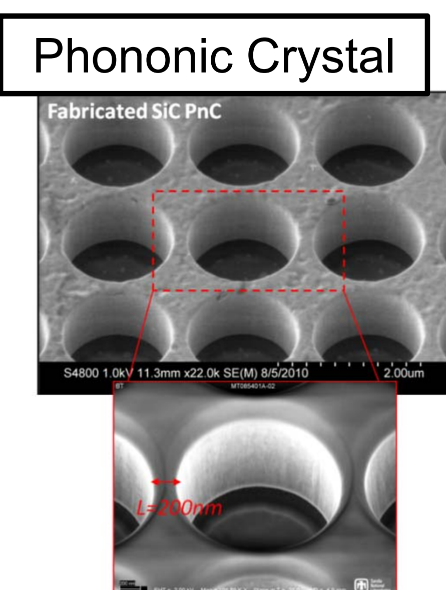
- Aluminum Nitride
- Piezoelectric Micromachined Ultrasonic Transducers
- Microphones
- Microresonators
- XMEMS: MEMS for Extreme Environments
- Fabrication Challenges

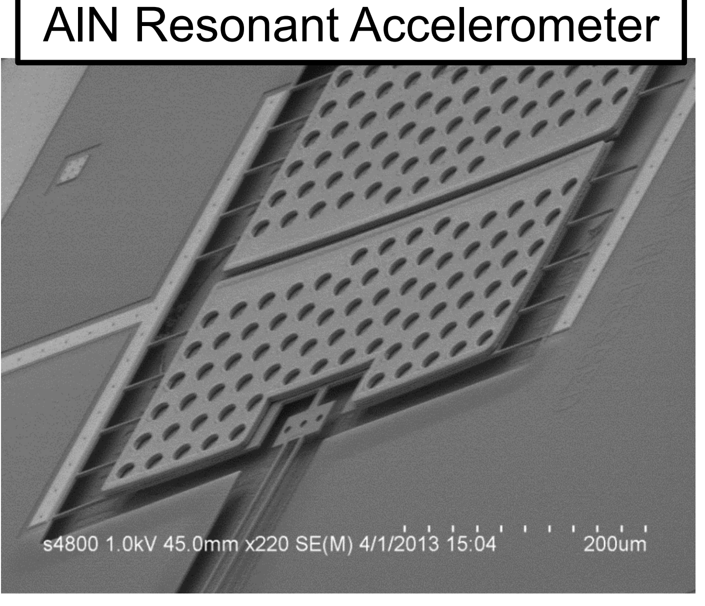
Sandia's AlN MEMS Program

- Microresonators
  - 2011 R&D 100
- Resonant Accelerometers
- Ultrasonic Transducers
- Microphones
- XMEMS
- Phononic Crystals





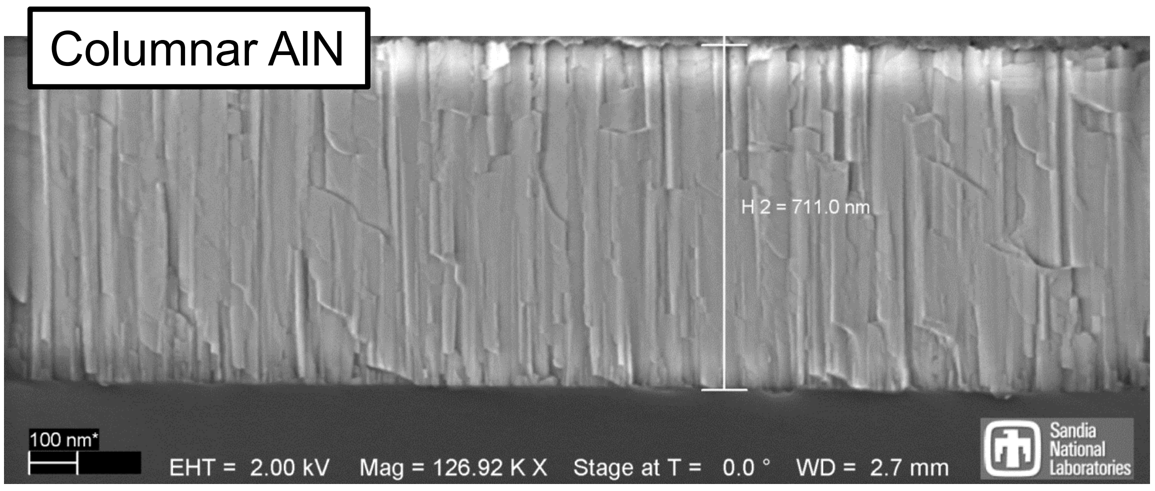




Aluminum Nitride (AlN)

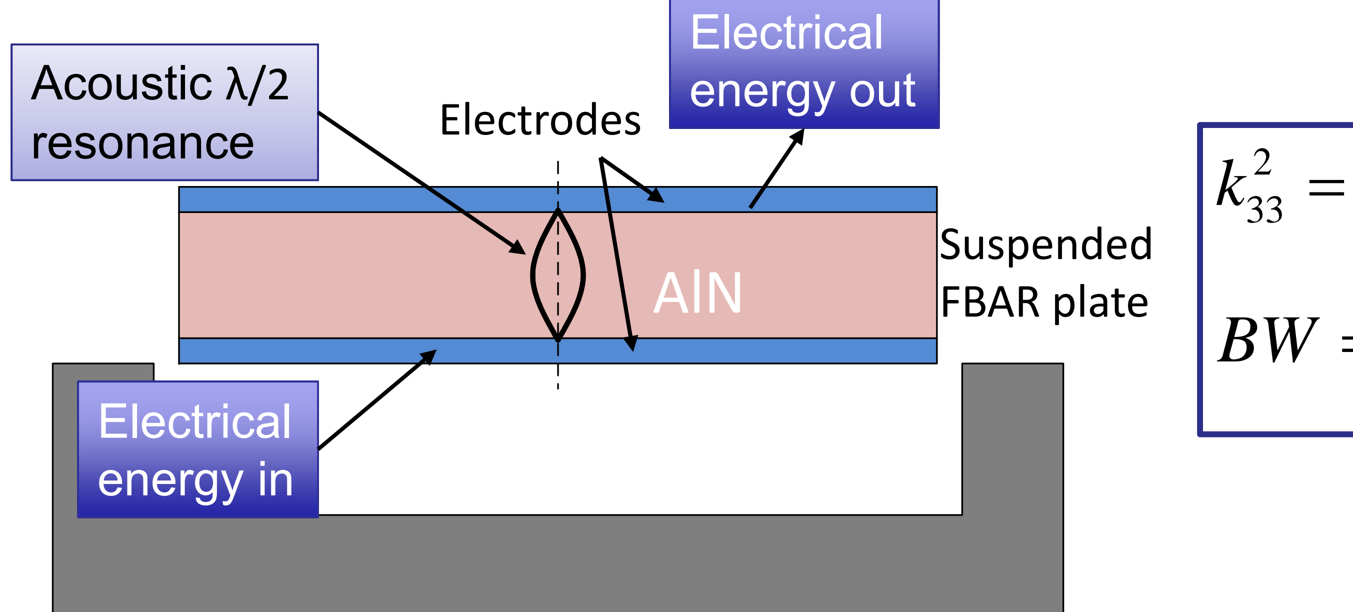
- Piezoelectric thin film
  - Physical vapor deposited
    - Low temperature deposition ~350˚C
  - CMOS compatible
  - Non-ferroelectric
    - No Curie temperature
    - Texture achieved during deposition
  - Large band-gap (6 eV)
  - High temperature capable
    - Melting point of 2,200˚C
    - Piezoelectric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

Property	AlN
Low permittivity, ε_{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}	2



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
    - >1 billion units produced per year from Avago Technologies
  - More than 40 discrete filter die in the modern smartphone



