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

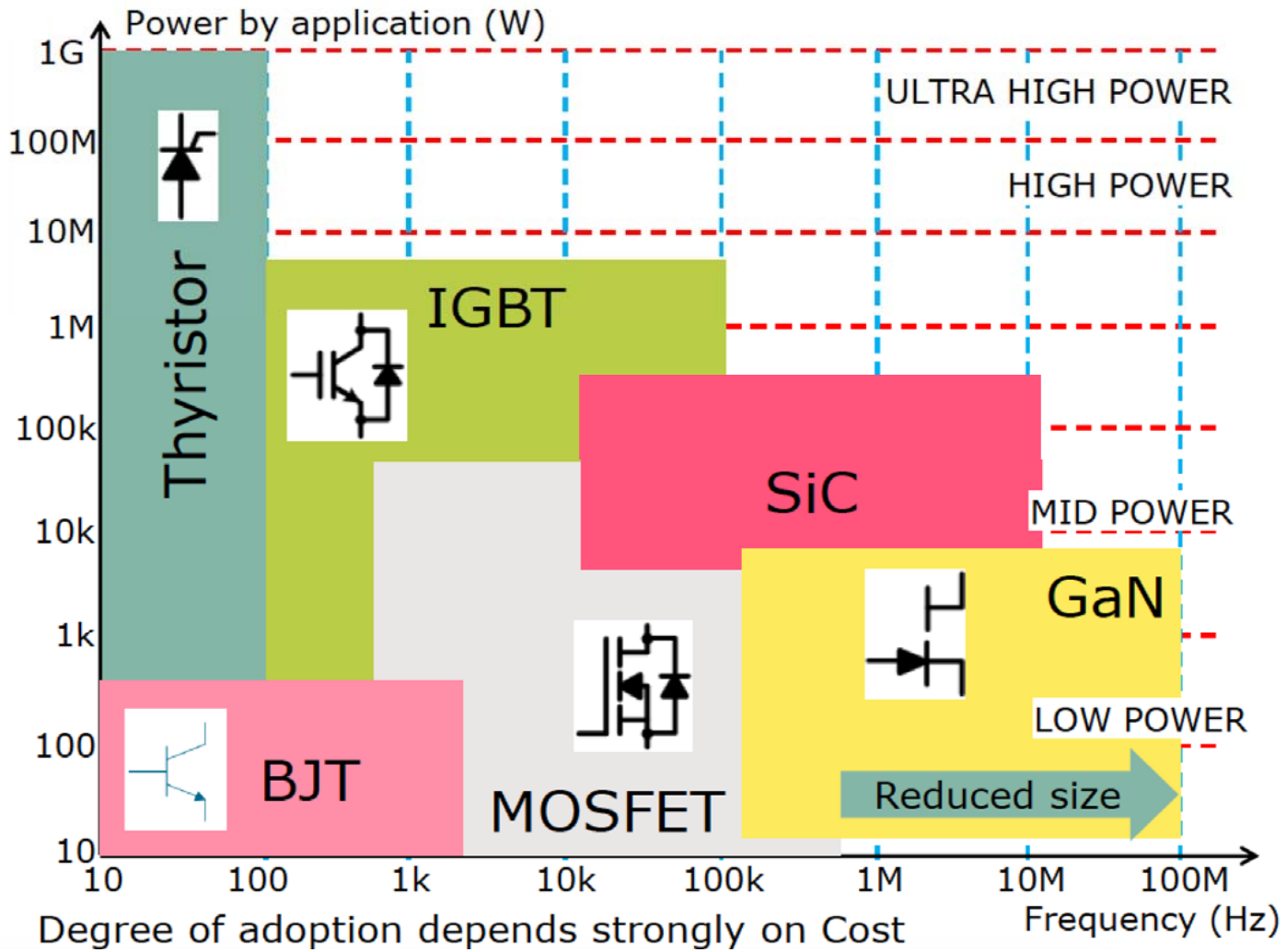
Power Conversion Efficiency

	Si Based	WBG Based on GaN or SiC
DC to DC	85%	95%
AC to DC	85%	90%
DC to AC	96%	99%

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

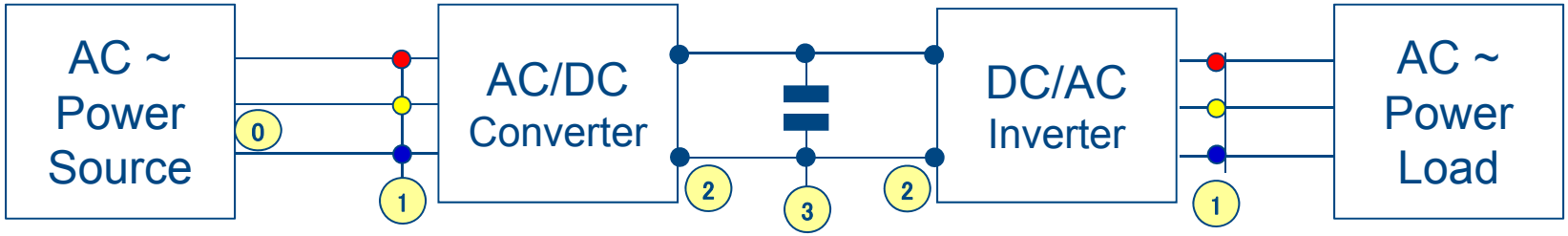
WBG Capacitor Requirements

WBG Semiconductor Trend	→	Capacitor Requirement
Higher Switching Frequencies 20kHz → 100kHz → 100's MHz	→	Smaller, low ESR, low ESL low loss capacitors with high dV/dt & current handling capability
Higher Operation Voltages 400V → 650V →1200V→1700V GaN SiC	→	Reliable performance at higher voltages

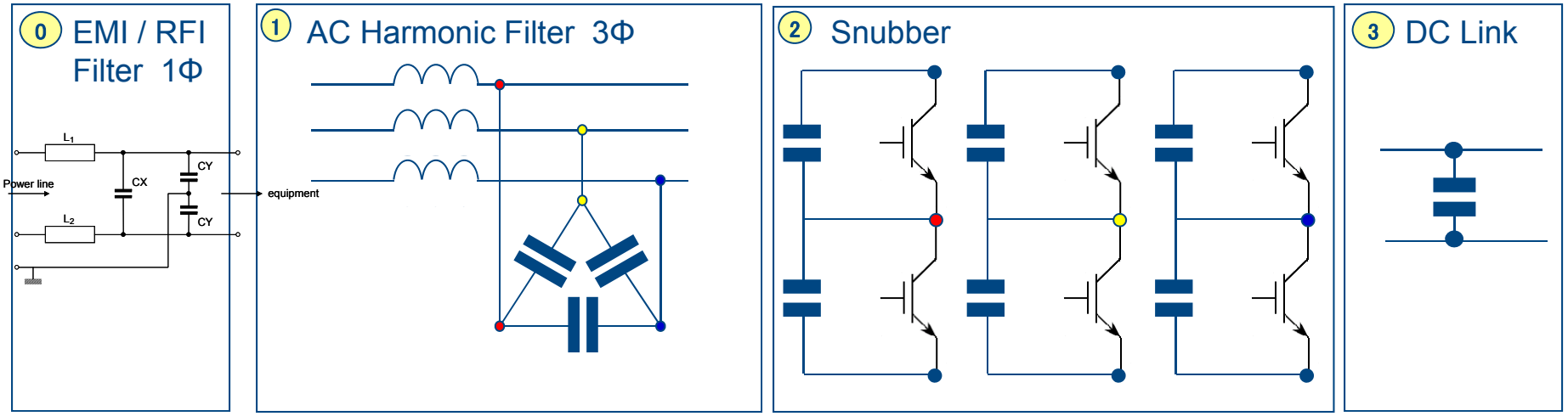
High Junction Temperatures
105°C → 125°C → 200°C+
SiC
	→	Reliable performance at elevated temperatures ≥ 125°C with robust mechanical performance
		• Packaging close to the hot semiconductor to:
		  • Lower ESL
		  • Minimize cooling costs

Power Converter Capacitors

System Overview:



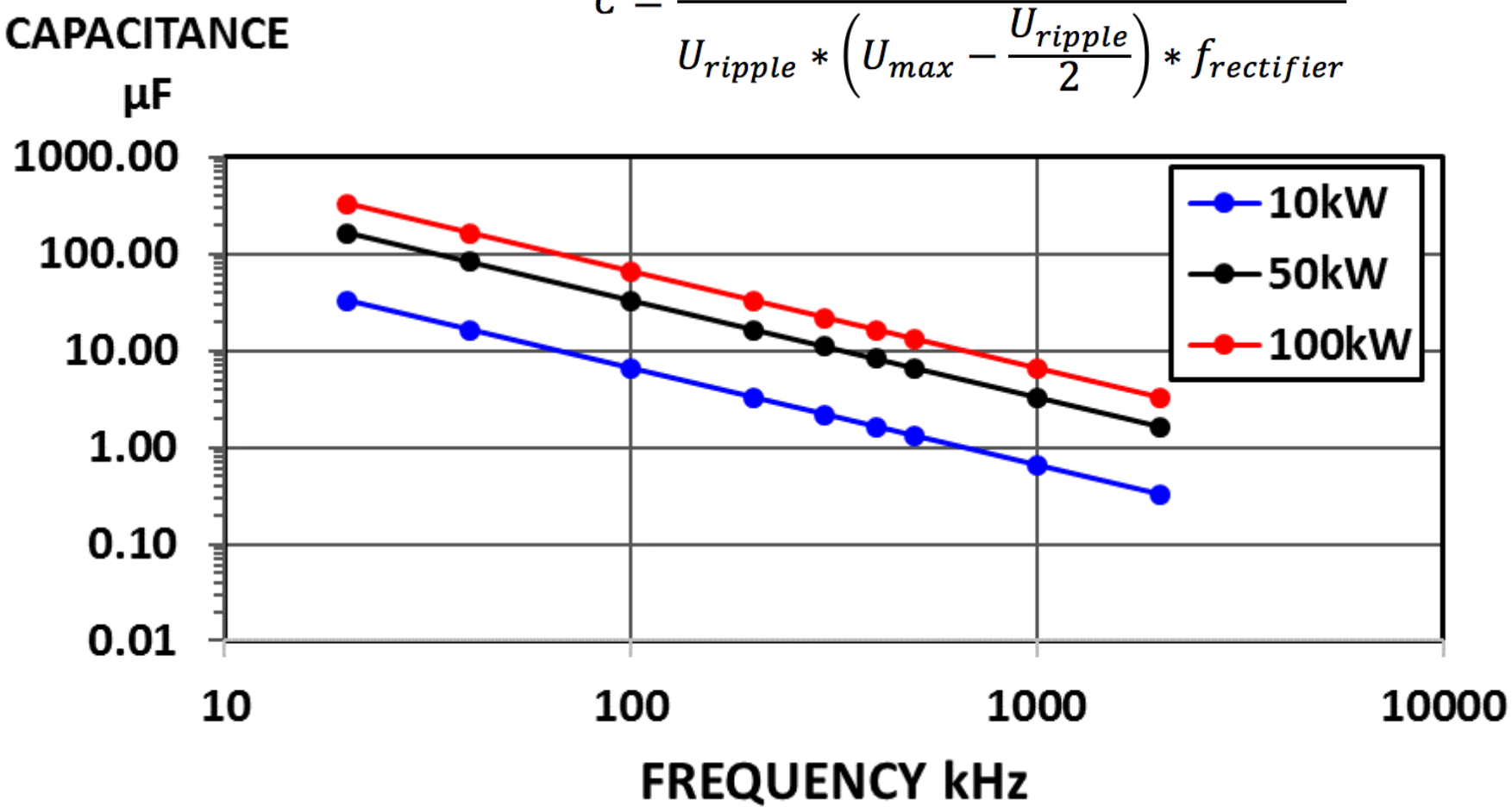
Typical Capacitor Types:



How Much Capacitance Do We Need?

