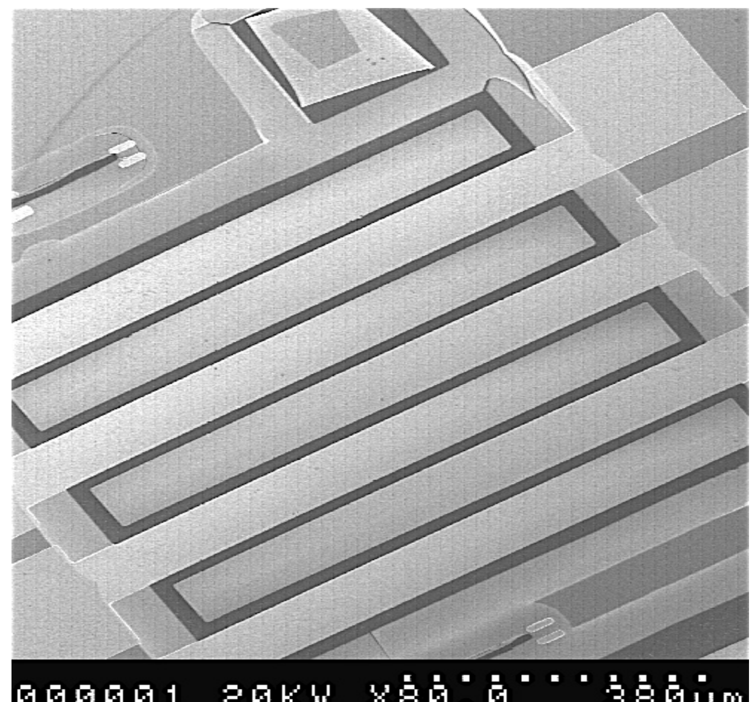
Thin Film Piezoelectric Energy Scavenging Systems for Wireless Sensor Networks

Paul Wright and

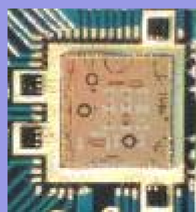
Elizabeth K. Reilly

Nanomorphic Systems at Stanford University on November 8 and 9, 2007

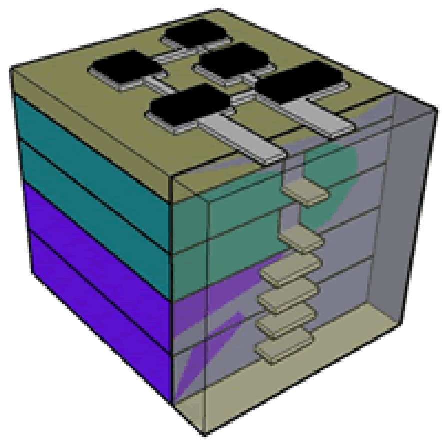


Wireless Sensor Networks

Low Power Radio



Power Storage



“Picocube”

Sensor

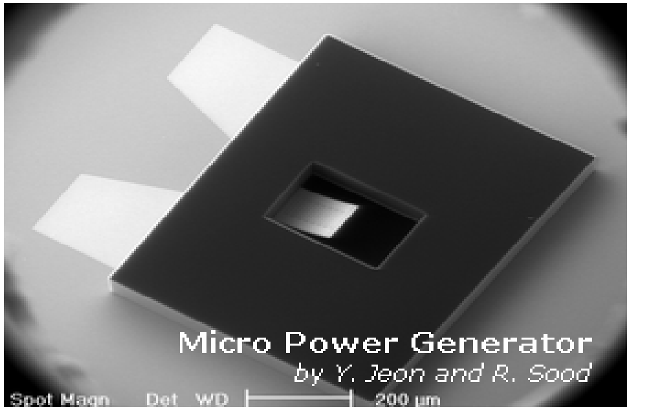
Renewable Power Supply

MEMS Energy Scavenging Systems

Piezoelectric

MIT - S. G. Kim

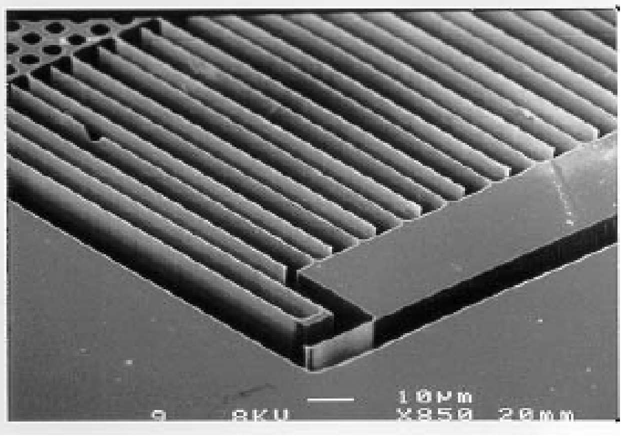
Piezoelectric Micro Power Generator



Electrostatic

UC Berkeley - Roundy

Electrostatic Vibrational Energy Scavenging Device



Inductive (Magnetic)

MIT – A. Chandrakasan

Moving Coil Electromagnetic Transducer Power Generator

Thermal

Washington State University - Richards

P^3 Micro Heat Engine

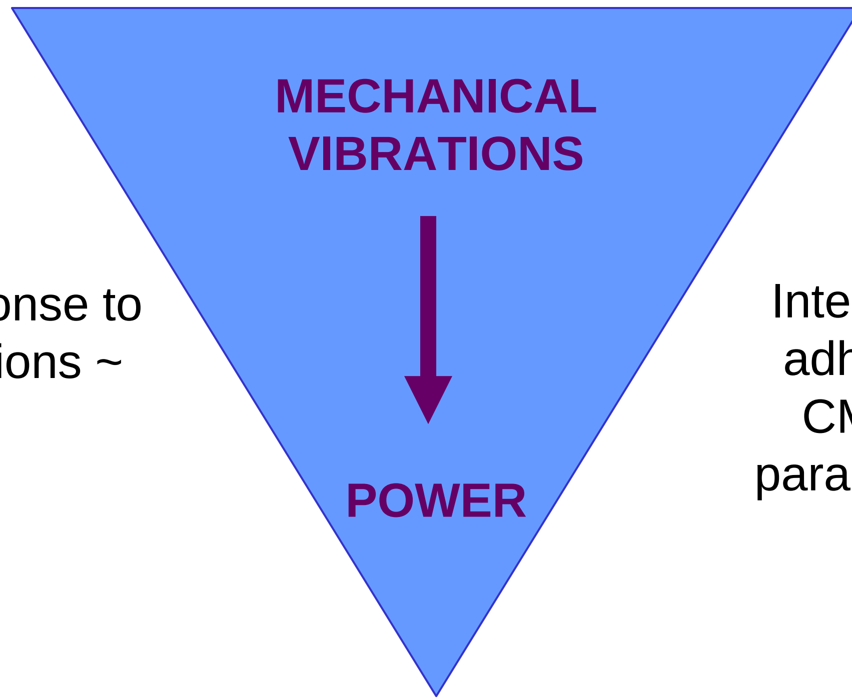
** All images available project websites*

