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

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

Kulicke & Soffa’s Flagship Semiconductor Wire Bonding Machine

Ultrasonic Transducer Used For Wire Bonding Machine

7 Dies

Transducer

Tool

Device

Forming Gas Wand for Cu Ball

Capillary Tool
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?
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

**SPECIFIC TRANSDUCER APPLICATION**

- **New IConn Transducer**
- **Piezo Stack**
- **Transducer Body**
- **Capillary Tool**
- **1¢ US**
- **PZT8 Piezoelectric Ceramics**
- **Diced Parts (thk=1mm)**

**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)

**Actual Wire Bonds From Multi-Tier Package**

**Typical Capillary Tool with Wire Compared to Sewing Needle**
Ratio of Equivalent Series Resistance (ESR) and the magnitude of capacitance reactance \( (X_c) \), i.e., \( DF = \frac{ESR}{|X_c|} \)

Also known as loss tangent or \( \tan(\delta) \), where angle \( \delta \) is deviation from 90° between voltage and current for an ideal capacitor or (i.e., no losses)

Also known as loss tangent or \( \tan(\delta) \), where angle \( \delta \) is deviation from 90° between voltage and current for an ideal capacitor or (i.e., no losses)

Ratio of (energy lost)/(energy stored) or \( \Re/|\Im| \) 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 \( I^2ESR \) heating
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 polluting 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
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
Rs: Series Resistance
Rp: Parallel Resistance
C0: Dielectric Absorption
R0: Dielectric Loss
\( \omega \): 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

\[
Z_{EQ}(\omega, C, R_p, C_0, R_0, R_s) = \frac{1}{\frac{-j}{\omega C} + \frac{1}{R_p} + \frac{1}{R_0 - \frac{j}{\omega C_0}} + \frac{1}{R_0} + \frac{1}{\frac{100}{\omega C_0}} + R_s}
\]

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

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

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

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

\[ \frac{-1}{\omega_{1k} C_{1k}} = Im\left(Z_{EQ}(\omega_{1k}, C, R_p, C_0, R_0, R_s)\right) \]
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:

<table>
<thead>
<tr>
<th>Type</th>
<th>$DF_{120}$</th>
<th>$C_{120}$ (pF)</th>
<th>$DF_{1k}$</th>
<th>$C_{1k}$ (pF)</th>
<th>$G$ (nS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excellent</td>
<td>.001</td>
<td>268</td>
<td>.001</td>
<td>268</td>
<td>0</td>
</tr>
<tr>
<td>Good</td>
<td>.001</td>
<td>283</td>
<td>.004</td>
<td>282</td>
<td>0</td>
</tr>
<tr>
<td>Bad</td>
<td>.073</td>
<td>269</td>
<td>.034</td>
<td>252</td>
<td>Varies</td>
</tr>
</tbody>
</table>
Parallel or leakage resistance \((R_p)\) reduces when taking transducer based measurements for DF with many piezo ceramics are in parallel.

\[
R_{eq} = \frac{1}{R_p + \frac{1}{R_p} + \frac{1}{R_p} + \frac{1}{R_p}} = \frac{1}{4} R_p
\]

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 \((\tau)\) for charge amp needs to be greater than \(\sim 30\) 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 model predictions based on individual piezo ceramic measurements

<table>
<thead>
<tr>
<th>Type</th>
<th>$DF_{120}$ ($\text{pF}$)</th>
<th>$C_{120}$ ($\text{pF}$)</th>
<th>$DF_{1k}$ ($\text{pF}$)</th>
<th>$C_{1k}$ ($\text{pF}$)</th>
<th>$C$ ($\text{pF}$)</th>
<th>$R_p$ ($\text{M}\Omega$)</th>
<th>$C_0$ ($\text{pF}$)</th>
<th>$R_0$ ($\text{M}\Omega$)</th>
<th>$R_s$ ($\text{M}\Omega$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Good</td>
<td>0.001</td>
<td>283</td>
<td>0.004</td>
<td>282</td>
<td>281</td>
<td>2e12</td>
<td>2</td>
<td>64</td>
<td>0</td>
</tr>
<tr>
<td>Bad</td>
<td>0.073</td>
<td>269</td>
<td>0.034</td>
<td>252</td>
<td>248</td>
<td>131</td>
<td>22</td>
<td>33</td>
<td>6637</td>
</tr>
</tbody>
</table>

