Ceramic Capacitors with Base Metal Electrodes for Power Electronics Applications

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Outline

- Power Electronics Trends
  - Power Converter Capacitors
  - Capacitance Vs. Switching Frequency

- Base Metal Ceramic Capacitor Development
  - Ni BME C0G MLCC
    - Key Characteristics
    - High Voltage and High Temperature Extensions
    - DC-Link Opportunities
  - U2J BME MLCC Development
    - Key Characteristics
    - Ripple Current Comparisons

- Summary
Power Electronics Trends

- Improved power conversion efficiency is driving the development of new systems and components

- The adoption of Wide Band Gap (WBG) Semiconductors (SiC & GaN) for more efficient power conversion is challenging traditional Si-technology

- These trends are changing the requirements for capacitors used in Power Electronics:
  - Higher switching frequencies ➔ Need Low Loss MLCC with high ripple current capability
  - High operating voltages ➔ GaN (to 650V), SiC (to >1700V)
  - Higher temperatures ➔ 125°C, 150°C, > 200°C for SiC
Power Converter Capacitors

System Overview:

![System Diagram](image)

Typical Capacitor Types:

1. AC Harmonic Filter 3Φ
2. Snubber
3. DC Link
Capacitance Vs. Switching Frequency

Example: DC Link for 400V with 10% Ripple

\[ C = \frac{P_{\text{load}}}{U_{\text{ripple}} \cdot \left( U_{\text{max}} - \frac{U_{\text{ripple}}}{2} \right) \cdot f_{\text{rectifier}}} \]

* Source: Prof. R. Kennel, Technical University Munich, Germany
Capacitance Vs. Switching Frequency
Polypropylene Film to MLCC

- For DC-Link Capacitors:
  - Lower capacitance requirement promotes miniaturization due to:
    - Increasing switching frequency
    - Higher voltages

- Lower capacitance needed are within the range of MLCC
  - But these MLCC (Multi-Layer Ceramic Capacitors) must be:
    - Extremely reliable
    - Over-Temperature and Over-Voltage Capable
    - High current capable
    - Mechanically Robust
Multi-Layer Ceramic Capacitors (MLCC) with base metal nickel inner electrodes were commercialized in the 90’s to replace more expensive palladium based inner electrodes.

KEMET launched BME MLCC using Ni Electrodes in 1990’s and a Class-I Para-electric calcium zirconate based C0G dielectric in 2005.

A new range of 200°C C0G NP0 rated ≤ 200V was added in 2010:
- Much higher capacitance values than PME C0G equivalents
- No change with temperature or voltage bias (flat TCC and VCC to 200°C)
- Available capacitance at 200°C equivalent to many Class-II MLCC with lower DF, higher IR and much higher voltage breakdown
- Testing at 260°C and 300°C continues and is showing robust reliability

The key characteristics of these C0G MLCC are compared to a competitor X8R (150°C rated) on the following slide.
Ni BME C0G MLCC Vs Competitor X8R
1206 Case Size Comparison

- Capacitance Change (ΔC/C %) vs Temperature (°C)
- Dissipation Factor (% DF) vs Temperature (°C)
- Insulation Resistance (IR, M.Ω/ohm) vs Temperature (°C)
- Breakdown Strength (V/µm) vs Temperature (°C)

Graphs showing performance comparisons between Ni BME C0G MLCC and Competitor X8R MLCC.
High Voltage Ni BME C0G MLCC Extensions

Typical Properties

- In 2013 a catalog range was launched rated for voltages 500-2000V and 200°C in case sizes 0805 to 2225
- Larger case sizes extensions 2824 to 4540 were added in 2016

