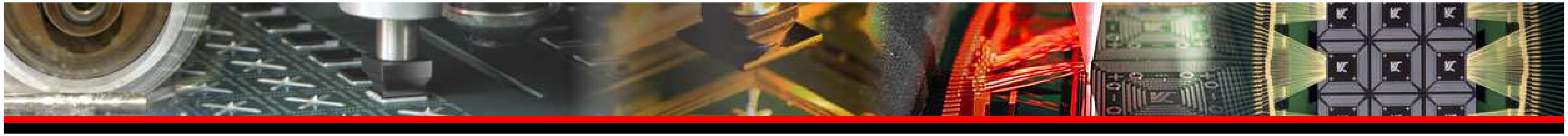
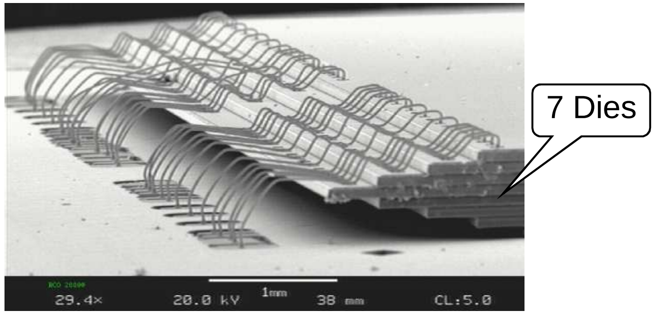
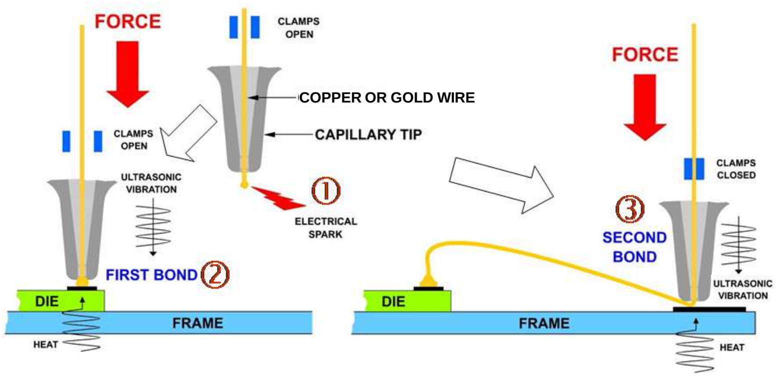


The Effects of Piezoelectric Ceramic Dissipation Factor on the Performance of Ultrasonic Transducers

Dominick A. DeAngelis and Gary W. Schulze

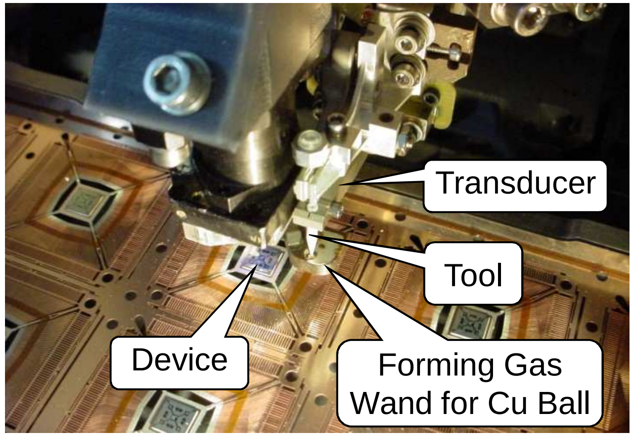


Bonded Stacked Die Device (SEM)

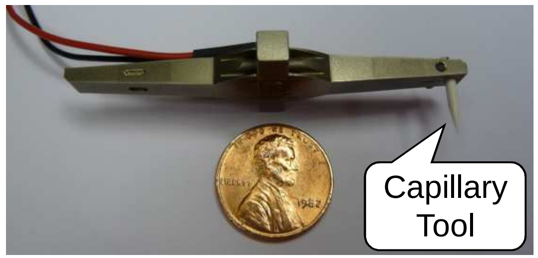


Primary steps of the Wire Bond Cycle

Kulicke & Soffa's Flagship Semiconductor Wire Bonding Machine



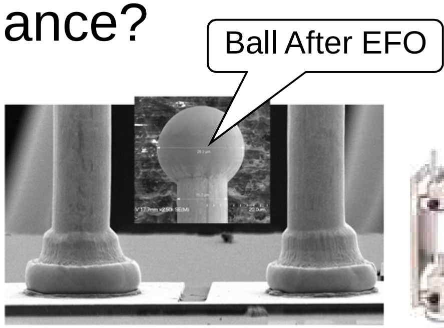
Wire Bonding in Action with Fine Copper Wire (20 Wires/Sec)

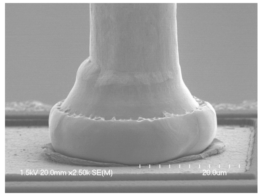


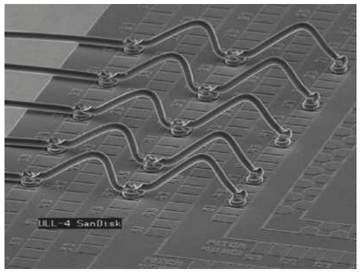
Ultrasonic Transducer Used For Wire Bonding Machine

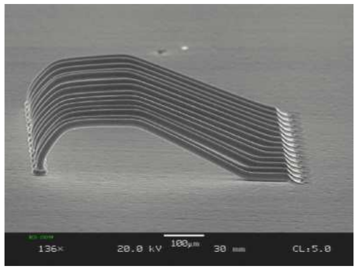
OUTLINE

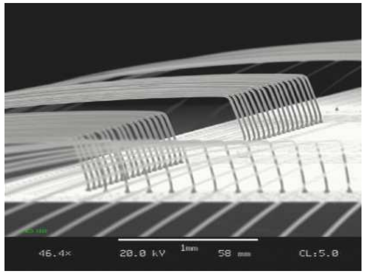
- Specific Application and Definition of Dissipation Factor (*DF*)
- How Does *DF* Affect Transducer Performance?
- Research Summary
- Equivalent Circuit Model for *DF*
- Measuring *DF* Model Parameters
- Measuring Porosity of Piezo Ceramics
- Mixing Rules for Piezo Properties
- FEA Modeling and Experimental Results
- Conclusions
- Questions?

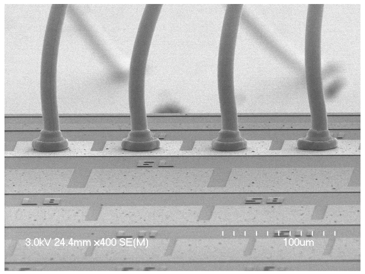


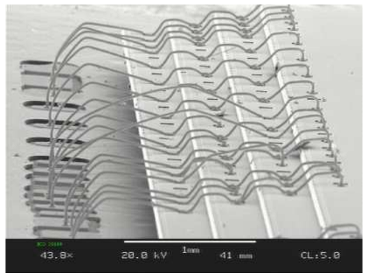


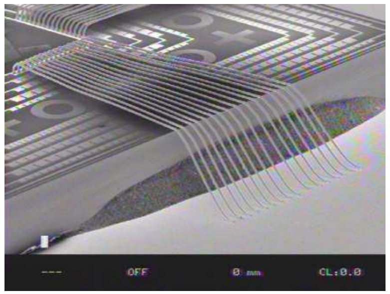


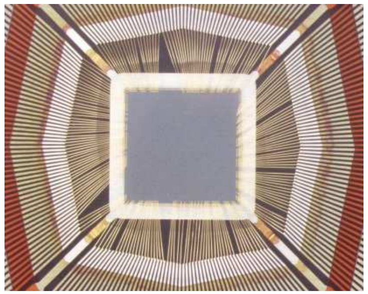


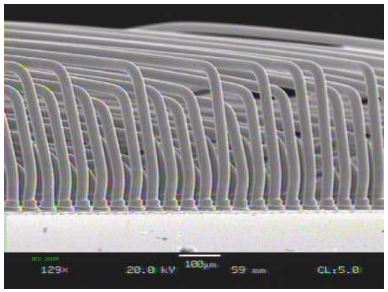


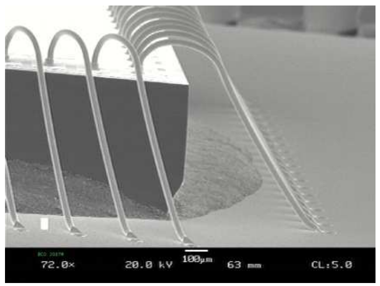


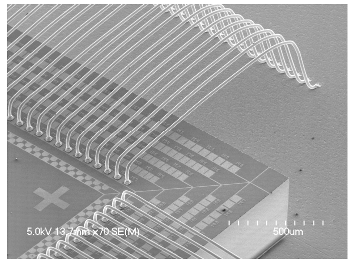






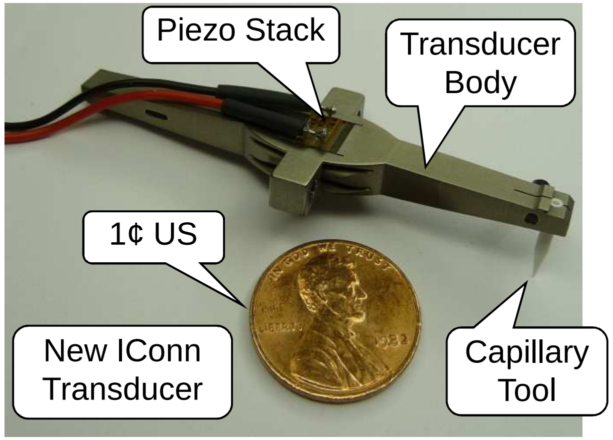


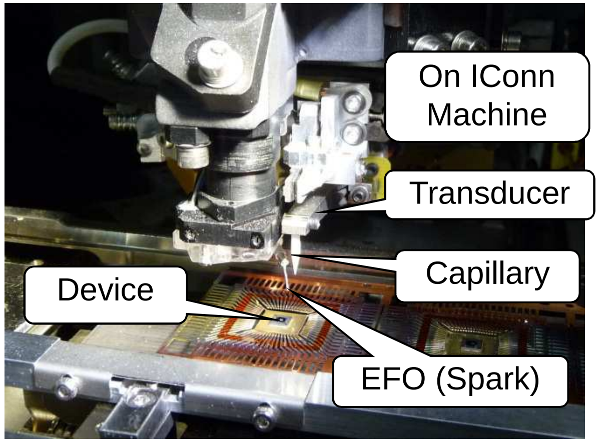




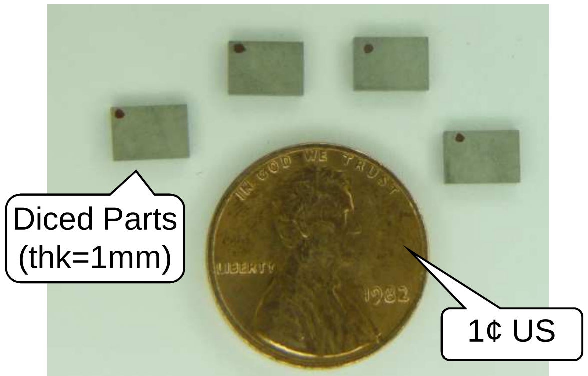
SPECIFIC TRANSDUCER APPLICATION

- K&S is the leading MFG of semiconductor wire bonding equipment
- Transducer delivers energy to a capillary tool for welding tiny wires
- Patented single piece “Unibody” design is ideal for research studies
- Portability across 100’s of machines required for same customer device

