Aluminum Nitride Enabled MEMS for Near-Zero Power Wakeup and High Temperature Capable Sensing

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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

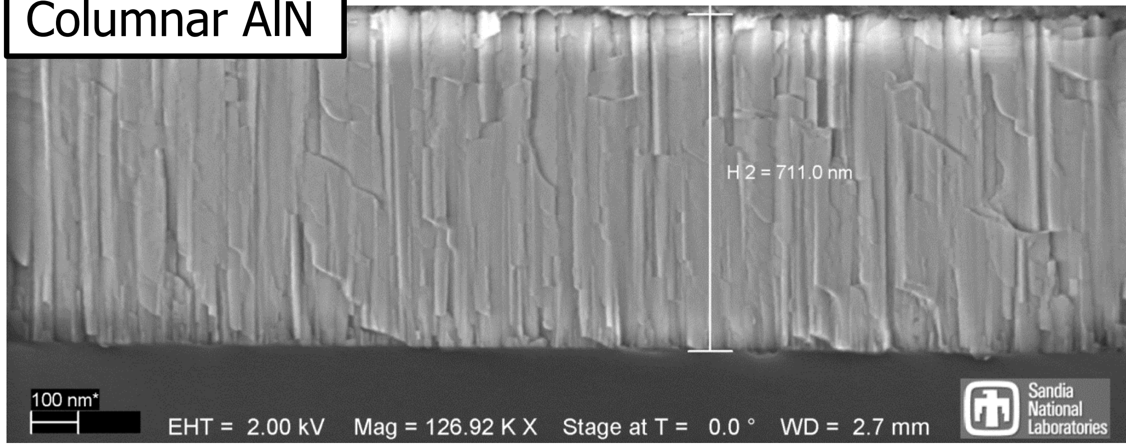
Large band-gap (6 eV)

High temperature capable

- Melting point of 2,200˚C
- Piezoelectric response has been measured at 1,150˚C

Property	**AlN**
Low permittivity, ε_{33}^{f}	10.3
High sensitivity, g_{31} (V/m / Pa)	0.030
High signal-to-noise ratio (√Pa)	21x10^{5}
Low loss tangent, $\tan\delta$	0.003
Parallel piezo coefficient, d_{33} (pm/V)	5.5
Transverse piezo coefficient, d_{31} (pm/V)	-2.7

Columnar AlN



Griffin, B. A., Nordquist, C. D., and Henry, M. D., "Beyond Aluminum Nitride: Piezoelectric Materials for RF MEMS Resonators," presentation at the *International Microwave Symposium*, Honolulu, Hawaii, June 4-9, 2017

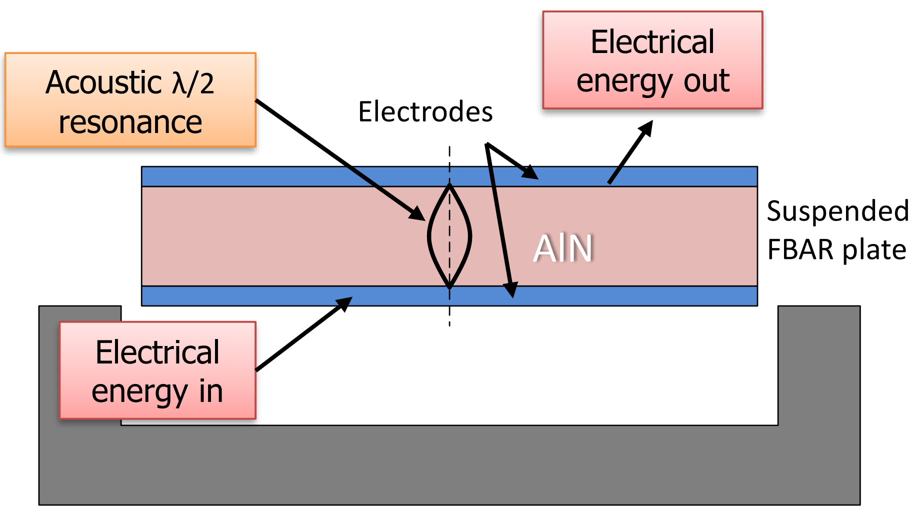
AlN Commercial Success

Bulk Acoustic Wave (BAW) Resonator Based Filters

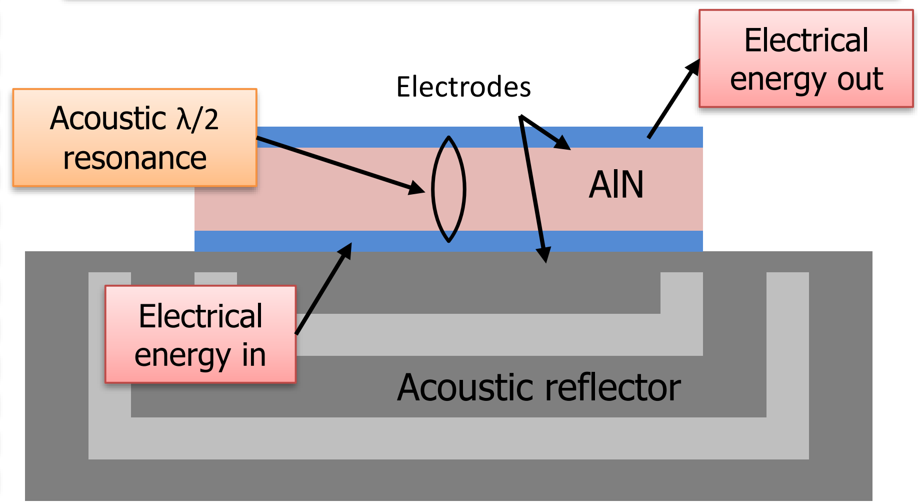
- Half-wavelength, thickness mode resonators
- Filter frequency is set by film thickness
- Commercial success for AlN MEMS
- Greater than 60 total RF filters in the modern smartphone*

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

Film Bulk Acoustic Resonator (FBAR)



Solidly Mounted Resonator (SMR)

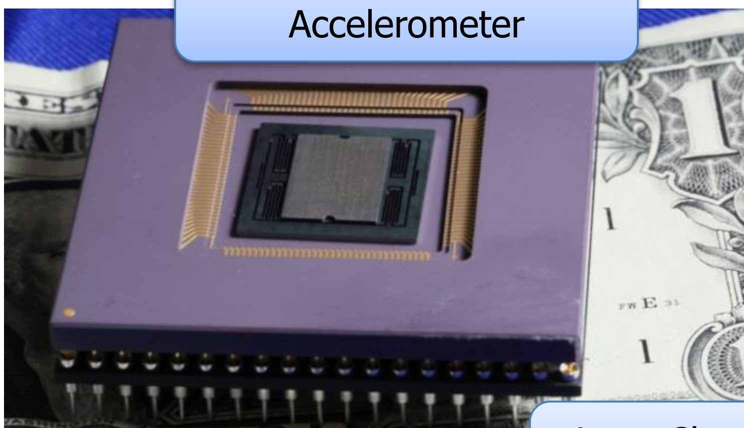


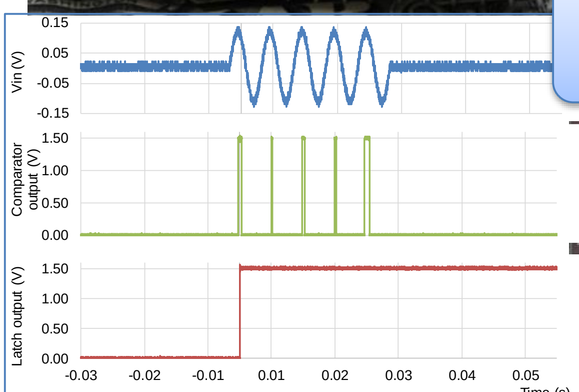
Volume market for AlN-based MEMS established by mobile platforms

