Micro-Power Generation

Elizabeth K. Reilly

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TAC-meeting

Energy Scavenging for Wireless Sensors

Enabling Wireless Sensor Networks:

- Ambient energy source

- Piezoelectric transducer technology

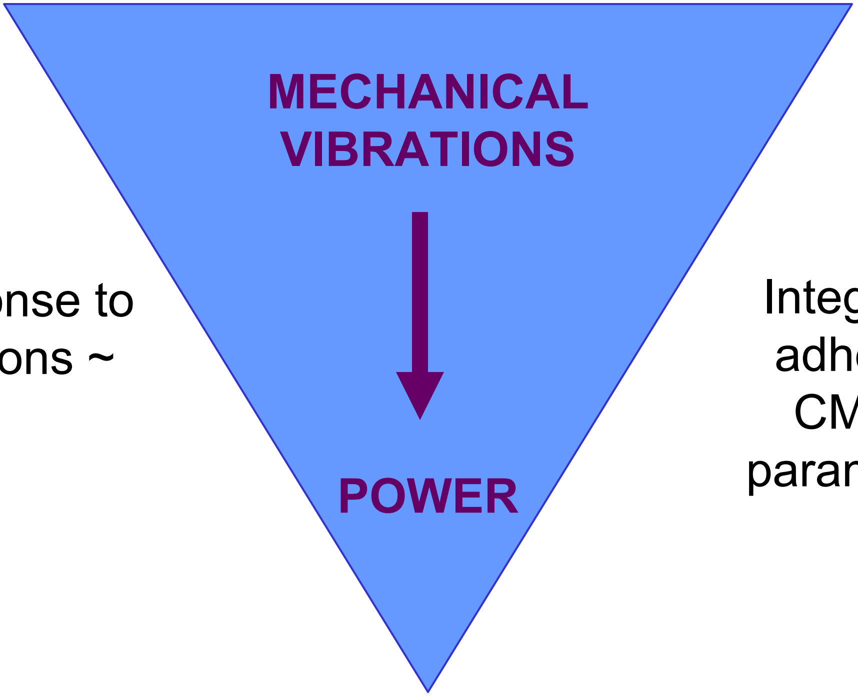
- Novel microelectromechanical system (MEMS)

