Bio-History of Kenji Uchino

- **University professor = 40 years**
  Tokyo Tech–10 yrs, Sophia Univ–8 yrs, Penn State–24 yrs
- **Company executive = 21 years**
- **Government Officer = 4 years**
- **Japanese 20 years vs. US 20 years**
- **"One step ahead"**
  Age 40s = Academic initiative
  Age 50s = Entrepreneur
  Age 60s = Program officer
- **"Discover/Inventor"**
  Piezoelectric ML actuators, PMN electrostrictors, Relaxor single crystals, Micro motors, Piezoelectric transformers, HiPoCS

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PENNSTATE ICAT

Loss Mechanisms in Smart Materials

Kenji Uchino
Int'l Center for Actuators & Transducers
The Pennsylvania State University

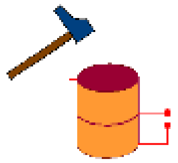
1. Background: Smart Materials
2. Fundamental Loss Equations for Piezoelectrics & Magnetostrictors
3. High Power Characterization System
4. New Q_M Determination Methods
5. Origin of High Power Performance
6. Summary

3

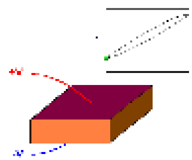
Background

What's "Piezoelectric Effect"?

DIRECT PIEZOELECTRIC EFFECT



CONVERSE PIEZOELECTRIC EFFECT



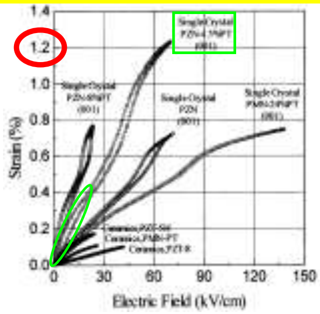
Igniter
Microphone
Pressure Sensor

Clock
Speaker
Actuator

4

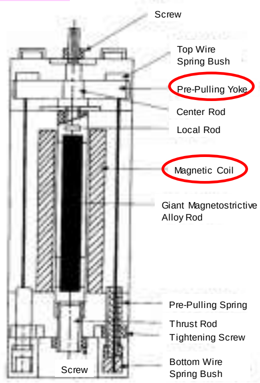
Background

Field Induced Strains in Single Crystals $Pb(Zn_{1/3}Nb_{2/3})O_3$-$PbTiO_3$ etc.

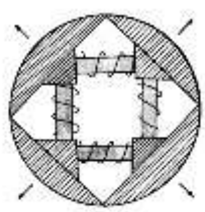


[S.E. Park and T.R. Shrout: Mat. Res. Innovat. 1, 20 (1997)]

Background



Construction of a giant magnetostrictive actuator.



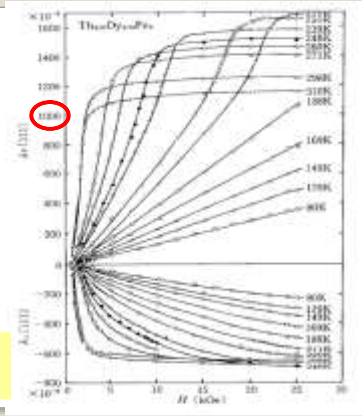
High power acoustic transducer using 4 magnetostrictive actuators.

Uchino and Giniewicz, "Micromechatronics," Marcel Dekker (2003)

6

Background

Longitudinally and transversely induced strains in a Terfenol-D for various temperatures.



Uchino and Giniewicz, "Micromechatronics," Marcel Dekker (2003)

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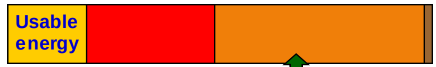
Background

Electromechanical Coupling Factor

Typical Piezoelectric PZT

k_{33} = 70 % ⇒ k_{33}^2 = 50 %

Input electrical energy 100



Mechanical energy converted 50

Electrical energy stored in a capacitor 49

Loss 1

Dissipated as heat

Energy Transmission Coefficient

λ = (Mech. Output Energy / Electr. Input Energy)

= (1/4~1/2) k^2

Uchino, "Ferroelectric Devices 2nd Edit.", CRC Press, NY (2009)

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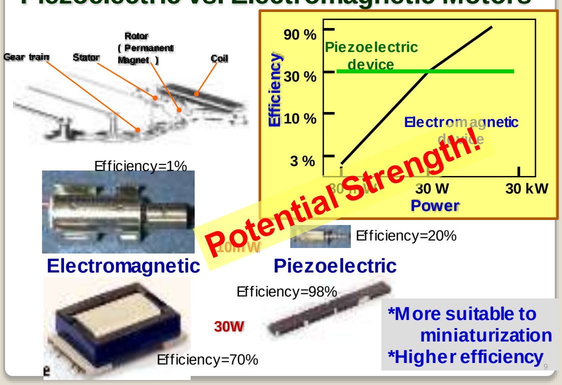
Background

Piezoelectric vs. Electromagnetic Motors



Electromagnetic

Piezoelectric

*More suitable to miniaturization

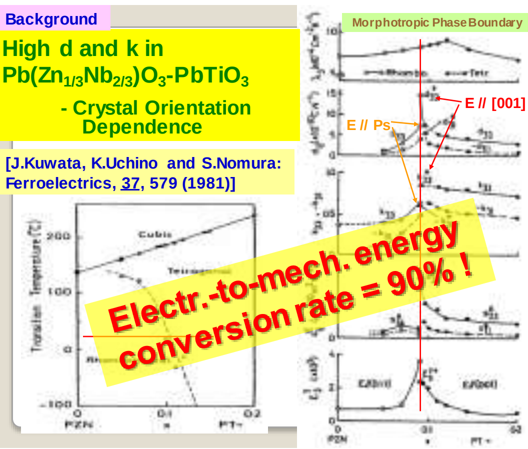
*Higher efficiency

Background

High d and k in $Pb(Zn_{1/3}Nb_{2/3})O_3$-$PbTiO_3$

- Crystal Orientation Dependence

[J.Kuwata, K.Uchino and S.Nomura: Ferroelectrics, 37, 579 (1981)]



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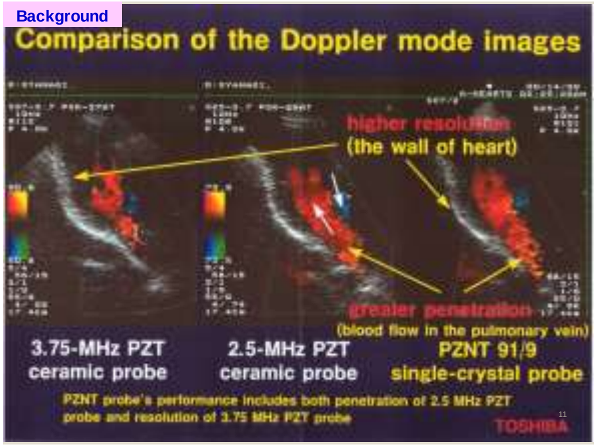
Background



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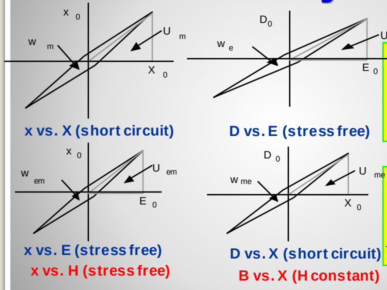
Fundamental

Hysteresis Losses

Piezoelectic & Piezomagnetic



$$x = s^* X + d^* E$$

$$D = d^* X + \varepsilon^* E$$

$$x = s^* X + d_m^* H$$

$$B = d_m^* X + \mu^* H$$

- Three losses: elastic, dielectric and piezoelectric (or piezomagnetic)

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Fundamental

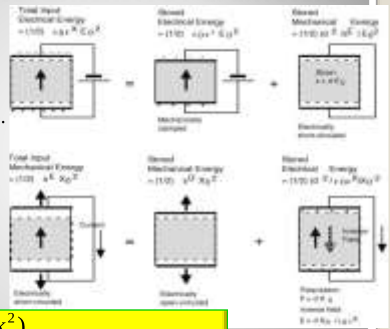
Intensive vs. Extensive Parameters

Intensive:

ε^X - dielectric constant (constant stress);
s^E - elastic compliance (constant electric field).

