Capacitor
What is it?

Capacitance ($F$) = \( \frac{Q}{V} = \frac{\text{Charge (C)}}{\text{Voltage (V)}} \)

\[
C = \frac{\varepsilon_0 K A}{d}
\]
Ideal Capacitors
Bucket of Water Analogy

Area = Capacitance

Amount of Water = Charge, $Q$

Depth of Water = Voltage

Much less water (charge) stored for the same voltage
Form Factor
Design
MLCCs

\[ C = \varepsilon_0 K A (n - 1) d \]

\( C \) = Design Capacitance
\( K \) = Dielectric Constant
\( A \) = Overlap Area
\( d \) = Ceramic Thickness
\( n \) = Number of Electrodes

Capacitances in parallel are additive

\[ C_T = C_1 + C_2 + C_3 + \ldots + C_n \]
Typical Construction

Termination (External Electrode, Cu for BME, Ag for PME)

Barrier Layer (Plated Ni)

Ceramic Dielectric

Internal Electrode (Ni for BME, Ag/Pd for PME)

Plated Sn finish for Solderability
Dielectric Technology

Commercial & Automotive Grade Dielectric Materials

Class 1
- C0G
- U2J
- X8R
- X8L
- X7R
- X5R
- Y5V
- Z5U

PME & BME
BME
BME
BME
BME
BME
BME
BME

200°C

Class 2

175°C

Class 3

Military & Hi-Rel Dielectric Materials

Class 1
- BP
- BX
- BR

PME

BP-01
X7R
X7R &+15/25%/40%
C0G @+15/25%/40%
Rated V
Rated V
Rated V

Class 2

PME

BP-01
X7R
X7R &+15/25%/40%
C0G @+15/25%/40%
Rated V
Rated V
Rated V

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Characteristics
Relative Capacitance vs. Temperature (TCC)

- **Y5V**
- **Z5U**
- **X5R**
- **X7R**
- **U2J C0G (NP0)**

Classes:
- **Class 1**
- **Class 2**
- **Class 3**

'Room' Ambient
## Dielectric Classification

**Class 1 (Per EIA – 198)**

<table>
<thead>
<tr>
<th>Alpha Symbol</th>
<th>Significant Figure of Temp Coefficient ppm/ºC</th>
<th>Numerical Symbol</th>
<th>Multiplier to significant figure</th>
<th>Alpha Symbol</th>
<th>Tolerance of Temp Coefficient ± ppm/ºC</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>0</td>
<td>0</td>
<td>-1</td>
<td>G</td>
<td>30</td>
</tr>
<tr>
<td>B</td>
<td>0.3</td>
<td>1</td>
<td>-10</td>
<td>H</td>
<td>60</td>
</tr>
<tr>
<td>L</td>
<td>0.8</td>
<td>2</td>
<td>-100</td>
<td>J</td>
<td>120</td>
</tr>
<tr>
<td>A</td>
<td>0.9</td>
<td>3</td>
<td>-1000</td>
<td>K</td>
<td>250</td>
</tr>
<tr>
<td>M</td>
<td>1.0</td>
<td>4</td>
<td>-10000</td>
<td>L</td>
<td>500</td>
</tr>
<tr>
<td>P</td>
<td>1.5</td>
<td>5</td>
<td>+1</td>
<td>M</td>
<td>1000</td>
</tr>
<tr>
<td>R</td>
<td>2.2</td>
<td>6</td>
<td>+10</td>
<td>N</td>
<td>2500</td>
</tr>
<tr>
<td>S</td>
<td>3.3</td>
<td>7</td>
<td>+100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T</td>
<td>4.7</td>
<td>8</td>
<td>+1000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>U</td>
<td>7.5</td>
<td>9</td>
<td>+10000</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **C0G Example:** U2J Example
- **Operating Temperature:** -55ºC to +125ºC

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### Dielectric Classification