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

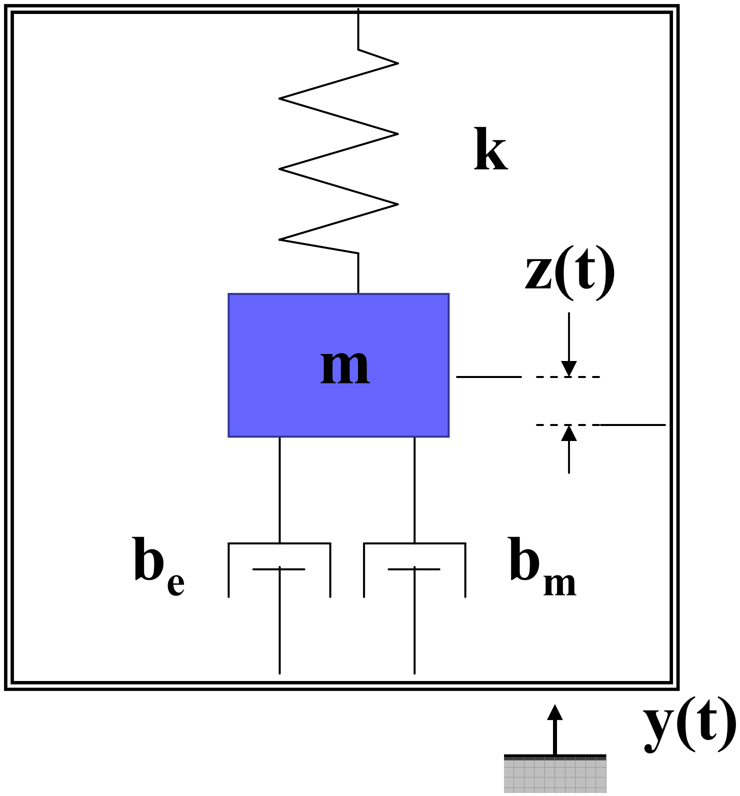
Ambient Vibration Sources

Vibrational Source	Peak Acc. (m/s^2)	Freq. (Hz)
Base of a 3 axis machine tool	10	70
Kitchen blender casing	6.4	121
Clothes dryer	3.5	121
Door frame just as door closes	3	125
Small microwave oven	2.25	121
HVAC vents in office building	0.2 - 1.5	60
Wooden deck with foot traffic	1.3	385
Breadmaker	1.03	121
External windows next to street	0.7	100
Laptop computer with CD running	0.6	75
Washing machine	0.5	109
2nd story of wood frame building	0.2	100
Refrigerator	0.1	240