$$k_{33}^2 = 6\%$$

$$BW = \frac{k_{33}^2}{2} = 3\%$$

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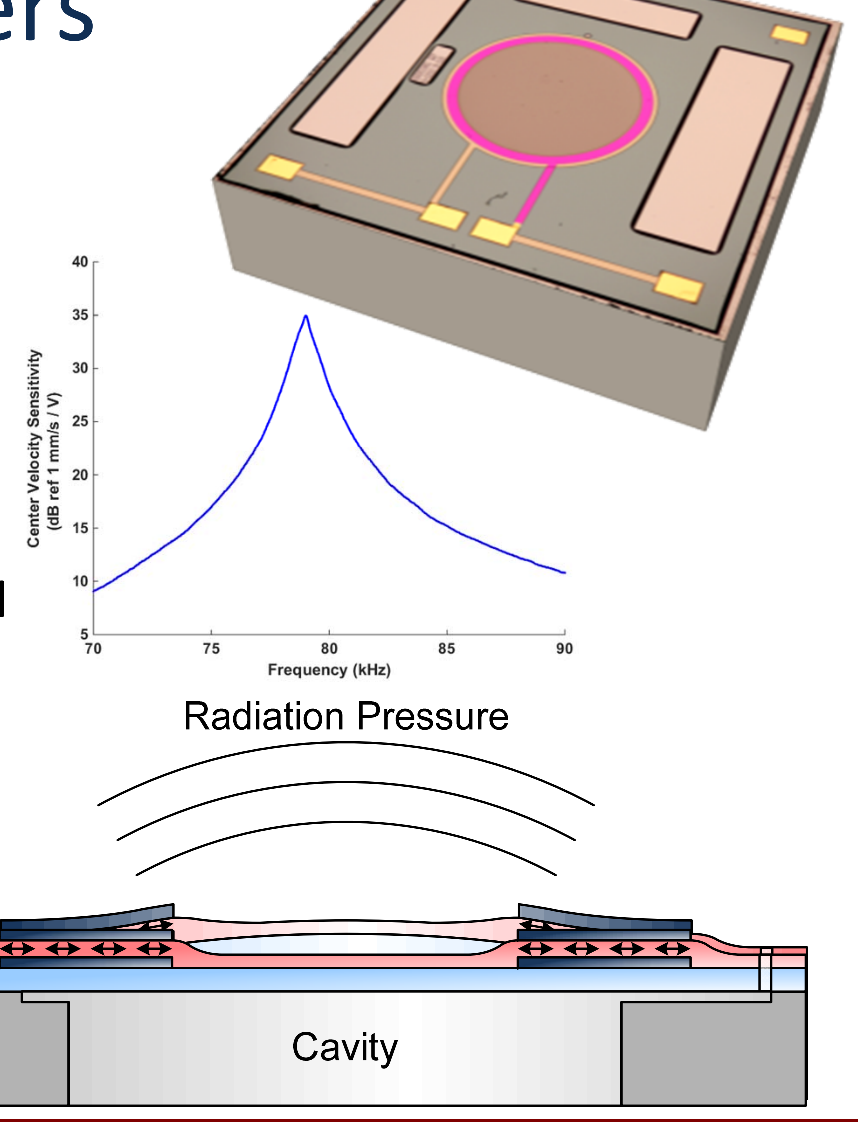
Piezoelectric Micromachined Ultrasonic Transducers

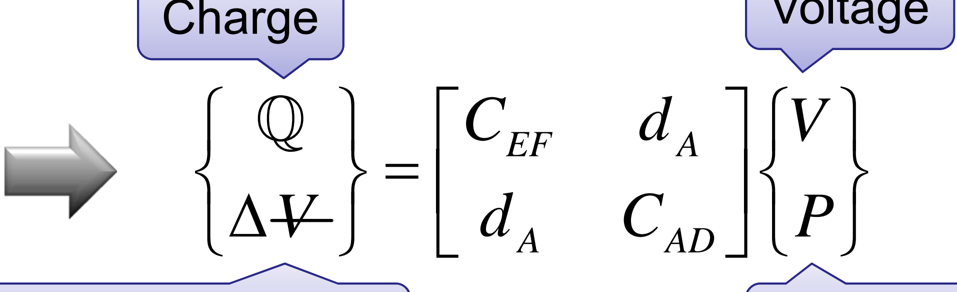
- Piezoelectrics are reciprocal
  - Transmitters
  - Microphones
- PMUT Applications
  - Proximity sensing
  - Short range communication
  - Extreme high sound pressure level microphones
  - Imaging
  - Gesture recognition
  - Flow metering



Electromechanical Coupling

- Piezoelectric constitutive relationship simplified to 1-D transformer equation

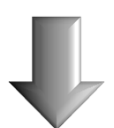
$$\begin{Bmatrix} \{D\} \\ \{S\} \end{Bmatrix} = \begin{bmatrix} [\varepsilon^T] & [d] \\ [d]^T & [s^E] \end{bmatrix} \begin{Bmatrix} \{E\} \\ \{T\} \end{Bmatrix}$$



$$\begin{Bmatrix} Q \\ \Delta V \end{Bmatrix} = \begin{bmatrix} C_{EF} & d_A \\ d_A & C_{AD} \end{bmatrix} \begin{Bmatrix} V \\ P \end{Bmatrix}$$

Volume Deflection

Pressure



$$\times j\omega$$

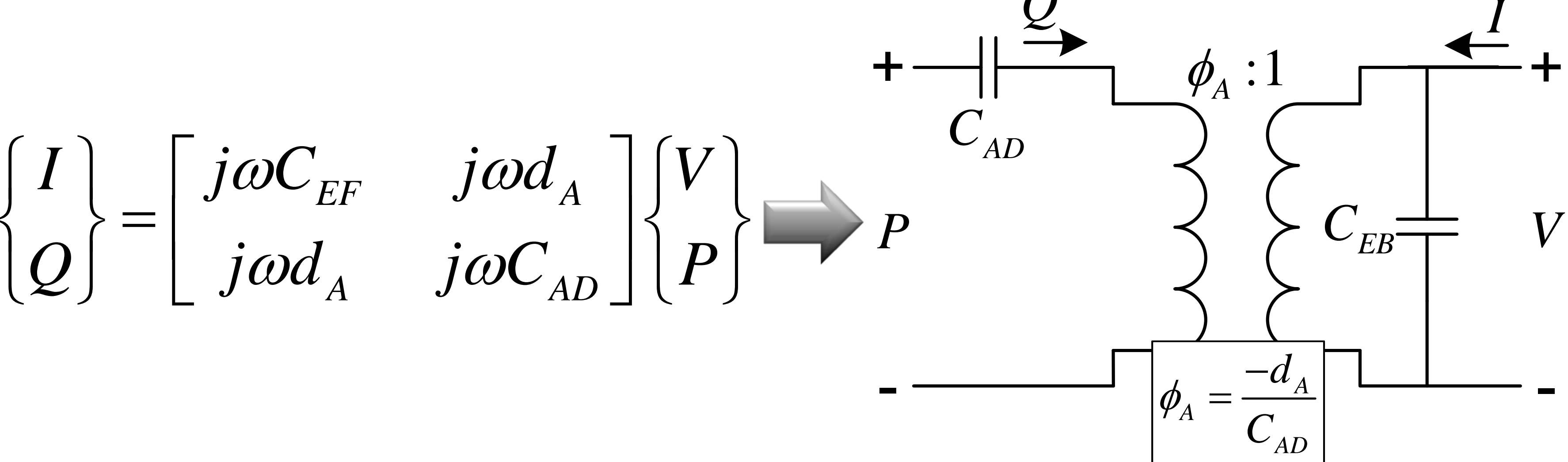
Dynamic Transformer Equation

Current

$$\begin{Bmatrix} I \\ Q \end{Bmatrix} = \begin{bmatrix} j\omega C_{EF} & j\omega d_A \\ j\omega d_A & j\omega C_{AD} \end{bmatrix} \begin{Bmatrix} V \\ P \end{Bmatrix}$$

