Elevated Temperature Sensors For On-line Critical Equipment Health Monitoring

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University Coal Research Program

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Presentation Outline

- Project Motivation
- Sensor History
- Research to Date:
  - Candidate Substrate Selection
  - Advanced Piezoelectric Film Deposition
  - Piezoelectric Film Ultrasonic Results
  - High Temperature Coupling Research

Presentation Outline

- **Planned Research in Second Half:**
  - **High Temperature Coupling Experiments**
  - **Deposit and Test Additional Piezoelectric Films**
  - **Alternative Sensor Approaches**
  - **Packaging and Testing For Use Environment**
- **Summary**

Project Motivations

Elevated Temperature Sensor Needs:

- Coal-Fired Power Generation Equipment
  - Gasifier Refractories
  - TBC/ EBC Integrity Monitoring
  - On-line Water-wall Wastage Monitoring
- Complementary Industrial Needs:
  - Glass and Steel Refractory Monitoring
  - Turbine and Reciprocating Engines
  - Chemical and Petroleum Equipment
  - Nuclear Power Generation

Project Motivations

Gasifier Refractory Monitoring

- Sensors used to send and receive ultrasonic pulses into refractory.
- Pulse travel time indicates thickness.
- Embedded in refractory at critical locations or applied as needed for testing.
- May be multiplexed if permanently installed.
- Possible issues: scattering in refractory, coupling of ultrasound.

Project Motivations

Barrier Coating Monitoring

- Sensor transmits ultrasonic pulses into component.
- Ultrasonic pulse mode- longitudinal, shear, or surface waves- selected for application.
- Interaction with component materials and interfaces reflects or attenuates sound pulse before it is received.
- Useful for sensing cracks or delaminations.

Sensor History

- Piezoelectric properties of AlN were reported in the literature as early as 1976.
- In 1990 Dr. N.D. Patel (McMaster University) showed that AlN remained piezoelectric at temperatures exceeding 1150ºC for 24 hours.
- In 1994 UDRI demonstrated the use of AlN as part of a high temperature ultrasonic transducer in a project funded by the AFRL NDE Branch (>900ºC , 140 MPa pressure)
- UDRI patented the use of AlN in ultrasonic transducers. (US Patent #5,886,456)
- Experiments at UDRI have shown promise for using the AlN sensor core for a variety of high temperature sensors.

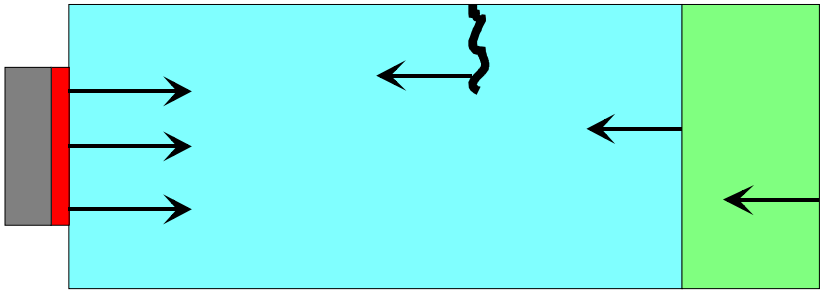
Sensor History: Piezoelectric AlN Properties

- Deposited as a ceramic film through a chemical vapor deposition process.
- Structurally piezoelectric- *not a poled material.*
- No known Curie point- AlN thought to remain intact until dissociation occurs near 2000°C.
- Useful film thickness is 10 to 100 microns.
- Physical and chemical properties are similar to those of aluminum oxide.
- Survives and operates under compressive stress exceeding 700 MPa (100 ksi).

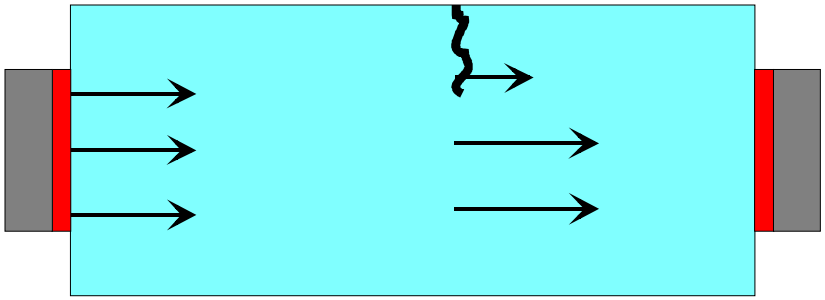
Sensor History: AlN Sensor Core

- AlN film deposited on conductive substrate of appropriate shape.
- Substrate acts as an electrode and structurally supports film.
- A second electrode is required:
  - -Press against metal part.
  - -Apply a conductive coating.
- Electrical shielding is necessary for optimal performance.

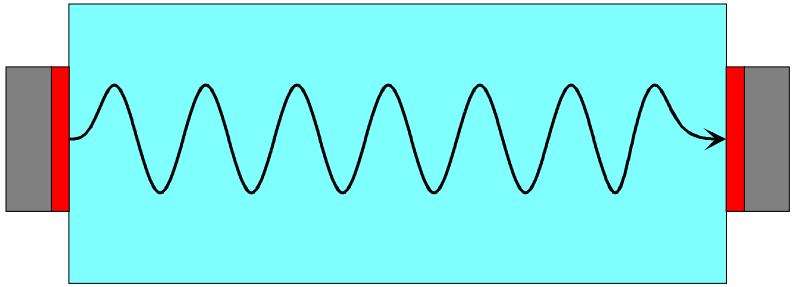
Ultrasonic Sensor Operation



Pulse-Echo



Pitch-Catch



Toneburst or
Continuous Wave

Completed Research:
Candidate Substrate Selection

- >1000°C use temperature required for novel sensor.
- Substrate must be electrically conductive.
- Good acoustic impedance match desired for increased transducer bandwidth.
- Substrate machinability is desirable.
- Deposition on in-service components is also desirable.