S. Roundy, *Computer Communications*, **26** (2003) 1131-1144

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

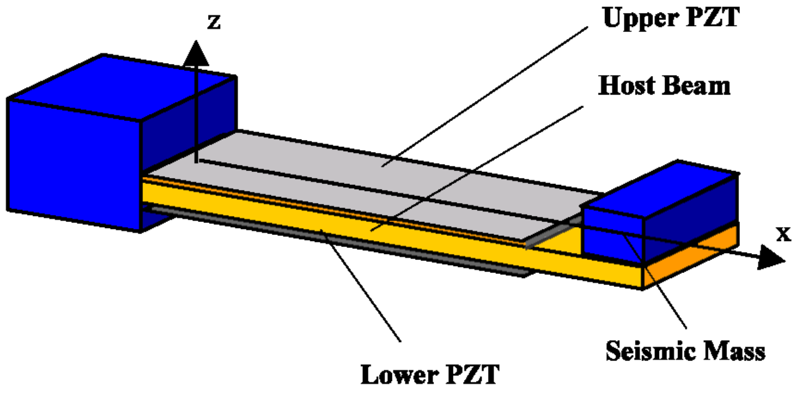
$b = 2m\zeta\omega_n$

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

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

Vibrational Energy Scavenging

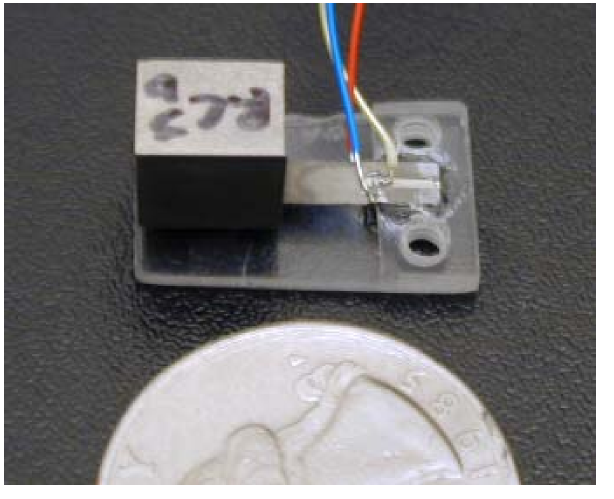
Mesoscale Proof of Concept



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

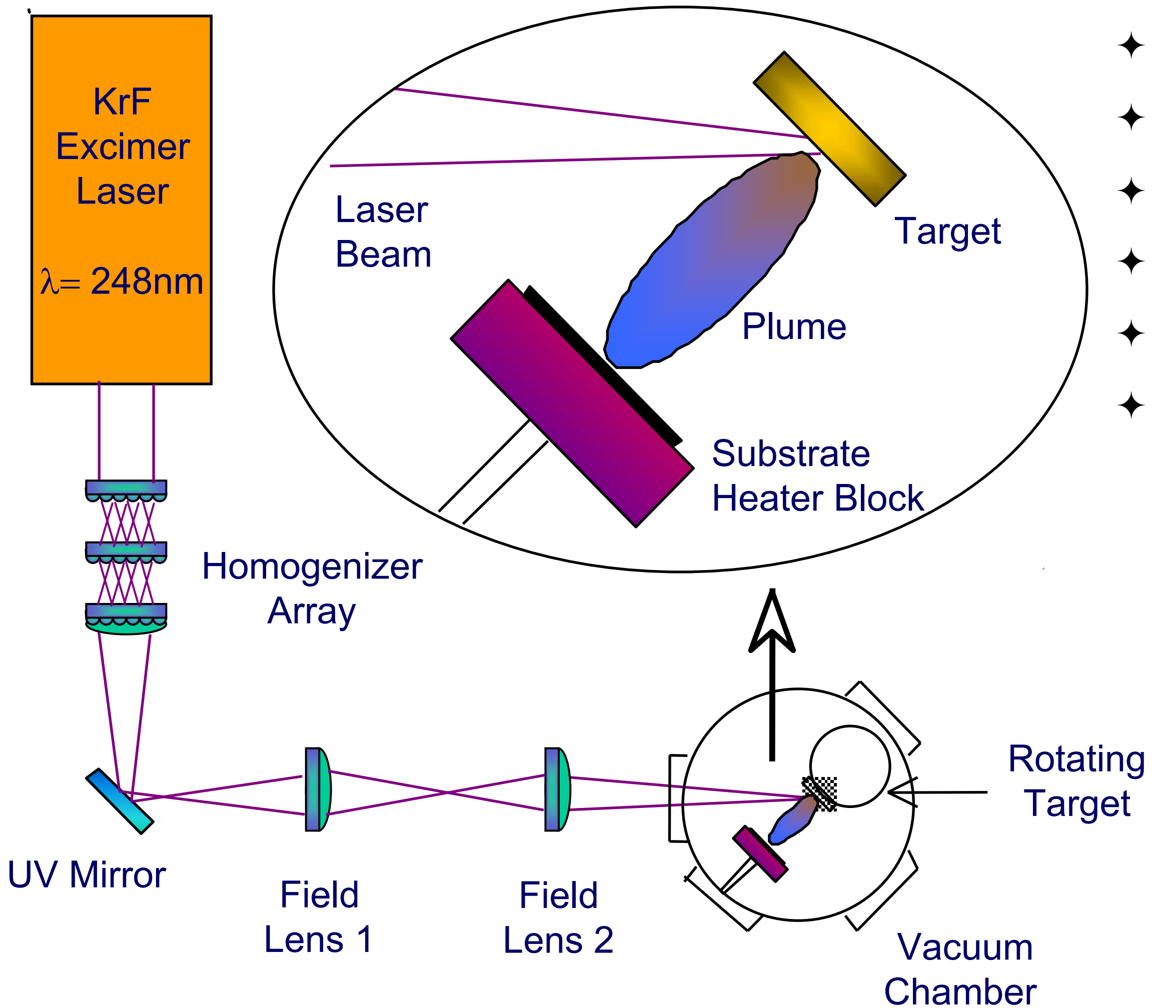


Heterogeneous Bimorph

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

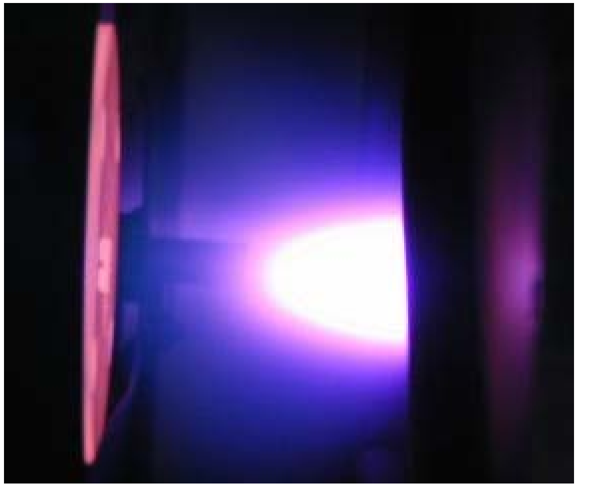
Thin Film Fabrication