New Applications for AlN

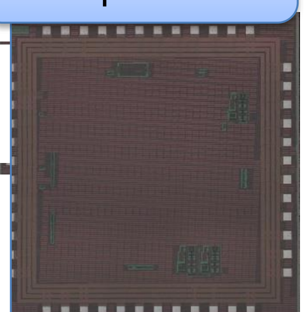
Near-Zero Power Wakeup System

Piezoelectric Resonant Accelerometer



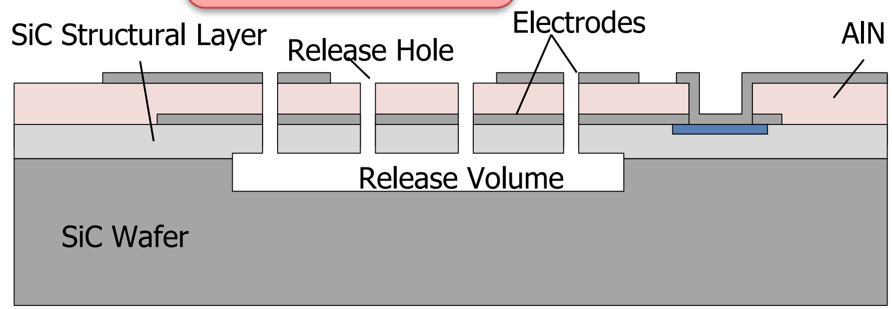


Long Channel 0.35 µm CMOS

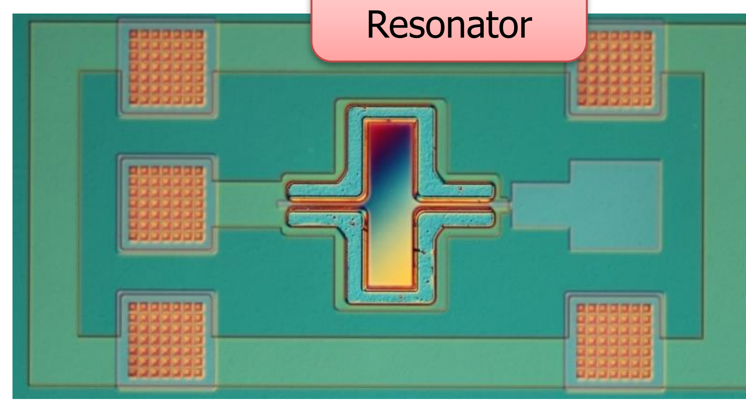


XMEMS: High Temperature Capable MEMS

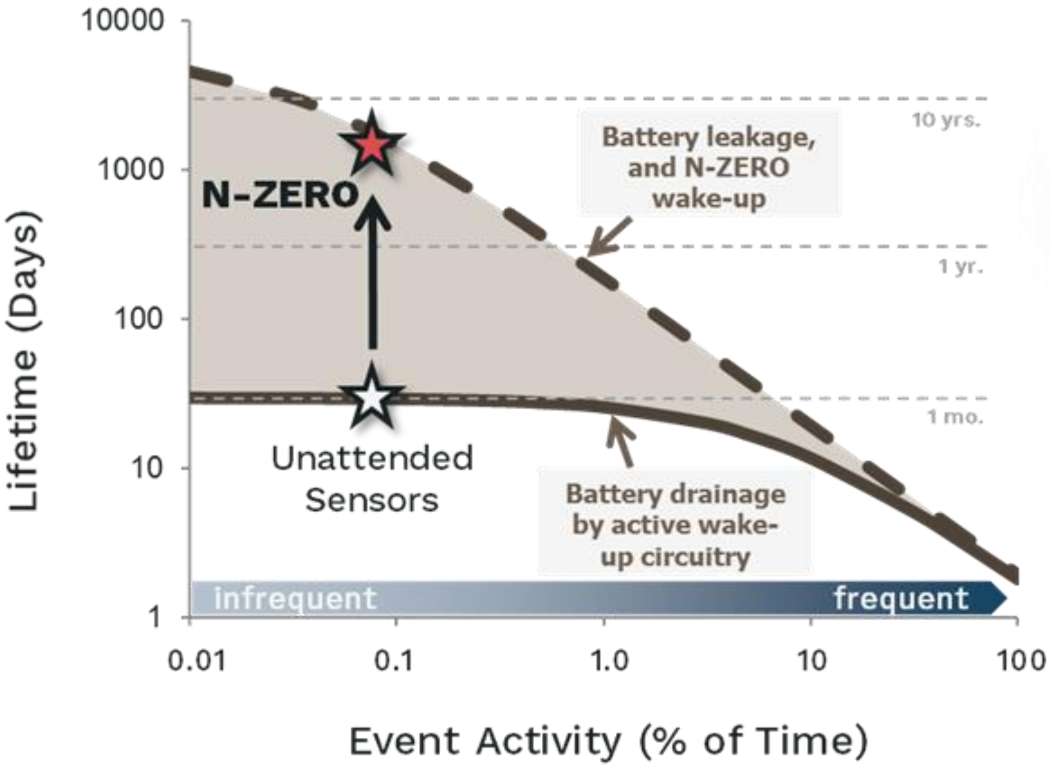
AlN/SiC-Based MEMS Process

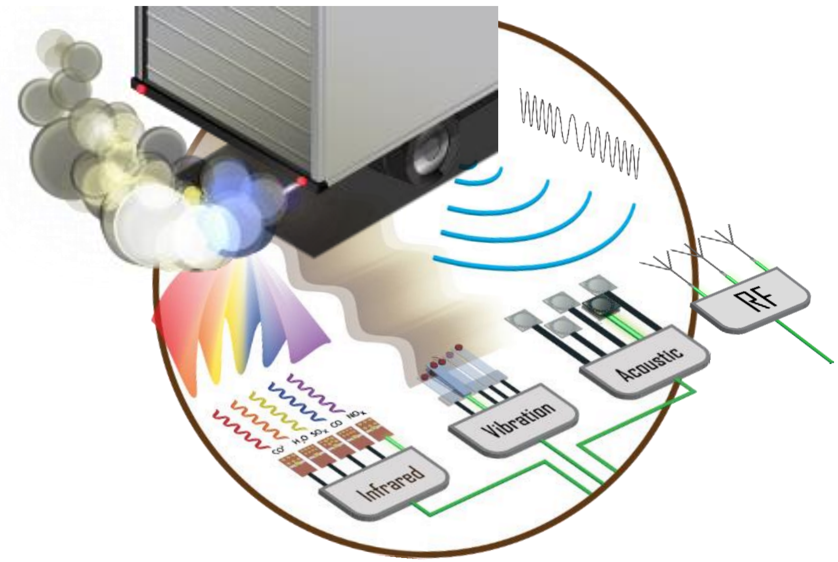


XMEMS RF Resonator



N-ZERO Vision: OFF but ALERT!

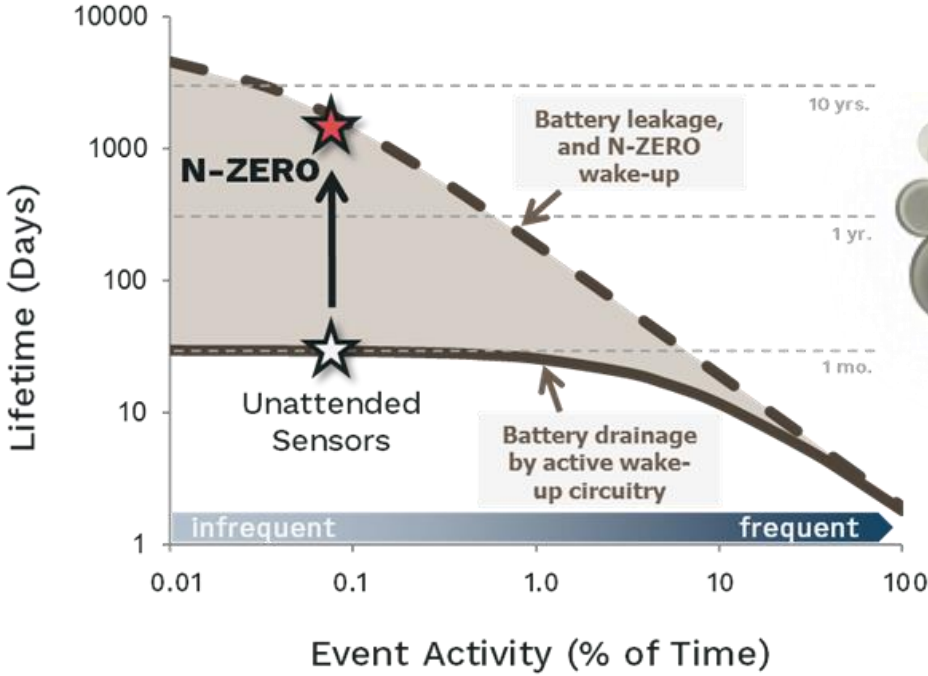


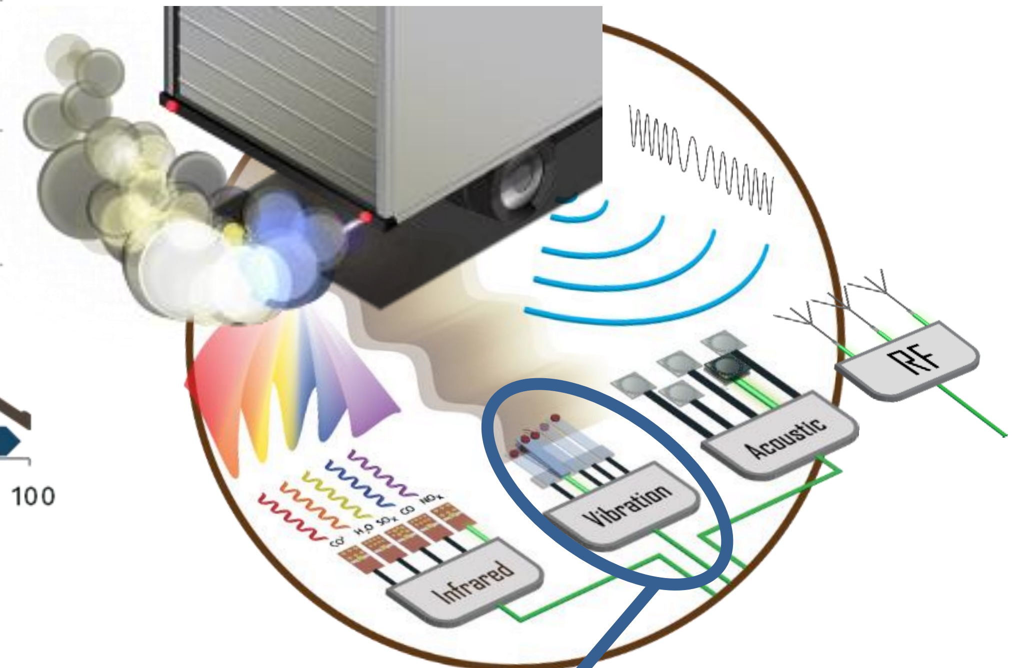


N-ZERO passive sensor wake-up:

- Continuous operation and near-zero power processing
- Persistent sensing with greatly extended lifetime and reduced cost

N-ZERO Vibration Solution





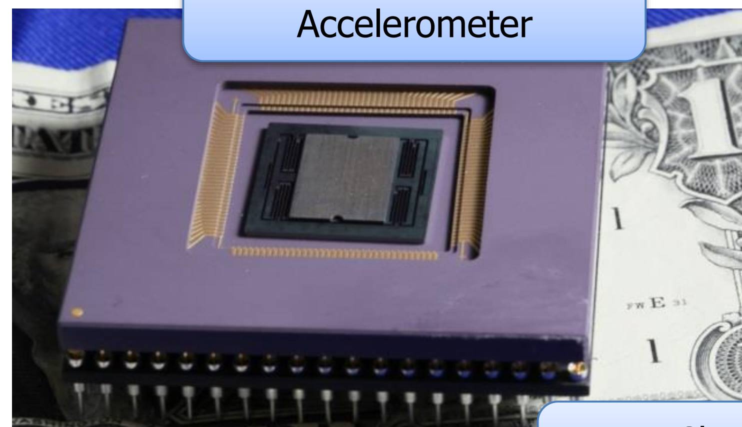
Piezoelectric MEMS combined with a subthreshold-CMOS ASIC offers a near-zero power solution

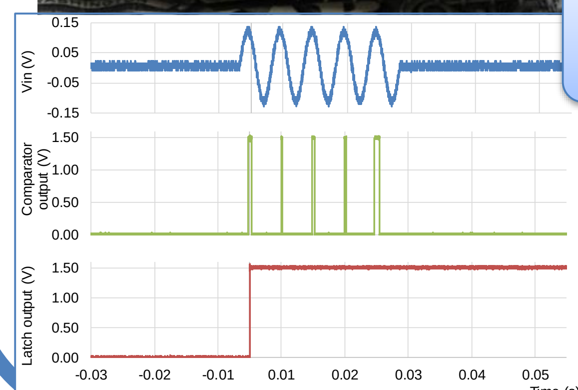
Near-Zero Power Vibration Based Classifier

- Piezoelectric materials require zero input power to provide an electrical output signal
- High-Q resonance enables passive filtering in the mechanical energy domain
- Aluminum nitride sensors integrated with very-low power subthreshold CMOS
- Dual channel wakeup requires 5.25 nW in alert mode; 6.75 nW after wakeup

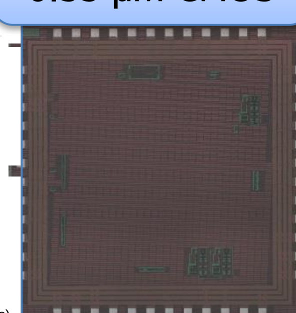
Near-Zero Power Wakeup System

Piezoelectric Resonant Accelerometer





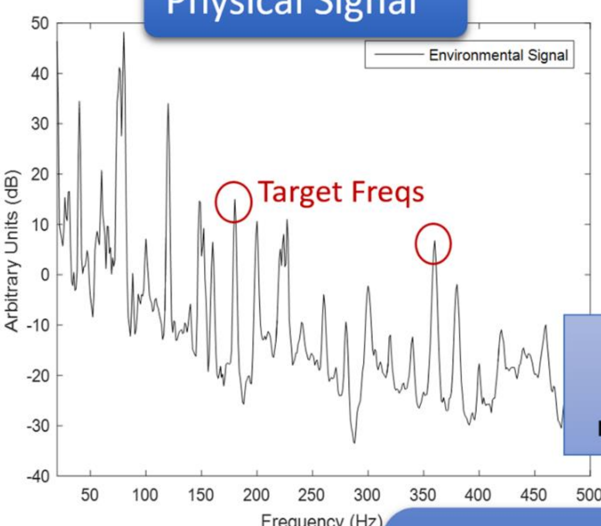
Long Channel 0.35 µm CMOS



Near-Zero Power Vibration Based Classifier

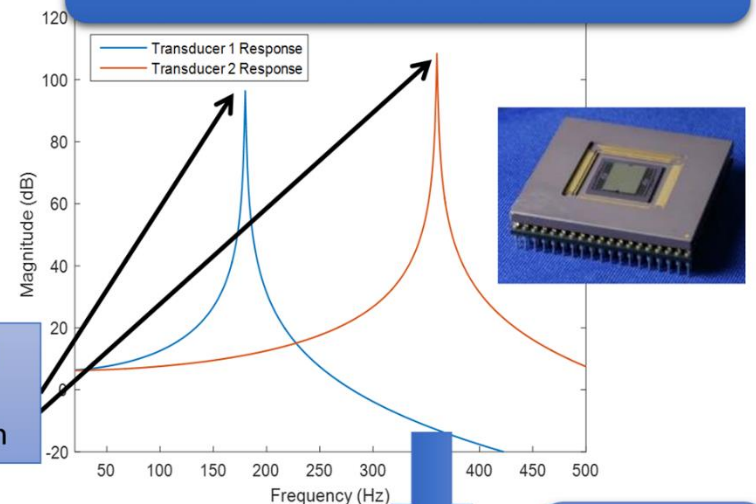
Generator Vibration Profile

Physical Signal



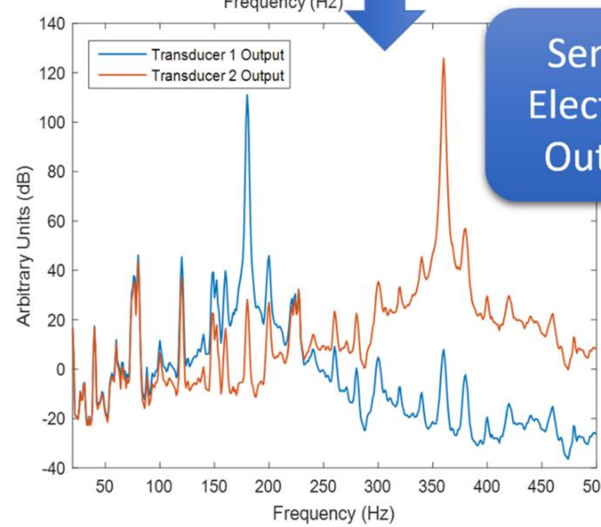
Zero power signal filtering in the mechanical domain

Passive, Piezoelectric, Frequency Selective Sensors

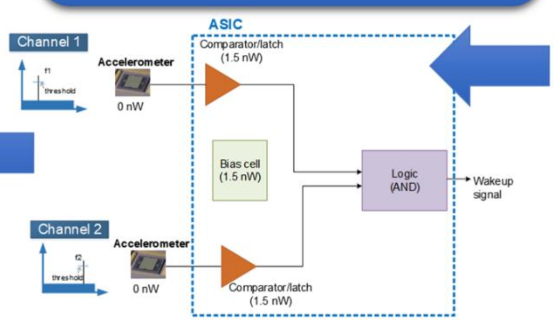


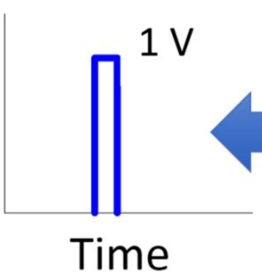
R. Reger et al., 2018 "Two-Channel Wakeup System Employing Aluminum Nitride Based MEMS Resonant Accelerometers for Near-Zero Power Applications", *Hilton Head Workshop 2018: A Solid-State Sensors, Actuators and Microsystems Workshop*, Hilton Head Island, June 3-7

