Optimizing Piezoelectric Crystal Preload in Ultrasonic Transducers

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Kulicke & Soffa’s Flagship Semiconductor Wire Bonding Machine

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

Ultrasonic Transducer Used For Wire Bonding Machine
OUTLINE

- Motivation for the Work
- Specific Transducer Application
- Research Summary
- Experimental Methods & Metrics
- Electromechanical Coupling
- Equivalent Circuits
- Bode Plot & Admittance Loop
- Experimental Results
- Conclusions
- References
- Questions
Preload is Required to Maintain the Piezo Stack in Compression
Most Often Integral Piezo Crystals Used as Force Sensor for Preload
A Press Fixture w/ Charge Amp Measures Voltage vs. Force
Method Inaccurate Since Crystal Properties Can Vary ±20% Lot-to-Lot
Vendor Preload Guidelines Based on Static Crystal Testing Only
Designers Often Struggle to Determine/Control Optimal Preload Level
Transducer Based Methods and Metrics are Needed
Why is Controlling Preload So Important?

- Inadequate Preload Results in Dynamic Gapping at Interfaces
- Dynamic Gapping Manifests as Higher Impedance, Heating, Etc.
- Inadequate Preload Results in Prolonged Stress-Aging Affects
- Excessive Preload Results in Pronounced Depolling
- Excessive Preload Produces Unstable Impedance and Aging with Use
SPECIFIC TRANSDUCER APPLICATION

- K&S is the Leading MFG of Semiconductor Wire Bonding Equipment
- Transducer Delivers Energy to a Capillary Tool for Welding Tiny Gold Wires
- Patented Single Piece “Unibody” Transducer Design Ideal for Preload Study
- Portability Across 100’s of Machines Required for Same Customer Device

PZT8 Piezoelectric Crystals

Actual Wire Bonds From of a Multi-Tier Package

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

Typical Capillary Tool with Wire Compared to Sewing Needle

1¢ US

Crystals
Transducer Body
Capillary Tool

On Machine
Transducer
Device
Capillary

38th UIA Symposium, Vancouver 3/23/09
Five Transducers Built at Various Preload Levels from 4.5 ksi to 18 ksi
All 5X Transducers Bodies and 20X Crystals from Same Production Lot
Experimental Methods were Both Crystal and Transducer Based
Transducers Subjected to Stabilizing Heat-Treatment & Cycling After Build

Crystal Based Bode Plot Technique

The Five Transducers Build for the Study
EXPERIMENTAL METHODS & METRICS

- Bode Plots, Cap, DF of Individual Crystals Before Build
- Calibrated Stack Voltage vs. Force Prior to Assembly
- Bode Plots, Cap, DF of Transducer After Build and Heat-Treat
- Laser Vibrometer Gain Measurements After Heat-Treatment & Cycling
Results from Voltage vs. Force Calibration Fixture

Piezoelectric Constant $d_{33}$ Increases with Applied Stress
Crystal Laser Vibrometry and Finite Element Analysis

Measured Out-of-Plane Motion From In-plane Structural Vibration (Poisson Effect)

METHODS & METRICS CON’T

Single Crystal Vibrometer Setup (3X Mirrors)

Finite Element Model

Example of weakly coupled mode

Mechanical Admittance Plot

Velocity

Frequency, kHz
**METHODS & METRICS CON’T**

- Bode Plot and Corresponding Finite Element Admittance
- Single Crystal Analysis Demonstrates Short and Open Circuit Properties

Typical Bode Plot of Admittance Vs. Frequency of Single PZT8 Crystal

**Elastic Moduli**

<table>
<thead>
<tr>
<th></th>
<th>$E^{33}$</th>
<th>$D^{33}$</th>
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</thead>
<tbody>
<tr>
<td>Catalog</td>
<td>7.4</td>
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<tr>
<td>Correlated</td>
<td>8.9</td>
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**Calculated Mechanical Admittance**

- Short Circuit Properties
- Open Circuit Properties
- Anticipated Phase Window ($f_a - f_r$)
**ELECTROMECHANICAL COUPLING** $k_{33}$

- $k_{33}$ Varies Proportionally to $d_{33}$, But Inversely to Square Root of Permittivity
- $k_{33}$ Varies Proportionally to Delta Between Open and Short Circuit Moduli

\[ k_{33} = d_{33}^2 \frac{Y_{33}^D}{Y_{33}^E} \]

Proportional \hspace{2cm} Inversely

\[ k_{33} = .63 \hspace{1cm} (PZT8) \]
\textbf{EQUIVALENT CIRCUITS}

- For $f_s$ Series Resonance $i_{pll} \approx i_{mo}$ and $i_{pll} \gg i_{co}$ (Via Short Circuit Modulus)
- For $f_p$ Parallel Resonance $i_{co} \approx -i_{mo}$ and $i_{pll} \ll i_{mo}$ (Via Open Circuit Modulus)
- Spacing of $f_p - f_s$ Proportional to Delta Between $Y_{33}^D - Y_{33}^E$ (And $k_{33}$ Too)

\begin{align*}
\text{Parasitic Capacitance} & \quad \text{Piezo Motor} \\
\text{PLL Drive} & \quad \text{Real} \\
V(t) & \quad Z_{mo} = R \\
C_0 & \quad Z_{pll} \\
L & \quad Z_{c0} = \frac{-1}{2\pi f_{mo} C_0} \\
C & \quad f_s = \frac{1}{2\pi \sqrt{LC}} \\
& \quad f_p = \frac{1}{2\pi} \sqrt{\frac{C_0 + C}{LC_0 C}}
\end{align*}
ADMITTANCE (Y) LOOP