Properties & Reliability Tests

<table>
<thead>
<tr>
<th>KEMET Part Number</th>
<th>Voltage Rating Vr (V)</th>
<th>Average Capacitance (nF)</th>
<th>Average DF (%)</th>
<th>IR (Ω)</th>
<th>TCC (PPM/°C)</th>
<th>Mean Voltage Breakdown in Air</th>
<th>Life Test 1000hr @ Vr 200°C</th>
<th>Thermal Cycling (-55 to +200°C)</th>
<th>Board Flex to 5mm</th>
<th>Mechanical Shock &amp; Vibration</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1206H332JCGAC</td>
<td>500</td>
<td>3.29</td>
<td>0.020</td>
<td>37,900</td>
<td>-10.56</td>
<td>1825</td>
<td>0/100</td>
<td>0/100</td>
<td>NA</td>
<td>0/30</td>
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<tr>
<td>C1210H472JBGAC</td>
<td>630</td>
<td>4.81</td>
<td>0.018</td>
<td>25,000</td>
<td>-10.96</td>
<td>2000</td>
<td>0/100</td>
<td>0/100</td>
<td>NA</td>
<td>0/30</td>
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<tr>
<td>C1808H292JDGAC</td>
<td>1000</td>
<td>4.75</td>
<td>0.021</td>
<td>21,500</td>
<td>-12.05</td>
<td>2931</td>
<td>0/100</td>
<td>0/100</td>
<td>NA</td>
<td>0/30</td>
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<tr>
<td>C1813H332JFGAC</td>
<td>1500</td>
<td>2.70</td>
<td>0.020</td>
<td>75,800</td>
<td>-10.63</td>
<td>3519</td>
<td>0/100</td>
<td>0/100</td>
<td>NA</td>
<td>0/30</td>
</tr>
<tr>
<td>C2220H332JGGAC</td>
<td>2000</td>
<td>3.31</td>
<td>0.020</td>
<td>56,300</td>
<td>-11.77</td>
<td>4116</td>
<td>0/100</td>
<td>0/100</td>
<td>NA</td>
<td>0/30</td>
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<tr>
<td>C2824H333KGBAC</td>
<td>630</td>
<td>34.30</td>
<td>0.010</td>
<td>13,430</td>
<td>-7.35</td>
<td>1783</td>
<td>0/100</td>
<td>0/231</td>
<td>0/30</td>
<td>0/90</td>
</tr>
<tr>
<td>C3040H393KDGAC</td>
<td>1000</td>
<td>39.03</td>
<td>0.010</td>
<td>8,982</td>
<td>-6.34</td>
<td>2678</td>
<td>0/150</td>
<td>0/231</td>
<td>0/30</td>
<td>0/90</td>
</tr>
<tr>
<td>C3640H153KGGAC</td>
<td>2000</td>
<td>15.36</td>
<td>0.009</td>
<td>6,509</td>
<td>-5.15</td>
<td>3919</td>
<td>0/100</td>
<td>0/231</td>
<td>0/30</td>
<td>0/90</td>
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<tr>
<td>C4540H273KFGAC</td>
<td>1500</td>
<td>27.95</td>
<td>0.010</td>
<td>2,125</td>
<td>-6.31</td>
<td>3608</td>
<td>0/150</td>
<td>0/231</td>
<td>0/30</td>
<td>0/90</td>
</tr>
</tbody>
</table>
High Voltage Ni BME C0G MLCC Extensions

*Life Testing @ 200°C for 1000hrs at Rated Voltage*

No IR degradation after 1000hr Life Test at 1xRV at 200°C

200°C Life - C1210H472JBGAC

Lognormal

1088T108803 1088T108804

Panel variable: Batch Number

1210, 4.7nF, 630V

200°C Life - C1813H332JFGAC

Lognormal

1235T123501 1235T123502

Panel variable: Batch Number

1813, 3.3nF, 1500V

1TΩ = 1.5nA Leakage Current (25°C)

200°C Life - C2824H333JBGAC

Lognormal

2037T203701 2268100T01

Panel variable: Batch

2824, 33nF, 630V

200°C Life - C4540H273JFGAC

Lognormal

2283100T02 3155100T09

Panel variable: Batch

4540, 27nF, 1500V
No IR degradation after 50 thermal cycles (-55°C to 200°C)

200°C Thermal Cycling - C210H472JBGAC
Lognormal

200°C Thermal Cycling - C1813H332JFGAC
Lognormal

Panel variable: BATCH_NUM

1210, 4.7nF, 630V

1813, 3.3nF, 1500V

3°C/min with 1hr Soak
High Voltage Ni BME C0G MLCC Extensions

Voltage Breakdown Vs. Temperature

Voltage Breakdown remains high even at 250°C
High Voltage Ni BME C0G MLCC Examples

Ripple Current Capability Comparisons

Case Size 2824, 33nF, 630Vr
C0G @ 500kHz

- The temperature rise of the C2824H333KBGAC parts were measured at different Vrms

<table>
<thead>
<tr>
<th>Part Type</th>
<th>Voltage (Vrms)</th>
<th>Current (Arms)</th>
<th>Part Temperature (°C)</th>
<th>Ambient Temperature (°C)</th>
<th>Temperature Rise (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>X7R</td>
<td>20.0</td>
<td>1.95</td>
<td>64.0</td>
<td>26.0</td>
<td>38.0</td>
</tr>
<tr>
<td>C0G</td>
<td>131</td>
<td>10.0</td>
<td>55.8</td>
<td>25.5</td>
<td>30.3</td>
</tr>
</tbody>
</table>

- Temperature rise < ~30°C is considered in a safe region so these parts have ≥ 10Arms capability @ 500kHz

Case Size 2220, 100nF, X7R Vs. C0G @ 150kHz

- The temperature rise of new 630Vr C0G were compared to 1000Vr X7R

| Voltage (Vrms) | 57.7 | 93.9 |
| Current (Arms) | 6.1  | 10.0 |
| Part Temperature (°C) | 33.5 | 50.4 |
| Ambient Temperature (°C) | 24.2 | 24.2 |

| Temperature Rise (°C) | 9.3 | 26.2 |

- New C0G cap has 5X higher ripple current capability than the standard X7R @ 150kHz
High Voltage Ni BME C0G MLCC are an excellent choice in power applications because of their:

- Reliable performance even at high temperatures (200°F)
- Stable capacitance with temperature and voltage
- High voltage ratings (no derating required!)
- **Very low dissipation factors**
- High IR (low leakage) & high breakdown voltages
- High ripple current capability