Extensive:

ε^x - dielectric constant (constant strain);
s^D - elastic compliance (constant electric displacement).



$$\varepsilon^x / \varepsilon^X = (1-k^2) \qquad k^2 = d^2 / s^E \varepsilon^X$$

$$s^D / s^E = (1-k^2)$$

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Fundamental

Loss Factors

Intensive loss factors

$$\varepsilon^{X*} = \varepsilon^X (1 - j \tan\delta')$$

$$s^{E*} = s^E (1 - j \tan\phi')$$

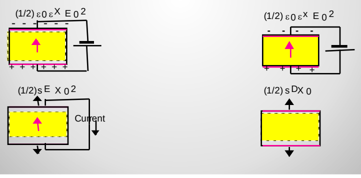
$$d^* = d(1 - j \tan\theta')$$

Extensive loss factors

$$\kappa^{x*} = \kappa^x (1 + j \tan\delta)$$

$$c^{D*} = c^D (1 + j \tan\phi)$$

$$h^* = h(1 + j \tan\theta)$$



Fundamental

Loss Factors

Intensive loss factors **Extensive loss factors**

$$\tan\delta' = \left(\frac{1}{1-k^2}\right)\left[\tan\delta + k^2(\tan\phi - 2\tan\theta)\right]$$

$$\tan\phi' = \left(\frac{1}{1-k^2}\right)\left[\tan\phi + k^2(\tan\delta - 2\tan\theta)\right]$$

$$\tan\theta' = \left(\frac{1}{1-k^2}\right)\left[\tan\delta + \tan\phi - (1+k^2)\tan\theta\right]$$

$$\begin{bmatrix}\tan\delta' \\ \tan\phi' \\ \tan\theta'\end{bmatrix} = K \begin{bmatrix}\tan\delta \\ \tan\phi \\ \tan\theta\end{bmatrix} \qquad K = \frac{1}{1-k^2}\begin{bmatrix}1 & k^2 & -2k^2 \\ k^2 & 1 & -2k^2 \\ 1 & 1 & -1-k^2\end{bmatrix}$$

K is involutory, i.e. $K^2 = I$, or $K = K^{-1}$.

The conversion relationship between the intensive (prime) and extensive (non-prime) exhibits full symmetry. The eigen values of the matrix K are 1, 1, and -1, and the invariant is $(2\tan\theta' - \tan\delta' - \tan\phi') = -(2\tan\theta - \tan\delta - \tan\phi)$

(Loss of k^2)

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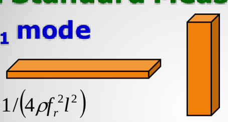
Fundamental

Wrong assumption that Qm is the same for both Resonance and Antiresonance state !

IEEE Standard Measurement on Q_m

k_{31} mode



k_{33} mode

$$s_{11}^E = 1/\left(4\rho f_r^2 l^2\right)$$

$$K_{31}^2 = \frac{\pi}{2}\frac{f_{ar}}{f_r}\tan\left(\frac{\pi}{2}\frac{\Delta f}{f_r}\right)$$

$$where, K_{31}^2 = \frac{k_{31}^2}{1-k_{31}^2}$$

$$Q_m = \frac{Y_m^{max} * \pi^2}{8 * \omega_0 * C * K_{31}^2}$$

$$s_{33}^D = 1/\left(4\rho f_{ar}^2 l^2\right)$$

$$K_{33}^2 = \frac{\pi}{2}\frac{f_r}{f_{ar}}\tan\left(\frac{\pi}{2}\frac{\Delta f}{f_{ar}}\right)$$

$$K_{33}^2 = \frac{k_{33}^2}{1-k_{33}^2}$$

$$Q_m = \frac{Y_m^{max}}{4 * \pi * \Delta f * C}$$

IEEE Standard on Piezoelectricity, ANSI/IEEE Std 176-1987

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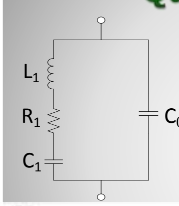
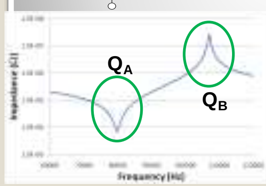
Fundamental

Quality Factors



$$Q = \frac{\sqrt{L_1 / C_1}}{R_1}$$

IEEE Std. $Q_A = Q_B = Q_m$.



Experiment $Q_A < Q_B$.

Difference → ***tan θ'***

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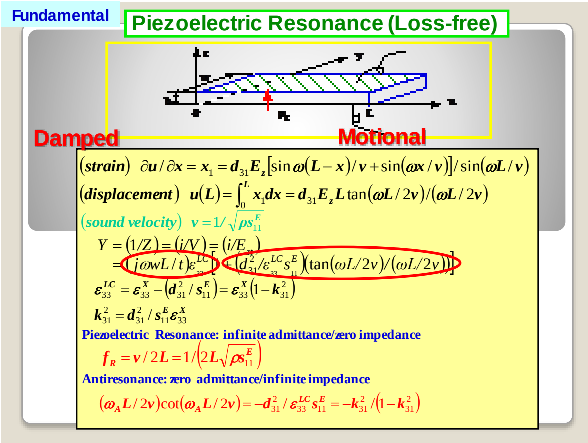
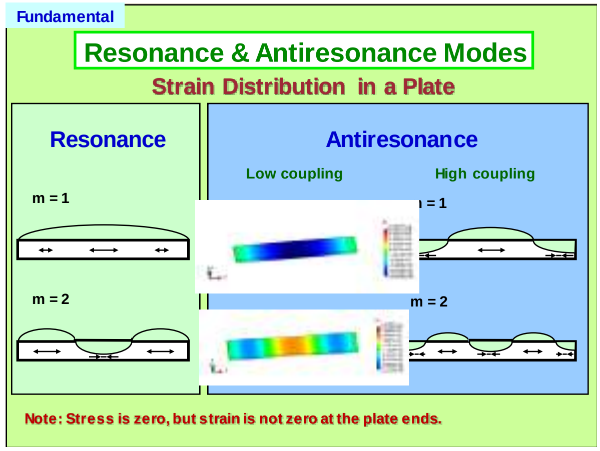
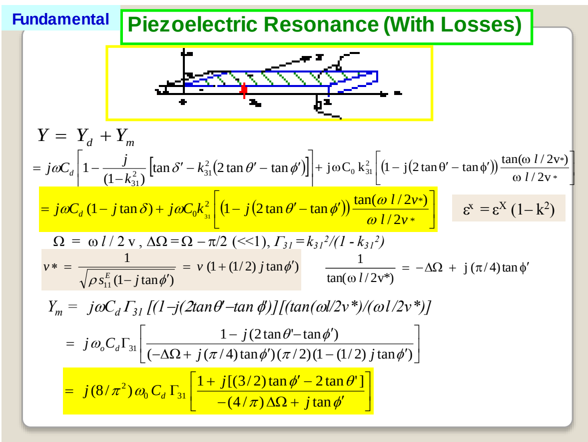
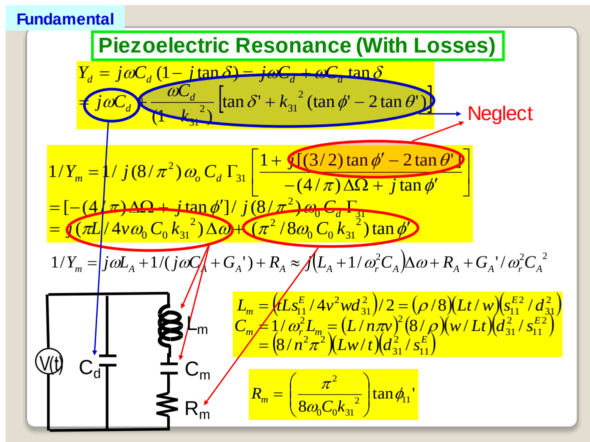
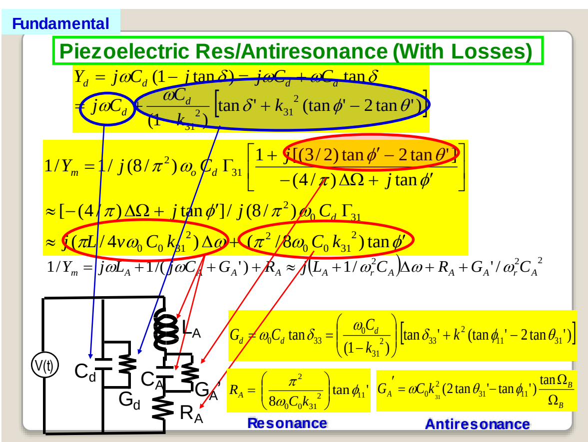
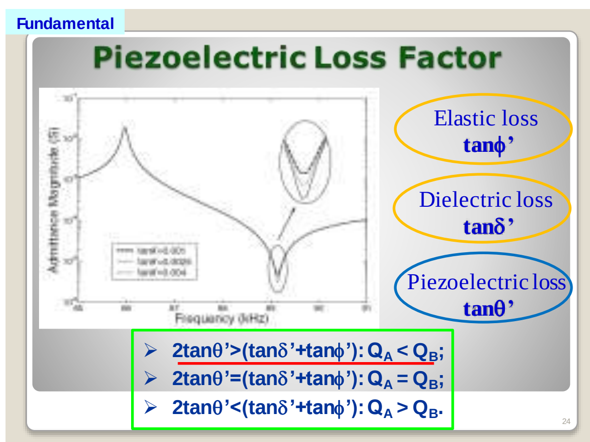

Fundamental
Piezoelectric Resonance (Loss-free)
Damped
Motional
(strain)
(displacement)
(sound velocity)
Piezoelectric Resonance: infinite admittance/zero impedance
Antiresonance: zero admittance/infinite impedance


Fundamental
Resonance & Antiresonance Modes
Strain Distribution in a Plate
Resonance
Antiresonance
Low coupling
High coupling
m = 1
m = 2
Note: Stress is zero, but strain is not zero at the plate ends.