Example: DC Link for 400V with 10% Ripple

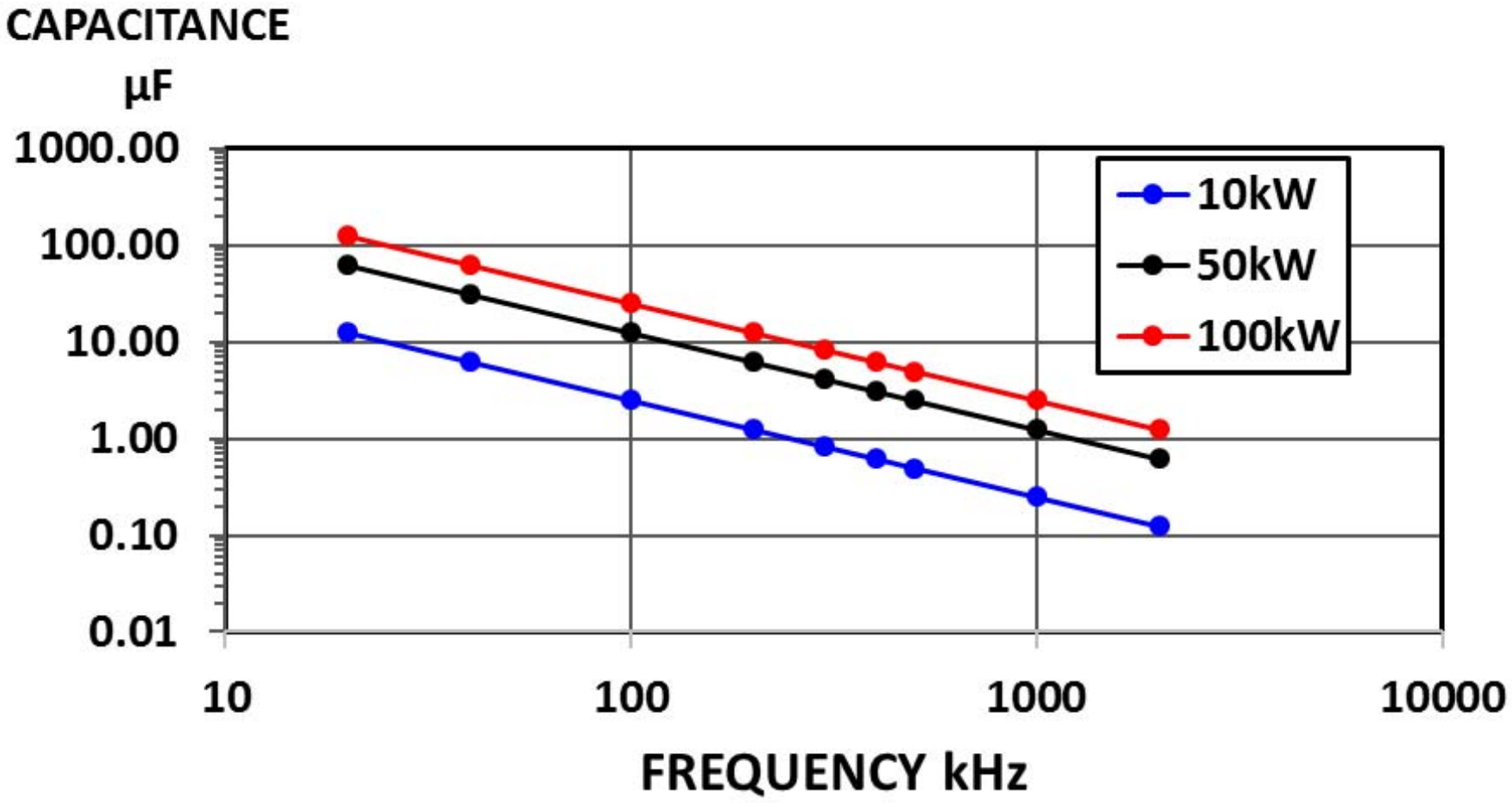
$$C = \frac{P_{load}}{U_{ripple} * \left(U_{max} - \frac{U_{ripple}}{2}\right) * f_{rectifier}} \quad *$$



**** Source: Prof. R. Kennel, Technical University Munich, Germany***

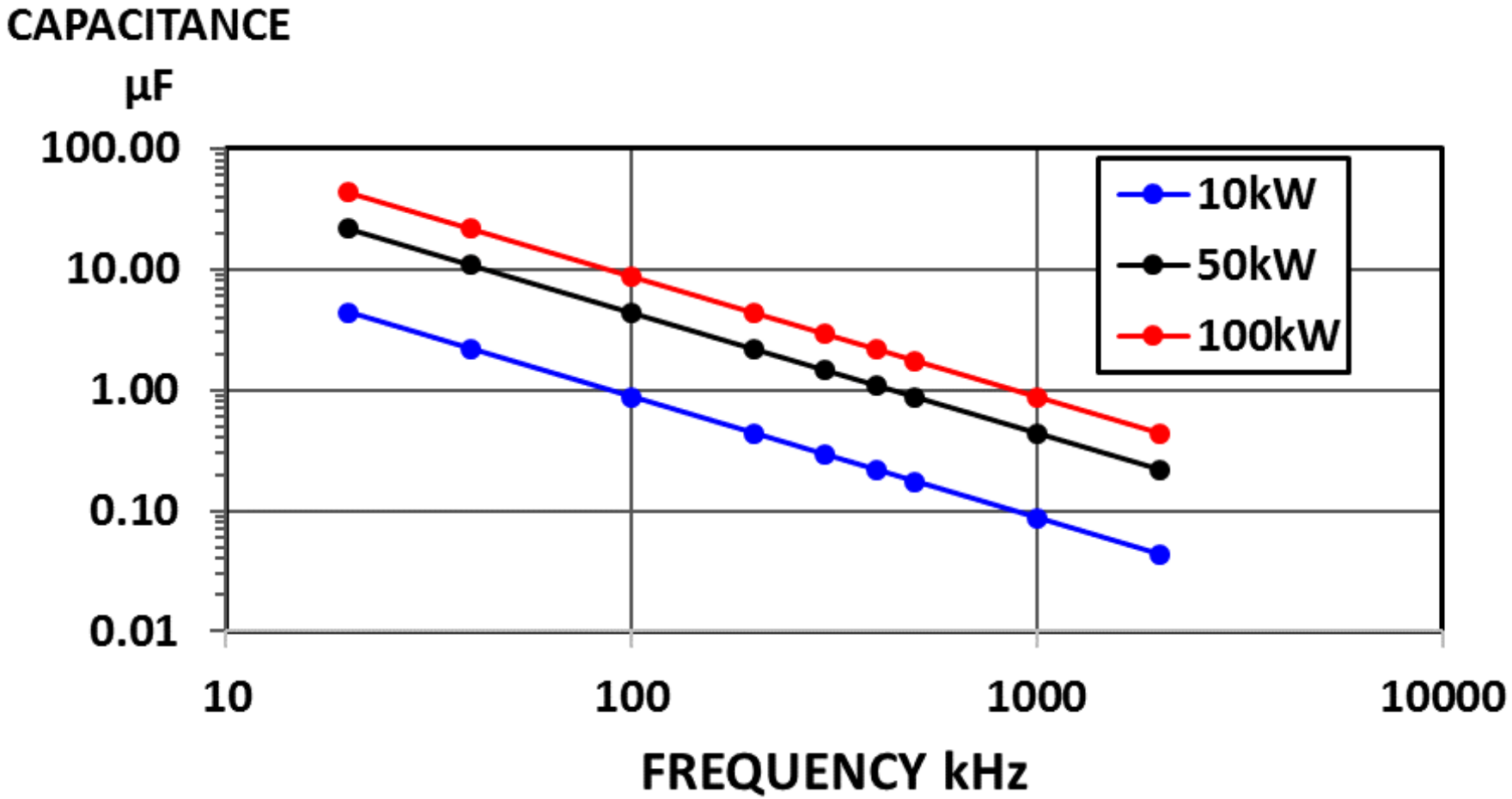
How Much Capacitance Do We Need?

Example: DC Link for 650V with 10% Ripple



How Much Capacitance Do We Need?