Completed Research:
Candidate Substrate Selection

	Aluminum Nitride	Tungsten carbide/ 6% cobalt cermet
Acoustic	ρ = 3.3 g/cm^3	ρ = 15 g/cm^3
	E = 310 GPa	E = 630 GPa
	c = 10.4 mm/μs	c = 7.2 mm/μs
	Z = 3.4 kg/(mm^2•s)	Z = 10.7 kg/(mm^2•s)
Thermal	α = 4.2-5.3 E-6/K	α = 5 E-6/K
Electrical	ρ ~ 10^{13} Ω•cm	ρ ~ 10^{-6} Ω•cm
Max Use	>1000° C	~750° C

Completed Research:
Candidate Substrate Selection

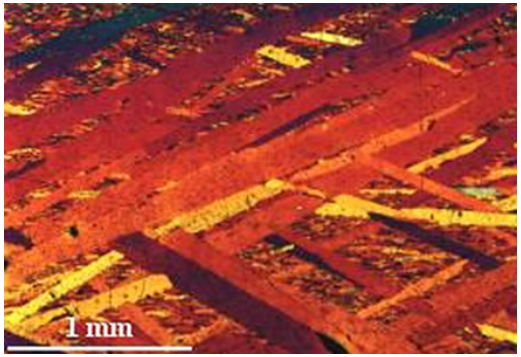
	Aluminum Nitride	Titanium
Acoustic	ρ = 3.3 g/cm^3	ρ = 4.5 g/cm^3
	E = 310 GPa	E = 115 GPa
	c = 10.4 mm/μs	c = 6.1 mm/μs
	Z = 3.4 kg/(mm^2•s)	Z = 2.8 kg/(mm^2•s)
Thermal	α = 4.2-5.3 E-6/K	α = 9 E-6/K
Electrical	ρ ~ 10^{13} Ω•cm	ρ ~ 10^{-5} Ω•cm
Max Use	>1000º C	720º C anneal

Completed Research:
Candidate Substrate Selection

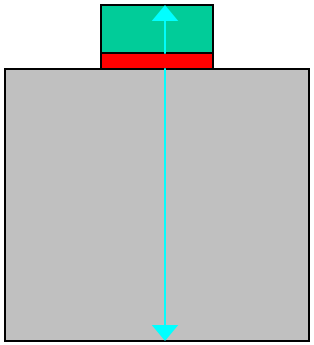
	Aluminum Nitride	Silicon Carbide
Acoustic	ρ = 3.3 g/cm^3	ρ = 3.1 g/cm^3
	E = 310 GPa	E = 410 GPa
	c = 10.4 mm/μs	c = 12.2 mm/μs
	Z = 3.4 kg/(mm^2•s)	Z = 3.8 kg/(mm^2•s)
Thermal	α = 4.2-5.3 E-6/K	α = 4.6 E-6/K
Electrical	ρ ~ 10^{13} Ω•cm	ρ ~ 10^{-2}-10^{6} Ω•cm
Max Use	>1000º C	~1600º C

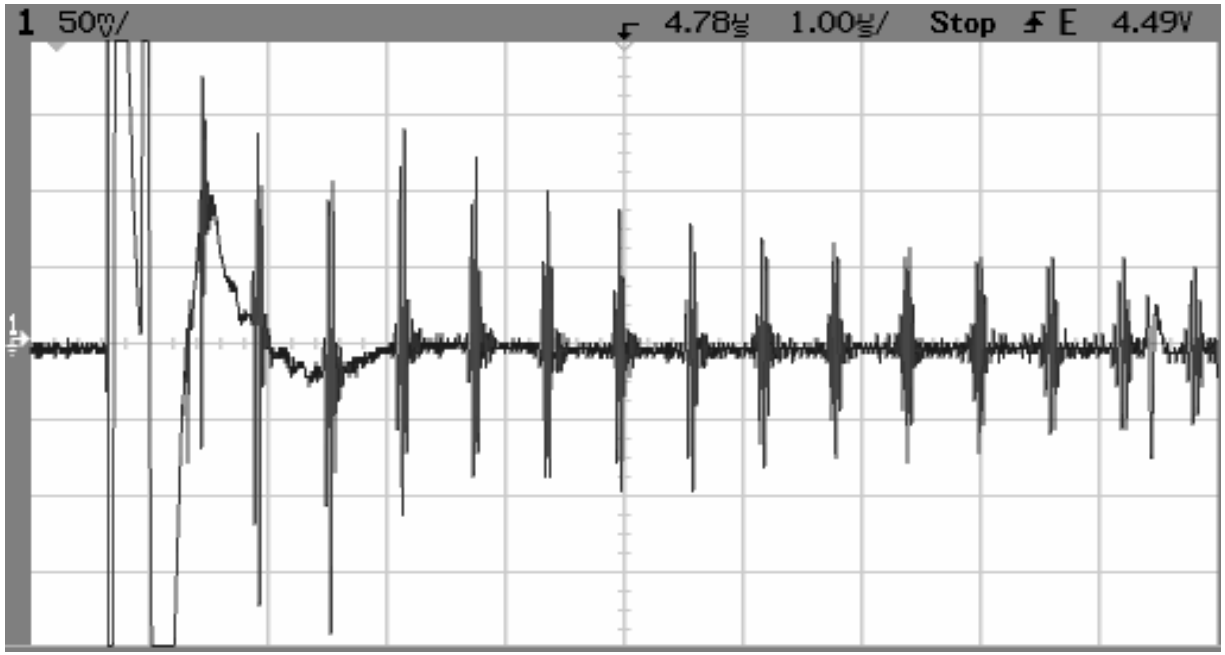
Completed Research:
Candidate Substrate Selection

- **Refractory Metals: W, Re, Mo, Ta**
  - **Oxidation, cost, and impedance issues.**
- **Conductive Ceramics:**
  - **$MoSi_2$: Thermal expansion of 7-8 vs. 5.6 for AlN.**
  - **TiB_2, TiC: Likely oxidation above 800 º C.**
- **Novel Materials:**
  - **Ti_3SiC_2: Cost issues, questionable CTE.**
  - **Conductive AlN: Investigating possible source.**