Fundamental
Piezoelectric Resonance (With Losses)


Fundamental
Piezoelectric Resonance (With Losses)
Neglect
Lm
Cm
Rm
Cd
V(t)


Fundamental
Piezoelectric Res/Antiresonance (With Losses)
LA
CA
GA
RA
Cd
Gd
V(t)
Resonance
Antiresonance


Fundamental
Piezoelectric Loss Factor
Elastic loss
tanφ'
Dielectric loss
tanδ'
Piezoelectric loss
tanθ'
Frequency (kHz)
Admittance Magnitude (S)
2tanθ'>(tanδ'+tanφ'): QA < QB;
2tanθ'=(tanδ'+tanφ'): QA = QB;
2tanθ'<(tanδ'+tanφ'): QA > QB.

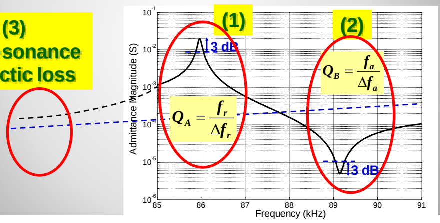
Fundamental

Theoretical Derivation k_{31} Mode

$$\frac{1}{Q_A} = \tan\phi' \qquad \frac{1}{Q_B} = \frac{1}{Q_A} + \frac{2}{1+(\frac{1}{k_{31}} - k_{31})^2\Omega_b^2}(\tan\delta' + \tan\phi' - 2\tan\theta') \qquad \Omega_b = \frac{\omega_b l}{2v}$$

➢ Because $Q_B > Q_A$, $2\tan\theta' > (\tan\delta' + \tan\phi')$.

(3) Off-resonance dielectric loss



Utilize the difference intentionally !

Fundamental

Anisotropic Losses in Piezoelectric & Piezomagnetic

10 independent parameters for *6mm* / *∞mm* materials (polycrystalline) – 20 loss factors

$$\varepsilon = \begin{bmatrix} \varepsilon_{11} & 0 & 0 \\ 0 & \varepsilon_{11} & 0 \\ 0 & 0 & \varepsilon_{33} \end{bmatrix} \quad 2$$

$$d = \begin{bmatrix} 0 & 0 & 0 & 0 & d_{15} & 0 \\ 0 & 0 & 0 & d_{15} & 0 & 0 \\ d_{31} & d_{31} & d_{33} & 0 & 0 & 0 \end{bmatrix} \quad 3$$

$$c = \begin{bmatrix} c_{11} & c_{12} & c_{13} & 0 & 0 & 0 \\ c_{12} & c_{11} & c_{13} & 0 & 0 & 0 \\ c_{13} & c_{13} & c_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & c_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & c_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & \left(\frac{c_{11}-c_{12}}{2}\right) \end{bmatrix} \quad 5$$

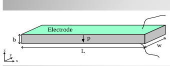
Fundamental

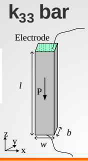
Quality Factor Anisotropy

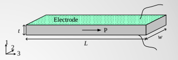
k_{31} plate — k_{33} bar — k_{15} shear mode

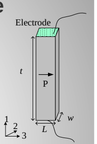
L>>t: Const D

L<<t: Const E









$$Q_{A,31} = \frac{1}{\tan\phi_{11}'} \qquad \frac{1}{Q_{B,31}} = \frac{1}{Q_{A,31}} + \frac{2}{1+(\frac{1}{k_{31}} - k_{31})^2\Omega_{B,31}^2}(\tan\delta_{33}' + \tan\phi_{11}' - 2\tan\theta_{31}')$$

$$Q_{B,33} = \frac{1}{\tan\phi_{33}} \qquad \frac{1}{Q_{A,33}} = \frac{1}{Q_{B,33}} - \frac{2}{k_{33}^2 - 1 + \Omega_{A,33}^2/k_{33}^2}(2\tan\theta_{33} - \tan\delta_{33} - \tan\phi_{33})$$

$$Q_{B,15}^D = \frac{1}{\tan\phi_{55}} \qquad \frac{1}{Q_{A,15}^D} = \frac{1}{Q_{B,15}^D} - \frac{2}{k_{15}^2 - 1 + \Omega_{A,15}^2/k_{15}^2}(2\tan\theta_{15} - \tan\delta_{11} - \tan\phi_{55})$$

$$Q_{A,15}^E = \frac{1}{\tan\phi_{55}'} \qquad \frac{1}{Q_{B,15}^E} = \frac{1}{Q_{A,15}^E} + \frac{2}{1+(\frac{1}{k_{15}} - k_{15})^2\Omega_{B,15}^2}(\tan\delta_{11}' + \tan\phi_{55}' - 2\tan\theta_{15}')$$

Fundamental

Loss Anisotropy Determination

Material parameters of ∞mm/6mm:

ε_{33}^X, ε_{11}^X, ε_{33}^x, ε_{11}^x; **16 loss factors can be derived.**

s_{11}^E, s_{12}^E, s_{13}^E, s_{33}^E, s_{44}^E, s_{11}^D, s_{12}^D, s_{13}^D, s_{33}^D, s_{44}^D;

d_{31}, d_{33}, d_{15}, h_{31}, h_{33}, h_{15}.

Loss factors of APC 841 (~10^{-3}) from k_{31} and k_{33} modes

$\tan\phi'_{11}$	$\tan\phi'_{33}$	$\tan\delta'_{33}$	$\tan\theta'_{31}$	$\tan\theta'_{33}$
0.77	0.90	3.5	3.7	2.5
$\tan\phi_{11}$	$\tan\phi_{33}$	$\tan\delta_{33}$	$\tan\theta_{31}$	$\tan\theta_{33}$
0.44	0.54	3.1	0.25	1.5

a) Piezoelectric loss factors are not small: $\tan\theta' > (½)(\tan\delta' + \tan\phi')$

b) Intensive losses are larger than the Extensive losses.

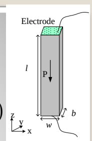
c) Loss anisotropy

Uchino, Zhuang and Ural, J. Adv. Dielectrics, 1(1), 17-31 (2011).

Fundamental

Piezo vs. Magnetostriction

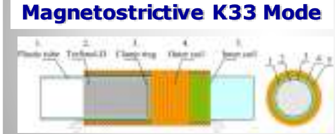
Piezoelectric K33 Mode

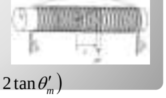


$$Q_{B,33} = \frac{1}{\tan\phi_{33}}$$

$$\frac{1}{Q_{A,33}} = \frac{1}{Q_{B,33}} - \frac{2}{k_{33}^2 - 1 + \Omega_{A,33}^2/k_{33}^2}(2\tan\theta_{33} - \tan\delta_{33} - \tan\phi_{33})$$

Magnetostrictive K33 Mode





$$Q_A = \frac{1}{\tan\phi_m'}$$

$$\frac{1}{Q_B} = \frac{1}{Q_A} + \frac{2}{\left[1+(\frac{1}{k_{33}} - k_{33})^2\Omega_b^2\right]}(\tan\delta_m' + \tan\phi_m' - 2\tan\theta_m')$$

Fundamental

Piezomagnetic Losses

(1) Three losses types-losses factors

$$s^{H*} = s^H(1 - j\tan\phi_m') \quad - \quad \text{Mechanical loss} \quad - \quad c^{B*} = c^B(1 + j\tan\phi_m)$$

$$d_m^* = d_m(1 - j\tan\theta_m') \quad - \text{Piezomagnetic loss} - \quad h_m^* = h_m(1 + j\tan\delta_m)$$

$$\mu^{x*} = \mu^x(1 - j\tan\delta_m') - \quad \text{Magnetic loss} \quad - \quad \upsilon^{x*} = \upsilon^x(1 + j\tan\theta_m)$$

(2) Impedance of Magneto-strictors

$$Z = j\omega\frac{\pi r^2 N^2}{l}\mu_{33}^x\left(1 + \frac{k_{33}^2}{1-k_{33}^2}\frac{\tan(\omega l/2v)}{(\omega l/2v)}\right)$$

(3) Mechanical Quality factors -losses factors

$$Q_A = (\tan\phi_m)^{-1}$$

$$\frac{1}{Q_B} = \frac{1}{Q_A} + \frac{2}{1+(1-k_{33}^2)^2\Omega_b^2/k_{33}^2}(2\tan\theta_m - \tan\delta_m - \tan\phi_m)$$

(4) Intensive and extensive losses factors

$$(-\tan\delta' - \tan\phi' + 2\tan\theta') = (\tan\delta + \tan\phi - 2\tan\theta)$$

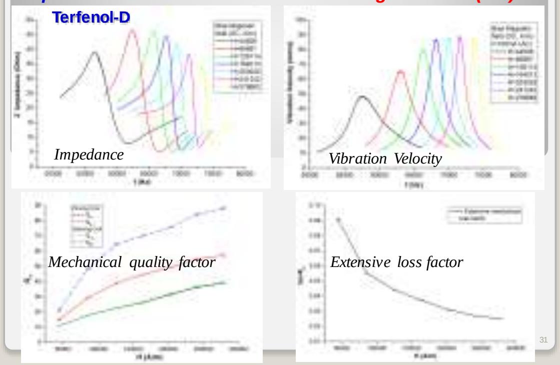
$$\begin{bmatrix} \tan\delta_m' \\ \tan\phi_m' \\ \tan\theta_m' \end{bmatrix} = K\begin{bmatrix} \tan\delta_m \\ \tan\phi_m \\ \tan\theta_m \end{bmatrix} \qquad K = \frac{1}{1-k_{33}^2}\begin{bmatrix} 1 & k_{33}^2 & -2k_{33}^2 \\ k_{33}^2 & 1 & -2k_{33}^2 \\ 1 & 1 & -1-k_{33}^2 \end{bmatrix}$$