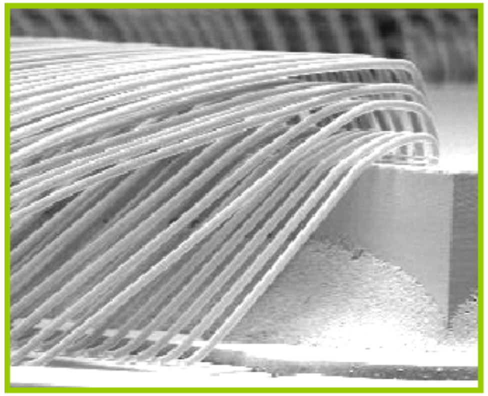




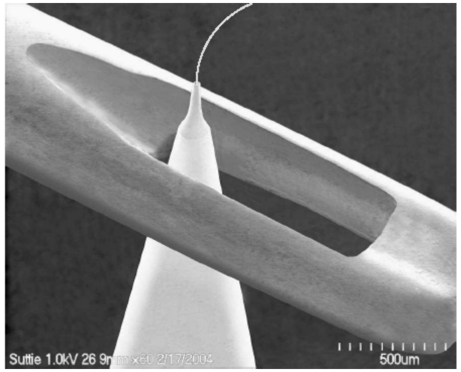
Transducer Specs
500 mA Max Current
50/120 kHz Operating Modes
80 Ohm Max Impedance
Operation 40 Bonds/Sec
Bond Duration ~10 mSec
PZT8 Ceramics (4X)



PZT8 Piezoelectric Ceramics



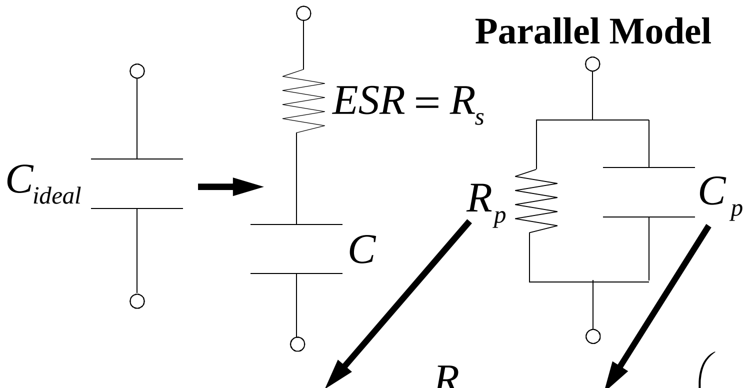
Actual Wire Bonds From Multi-Tier Package



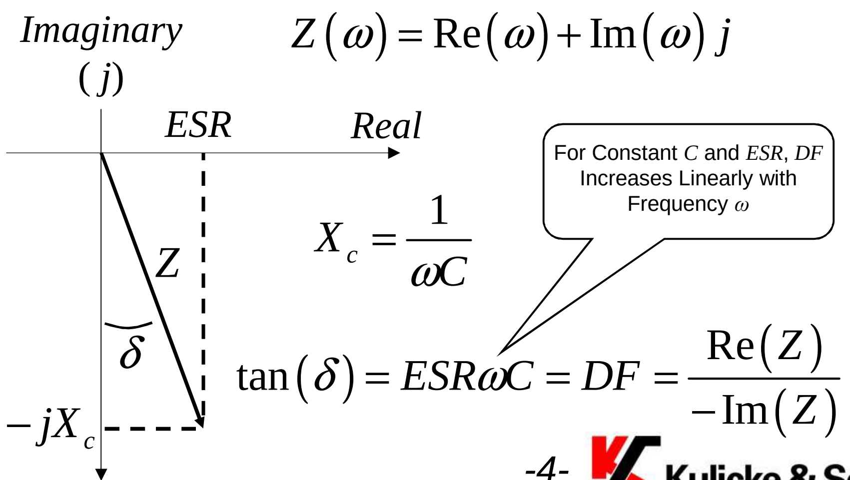
Typical Capillary Tool with Wire Compared to Sewing Needle

DEFINITION OF DISSIPATION FACTOR (*DF*)

- Ratio of Equivalent Series Resistance (*ESR*) and the magnitude of capacitance reactance (X_c), i.e., $DF = ESR/|X_c|$
- Also known as loss tangent or $\tan(\delta)$, where angle δ is deviation from 90° between voltage and current for an ideal capacit or (i.e., no losses)
- Ratio of (energy lost)/(energy stored) or $\mathrm{Re}/|\mathrm{Im}|$ of the impedance
- Typically measured at 120 Hz (for AC) and 1000 Hz (more common)
- The higher the *DF* the more heat is generated via $I^2 ESR$ heating



$$ESR = \frac{R_p}{1+\omega^2 C_p^2 R_p^2} \qquad C = C_p\left(1+\frac{1}{\omega^2 C_p^2 R_p^2}\right)$$



$$Z(\omega) = \mathrm{Re}(\omega) + \mathrm{Im}(\omega)\, j$$

$$X_c = \frac{1}{\omega C}$$

$$\tan(\delta) = ESR\omega C = DF = \frac{\mathrm{Re}(Z)}{-\mathrm{Im}(Z)} = \frac{1}{Q}$$

HOW DOES *DF* AFFECT TRANSDUCERS?

- *DF* is an important material property of the piezo ceramics
- It governs the amount of self-heating under resonant conditions
- It quantifies a particular material type for either an actuator or resonator
- High *DF* materials with higher output (d_{33}) are better for actuators
- Low *DF* materials with typically lower d_{33} are better for resonators
- Designers must often compromise between mechanical output and *DF* in the selection of piezo ceramics for power ultrasonic applications

- Abnormally high *DF* is one of the main causes of production stoppages of power transducers used in wirebonding
- Abnormally high *DF* is typically caused by moisture absorption due to poor piezo ceramic porosity (manufacturing issue)
- MFG's often use heat drying after aqueous degreasing to remove polling oil: this can mask *DF* issues in final inspection before shipping
- Moisture absorption can cause voltage leakage effects; e.g., first seen in production when setting piezo stack preload via charge amp
- Corresponding large increases in capacitance can also be associated with poor porosity, which is counterintuitive unless there is moisture absorption or electrodes are wicking/penetrating

RESEARCH SUMMARY

- Investigated the mechanisms for abnormally high *DF* in piezo ceramics, and its corresponding effect on transducer performance

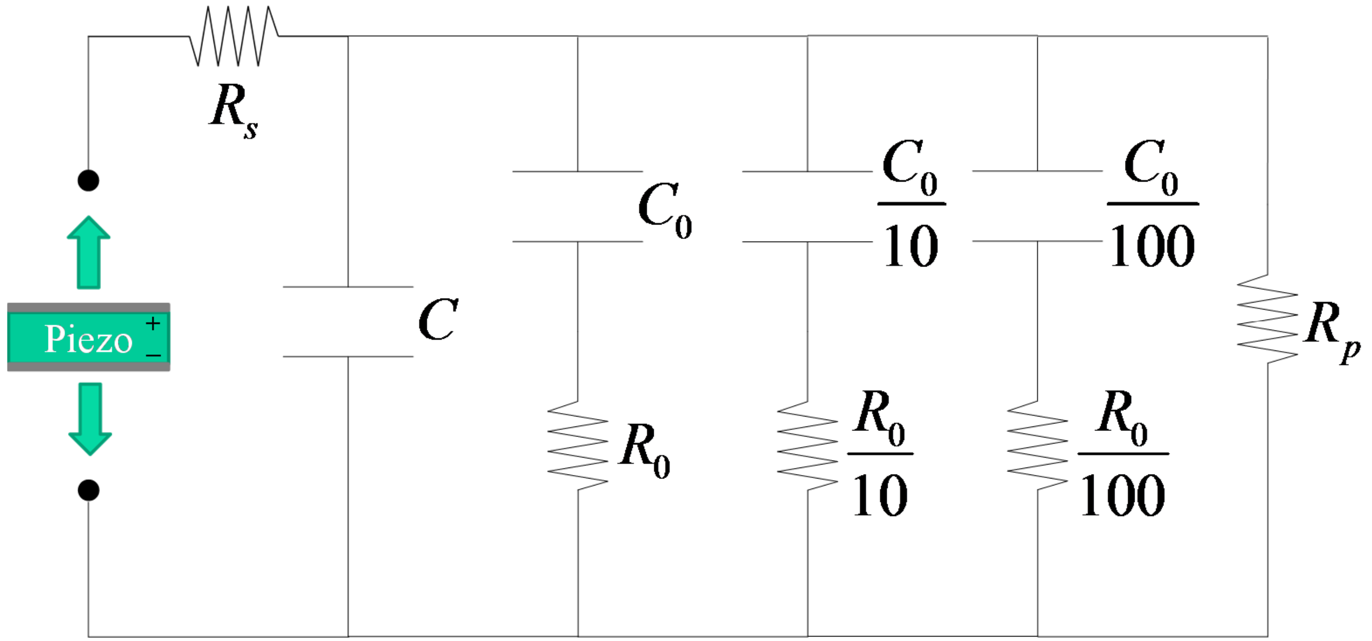
- Investigated if *DF* is only affected by the bulk dielectric properties of the piezo ceramics (e.g. porosity and moisture), or also influenced by non-uniform electric field effects such as from electrode wicking

- Explored if higher *DF* ceramics can affect transducer current/voltage to displacement gain stability via moisture expulsion at higher drive levels

- Investigation focused solely on the common PZT8 piezoelectric material used with welding transducers for semiconductor wire bonding

- Transducers were built with both normal *DF* piezo ceramics, and those with abnormally high *DF* ceramics which caused production stoppages
- Several metrics were investigated such as impedance, capacitance, displacement/current gain and displacement/voltage gain
- The experimental and theoretical research methods included Bode plots, equivalent circuits, scanning laser vibrometry and coupled-field finite element analysis

EQUIVALENT CIRCUIT MODEL FOR DF



C: Nominal Capacitance
R_s: Series Resistance
R_p: Parallel Resistance
C_0: Dielectric Absorption
R_0: Dielectric Loss
ω: Frequency

$R_{DC} = R_s + R_p$
$\omega_{120} = 2\pi(120)$
$\omega_{1k} = 2\pi(1000)$
$DF_{120} = DF$ at 120 Hz
C_{120} = Capacitance at 120 Hz
$DF_{1k} = DF$ at 1000 Hz
C_{1k} = Capacitance at 1000 Hz

