New Inertial Sensor for Aviation Navigation Application

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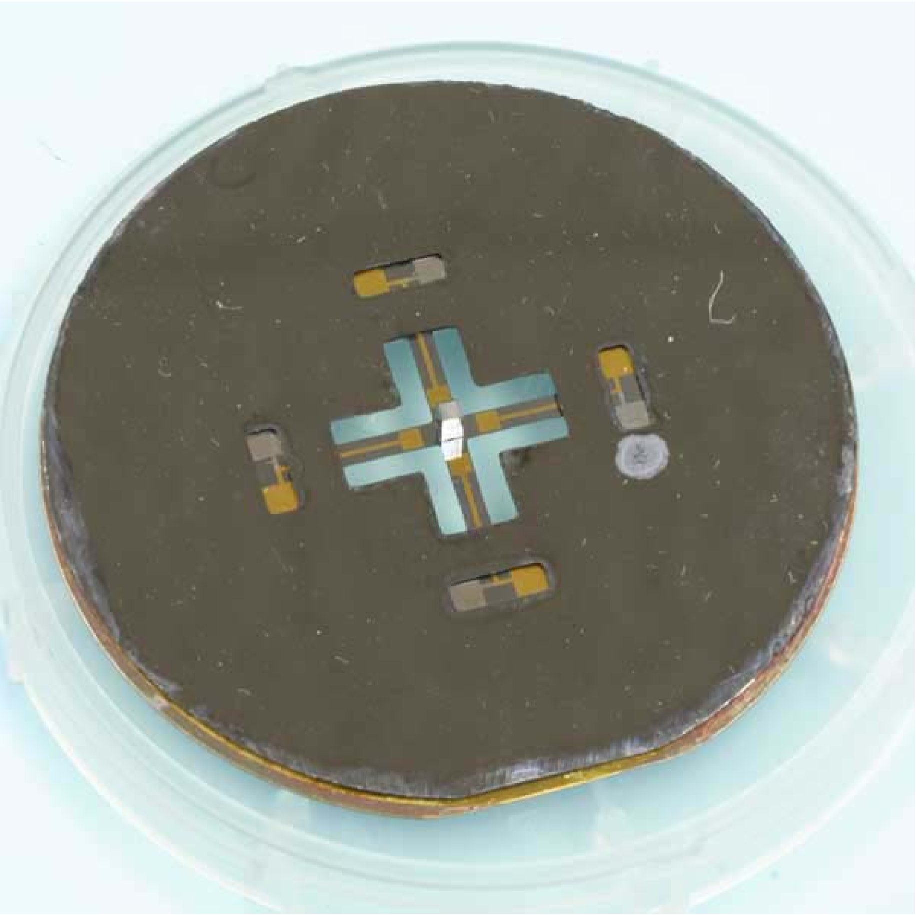
Research Overview

- *To improve MEMS-technology gyro beyond that achieved by the premier navigation research institutions requires an aggressive, high-risk research program*
- At UA we have attacked the technical challenge by concentrating on three premises:
  - Increase mass of the gyro (dimensions in centimeter scale-JPL calls this a meso-scale gyro)
  - Increase signal amplitude by using piezoelectric actuators and sensors (instead of conventional electrostatics)
  - Use alternatives to Silicon (for example, Quartz) that should reduce accuracy degradation caused by temperature changes
- We call the current design the UA X-Post gyro

The UA X-Post Gyro: First completed model



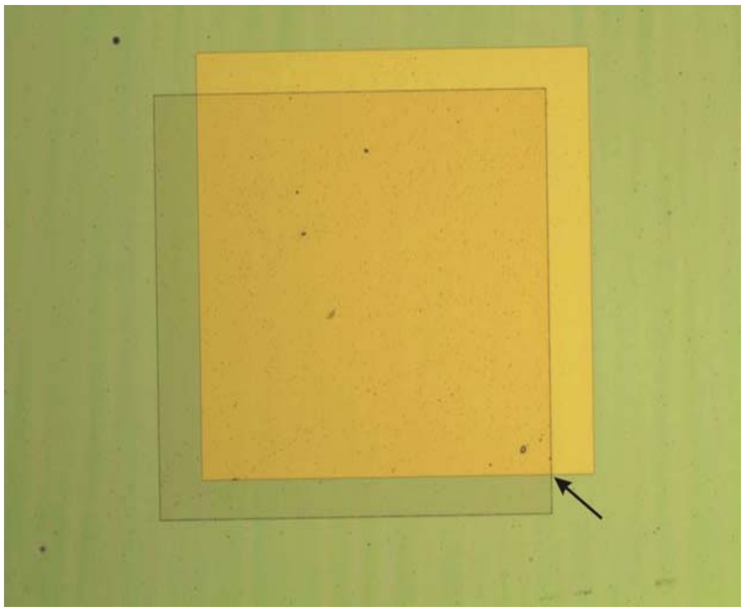
Overview of Device Fabrication

- Fabricate the active wafer
  - Build a complete stack, then etch
- Fabricate two handle wafers.
- Fabricate the post.
- Bond the handle wafers to the active wafer
- Bond the post to the three wafer bonded stack

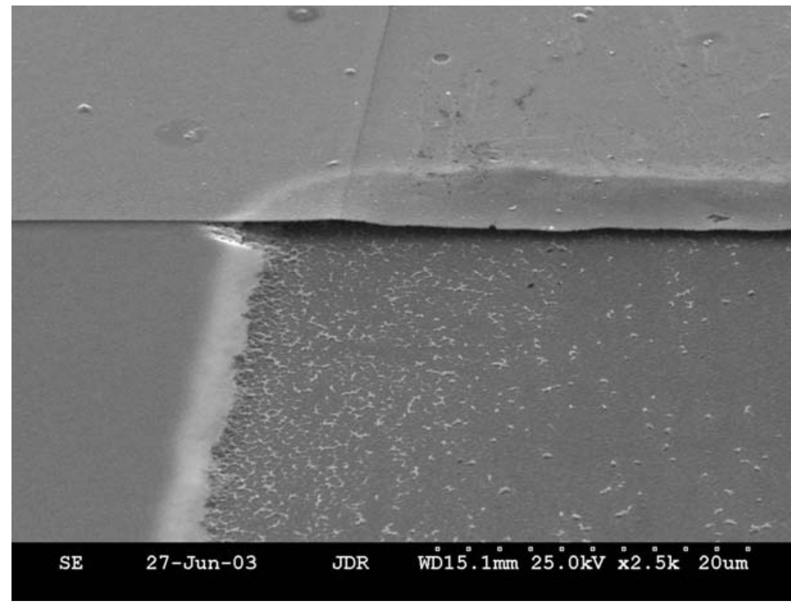
Technological Complications

- The x-post device is two-sided.
- The x-post device is large.
- The wet etching of PNZT is far from ideal.