Fundamental

Piezomagnetic Losses

Dependence of losses factors on Bias magnetic field (DC)

Terfenol-D



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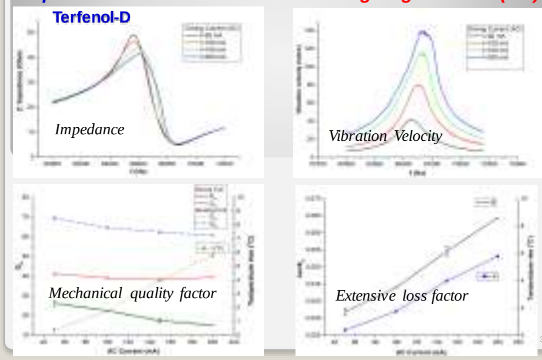
Fundamental

Piezomagnetic Losses

Dependence of losses factors on Driving magnetic field (AC)

Terfenol-D



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Fundamental

Piezomagnetic Losses

(1) Magnetic phase lag: $\delta'_m = 2.54^o, \tan\delta'_m = 0.044$

Terfenol-D

	Intensive losses factors		Extensive losses factors	
Elastic loss	$\tan\phi'_m$	0.0657	$\tan\phi_m$	0.0556
Magnetic loss	$\tan\delta'_m$	0.0440	$\tan\delta_m$	0.0338
Piezomagnetic loss	$\tan\theta'_m$	0.0893	$\tan\theta_m$	0.0103

(2) Magnetic phase lag: $\delta'_m = 3.90^o, \tan\delta'_m = 0.068$

	Intensive losses factors		Extensive losses factors	
Elastic loss	$\tan\phi'_m$	0.0622	$\tan\phi_m$	0.0556
Magnetic loss	$\tan\delta'_m$	[illegible]	$\tan\delta_m$	0.0614
Piezomagnetic loss	$\tan\theta'_m$	0.0875	$\tan\theta_m$	0.0361

Piezoelectric loss ~ 0.3%
Piezomagnetic loss ~ 9%

Conditions: (a)DC bias magnetic field ***H***= 126114 **A/m**;
(b) AC driving Current: ***I*** =100**mA**

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PENNSTATE

ICAT

Loss Mechanisms in Smart Materials

Kenji Uchino
Int'l Center for Actuators & Transducers
The Pennsylvania State University

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4. New Q_M Determination Methods
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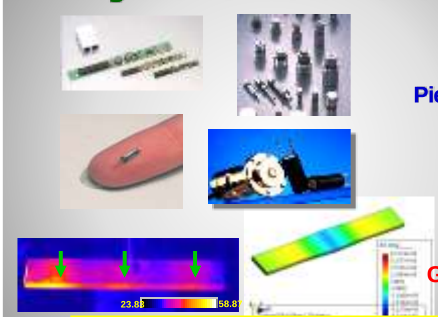
6. Summary

34

High Power

High Power Piezo-Devices



Piezoelectric Devices

Heat Generation

- Miniaturization
- High power density

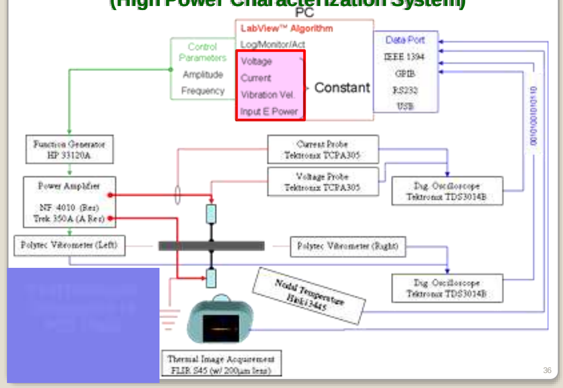
Low Loss

35

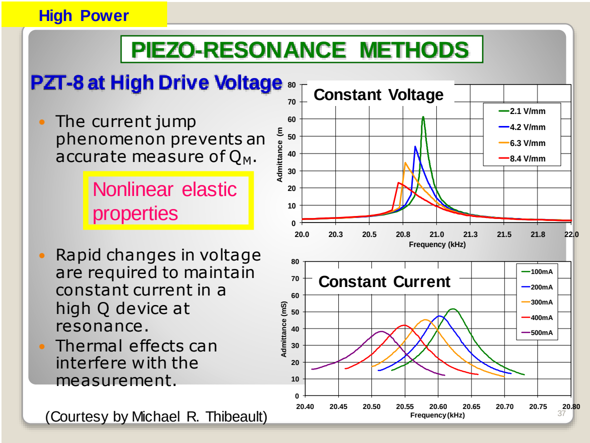
High Power

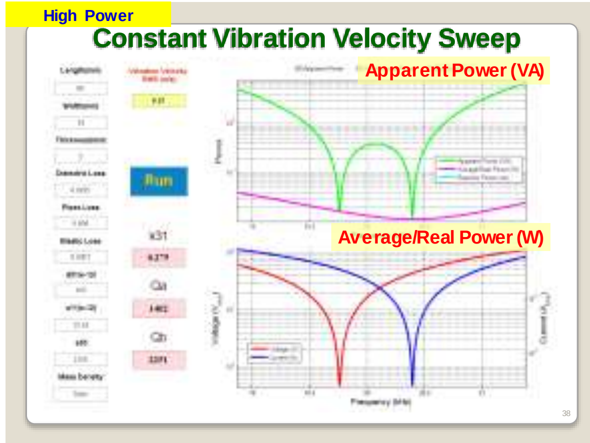
HiPoCS (ICAT/PSU)

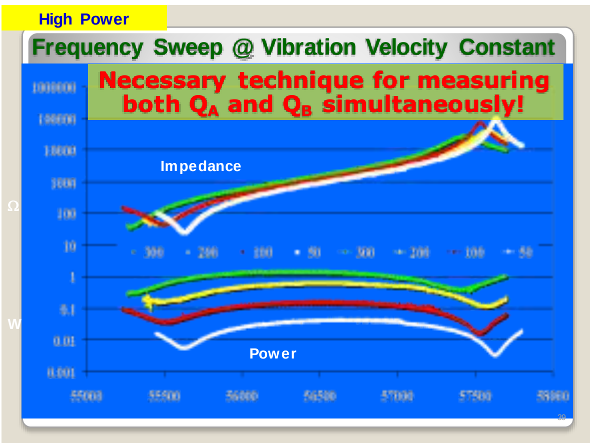
(High Power Characterization System)

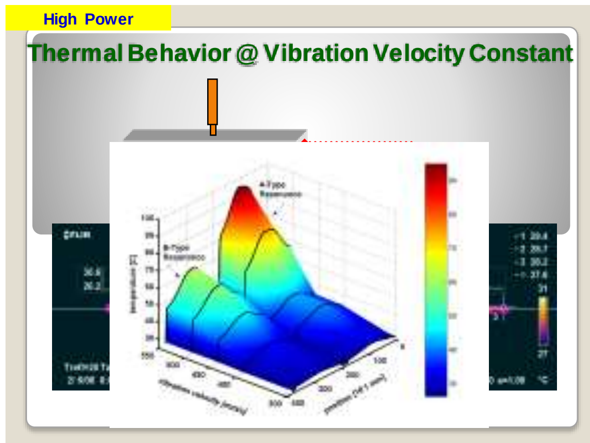


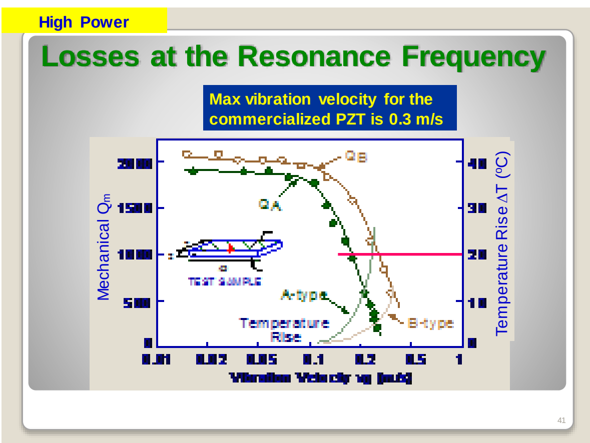
36

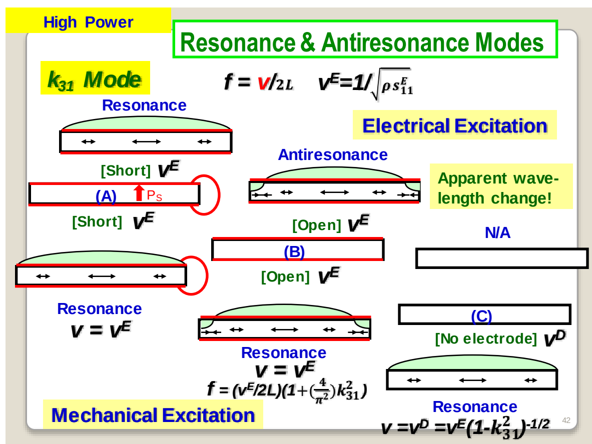

High Power
PIEZO-RESONANCE METHODS
PZT-8 at High Drive Voltage
The current jump phenomenon prevents an accurate measure of Q_M.
Nonlinear elastic properties
Rapid changes in voltage are required to maintain constant current in a high Q device at resonance.
Thermal effects can interfere with the measurement.
Constant Voltage
2.1 V/mm
4.2 V/mm
6.3 V/mm
8.4 V/mm
Frequency (kHz)
Constant Current
100mA
200mA
300mA
400mA
500mA
Frequency (kHz)
(Courtesy by Michael R. Thibeault)
37