**Imaginary Axis**

**Susceptance B (mS)**

- Admittance
- Conducance
- Impedance
- Reactance
- Resistance

\[ Y = G + jB = \frac{1}{Z} \]

\[ Z = R + jX = \frac{V}{I} = \frac{1}{Y} \]

\[ f = \frac{1}{2\pi f_s C_0} = B_s \]

\[ C_0 = \frac{f_r^2}{f_2^2 - f_r^2} C \approx \frac{B_s}{2\pi f_s} \]

**Real Axis**

**Conducance G (mS)**

- Zero Phase, Electrical Anti-resonance
- Zero Phase, Electrical Resonance

\[ f_p = \frac{1}{2\pi} \sqrt{\frac{C_0 + C}{LC_0 C}} \]

\[ f_a > f_p > f_2 > f_r > f_s > f_{Y_{\text{min}}} > f_1 \]

\[ G_{\text{max}} = \frac{1}{R} \]

\[ Q_m = \frac{f_s}{f_2 - f_1} = \frac{2\pi f_s L}{R} = \frac{1}{2\pi f_s CR} \]

\[ Q_e = \frac{B_s}{G_{\text{max}}} = 2\pi f_s C_0 R \]

\[ Q = \frac{1}{G_{\text{max}}} \]

\[ L = \frac{Q_m R}{2\pi f_s} \]

\[ C = \frac{1}{Q_m R^2 2\pi f_s} \]
EXPERIMENTAL RESULTS

- Typical Single Free-Free Crystal Bode Plot Results Prior to Build
- $k_{33}$ Proportional to Phase Window $f_a - f_r$ (Similar for All Crystals)
- Dissipation Factor DF was .004 for All Crystals ($\tan\delta$)
Transducer Bode Plot Results After Stabilizing Heat-Treatment

\( k_{33} \) Proportional to Phase Window \( f_a - f_r \)

Bode Plot of Admitance Vs. Frequency for Various Piezo Stack Preload
EXPERIMENTAL RESULTS CON’T

- Transducer Admittance Loop Bode Results After Stabilizing HT
- Find Preload that Maximizes $k_{33}$ and $Q_m$, but Minimizes $Q_e$

Bode Plot of Admittance (Y) Loop for Various Piezo Stack Preloads

### Equivalent Circuit Properties

<table>
<thead>
<tr>
<th>Preload (ksi)</th>
<th>$C_0$ (pF)</th>
<th>$C$ (pF)</th>
<th>$L$ (mH)</th>
<th>$R$ (ohms)</th>
<th>$f_1$ (kHz)</th>
<th>$f_2$ (kHz)</th>
<th>$f_3$ (kHz)</th>
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<th>$k_{33}$</th>
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<td>747</td>
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EXPERIMENTAL RESULTS CON’T

Tool Displacement to Current Gain Results After Stabilizing HT & Cycling

Capillary Tool Displacement Versus Current Using Laser Vibrometer
(For Various Piezo Stack Preloads, After Stabilizing Heat Treatment and Burn-in Cycling)

y = 0.00590x - 0.02298
y = 0.00541x - 0.01278
y = 0.00574x + 0.00069
y = 0.00609x - 0.02058
y = 0.00942x - 0.02936

Slope is Effective Gain

High Gain Indicates Depolling

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Impedance Versus Current Results After Stabilizing Heat-Treatment & Cycling

![Graph showing impedance vs. current for various piezo stack preloads](image)

- Unstable
- Lowest Overall Impedance and Change with Current

**EXPERIMENTAL RESULTS CON’T**

- Impedance Versus Current For Various Piezo Stack Preloads
  - (After Stabilizing Heat-Treatment and Burn-in Cycling)
**EXPERIMENTAL RESULTS CON’T**

- **Frequency Vs. Current Results After Stabilizing Heat-Treatment & Cycling**

> Higher Negative Slope Indicates Dynamic Gapping and Insufficient Preload

![Graph showing Frequency Versus Current for Various Piezo Stack Preloads](image-url)

- Stack Preload 4.5 ksi
- Stack Preload 9 ksi
- Stack Preload 11.5 ksi
- Stack Preload 14 ksi
- Stack Preload 18 ksi
CONCLUSIONS

- Optimal Preload Range for PZT8 Found From 9 to 14 ksi (11.5 ksi Best)
- Design Methodology Presented for Optimizing Transducer Preload
- Insufficient Preload Causes High Impedance and Dynamic Gapping
- Excessive Preload Causes Severe Depolling and High Impedance
- Stress Related Aging Affects Minimized at Higher Preloads
- New Preload Method Using Calibrated Stack Voltages Presented
- Bode Plot Method for Individual Crystals Presented
REFERENCES