Design Flow

Strain converts to output voltage ~ electromechanical coupling

Mechanical Design

Material Properties



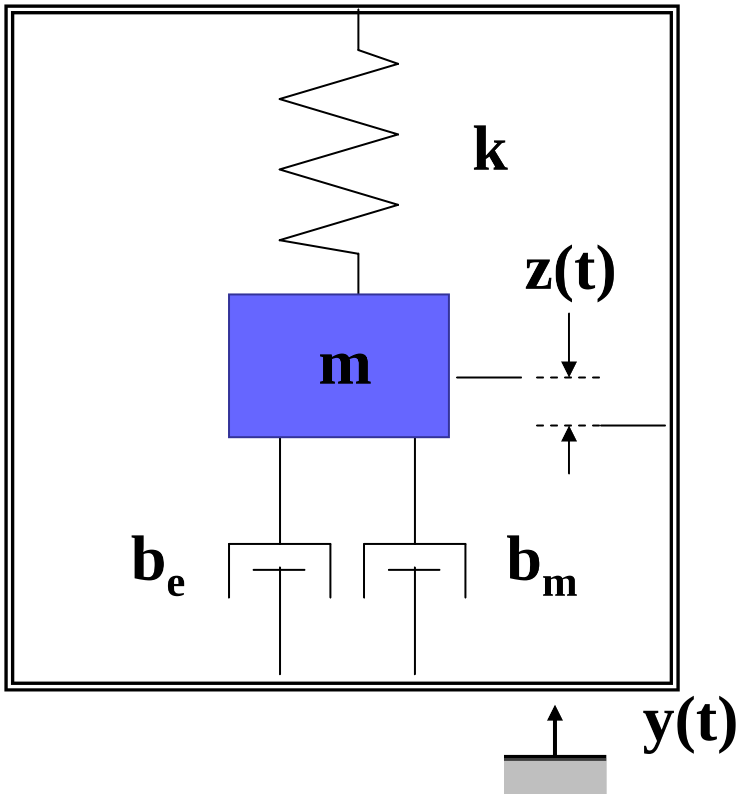
Structural response to ambient vibrations ~ strain

Integrated on Silicon, adheres to standard CMOS processing parameters ~ “on chip”

Manufacturability

Generic Vibration-to-Electricity Conversion Model

$$m\ddot{z} + (b_e + b_m)\dot{z} + kz = -m\ddot{y}$$



z = spring defection

y = input displacement

m = mass

b_e = electrical damping coefficient

b_m = mechanical damping coefficient

k = spring coefficient

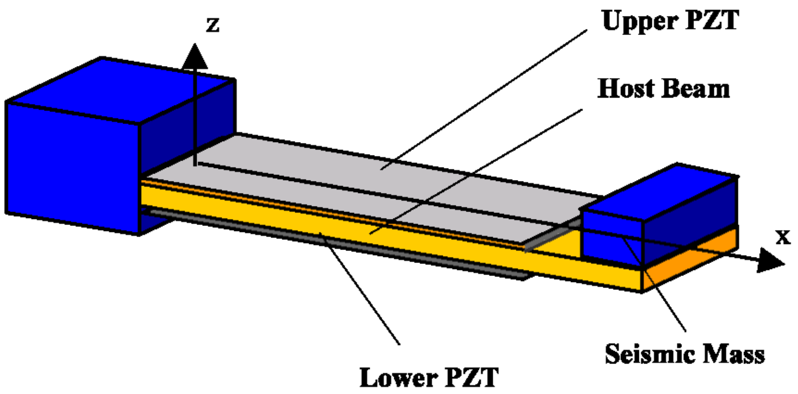
$b = 2m\zeta\omega_n$

$$P = \frac{m\zeta_e A^2}{4\omega(\zeta_e + \zeta_m)^2} \quad ; \omega = \omega_n$$

Willams and Yates, *Transducers 95/Eurosensors IX*, (1995) 368-372

Vibrational Energy Scavenging

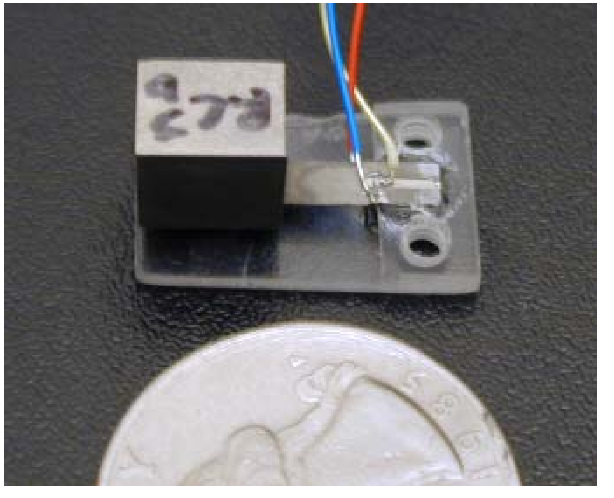
Mesoscale Proof of Concept



Piezoelectric Material -$PbZr_xTi_{1-x}O_3$

- High piezoelectric coefficient
- Large range of solid solubility
- Well characterized properties in the bulk as well as thin film form