Equivalent Impedance (Z_{EQ}) of Circuit

$$Z_{EQ}\left(\omega, C, R_p, C_0, R_0, R_s\right) = \frac{1}{\frac{1}{\left(\frac{-j}{\omega C}\right)} + \frac{1}{R_p} + \frac{1}{\left(R_0 - \frac{j}{\omega C_0}\right)} + \frac{1}{\left(\frac{R_0}{10} - \frac{10j}{\omega C_0}\right)} + \frac{1}{\left(\frac{R_0}{100} - \frac{100j}{\omega C_0}\right)}} + R_s$$

Equations for Solve Block (Mathcad) to Determine Unknowns from Equivalent Circuit

$DF_{120} = \mathrm{Re}\left(Z_{EQ}\left(\omega_{120}, C, R_p, C_0, R_0, R_s\right)\right)\omega_{120} C_{120}$ ⟶ Relation for Dissipation Factor at 120 Hz

$DF_{1k} = \mathrm{Re}\left(Z_{EQ}\left(\omega_{1k}, C, R_p, C_0, R_0, R_s\right)\right)\omega_{1k} C_{1k}$ ⟶ Relation for Dissipation Factor 1000 Hz

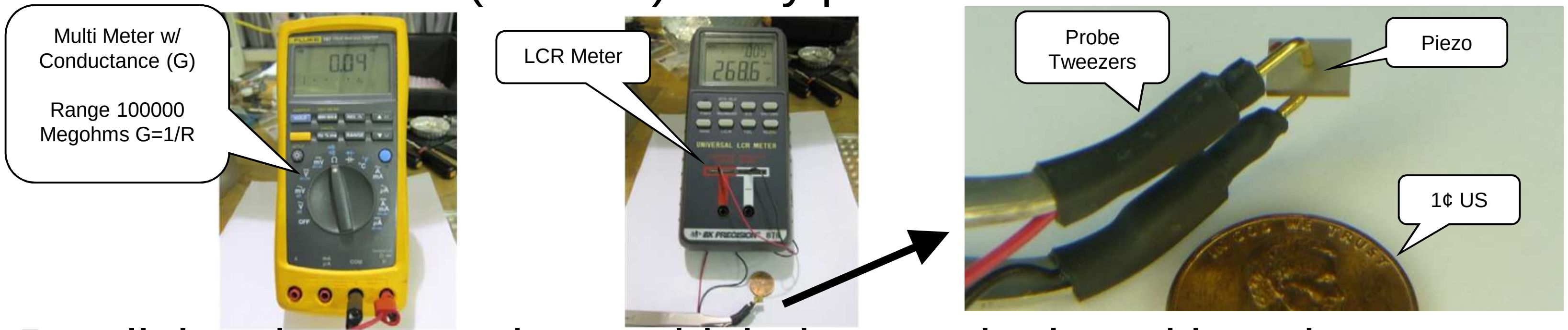
$\frac{-1}{\omega_{120} C_{120}} = \mathrm{Im}\left(Z_{EQ}\left(\omega_{120}, C, R_p, C_0, R_0, R_s\right)\right)$ ⟶ Relation for Capacitance at 120 Hz

$\frac{-1}{\omega_{1k} C_{1k}} = \mathrm{Im}\left(Z_{EQ}\left(\omega_{1k}, C, R_p, C_0, R_0, R_s\right)\right)$ ⟶ Relation for Capacitance at 1000 Hz

$R_{DC} = R_s + R_p$ ⟶ Series and Parallel (Leakage) Resistance at DC

MEASURING DF MODEL PARAMETERS

- LCR meter used to measure capacitance and dissipation factor at 120 Hz & 1000 Hz (BK 878). Tiny probes avoids inductance errors

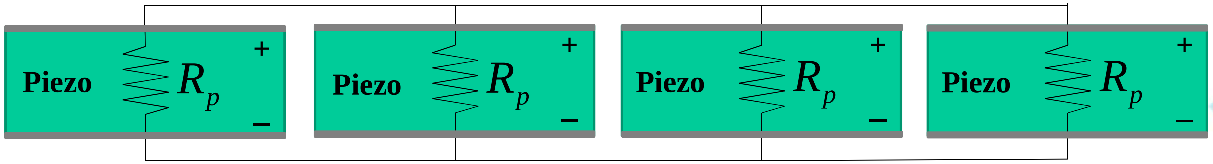


- Parallel resistance R_p is very high, but can ionize with moisture to cause shorts at DC. Used conductance measurement ($1/R$) with Fluke 187
- Conductance is affected by moisture expulsion due to current heating from multimeter, and typically decreases rapidly for times longer than RC time constant. This is not an accurate method for measuring R_{DC}
- Conductivity of moisture is not a major factor for dissipation factor with respect to leakage across electrodes, but rather affects internal operation of capacitor to store charge due to local ionization with AC
- Typical measurements for excellent, good and bad piezo ceramics

Type	DF_{120}	C_{120} (pF)	DF_{1k}	C_{1k} (pF)	G (nS)
Excellent	.001	268	.001	268	0
Good	.001	283	.004	282	0
Bad	.073	269	.034	252	Varies

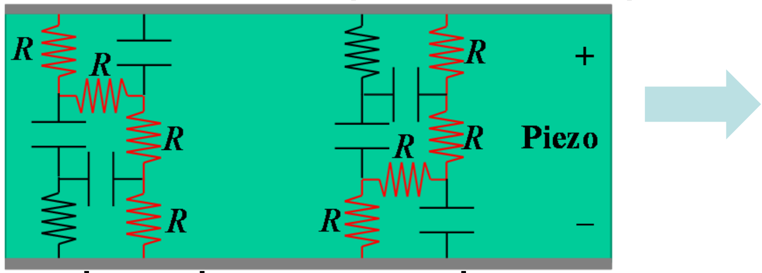
MEASURING DF MODEL CON'T

- Parallel or leakage resistance (R_p) reduces when taking transducer based measurements for DF with many piezo ceramics are in parallel



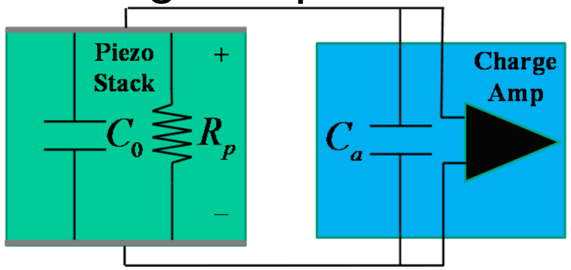
$$R_{eq} = \frac{1}{\frac{1}{R_p} + \frac{1}{R_p} + \frac{1}{R_p} + \frac{1}{R_p}} = \frac{1}{4} R_p$$

- Parallel leakage resistance (R_p) also decreases in similar fashion when several conductive percolation paths (in red) appear due to moisture



$$R_{eq} = \frac{1}{\frac{1}{4R} + \frac{1}{4R}} = 2R$$

- When using piezo ceramics to set preload, RC time constant (τ) for charge amp needs to be greater than ~30 sec in practice for accuracy



$$R_p \geq \frac{\tau}{C_0 + C_a} = \frac{30}{1550\,pF + 2\,\mu F} = 15\,M\Omega$$

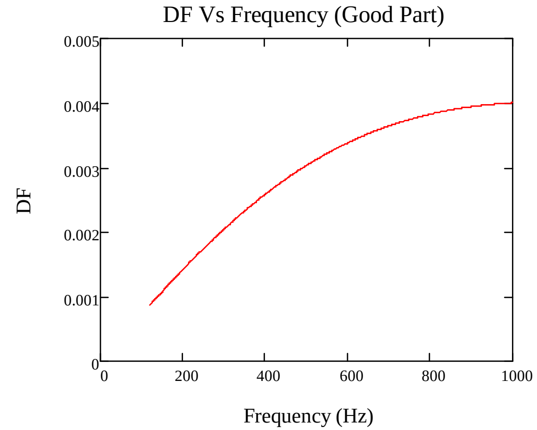
- Percolated conduction paths due to moisture can cause rapid decay or excessive preload due to charge leakage via R_p (production stoppage)

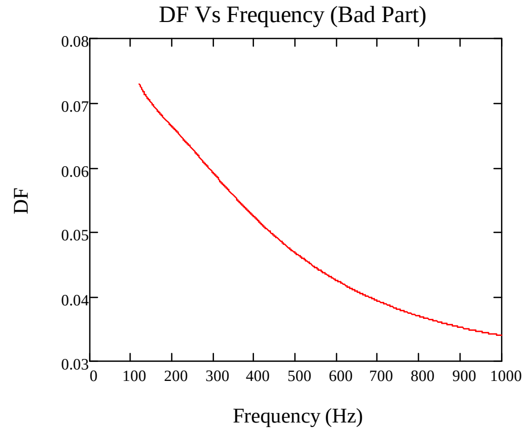
DF CIRCUIT MODEL EXAMPLES

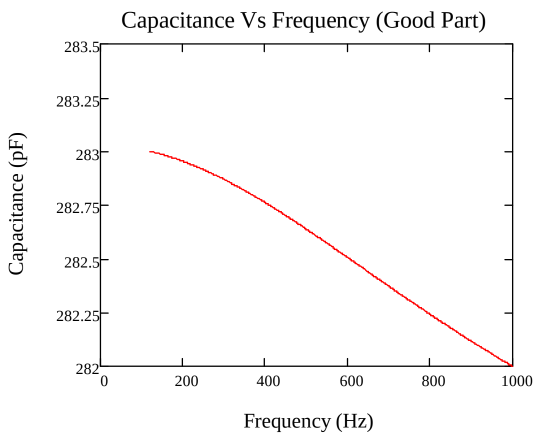
- *DF* model predictions based on individual piezo ceramic measurements

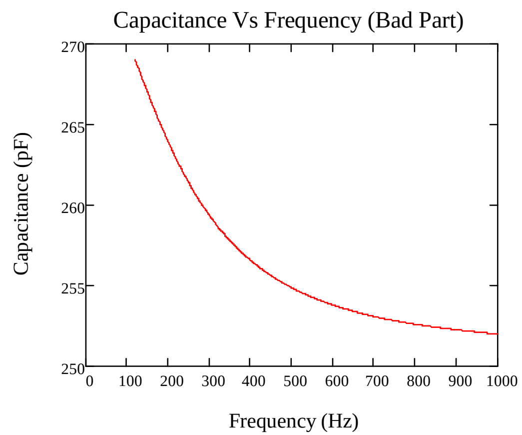
Type	DF_{120}	C_{120} (pF)	DF_{1k}	C_{1k} (pF)	C (pF)	R_p (MΩ)	C_0 (pF)	R_0 (MΩ)	R_s (MΩ)
Good	.001	283	.004	282	281	2e12	2	64	0
Bad	.073	269	.034	252	248	131	22	33	6637

Bad Part has More: Leakage, Dielectric Absorption (Moisture), and Series Resistance