Sensor Electrical Output



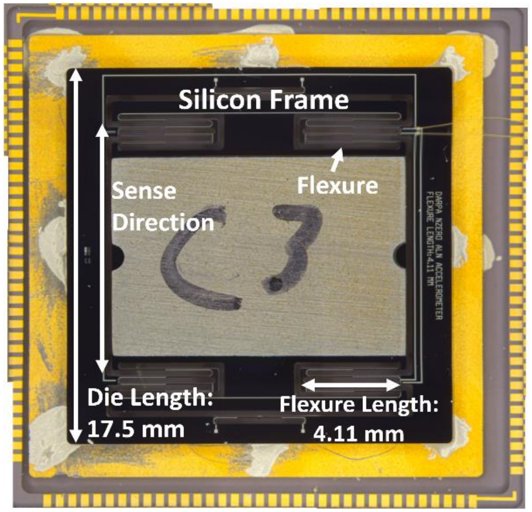
5.25 nW, dual-channel 0.35 µm CMOS comparator/latch

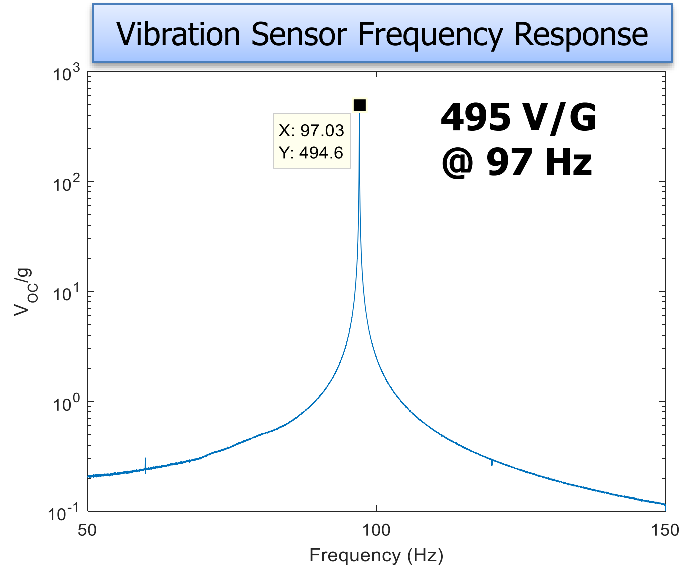




Wakeup Accelerometer

AlN Vibration Sensor with Trimmable Resonant Frequency





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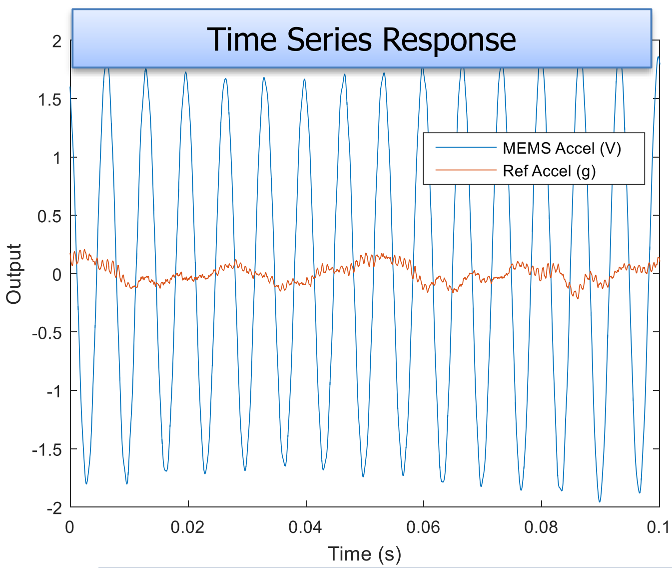

- Matched resonant frequency to target signature within 0.1%
- Demonstrated frequencies as low as 43 Hz

Sensor Performance of Nearly 500 V/G and Q > 12,500

Vibration Classifier Block Diagram

- ASIC fabricated in 0.35 µm, trench isolated SOI using long channel (1:10) transistors operating subthreshold
- Each ASIC contains two comparator/latch circuits followed by digital logic

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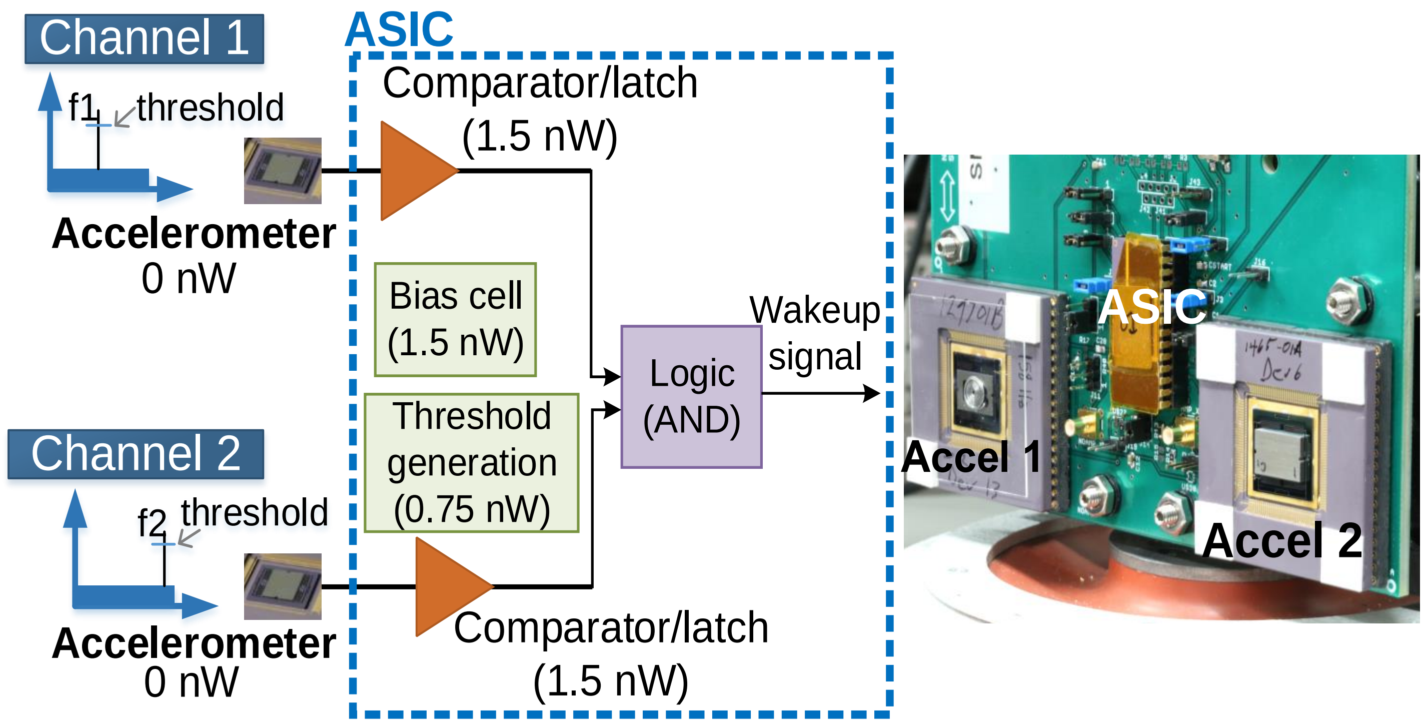
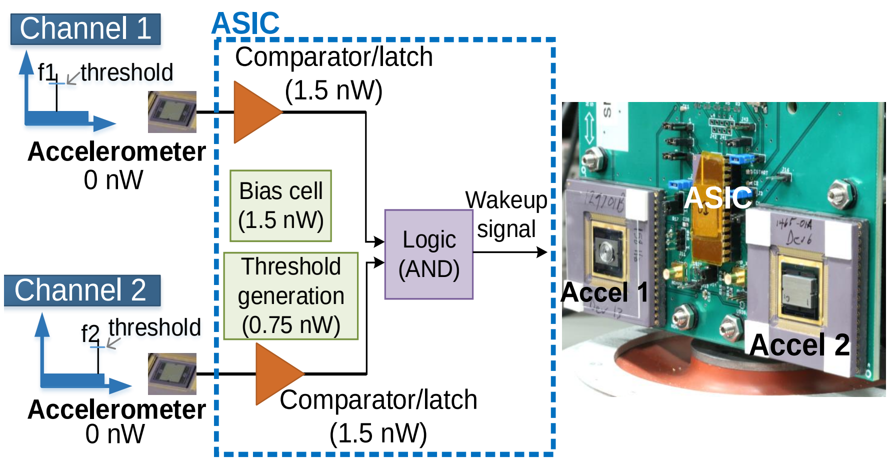