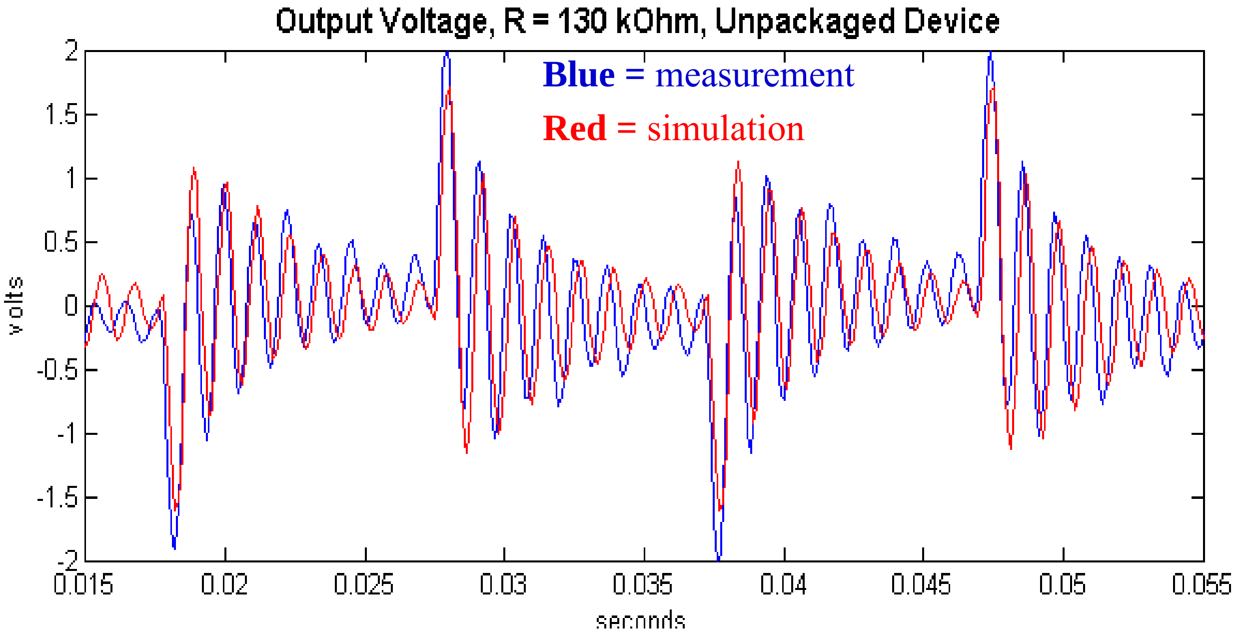
40 mm x 3.5 mm, 2 g mass

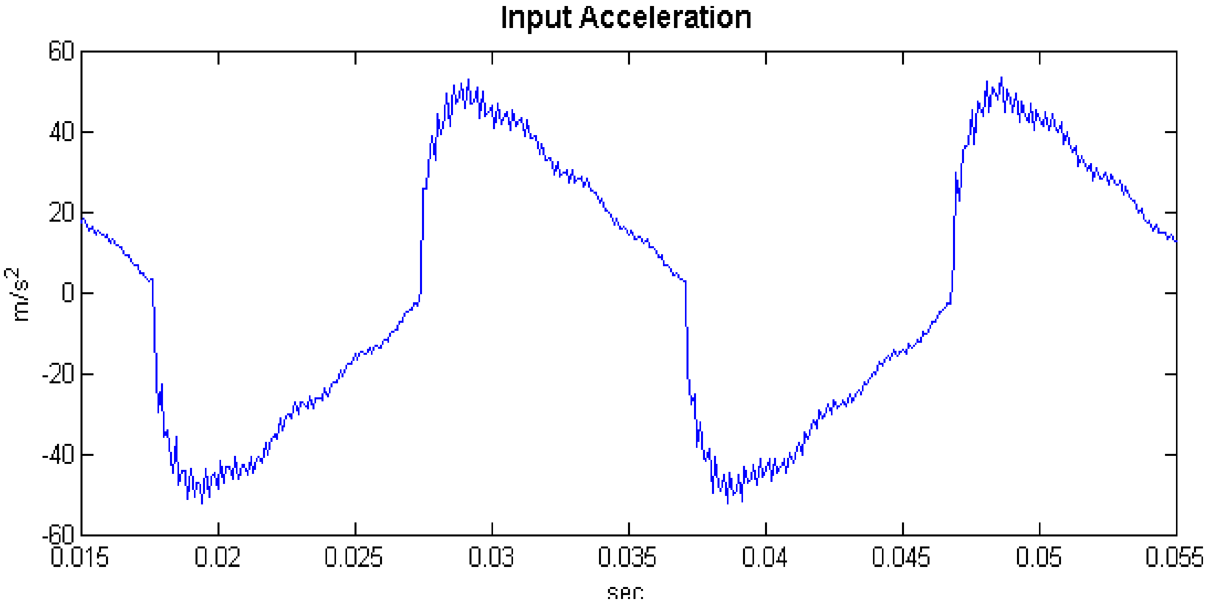


Heterogeneous Bimorph

- Two layers (piezoelectric, elastic)
- Proof mass
- Constitutive equations readily solved
  - adaptable to empirical modifications
  - adaptable to analytical modifications

Mesoscale Results



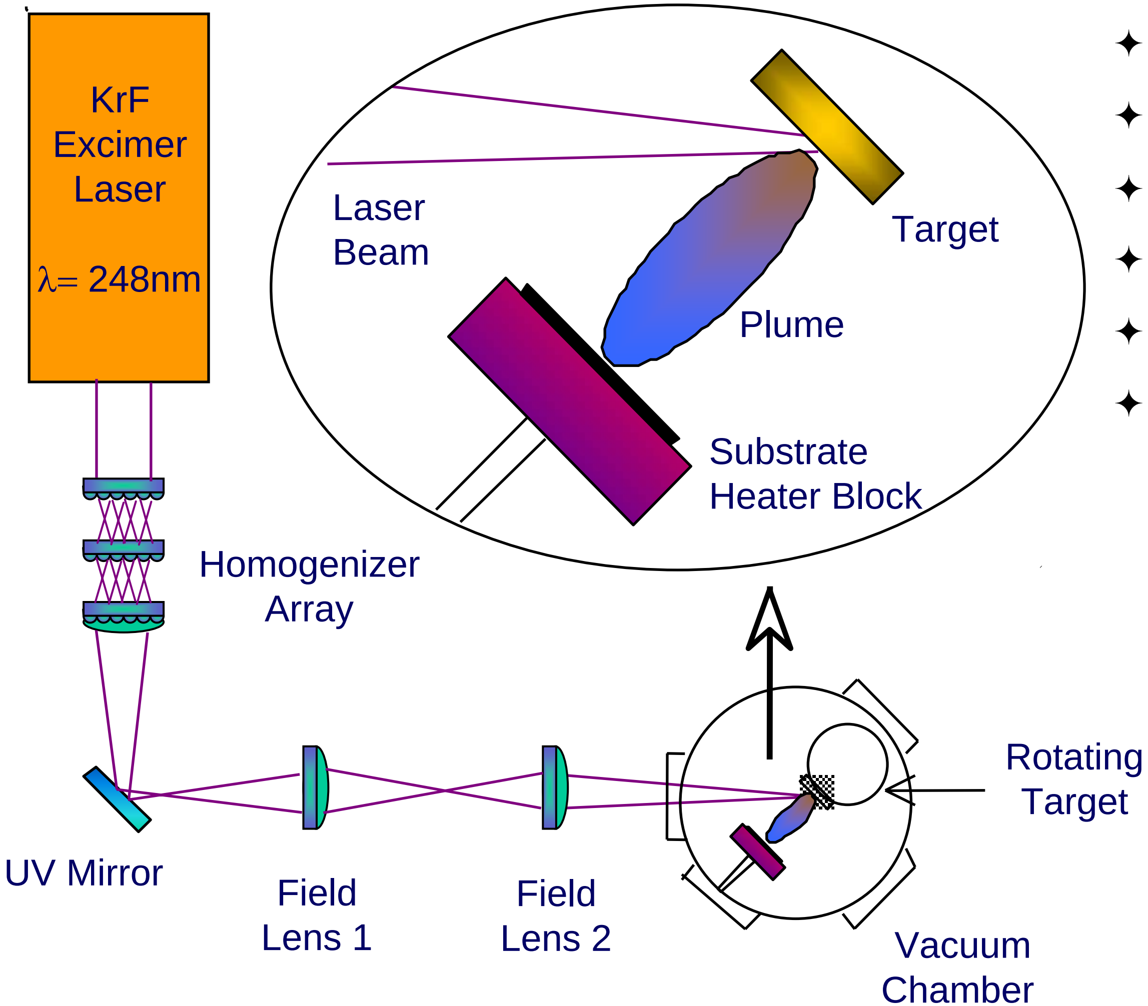


Outline

- Mechanical Design
  - Vibration Sources
  - Beam-Mass System
  - Proof of concept experiment
- Material Considerations
  - Epitaxy
  - Growth Methods
- Manufacturability
  - MEMS Device Constraints (resonant frequency, power output)
  - Residual Stress
- Current Devices
- Preliminary Findings

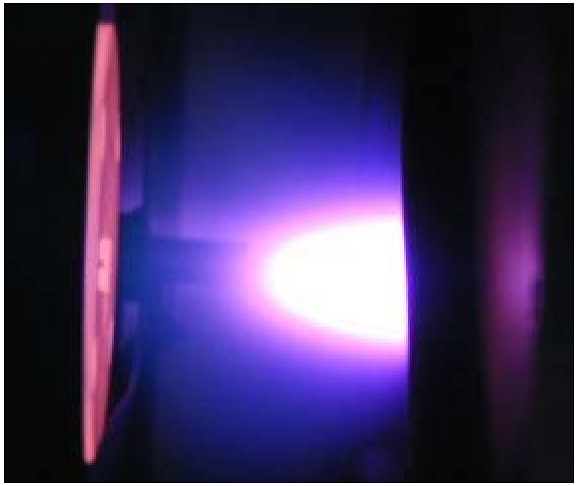
Thin Film Fabrication

Pulsed Laser Deposition



PLD growth conditions

- **650°C - 100 mtorr O_2**
- **Homogenized energy (±5%)**
- **2.5 J/cm² @ 3 Hz (≈ 6-7 Å/s)**
- **$Pb_{1.15}(Zr_{0.47}Ti_{0.53})O_3$** *ferroelectric*
- **$SrRuO_3$** *oxide electrode*
- **$SrTiO_3$/Si** *substrate*