Volume Velocity

Transformer Elements

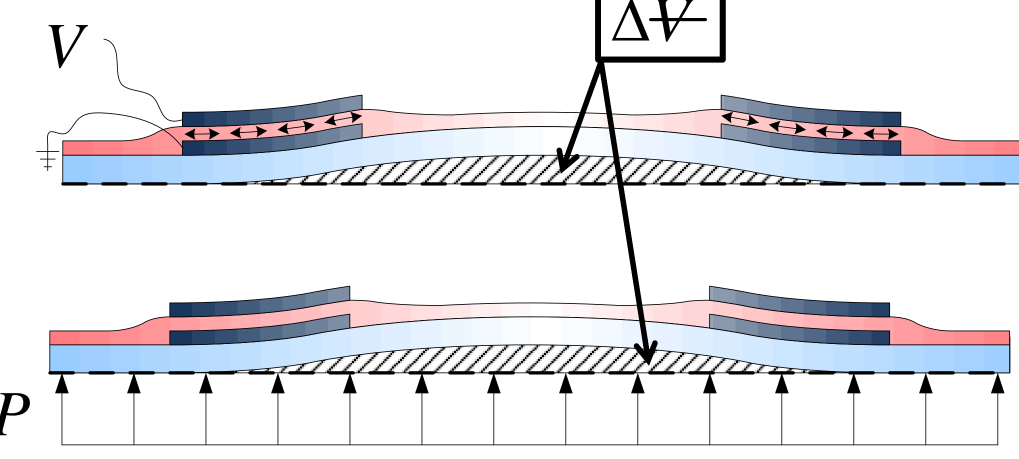


- Effective acoustic piezoelectric coefficient

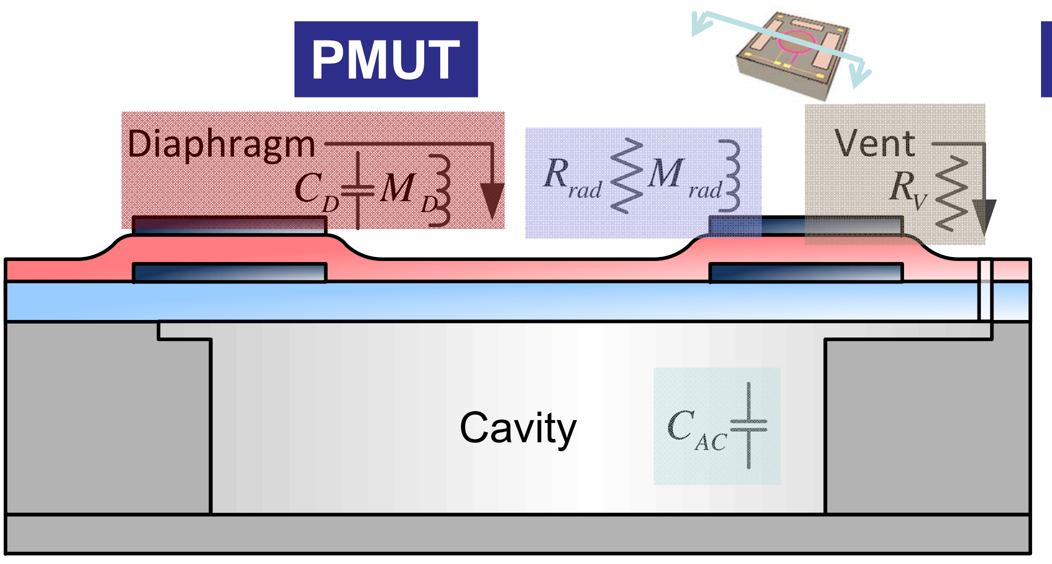
$$d_A = \frac{\Delta \mathcal{V}}{V}$$

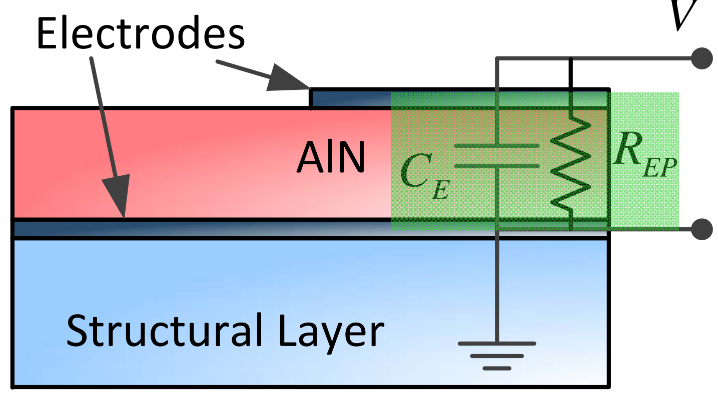
- Acoustic compliance

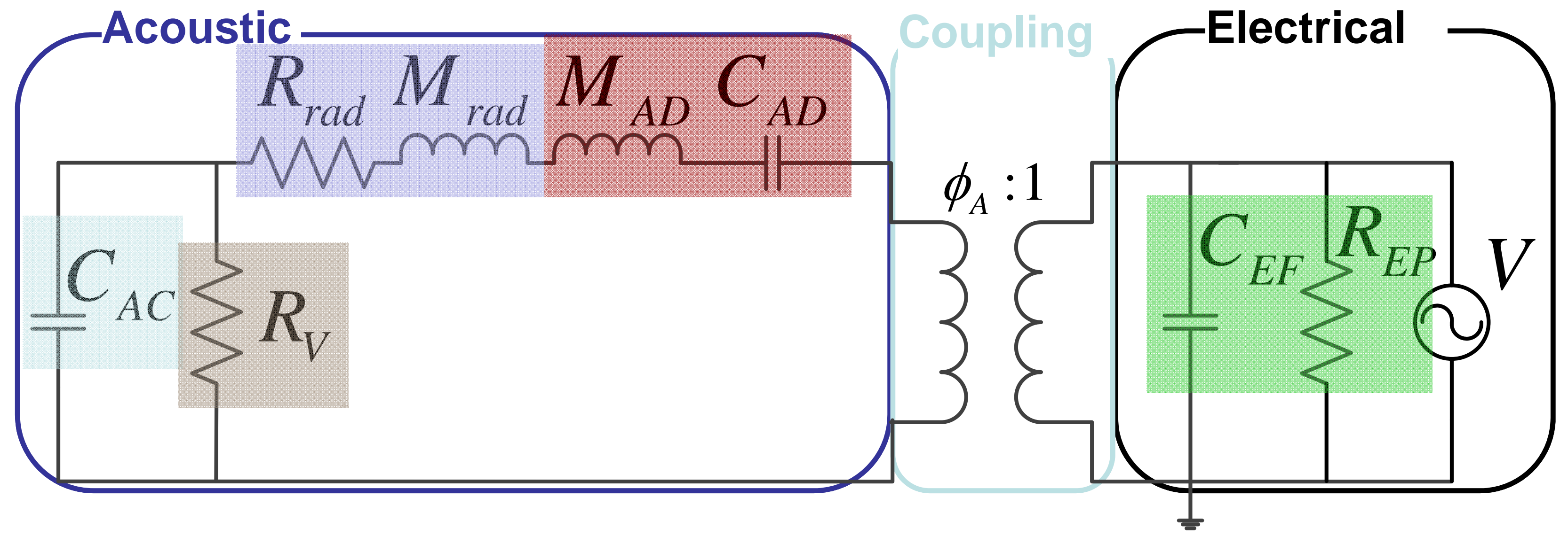
$$C_{AD} = \frac{1}{K_{AD}} = \frac{\Delta \mathcal{V}}{P}$$



PMUT Equivalent Circuit

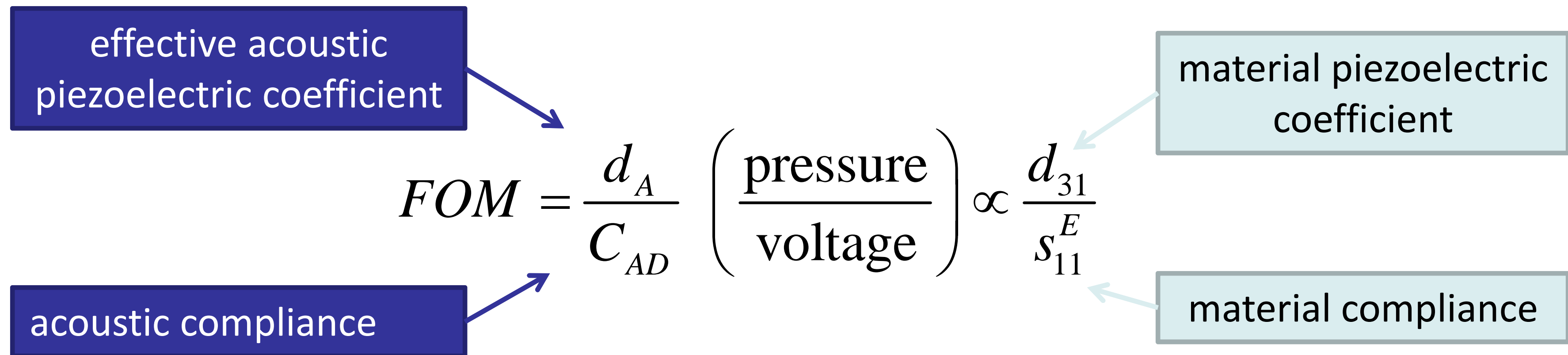






Large Amplitude PMUT Design

- Design goal is to maximize amplitude
  - Constraints are operating frequency, power, harmonic distortion, etc.
- Resonant actuation figure-of-merit (FOM)



$$FOM = \frac{d_A}{C_{AD}} \left(\frac{\text{pressure}}{\text{voltage}} \right) \propto \frac{d_{31}}{s_{11}^E}$$

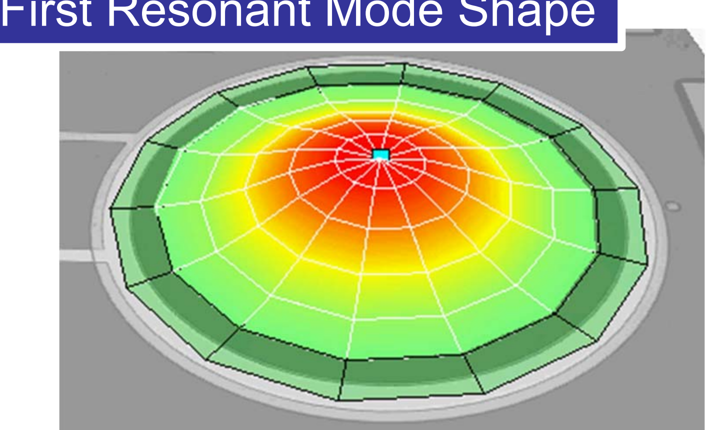
- Other factors that affect maximum drive amplitude
  - Maximum sustainable electric field

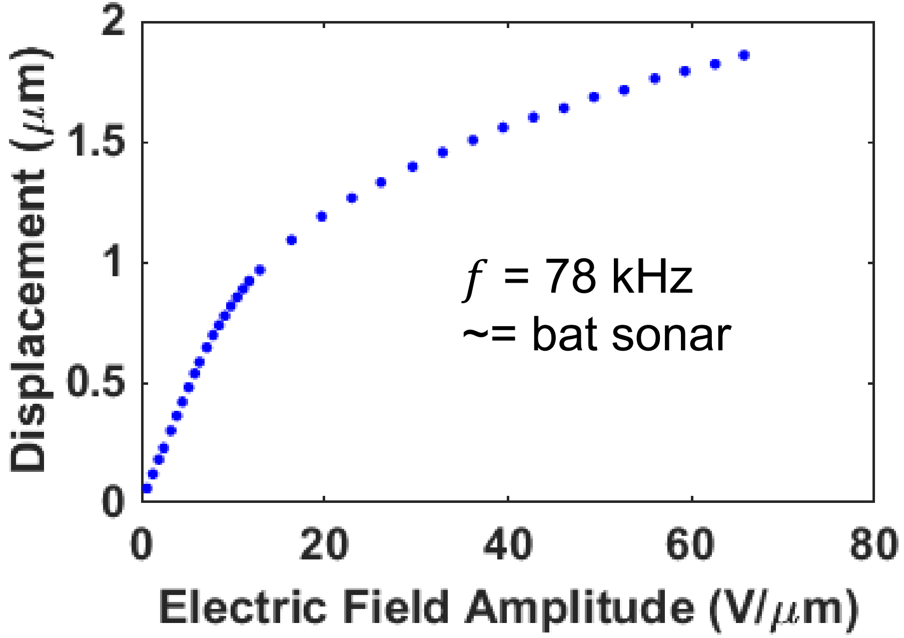
Large Amplitude Drive

- AlN has a much lower piezoelectric strain coefficient than PZT
- PZT has a much lower dielectric strength than AlN
- Can AlN be driven to much higher voltages to achieve PZT type amplitudes?