However DC-Link applications need higher capacitance values, so work is underway to extend the cap offerings.
DC-Link Extensions
Ni BME C0G 3640 Case Size

<table>
<thead>
<tr>
<th>Capacitance (nF)</th>
<th>0.22 µF</th>
<th>0.33 µF</th>
<th>0.47 µF</th>
</tr>
</thead>
<tbody>
<tr>
<td>DF (%)</td>
<td>0.0080</td>
<td>0.0117</td>
<td>0.0110</td>
</tr>
<tr>
<td>IR @ 25°C (GΩ)</td>
<td>458</td>
<td>277</td>
<td>242</td>
</tr>
<tr>
<td>IR @ 125°C (GΩ)</td>
<td>7.42</td>
<td>6.47</td>
<td>6.24</td>
</tr>
</tbody>
</table>

- Ni BME C0G 3640 have:
  - Low DF
  - High IR
  - Stable Capacitance at high temperatures & voltages

Case Size 3640
L x W x TH
0.36” x 0.40” x 0.10”
9.1mm x 10.2mm x 2.5mm
Volume = 0.23cm³
DC-Link Extensions

3640 0.22µF 500V 150°C Ripple Current

- Lower DF & ESR reduce the power dissipated

\[ P = \frac{i^2d}{2\pi fc} = i^2R \]

P = power dissipated
i = current
d = dissipation factor
f = frequency
C = capacitance
R = resistance, ESR

- No failures after 1000hrs testing @ 150°C 15A_{RMS} 100kHz

\[ \approx 75 \text{ A}_{RMS}/\mu\text{F or } \approx 65 \text{ A}_{RMS}/\text{cm}^3 \]

U2J MLCC Development

- Although the BME C0G capacitors perform well in power electronics applications, the need for higher capacitance values in smaller sizes continues.

- KEMET has recently commercialized U2J MLCC that extends the Class-I capacitance range up to 50V ratings making them suitable for 48V DC-DC power supply applications.

  - Temp Range -55°C to +125°C, Pb-Free, RoHS and REACH compliant
  - Low dissipation factor DF < 0.1%
  - Low ESR & ESL
  - No piezoelectric noise similar to C0G
  - High thermal stability, Pb-free soldering compatible
  - High ripple current capability
  - Small, predictable and linear capacitance change vs temperature
  - Non-polar device, minimizing installation concerns
### Dielectric Classification (Temperature Performance)
#### Class I (Per EIA – 198)

Class-I Dielectrics (Examples C0G: 0±30ppm/°C vs. U2J: -750±120ppm/°C)

<table>
<thead>
<tr>
<th>Temperature coefficient $\alpha$ 10^{-6}/K</th>
<th>Multiplier of the temperature coefficient</th>
<th>Tolerance of the temperature coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Letter code</strong></td>
<td><strong>Number code</strong></td>
<td><strong>Letter code</strong></td>
</tr>
<tr>
<td>C: 0.0</td>
<td>0: -1</td>
<td>G: ±30</td>
</tr>
<tr>
<td>B: 0.3</td>
<td>1: -10</td>
<td>H: ±60</td>
</tr>
<tr>
<td>L: 0.8</td>
<td>2: -100</td>
<td>J: ±120</td>
</tr>
<tr>
<td>A: 0.9</td>
<td>3: -1000</td>
<td>K: ±250</td>
</tr>
<tr>
<td>M: 1.0</td>
<td>4: +1</td>
<td>L: ±500</td>
</tr>
<tr>
<td>P: 1.5</td>
<td>6: +10</td>
<td>M: ±1000</td>
</tr>
<tr>
<td>R: 2.2</td>
<td>7: +100</td>
<td>N: ±2500</td>
</tr>
<tr>
<td>S: 3.3</td>
<td>8: +1000</td>
<td></td>
</tr>
<tr>
<td>T: 4.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>V: 5.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>U: 7.5</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Temperature Range: -55°C to +125°C
KEMET U2J Dielectric
Relative Capacitance vs. Temperature

Temperature Effects (TCC)

Capacitance Change % vs. Temperature (°C)

-55 -35 -15 5 15 25 45 65 85 105 125

Temperature (°C)

-20 -15 -10 -5 0 5 10 15 20

Capacitance Change %

U2J

X7R

C0G
Effective Capacitance
X7R vs. U2J

~13.8% capacitance loss
Effective capacitance of ~86nF
About 2x CAP of C0G
BME C0G and BME U2J both show high current carrying capability.

Temperature rise <14°C up to ripple current of 10A_{rms}
Summary

- Increase in switching frequency change capacitor needs:
  - Need Lower Capacitance Values
  - High Current Carrying Capability
  - Higher Voltage Capability (450-2000V)
  - Reliable at High Temperatures (125°C, 150°C, > 200°C)

- BME C0G MLCC have:
  - High reliability at high temperatures and voltages
  - High ripple current capability with ultra-low losses and ESR

- BME U2J MLCC:
  - Extend the capacitance values available in Class-I, 50 V ratings
  - Have similar ripple current performance to C0G allowing at higher frequency enabling further miniaturization for higher power density
Thank You!