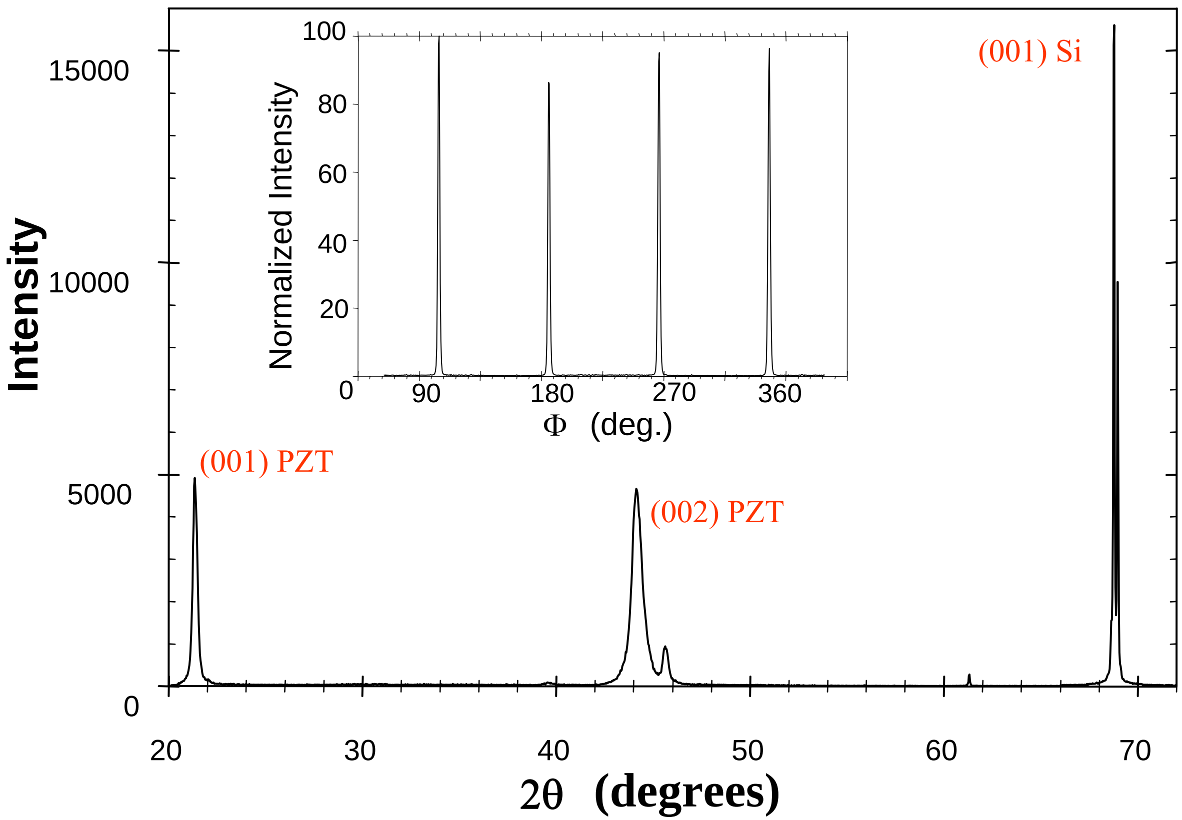


Material Properties

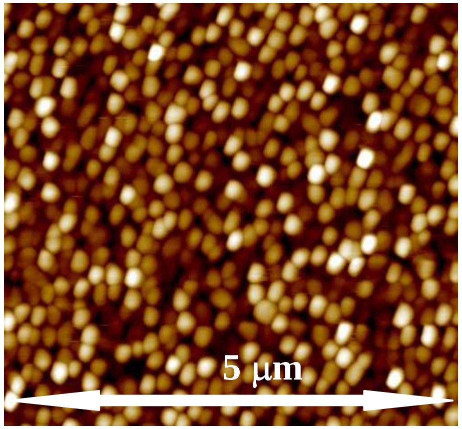
Crystal Structure and Piezoresponse

Epitaxial $PbZr_{0.47}Ti_{0.53}O_3$ (PZT) thin films

- Out-of-plane (c-axis) epitaxy
- Surface Roughness 65 nm, rms 11 nm

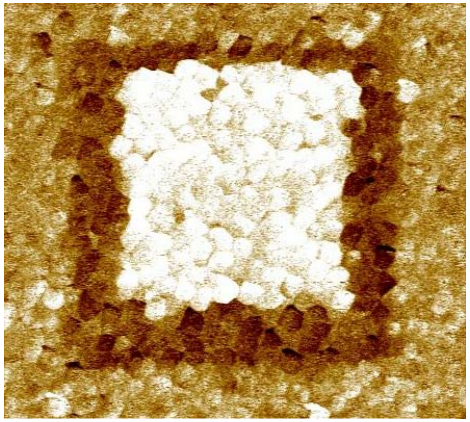


a



Surface Morphology

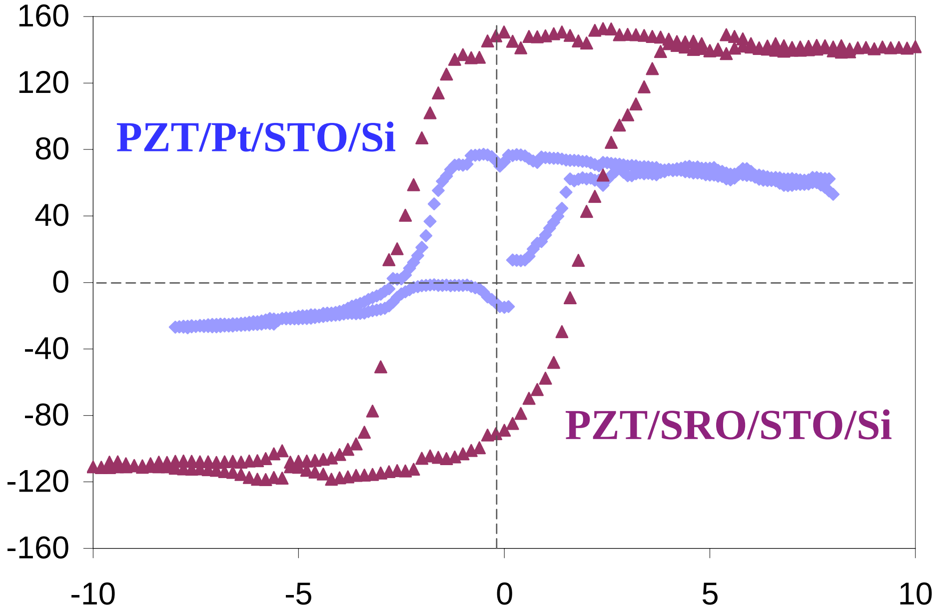
b



Piezoelectric response to -/+ 5 V

Material Properties

Piezoelectric Coefficient and Polarization