	AlN	PZT
d_{31} [pm/V]	2	274
s_{11} [1/MPa]	3e-6	14e-6
d_{31}/s_{11} [pC/μm²]	0.7	20
Dielectric Strength (V/μm)	>267	~50

First Resonant Mode Shape





Duffing Behavior

Displacement response under increase drive voltage amplitude

Duffing behavior for a drive voltage of 50 V showing the hysteresis loop

Next task: Lock PMUT in an oscillator loop and control them beyond the Duffing nonlinearity.

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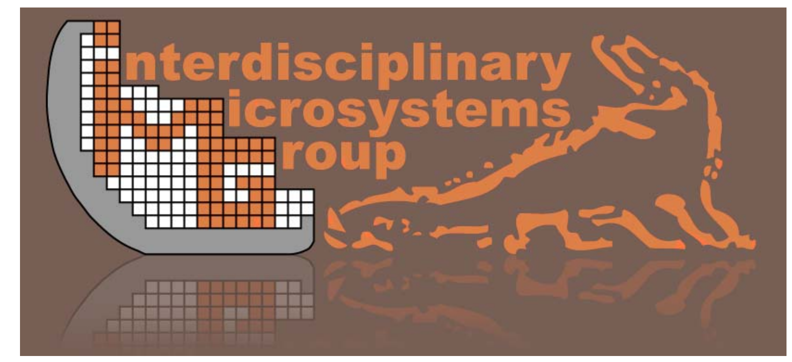
AlN Aeroacoustic Microphone

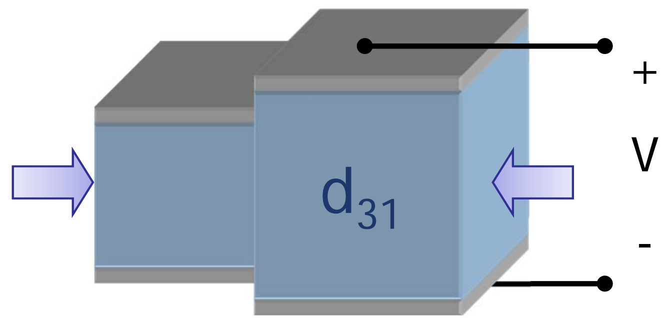
- Developed for measurement of aircraft noise
- University of Florida
  - Dr. Matthew Williams
  - Professor Mark Sheplak

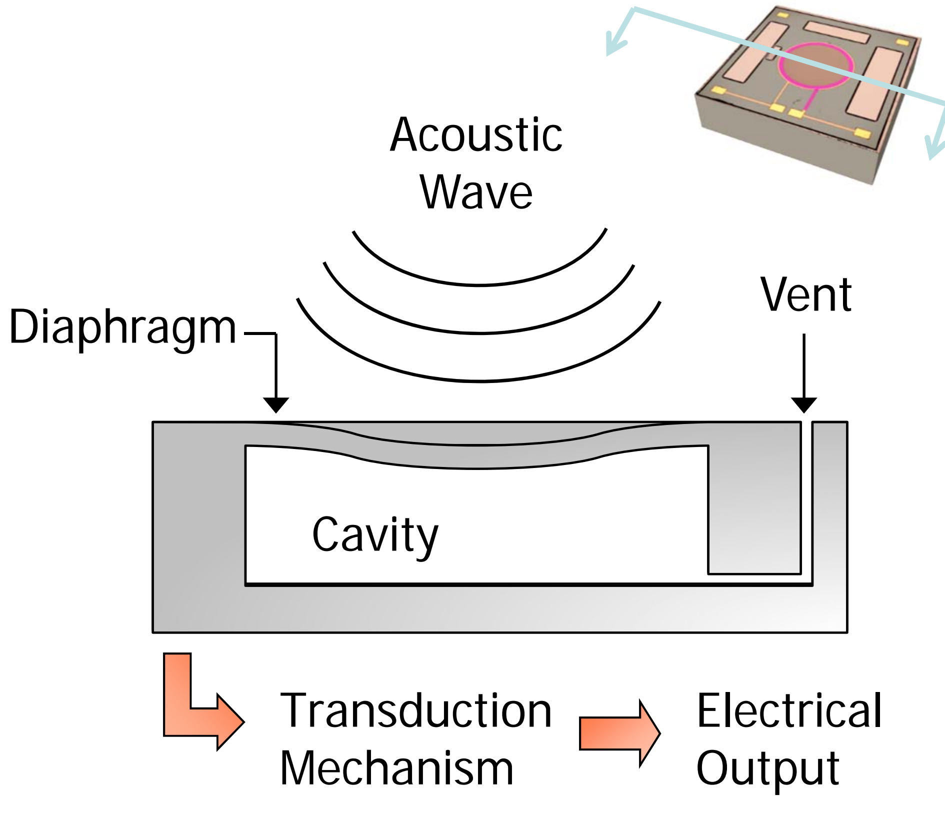


Metric	Obtained
Sensing element size	Ø 746 µm
Sensitivity	39 µV/Pa
MDP (at 1 kHz, 1 Hz bin)	40.4 dB
PMAX	> 171.6 dB
Bandwidth	70 Hz – >20 kHz
Resonant Frequency	104 kHz *