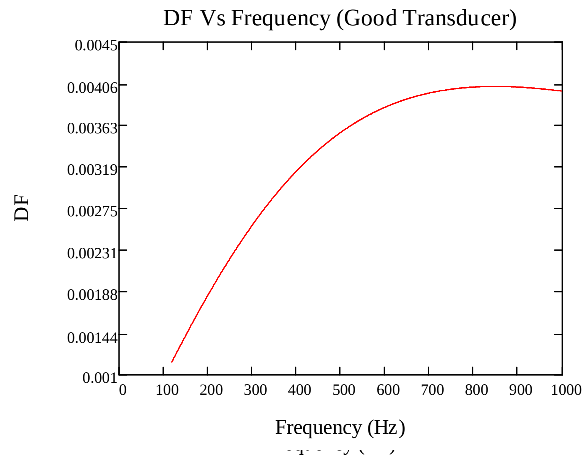


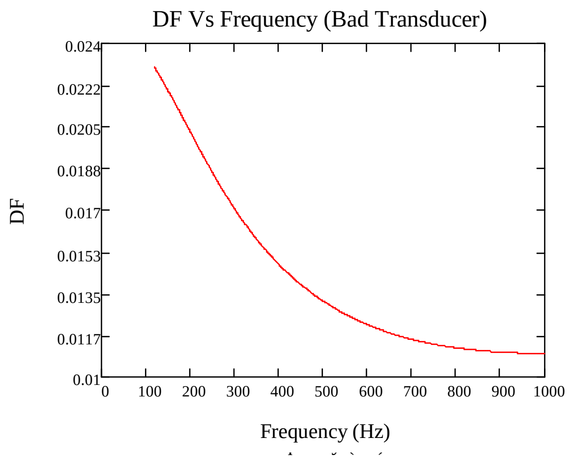


DF CIRCUIT MODEL EXAMPLES

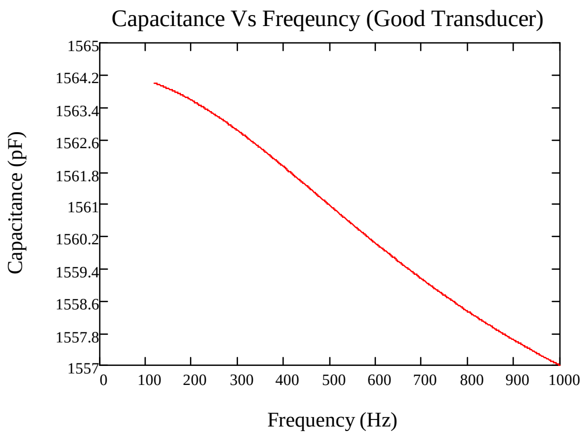
❖ *DF* Model predictions based on transducer assembly measurements

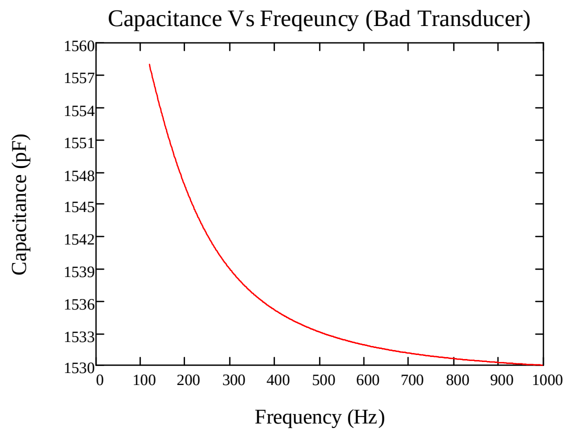
Type	DF_{120}	C_{120} (pF)	DF_{1k}	C_{1k} (pF)	C (pF)	R_p (MΩ)	C_0 (pF)	R_0 (MΩ)	R_s (MΩ)
Good	.001	1564	.004	1557	1551	16470822	12	16	16
Bad	.023	1558	.011	1530	1524	100	45	23	548





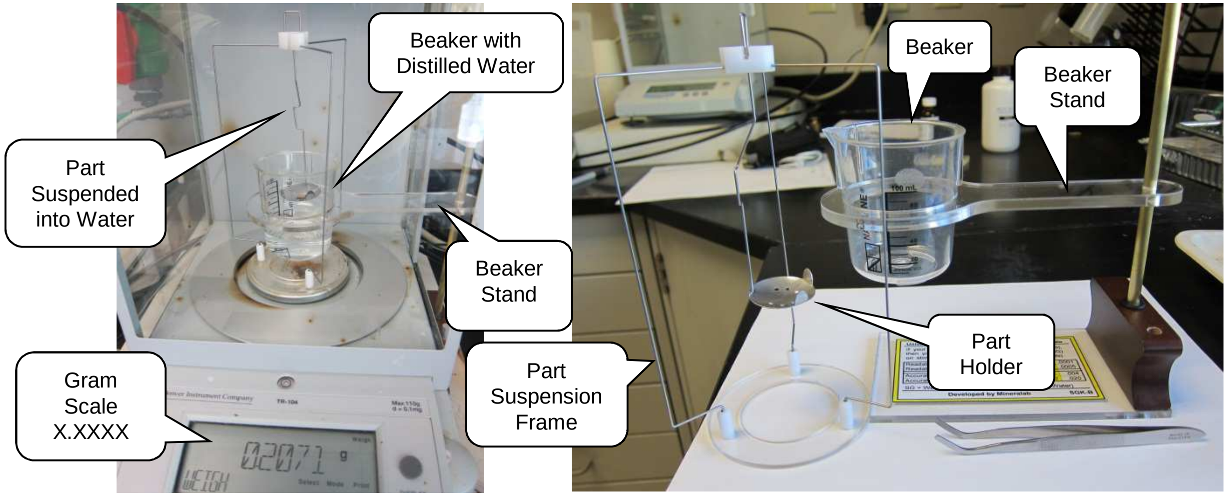
Bad Transducer has More: Leakage, Dielectric Absorption (Moisture), Dielectric Loss and Series Resistance





MEASURING POROSITY OF PIEZO CERAMICS

- Porosity (ϕ) is defined as the Pore Volume/Bulk Volume (V_ϕ / V_b)
- Porosity pores can be closed or open/interconnected to exterior surfaces
- Silver electrodes may wick more than plated or sputtered (e.g., nickel)
- Porosity measured using Archimedes method with submersion in water

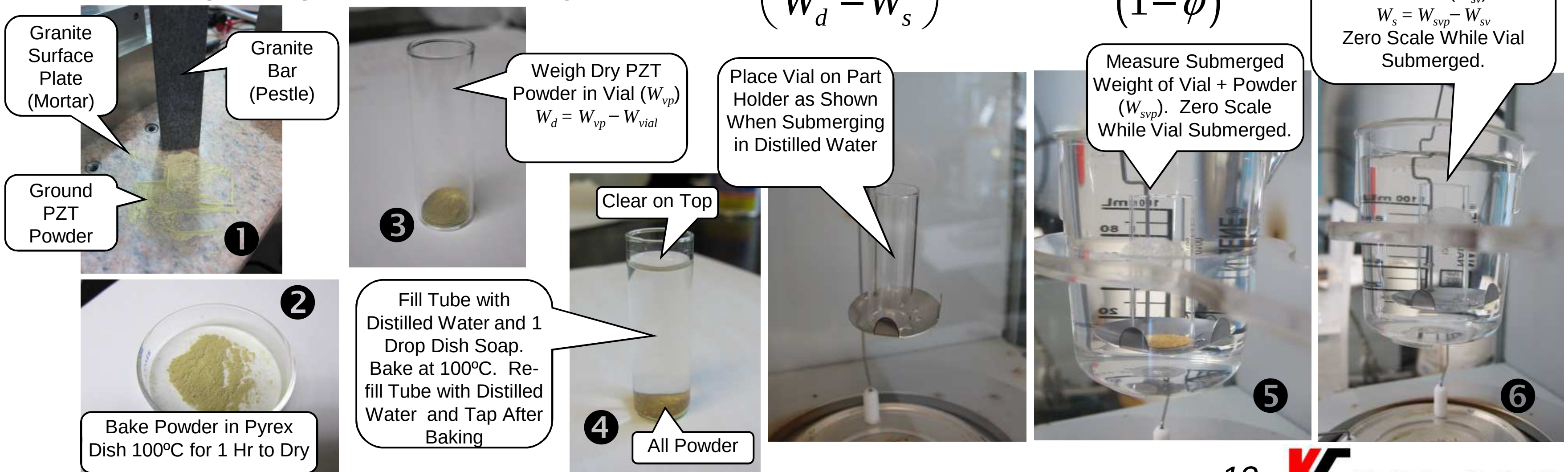


W_d: Dry Weight
W_s: Submerged Weight (air in pores)
W_{ss}: Saturated Submerged Weight
W_{sa}: Saturated Weight in Air
V_ϕ: Pore Volume
V_b: Bulk Volume (e.g., $L*W*t$)
ρ_w: Water Density (996 kg/m^3)
ρ_b: Bulk Density (W_d / V_b)
ρ_p: Particle Density (without ϕ)

- Determine bulk part volume via dimensions or use equation: $V_b = \dfrac{W_d - W_s}{\rho_w}$
  - Measure submerged weight (W_s) quickly to limit surface saturation
- Saturate open porosity exposed to surface for W_{ss} following ASTM C373
  - Boil for 5 hours in distilled water (100ºC). Cool for 24 hours in distilled water
- If particle density (ρ_p) is known: $\phi = 1 - \dfrac{W_d}{\rho_p V_b} = 1 - \dfrac{\rho_b}{\rho_p}$ If not: $\phi = \dfrac{W_{sa} - W_d}{W_{sa} - W_{ss}}$

MEASURING POROSITY CON'T

- Particle density (ρ_p) more accurately determined via destructive method
  - Grind ceramic part(s) to fine powder exposing all porosity cavities using granite surface plates/bars with mortar and pestle method (need >1g powder)
  - Use multiple parts (same lot) to improve accuracy for small parts <1g
  - Thick electrodes such as silver should be lapped off (sputtered not an issue)
  - Bake powder at 100ºC for 1 hr to dry and then place in glass shell vial
  - Measure W_d of powder, fill with distilled water and add 1 drop dish soap
  - Saturate powder in vial as per ASTM C373 and re-fill with distilled water
  - Tap tube to remove all bubbles and to insure all PZT particles submerged
  - Measure submerged weight (W_s) of ground powder in vial
  - Compute particle density: $\rho_p = \rho_w \left(\dfrac{W_d}{W_d - W_s} \right)$ $\qquad \rho_p = \dfrac{\rho_b}{(1-\phi)}$



MEASURING POROSITY CON'T

- Grain density measurement for PZT8 (5 parts ground)

Still Perfecting Technique (Result Not Consistent)

W_{vial} (g)	W_{vp} (g)	W_d (g)	W_{svp} (g)	W_{sv} (g)	W_s (g)	ρ_w (kg/m^3)	ρ_p (kg/m^3)
3.6064	4.6244	1.0180	2.9378	2.0477	.8901	998	7943