Piezoelectric Coefficient

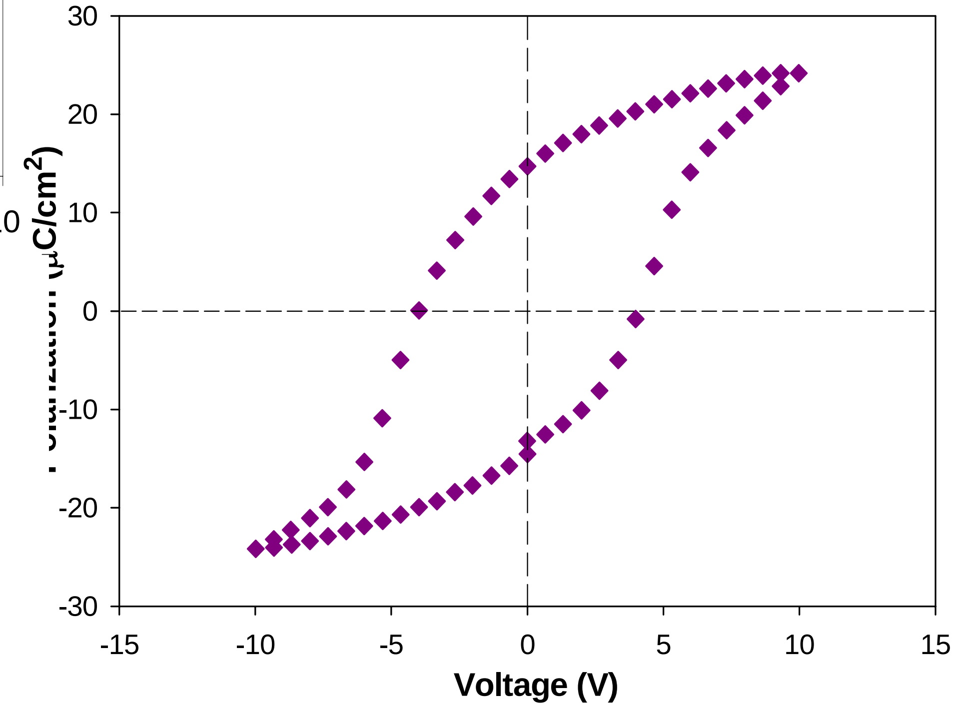
$d_{33} = 155$ pm/V

$d_{33} = 37$ pm/V

Remnant Polarization

$P_r = 15\ \mu C/cm^2$

$P_s = 25\ \mu C/cm^2$



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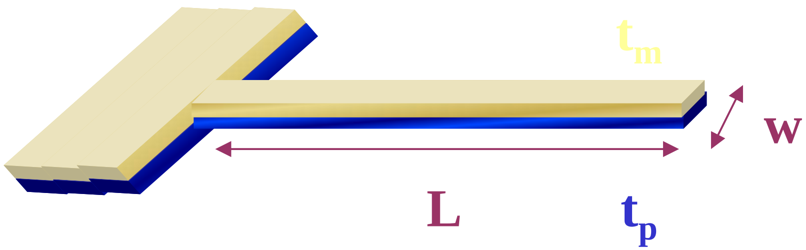
Geometry and Resonant Frequency

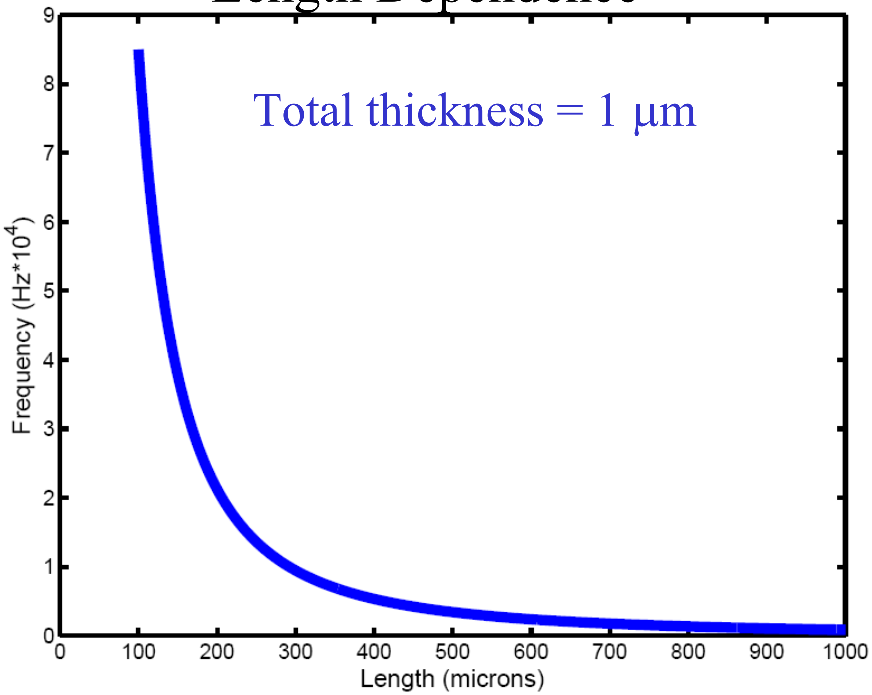
Heterogeneous Unimorph



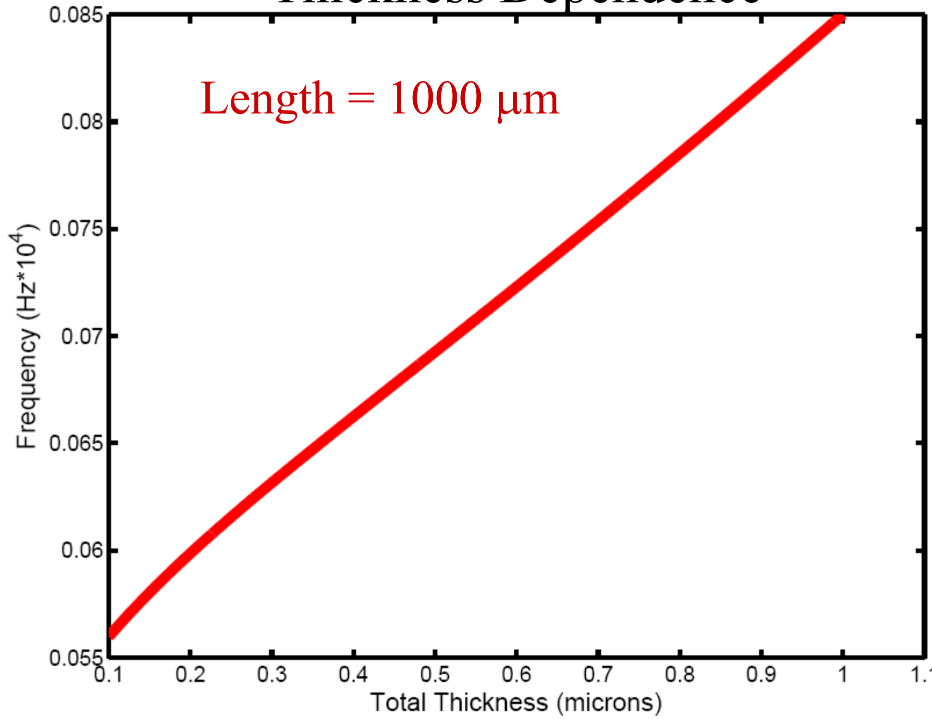
$$f_r = \mathrm{f}\left(L, \rho, \frac{E_m}{E_p}, \frac{t_m}{t_p}\right)$$