Example: DC Link for 1200V with 10% Ripple

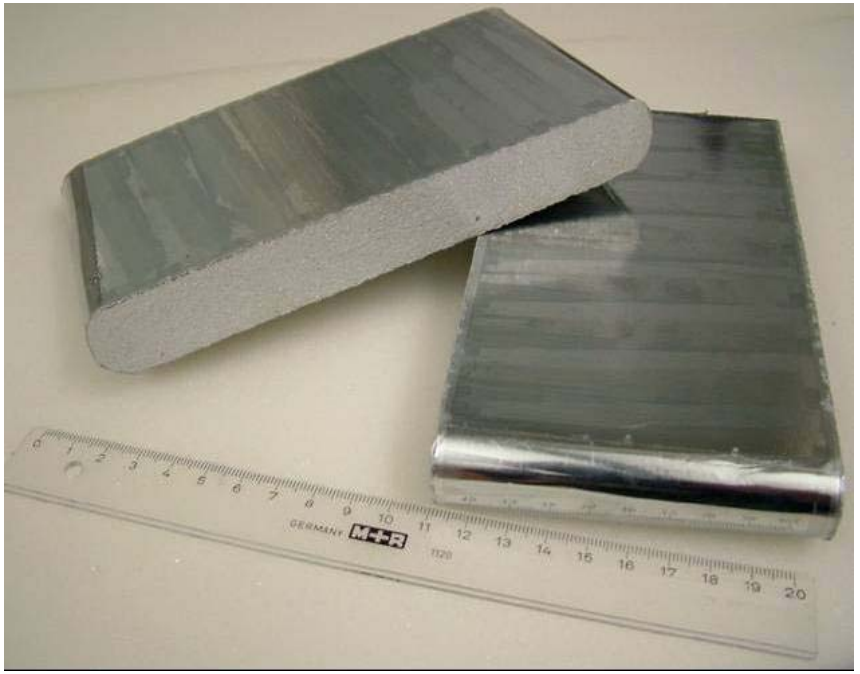


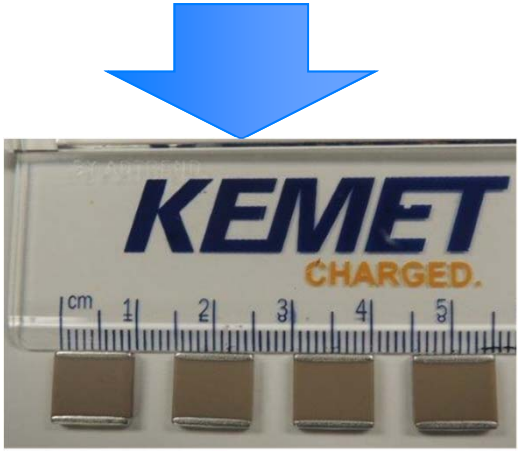
- Higher Frequencies, Higher Voltages & Lower Power requires less capacitance

How Much Capacitance Do We Need?

Polypropylene Film to MLCC

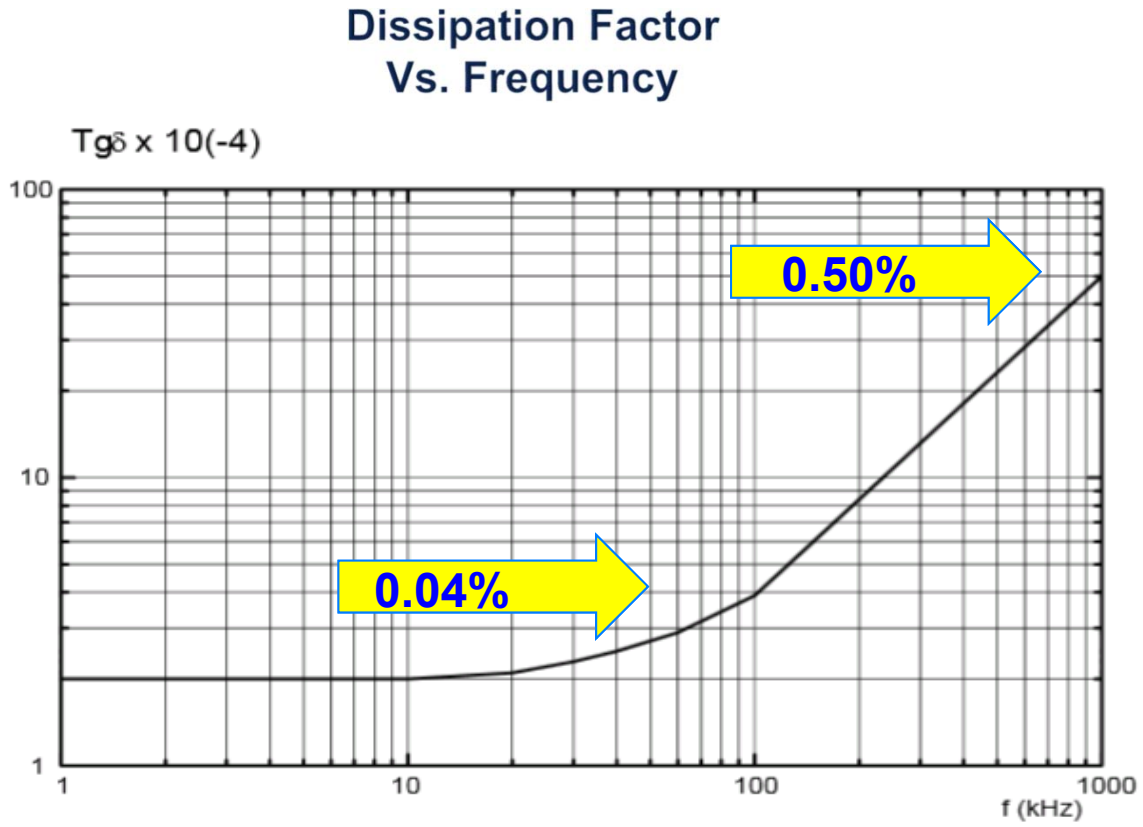
- For WBG DC-Link Capacitors:
  - Lower capacitance required promotes miniaturization due to:
    - Increasing switching frequency
    - Higher voltages
- Lower capacitance is within the range of MLCC.
  - But these need must be:
    - Extremely reliable
    - Over-Temperature and Over-Voltage Capable
    - High current capable
    - Mechanically Robust





Power Film Technology (Metallized PP)

Effect of Frequency

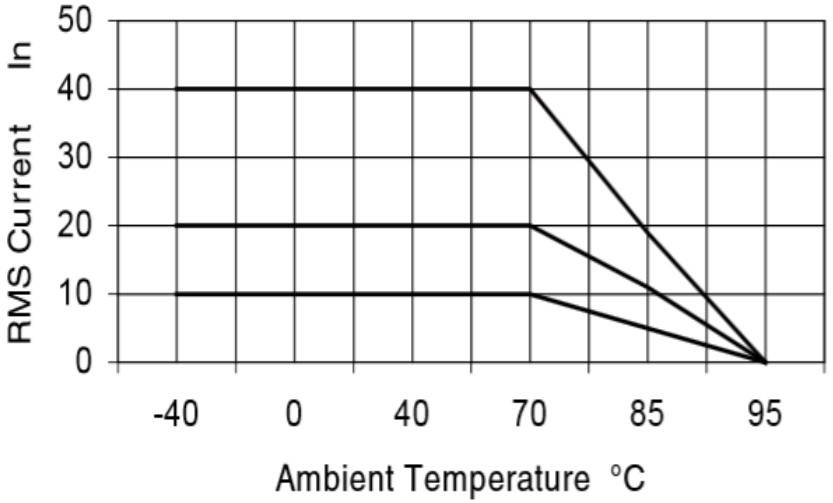


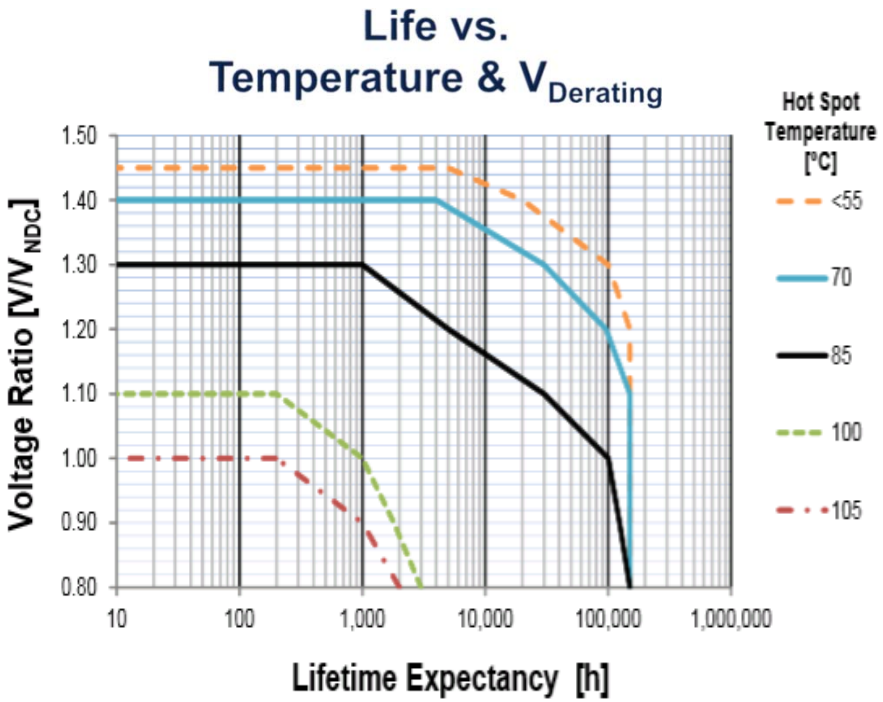
Dissipation factor vs. frequency (Room temperature)

Increasing Frequency = Higher DF

Power Film Technology (Metallized PP)

Effect of Higher Temperature





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

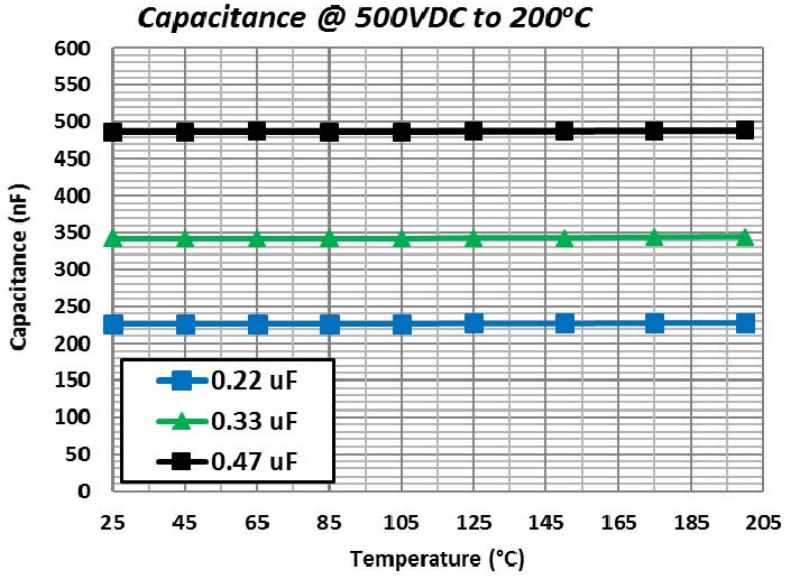
MLCC Capacitor Development

Ni BME C0G 3640 Case Size

3640
L x W x TH
0.36” x 0.40” x 0.10”
9.1mm x 10.2mm x 2.5mm
Volume = 0.23cm^3

	Ni BME C0G 3640 Prototypes		
Nominal Cap	**0.22 µF**	**0.33 µF**	**0.47 µF**
Capacitance (nF)	227	343	487
DF (%)	0.0080	0.0117	0.0110
IR @ 25°C (GΩ)	458	277	242
IR @ 125°C (GΩ)	7.42	6.47	6.24