- Example porosity (ϕ) measurements for good and bad piezo ceramics

Type	*DF* (120/1kHz)	*C* (120/1kHz)	W_d (g)	V_b (m^3)	ρ_b (kg/m^3)	ρ_p (kg/m^3)	ϕ
Good1	.002/.001	275/276 pF	.2158	2.776e-8	7774	7943	.021
Good2	.001/.001	295/297 pF	.2140	2.754e-8	7770	7943	.022
Good3	.001/.001	282/282 pF	.2137	2.732e-8	7821	7943	.015
Bad1	.041/.019	264/255 pF	.2076	2.692e-8	7711	7943	.029
Bad2	.042/.023	270/255 pF	.2086	2.715e-8	7682	7943	.033
Bad3	.095/.041	274/256 pF	.2078	2.740e-8	7485	7943	.045

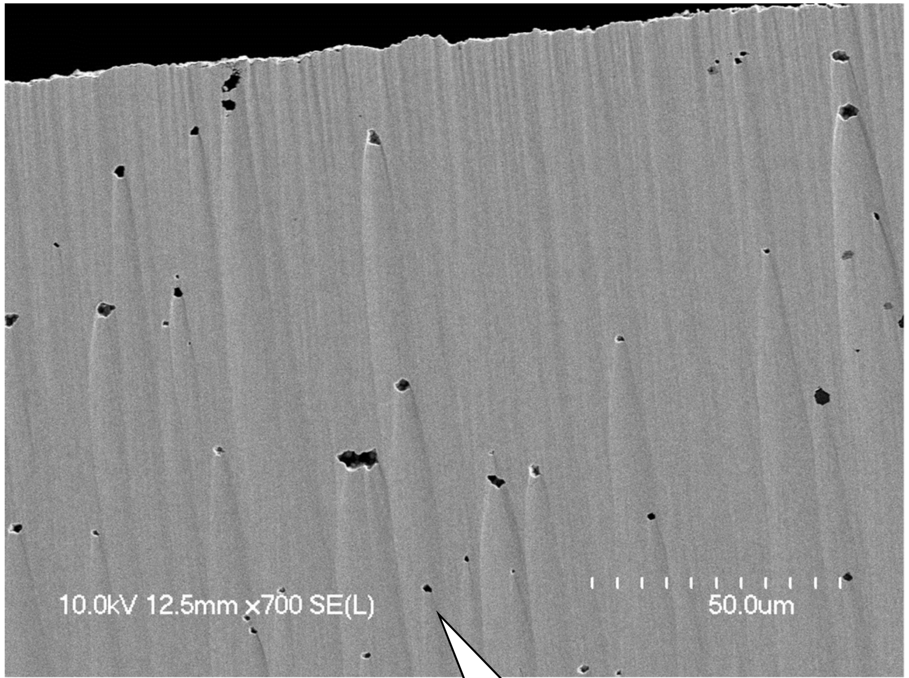
- Porosity for good and bad piezo ceramics used in SEM cross-sections

Type	*DF* (120/1kHz)	*C* (120/1kHz)	W_d (g)	V_b (m^3)	ρ_b (kg/m^3)	ρ_p (kg/m^3)	ϕ
Good	.001/.001	268/268 pF	.2160	2.777e-8	7778	7943	.021
Bad	.067/.035	271/255 pF	.2098	2.730e-8	7685	7943	.033

MEASURING POROSITY CON'T

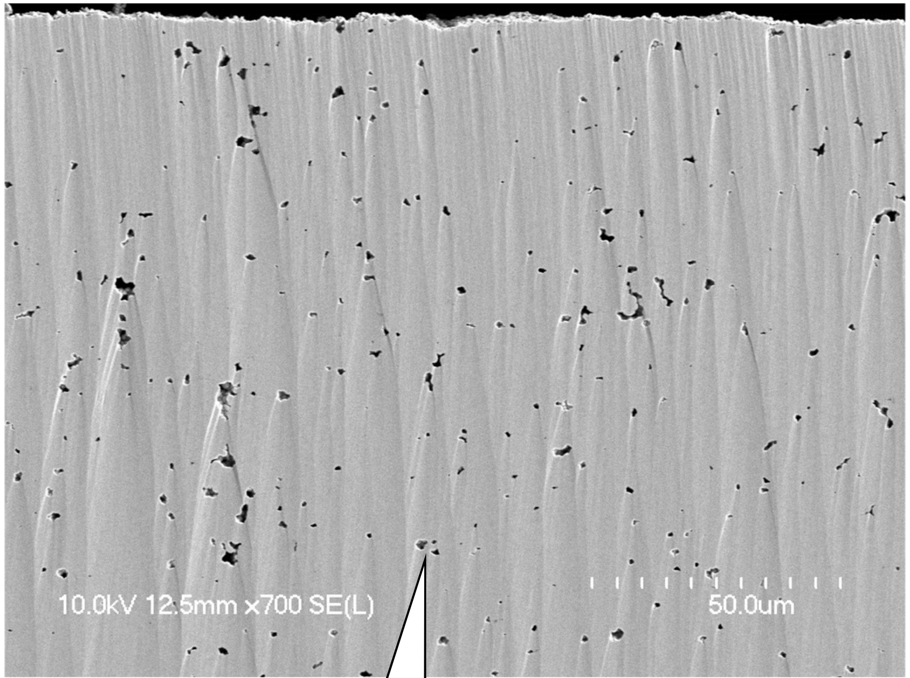
❖ SEM cross-sections for good and bad piezo ceramics listed above

Good Piezo Cross-Section



Less Overall Porosity (Measured 2.1%)

Bad Piezo Cross-Section

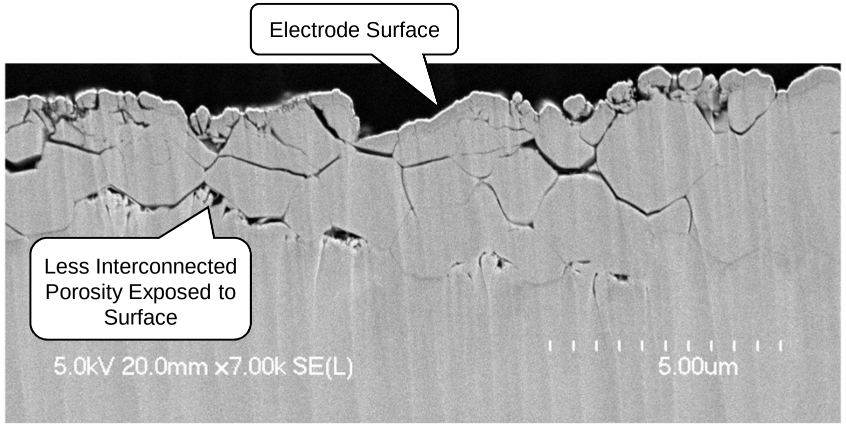


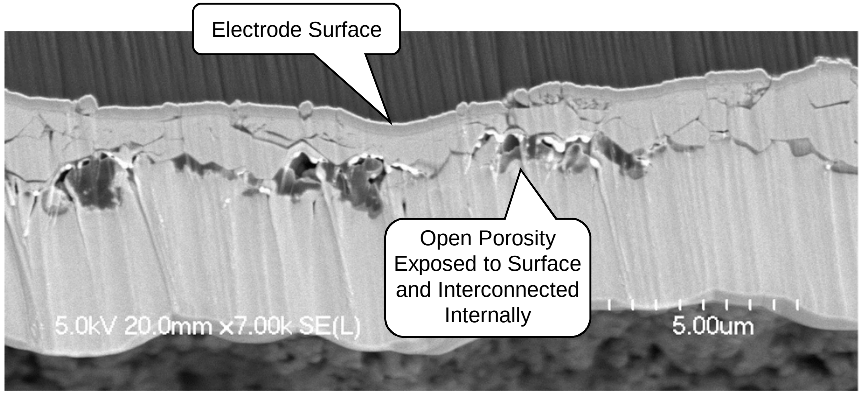
More Overall Porosity (Measured 3.3%)

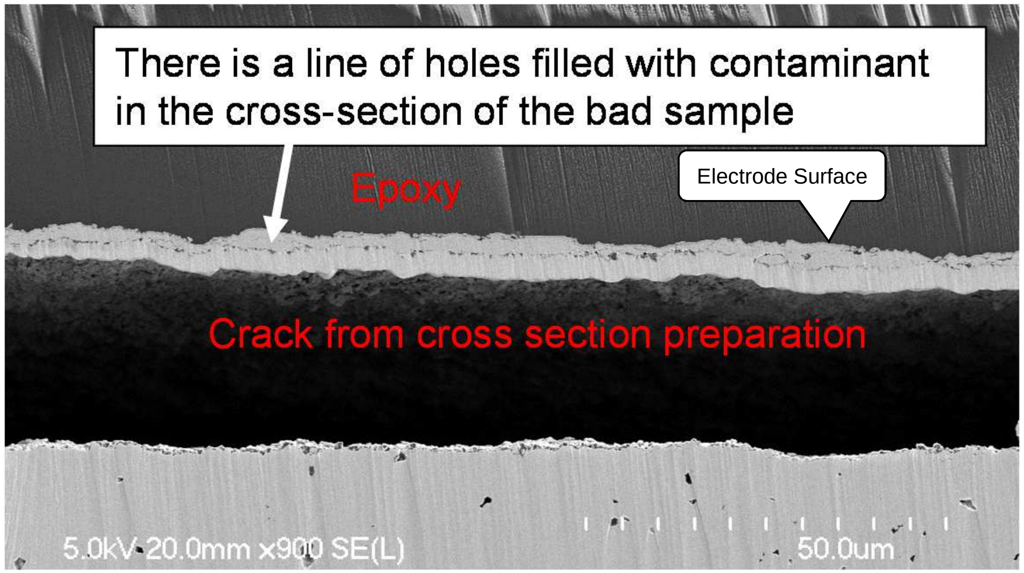
MEASURING POROSITY CON'T

- SEM cross-sections for good and bad piezo ceramics listed above con't

Good Piezo Cross-Section	Bad Piezo Cross-Section







MIXING RULES FOR PIEZO PROPERTIES

❖ Parallel mixing rule for relative permittivity of two phase dielectric

$$\varepsilon_m = V_H \varepsilon_H + V_L \varepsilon_L$$

$$\phi = \frac{V_L}{V_H} \quad V_H + V_L = 1$$

Type	ϕ	ε_H (PZT)	ε_L (Air)	ε_m	C (pF)
Good	.020	1173	1	1150	298
Bad	.040	1173	1	1126	291

- ε_H and ε_L are relative permittivities for high and low dielectric phases
- V_H and V_L are the volume fractions for high and low dielectric phases
- Effective permittivity (ε_m) of high phase (PZT) and low phase (air) based on ϕ
- Parallel mixing rule gives upper limit of dielectric constant (serial gives lower)

❖ Logarithmic mixing rule for relative permittivity of two phase dielectric

- Gives Intermediate values of dielectric constant between serial and parallel

$$\log \varepsilon_m = V_H \log \varepsilon_H + V_L \log \varepsilon_L \qquad \varepsilon_m = 10^{(V_H \log \varepsilon_H + V_L \log \varepsilon_L)}$$