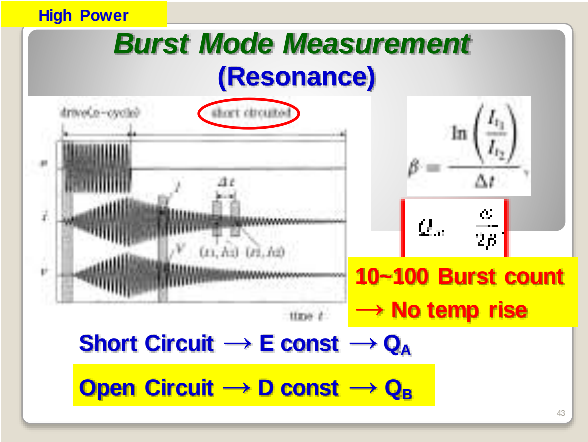

High Power
Constant Vibration Velocity Sweep
Apparent Power (VA)
Average/Real Power (W)
Run
38

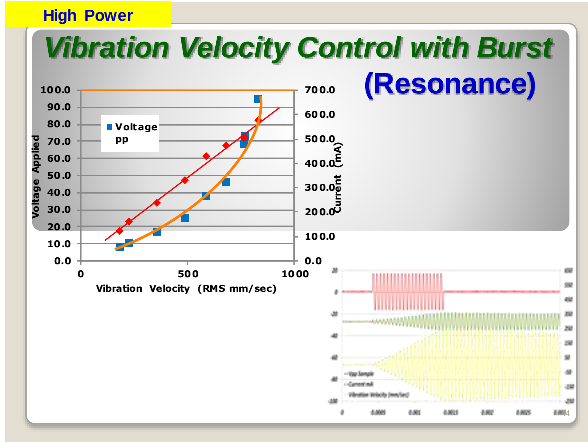

High Power
Frequency Sweep @ Vibration Velocity Constant
Necessary technique for measuring both Q_A and Q_B simultaneously!
Impedance
Power
55000
55500
56000
56500
57000
57500
58000

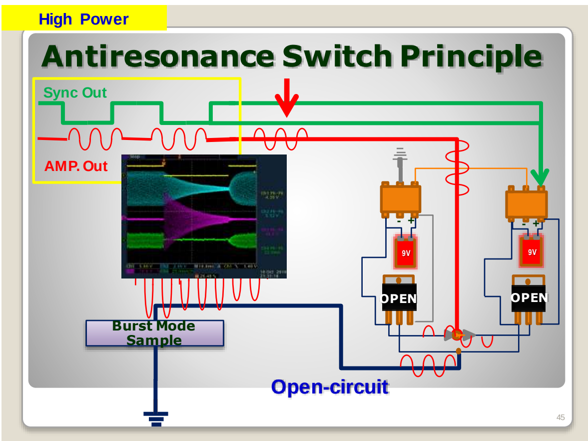

High Power
Thermal Behavior @ Vibration Velocity Constant

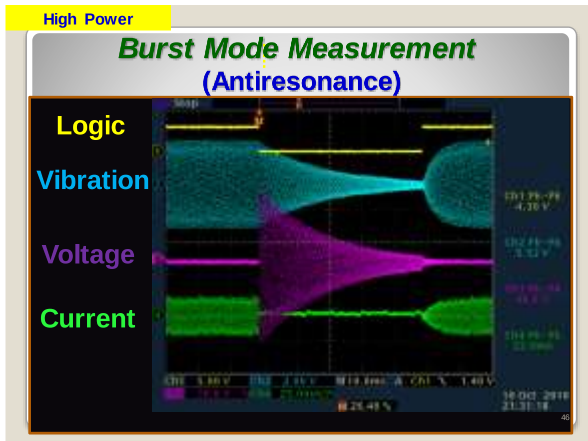

High Power
Losses at the Resonance Frequency
Max vibration velocity for the commercialized PZT is 0.3 m/s
Mechanical Q_m
Temperature Rise ΔT (ºC)
QB
QA
TEST SAMPLE
A-type
B-type
Temperature Rise
41

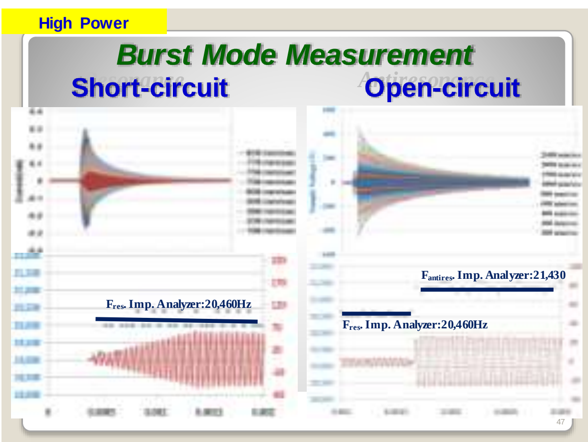

High Power
Resonance & Antiresonance Modes
k_{31} Mode
$f = v/2L$ $v^E = 1/\sqrt{\rho s_{11}^E}$
Resonance
Electrical Excitation
Antiresonance
[Short] v^E
(A) Ps
Apparent wave-length change!
[Short] v^E
[Open] v^E
N/A
(B)
[Open] v^E
Resonance
$v = v^E$
(C)
[No electrode] v^D
Resonance
$v = v^E$
$f = (v^E/2L)(1+(\frac{4}{\pi^2})k_{31}^2)$
Resonance
Mechanical Excitation
$v = v^D = v^E(1-k_{31}^2)^{-1/2}$
42

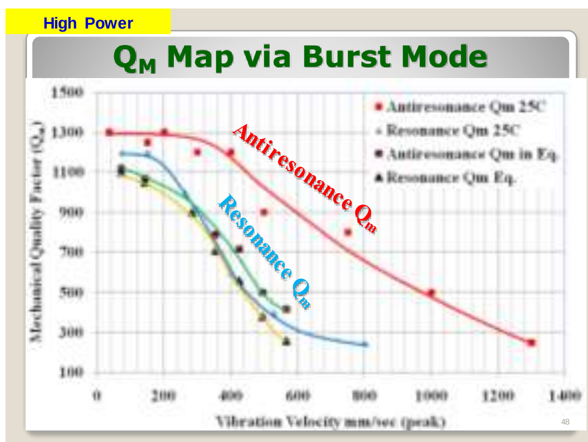

High Power
Burst Mode Measurement
(Resonance)
short circuited
10~100 Burst count
→ No temp rise
Short Circuit → E const → Q_A
Open Circuit → D const → Q_B
43


High Power
Vibration Velocity Control with Burst
(Resonance)
Voltage pp
Voltage Applied
Current (mA)
Vibration Velocity (RMS mm/sec)


High Power
Antiresonance Switch Principle
Sync Out
AMP. Out
9V
OPEN
9V
OPEN
Burst Mode Sample
Open-circuit
45


High Power
Burst Mode Measurement
(Antiresonance)
Logic
Vibration
Voltage
Current
46


High Power
Burst Mode Measurement
Short-circuit
Open-circuit
Fres, Imp. Analyzer:20,460Hz
Fantires, Imp. Analyzer:21,430
Fres, Imp. Analyzer:20,460Hz
47


High Power
QM Map via Burst Mode
Antiresonance Qm 25C
Resonance Qm 25C
Antiresonance Qm in Eq.
Resonance Qm Eq.
Antiresonance Qm
Resonance Qm
Mechanical Quality Factor (Qm)
Vibration Velocity mm/sec (peak)
48

Loss Mechanisms in Smart Materials

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New Method

How to Determine Qm

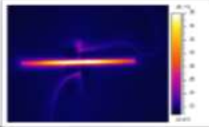
$$Q_m = 2\pi \frac{\text{Energy Stored/Cycle}}{\text{Energy Lost/Cycle}}$$

1. Admittance/Impedance Spectra
   - Under constant voltage
   - Under constant current
   - Under constant vib. velocity
   - Under constant power

At Res/Antires frequencies

$$Q_m = \left(\frac{\omega_0}{\Delta\omega_{3dB}}\right)$$

2. Precise Input Electric Energy $Q_{m,l} = 2\pi f \frac{\frac{1}{2}\rho V_{RMS}^2}{P_d/(L\,w\,t)}$
3. Precise Temperature Distribution Profile