Bad Part has More: Leakage, Dielectric Absorption (Moisture), and Series Resistance
DF Model predictions based on transducer assembly measurements

<table>
<thead>
<tr>
<th>Type</th>
<th>$DF_{120}$</th>
<th>$C_{120}$ (pF)</th>
<th>$DF_{1k}$</th>
<th>$C_{1k}$ (pF)</th>
<th>$C$ (pF)</th>
<th>$R_p$ (MΩ)</th>
<th>$C_0$ (pF)</th>
<th>$R_0$ (MΩ)</th>
<th>$R_s$ (MΩ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Good</td>
<td>.001</td>
<td>1564</td>
<td>.004</td>
<td>1557</td>
<td>1551</td>
<td>16470822</td>
<td>12</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Bad</td>
<td>.023</td>
<td>1558</td>
<td>.011</td>
<td>1530</td>
<td>1524</td>
<td>100</td>
<td>45</td>
<td>23</td>
<td>548</td>
</tr>
</tbody>
</table>

Bad Transducer has More:
Leakage, Dielectric Absorption (Moisture), Dielectric Loss and Series Resistance
Porosity ($\phi$) is defined as the Pore Volume/Bulk Volume ($V_\phi / V_b$)

- 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

Determine bulk part volume via dimensions or use equation:

\[
V_b = \frac{W_d - W_s}{\rho_w}
\]

- 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 ($100^\circ$C). Cool for 24 hours in distilled water

If particle density ($\rho_p$) is known:

\[
\phi = 1 - \frac{W_d}{\rho_p V_b} = 1 - \frac{\rho_b}{\rho_p}
\]

If not:

\[
\phi = \frac{W_{sa} - W_d}{W_{sa} - W_{ss}}
\]
Particle density ($\rho_p$) 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:

$$\rho_p = \frac{\rho_w}{1-\phi}$$

where

- $\rho_w$ = weight of dry powder
- $\rho_b$ = weight of vial
- $W_d$ = weight of dry powder
- $W_s$ = weight of submerged powder
- $\phi$ = porosity

Granite Surface Plate (Mortar)
Granite Bar (Pestle)
Ground PZT Powder
Bake Powder in Pyrex Dish 100ºC for 1 Hr to Dry
Fill Tube with Distilled Water and 1 Drop Dish Soap. Bake at 100ºC. Refill Tube with Distilled Water and Tap After Baking
Place Vial on Part Holder as Shown When Submerging in Distilled Water
Weigh Dry PZT Powder in Vial ($W_w$) $W_j = W_p - W_vial$
Zero Scale While Vial Submerged.
Clear on Top
Measure Submerged Weight of Vial + Powder ($W_{vp}$). Zero Scale While Vial Submerged.
Subtract Submerged Weight of Vial Without Powder ($W_v$) $W_s = W_{vp} - W_v$
Grain density measurement for PZT8 (5 parts ground)

<table>
<thead>
<tr>
<th>$W_{vial}$ (g)</th>
<th>$W_{vp}$ (g)</th>
<th>$W_d$ (g)</th>
<th>$W_{svp}$ (g)</th>
<th>$W_s$ (g)</th>
<th>$\rho_w$ (kg/m$^3$)</th>
<th>$\rho_p$ (kg/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.6064</td>
<td>4.6244</td>
<td>1.0180</td>
<td>2.9378</td>
<td>2.0477</td>
<td>.8901</td>
<td>998</td>
</tr>
</tbody>
</table>

Example porosity ($\phi$) measurements for good and bad piezo ceramics

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

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

<table>
<thead>
<tr>
<th>Type</th>
<th>$DF$ (120/1kHz)</th>
<th>$C$ (120/1kHz)</th>
<th>$W_d$ (g)</th>
<th>$V_b$ (m$^3$)</th>
<th>$\rho_b$ (kg/m$^3$)</th>
<th>$\rho_p$ (kg/m$^3$)</th>
<th>$\phi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Good</td>
<td>.001/.001</td>
<td>268/268 pF</td>
<td>.2160</td>
<td>2.777e-8</td>
<td>7778</td>
<td>7943</td>
<td>.021</td>
</tr>
<tr>
<td>Bad</td>
<td>.067/.035</td>
<td>271/255 pF</td>
<td>.2098</td>
<td>2.730e-8</td>
<td>7685</td>
<td>7943</td>
<td>.033</td>
</tr>
</tbody>
</table>
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

