NEPP Capacitor Update - BME Technology for High-Reliability Applications

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What are Multilayer Ceramic Capacitors (MLCCs)?

- MLCCs are monoliths of dielectric oxide and alternated internal metals co-fired at around 1350 °C

- Capacitance:

\[
C = \varepsilon_0 \cdot \varepsilon_r \cdot N \cdot \frac{S}{d}
\]

- Challenges:
  - Dielectric needs oxygen for insulating resistance (IR)
  - Electrode needs no oxygen for conducting

- Solution:
  - The first MLCCs were made with oxidation resistance *precious metal electrodes* (PME) made from combinations of Ag, Pt, and Pd
Why Change from PME to BME?

- High materials cost plus questionable supply assurance forced an industry shift from PME to *base metal electrode* (Ni, Cu) technology (BME) for commercial applications
  - Palladium: $675/oz on 1/20/2012 ($1080/oz in 2/2001)
  - Nickel: $0.61/oz on 1/20/2012 ($1.65/oz in 4/2007)
  - Russia controls 90% of world palladium supply?
- The change was totally driven by economics!
PME vs. BME: The Reality

• 99% of MLCCs worldwide are manufactured using BME technology
  ➢ Lion’s share of research activity and technical support
  ➢ Complete selection of products with short lead time
  ➢ Low cost
• NASA had used BME capacitors for some non-critical applications
  ➢ NASA cautious to new technologies due to type of business
  ➢ Restrictions in MIL-PRF-123
  ➢ Concerns regarding the reliability of BME technology
• It is just a matter of time to begin using BME capacitors for high reliability applications
  ➢ Several hybrid manufacturers have used BME capacitors for space-level products
  ➢ Comparable reliabilities and better performance
  ➢ Limited product selection for PME products and long lead time
  ➢ BME technology is more than 20 years old
• It is about time to take action!

Deliverable to NASA Electronic Parts and Packaging (NEPP) Program to be published on nepp.nasa.gov.
A Glimpse of BME Technology

• BMEs represent a commercial technology, developed for high volumetric efficiency ($\mu$F/cm$^3$) applications, not for high-reliability applications. However, BME capacitors can be manufactured for high-reliabilities comparable to PME capacitors.

• To meet the high demand for volumetric efficiency, manufacturers have pushed the technology envelope to the limit:
  – Number of dielectric layers $N$: $>500 \rightarrow 1000$
  – Dielectric thickness: $<1.0 \mu$m, $\rightarrow 0.5 \mu$m or less

• To meet the high demand for volumetric efficiency, suppliers and end users have mutually agreed to lower the bar for reliability:
  – Life test: 2X rated voltage $\rightarrow 1.5X, 1.25X, 1.0X$
  – Dielectric: X7R characteristics $\rightarrow$ X5R
MLCCs for High-Reliability Applications

• The reliability of an MLCC device is determined by its microstructure. An MLCC can’t be qualified for high reliability; it has to be made for it!

• Historically, the minimum dielectric thickness requirement per MIL-PRF-123 has ensured that most PME capacitors have been able to be used for high-reliability applications for many years without major issues.
  – MIL-PRF-123, paragraph 3.4.1: Dielectric parameters. Capacitors supplied to this specification shall have a minimum dielectric thickness of 0.8 mil (20 μm) for 50 volt-rated capacitors or 1 mil (25 μm) for capacitors with ratings above 50 volts.
  – MIL-PRF-123 requires all MLCCs for high-reliability and space projects to be PME capacitors.

• A simple dielectric thickness requirement may not qualify BME products for high-reliability applications due to their complexity and diversity with regard to capacitor structure.
What Determine the Reliability of a MLCC?