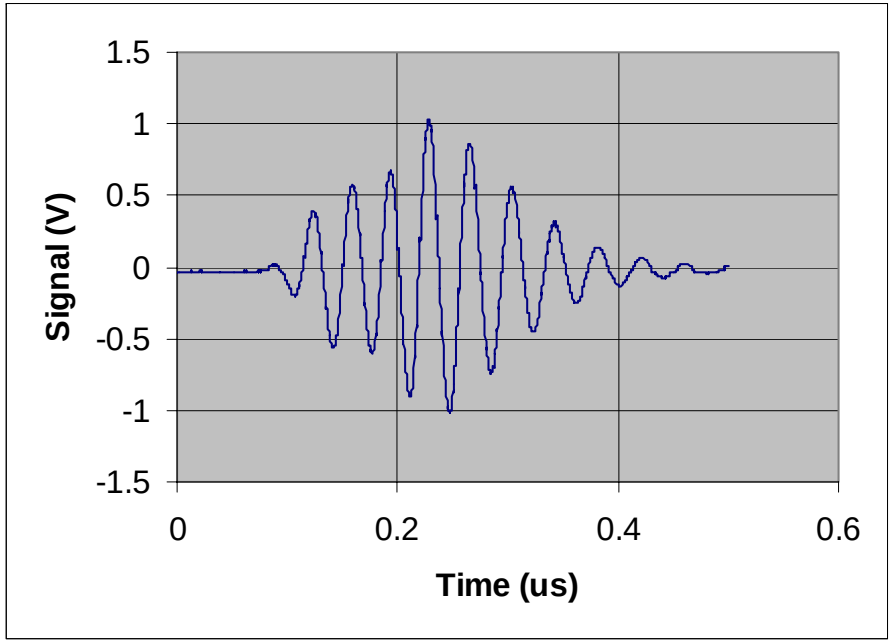
Completed Research:
Piezoelectric AlN Films

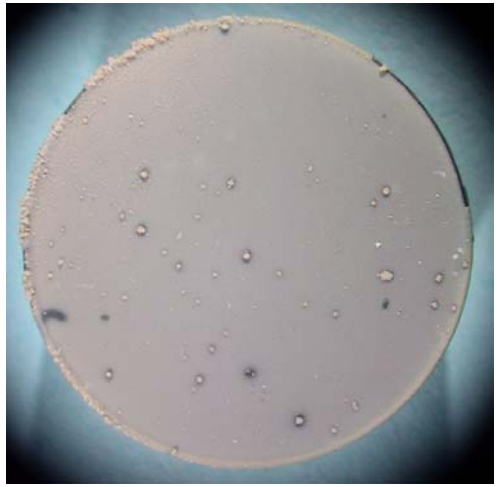


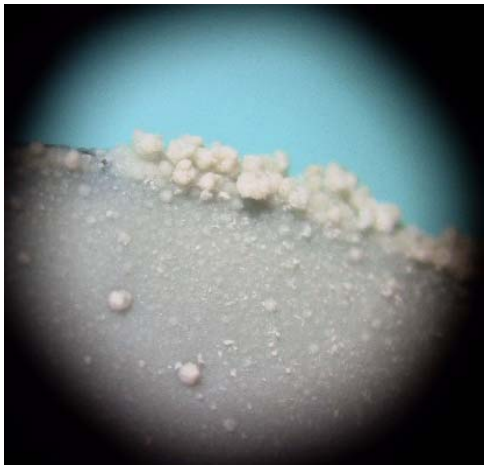


Completed Research: Piezoelectric AlN Films

Revived CVD process and replicated previous results on WC.

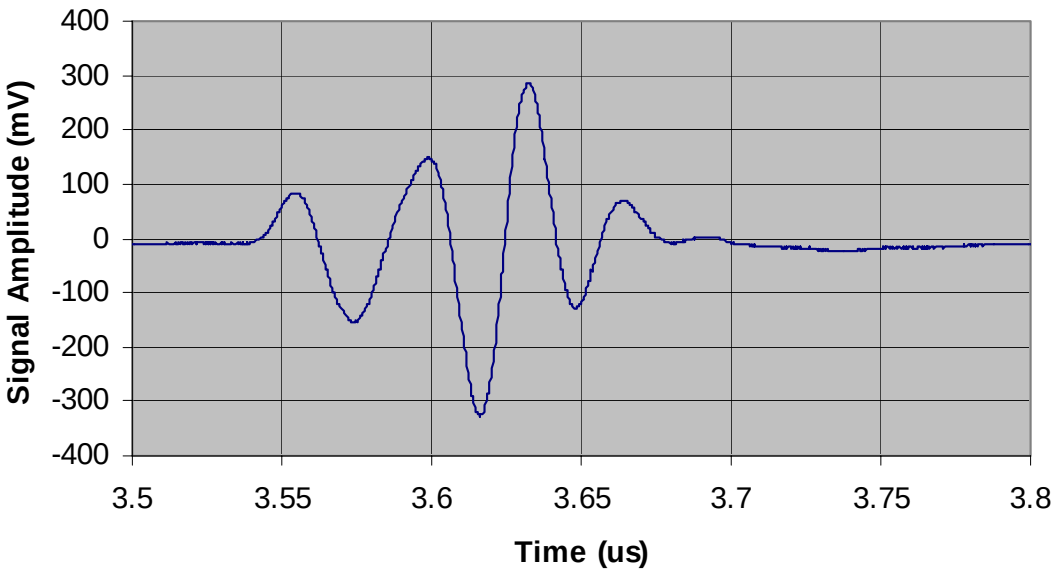


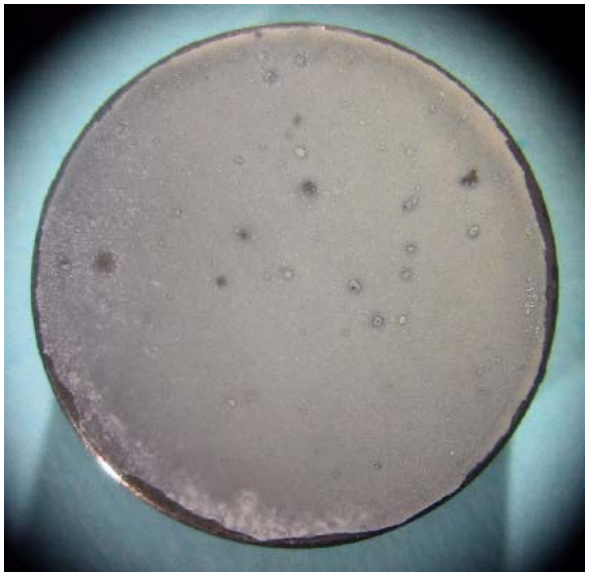




Completed Research: Piezoelectric AlN Films

- **Advanced CVD process to titanium substrates.**
- **Grade 5- no successful films.**
- **Grade 2- films achieved.**