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*

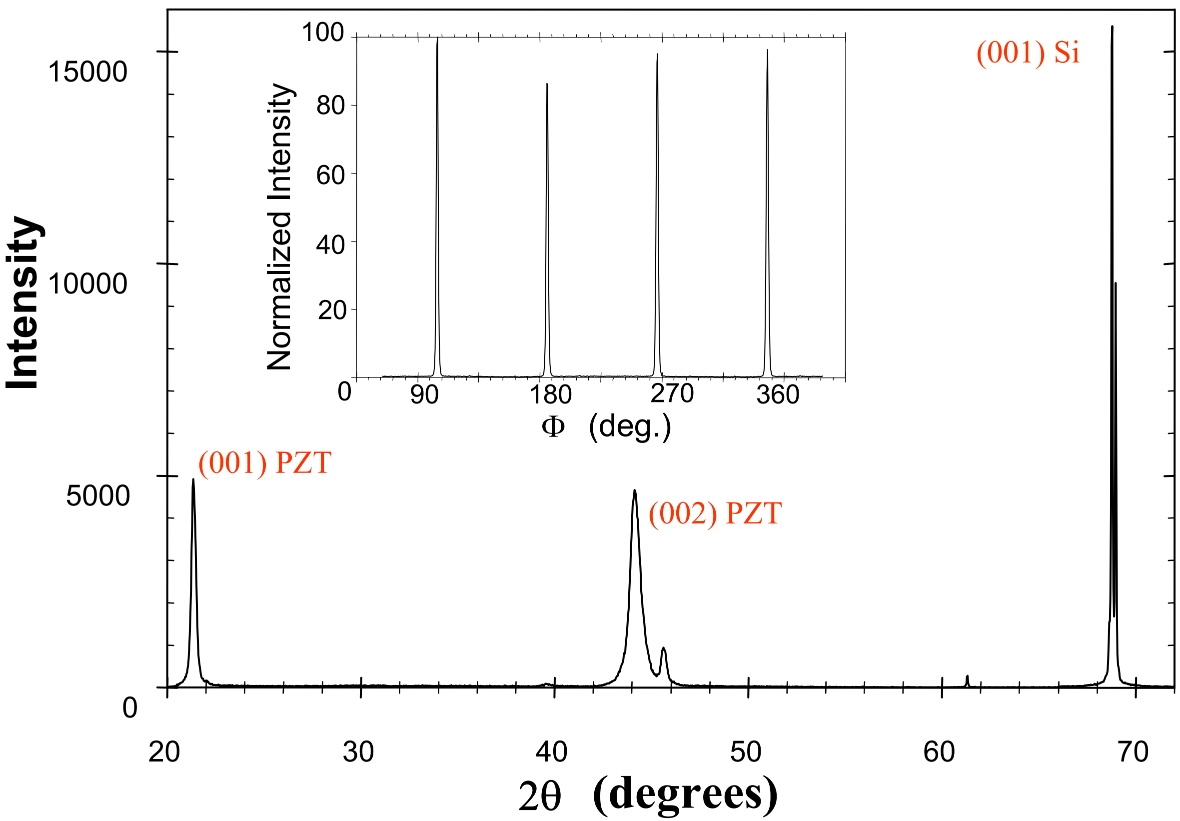


Material Properties

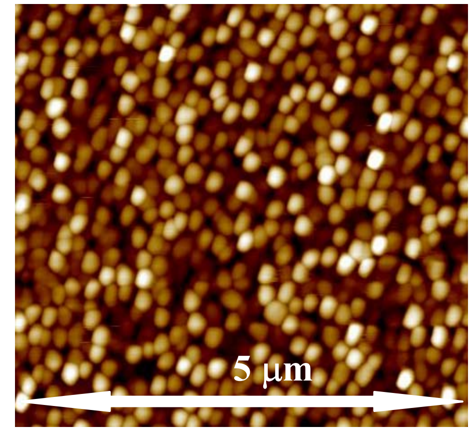
Crystal Structure and Piezoresponse

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

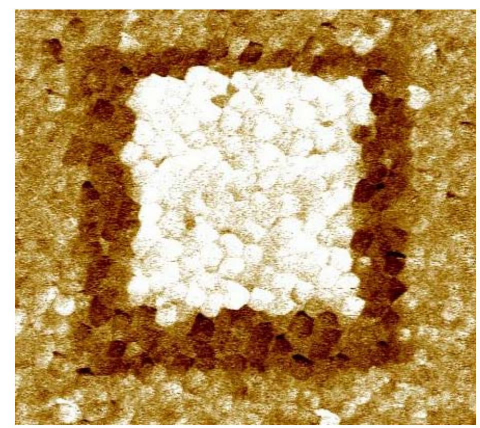


a



Surface Morphology

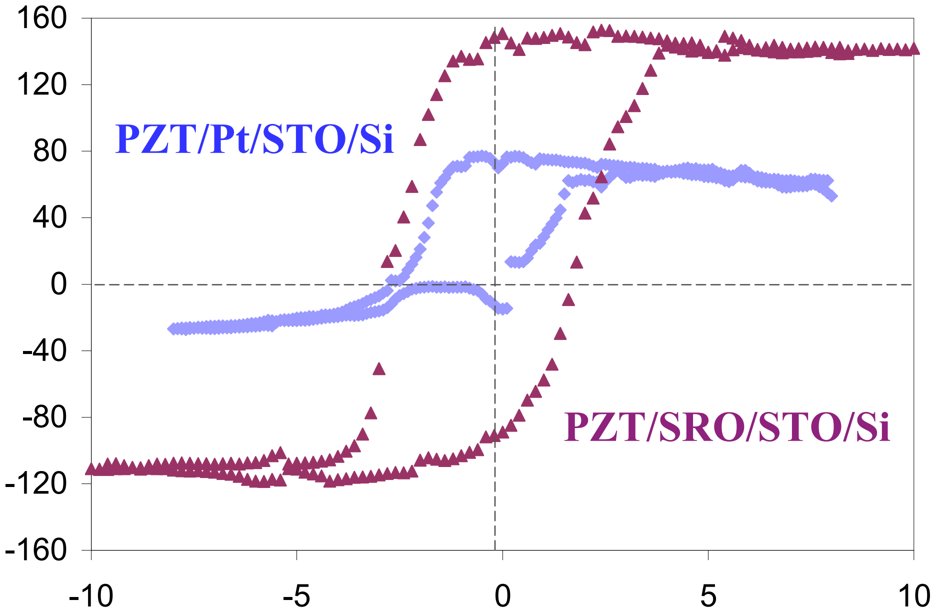
b



Piezoelectric response to -/+ 5 V

Material Properties

Piezoelectric Coefficient and Polarization



Piezoelectric Coefficient

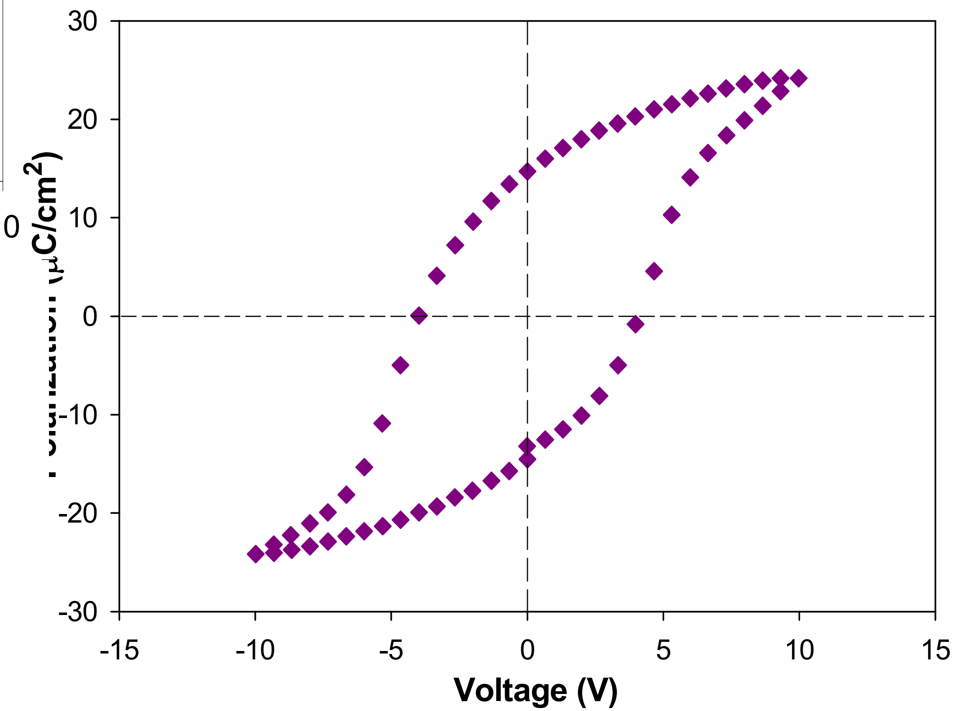
$d_{33} = 155$ pm/V

$d_{33} = 37$ pm/V

Remnant Polarization