At any frequencies

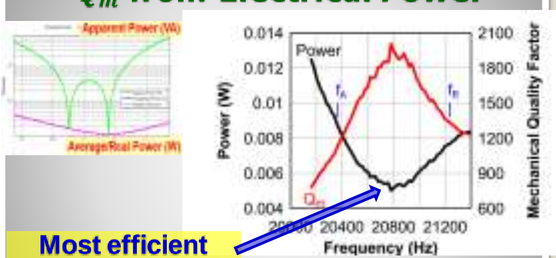
$$Q_m = 2\pi f\left(\frac{\rho V_{rms}^2}{h_g}\right)$$

Elevated Temperature of Piezoelectric Ceramic under Resonance Excitation

50

New Method

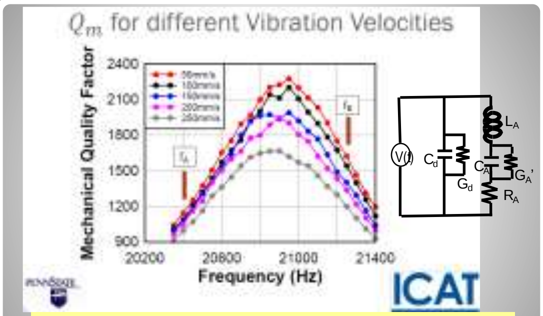
Q_m from Electrical Power



Most efficient driving frequency

$$Q_{m,l} = 2\pi f \frac{\frac{1}{2}\rho V_{RMS}^2}{P_d/(L\,w\,t)}$$

51

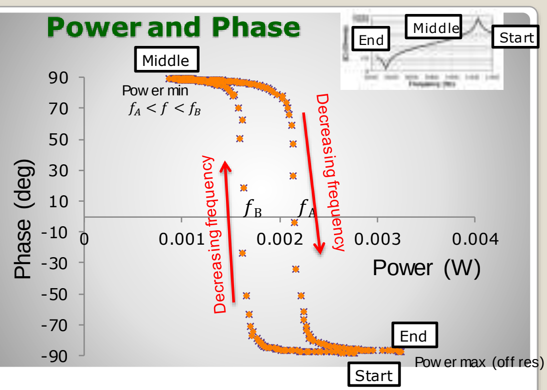


Quality Factor Maximum: $(\omega^4 - \omega_r^2\omega_a^2)(\omega^2 - \omega_a^2) + \omega_r^2\omega_c^4 = 0$

where $\omega_c^2 = \omega_a^2 \tan\phi' + (\omega_a^2 - \omega_r^2)[\tan\phi' + \tan\delta' - 2\tan\theta']$

52

Power and Phase



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Loss Mechanism

Four Types of Losses in Piezoelectrics

(1) Domain wall motion
(2) Fundamental lattice contribution, which should also happen in domain free monocrystals
(3) Microstructural contribution, which occurs typically in polycrystalline samples
(4) Conductivity contribution in highly-ohmic samples

In typical piezoelectric ceramics, the loss due to the domain wall motion significantly exceeds the other three types.

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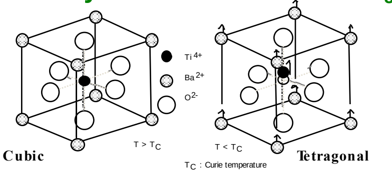
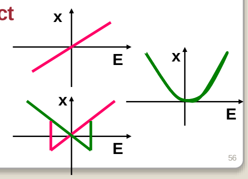
Loss Mechanism

Crystal Structure of $BaTiO_3$



Origins of Field Induced Strain

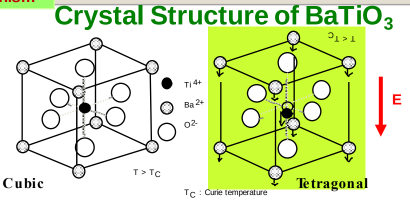
1. Converse piezoelectric effect
   x = d E
2. Electrostrictive effect
   x = M E^2
3. Strain associated with polarization reversal



56

Loss Mechanism

Crystal Structure of $BaTiO_3$



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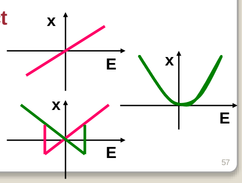
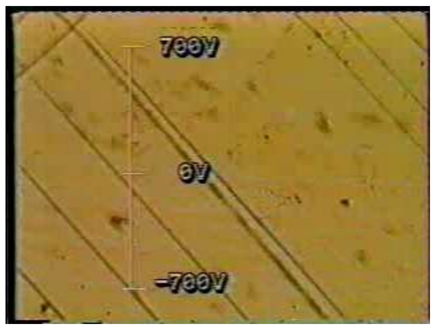


57

Loss Mechanism



Domain Dynamics in BT

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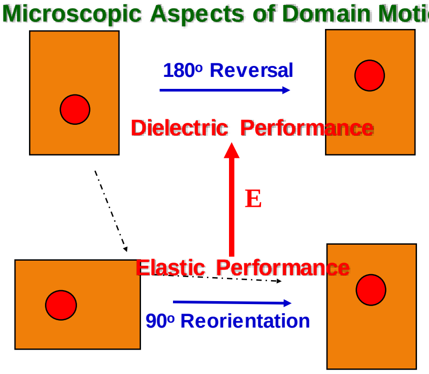
Loss Mechanism

Microscopic Aspects of Domain Motion



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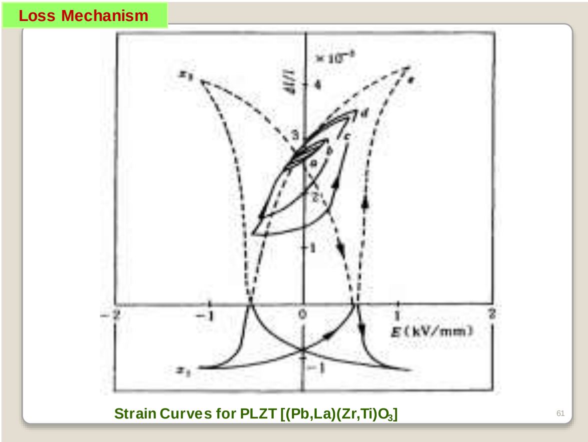
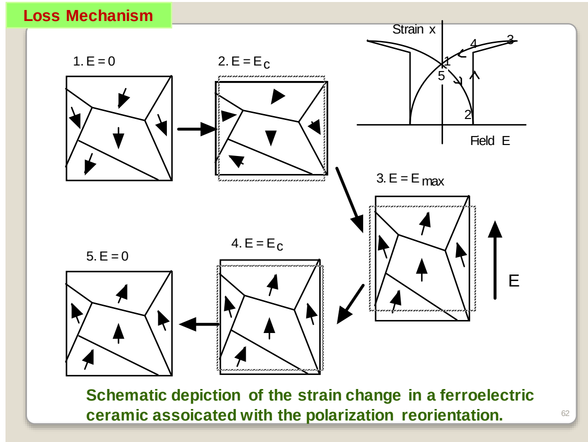
Loss Mechanism

Microscopic Origins of the Losses

	Electric Field	Stress
dielectric tan δ		
mechanical tan ϕ		Strain
piezoelectric tan θ	Strain	Polarization