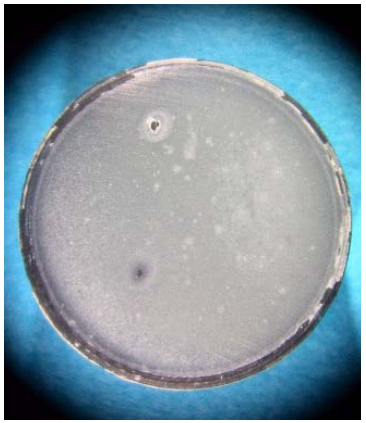


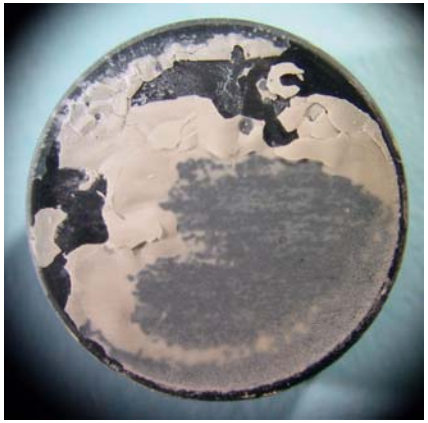
Completed Research:
Piezoelectric AlN Films

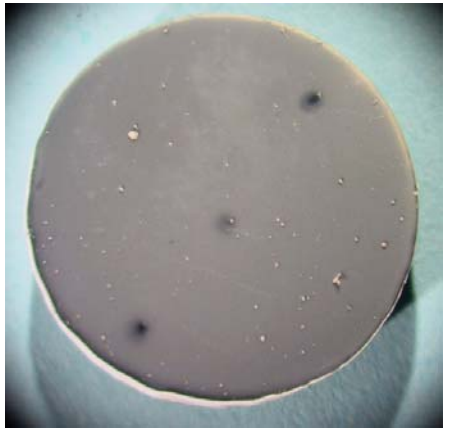
– **Films on titanium disbonded upon reheating.**

Completed Research: Piezoelectric AlN Films

- **Advanced CVD process to SiC.**
  - **Initial film depositions visually good.**
  - **Trouble producing ultrasonic signal from film; problem traced to substrate conductivity and solved with electrode.**
  - **Mixed results upon heating AlN films on SiC substrates.**
  - **Three types of SiC tried to date; sintered and CVD material.**