Type	ϕ	ε_H (PZT)	ε_L (Air)	ε_m	C (pF)
Good	.020	1328	1	1150	298
Bad	.040	1328	1	996	258

Better Prediction

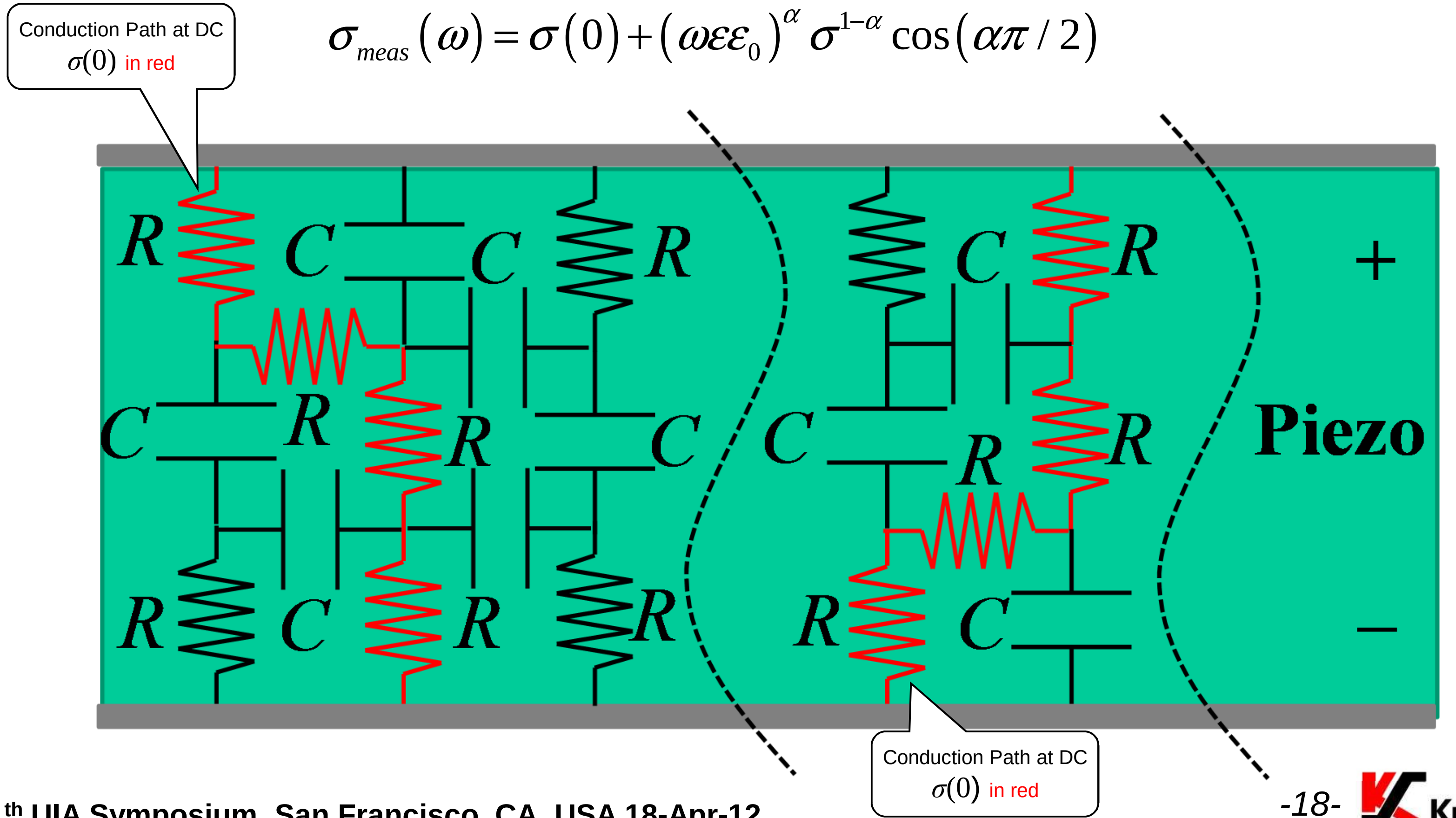
0% Porosity Prediction

POWER LAW RESPONSE FOR PIEZO PROPS

- Power law response for material with dielectric and conductive phases
  - Model as complex frequency dependent network of resistors and capacitors
  - Dielectric (PZT) has relative permittivity (ε) and conductivity of water is (σ)

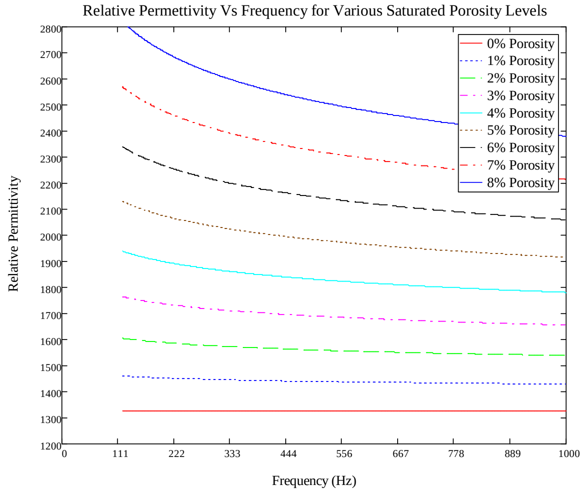
$$\varepsilon_{meas}(\omega) = (\omega\varepsilon_0)^{\alpha}\,\varepsilon^{\alpha-1}\sigma^{1-\alpha}\sin(\alpha\pi/2) \qquad \alpha = (1-\phi)$$

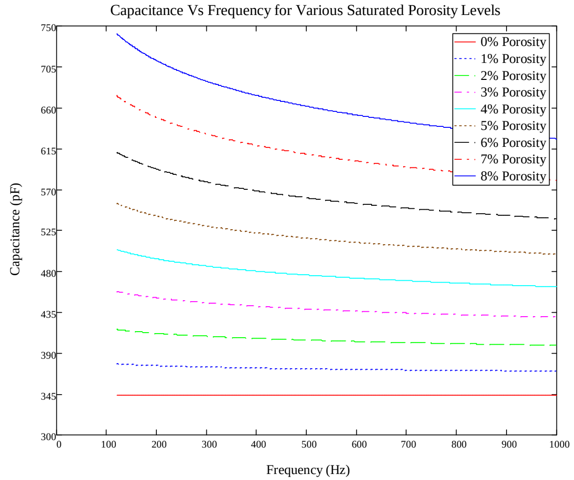
$$\sigma_{meas}(\omega) = \sigma(0) + (\omega\varepsilon\varepsilon_0)^{\alpha}\,\sigma^{1-\alpha}\cos(\alpha\pi/2)$$

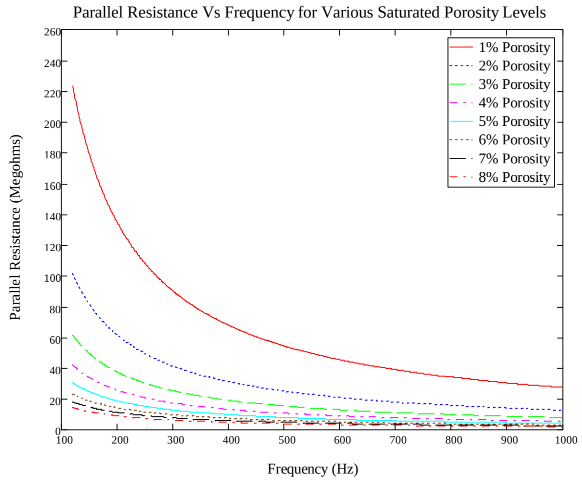


POWER LAW RESPONSE CON'T

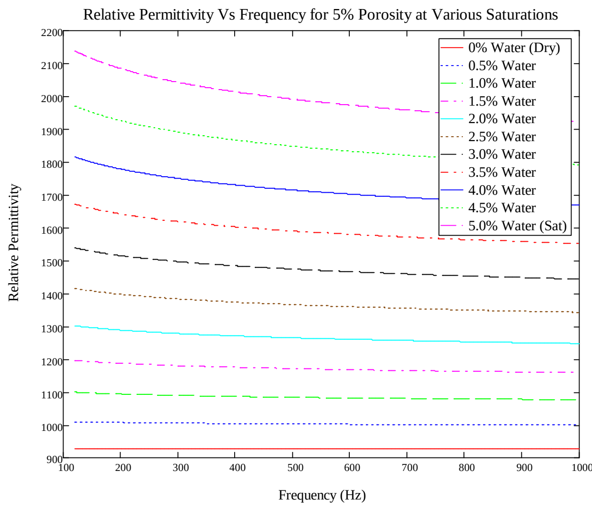
- Power law response predictions based on porosity with 100% saturation