Difficulties with the PNZT Wet Etch



Etch test sample prior to wet etching of PNZT



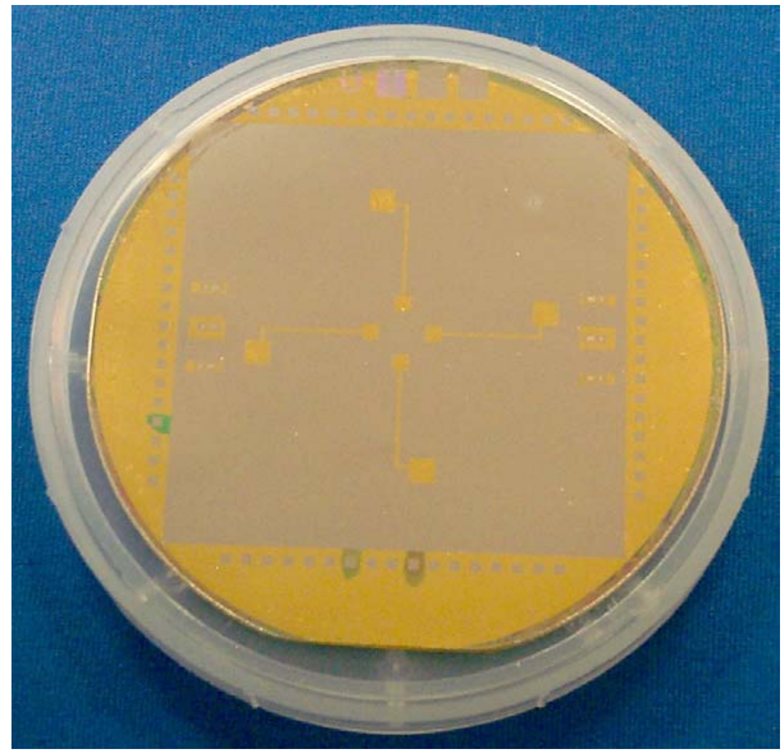
SEM image taken after wet etching of PNZT

Difficulties With the PNZT Wet Etch

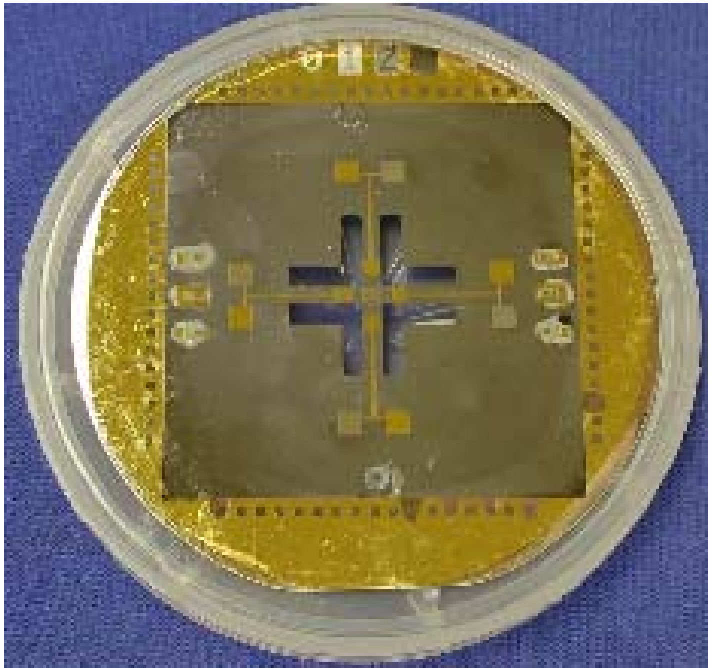
Attempts to circumvent shorting problems by using an overlap of photoresist were thwarted by the presence of foreign particles in the PNZT film.

Two Step PNZT Etch

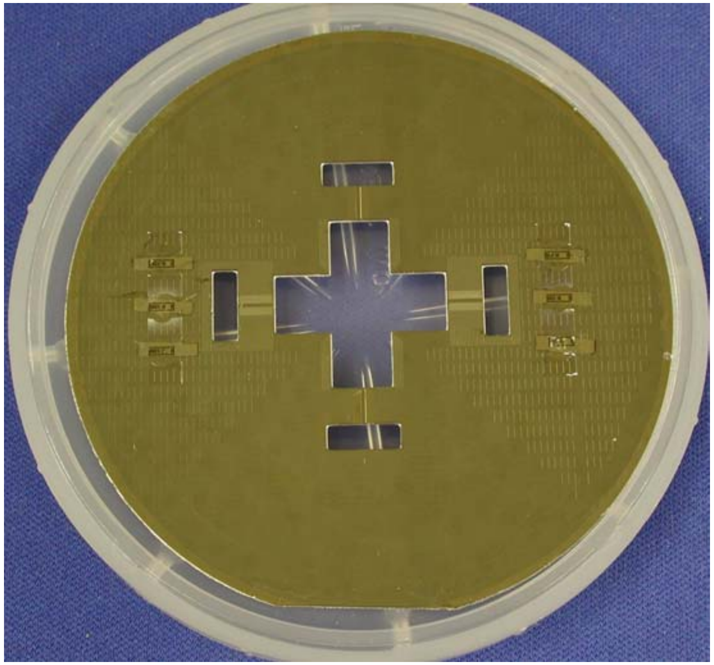
- First, remove about 90% of the PNZT via ion milling.
- Then finish removing the PNZT with a wet etchant



Active Wafer and Handle Wafers

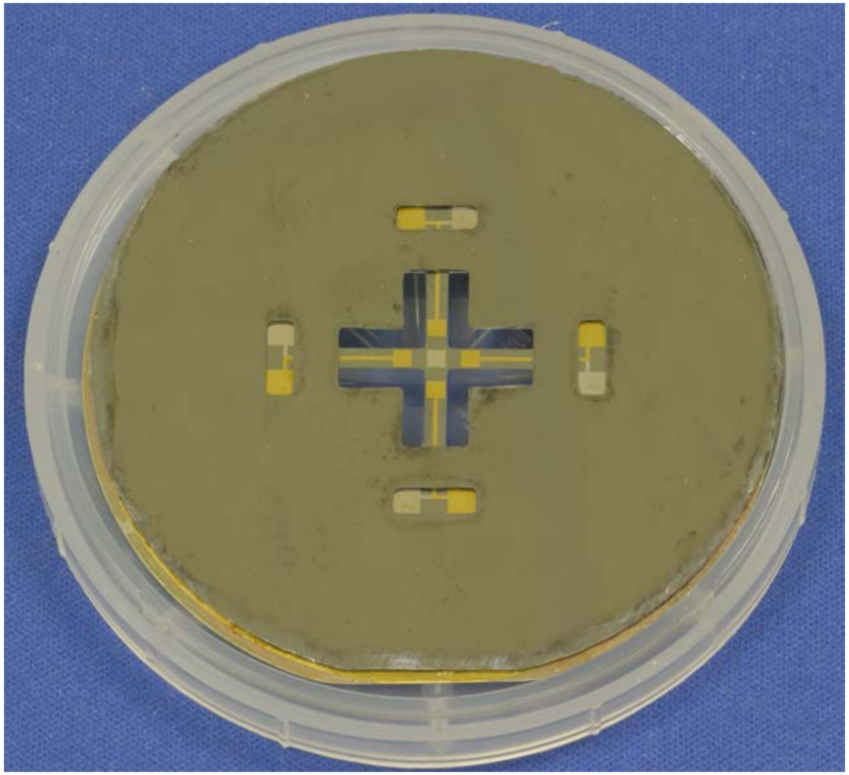


Completed Active Wafer



Completed Handle Wafer

Bonded Three Wafer Stack



Materials Integration and Evaluation

Objectives

- Develop a sol-gel and PLD growth process for PNZT integrated structures on Pt/Si and Pt/quartz substrates with the highest piezoelectric response.
- Quantify ferroelectric, piezoelectric and mechanical properties of PNZT films.
- Develop and evaluate an experimental setup for piezoelectric measurements.