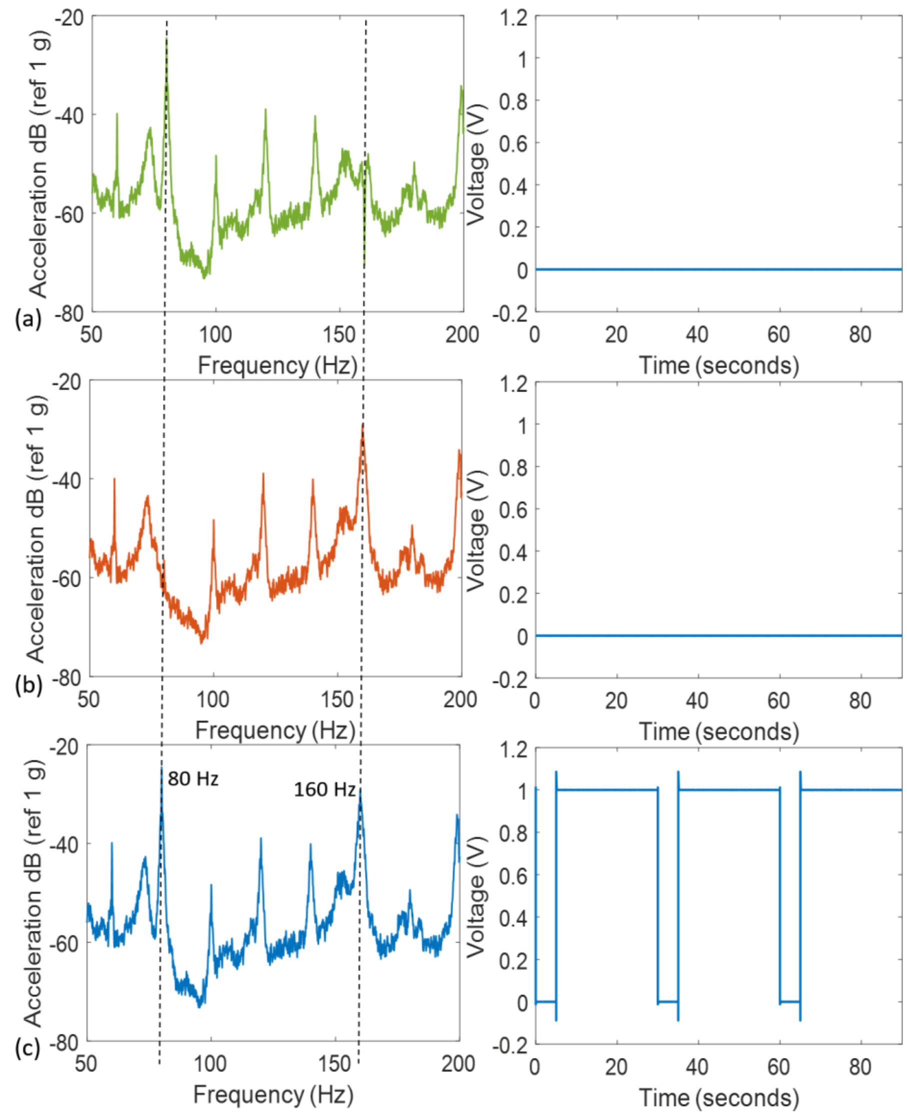
Additional Channels Add Additional Power Consumption of 2.5 nW/Channel

Near-Zero-Power Vibration Classifier Testing

2-Channel Vibration Sensor Microsystem



- **Field testing revealed 100% POD and 0% FA up to 0.18 m from generator**



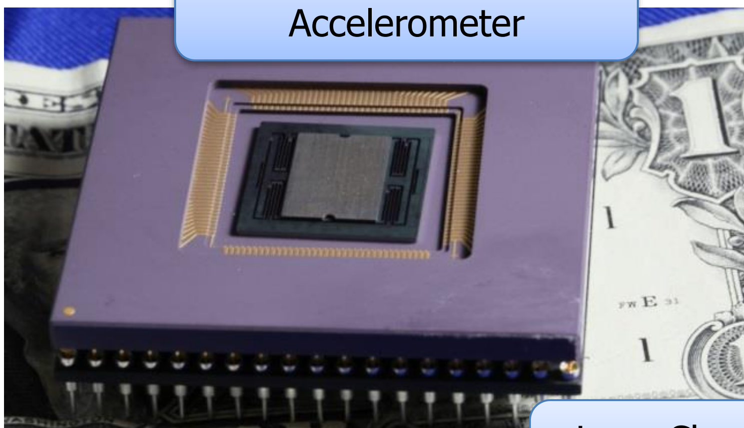
Microsystem Measured Performance

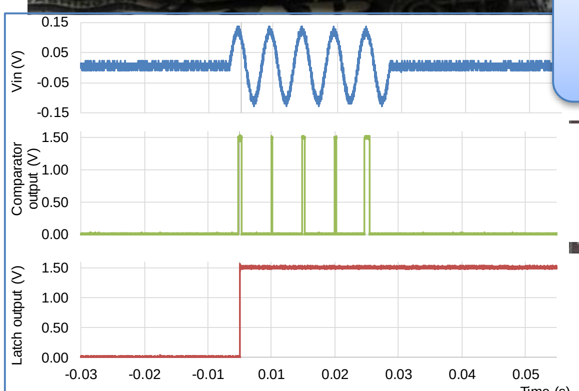
R. Reger et al., 2018 "Two-Channel Wakeup System Employing Aluminum Nitride Based MEMS Resonant Accelerometers for Near-Zero Power Applications", *Hilton Head Workshop 2018: A Solid-State Sensors, Actuators and Microsystems Workshop*, Hilton Head Island, June 3-7

New Applications for AlN

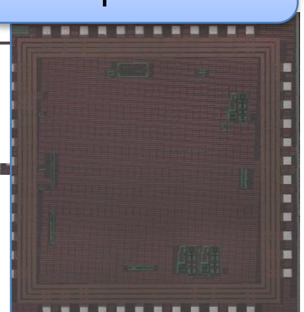
Near-Zero Power Wakeup System

Piezoelectric Resonant Accelerometer



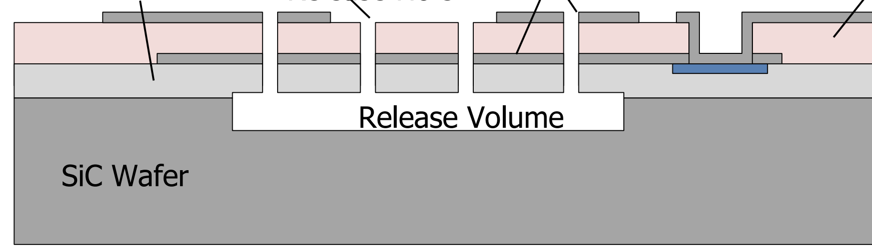


Long Channel 0.35 μm CMOS

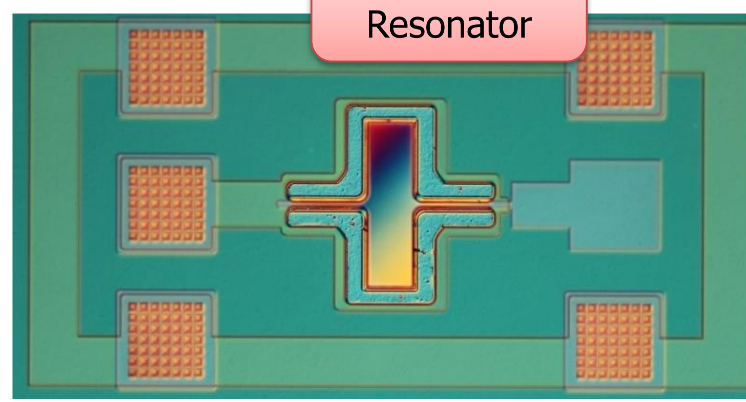


XMEMS: High Temperature Capable MEMS

AlN/SiC-Based MEMS Process

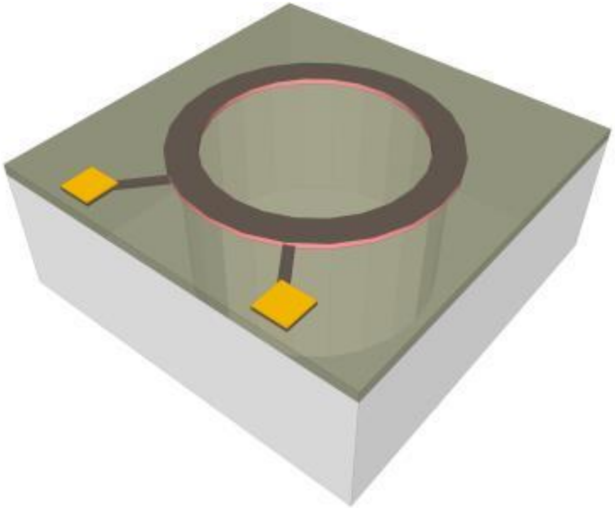


XMEMS RF Resonator



Sensor Systems for Extreme Environments

Objective: develop material set to enable extreme temperature capable transducers, control electronics, packaging solutions, wireless communication, etc.