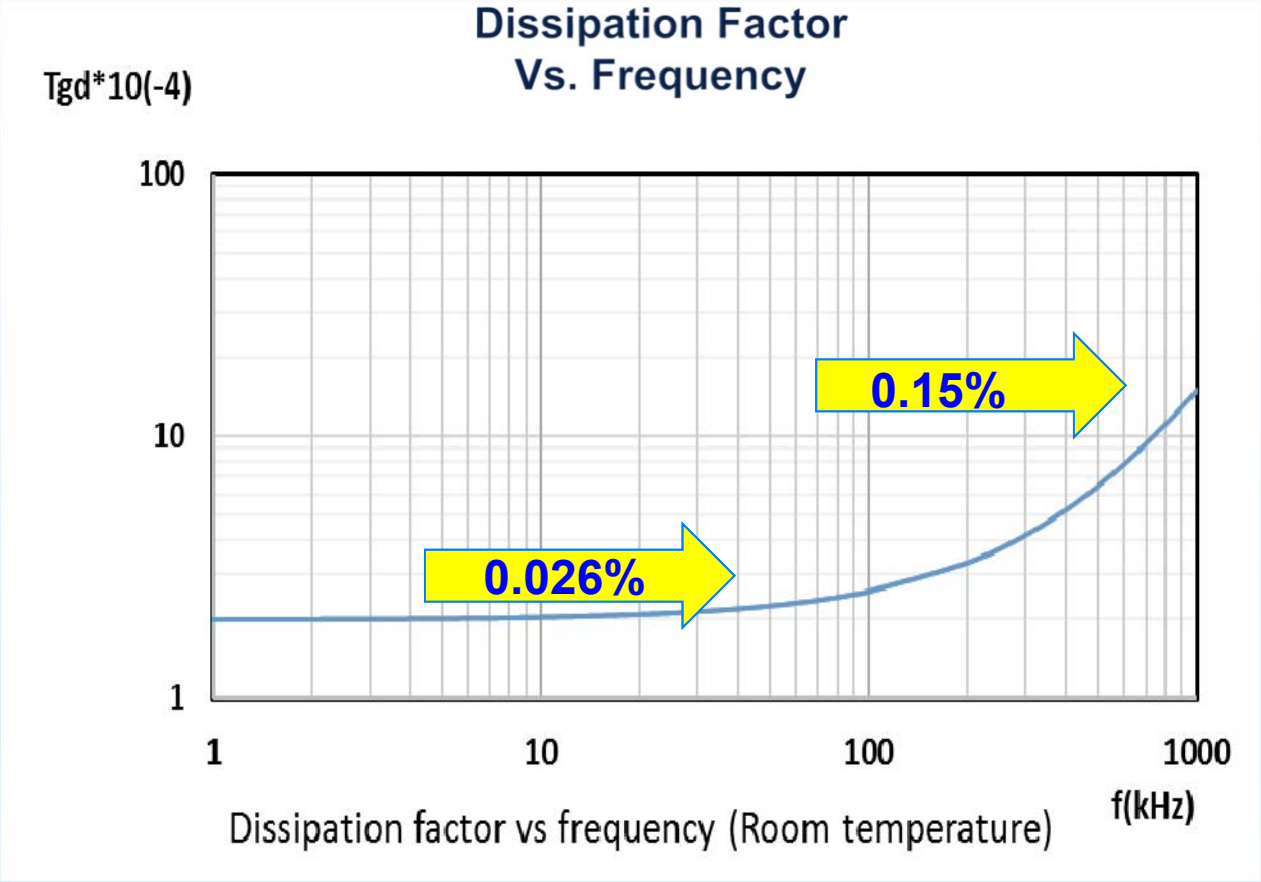
- Ni BME C0G 3640 have:
  - Low DF
  - High IR
  - Stable Capacitance at high temperatures & voltages



Ref. J. Bultitude et al; Proc. Intl. Symposium on 3D Power Electronics, NC State, June 13-15, 2016

Ni BME C0G MLCC 3640 500V 150ºC

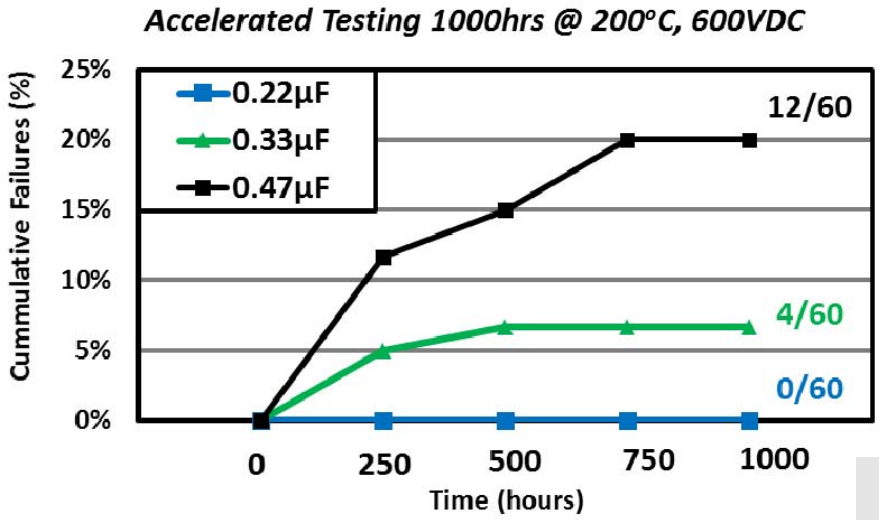
Higher Frequency



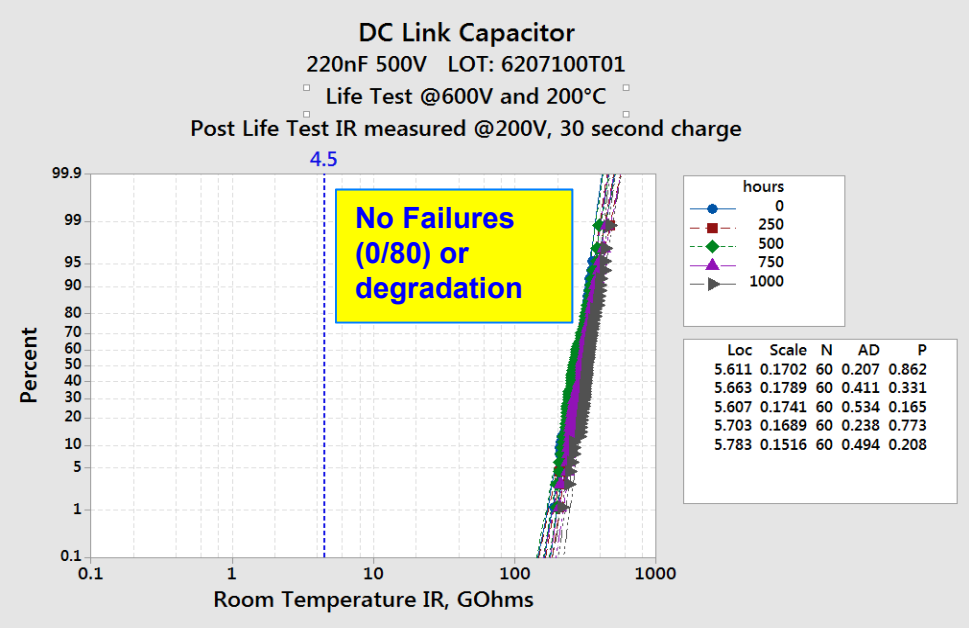
Increasing Frequency = Higher DF
but < Metallized PP