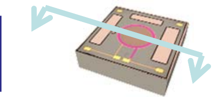
Microphone Operation

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

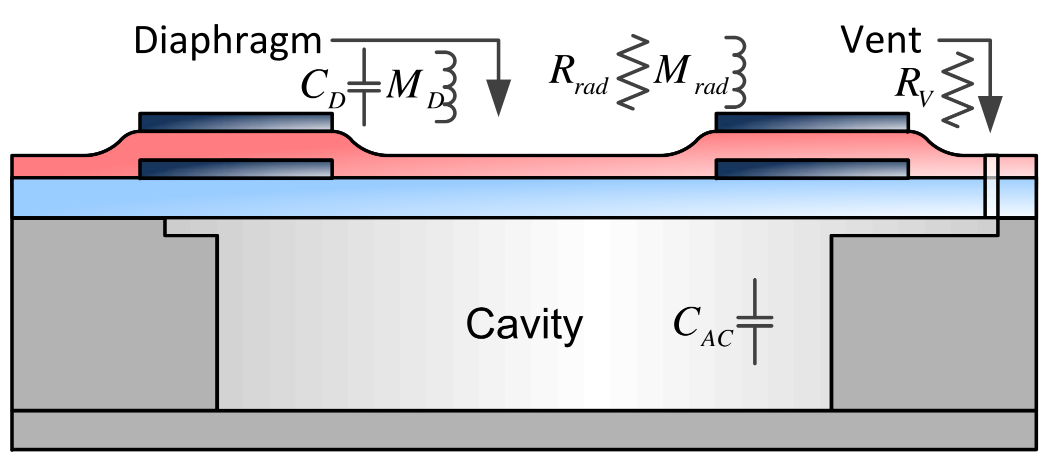


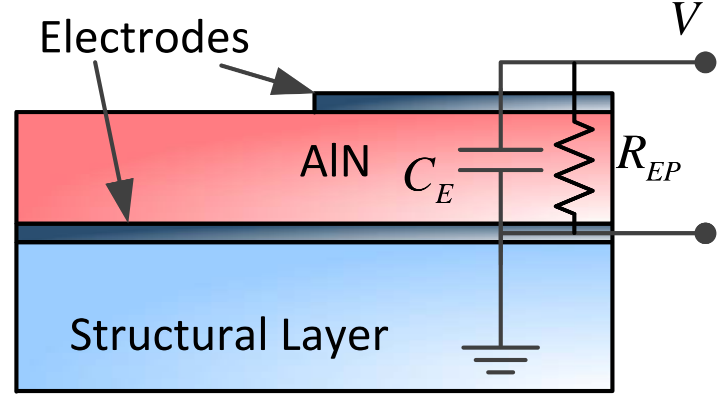


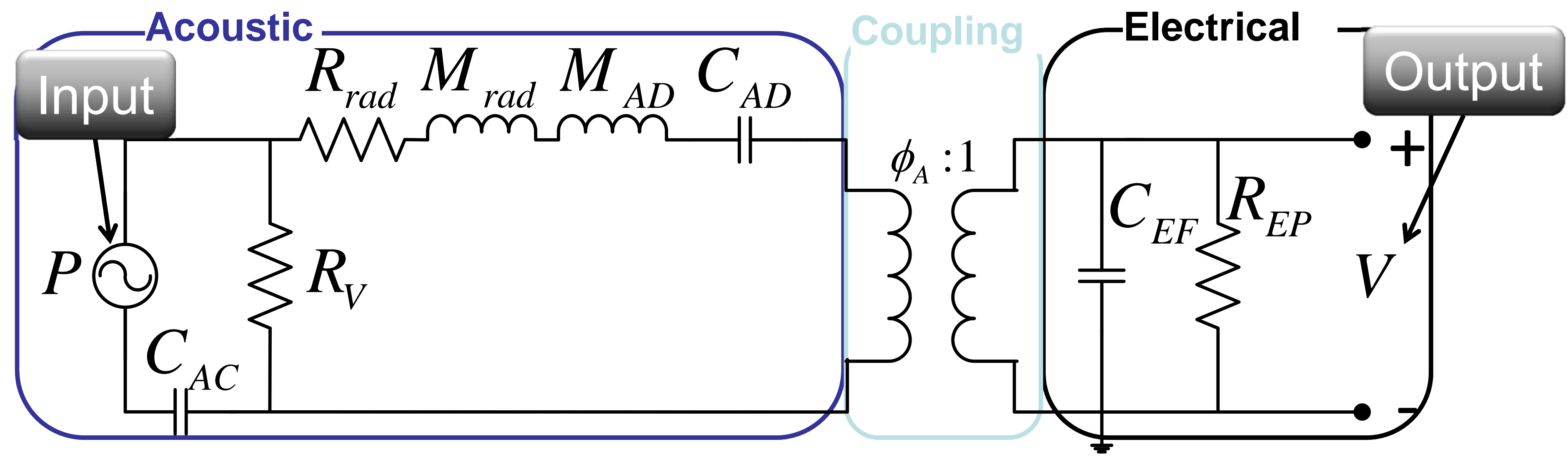
PMUT Equivalent Circuit



Piezoelectric Transduction

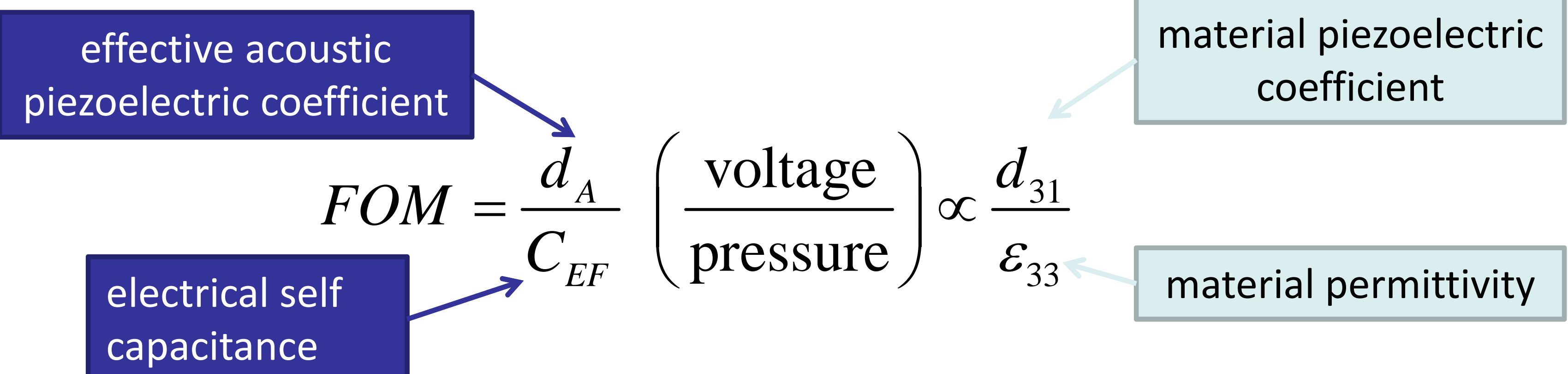






Microphone Design

- Design goal: minimize the Minimum Detectable Pressure (MDP)
  - Constraints: bandwidth, maximum pressure, size, etc.
- Sensing FOM



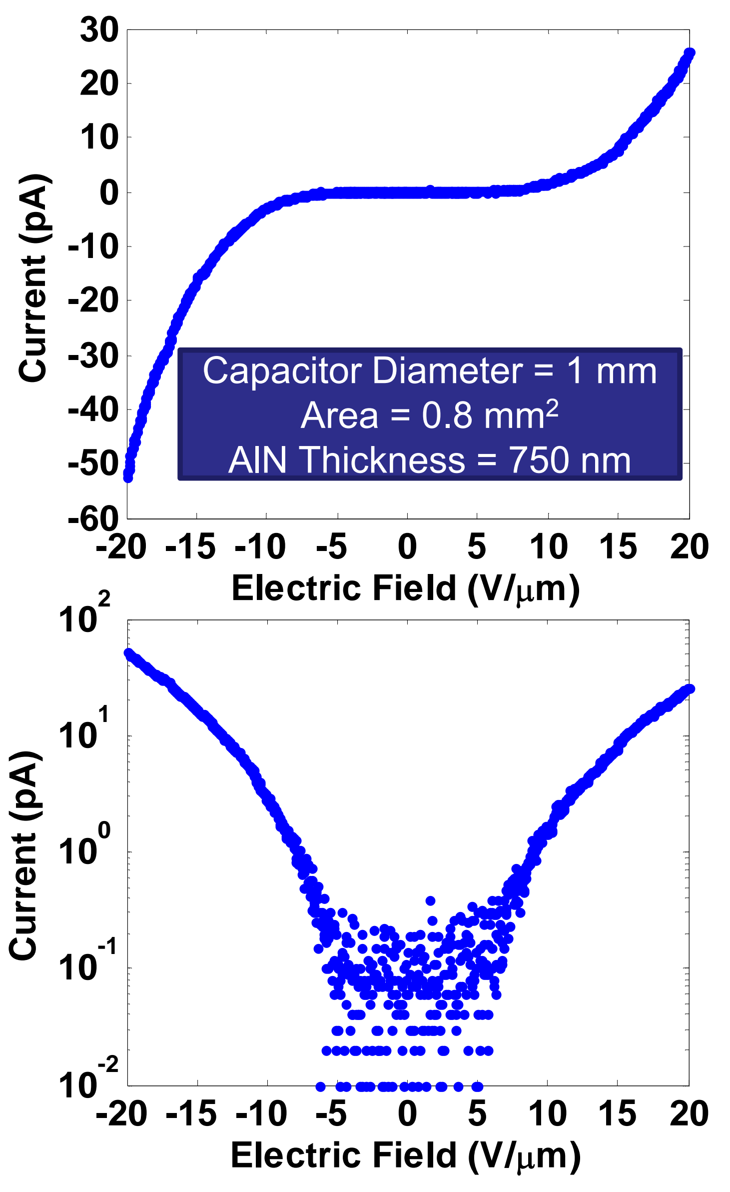
$$FOM = \frac{d_A}{C_{EF}} \left(\frac{\text{voltage}}{\text{pressure}} \right) \propto \frac{d_{31}}{\varepsilon_{33}}$$

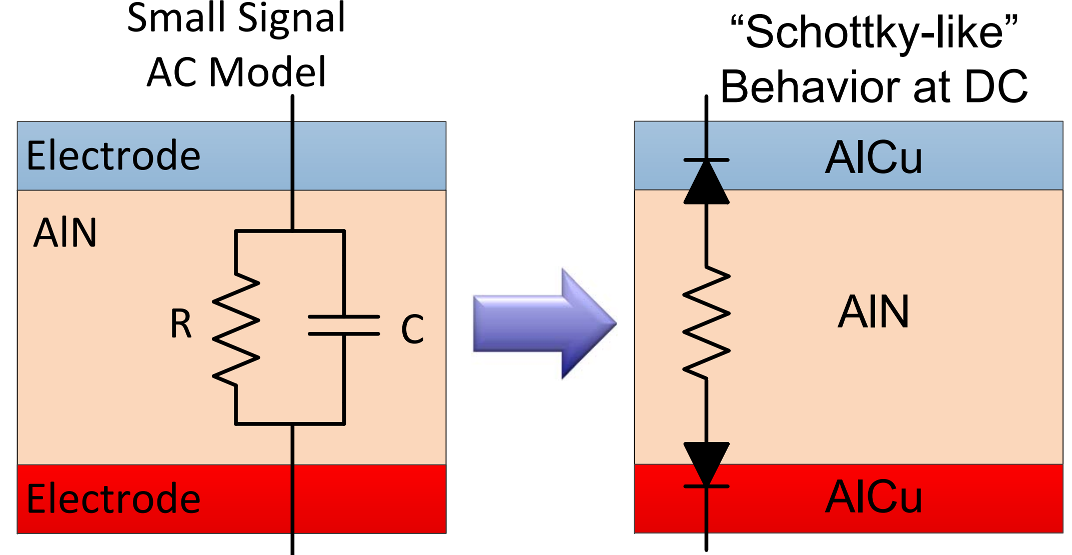
- Minimum Detectable Pressure
  - Open circuit pressure referred noise

$$p_{\min} \approx \sqrt{\int_{f_1}^{f_2} \frac{4k_B T}{(\omega d_A)^2 R_{EP}}}$$

AlN C_{EF} R_{EP}

Dielectric Leakage





- Small signal estimates
  - $R > 20\ teraOhms$
  - $f_{cutoff} = \frac{1}{2\pi RC} = 160\ \mu Hz$
- Quasi-DC possible at *mHz* frequencies?
  - 1 dB error after 2 minutes (7200 PLC)