**Class 2 and 3 (per EIA-198)**

<table>
<thead>
<tr>
<th>Alpha Symbol</th>
<th>Low Temperature (°C)</th>
<th>Numerical Symbol</th>
<th>High Temperature (°C)</th>
<th>Alpha Symbol</th>
<th>Max cap change over temp. range (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Z</strong></td>
<td>+10</td>
<td>2</td>
<td>+45</td>
<td><strong>A</strong></td>
<td>±1.0</td>
</tr>
<tr>
<td><strong>Y</strong></td>
<td>-30</td>
<td>4</td>
<td>+65</td>
<td><strong>B</strong></td>
<td>±1.5</td>
</tr>
<tr>
<td><strong>X</strong></td>
<td>-55</td>
<td>5</td>
<td>+85</td>
<td><strong>C</strong></td>
<td>±2.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6</td>
<td>+105</td>
<td><strong>D</strong></td>
<td>±3.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7</td>
<td>+125</td>
<td><strong>E</strong></td>
<td>±4.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8</td>
<td>+150</td>
<td><strong>F</strong></td>
<td>±7.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9</td>
<td>+200</td>
<td><strong>P</strong></td>
<td>±10</td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>R</strong></td>
<td></td>
<td><strong>R</strong></td>
<td>±15</td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>S</strong></td>
<td></td>
<td><strong>S</strong></td>
<td>±22</td>
</tr>
<tr>
<td></td>
<td></td>
<td><em>L</em>*</td>
<td></td>
<td><em>L</em>*</td>
<td>+15 to -40</td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>T</strong></td>
<td></td>
<td><strong>T</strong></td>
<td>+22 to -33</td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>U</strong></td>
<td></td>
<td><strong>U</strong></td>
<td>+22 to -56</td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>V</strong></td>
<td></td>
<td><strong>V</strong></td>
<td>+22 to -82</td>
</tr>
</tbody>
</table>

* Industry Classification (Non EIA-198)
Capacitance Stability
Versus DC Voltage – Class 2 and Class 3

Capacitance versus DC Voltage
X7R 1206 10uF 16V

-90% Capacitance Drift
Capacitance Stability
Versus DC Voltage – Class 2 and Class 3

Capacitance Change vs. DC Bias
1210 vs 0805, X7R, 10uF, 6.3V

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Voltage Coefficient (Class 2 and 3)

**DC Bias**

Face Centered Cubic Crystal Structure

**BaTiO$_3$ above Curie point**
- Cubic
- No Dipole

**BaTiO$_3$ below Curie point**
- Tetragonal
- Creates Dipole
Voltage Coefficient (Class 2 and 3)

DC Bias

Capacitance versus DC Voltage
X7R 1206 10uF 16V

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AC Coupling and Signal Distortion

X7R vs. C0G

Class 2 BaTiO$_3$
Ferroelectric

Ferroelectric dipoles in *domains* align with the AC Field

Domain wall heating & Signal distortion

Class 1 CaZrO$_3$
Paraelectric

Paraelectric dipoles align with AC field

No domains, so
No Domain wall heating &
Reduced signal distortion
Voltage Coefficient (Class 2 and 3)

AC Bias

Capacitance versus AC Voltage
X7R 1206 10uF 16V

Measurement Conditions

<table>
<thead>
<tr>
<th>Capacitance</th>
<th>Frequency</th>
<th>Voltage (AC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>≤10uF</td>
<td>1kHz</td>
<td>1Vrms</td>
</tr>
<tr>
<td>&gt;10uF</td>
<td>120Hz</td>
<td>0.5Vrms</td>
</tr>
</tbody>
</table>

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Capacitance Measurements of Class 2

Capacitance out of Spec?????

- Instrument Calibrated
- AC Voltage 1Vrms
- Frequency 1kHz

Example: 1210 10uF 10% Tolerance

Capacitance out of Specification!!!!
Capacitance Measurements of Class 2

\[ V_{cap} = V_s \times \frac{Z_{cap}}{Z_{cap} + Z_s} \]

**Danger Zone: >1\mu F**

Measurement frequency switches from 1kHz to 120Hz

**Instrument**

\[ V_s \]

\[ Z_s \]

\[ V_{cap} \]

\[ Z_{cap} \]

\[ Z_{cap} = \frac{1}{\omega C} \]
Capacitance Measurements of Class 2
ALC Function (Auto Leveling Control)

Example: 1210 10uF 10% Tolerance

Within Specification!!!
Capacitance Measurements of Class 2
Lower Source Impedance Meters