60



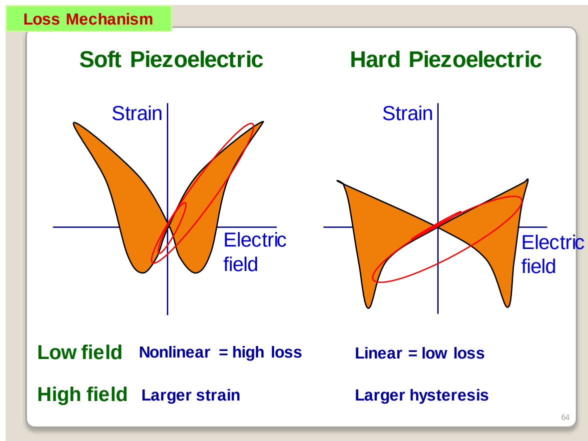


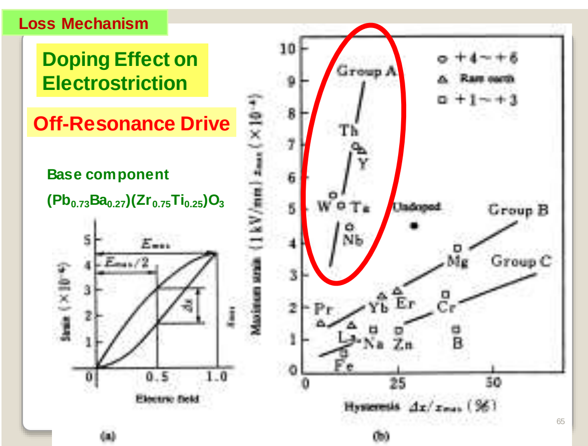
Loss Mechanism

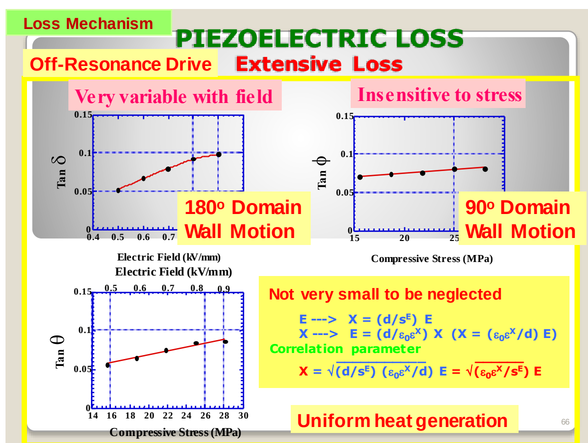
HARD & SOFT MATERIALS AND LOSS

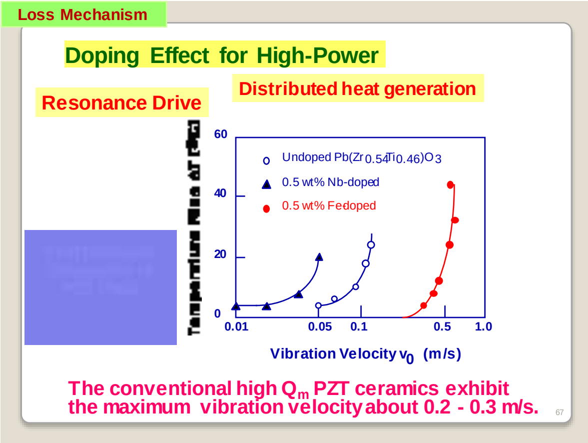
	d	k	Qm	Off-Resonance Application	Resonance Application
Electro-strictor (PMN)	High	High *(under DC bias)	Low	High displacement No hysteresis	 Motor
Soft Piezo (PZT-5H)	High	High	Low	High displacement ($\Delta L = dEL$)	*Heat generation
Hard Piezo (PZT- 8)	Low ⇩ Half	Low	High ⇩ Hundred times	*Low strain	High AC displacement ($\Delta L \propto Q_m \cdot dEL$)

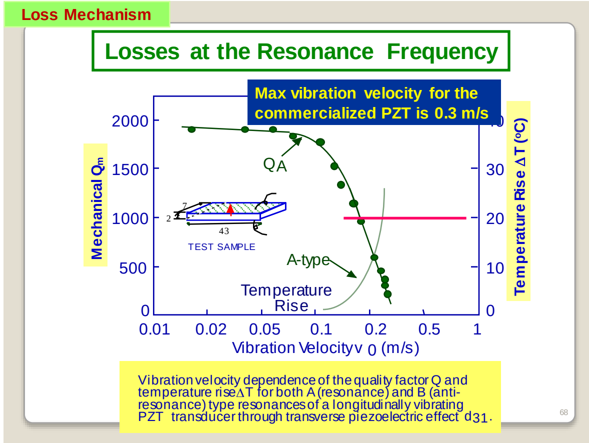
* Demerit

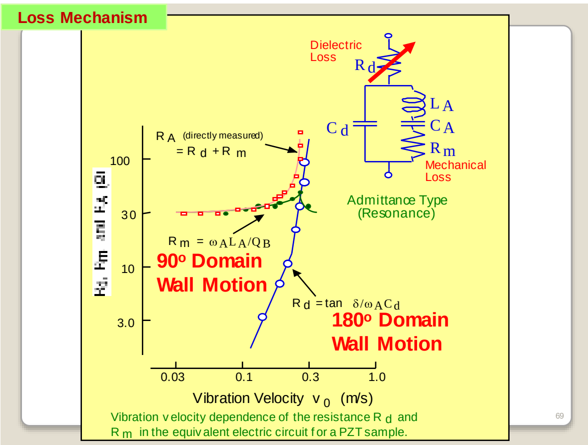


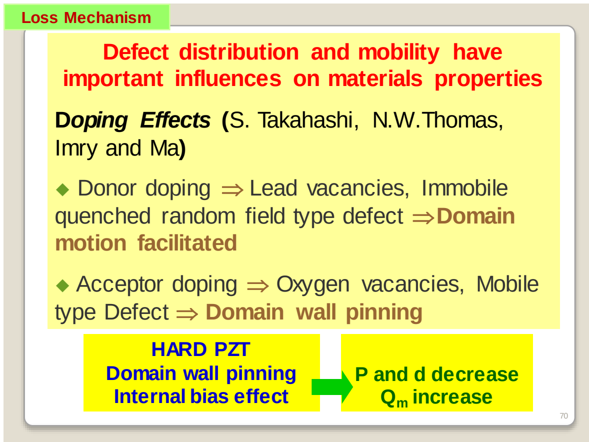


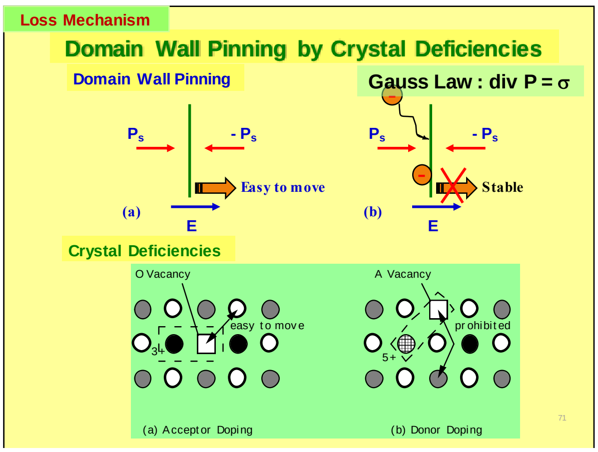


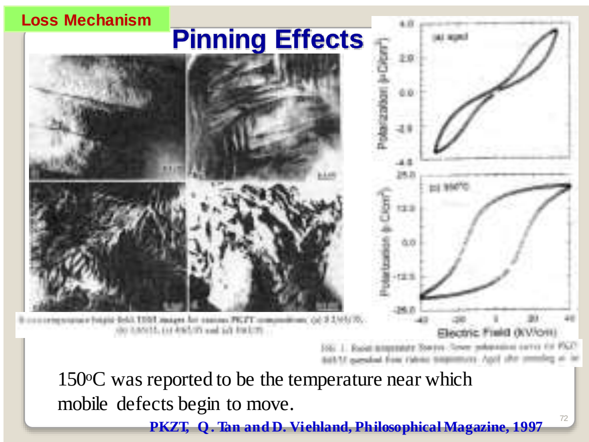

Loss Mechanism
Doping Effect for High-Power
Resonance Drive
Distributed heat generation
Temperature Rise ΔT (°C)
60
40
20
0
Undoped Pb(Zr0.54Ti0.46)O3
0.5 wt% Nb-doped
0.5 wt% Fedoped
0.01
0.05
0.1
0.5
1.0
Vibration Velocity v0 (m/s)
The conventional high Qm PZT ceramics exhibit the maximum vibration velocity about 0.2 - 0.3 m/s.
67

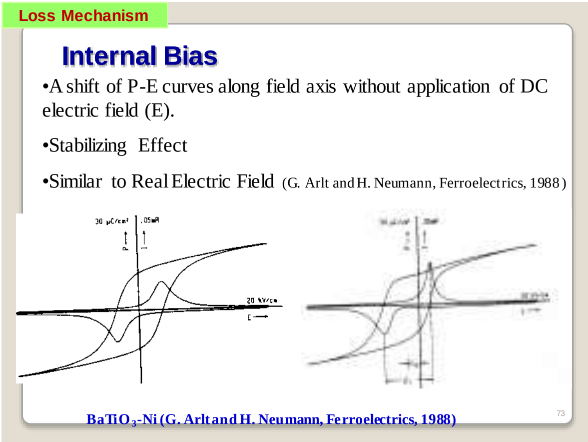

Loss Mechanism
Losses at the Resonance Frequency
Max vibration velocity for the commercialized PZT is 0.3 m/s
Mechanical Qm
2000
1500
1000
500
0
QA
TEST SAMPLE
A-type
Temperature Rise
Temperature Rise ΔT (°C)
30
20
10
0
0.01
0.02
0.05
0.1
0.2
0.5
1
Vibration Velocity v0 (m/s)
Vibration velocity dependence of the quality factor Q and temperature rise ΔT for both A (resonance) and B (anti-resonance) type resonances of a longitudinally vibrating PZT transducer through transverse piezoelectric effect d31.
68

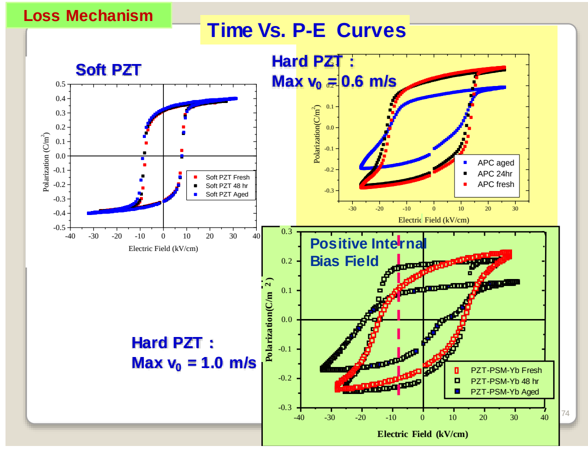

Loss Mechanism
Dielectric Loss
Rd
Cd
LA
CA
Rm
Mechanical Loss
RA (directly measured) = Rd + Rm
Admittance Type (Resonance)
Rm = ωALA/QB
90° Domain Wall Motion
Rd = tan δ/ωACd
180° Domain Wall Motion
Rd, Rm and RA (Ω)
100
30
10
3.0
0.03
0.1
0.3
1.0
Vibration Velocity v0 (m/s)
Vibration velocity dependence of the resistance Rd and Rm in the equivalent electric circuit for a PZT sample.
69