Applications for sensor systems 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)

Griffin, B. A., Habermehl, S. D., and Clews, P. J., "XMEMS: An Aluminum Nitride and Silicon Carbide MEMS Process for High Temperature Capable Transducers," presentation at *Material Science & Technology: Advanced Materials for Harsh Environments*, Columbus, Ohio, October 4-8, 2015

Current Approach

Turbine Engines

- Approach: open loop operating conditions are set off peak-performance to allow margins of safety to prevent surge/stall
- Lack of knowledge of the hot zone increases development time
- Extracting overall potential performance gains out of a highly coupled system is a large task

- Limitations: conventional sensing technologies are non-options
  - Silicon based electronics < 250 °C
  - Cooling infrastructure incurs too much weight and cost
  - Connector failures lead to no fault found aircraft downtime

F22

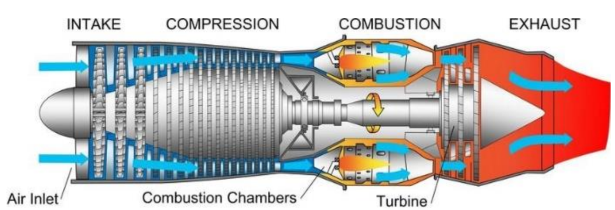
http://www.aero-news.net

Sensing in the hot zone will enable adaptive controls, shorter development cycles, and condition based maintenance for next generation turbine engines

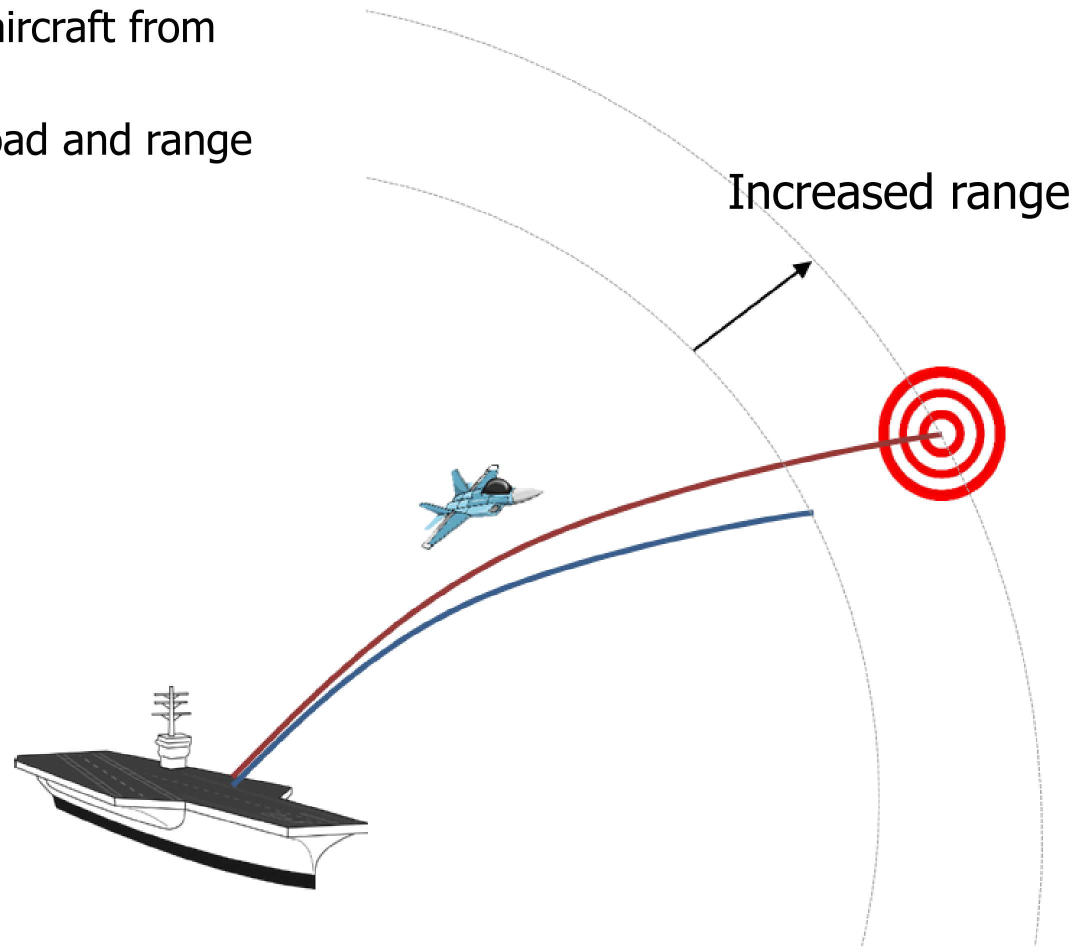
Impact on National Security

Turbine Engines

- Increased stand-off distance for aircraft from carriers and bases
- Tradeoff between increased payload and range
- Potential for higher prime power
- Dynamic performance
- Fuel savings



http://cset.mnsu.edu/engagethermo/components_gasturbine.html



Enable enhanced performance for future DoD systems

Wide Bandgap Approach

Wide band gap (WBG: SiC, GaN, etc.) and ultra-wide band gap (UWBG: AlGaN/AlN, Diamond, etc.) semiconductor and MEMS materials can survive and operate through high temperature environments enabling direct sensing in the hot zone

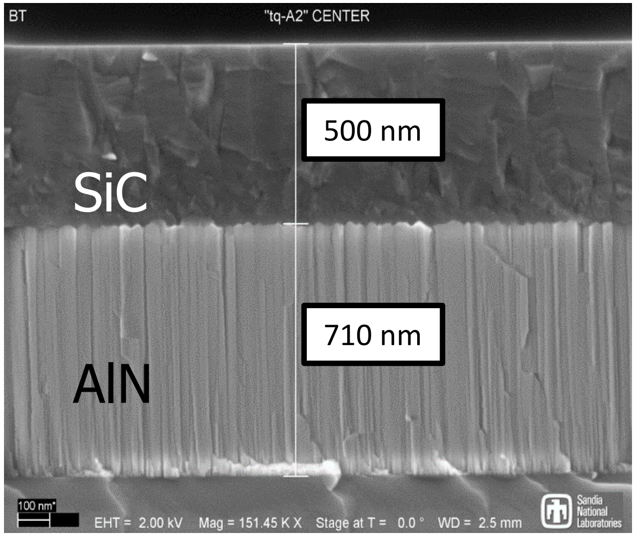
Conventional silicon (1.1 eV) electronics < 250˚C

WBG Silicon Carbide

- Material temperature limit > 2,500˚C (sublimates)
- Bandgap 3.3 eV (4H)
- Electronics temperature limit: ≥800˚C (demonstrated)

UWBG Aluminum Nitride

- Melting point of 2,200˚C
- Piezoelectric response measured at 1,150˚C
- Bandgap 6.0 eV
- Electronics temperature limit: ≥1000˚C (theoretical)



Griffin, B. A., et al., "Development of an aluminum nitride-silicon carbide material set for high-temperature sensor applications," *Proceedings SPIE*, Baltimore, MD, 6/5/2014

WBG and UWBG materials enable higher temperature capable MEMS and electronics

High Temperature Capable Material Set

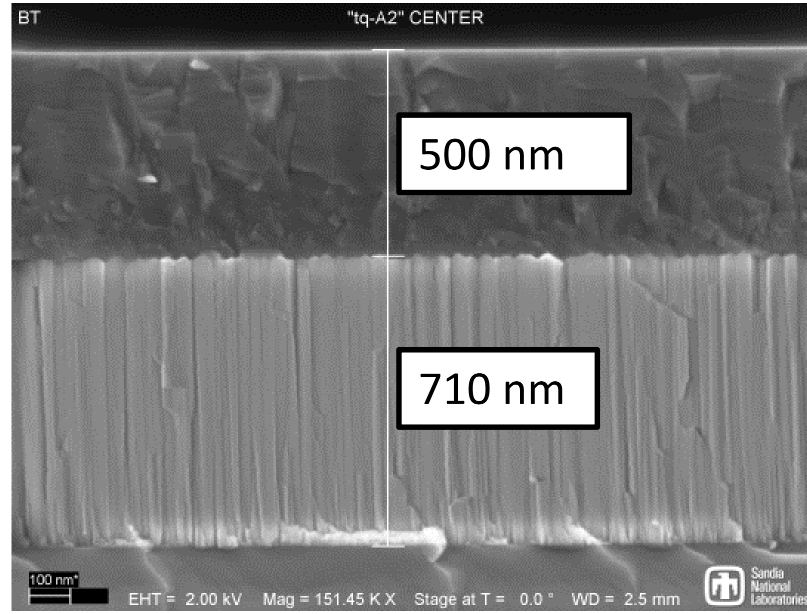
Aluminum nitride (AlN) piezoelectric thin film