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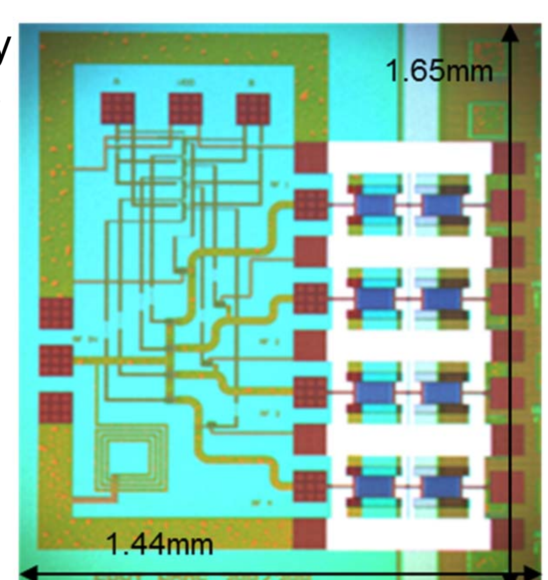
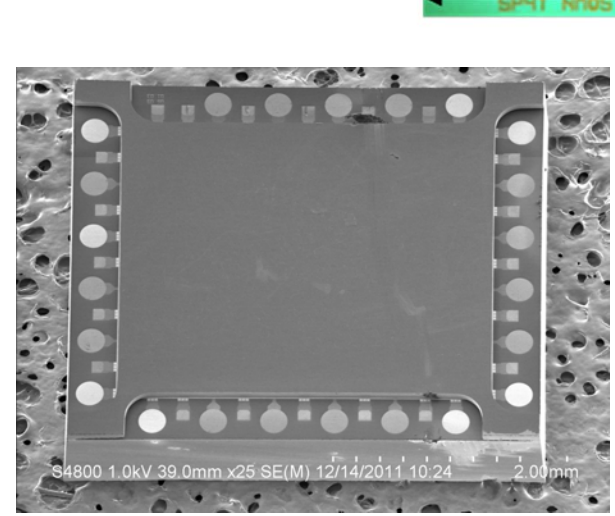
Switched Filter Array on CMOS



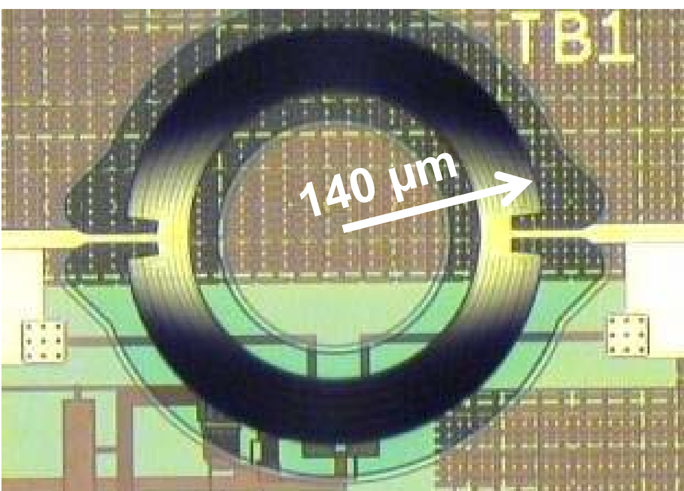


Wafer Level Packaged Microresonators

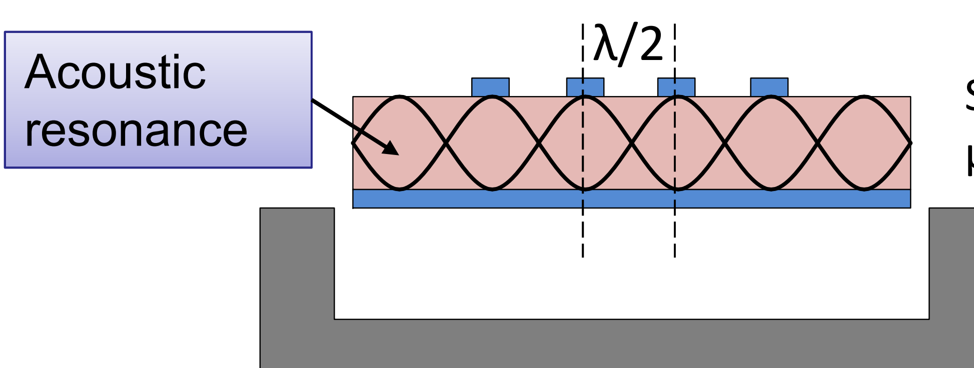
Aluminum Nitride Microresonators

- 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

2011 R&D100



µRes on CMOS



Suspended µRes plate

$$d_{31} = 2\,\text{pm/V}$$
$$k_{31}^2 = 2\%$$

Resonator Equivalent Circuit

Length Extensional Resonator

$\lambda/2$ = 180 μm

s4800 5.0kV 12.4mm x600 SE(M) 6/17/2013 11:40 50.0um

IN

C_0

OUT

Top electrode

Piezoelectric (AlN)

Bottom electrode

L_X M_A

C_X C_0

R_X R_A

$\phi : 1$

C_X = 1/stiffness

L_X = mass

$R_X \approx$ Damping + Electro-Acoustic Coupling

$C_0 \approx$ Self-Capacitance

Electrical Equivalent **ustic** **Coupling** **Electrical**

Resonator Figure-of-Merit

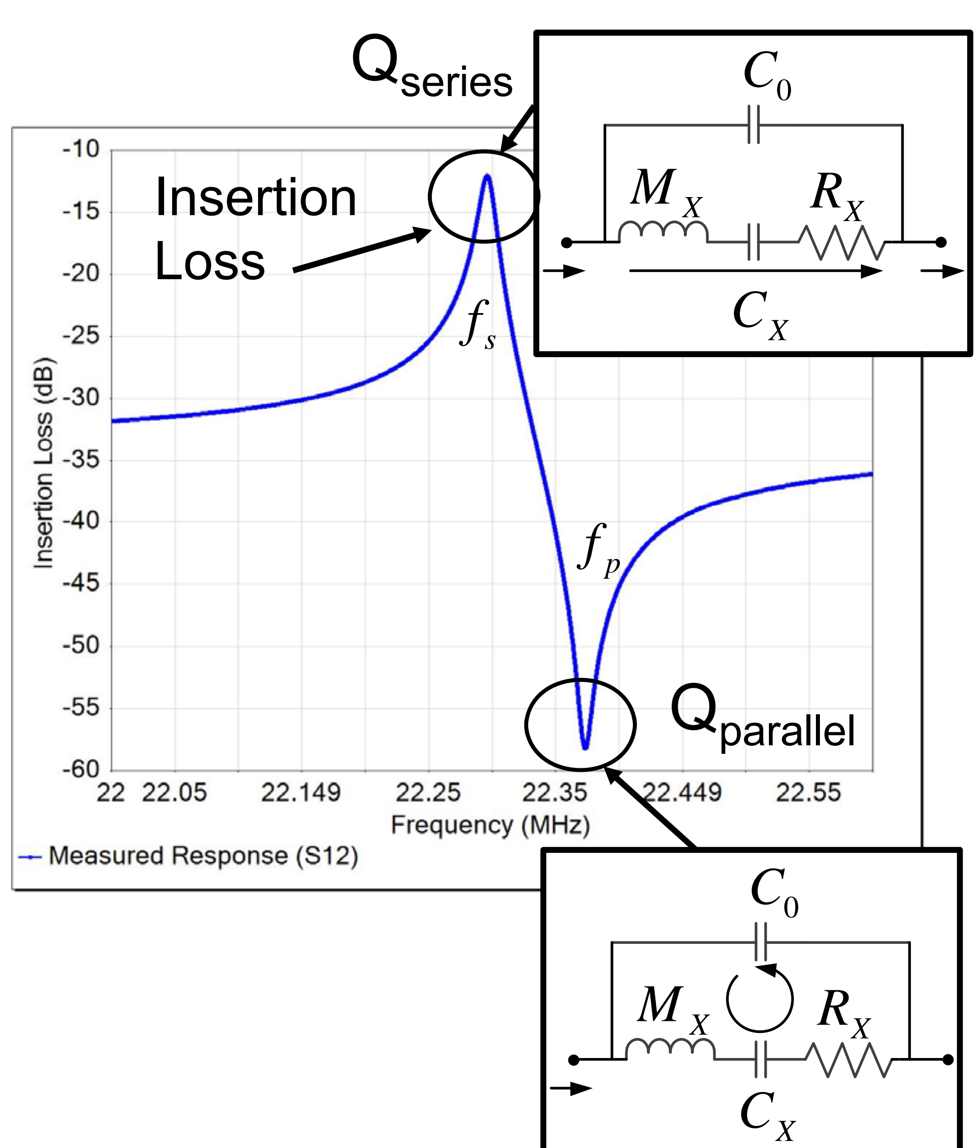
- Insertion Loss
  - Proportional to FOM

$$FOM = k_t^2 Q$$

- Tuning
  - Maximum tuning range is determined by k_t^2

$$k_t^2 = \frac{d_{31}^2}{\varepsilon_{33} s_{11}^E} \cong \frac{\pi^2}{4} \frac{f_p - f_s}{f_s}$$

- Bandwidth
  - Minimum practical filter BW
    - Determined by Q
  - Maximum practical filter BW
    - Determined by k_t^2



Coupling Coefficient Analogy

$$\frac{d^2}{\varepsilon_{33} s_{11}} \quad \left(\frac{d_{31}}{s_{11}^E}\right)\left(\frac{d_{31}}{\varepsilon_{33}}\right)$$