Ni BME C0G MLCC 3640 500V 150ºC

Reliability by Accelerated Testing



- Higher Temperature
  - Low failure rates @ 200ºC*
  - Repeatable Capability



**Ref. J. Bultitude et al; Proc. Intl. Symposium on 3D Power Electronics, NC State, June 13-15, 2016*

Ni BME C0G MLCC 3640 0.22µF 500V 150ºC

ESR & Current Handling @ 150ºC 100kHz

- Lower DF & ESR reduce the power dissipated

$$P = \frac{i^2 d}{2\pi f C} = i^2 R$$

P = power dissipated

i = current

d = dissipation factor

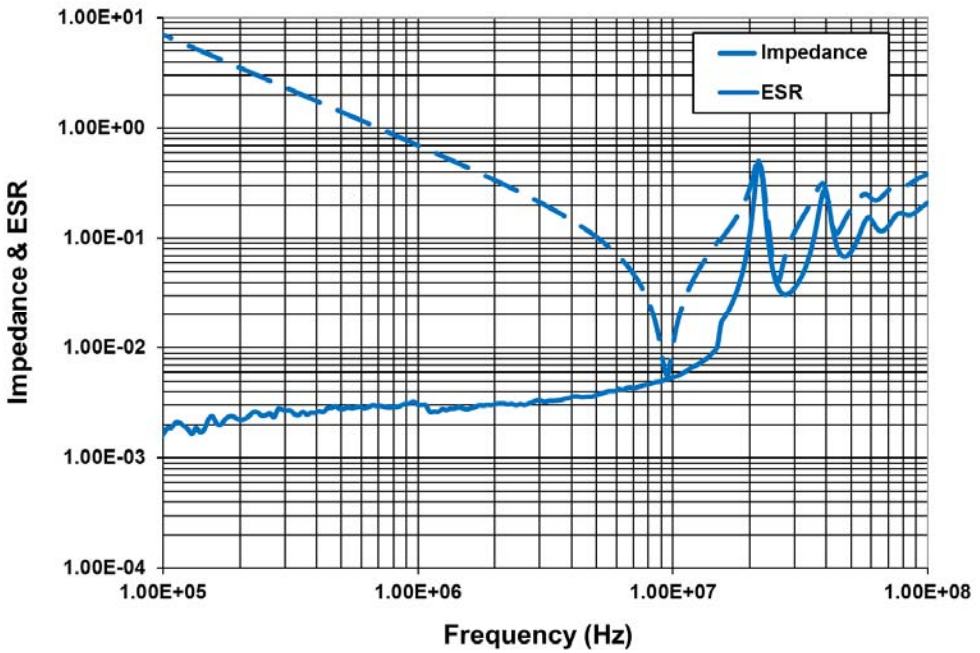
f = frequency

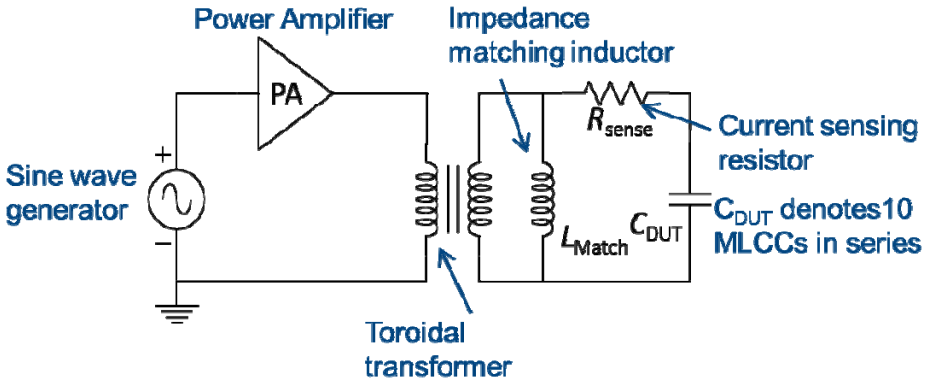
C = capacitance

R = resistance, ESR

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

≈ 75 A_{RMS}/µF or ≈ 65 A_{RMS}/cm^3



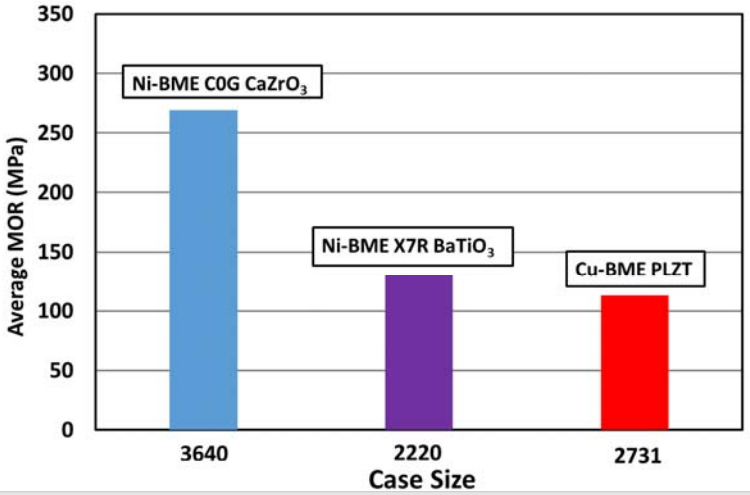


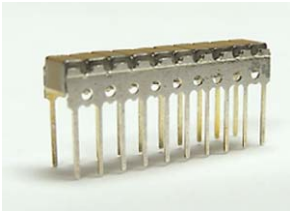
Ref. J. Bultitude et al; Proc. Intl. Symposium on 3D Power Electronics, NC State, June 13-15, 2016

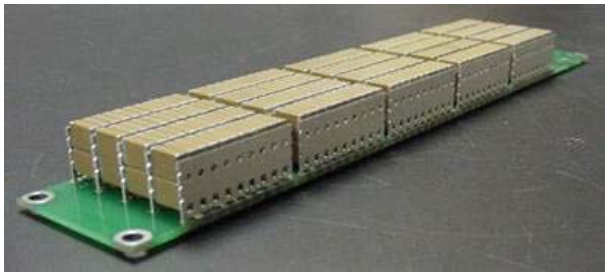
MLCC Packaging

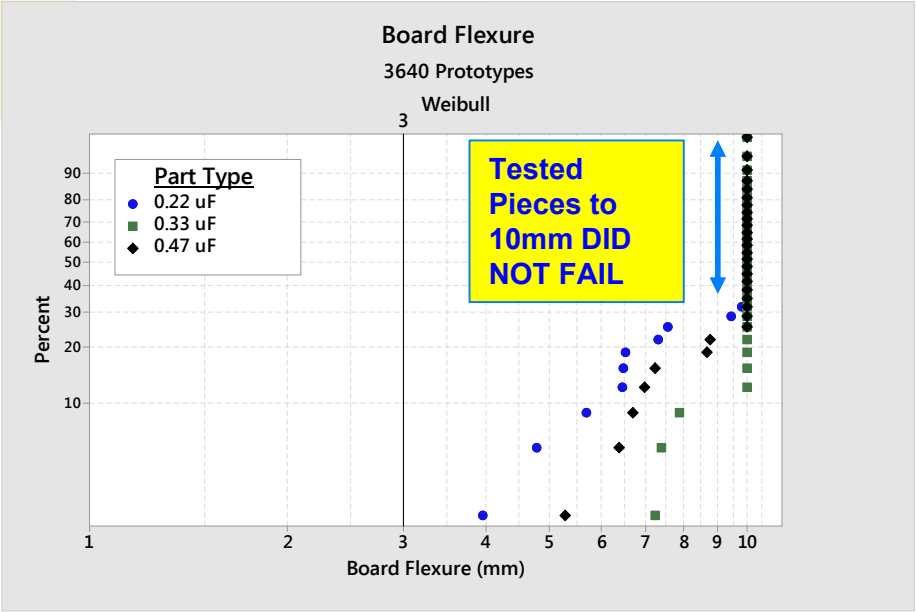
Different Assembly Options

- 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**









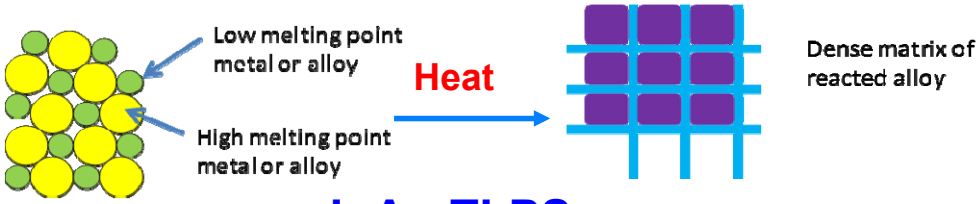
**Ref. J. Bultitude et al; Proc. Intl. Symposium on 3D Power Electronics, NC State, June 13-15, 2016*

Transient Liquid Phase Sintering (TLPS)

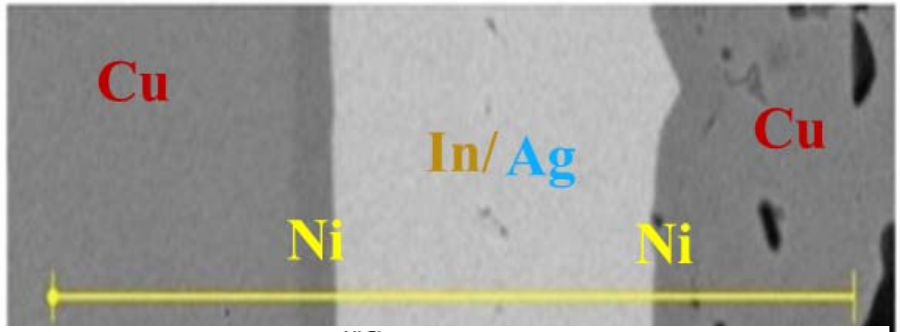
Basic Technology & Types

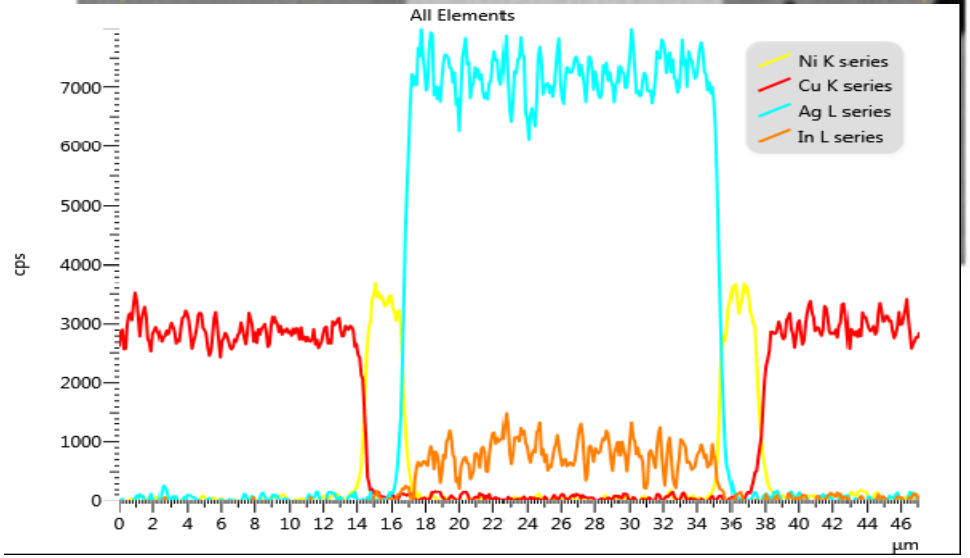
What is TLPS?