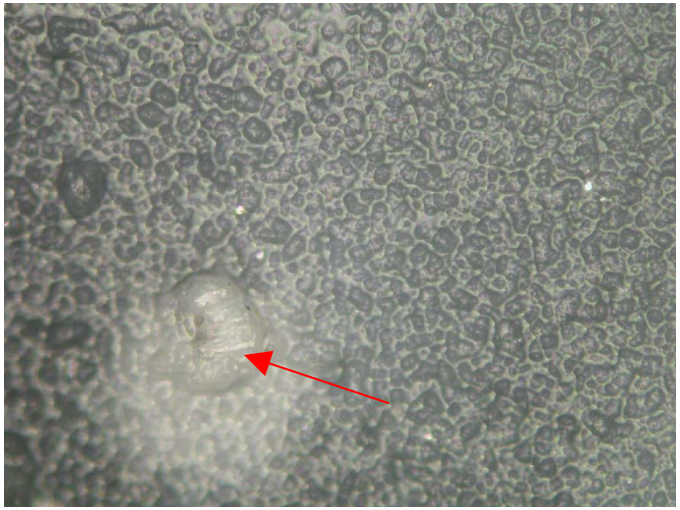




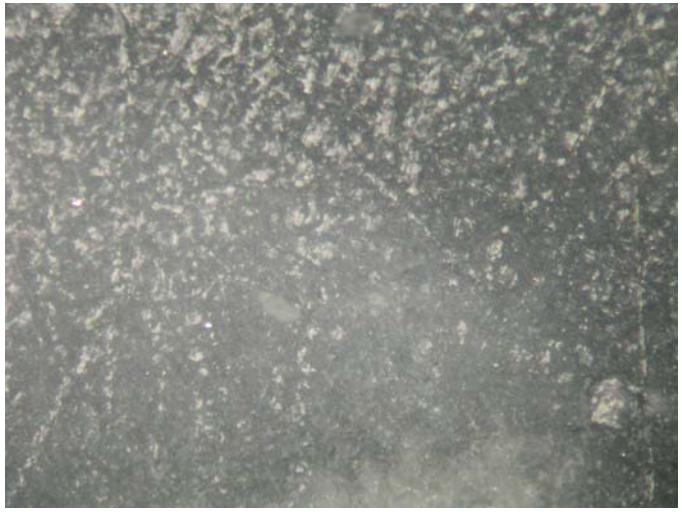


Completed Research:
Piezoelectric AlN Films

400X Photomicrographs

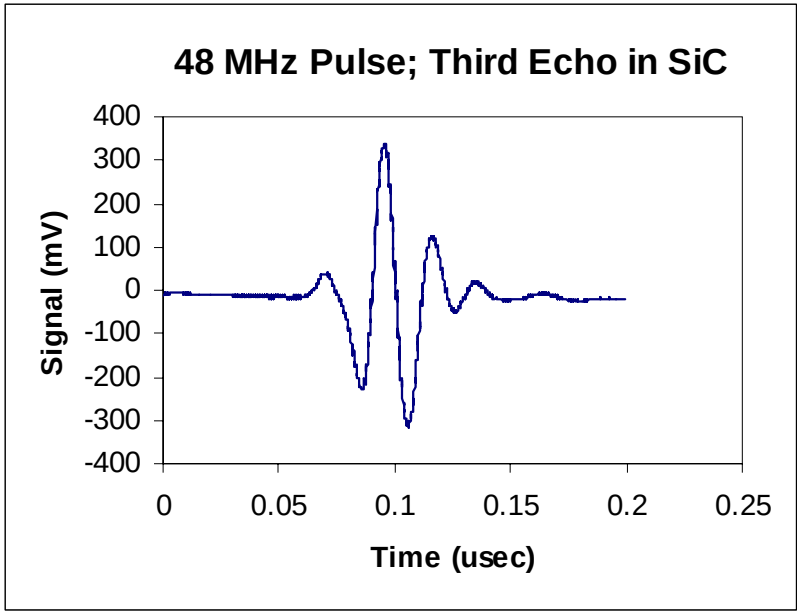


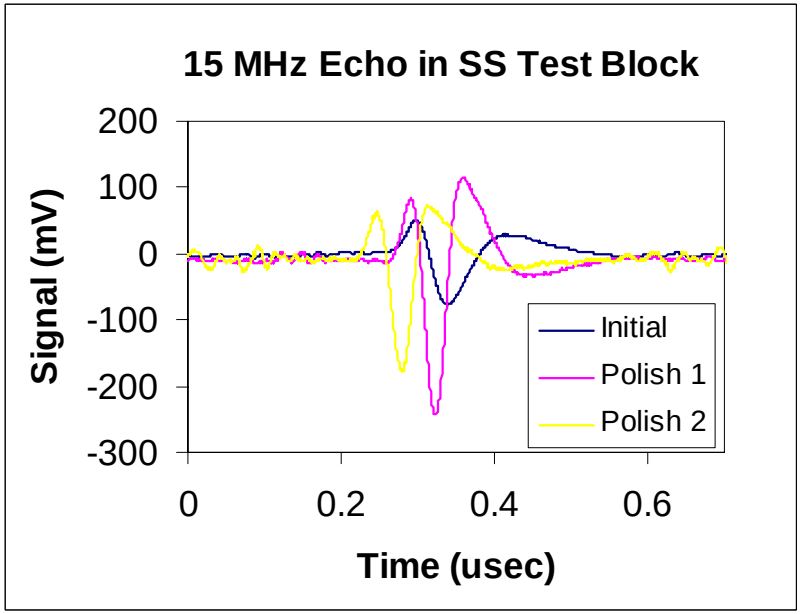
Initial Polish



Second Polish

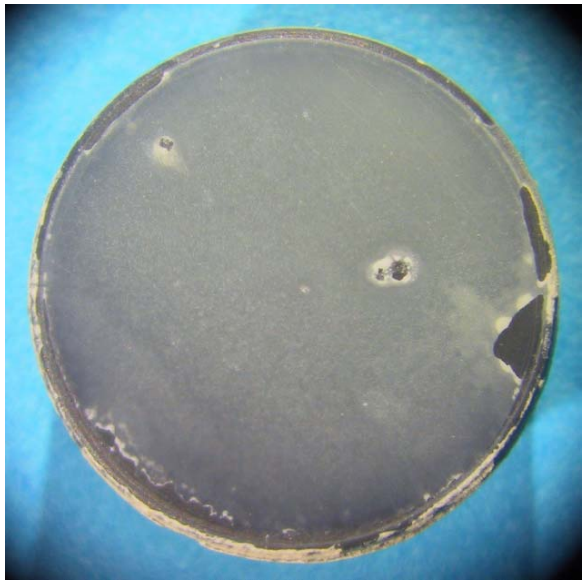
Completed Research:
Piezoelectric AlN Films





Completed Research:
Piezoelectric AlN Films

Thermally damaged AlN film on sintered SiC.

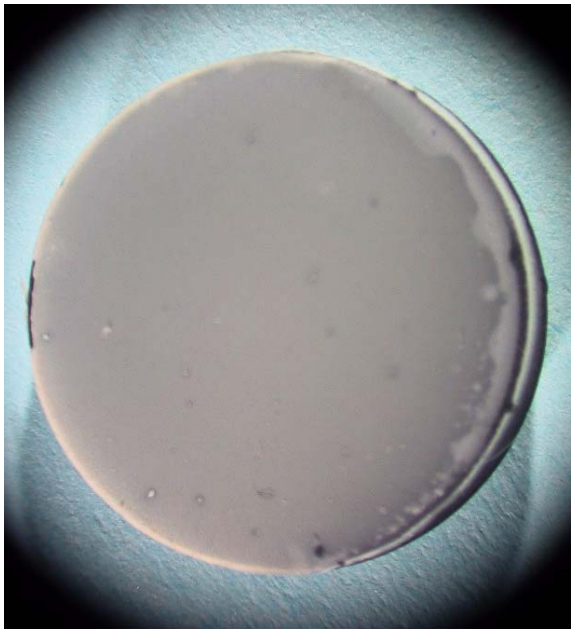


Before Heating

After Heating to 450ºC

Completed Research:
Piezoelectric AlN Films

Thermally damaged AlN film on CVD SiC.