$$\approx \frac{t}{L^2}$$

Length Dependence



Thickness Dependence



Q.M. Wang, et. al., *J. Appl. Phys.*, **83** 3 (1999) 1702

Preliminary Power Modeling

Assumptions

$$P = \frac{1}{2} C V^2 \omega$$

- No coupling between cantilever beams

- Single mode bending

- Input acceleration = 2.25 m/s^2

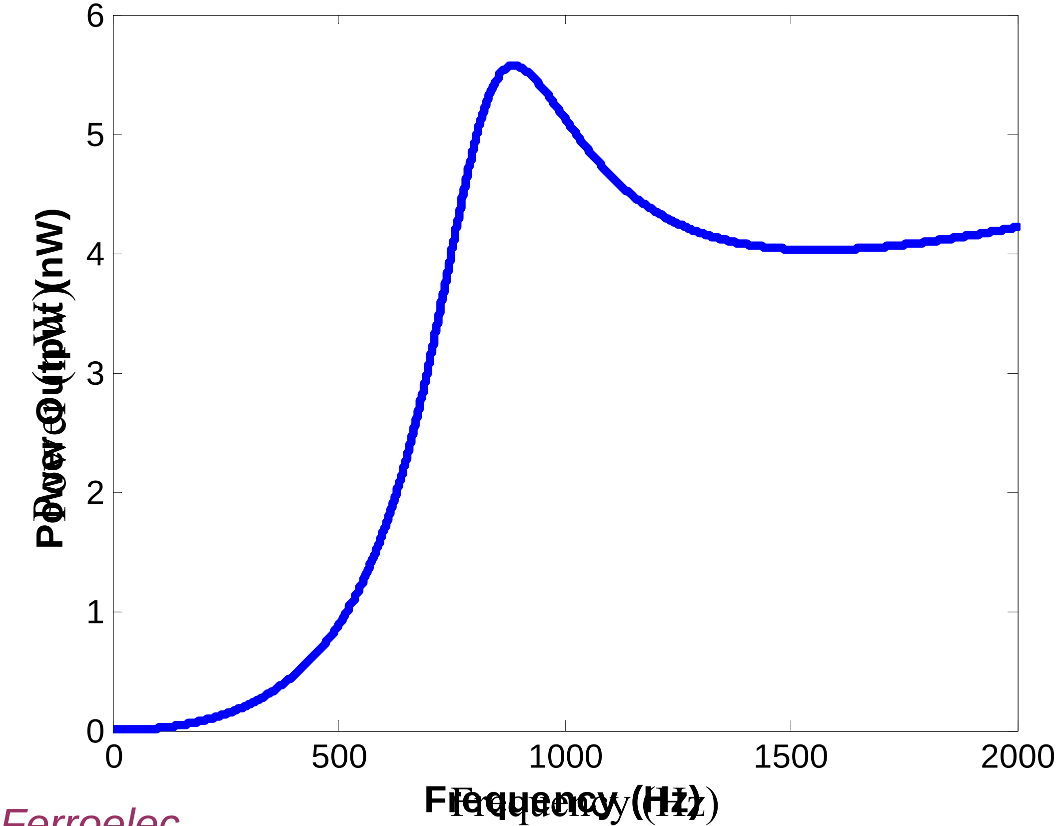
- Length = 800 μm

-Elastic/ piezoelectric layer thickness = 1 μm

Estimated Power Density

• Single Beam - **1-5 nW**

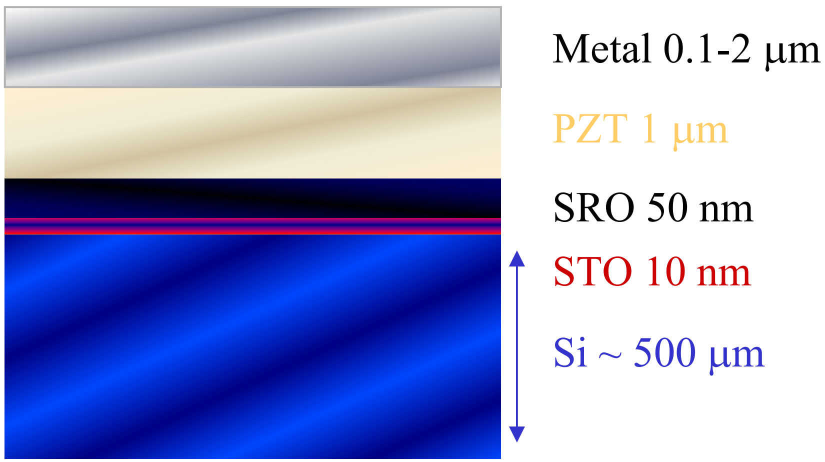
• Volume (1cm^3) - **100-200 μW**



Smits and Choi., *IEEE Trans. Ultrason. Ferroelec. Freq. Control*, **38** 3 (1991) 256

Fabrication Process

Piezoelectric and Elastic Layers



1. $SrTiO_3$ (STO) coated (20 nm) single crystal Silicon **[Motorola, Inc.]**

2. Deposition of $SrRuO_3$ (SRO) bottom electrode, and PZT with pulsed laser deposition.

3. Deposition of metallic elastic layer via e-beam evaporation/thermal evaporation

Elastic Layer Deposition Methods

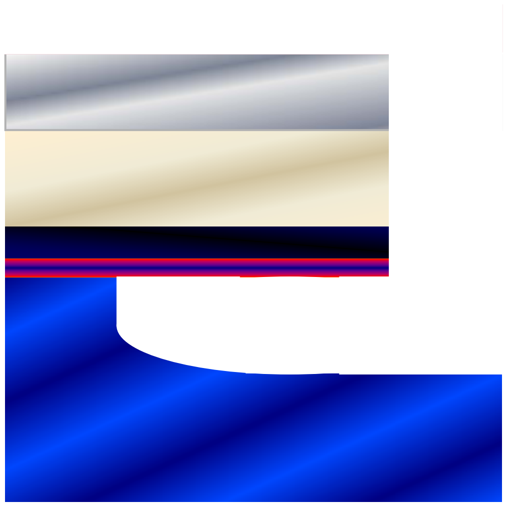
***Pt-** electron beam evaporation, Ti adhesion layer