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

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



Preliminary Power Modeling

Assumptions

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

- No coupling between cantilever beams

- Single mode bending

- Input acceleration = 2.25 m/s^2

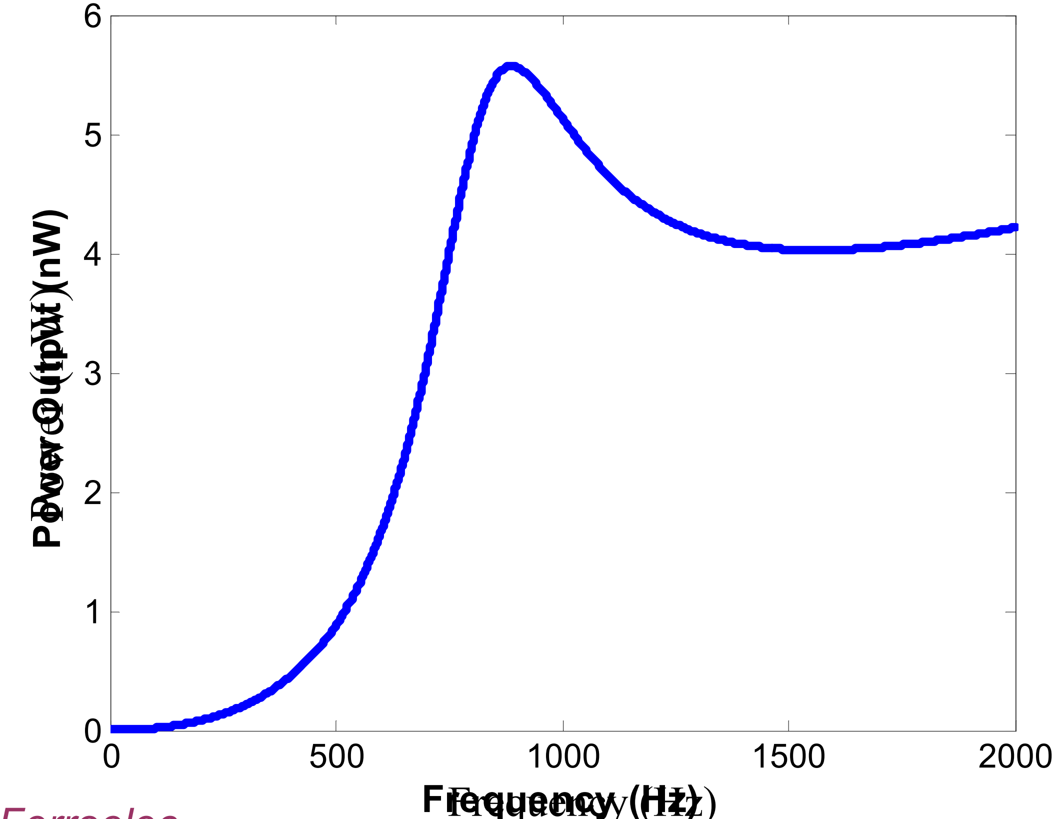
- Length = 800 μm

-Elastic/ piezoelectric layer thickness = 1 μm

Estimated Power Density

• Single Beam - **1-5 nW**

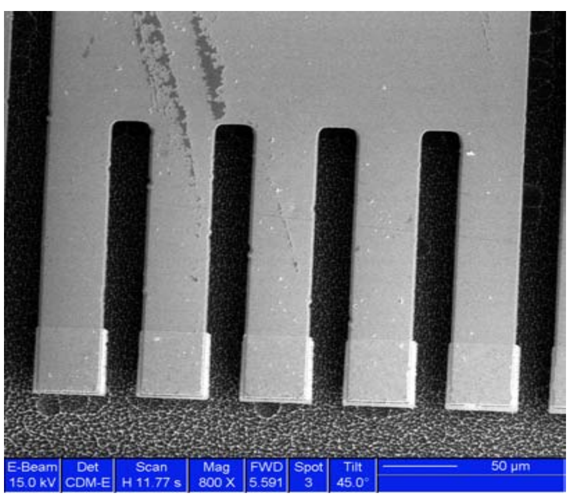
•Volume (1cm^3) - **100-200 μW**



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

Microfabrication

Cantilever Array Structures