1. Number of Dielectric Layers $N$

Total capacitance: $C_t = C_1 + C_2 + C_3 \ldots + C_i \ldots + C_N = N \cdot C_i$

Total reliability: $R_t = R_1 \times R_2 \times R_3 \ldots \times R_i \ldots \times R_N = R_i^N$

Weibull reliability: $R_i(t) = e^{-\left(\frac{t}{\eta}\right)^\beta}$  $R_i(t)$: Dielectric reliability
What Determine the Reliability of a MLCC?
1. Number of Dielectric Layers $N$

- The reliability of an MLCC $R_t$ decreases with increasing $N$. $R_t$ is almost independent from $N$ if the reliability of the dielectric layer $R_i$ is very close to unity.
- The $N$ will make the $R_t$ go from bad to worse quickly if $R_i$ declines only slightly, demonstrating the *amplifying effect* of $N$.
- Most BME capacitors have a very high $N$ value, and so they pose higher challenges to the reliability of the single-layer dielectric $R_i$. 
What Determine the Reliability of MLCC?

2. Microstructure Parameter \( \left( \frac{d}{\bar{r}} \right) \)

• Important microstructure parameter of a single-layer capacitor:

\[
\left( \frac{d}{\bar{r}} \right) : \text{Number of stacked grains per dielectric layer}
\]
What Determine the Reliability of MLCC?

3. Voltage Robustness vs. \( \frac{d}{\bar{r}} \)

A number of commercial BME capacitors, all with 25 V rated voltage and various chip sizes and capacitance, have significantly different dielectric thicknesses.

The number of stacked grains per layer is relatively unvaried, indicating that \( \frac{d}{\bar{r}} \) is a determining factor for the rated voltage.
What Determine the Reliability of MLCC?

4. Mean-Time-To-Failure (MTTF) vs. \( \left( \frac{d}{\bar{r}} \right) \)

- MTTF is directly related to the microstructure parameter \( \left( \frac{d}{\bar{r}} \right) \).
- Longer MTTF is attainable with higher \( \left( \frac{d}{\bar{r}} \right) \) values (left).
- When applied voltage per grain is adjusted to a similar value, all four MLCCs with different \( \left( \frac{d}{\bar{r}} \right) \) values show similar MTTF values.
How to Characterize MTTF? HAST

- Highly Accelerated Stress Testing (voltage and temperature typical):
  - Reverse Power Law (Eyring Model): 
    \[
    \frac{t_1}{t_2} = \left( \frac{V_2}{V_1} \right)^n \left( \frac{E_0}{e^K(T_1 - T_2)} \right)
    \]
  - Use-level Weibull probability plots are extrapolated using a maximum likelihood estimation algorithm for each failure obtained at a given overstress condition. *This can be done using ALTA-Pro!*

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How to Characterize MTTF? HAST (2)

- Use-level MTTF data for a BME capacitor can be normalized into one plot for better comparison.
- In many cases, calculated MTTF using dielectric wearout failure mode is longer than that obtained experimentally. (Why?)
Reliability of MLCCs: Mixed Failure Modes

- If the assumed model adequately fits the data, then the residuals should appear to follow a straight line on such a probability plot.
- The standardized residual plot shows scattering and outliers.

\[ \hat{e}_i = \hat{\beta} [\ln(t_i) - \ln(\hat{\eta}(V))] \]

- Two possibilities:
  - Early failures can’t be 100% removed (\( \beta > 1 \), failure rate increase with time).
  - The two failure modes are competing with each other. (Under certain conditions, a unit can fail in either one of the two failure modes.)
- Early failures present the worst-case scenario and would determine the reliability of an MLCC!
How to Distinguish the Failure Modes? By Leakage Current

- Leakage current characteristics are experimentally distinguishable: precursing vs. non-precursing. (Arrows indicate precursing breakdown.)
- The higher the external stress, the more failures with non-precursing breakdown.

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How to Distinguish the Failure Modes? By Leakage Current (2)

- Non-precursing breakdown: catastrophic and rapid, no sign of breakdown (avalanche-like). *It occurs early and corresponds to early failure defect.*
- Precursing breakdown: slower and more gradual leakage current increase prior to breakdown (thermal runaway-like). *It corresponds to traditional dielectric wearout.*
- Slow degradation: unique for BME capacitors due to oxygen vacancy migrations. *Indistinguishable* from precursing breakdown mode.
A number of failure analyses (FA) have been processed for BME MLCCs that failed with precursing leakage breakdown and that failed with non-precursing leakage breakdown.