- Electrode Surface
- Less Interconnected Porosity Exposed to Surface

Bad Piezo Cross-Section

- Electrode Surface
- Open Porosity Exposed to Surface and Interconnected Internally

There is a line of holes filled with contaminant in the cross-section of the bad sample

- Epoxy
- Crack from cross section preparation
Parallel mixing rule for relative permittivity of two phase dielectric

\[ \varepsilon_m = V_H \varepsilon_H + V_L \varepsilon_L \]

\[ \phi = \frac{V_L}{V_H} \text{ with } V_H + V_L = 1 \]

- \( \varepsilon_H \) and \( \varepsilon_L \) 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 (\( \varepsilon_m \)) of high phase (PZT) and low phase (air) based on \( \phi \)
- 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

\[ \log \varepsilon_m = V_H \log \varepsilon_H + V_L \log \varepsilon_L \]

\[ \varepsilon_m = 10^{(V_H \log \varepsilon_H + V_L \log \varepsilon_L)} \]
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 ($\varepsilon$) and conductivity of water is ($\sigma$)

\[
\varepsilon_{\text{meas}}(\omega) = (\omega \varepsilon_0)\alpha \varepsilon^{\alpha-1} \sigma^{1-\alpha} \sin(\alpha \pi / 2) \quad \alpha = (1 - \phi)
\]

\[
\sigma_{\text{meas}}(\omega) = \sigma(0) + (\omega \varepsilon_0)\alpha \sigma^{1-\alpha} \cos(\alpha \pi / 2)
\]
Power law response predictions based on porosity with 100% saturation

Power law response predictions at 5% porosity with various saturations

\[ \sigma_0 = 0.0000005 \text{ S/m} \]
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.
Electric Field and Capacitance (no edge effects)

Defect / Full Gap = 10%

Defect / Full Gap = 20%

Calculated PZT Element Capacitance
## EXPERIMENTAL RESULTS

### Bad piezo ceramic results before and after 100°C “bake” test

<table>
<thead>
<tr>
<th>Test Description</th>
<th>LCR Meter 120 Hz</th>
<th>LCR Meter 1 kHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial State After MFG</td>
<td>$DF$</td>
<td>$C$ (pF)</td>
</tr>
<tr>
<td>After 24 Hrs at 100°C</td>
<td>0.089</td>
<td>273</td>
</tr>
<tr>
<td>After 48 Hrs at 100°C</td>
<td>0.011</td>
<td>281</td>
</tr>
<tr>
<td>After 7 Days at 100°C</td>
<td>0.007</td>
<td>279</td>
</tr>
</tbody>
</table>

### Good and bad piezo ceramic results before and after water “dunk” test

<table>
<thead>
<tr>
<th>Test Description</th>
<th>LCR Meter 120 Hz</th>
<th>LCR Meter 1 kHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial State After MFG</td>
<td>$DF$</td>
<td>$C$ (pF)</td>
</tr>
<tr>
<td>After 3 Days in Distilled Water</td>
<td>0.048</td>
<td>273</td>
</tr>
<tr>
<td>After 17 Days in Distilled Water</td>
<td>0.003</td>
<td>282</td>
</tr>
<tr>
<td>After 15 Min in Distilled Water</td>
<td>0.015</td>
<td>256</td>
</tr>
<tr>
<td>After 30 Min in Distilled Water</td>
<td>0.017</td>
<td>255</td>
</tr>
<tr>
<td>After 1 Hr in Distilled Water</td>
<td>0.030</td>
<td>269</td>
</tr>
</tbody>
</table>

### Density and Porosity Measurements

<table>
<thead>
<tr>
<th>Part</th>
<th>$W_d$ (g)</th>
<th>$V_b$ (m$^3$)</th>
<th>$\rho_b$ (kg/m$^3$)</th>
<th>$\rho_p$ (kg/m$^3$)</th>
<th>$\phi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bad #1</td>
<td>0.2082</td>
<td>2.738E-08</td>
<td>7604</td>
<td>7943</td>
<td>0.043</td>
</tr>
<tr>
<td>Bad #2</td>
<td>0.2065</td>
<td>2.693E-08</td>
<td>7667</td>
<td>7943</td>
<td>0.035</td>
</tr>
<tr>
<td>Good #1</td>
<td>0.2165</td>
<td>2.779E-08</td>
<td>7791</td>
<td>7943</td>
<td>0.019</td>
</tr>
<tr>
<td>Bad #3</td>
<td>0.2108</td>
<td>2.744E-08</td>
<td>7682</td>
<td>7943</td>
<td>0.033</td>
</tr>
<tr>
<td>Bad #4</td>
<td>0.2114</td>
<td>2.742E-08</td>
<td>7710</td>
<td>7943</td>
<td>0.029</td>
</tr>
</tbody>
</table>
Transducer test results before and after distilled water “dunk” test