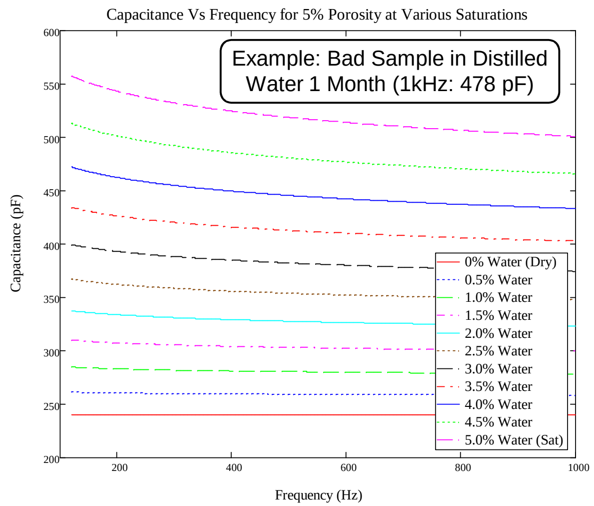


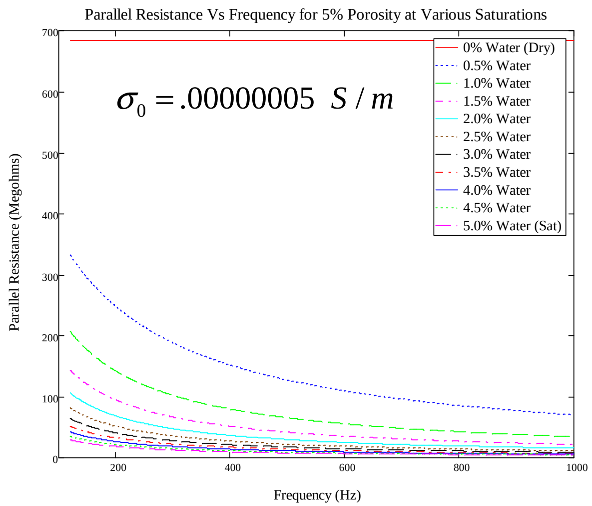




- Power law response predictions at 5% porosity with various saturations



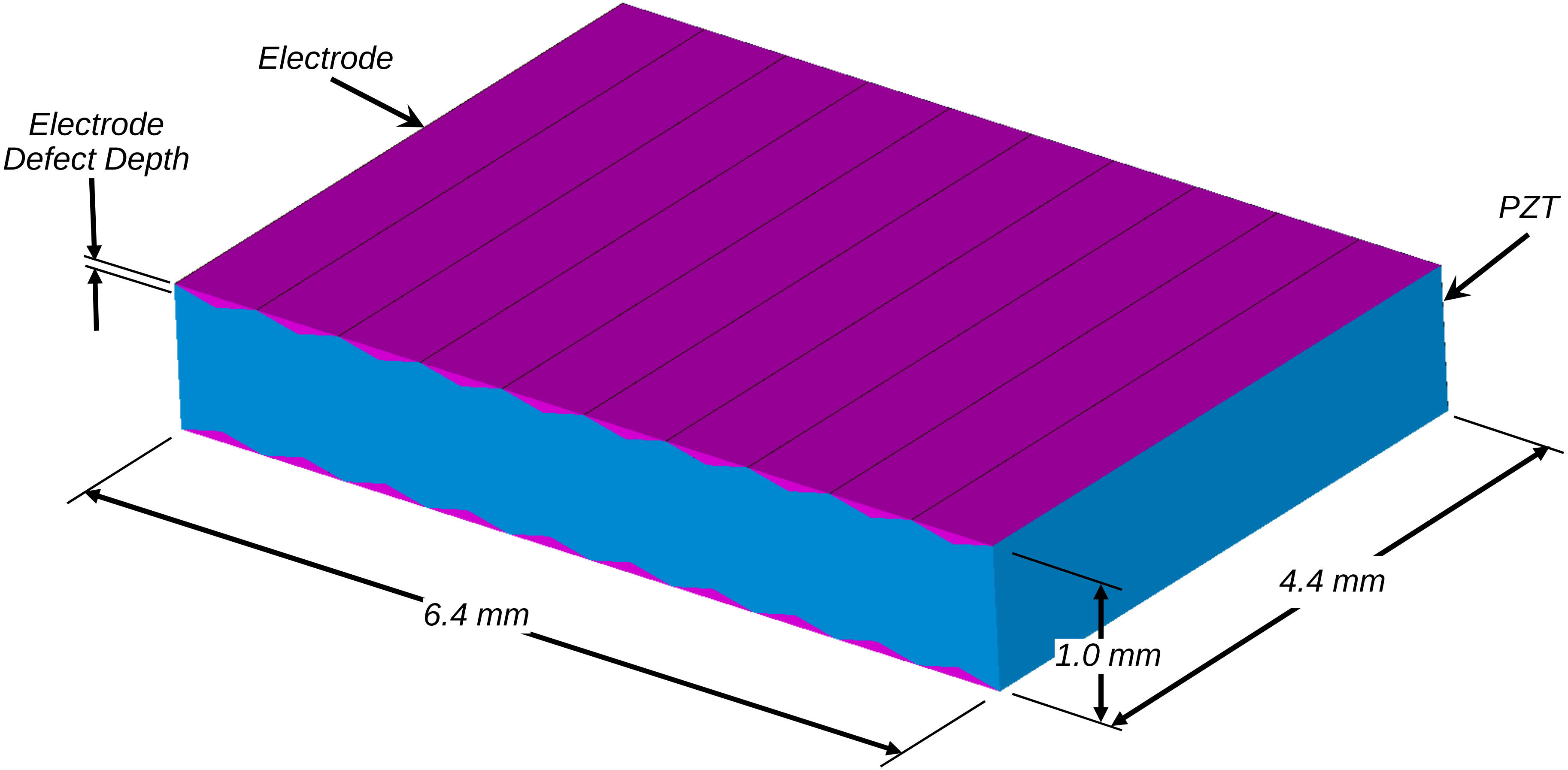




$$\varepsilon(\phi,\phi_{water}) = 10^{\left[(1-\phi+\phi_{water})\log(\varepsilon_H)+(\phi-\phi_{water})\log(\varepsilon_L)\right]}$$

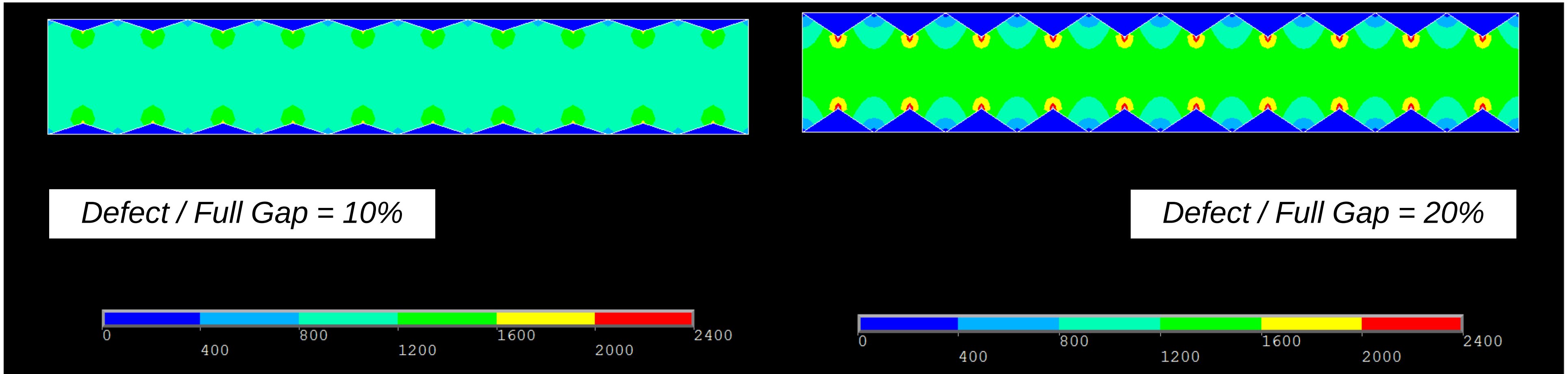
FINITE ELEMENT MODELING

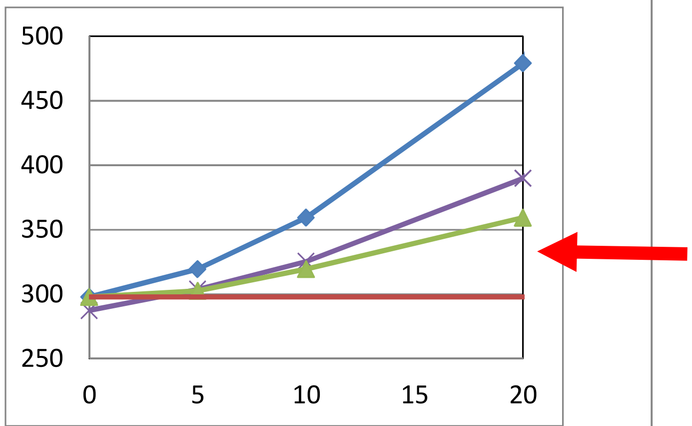
- To examine the effect of electrode defects which extend below the surface of the PZT element face, a simple ANSYS finite element model was created

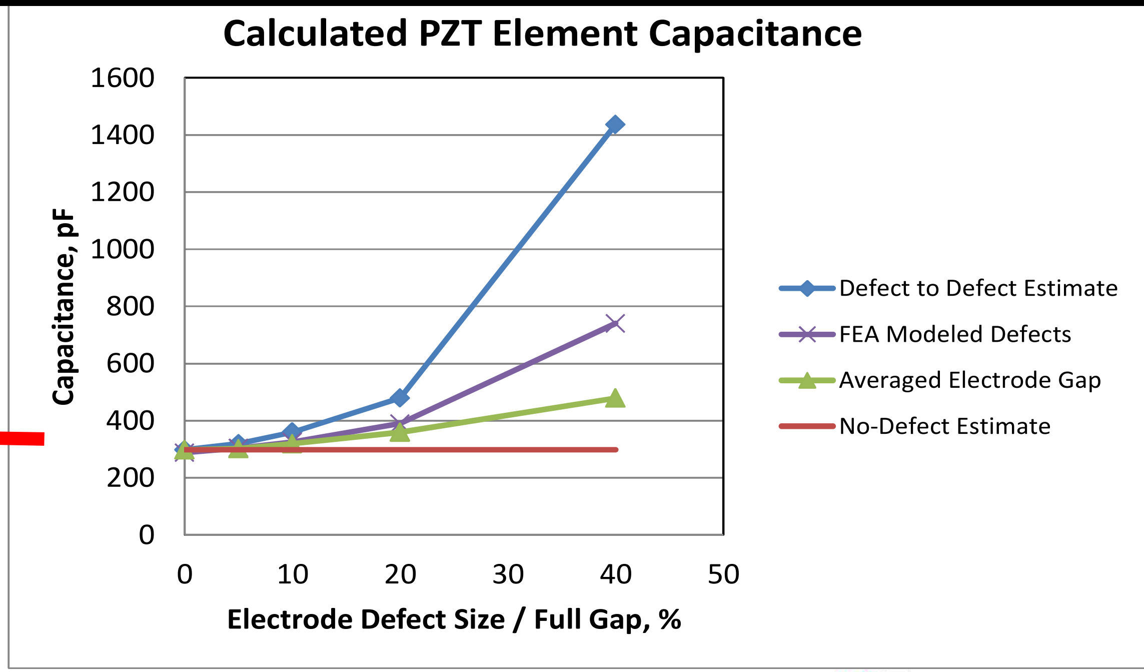


FINITE ELEMENT MODELING CON'T

- Electric Field and Capacitance (no edge effects)







EXPERIMENTAL RESULTS

❖ Bad piezo ceramic results before and after 100ºC "bake" test

Bad Part #1 (Bake)	LCR Meter 120 Hz		LCR Meter 1 kHz	
Test Description	***DF***	***C* (pF)**	***DF***	***C* (pF)**
Initial State After MFG	0.089	273	0.036	257
After 24 Hrs at 100ºC	0.011	281	0.006	282
After 48 Hrs at 100ºC	0.007	279	0.005	279
After 7 Days at 100ºC	0.005	276	0.004	276

Density and Porosity Measurements (Bad #1)				
W_d (g)	V_b (m^3)	ρ_b (kg/m^3)	ρ_p (kg/m^3)	ϕ
0.2082	2.738E-08	7604	7943	0.043

Bad Part #2 (Bake)	LCR Meter 120 Hz		LCR Meter 1 kHz	
Test Description	***DF***	***C* (pF)**	***DF***	***C* (pF)**
Initial State After MFG	0.048	273	0.023	263
After 24 Hrs at 100ºC	0.003	282	0.002	284
After 48 Hrs at 100ºC	0.002	284	0.002	284
After 7 Days at 100ºC	0.002	277	0.002	278

Density and Porosity Measurements (Bad #2)				
W_d (g)	V_b (m^3)	ρ_b (kg/m^3)	ρ_p (kg/m^3)	ϕ
0.2065	2.693E-08	7667	7943	0.035

❖ Good and bad piezo ceramic results before and after water "dunk" test

Good Part #1 (Dunk)	LCR Meter 120 Hz		LCR Meter 1 kHz	
Test Description	***DF***	***C* (pF)**	***DF***	***C* (pF)**
Initial State After MFG	0.001	268	0.001	268
After 3 Days in Distilled Water	0.001	269	0.001	269
After 17 Days in Distilled Water	0.001	269	0.001	269