- 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

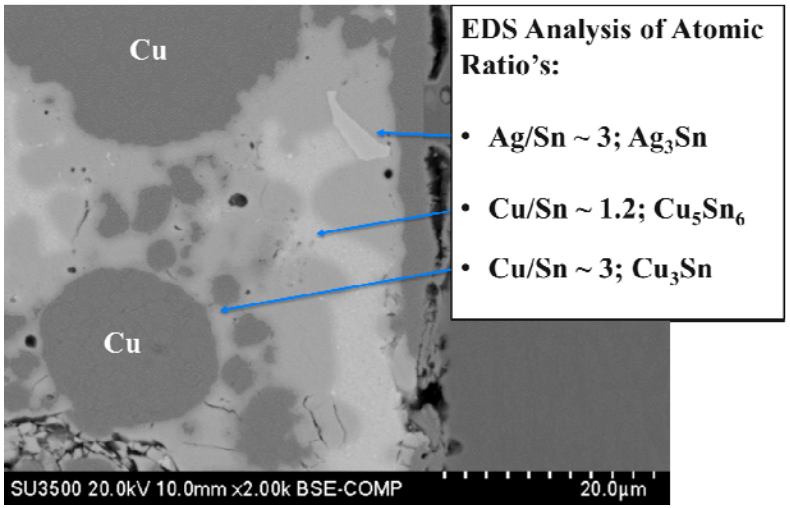


InAg TLPS





CuSn TLPS



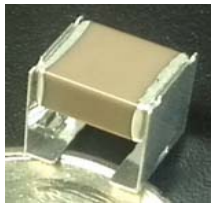
Ref. J. Bultitude et al; MS&T 15, Columbus, OH, USA, October 5, 2015

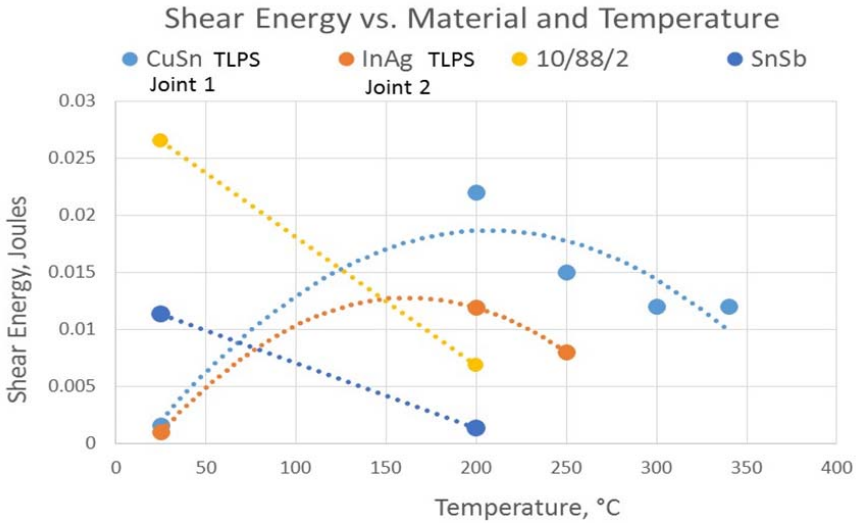
Transient Liquid Phase Sintering (TLPS)

Leaded & Leadless Case Size 2220 MLCC Performance

Leaded

- Improved High Temperature performance Vs. solders





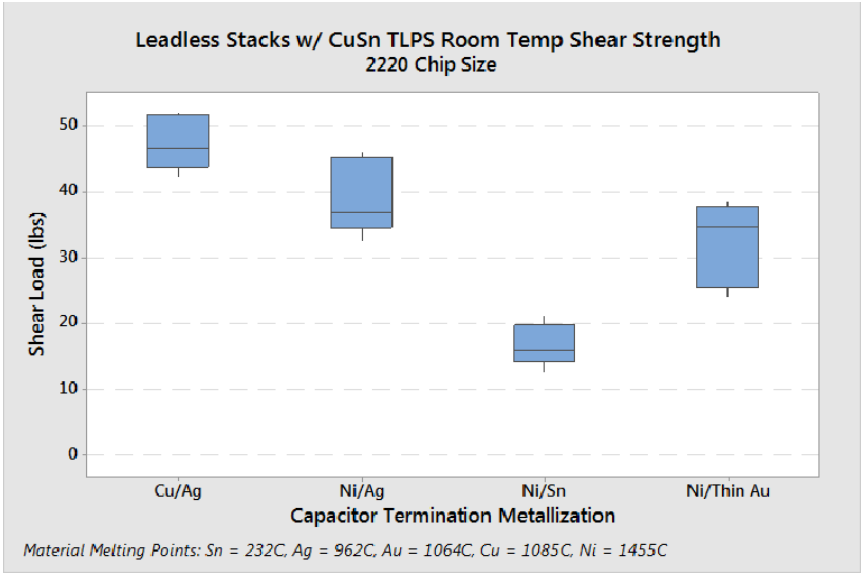
TLPS Type MLCC Termination	Temperature Cycling: -40C to +200C: Cycles			
	250	500	750	1000
In-Ag/Ni underplate	0/30	0/30	0/30	0/30
In-Ag/Cu underplate	0/30	0/30	0/30	0/30

Leadless

- Pass 125°C Temp. Cycling

Leadless Stacks Sn Plated Termination, CuSn TLPS Failures per Test Quantity				
Thermal Cycles	117	500	1000	2000
Lot 1	0/40	0/40	0/40	0/40
Lot 2	0/40	0/40	0/40	0/40

- High Shear Strength

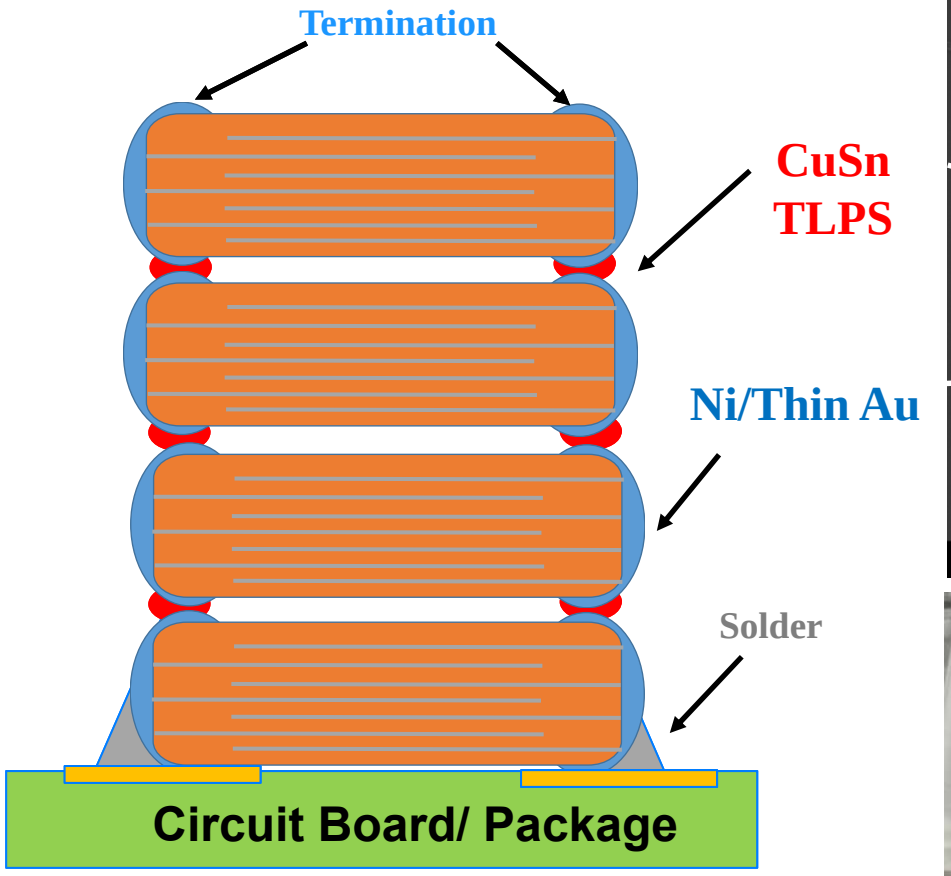


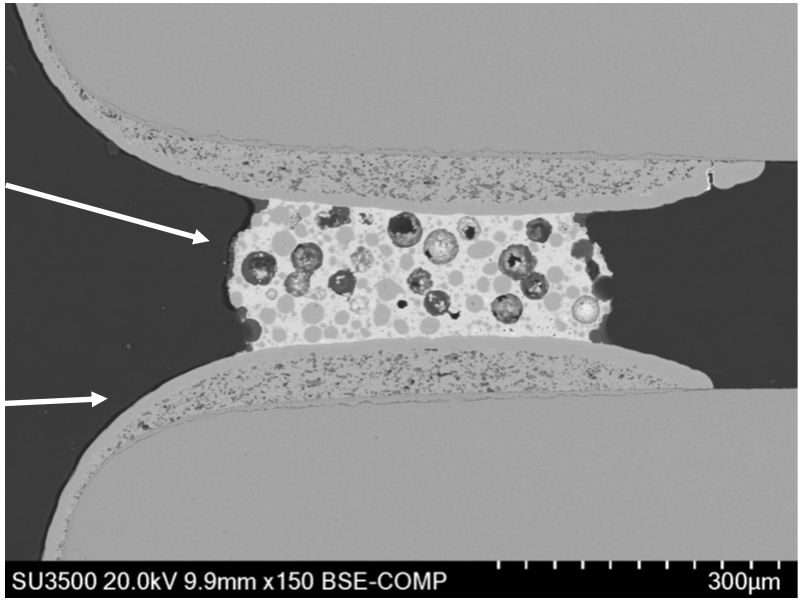
US Patents 8,331,078B2, 8,902,565B2 & 9,472,342B2