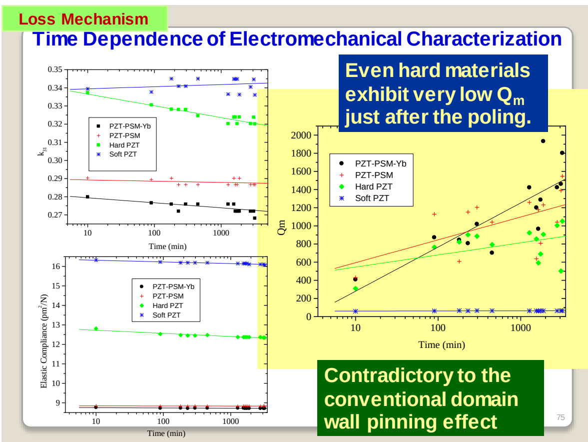

Loss Mechanism
Defect distribution and mobility have important influences on materials properties
Doping Effects (S. Takahashi, N.W.Thomas, Imry and Ma)
◆ Donor doping ⇒ Lead vacancies, Immobile quenched random field type defect ⇒ Domain motion facilitated
◆ Acceptor doping ⇒ Oxygen vacancies, Mobile type Defect ⇒ Domain wall pinning
HARD PZT
Domain wall pinning
Internal bias effect
P and d decrease
Qm increase
70

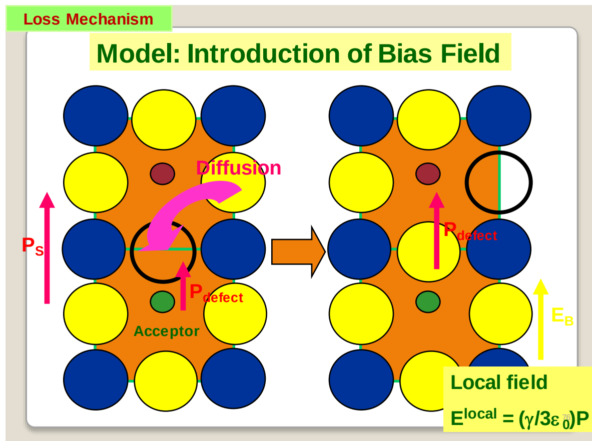

Loss Mechanism
Domain Wall Pinning by Crystal Deficiencies
Domain Wall Pinning
Gauss Law : div P = σ
Ps
- Ps
Easy to move
(a)
E
Stable
(b)
Crystal Deficiencies
O Vacancy
easy to move
A Vacancy
prohibited
(a) Acceptor Doping
(b) Donor Doping
71

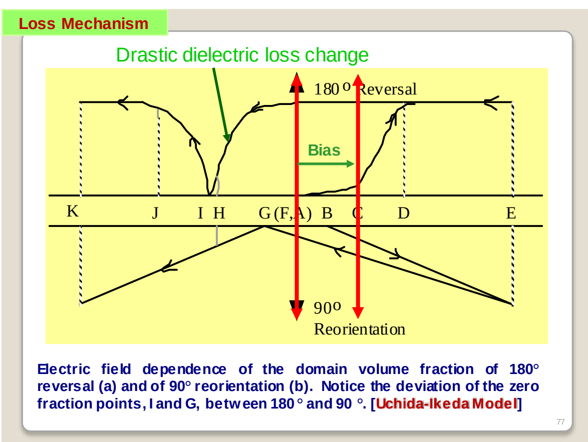

Loss Mechanism
Pinning Effects
Electric Field (kV/cm)
150°C was reported to be the temperature near which mobile defects begin to move.
PKZT, Q. Tan and D. Viehland, Philosophical Magazine, 1997
72


Loss Mechanism
Internal Bias
•A shift of P-E curves along field axis without application of DC electric field (E).
•Stabilizing Effect
•Similar to Real Electric Field (G. Arlt and H. Neumann, Ferroelectrics, 1988)
BaTiO3-Ni (G. Arlt and H. Neumann, Ferroelectrics, 1988)
73


Loss Mechanism
Time Vs. P-E Curves
Soft PZT
Hard PZT :
Max v0 = 0.6 m/s
Hard PZT :
Max v0 = 1.0 m/s
Positive Internal
Bias Field
Soft PZT Fresh
Soft PZT 48 hr
Soft PZT Aged
APC aged
APC 24hr
APC fresh
PZT-PSM-Yb Fresh
PZT-PSM-Yb 48 hr
PZT-PSM-Yb Aged
Electric Field (kV/cm)
74


Loss Mechanism
Time Dependence of Electromechanical Characterization
Even hard materials exhibit very low Qm just after the poling.
Contradictory to the conventional domain wall pinning effect
PZT-PSM-Yb
PZT-PSM
Hard PZT
Soft PZT
Time (min)
Elastic Compliance (pm²/N)
Qm
75


Loss Mechanism
Model: Introduction of Bias Field
Diffusion
Ps
Pdefect
Acceptor
Pdefect
EB
Local field
Elocal = (γ/3ε0)P


Loss Mechanism
Drastic dielectric loss change
180° Reversal
Bias
K J I H G (F, A) B C D E
90° Reorientation
Electric field dependence of the domain volume fraction of 180° reversal (a) and of 90° reorientation (b). Notice the deviation of the zero fraction points, I and G, between 180° and 90°. [Uchida-Ikeda Model]
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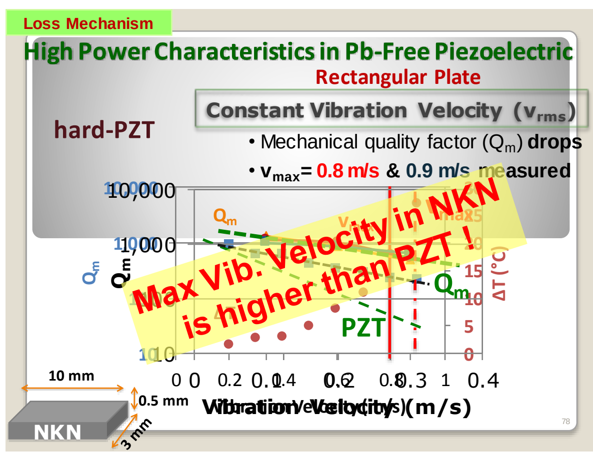
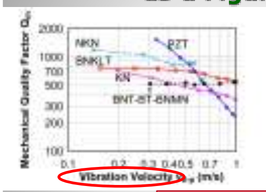
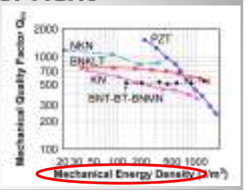

Loss Mechanism
High Power Characteristics in Pb-Free Piezoelectric
Rectangular Plate
Constant Vibration Velocity (vrms)
hard-PZT
• Mechanical quality factor (Qm) drops
• vmax= 0.8 m/s & 0.9 m/s measured
Max Vib. Velocity in NKN is higher than PZT !
PZT
Qm
ΔT (°C)
10 mm
0.5 mm
3 mm
NKN
Vibration Velocity (m/s)
78

Loss Mechanism

Mechanical Energy Density as a Figure of Merit





$$Mech.Energy\ Density = (1/2)\rho V_{rms}^2$$

Light mass-density Pb-free piezoelectrics need to vibrate much larger for generating the same mechanical energy.

Thermal Conductivity

Thermal Properties	c_p (J/g/K)	κ (W/m/K)
Hard-PZT	0.42	1.25
NKN-Cu	0.58	3.10

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Loss Mechanisms in Smart Materials

Kenji Uchino
Int'l Center for Actuators & Transducers
The Pennsylvania State University

1. Background: Smart Materials
2. Fundamental Loss Equations for Piezoelectrics & Magnetostrictors
3. High Power Characterization System
4. New Q_M Determination Methods
5. Origin of High Power Performance
6. Summary

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Summary

SUMMARY

1. Phenomenological equations derived for piezoelectrics & magnetostrictors: dielectric, elastic and piezoelectric losses; magnetic, elastic and piezomagnetic losses. Coupling losses are significant (not negligible).
2. Three losses can be determined from Q_M values for the resonance and antiresonance ranges.
3. Three high-power characterization methods (HiPoCS) for determining Q_M's; (1) admittance spectra under a constant vibration velocity, (2) burst mode (mechanical drive) to eliminate the heat generation, (3) precise input electric power.
4. Losses in magnetostrictors: 10 times of losses in piezoelectrics
5. Most efficient driving frequency exists between the resonance and antiresonance frequencies.
6. High power origin: (1) Domain wall pinning, (2) Internal bias. Internal bias generation due to oxygen vacancy diffusion seems to be the best explanation.
7. High power FOM: $\text{Mech. Energy Density} = (1/2)\rho V_{rms}^2$

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END

Thank you!

www.psu.edu/dept/ICAT

Contact: Kenji Uchino, Director, ICAT
E-mail: kenjiuchino@psu.edu; Phone: 814-863-8035, Fax: 814-865-2326

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