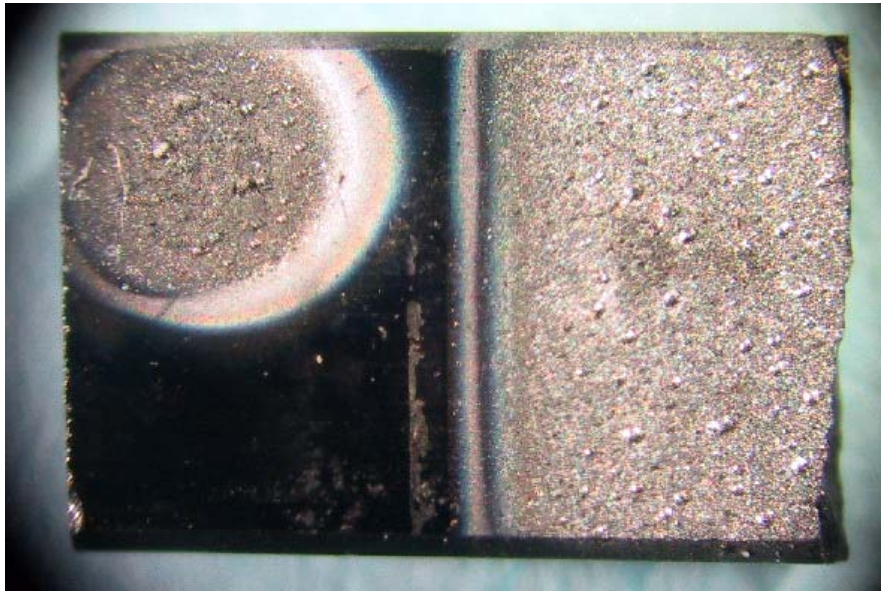
Before Heating

After Heating
to 450ºC

Completed Research:
Piezoelectric AlN Films

Pulsed Laser Deposition (PLD) process tested on SiC.

- **Three small AlN films were produced.**
- **Small areas of films difficult to work with.**
- **No ultrasonic data collected.**
- **Candidate process for repair of defects in films made by CVD process.**

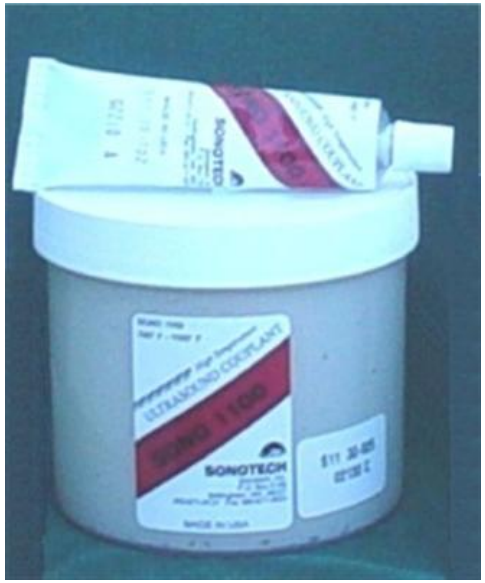


Completed Research:
High Temperature Coupling

- **High frequency ultrasound attenuates quickly in air.**
- **Impedance mismatch ~10^5 causes essentially total reflection at boundary.**
- **Couplants provide a medium for transmission of UT energy.**
- **Other options include laser-based ultrasound, EMATs, and buffer rods.**

Completed Research: High Temperature Coupling

- **Sono 1100- best available commercial couplant.**



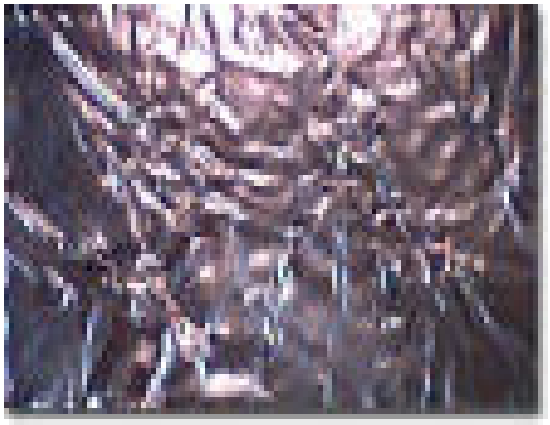
Thickness Gaging * (Less than 15 Second Contact)	700° to 1,100° F 370° to 593°C
Flaw Detection* (1 - 5 Minute Contact)	700° to 900° F 370° to 482°C
Smoke Point (Dense Plume)	850° F 454ºC
Auto-Ignition Temperature	1040ºF 560ºC
Viscosity**	>3,000,000 cps
Water soluble	NO
Humectant	NO
Halogens	< 2,500 ppm
Sulfur	< 50,000 ppm

* A couplant's upper temperature range for short duration thickness gaging is higher

Completed Research:
High Temperature Coupling

Metal foil approach

- Aluminum used in the past to >500ºC.
  - Coupling may be maintained after cooling.
  - Pressure is also required.
- Literature also indicates use of platinum, gold, and a “sandwich” of gold and zinc.
- Foil thickness may need to be matched to ultrasonic wavelength.
- Provides good outer electrode.



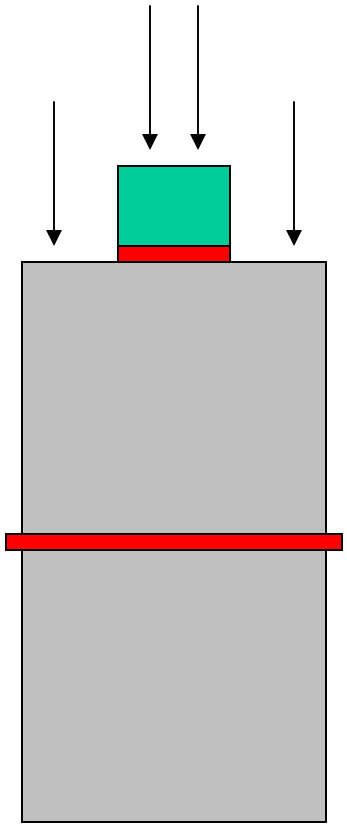
Completed Research:
High Temperature Coupling

Molten glass approach

- Tailorable softening points from 400ºC to above 800ºC.
- Better for irregular surfaces.
- Chemical compatibility with test object required.
- Implemented with glass powder; may be semi-permanent installation.
- Would not provide outer electrode for sensor.