Ref. J. McConnell et al; IMAPS 2016, Pasadena, CA, USA, October 13, 2016

Leadless Packaging 3640 0.22µF 500V MLCC

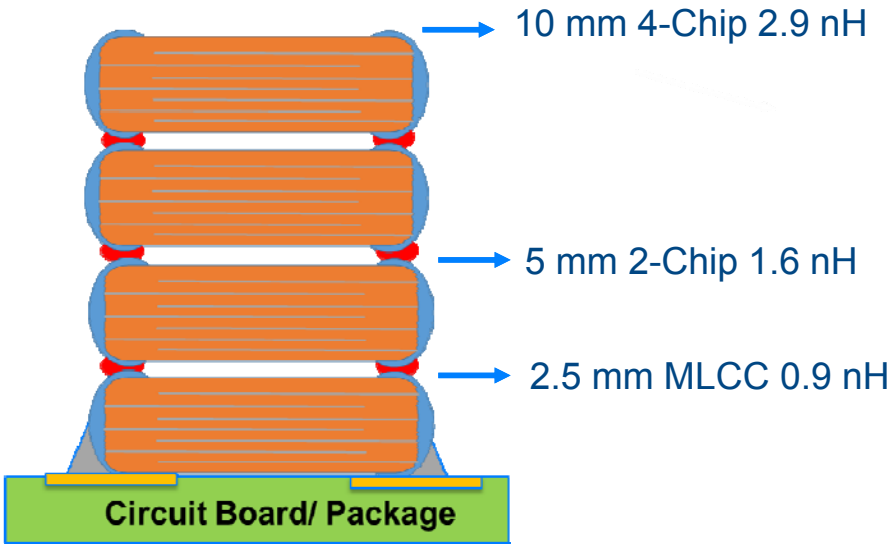
Form Factors & Materials



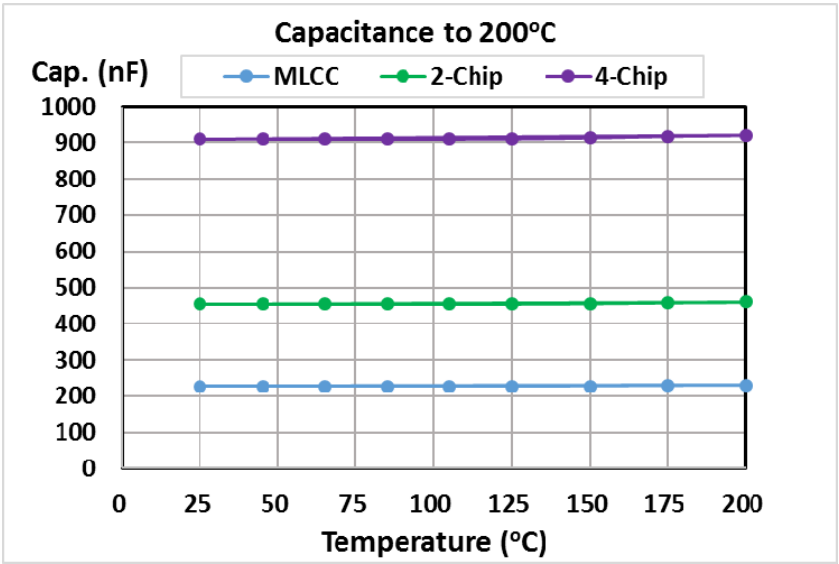


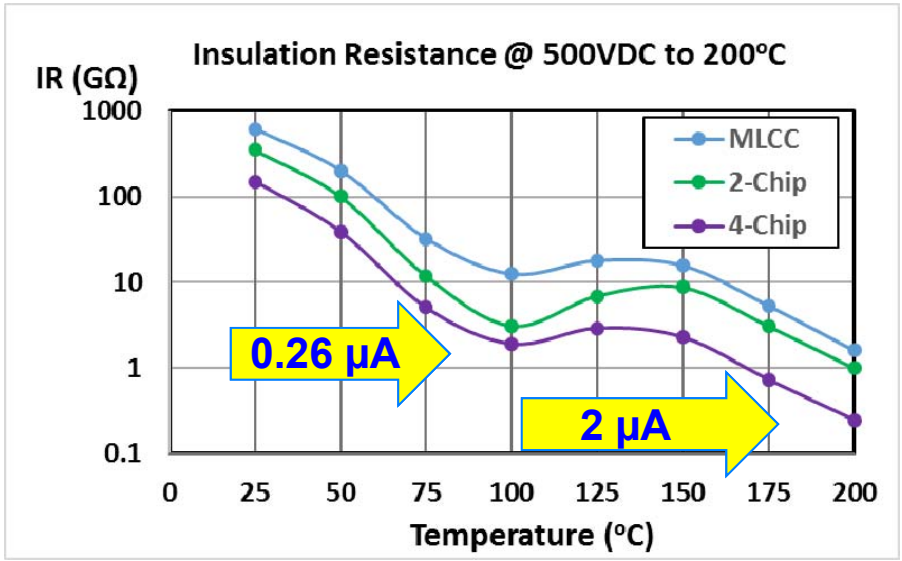
Leadless Packages of 3640 0.22µF 500V MLCC

Performance



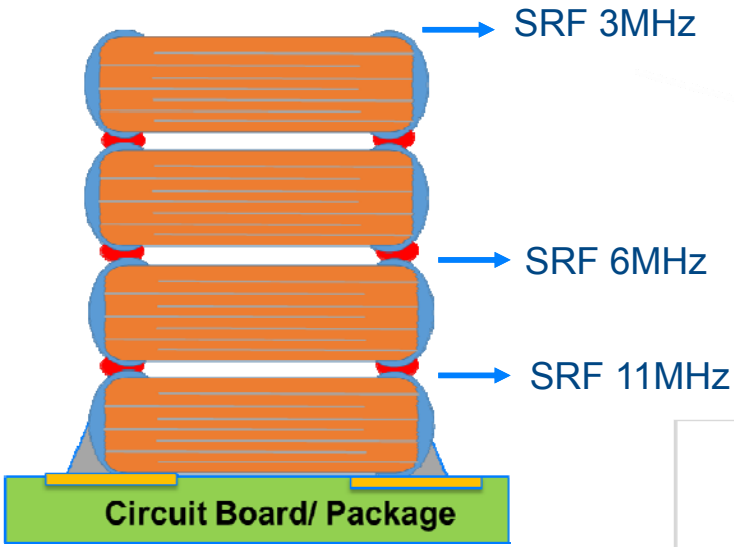
- Higher Capacitance to ≈ 1µF
- Increased height of Leadless Stacks increases maximum inductance
- High Insulation Resistance to 200°C



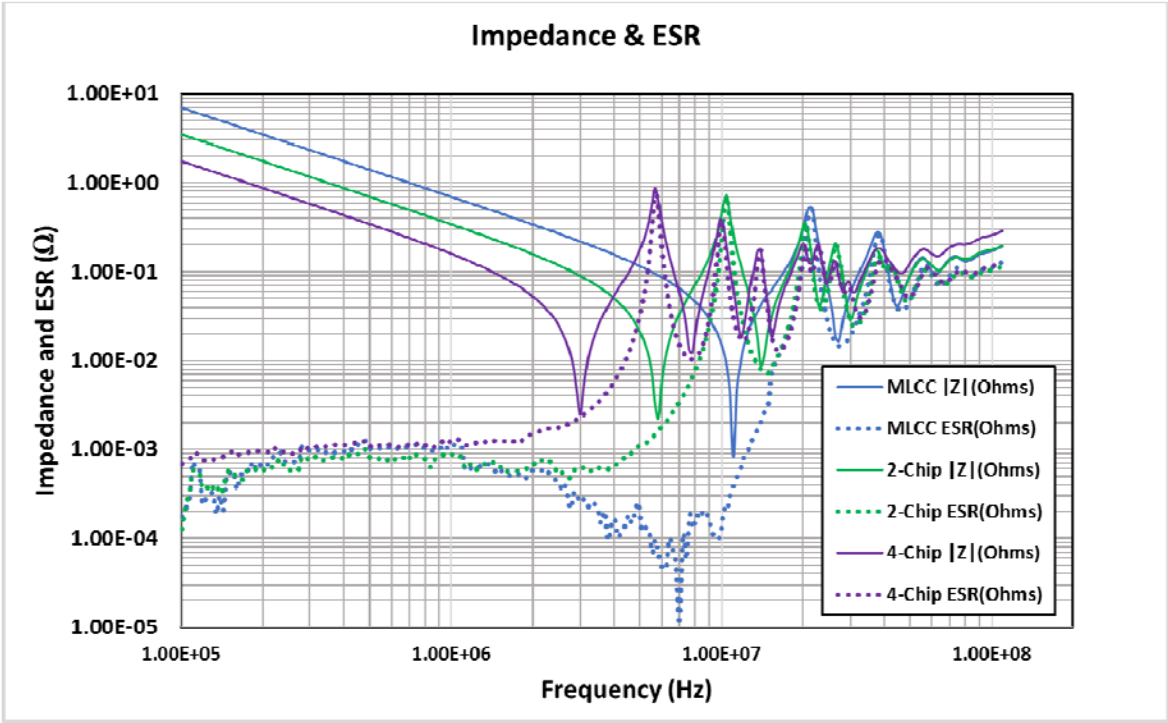


Leadless Packages of 3640 0.22µF 500V MLCC

Performance

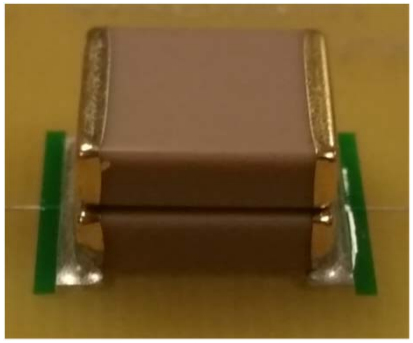


- SRF decreases with increasing capacitance to ≈ 1µF
- ESR remains < 3 mΩ below 2MHz