### Experimental Results Cont’d

#### Good Transducer

<table>
<thead>
<tr>
<th>Test Description</th>
<th>LCR Meter 120 Hz</th>
<th>LCR Meter 1 kHz</th>
<th>Bode Plot</th>
<th>Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$C$ (pF)</td>
<td>$C$ (pF)</td>
<td>$F_r$ (Hz)</td>
<td>$Z$ ($\Omega$)</td>
</tr>
<tr>
<td>Initial State After Build</td>
<td>0.001</td>
<td>1564</td>
<td>0.004</td>
<td>1557</td>
</tr>
<tr>
<td>After 48 Hrs in Distilled Water</td>
<td>0.001</td>
<td>1573</td>
<td>0.004</td>
<td>1566</td>
</tr>
<tr>
<td>After 2 Hrs at 500mA</td>
<td>0.001</td>
<td>1604</td>
<td>0.004</td>
<td>1598</td>
</tr>
<tr>
<td>After 24 Hrs at 500mA</td>
<td>0.001</td>
<td>1607</td>
<td>0.004</td>
<td>1603</td>
</tr>
</tbody>
</table>

#### Bad Transducer

<table>
<thead>
<tr>
<th>Test Description</th>
<th>LCR Meter 120 Hz</th>
<th>LCR Meter 1 kHz</th>
<th>Bode Plot</th>
<th>Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$C$ (pF)</td>
<td>$C$ (pF)</td>
<td>$F_r$ (Hz)</td>
<td>$Z$ ($\Omega$)</td>
</tr>
<tr>
<td>Initial State After Build</td>
<td>0.023</td>
<td>1558</td>
<td>0.011</td>
<td>1530</td>
</tr>
<tr>
<td>After 75 min at 500mA</td>
<td>0.010</td>
<td>1603</td>
<td>0.007</td>
<td>1587</td>
</tr>
<tr>
<td>After Soaked 48 Hrs in Water</td>
<td>0.056</td>
<td>1731</td>
<td>0.037</td>
<td>1628</td>
</tr>
<tr>
<td>After 24 Hrs at 500mA</td>
<td>0.022</td>
<td>1628</td>
<td>0.012</td>
<td>1596</td>
</tr>
</tbody>
</table>

### Graphs

#### Bad Transducer Current and Voltage Gain

#### Good Transducer Current and Voltage Gain
Sensitivity analysis of transducer test results as moisture is absorbed

<table>
<thead>
<tr>
<th>Sensitivity to Moisture Absorption</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Transducer Parameter</strong></td>
<td><strong>Direction</strong></td>
</tr>
<tr>
<td>Impedance</td>
<td>↑</td>
</tr>
<tr>
<td>Resonant Frequency</td>
<td>↑</td>
</tr>
<tr>
<td>Electro-Mechanical Coupling</td>
<td>↓</td>
</tr>
<tr>
<td>Dissipation Factor ($DF^*$)</td>
<td>↑</td>
</tr>
<tr>
<td>Capacitance</td>
<td>↑</td>
</tr>
<tr>
<td>Mechanical Quality Factor</td>
<td>↓</td>
</tr>
<tr>
<td>Gain $\mu$m/mA</td>
<td>↑</td>
</tr>
<tr>
<td>Gain $\mu$m/V</td>
<td>↓</td>
</tr>
<tr>
<td>Impedance Change $\Omega$/mA</td>
<td>↑</td>
</tr>
<tr>
<td>Frequency Change Hz/mA</td>
<td>↑</td>
</tr>
</tbody>
</table>
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 $C_o$ 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 conduction 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


❖ M. Gebbia, “Low ESR Capacitors: Fact or Fiction?,” ECN Magazine, p. 95, February 2001