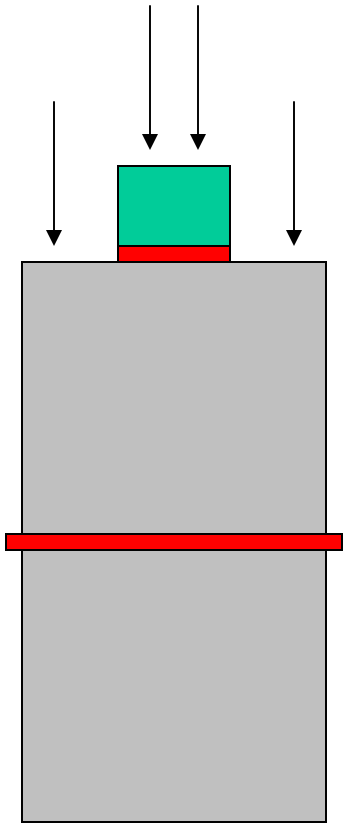
Planned Research:
High Temperature Coupling

- Couplant test apparatus designed.
- Couplant required at both interfaces.
- Baseline tests with water-based couplant and commercial transducer at room temperature.
- Elevated temperature tests to follow with AlN transducer and metal foil and glass couplant.



Planned Research:
High Temperature Coupling

- Substrate echo will be used to insure AlN film is emitting pulse.
- Echoes from test blocks will indicate the performance of the couplants.
- Possible issues:
  - Effects of couplant layer thickness
  - Glass effects on electric field in AlN
  - Glass adhesion to AlN



Planned Research:
Additional AlN Film Deposition

- Improve bond between AlN and SiC
  - Chemistry
  - Texture
  - Transition layer?
- Try for thicker films with multiple deposition runs
- Try new substrate: polycrystalline conductive AlN

Planned Research:
Additional AlN Film Deposition

- Change substrate heating in deposition apparatus from induction heater to furnace
- Substrate shaping:
  - Reduce edge chipping
  - Reduce or eliminate substrate echoes
  - Assist in incorporation in transducer

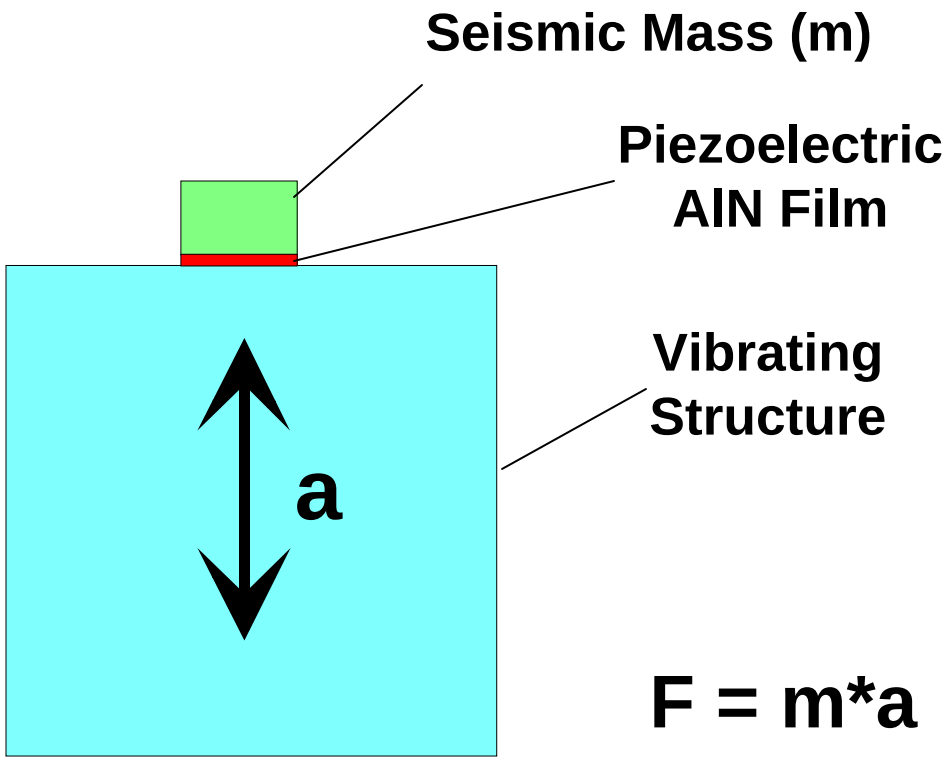
Planned Research:
AlN Film Characterization

- Additional thermal exposure testing
- Ultrasonic testing at room temperature
- Ultrasonic testing at elevated temperature
- Structural evaluation
  - SEM and composition analysis
  - Crystal orientation

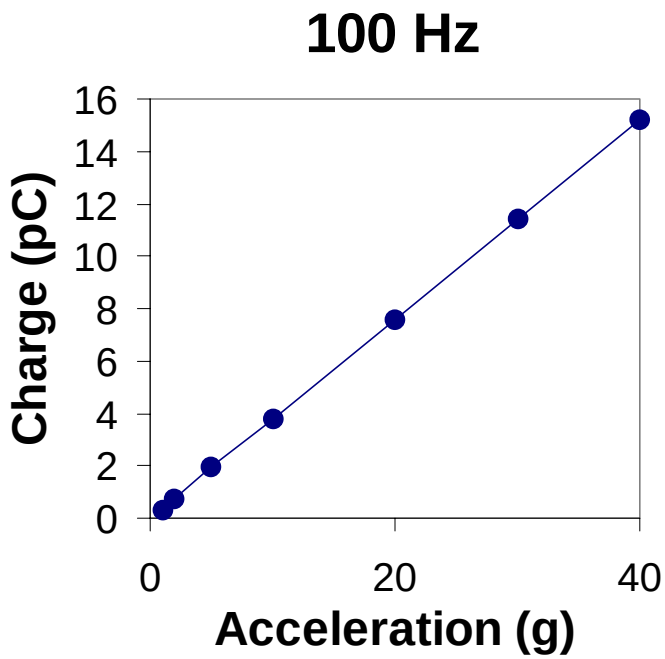
Planned Research:
Alternative to AlN Film

