Development Challenges for DC-Link Capacitors for Wide Band Gap Semiconductor Applications

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Outline

• WBG Semiconductors
  – Background
  – Capacitor Needs

• Capacitor Types
  – Film Capacitors using Metallized Polypropylene
  – Ceramic Capacitors of Ni BME C0G MLCC

• MLCC Packaging
  – Transient Liquid Phase Sintering (TLPS) Technology
  – Leadless for Max. Cap. In given assembly area

• Summary
WBG Semiconductors

Background

• Gallium Nitride (GaN)
  • Volume production since the 1990’s
    • RF
    • LED

• Silicon Carbide (SiC)
  • Commercial production since 2008
    • Power Inverters
    • Low Voltage Power Distribution

• Advantages over Silicon
  – More energy efficient
  – Less cooling
  – Miniaturization

• As WBG costs decrease more they will increasingly replace silicon mid and lower power applications in the future

Power Conversion Efficiency

<table>
<thead>
<tr>
<th></th>
<th>Si Based</th>
<th>WBG Based on GaN or SiC</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC to DC</td>
<td>85%</td>
<td>95%</td>
</tr>
<tr>
<td>AC to DC</td>
<td>85%</td>
<td>90%</td>
</tr>
<tr>
<td>DC to AC</td>
<td>96%</td>
<td>99%</td>
</tr>
</tbody>
</table>

Source: Mouser Electronics, L. Cuthbertson, 2016
Future Power Electronics
Semiconductor vs Power vs Frequency

Source: P. Friedrichs & M. Buschkuhle, Infineon AG, Energetica India, May/June 2016
WBG Capacitor Requirements

**WBG Semiconductor Trend**  ➔  **Capacitor Requirement**

### Higher Switching Frequencies
- 20kHz → 100kHz → 100’s MHz

### Higher Operation Voltages
- 400V → 650V → 1200V → 1700V
  - GaN  SiC

### High Junction Temperatures
- 105°C → 125°C → 200°C+
  - SiC

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**Smaller, low ESR, low ESL low loss capacitors with high dV/dt & current handling capability**

**Reliable performance at higher voltages**

**Reliable performance at elevated temperatures ≥ 125°C with robust mechanical performance**
- Packaging close to the hot semiconductor to:
  - Lower ESL
  - Minimize cooling costs
Power Converter Capacitors

System Overview:

Typical Capacitor Types:
How Much Capacitance Do We Need?
Example: DC Link for 400V with 10% Ripple

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

* Source: Prof. R. Kennel, Technical University Munich, Germany
How Much Capacitance Do We Need?
Example: DC Link for 650V with 10% Ripple
How Much Capacitance Do We Need?
Example: DC Link for 1200V with 10% Ripple

- Higher Frequencies, Higher Voltages & Lower Power requires less capacitance

![Graph showing capacitance vs. frequency for different power levels (10kW, 50kW, 100kW).](image)
How Much Capacitance Do We Need?
*Polypropylene Film to MLCC*

• For WBG DC-Link Capacitors:
  – Lower capacitance required promotes miniaturization due to:
    • Increasing switching frequency
    • Higher voltages

• Lower capacitance is within the range of MLCC.
  – But these need must be:
    • Extremely reliable
    • Over-Temperature and Over-Voltage Capable
    • High current capable
    • Mechanically Robust
Power Film Technology (Metallized PP)

Effect of Frequency

Dissipation Factor
Vs. Frequency

Dissipation factor vs. frequency (Room temperature)

Increasing Frequency = Higher DF
Power Film Technology (Metallized PP)

Effect of Higher Temperature

- Higher Temperature
  - Voltage & Current Limitation
  - Shorter Life, Lower Reliability
MLCC Capacitor Development

Ni BME C0G 3640 Case Size

<table>
<thead>
<tr>
<th>Nominal Cap</th>
<th>0.22 µF</th>
<th>0.33 µF</th>
<th>0.47 µF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacitance (nF)</td>
<td>227</td>
<td>343</td>
<td>487</td>
</tr>
<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>

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

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

Ni BME C0G MLCC 3640 500V 150°C

*Higher Frequency*

**Dissipation Factor**

*Vs. Frequency*

Increasing Frequency = Higher DF but < Metallized PP
Ni BME C0G MLCC 3640 500V 150°C

Reliability by Accelerated Testing

- Higher Temperature
  - Low failure rates @ 200°C*
  - Repeatable Capability

Ni BME C0G MLCC 3640 0.22µF 500V 150°C
ESR & Current Handling @ 150°C 100kHz

- Lower DF & ESR reduce the power dissipated

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

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

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

MLCC Packaging
Different Assembly Options

- Surface Mounting*
  - High MOR with Board Flex > 3mm
  - 3640 pass AEC Q200 temp. cycle testing
- Embedding
- Leaded MLCC
  - Through-hole/Surface Mount/Press-fit
  - Lead to MLCC > 200°C HMP Pb-solder
- Transient Liquid Phase Sintering
  - Replace Solders in MLCC packaging

What is TLPS?