Sol-Gel technique

Advantages:

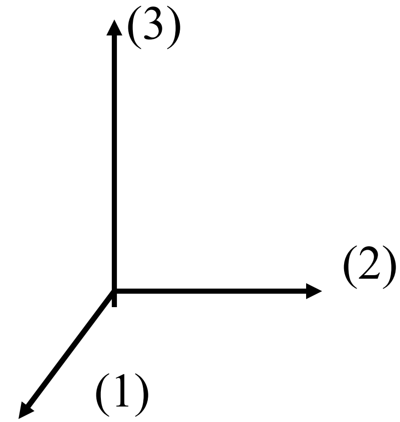
- Low cost
- Easy control of composition
- Uniformity over large area
- Coatings in very complex shapes
- Low processing temperatures
- Spinning, dipping, spraying

Steps:

- Film deposition » spinning 3000rpm/30s;
- Heat treatment of the film at low temperature (400 ° C/10 min) for organic pyrolysis;
- High temperature annealing (700 °C or 650 °C) of the film for crystallization and densification.

Basic Definitions

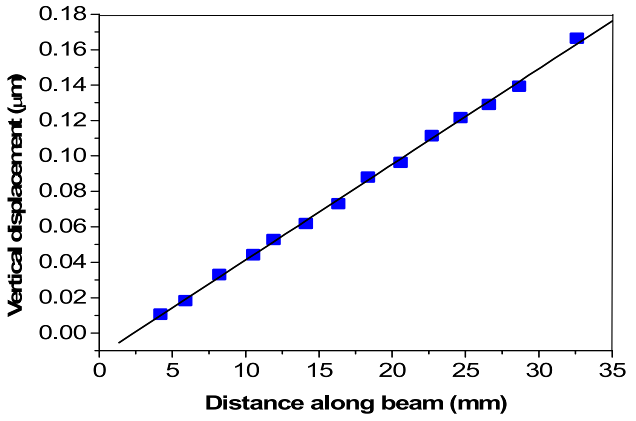
- Piezoelectric strain coefficient, d_{ij} ,
- d_{ij} = (strain/field) = ϵ/E (mV^{-1})
- Piezoelectric charge coefficient, e_{ij}
- e_{ij} = (charge density/strain) = Q/ϵ (Cm^{-2})
- Young's Modulus, Ω
- Ω = (stress/strain) = σ/ϵ (Nm^{-2})

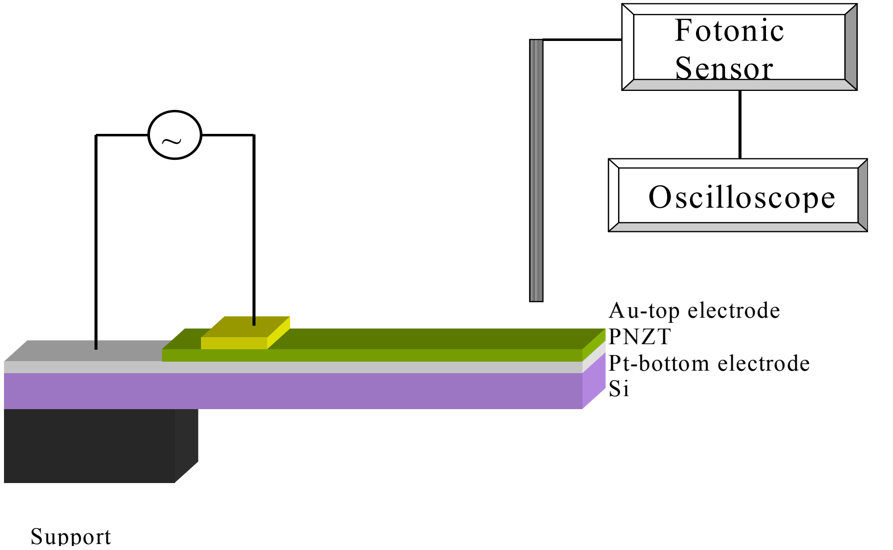


Subscript i gives the direction of the excitation agency, and j describes the direction of the system response.

d_{31} denotes the electric field in the polarization axis (3) and strain along axis (1) which is orthogonal to (3).

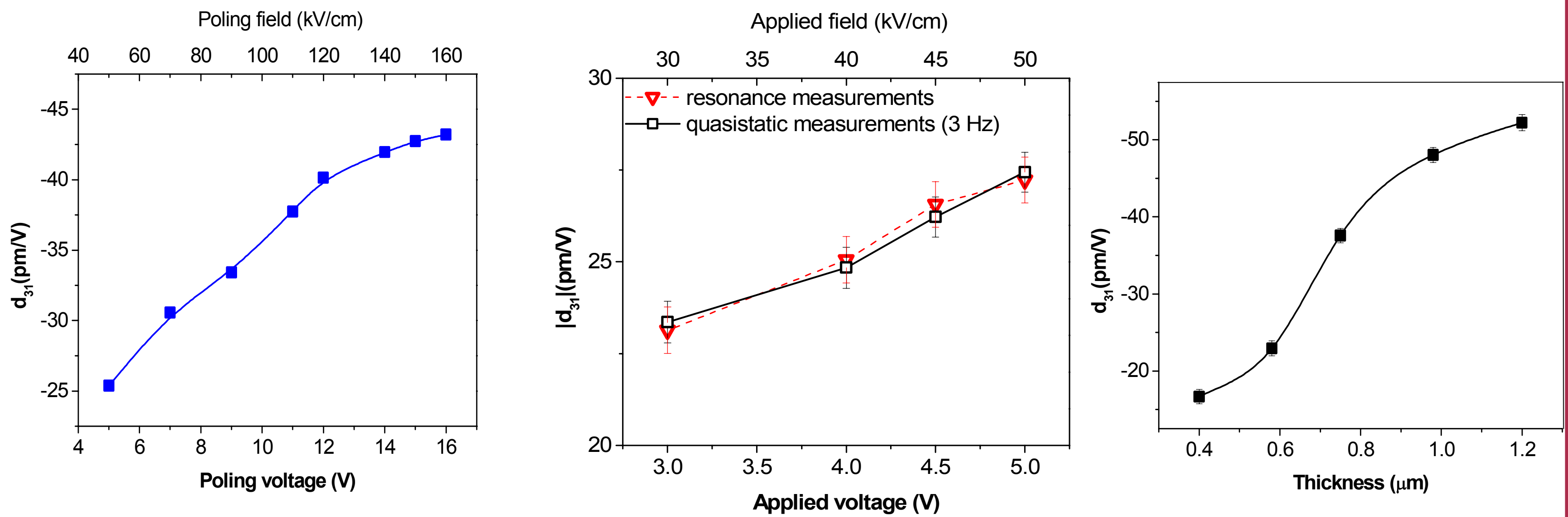
Piezoelectric Coefficient d_{31} (I)