No ALC Needed

Keysight E4981A Capacitance Meter

<table>
<thead>
<tr>
<th>Frequency: 120 Hz</th>
<th>Output Impedance</th>
</tr>
</thead>
<tbody>
<tr>
<td>SLC OFF (± 220 μF range)</td>
<td>1.5 Ω (nom.)¹</td>
</tr>
<tr>
<td>SLC ON (± 220 μF range)</td>
<td>0.3 Ω (nom.)¹</td>
</tr>
<tr>
<td>2.2 μF to 100 μF range</td>
<td>0.3 Ω (nom.)¹</td>
</tr>
<tr>
<td>10 nF to 1 μF range</td>
<td>20 Ω (nom.)²</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Frequency: 1 kHz</th>
<th>Output Impedance</th>
</tr>
</thead>
<tbody>
<tr>
<td>SLC OFF (± 220 μF range)</td>
<td>1.5 Ω (nom.)¹</td>
</tr>
<tr>
<td>SLC ON (± 220 μF range)</td>
<td>0.5 Ω (nom.)¹</td>
</tr>
<tr>
<td>220 nF to 10 μF range</td>
<td>0.3 Ω (nom.)¹</td>
</tr>
<tr>
<td>100 pF to 100 nF range</td>
<td>20 Ω (nom.)²</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Frequency: 1 MHz / 1 MHz ± 2% / 1 MHz ± 1%</th>
<th>Output Impedance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>20 Ω (nom.)²</td>
</tr>
</tbody>
</table>

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Class 1 MLCCs
Ultra Stable versus Voltage

Capacitance Change vs DC Voltage
C0G 1210 220nF 25V

No change with DC voltage

Capacitance Change vs AC Bias
C0G 1210 220nF 25V

No change with AC voltage

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Capacitance Stability
Versus Time (Aging) Class 2

https://ec.kemet.com/design-tools/aging-calculator-for-ceramics
Capacitance Stability
Versus Time (Aging) Class 1

No change with Time
Piezoelectricity and Electrostriction

Mechanical Distortion
Piezoelectricity and Electrostriction

- Piezoelectricity
  - Electrical Noise

- Electrostriction
  - Audible Noise

- Diagram with labeled axes: X, Y, Z

- Graph showing sound pressure level (dB) vs. Vp-p with two curves:
  - Standard SMD MLCC
  - KPS - 2 Chip Stack
Common Failure Modes
Ceramic Materials are Inherently Brittle

Ceramic Properties
• High chemical bond strength
• High Elastic Modulus
• Low Ductility
• Very Hard
Typical Crack Signatures

The major sources of MLCC cracks are:

- **Mechanical damage (impact)**
  - Aggressive pick and place
  - Physical mishandling

- **Thermal shock (parallel plate crack)**
  - Extreme temperature cycling
  - Hand soldering
    - *Do not touch electrodes while hand soldering!*

- **Flex or Bend stress**
  - Occurs after mounted to board
  - Common for larger chips (>0805)

Failure is *not always immediate!*
External Forces on Ceramic Material

Compression

Lump of Ceramic

Strong under compression

Tension

Lump of Ceramic

Weak under tension

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Flex Cracking
Excessive Bending

MLCC Under Tension

High Stress Region

Finite Element Analysis

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Flex Cracking
Excessive Bending

MLCC Active Area

Flex crack signature

 Starts here
Capacitor Mitigation Solutions
Level 1 Protection – Basic Level of Crack Protection

Floating Electrode

Pros
• Serial design
• Fails open

Cons
• Reduced capacitance in the same volume

Open Mode

Pros
• Crack doesn’t go through active area
• Fails open

Cons
• Reduced capacitance in the same volume
Capacitor Mitigation Solutions
Level 2 Protection – Intermediate Level of Crack Protection

Flexible Termination (FT-CAP)

Pros
• Increased flex capability
• High volumetric efficiency

Cons
• Fail short

Termination Finish (100% Matte Sn/SnPb–5% Pb min)
End Termination/External Electrode (Cu)
Flexible Termination Epoxy Layer (Ag)
Barrier Layer (Ni)

Conductive-Epoxy
Crack
Capacitor Mitigation Solutions
Level 3 Protection – High Level of Crack Protection (Hybrid Technology)

Pros
• Increased flex capability
• Floating Electrode design
• Fail Open

Cons
• Reduced capacitance in the same volume
Thermal Shock

Why is it an issue?

CTE – Coefficient of Thermal Expansion

Thermal Shock Cracks \(\rightarrow\) CTE Mismatch
Thermal Shock
Causes – Hand Soldering

Internal Temperature Gradients
Uneven Expansion and Contraction

Hand Solder Tips
- Don’t touch capacitor termination
- Pre-heat assembly
- Larger case sizes are more sensitive
Thermal Shock
Causes – Solder Wave

PCB Travel

Solder Wave

Molten Solder
Thank You