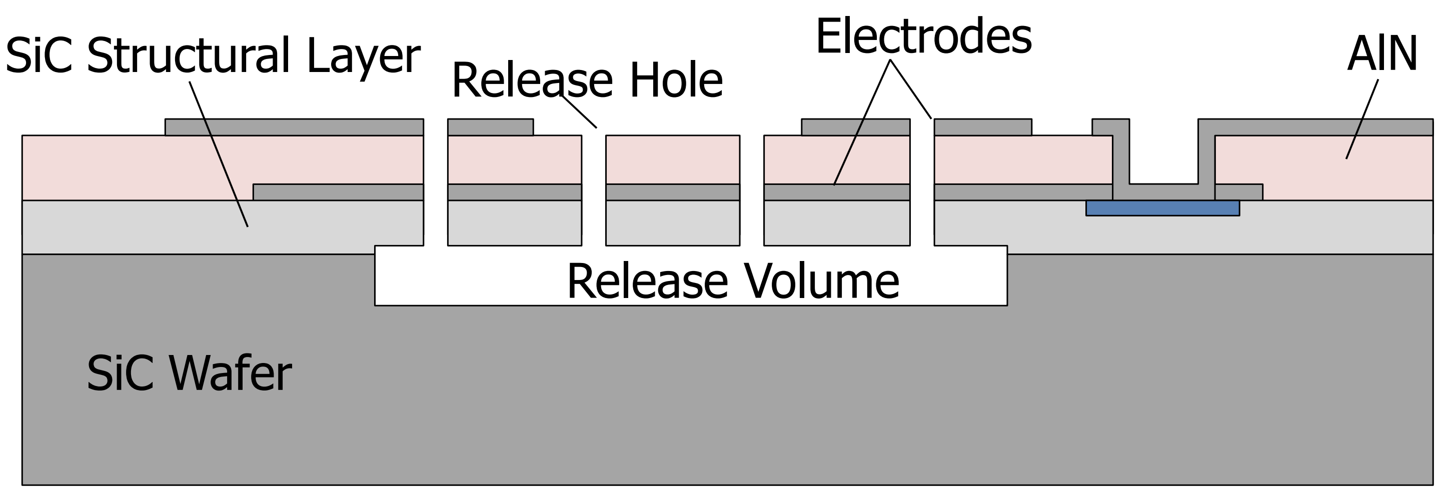
Silicon carbide (SiC) structural film and wafer

- Sublimates at >2500°C
- Coefficient of thermal expansion nearly matched to AlN

High temperature capable electrodes

- Titanium/Titanium nitride (Ti/TiN)
    - CMOS compatible





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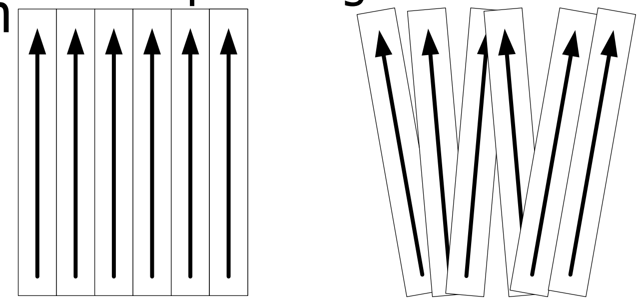
Annealed AlN Alignment

Anneal of AlN on titanium / titanium nitride bottom metal electrode at 950˚C for 3 hr

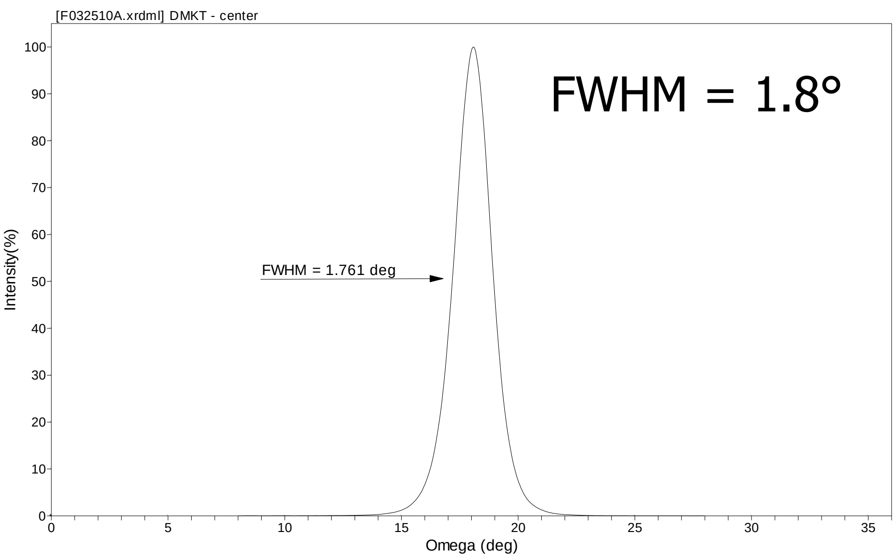
- X-Ray diffraction measurements to determine if AlN is still columnar
- In general, the goal is <2˚

Dipole Alignment

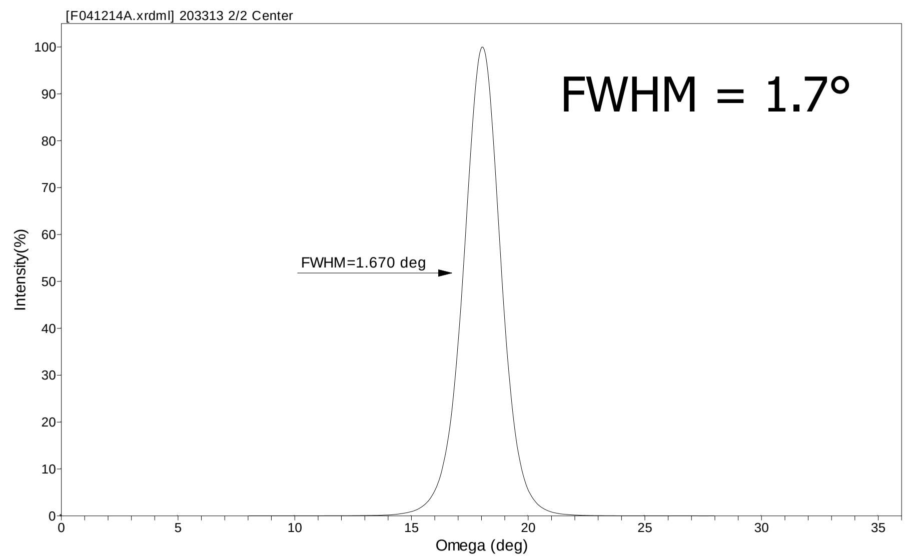


Ideal Reality

Before



After



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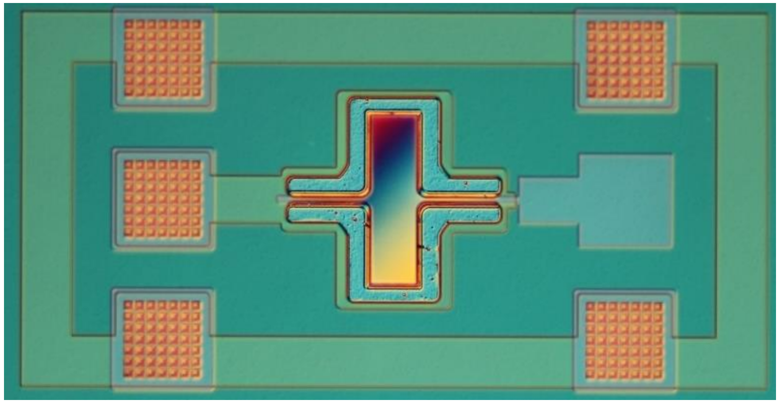
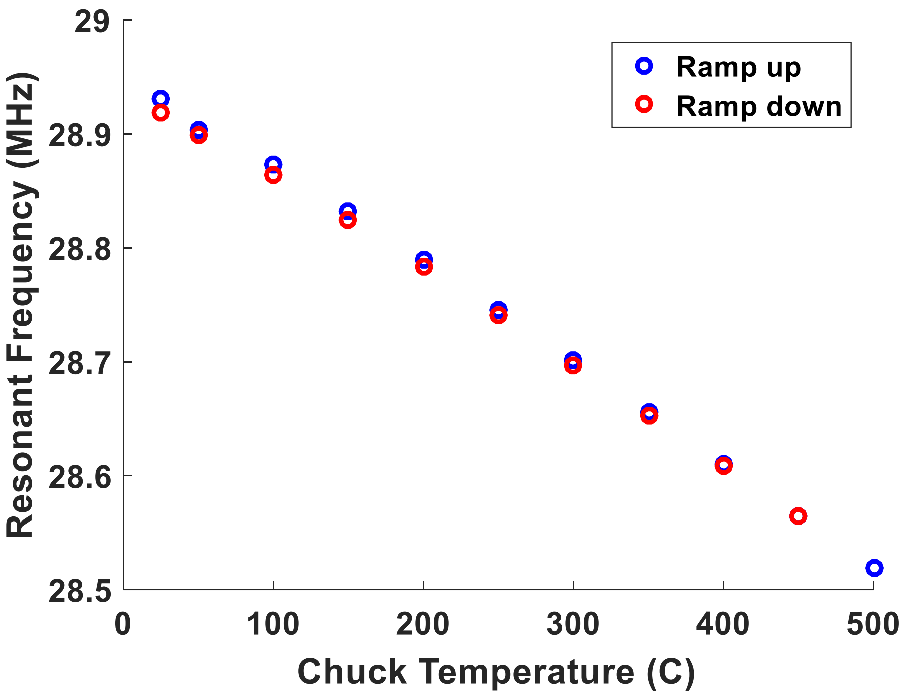
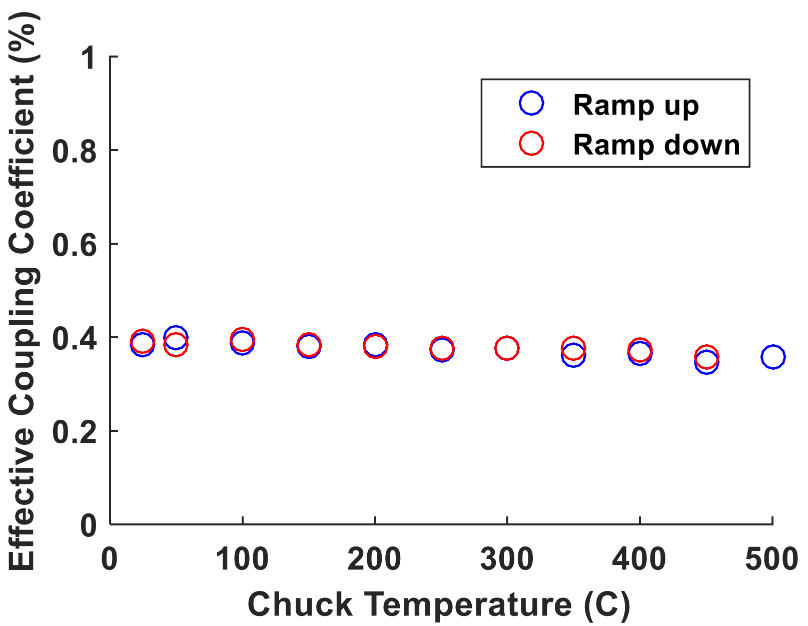
XMEMS Resonator