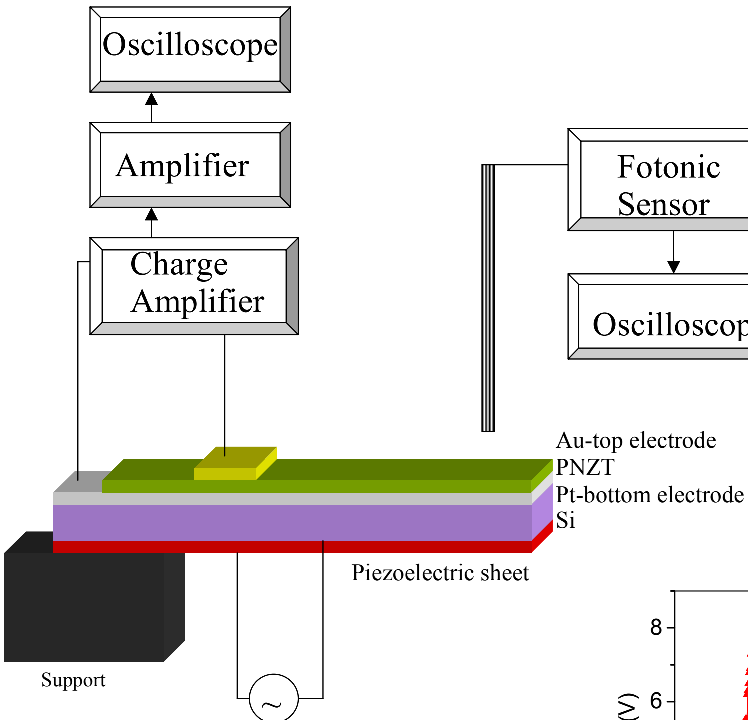
- Static equilibrium
- Piezoelectric layer+elastic layer
- Strain compatibility between successive layers
- Radius of curvature much larger than beam thickness
- Avoid dielectric breakdown by using smaller electrodes
- Amplified displacement using long cantilevers

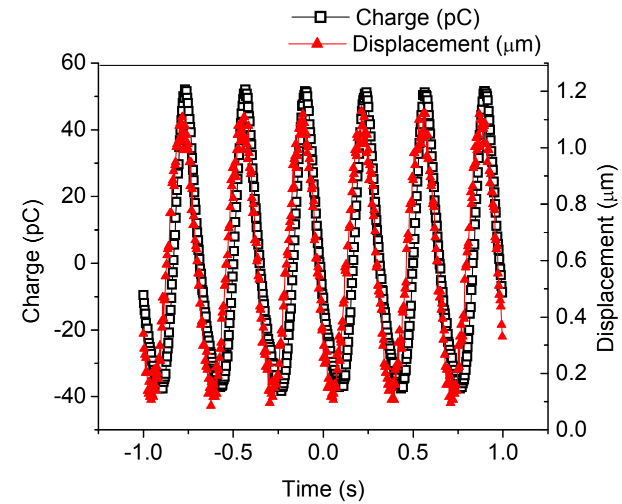
Piezoelectric Coefficient d31 (II)

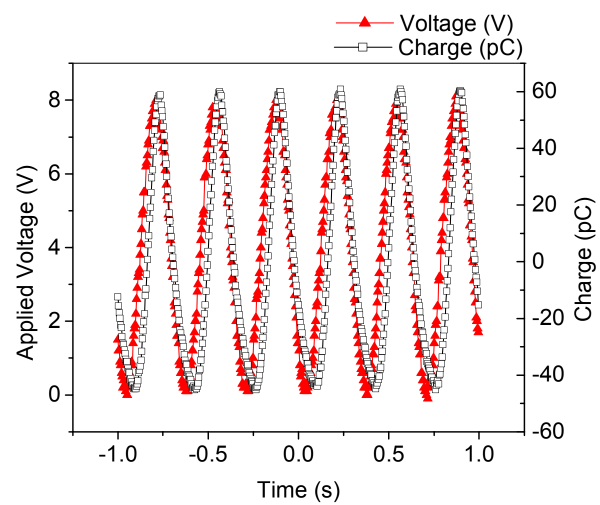


High piezoelectric coefficients in the as-grown PNZT films: 17-52 pm/V

Piezoelectric Coefficient e31(I)







Piezoelectric Coefficient e31 (II)

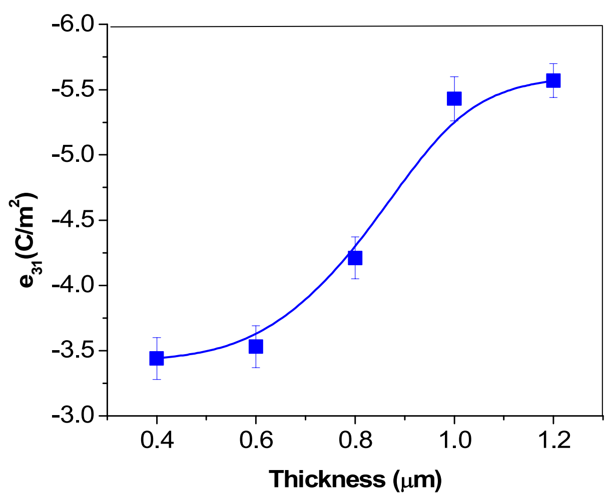


Fig. 1Thickness Dependence

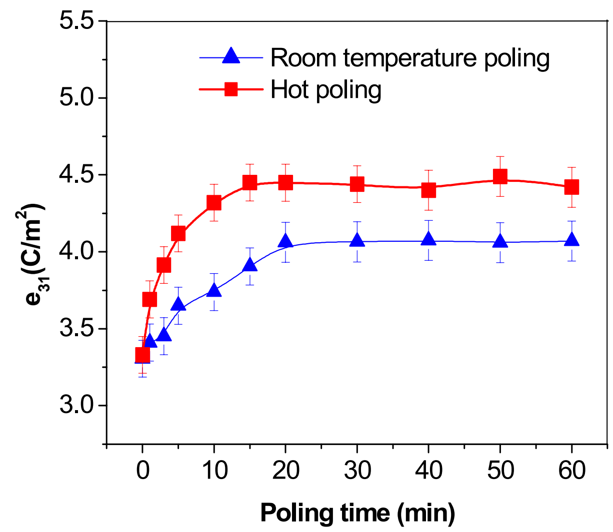


Fig. 2 Poling time dependence

- High e_{31} piezoelectric coefficients for the as-grown PNZT films
- Higher errors than for d_{31} measurements caused by environmental noise and uncertainty in the value of the Young's modulus