FA samples that failed with non-precursing breakdown normally revealed some visible localized failure sites, likely due to extrinsic processing defects.

High carbon concentrations were often observed at these failure sites. Contaminations were likely introduced during manufacturing (as shown above), i.e., binder residuals.
How to Characterize Early Failures: Construction Analysis

- Cross-section SEM examination of 50+ samples per EIA-469D revealed some voids and minor delamination; cracks were rarely observed.
- Defect feature size $r$ is generally related to the average grain size $\bar{r}$:

$$r \approx c \times \bar{r}$$

where $c$ is a constant

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A Reliability Model Due to Defects

Dielectric layer reliability:

\[ R_i(t) \to 1, \text{when } d \gg r; \quad R_i(t) \to 0, \text{when } d \approx r. \]

For Weibull model:

\[ R(t) = e^{-\left(\frac{t}{\eta}\right)^\beta} \cdot \left[1 - \left(\frac{r}{d}\right)^\xi\right] \]

Since:

\[ r \approx c \times \bar{r}, \quad \bar{r} \text{ is the average grain size} \]

We have:

\[ P = \left[1 - \left(\frac{r}{d}\right)^\xi\right] = \left[1 - \left(\frac{\bar{r}}{d}\right)^\alpha\right], \quad (\alpha \geq 5) \]

\( P \) is a geometric factor that determines the dielectric reliability with respect to the microstructure of an MLCC.
A Reliability Model Due to Defects (Cont’d)

With External Stress: \[ \eta(V, T) = \frac{C}{V^n} \cdot e^{-\frac{E}{kT}} \]

We have: \[ R_i(t) = R_w(t) \cdot \left[ 1 - \left( \frac{\bar{r}}{d} \right)^\alpha \right] = e^{-\left[ \frac{t}{C V^n e^{kT}} \right]^\beta} \cdot \left[ 1 - \left( \frac{\bar{r}}{d} \right)^\alpha \right], \alpha \geq 5 \]

In many cases: \[ R_w(t \leq 10^3 \text{ years}) = e^{-\left[ \frac{t}{C V^n e^{kT}} \right]^\beta} = 1 \]

So finally a single layer dielectric reliability can be simplified as:

\[ R_i(t \leq \eta) \approx \left[ 1 - \left( \frac{\bar{r}}{d} \right)^\alpha \right] \]

\( \alpha \) is an empirical constant that depends on the processing conditions and microstructure of a ceramic capacitor.
\( \alpha \approx 6 \) \((V \leq 50)\) and \( \alpha \approx 5 \) \((V > 50)\) For BME MLCCs
\( \alpha \approx 5 \) for most PME MLCCs
Case Study: Selection of BME MLCCs for High-Reliability Applications

1. Reliability of an MLCC:
   \[ R_t(t) = R_i(t)^N \]

2. Single-layer dielectric reliability:
   \[ R_i \approx 1 - \left( \frac{\bar{r}}{d} \right)^\alpha \]

3. Reliability with respect to \( N \) and \( \left( \frac{d}{\bar{r}} \right) \):
   \[ R_t = \left[ 1 - \left( \frac{r}{d} \right)^\alpha \right]^N \geq 99.999\% \]

Commercial BME capacitors satisfying \( R_t \) above will meet the minimum requirements for high-reliability applications
Case Studies: High-Performance BME MLCCs

C08X22516(BME)

- 2.2 μF, 16 V, 0805, mfr. C, passed 4000-hr life testing at 125°C at 2X rated voltage
- Meets MIL-PRF-123
- Nano-size grains ≈ 0.11 μm
- 250 dielectric layers
- Dielectric thickness ≈ 3.85 μm

B12X68316 (BME)

- 0.68 μF, 16 V, 1206, mfr. B, passed 4000-hr life testing at 125°C at 2X rated voltage
- Meets MIL-PRF-123
- Grain size ≈ 0.38 μm
- 64 dielectric layers
- Dielectric thickness ≈ 6.29 μm