Sensor FOM

Example: IDT Microresonator

Input » Actuator

Output » Sensor

Actuator FOM

C_p

$$\left(\frac{d_{31}}{s_{11}^E}\right)$$

IN

OUT

C_o

C_o

GND

$$\left(\frac{d_{31}}{\varepsilon_{33}}\right)$$

Top electrode Bottom electrode Piezoelectric Film (AlN)

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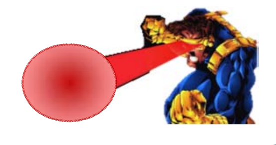


XMEMS: MEMS for Extreme Environments

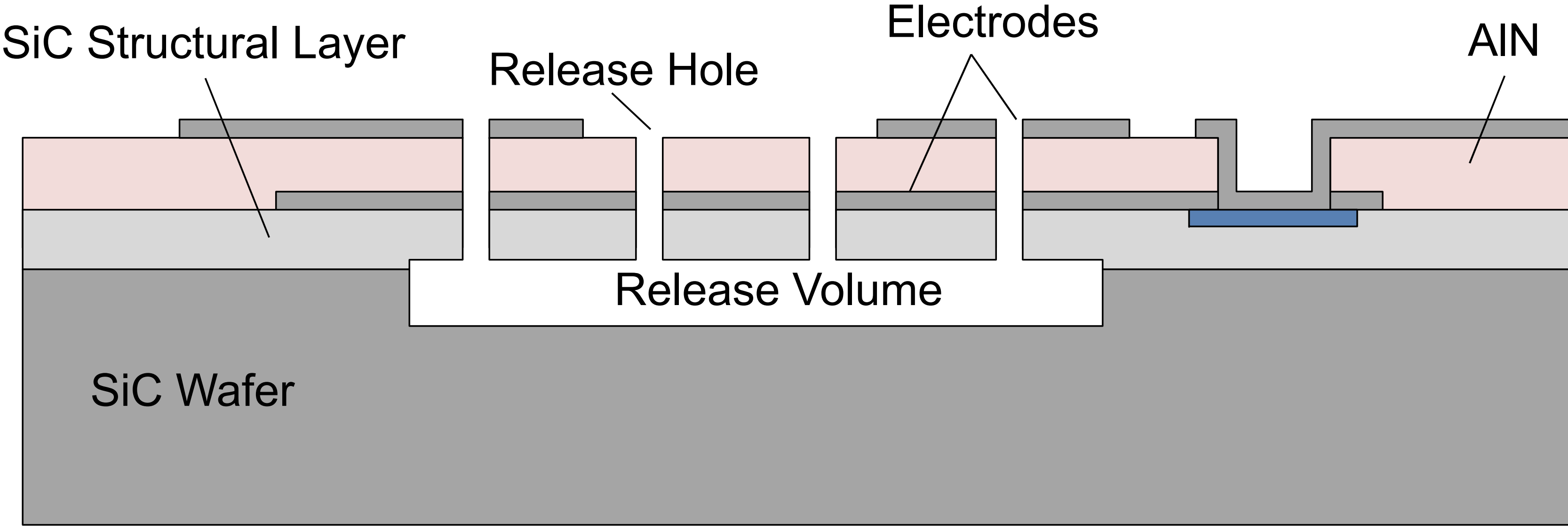
- Objective: develop material set to enable development of extreme temperature capable transducers
- Applications for transducers that can withstand extreme temperatures
  - Gas turbines (1250˚C)
  - Hypersonic flight research (755˚C)
  - Automotive engines (300-1000˚C)
  - Nuclear power plant (300˚C)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

*

*grc.nasa.gov

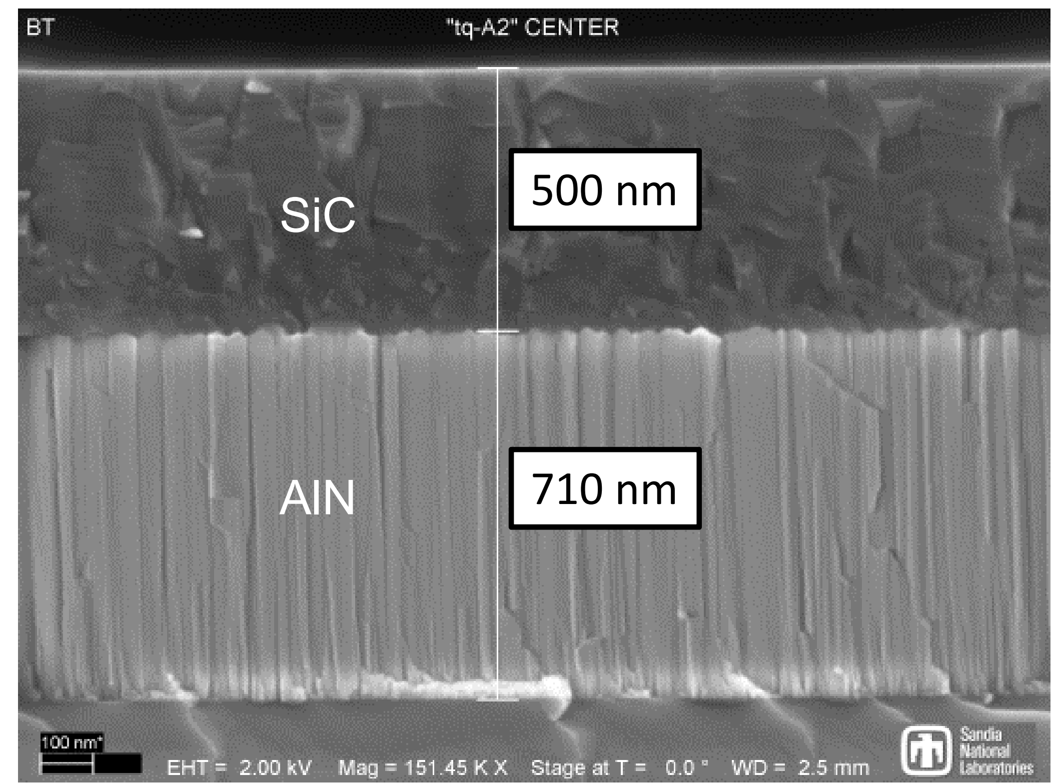
Proposed Technology

- 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 SiC
  - 850-950˚C
  - Pressure ~250 mTorr
  - Stress controlled by varying gas flow rates of the SiH_2Cl_2 (DCS) and $C_2H_2Cl_2$ (DCE)
  - Mainly hexagonal 6H-SIC
  - Surface roughness ~50 nm



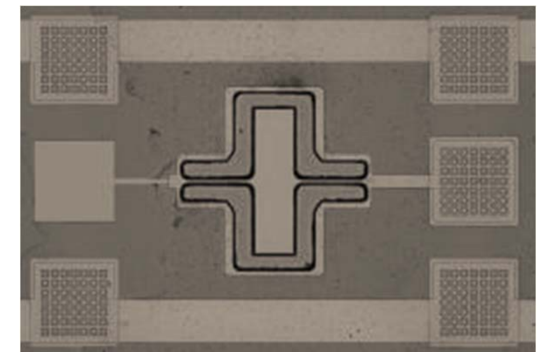
Devices Fabricated

Ultrasonic Transducers

Phononic Crystals

Annealing Results - Microresonator

- Rapid thermal anneals
- Device survives and operates post 935˚C anneal
- Maximum frequency shift is less than 3%



C_0
R_{series} M_X R_X
C_X

Transmission (dB)
Frequency (MHz)
-25 -30 -35 -40 -45 -50 -55
31 31.2 31.4 31.6 31.8

No Anneal
400˚C
500˚C
750˚C

Transmission (dB)
Frequency (MHz)
-25 -30 -35 -40 -45 -50
31.3 31.4 31.5 31.6 31.7 31.8