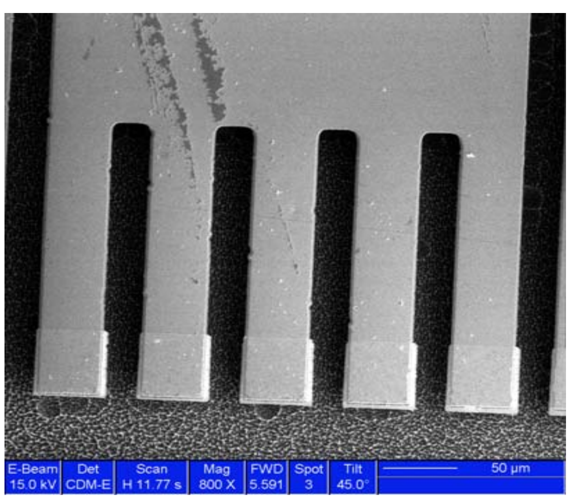
***Pd-** thermal evaporation

***Au-** electron beam/thermal evaporation, Cr adhesion layer

Fabrication Initial Attempt

Cantilever Array Structures



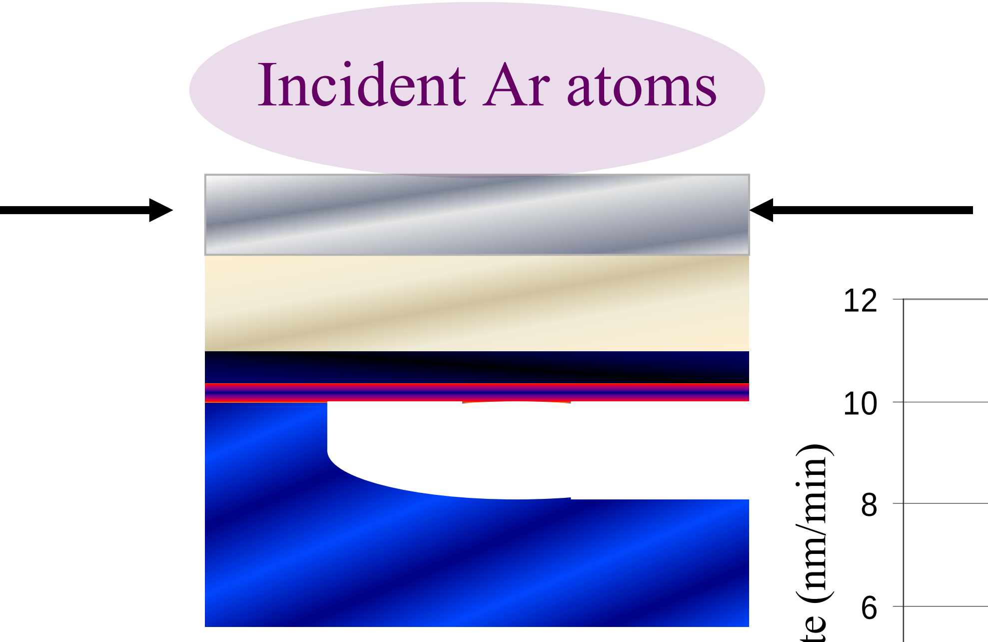


4. Definition of devices using photolithography

5. Etch heterostructure with Ar ion milling to expose Si substrate

6. Release cantilever structure from Si substrate with XeF_2 gaseous etchant

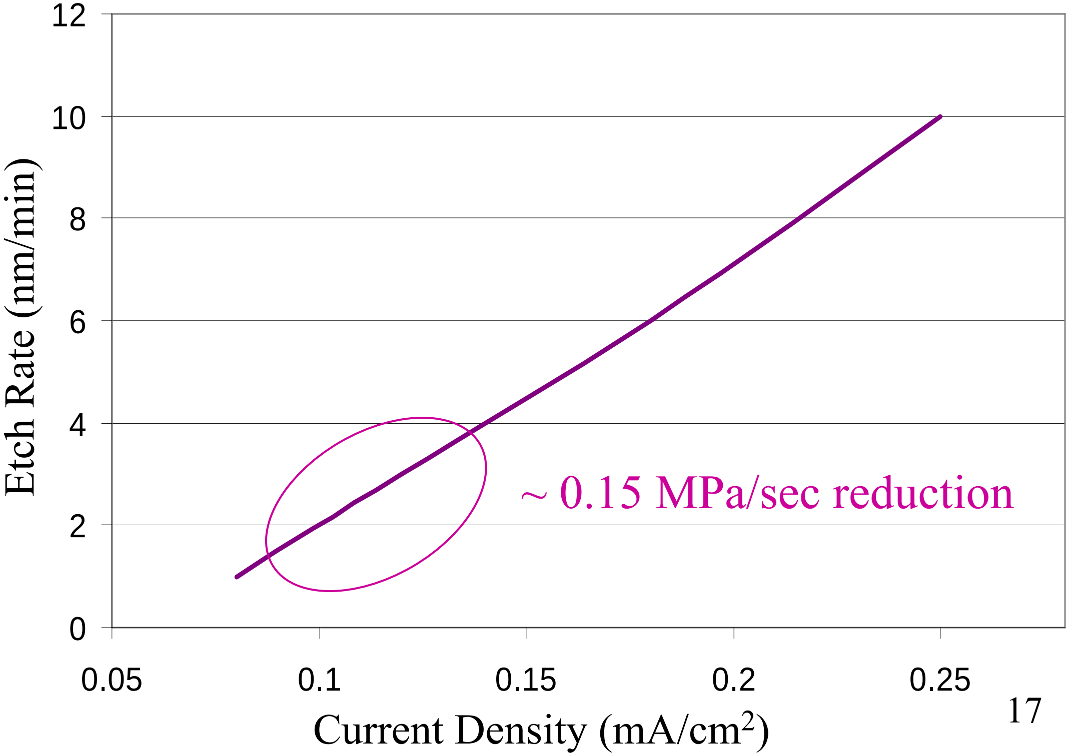
Additional Stress Reduction



Argon Ion Machining

1. Disrupting crystalline structure

Compression



Bifano et al. *J. MEMS*, **11** (5) 2002

Nowack et al. *Mat. Lett.*, **33** (1-2) 1997

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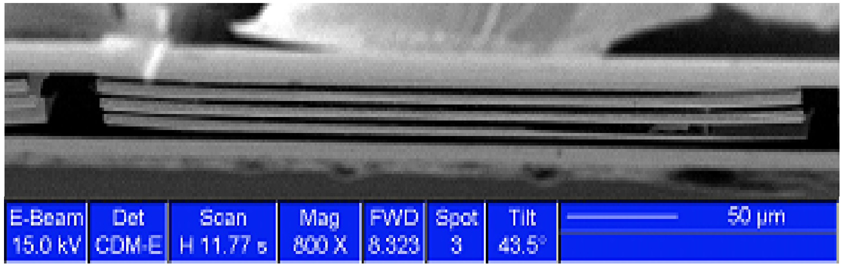
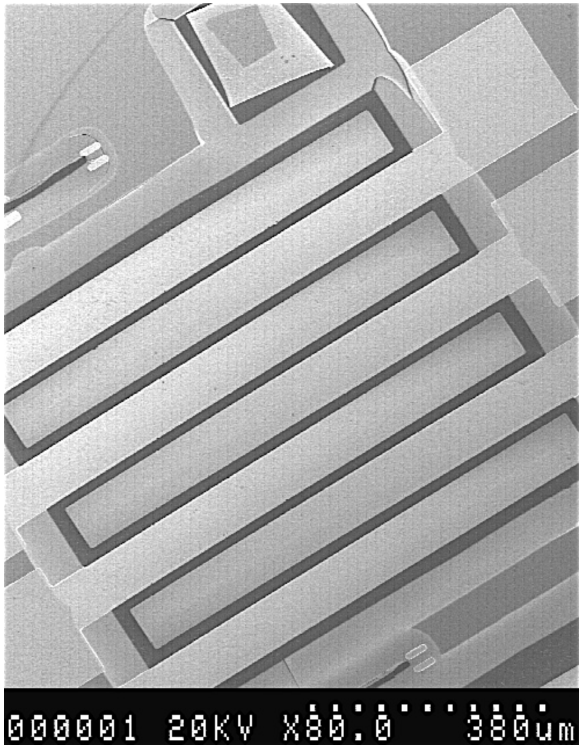
Current Results