- **C-axis oriented AlN single crystal:**
  - **Made possible by research for the semiconductor industry with substantial DARPA funding.**
  - **Produced by Crystal-IS in New York.**
  - **Should produce ~20 MHz ultrasound.**
  - **Up to 12mm DIA, 0.3 mm thick**
- **Will provide an additional baseline for evaluation of AlN films; may be a future transducer element.**

Planned Research:
AlN-Based Accelerometer



F = m*a



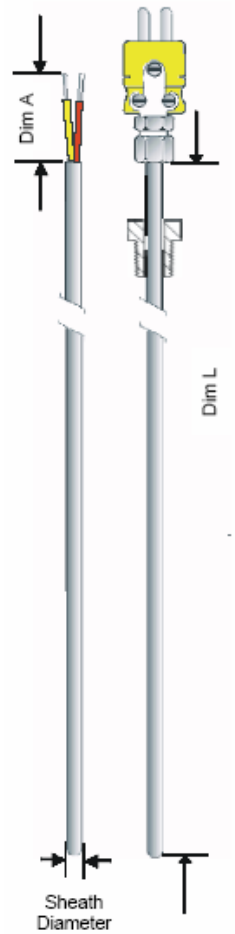
Planned Research:
Sensor Packaging

- **Housing design**
  - **Structure**
  - **Preloading or bonding**
  - **Electrical insulation and shielding**
  - **AlN film outer electrode**
- **Insulation (ceramic)**
- **Wiring: electrodes to instrument**

Planned Research:
Sensor Packaging

Sheathed thermocouple for wiring

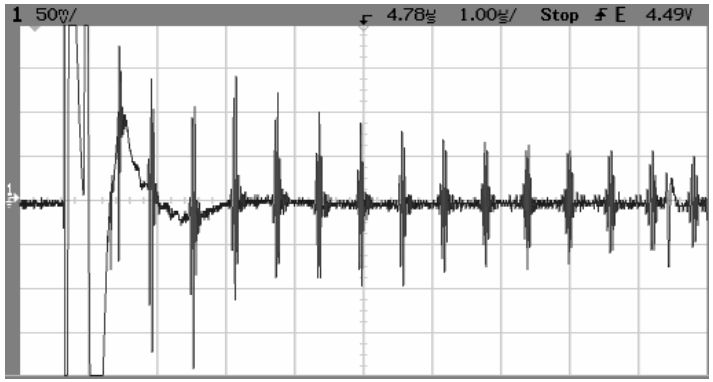
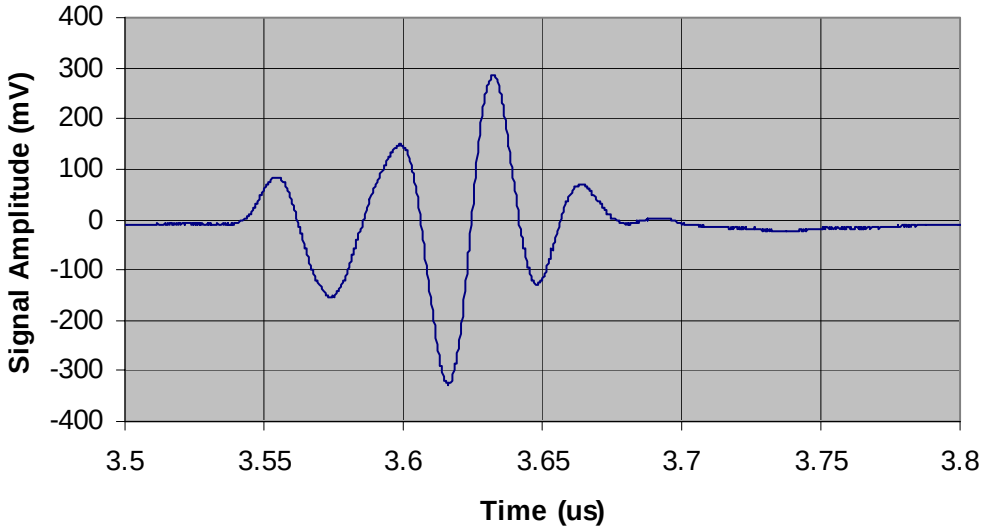
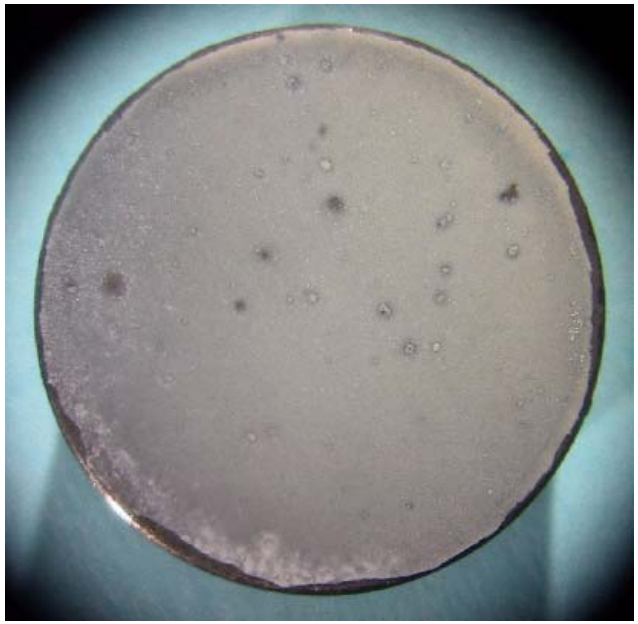
- **MI-Dry insulated thermocouple from Accutru International**
- **1260ºC max**
- **100X greater insulation resistance than MgO**
- **Not hygroscopic!**
- **IN 600 or 316 stainless steel sheath**



Planned Research:
Test Application Selection

- Test material(s) and expected defects or damage
- Operating temperature and range
- Chemical environment
- Vibration
- Other issues
- Suggestions appreciated!

Project Summary

- Goal: sensor for equipment health monitoring at >1000ºC.
- AlN films and ultrasonic couplant for sensor are evolving.
- Demonstration application will be simulated with sensors designed for the application.

Questions and Comments?