No Anneal
750˚C
935˚C

C_0
R_{series} M_X R_X
C_X

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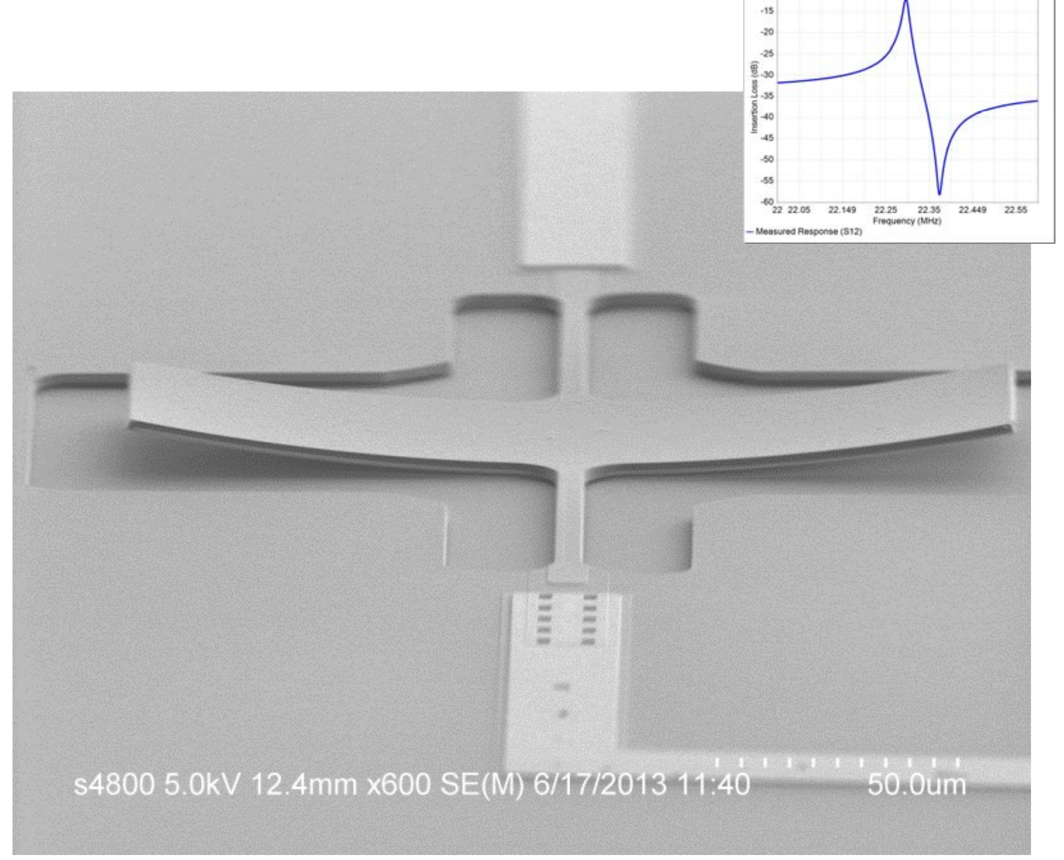
Device Integration Challenges

- Good film properties
- Interconnects
- Film Stress
- Etch with low sidewall angle
- Compatibility with metal electrodes
- Etch stops
- Etch selectivity



Example: AlN Film Quality

PCPLY004A-06 CENTER

100 nm*

EHT = 3.00 kV Mag = 99.64 K X Stage at T = 0.0 ° WD = 3.6 mm

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PC111501B-F1

100 nm*

EHT = 3.00 kV Mag = 100.42 K X Stage at T = 0.0 ° WD = 5.0 mm

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Example: Interconnects

BT
PCPLY005A-19 CENTER
Top Electrode
AlN
AlN
0.405µm
0.171µm
H 5 = 299.1 nm
H 4 = 4.023 µm
H 3 = 515.8 nm
s4800 3.0kV 7.3mm x25.0k SE(M) 8/6/2014 09:01
2.00um
Bottom Electrode
Bottom Electrode
H 6 = 1.805 µm
H 1 = 1.217 µm
W etch stop
1 µm*
EHT = 3.00 kV Mag = 28.40 K X Stage at T = 0.0 ° WD = 2.9 mm
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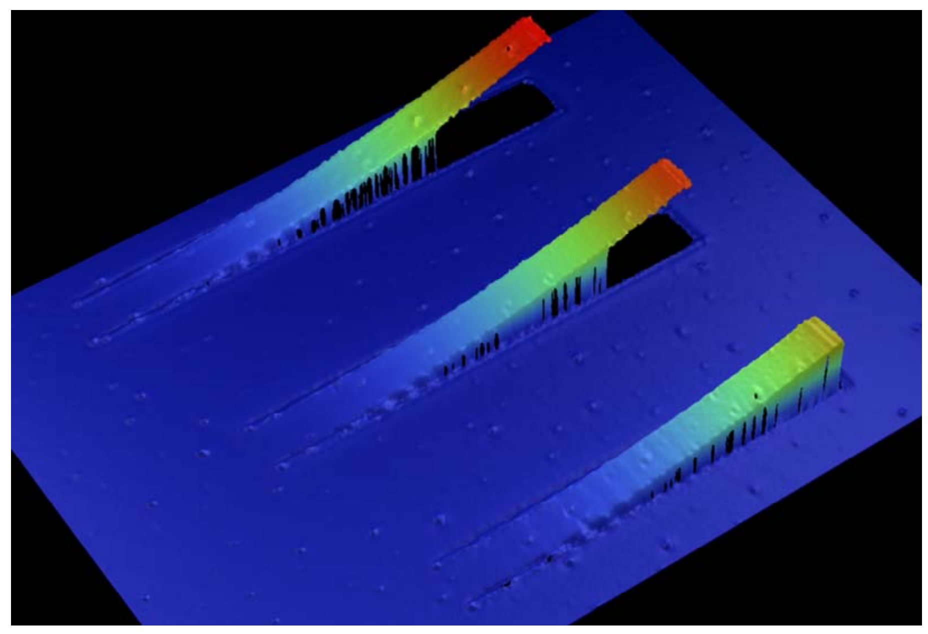
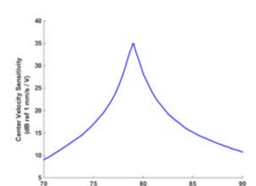
Film Stress

- Shifts performance and lowers yield
- Stress uniformity across wafer needs improvement (<±50 MPa)
- Accurate local device stress measurements are needed to improve modeling accuracy

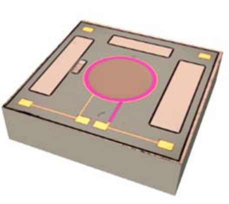


Summary

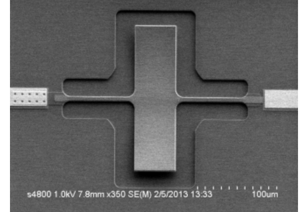
- **Actuator: PMUT**
  - $FOM = \frac{d_A}{c_{AD}}\left(\frac{\text{pressure}}{\text{voltage}}\right)$
  - Dielectric Strength



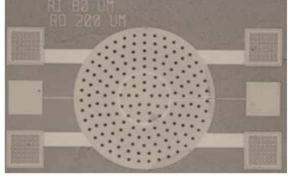
- Sensor: Microphone
  - $FOM = \frac{d_A}{c_{EF}}\left(\frac{\text{voltage}}{\text{pressure}}\right)$
  - Dielectric leakage



- Microresonator
  - $FOM = \frac{d_{31}^2}{\varepsilon_{33} s_{11}^E}$
  - Quality factor



- XMEMS
  - AlN temperature limit >1000˚C
  - SiC CTE is closely matched



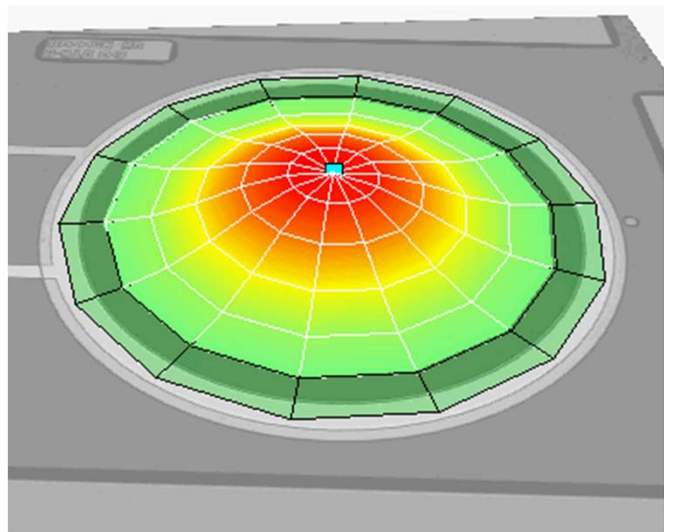
Sandia's AlN Team

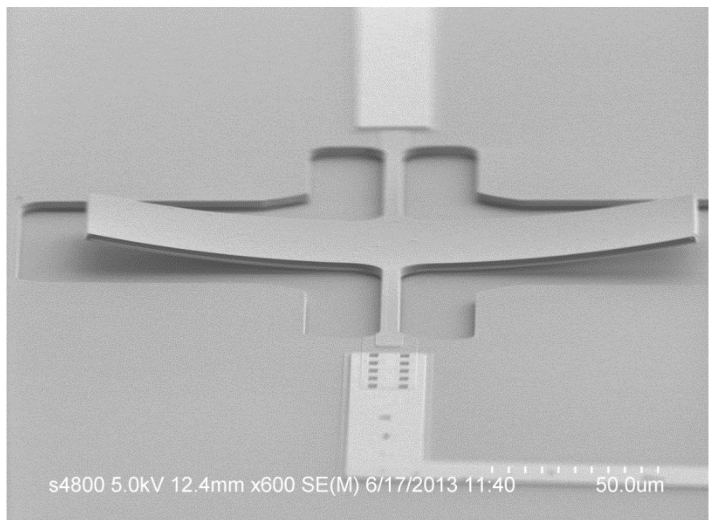
- Current: Ben Griffin, Chris Nordquist, Ken Wojciechowski, David Henry, Peggy Clews, Tammy Pluym, Jim Stevens, Travis Young, Matt Eichenfield, Ihab El-Kady, Charles Reinke, Emily Crispin, Chris Dyck, Todd Bauer, Katherine Knisely, Chris Berry, Jeremy Moore, Sukwon Choi, Sasha Summers, Kenneth Douglas, Alex Grine, Alex Hsia, Dan McClanahan, Adrian Schiess, Mark Balance, Ian Young

- Former: Troy Olsson, Bongsang Kim, James Fleming, Janet Nguyen, Melanie Tuck, Maryam Ziaei-Moayyed

Sponsors

LABORATORY DIRECTED RESEARCH & DEVELOPMENT





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Questions?