- Low temperature reaction of low melting point metal or alloy with a high melting point metal or alloy to form a reacted metal matrix or alloy
- Forms a metallurgical bond between 2 surfaces

**CuSn TLPS**

EDS Analysis of Atomic Ratio's:
- Ag/Sn ~ 3; Ag₅Sn
- Cu/Sn ~ 1.2; Cu₅Sn₆
- Cu/Sn ~ 3; Cu₃Sn

Ref. J. Bultitude et al; MS&T 15, Columbus, OH, USA, October 5, 2015
Transient Liquid Phase Sintering (TLPS)  
Leaded & Leadless Case Size 2220 MLCC Performance

**Leaded**
- Improved High Temperature performance Vs. solders

**Leadless**
- Pass 125°C Temp. Cycling
- High Shear Strength

![Shear Energy vs. Material and Temperature](chart)

<table>
<thead>
<tr>
<th>TLPS Type MLCC Termination</th>
<th>Temperature Cycling: -40°C to +200°C: Cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>250</td>
</tr>
<tr>
<td>In-Ag/Ni underplate</td>
<td>0/30</td>
</tr>
<tr>
<td>In-Ag/Cu underplate</td>
<td>0/30</td>
</tr>
</tbody>
</table>

![Leadless Stacks Sn Plated Termination, CuSn TLPS](chart)

<table>
<thead>
<tr>
<th>Thermal Cycles</th>
<th>117</th>
<th>500</th>
<th>1000</th>
<th>2000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lot 1</td>
<td>0/40</td>
<td>0/40</td>
<td>0/40</td>
<td>0/40</td>
</tr>
<tr>
<td>Lot 2</td>
<td>0/40</td>
<td>0/40</td>
<td>0/40</td>
<td>0/40</td>
</tr>
</tbody>
</table>


Ref. J. McConnell et al; IMAPS 2016, Pasadena, CA, USA, October 13, 2016
Leadless Packaging 3640 0.22µF 500V MLCC
Form Factors & Materials

Circuit Board/Package

Termination
CuSn TLPS
Ni/Thin Au
Solder
Leadless Packages of 3640 0.22µF 500V MLCC

Performance

- Higher Capacitance to ≈ 1µF
- Increased height of Leadless Stacks increases maximum inductance
- High Insulation Resistance to 200°C

10 mm 4-Chip 2.9 nH
5 mm 2-Chip 1.6 nH
2.5 mm MLCC 0.9 nH

Circuit Board/Package

![Graphs showing capacitance and insulation resistance over temperature]

Capacitance to 200°C

<table>
<thead>
<tr>
<th>Capac. (nF)</th>
<th>MLCC</th>
<th>2-Chip</th>
<th>4-Chip</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>900</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>800</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>700</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>600</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>500</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>400</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>300</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>200</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Temperature (°C)

Insulation Resistance @ 500VDC to 200°C

IR (GΩ)

<table>
<thead>
<tr>
<th>IR (GΩ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
</tr>
<tr>
<td>100</td>
</tr>
<tr>
<td>10</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>0.1</td>
</tr>
<tr>
<td>0.01</td>
</tr>
</tbody>
</table>

Temperature (°C)

0.26 µA
2 µA
**Leadless Packages of 3640 0.22µF 500V MLCC Performance**

- SRF decreases with increasing capacitance to ≈ 1µF
- ESR remains < 3 mΩ below 2MHz
Leadless Packages of 3640 0.22µF 500V MLCC
Surface Mounted Performance

- Board Flexure is > 3mm similar to MLCC
- No Failures 0/50 through 500 cycles -55 to +150°C

![Image of MLCC package]

Board Flexure
3640 2 and 4 Chip Stacks Thin Au w/CuSn TLPS
Weibull

Tested Pieces to 10mm DID NOT FAIL

5 second dwell at 10 mm flex
Leadless Packages of 4 X 3640 0.22µF 500V MLCC
Stack Orientation; Horizontal Vs. Vertical

**Horizontal**  
**Vertical**

**Vertical Orientation has:**
- Higher SRF
- Lower ESR

**ESR**

- **Horizontal**
- **Vertical**

**Impedance**

- 4-Chip Horizontal |Z|
- 4-Chip Vertical |Z|

**3 MHz**  
**5.7 MHz**
Leadless Packages of 4 X 3640 0.22µF 500V MLCC
Ripple Current Heating; Horizontal Vs. Vertical

**Horizontal**

- Heat dissipation into Cu board.
- Top View
- Side View

12A_{RMS} @ 140kHz WARMING UP

**Vertical**

- Heat dissipation in Air above.
- Top View
- Side View

**STEADY STATE**

- Vertical Orientation:
  - More even heating
  - Lower Temp. @ Steady State ≈ -5°C

- 34.9°C
- 29.2°C
Summary

• WBG requirements & increases in switching frequency change capacitor needs:
  – Smaller Values
  – High Voltage & High Current Capability
  – Reliable at High Temperatures

• BME Ni C0G MLCC solutions have:
  – High reliability at high temperature & voltage
  – High ripple current capability
  – High MOR & flexure

• Transient Liquid Phase Sintering Technology can be used for:
  – Solder Replacement (TLPS is Pb-free)
  – Leadless Packaging to realize higher capacitance in a given pad size
  – Vertical Orientation has higher SRF, lower ESR and less ripple heating
Thank You!