When compared with PME MLCCs, high reliabilities can be attained in BME MLCCs with thinner dielectrics.
Case Studies: High-Performance BME MLCCs

<table>
<thead>
<tr>
<th></th>
<th>Thin Dielectric BME</th>
<th>D08X10425 (PME)</th>
<th>C08X22516 (BME)</th>
<th>B12X68316 (BME)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N$</td>
<td>200</td>
<td>30</td>
<td>250</td>
<td>64</td>
</tr>
<tr>
<td>$d$ ($\mu m$)</td>
<td>1.00</td>
<td>20.2</td>
<td>3.85</td>
<td>6.29</td>
</tr>
<tr>
<td>$\bar{a}$ ($\mu m$)</td>
<td>0.10</td>
<td>0.61</td>
<td>0.11</td>
<td>0.38</td>
</tr>
<tr>
<td>$A$</td>
<td>6.0</td>
<td>5.0</td>
<td>6.0</td>
<td>6.0</td>
</tr>
<tr>
<td>$R_i(5\text{ year})$</td>
<td>99.9999%</td>
<td>100.0000%</td>
<td>100.0000%</td>
<td>100.0000%</td>
</tr>
<tr>
<td>$R_t(5\text{ year})$</td>
<td>99.9800%</td>
<td>99.9999%</td>
<td>99.9999%</td>
<td>99.9997%</td>
</tr>
</tbody>
</table>

- MLCC reliability can be empirically estimated using only microstructure and construction parameters $N$, $d$, $\bar{a}$, and $\alpha$.
- The microstructure parameters for thin dielectric BME MLCCs was assumed based on an Intel report.
- Structural parameters for all other MLCCs were experimentally determined.
Case Studies: An Intel Application

- 0.045 \(\mu\)m Si processing technology
- 140 MLCCs per package
- System reliability: \(R_s\)

\[
R_s(5\ year) = R_t(5\ year)^{140} \geq 99.9\%
\]

<table>
<thead>
<tr>
<th>Dielectric</th>
<th>Thin Dielectric BME</th>
<th>D08X10425 (PME)</th>
<th>C08X22516 (BME)</th>
<th>B12X68316 (BME)</th>
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<tr>
<td>(R_i(5\ year))</td>
<td>99.9999%</td>
<td>100.0000%</td>
<td>100.0000%</td>
<td>100.0000%</td>
</tr>
<tr>
<td>(R_t(5\ year))</td>
<td>99.9800%</td>
<td>99.9999%</td>
<td>99.9999%</td>
<td>99.9997%</td>
</tr>
<tr>
<td>System (R_s(5\ year))</td>
<td><strong>97.2388%</strong></td>
<td>99.9895%</td>
<td>99.9887%</td>
<td>99.9569%</td>
</tr>
</tbody>
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Summary

- BMEs represent a commercial technology. Not all BME capacitors can be qualified for high-reliability applications.

- A minimum dielectric thickness requirement that has been used for making high-reliability PME capacitors is not applicable to BME capacitors. BME capacitors have more complicated structures than PME capacitors:
  - Number of dielectric layers $N$ in a BME capacitor is extremely high;
  - Dielectric thickness $d$ is extremely thin;
  - Grain size varies from $0.5 \mu m$ down to $0.1 \mu m$.

- The reliability of a BME MLCC has been found to be directly related to the microstructure parameter $N$ (# of dielectric layers) and $\left(\frac{d}{r}\right)$ (# of stacked grains per dielectric layer).

- A reliability model regarding the microstructure of a BME MLCC is developed and has been applied to eliminate the BME capacitors with potential reliability concerns.

- More reliability evaluations regarding the microstructure of BME capacitors are to be performed.
Acknowledgements

• NASA NEPP program for funding this work

• NASA GSFC Code 562 Parts Analysis Laboratory for assistance with some electrical testing

• This work has been presented previously at CARTS International Conference at Las Vegas, March 2012