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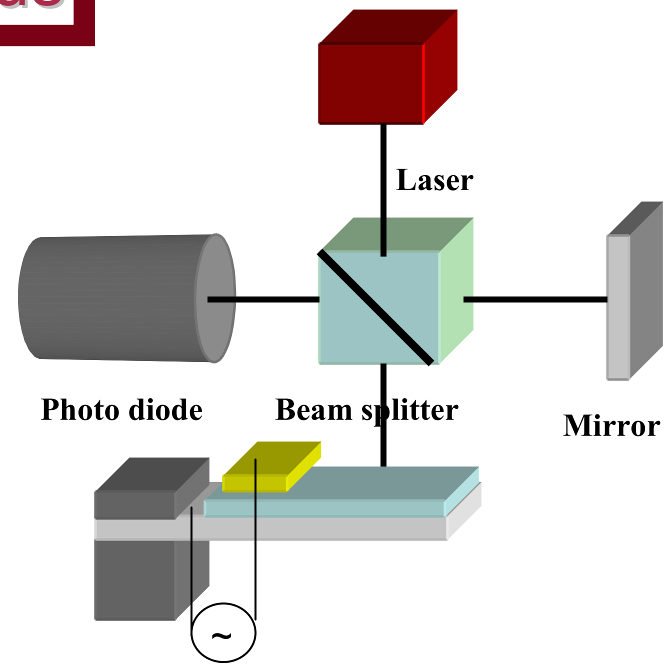
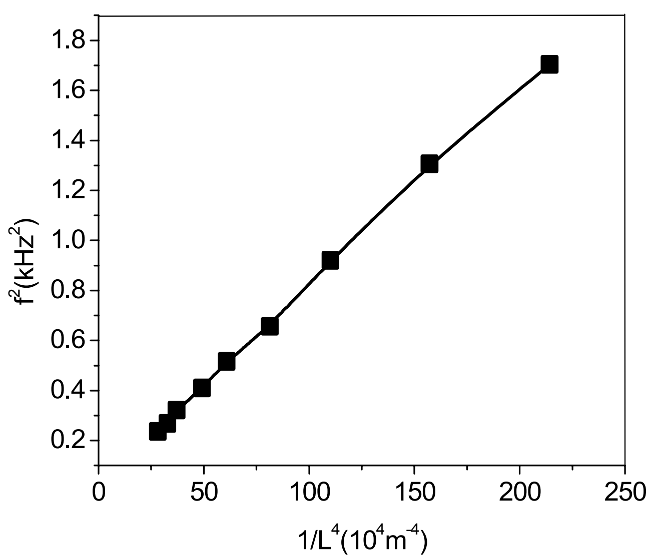
Young's Modulus

	Mean	Standard deviation
Young's modulus substrate $Si/SiO_2/TiO_2/Pt$ (Gpa)	148.09 GPa	7.11 GPa
Young's modulus PNZT (Gpa)	98.79 GPa	14.81 GPa





Sources of error: boundary conditions, geometry and damping (caused by agents other than air.

Conclusions-Materials Development

Successfully developed a sol-gel processing for PNZT thin film growth

- High piezoelectric coefficients in the as-grown films
- Largest area covered: 4 inch wafer
- Largest thickness: 1.2 µm.

Designed and tested a method for reliable measurements of the effective piezoelectric coefficients d_{31} and e_{31}.

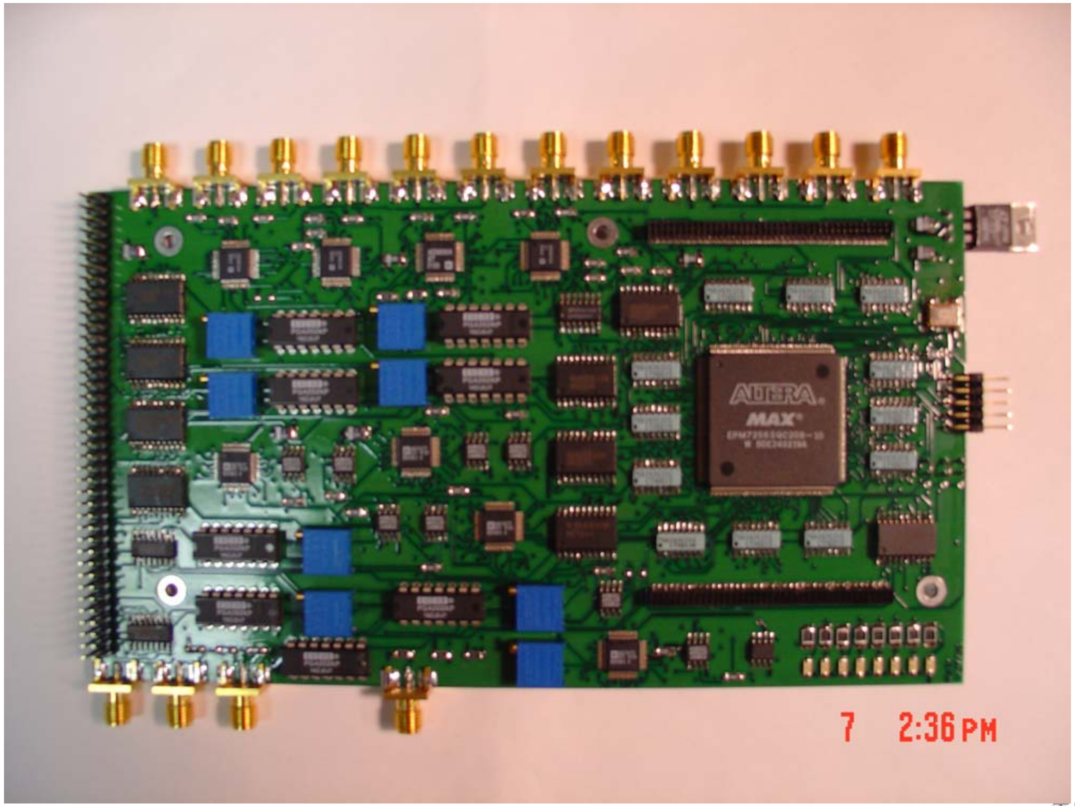
Electrical and mechanical characterization of sol-gel PNZT thin films

- Established a method for reducing piezoelectric aging.

Successfully integrated approximately 300 nm thick PNZT films on 4 inch Si/SiO2 and Si/Pt wafers.

Electronics: Digital Controller Design for the X-Post Gyroscope

The figure below shows a top view of the first version of the digital controller daughter board.