- Survived rapid thermal anneal at 935˚C, <1 Torr Argon, for 5 minutes before heated chuck testing in air
- Operation in air up to 500 ˚C







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Technical Challenges

Electronics/MEMS

- Large bandgap to minimize intrinsic doping concentration at temperature (E_g vs kT)
- Thermal stresses
- High quality metal contacts
- For III-Vs, reactions/oxidations
- Thermal leakage power

Packaging

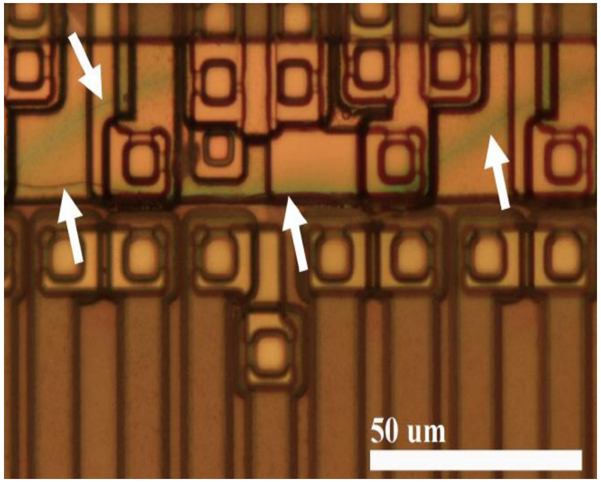
- Materials that can survive and operate through the high temperature environment

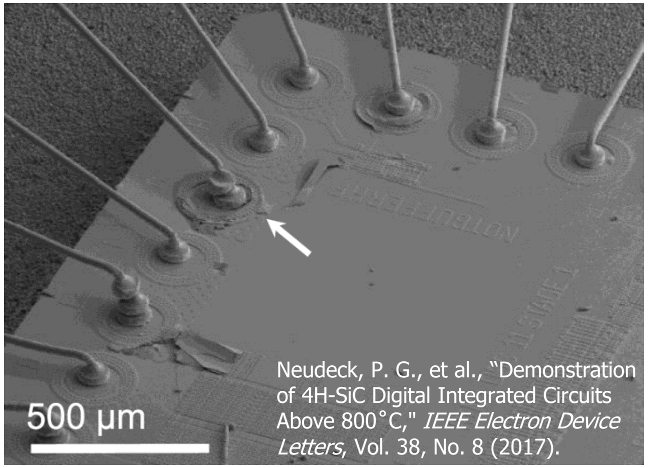
Communication

- Free-space: wireless RF or free-space optics
- Directed: multiplexed routing via optical or RF waveguides; ultrasonic communication

Power

- Powered via comms channel or harvest energy (i.e., thermal, vibration) from the environment

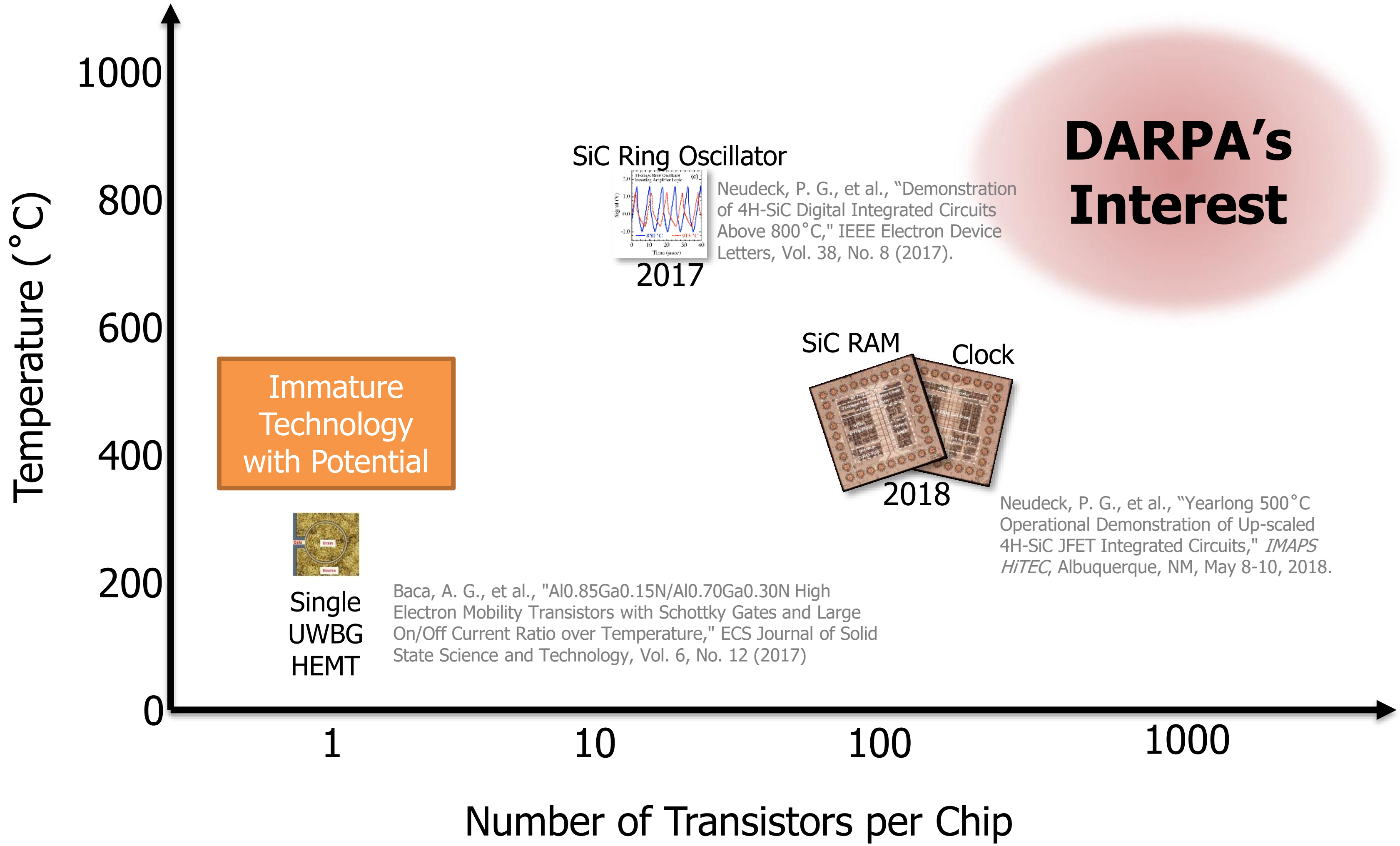




Neudeck, P. G., et al., "Demonstration of 4H-SiC Digital Integrated Circuits Above 800°C," *IEEE Electron Device Letters*, Vol. 38, No. 8 (2017).

Complete solutions must address challenges facing the entire sensing system

High Temperature Electronics Landscape



Demonstrate full-functioning sensor systems at high temperatures

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