Density and Porosity Measurements (Good #1)				
W_d (g)	V_b (m^3)	ρ_b (kg/m^3)	ρ_p (kg/m^3)	ϕ
0.2165	2.779E-08	7791	7943	0.019

Bad Part #3 (Dunk)	LCR Meter 120 Hz		LCR Meter 1 kHz	
Test Description	***DF***	***C* (pF)**	***DF***	***C* (pF)**
Initial State After MFG	0.011	254	0.006	252
After 15 Min in Distilled Water	0.013	256	0.008	254
After 30 Min in Distilled Water	0.015	256	0.008	254
After 1 Hr in Distilled Water	0.017	258	0.009	256
After 24 Hrs in Distilled Water	0.030	269	0.021	262

Density and Porosity Measurements (Bad #3)				
W_d (g)	V_b (m^3)	ρ_b (kg/m^3)	ρ_p (kg/m^3)	ϕ
0.2108	2.744E-08	7682	7943	0.033

Bad Part #4 (Dunk)	LCR Meter 120 Hz		LCR Meter 1 kHz	
Test Description	***DF***	***C* (pF)**	***DF***	***C* (pF)**
Initial State After MFG	0.018	254	0.009	249
After 15 Min in Distilled Water	0.023	258	0.013	253
After 30 Min in Distilled Water	0.024	258	0.013	252
After 1 Hr in Distilled Water	0.024	258	0.013	253
After 24 Hrs in Distilled Water	0.045	277	0.030	262

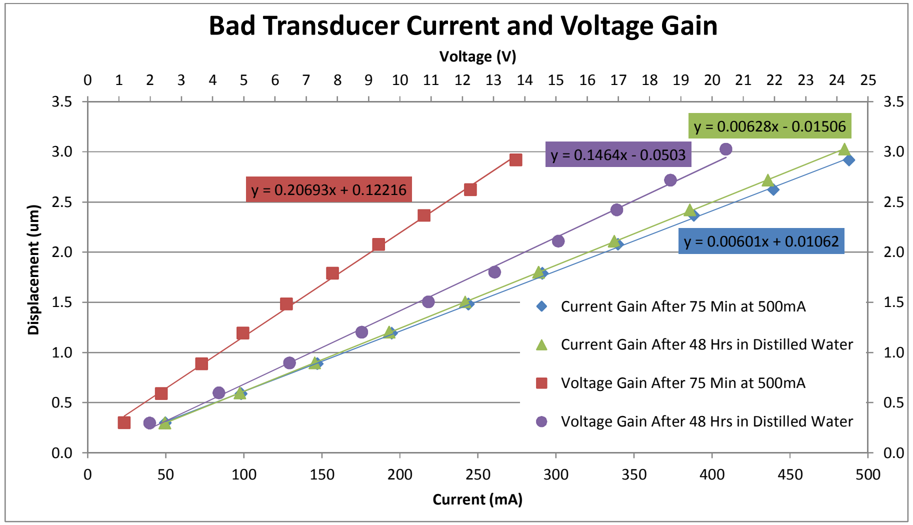
Density and Porosity Measurements (Bad #4)				
W_d (g)	V_b (m^3)	ρ_b (kg/m^3)	ρ_p (kg/m^3)	ϕ
0.2114	2.742E-08	7710	7943	0.029

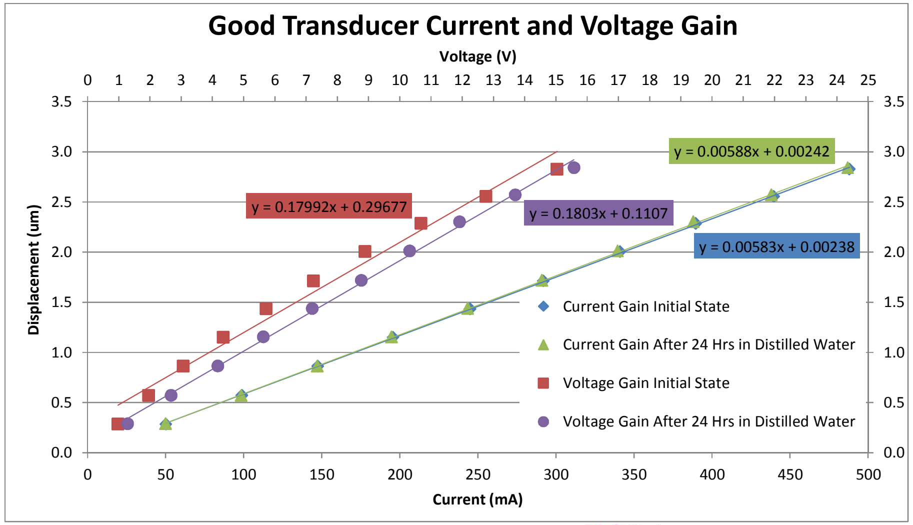
EXPERIMENTAL RESULTS CON'T

- Transducer test results before and after distilled water "dunk" test

Good Transducer	LCR Meter 120 Hz		LCR Meter 1 kHz		Bode Plot		Gain				
Test Description	*DF*	*C* (pF)	*DF*	*C* (pF)	*Fr* (Hz)	*Z* (Ω)	µm/mA		µm/V		*Z* @ 500mA (Ω)
Initial State After Build	0.001	1564	0.004	1557	121925	22	0.00583	0.0%	0.17992	0.0%	31
After 48 Hrs in Distilled Water	0.001	1573	0.004	1566	121725	28	0.00588	0.9%	0.18033	0.2%	33
After 2 Hrs at 500mA	0.001	1604	0.004	1598	121625	23	0.00582	-0.2%	0.27526	53.0%	21
After 24 Hrs at 500mA	0.001	1607	0.004	1603	121675	22	0.00580	-0.5%	0.28171	56.6%	21

Bad Transducer	LCR Meter 120 Hz		LCR Meter 1 kHz		Bode Plot		Gain				
Test Description	*DF*	*C* (pF)	*DF*	*C* (pF)	*Fr* (Hz)	*Z* (Ω)	µm/mA		µm/V		*Z* @ 500mA (Ω)
Initial State After Build	0.023	1558	0.011	1530	121700	27	0.00617	0.0%	0.19619	0.0%	29
After 75 min at 500mA	0.010	1603	0.007	1587	121425	26	0.00601	-2.6%	0.20693	5.5%	28
After Soaked 48 Hrs in Water	0.058	1731	0.037	1628	121750	48	0.00628	1.8%	0.14640	-25.4%	45
After 24 Hrs at 500mA	0.022	1628	0.012	1596	121400	26	0.00604	-2.1%	0.23269	18.6%	26





EXPERIMENTAL RESULTS CON'T

❖ Sensitivity analysis of transducer test results as moisture is absorbed

Sensitivity to Moisture Absorption	
Transducer Parameter	***Direction***
Impedance	↑
Resonant Frequency	↑
Electro-Mechanical Coupling	↓
Dissipation Factor (*DF*)	↑
Capacitance	↑
Mechanical Quality Factor	↓
Gain μm/mA	↑
Gain μm/V	↓
Impedance Change Ω/mA	↑
Frequency Change Hz/mA	↑

CONCLUSIONS

- Taking C and DF measurements at both 120 Hz and 1kHz with LCR meter has great advantages as a diagnostic tool for high DF issues
- Equiv. circuit can distinguish DF between dielectric absorption and dielectric loss
- Moisture absorption causes $C_{120} > C_{1k}$ seen as dielectric absorption C_0 in circuit
- When $C_{120} \approx C_{1k}$ equivalent circuit model predicts DF unrelated to moisture
- Charge leakage at DC, as seen during preload with charge amp, is caused by percolated conductions path due to moisture

- High DF can be caused by poor porosity due to increased moisture absorption
- Power law response showed frequency dependencies (e.g., with C) caused by both capacitive (PZT) and conductive (water) regions in the piezos
- At some threshold the porosity becomes interconnected and open to surface allowing the piezo ceramic to become permeable to moisture
- The type of porosity (i.e., closed vs. open/interconnected) is also very important
- SEM cross-sections showed big porosity differences between good & bad piezos

- FEA modeling showed electrode wicking alone can cause high C but not high DF
- High current drive of transducer can cause moisture expulsion and affect DF
- Moisture absorption/expulsion (porosity) affects both current and voltage gains
- Moisture expulsion is only temporary until piezos equilibrate again
- Heating piezo ceramics can also expel moisture temporarily and affect DF
- Heating does not always improve DF to normal range (piezo composition issue?)

REFERENCES

- C. R. Bowen and D. P. Almond, "Modelling the 'Universal' Dielectric Response in Heterogeneous Materials Using Microstructural Electric Networks," Materials Science Technology, Vol 22, No 6, 719-724, 2006.
- R. Elliott, "Capacitor Characteristics," Elliott Sound Products, www.sound.westhost.com, 2005.
- Y. Wu, X. Zhao, F. Li and Z. Fan, "Evaluation of Mixing Rules for Dielectric Constants of Composite Dielectrics by MC-FEM Calculation on 3D Cubic Lattice," Journal of Electroceramics, 11, 227-239, 2003.
- QuadTech Application Note, "Equivalent Series Resistance of Capacitors", www.quadtech.com, 2003
- M. Gebbia, "Low ESR Capacitors: Fact or Fiction?," ECN Magazine, p. 95, February 2001
- M. Bengisu, Engineering Ceramics. New York, NY : Springer-Verlag Berlin Heidelberg, 2001.

REFERENCES CON'T

- D. Stansfield, Underwater Electroacoustic Transducers. Los Altos, CA: Peninsula Publishing, 1991.
- O. B. Wilson, Introduction to Theory and Design of Sonar Transducers. Los Altos, CA: Peninsula Publishing, 1991.
- C. H. Sherman and J. L. Butler, Transducers and Arrays for Underwater Sound. New York, NY: Springer Science, 2007.
- K. Uchino and J. R. Giniewicz, Micromechatronics. New York, NY: Marcel Dekker, 2003.
- K. Uchino, Ferroelectric Devices. New York, NY: Marcel Dekker, 2010.
- D. A. DeAngelis and G. W. Schulze, "Advanced Bode Plot Techniques for Ultrasonic Transducers," 2011 UIA Symposium Proceedings, American Institute of Physics.
- D. A. DeAngelis and G. W. Schulze, "Optimizing Piezoelectric Ceramic Thickness in Ultrasonic Transducers," 2010 UIA Symposium Proceedings, IEEE XPlore.
- D. A. DeAngelis and G. W. Schulze, "Optimizing Piezoelectric Crystal Preload in Ultrasonic Transducers," 2009 UIA Symposium Proceedings, IEEE XPlore.
- D. A. DeAngelis and D. C. Schalcosky, "The Effect of PZT8 Piezoelectric Crystal Aging on Mechanical and Electrical Resonances in Ultrasonic Transducers," 2006 IEEE Ultrasonics Symposium, Session P2O-10.

QUESTIONS?