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. Definition of devices using photolithography

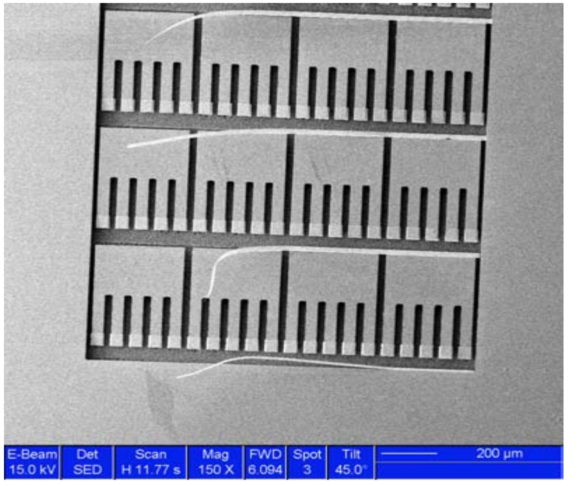
4. Etch heterostructure with Ar ion milling to expose Si substrate

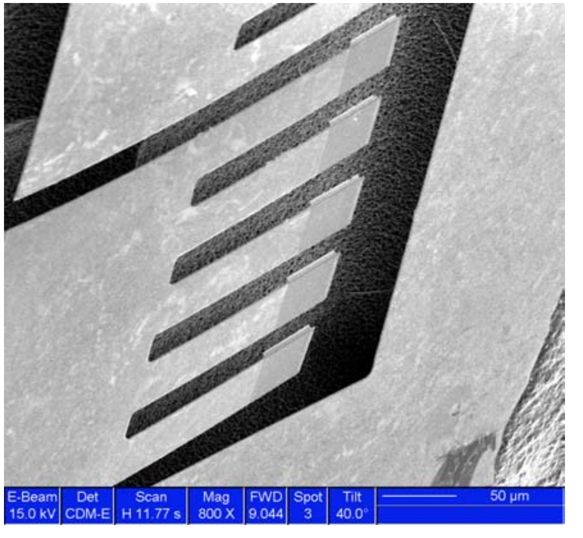
5. Deposition of metallic elastic layer via e-beam evaporation/thermal evaporation

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

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
- Cantilever beams are highly damped
- Intial power output 1-2 $\mu W/cm^3$





Conclusions

- Energy scavenging is essential for ubiquitous integration of wireless sensor networks in residential and industrial settings
- Ambient mechanical vibrations represent a viable energy source
- Previous research has shown piezoelectric materials to be an efficient energy transducer
- Microscale piezoelectric energy scavenging devices successfully designed and fabrication
- Power modeling indicates achievable power density to be 100 $\mu W/cm^3$
- Current results are 1 $\mu W/cm^3$
- Improvements are underway in both design and material selection

Micro-Power take always!

Enabling Wireless Sensor Networks:

- **Ambient energy source**
- **Piezoelectric transducer technology**
- **Novel microelectromechanical system (MEMS)**