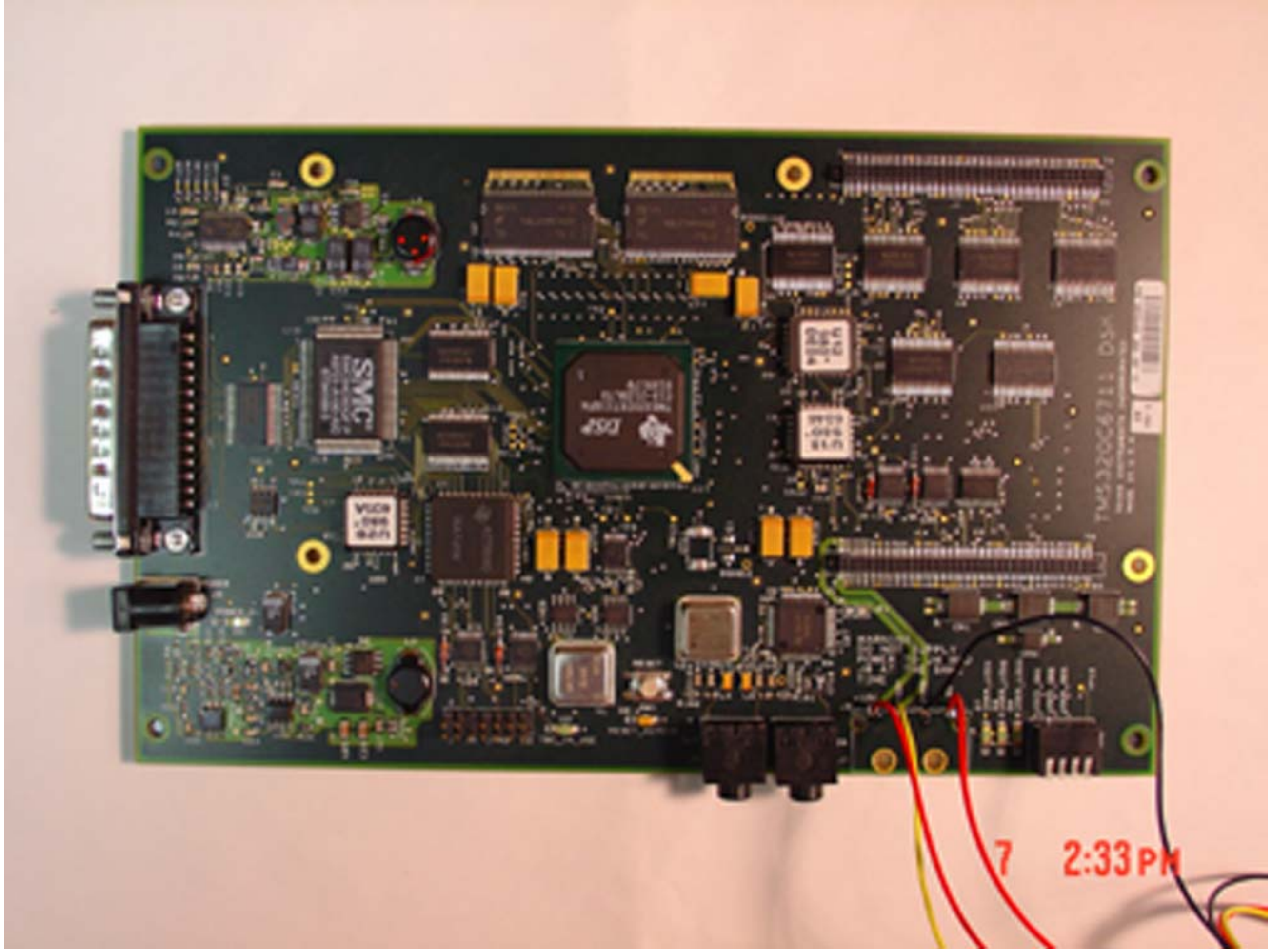
The custom daughter board

- The custom daughter board provides the peripheral support needed to monitor and drive four channels of the MEMs-based sensor.
- The heart of the custom daughter board is Altera's EPM7256 CPLD which supports a programmable interface between the four control channels and the DSP processor.
- The EPM7256 additionally supports service functions to lesson the DSP processor burden.

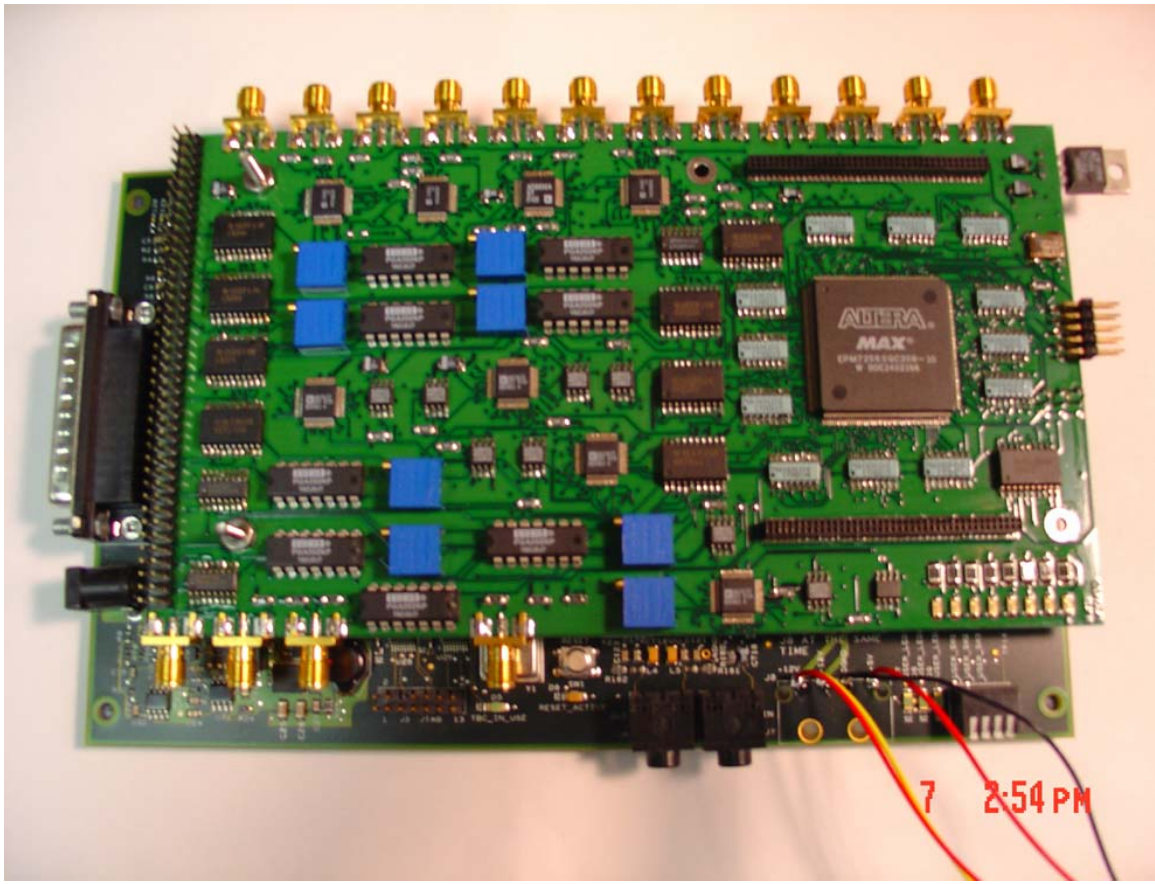
Texas Instruments high performance MS320C6711 DSK development board

- The custom-designed daughter board is paired with the Texas Instruments high performance MS320C6711 DSK development board shown below.
- The TI board supports one of the industries highest performance DSP processors, the floating point TMS320C6711 processor. Clocked at 100 MHz, the processor provides 32-bit floating point capability at 600 MFLOPS.
- Selection of this processor was based on the need to implement state-of-the-art digital filtering concepts for low-noise control of the MEMs-based sensor.