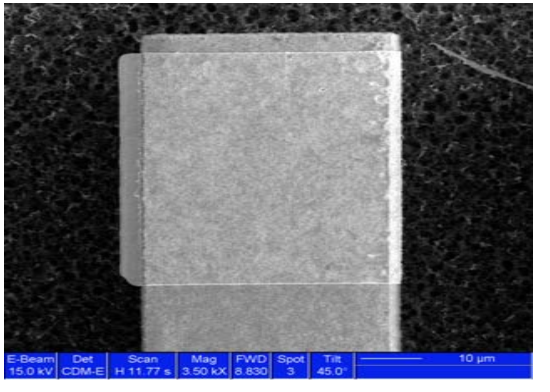
Cantilever array lies completely in-plane





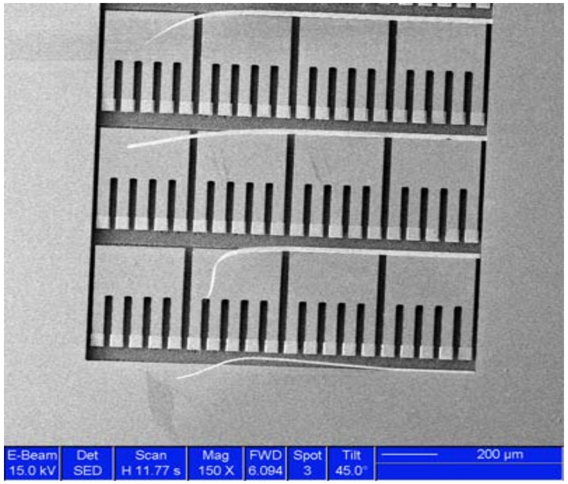
Interdigitated beam design for maximum packing density

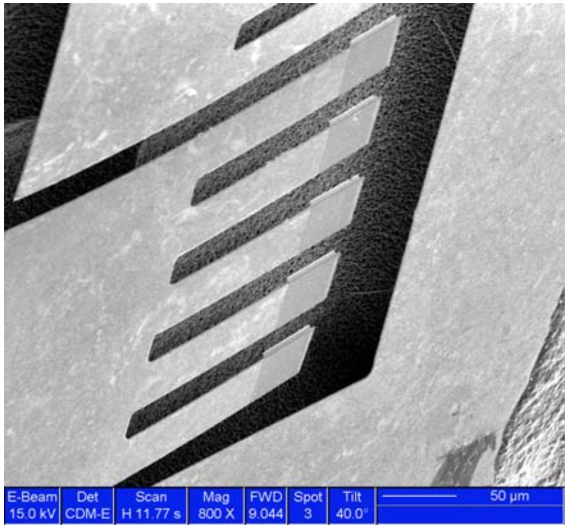
Proof mass design



Preliminary Findings

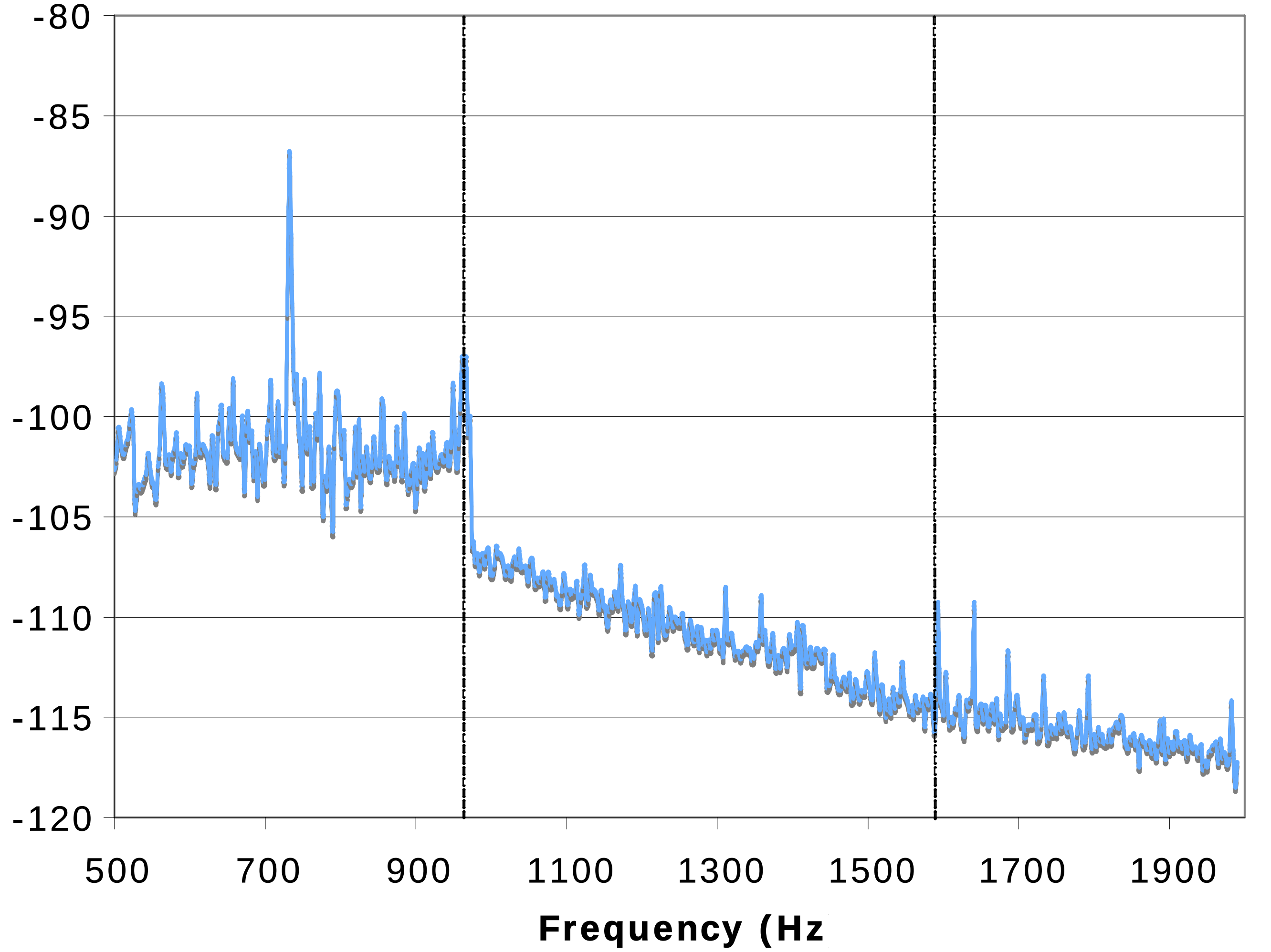
- Pulsed laser deposition can be used to grow epitaxial PZT films on Si substrate
- Thin film piezoelectric coefficient approaches bulk values, shows good switching capabilities
- Power modeling indicates a power density approaching 200 $\mu W/cm^3$
- Cantilever arrays fabricated and released using standard-CMOS compatible processes
- Residual stresses in film reduced





Preliminary Findings (con't)

Resonant Peaks
~ 950 Hz
~ 1.6 kHz



Future Work

- Testing
  – Laser Doppler Vibrometer
- Modeling
  – Power modeling needs to reflect non-linear behavior
  – Damping
- Structure
  – Increase proof mass
  – Coupling Effects
- Electrode Design
  – Integration considerations