Photo: TI MS320C6711 DSK development board



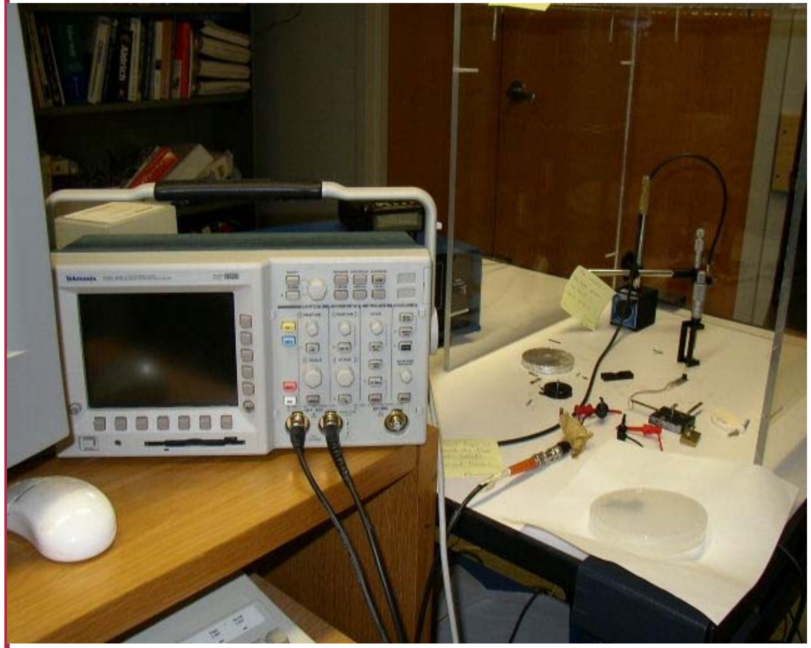
Custom daughter board and 6711 DSK stacked

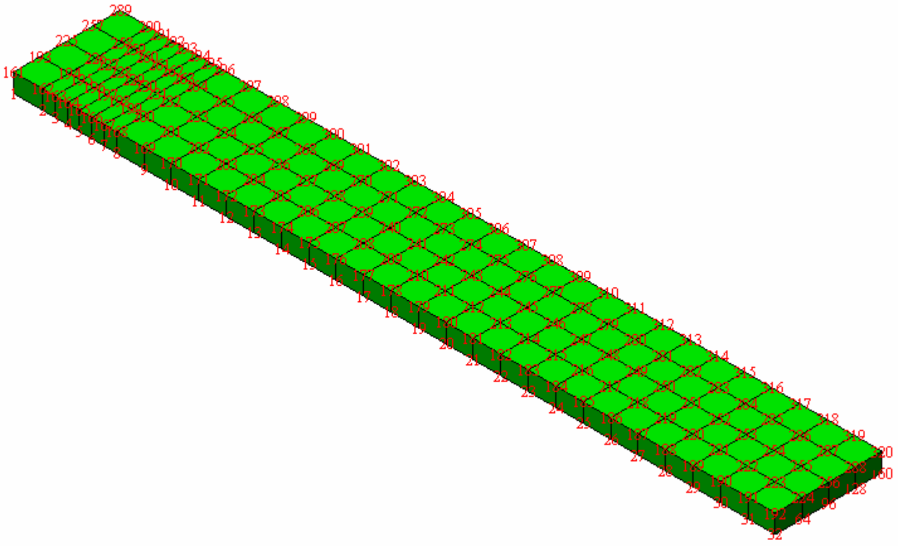


Simulation

- We have developed an in-house FEM code (BAMAFEM) capable of performing modal analysis and dynamic response analysis of 3D solids such as the X-Post gyro
- A special thin film piezoelectric element was developed in order to simulate the piezoelectric actuators and sensors (can input a voltage at actuators and compute the voltages produced at the sensor pads)
- Can input an arbitrary angular rate input about an arbitrary axis
- The code provides a tool for shortening the design iteration process

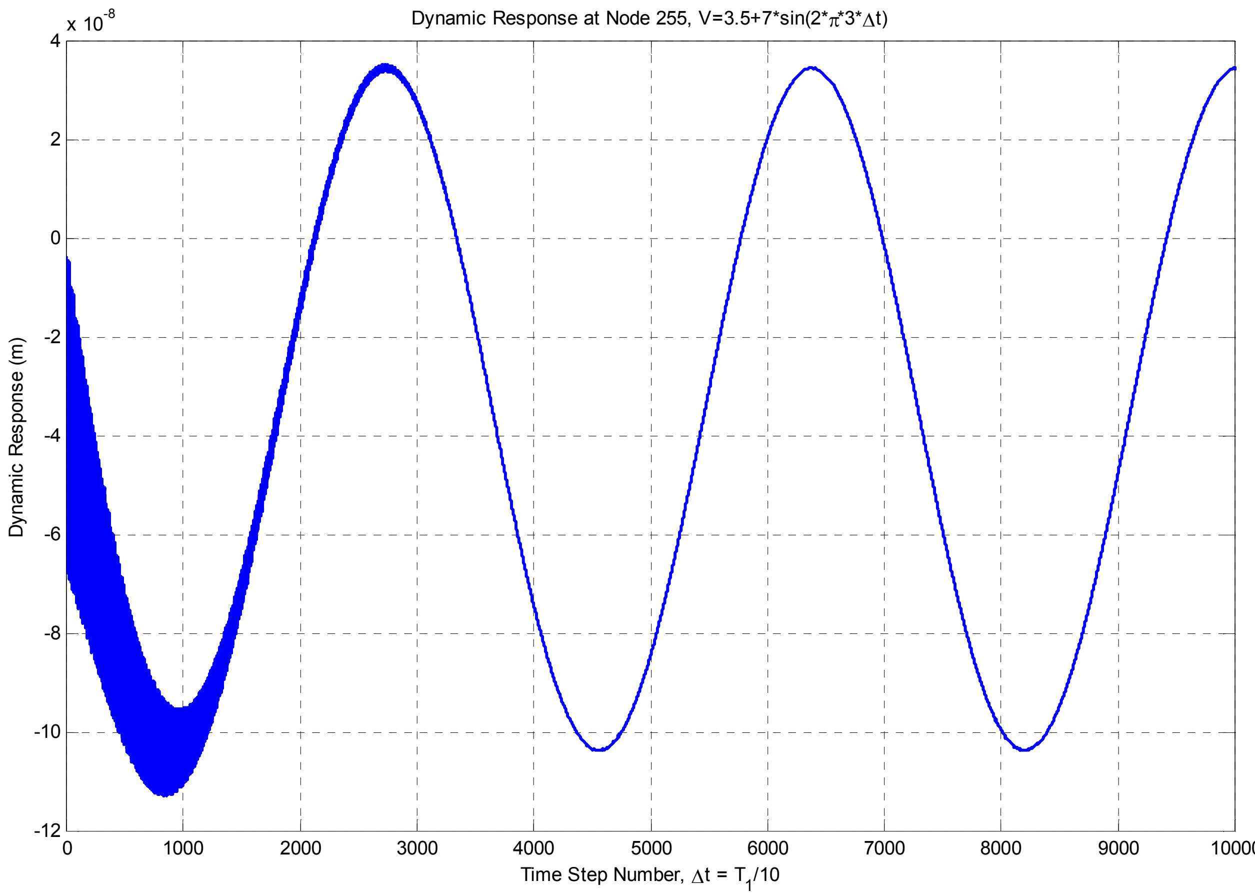
Experimental Verification of BAMAFEM Thin Film Finite Element



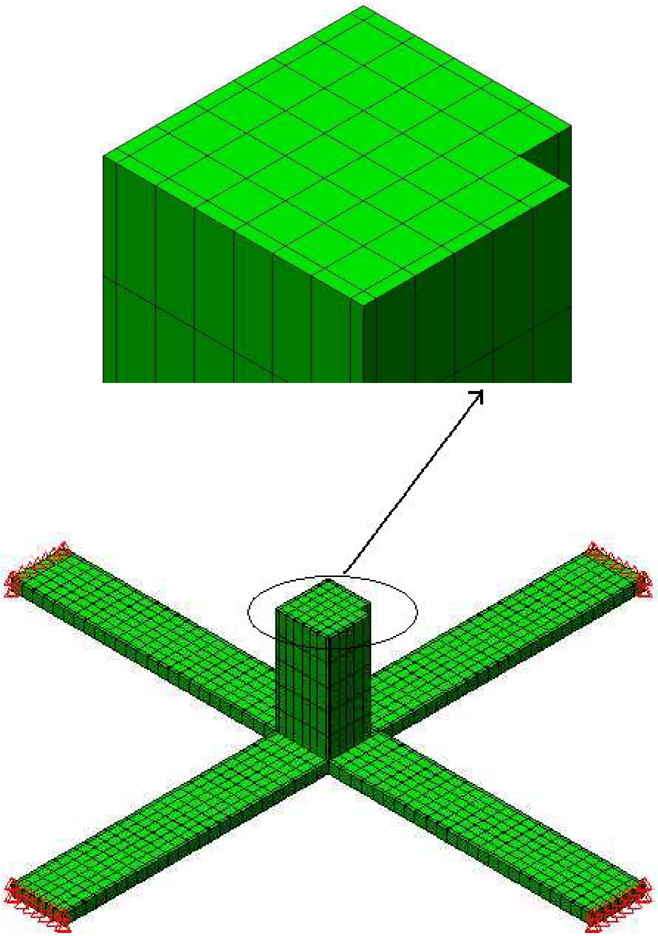


Displacement at End of Cantilever

Experimental: 1.12014 ×10-7m FEM: 1.0363×10-7 m

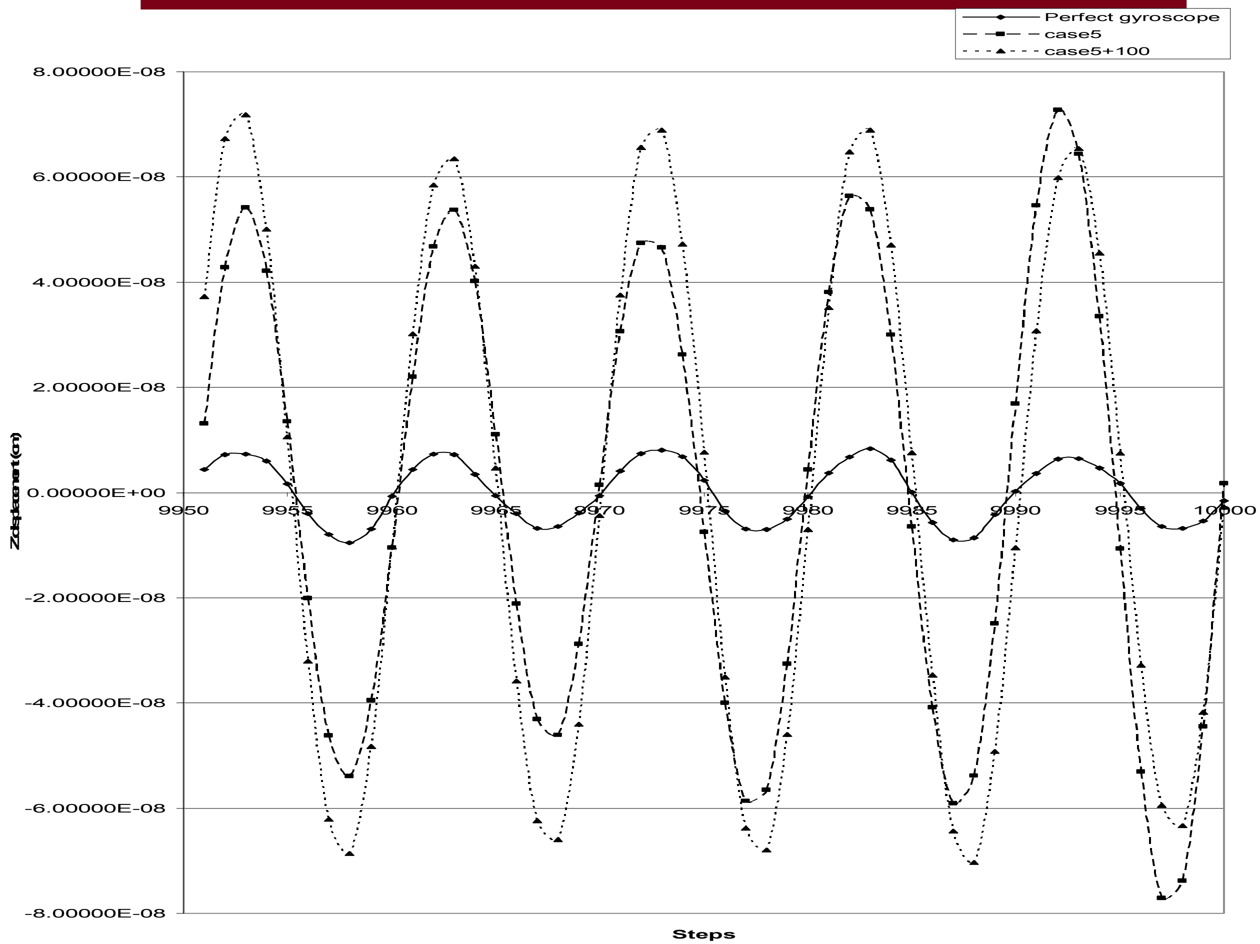


X-Post Gyro with Manufacturing Defect



Manufacturing imperfection in corner of post

Effect of Temperature and Imperfection on Quadrature Error



Summary

- **Currently, the first model of the X-Post gyro design is in the initial testing stage. The team expects to report initial results and lessons learned in a later paper.**

Acknowledgments

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