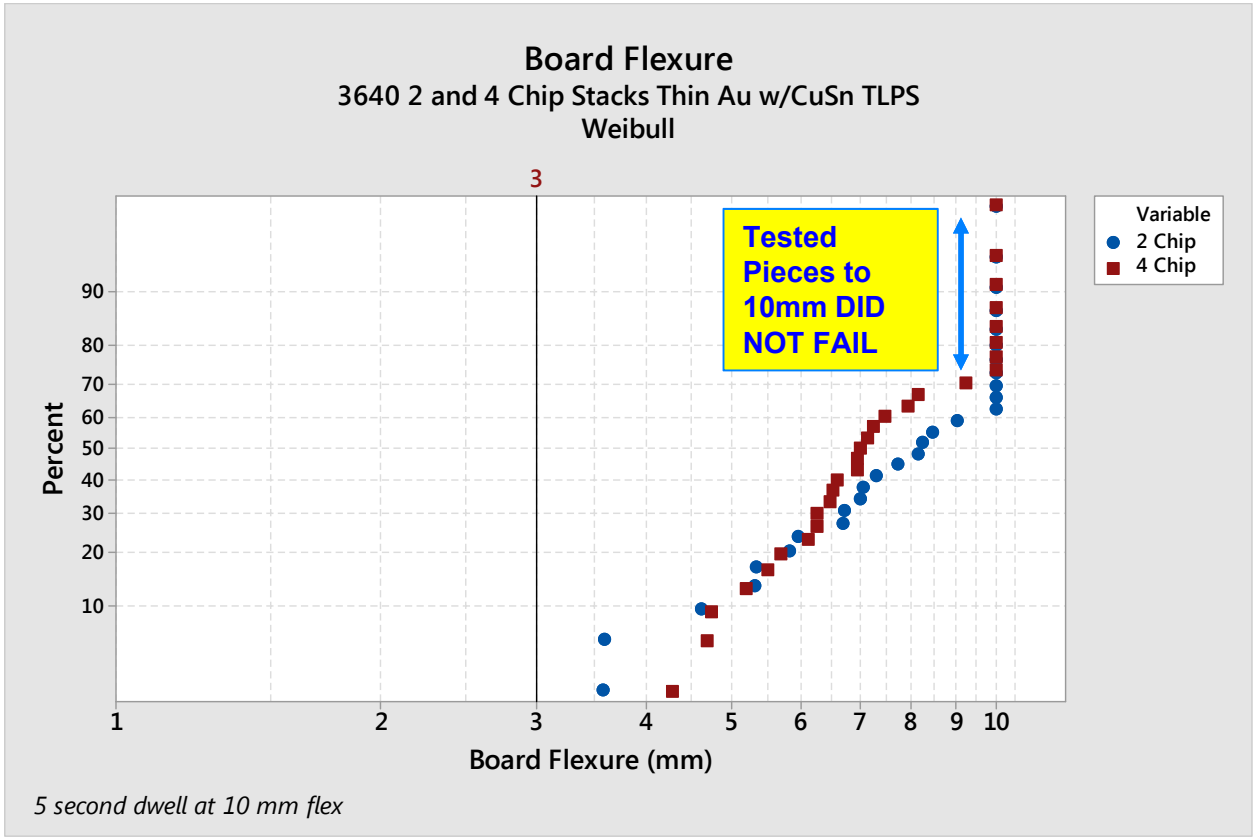


Leadless Packages of 3640 0.22µF 500V MLCC

Surface Mounted Performance



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



5 second dwell at 10 mm flex

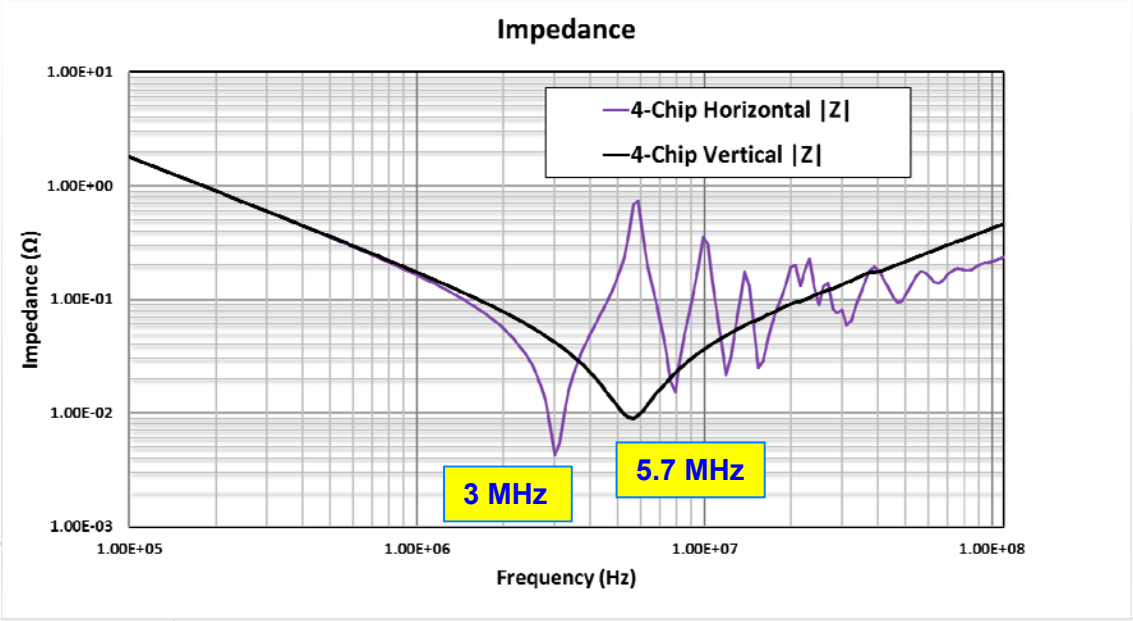
Leadless Packages of 4 X 3640 0.22µF 500V MLCC

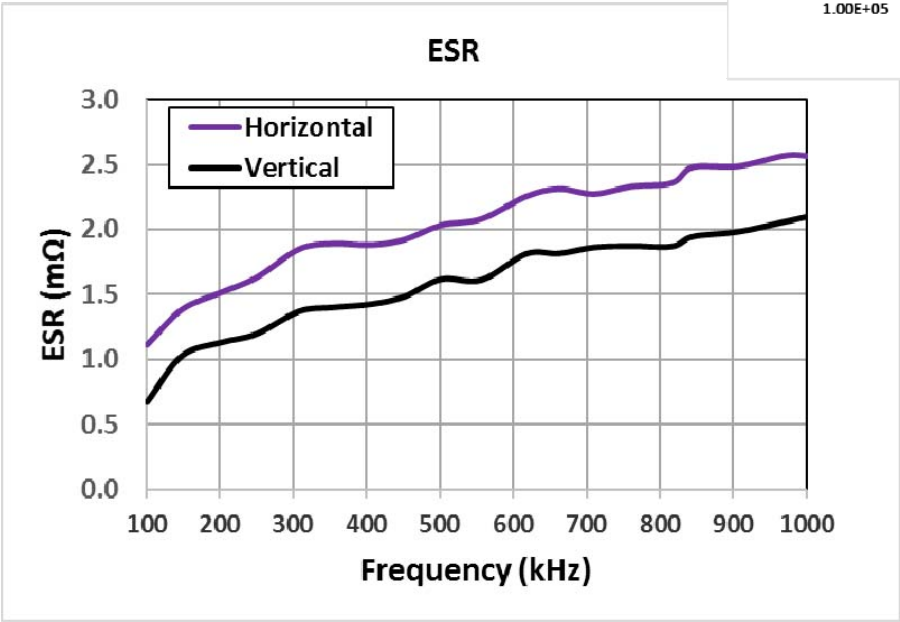
Stack Orientation; Horizontal Vs. Vertical

Electronic Components KEMET CHARGED.

Horizontal

Vertical





Vertical Orientation has:

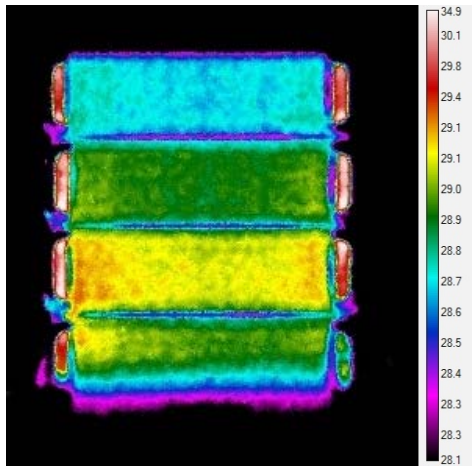
- Higher SRF
- Lower ESR

Leadless Packages of 4 X 3640 0.22µF 500V MLCC

Ripple Current Heating; Horizontal Vs. Vertical

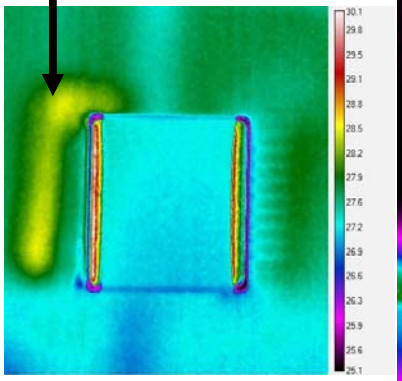
Electronic Components KEMET CHARGED.

Horizontal

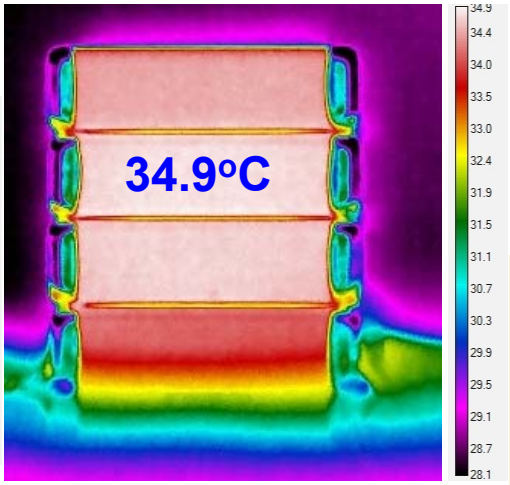


Side View

Heat dissipation into Cu board.



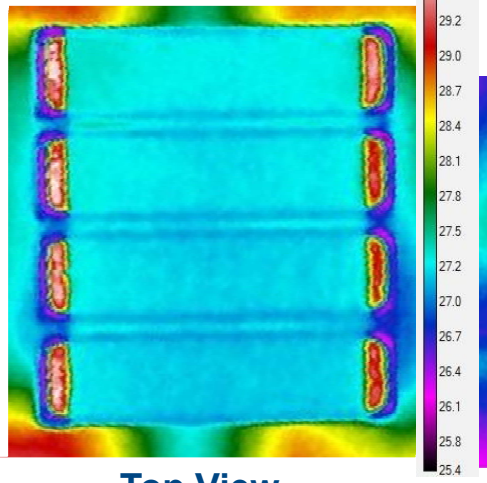
Top View



$12A_{RMS}$ @ 140kHz WARMING UP

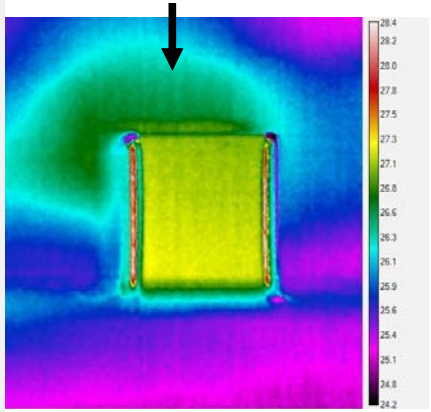
STEADY STATE

Vertical

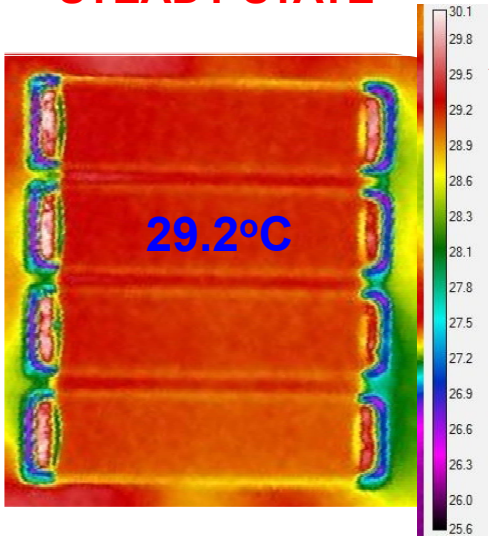


Top View

Heat dissipation in Air above.



Side View

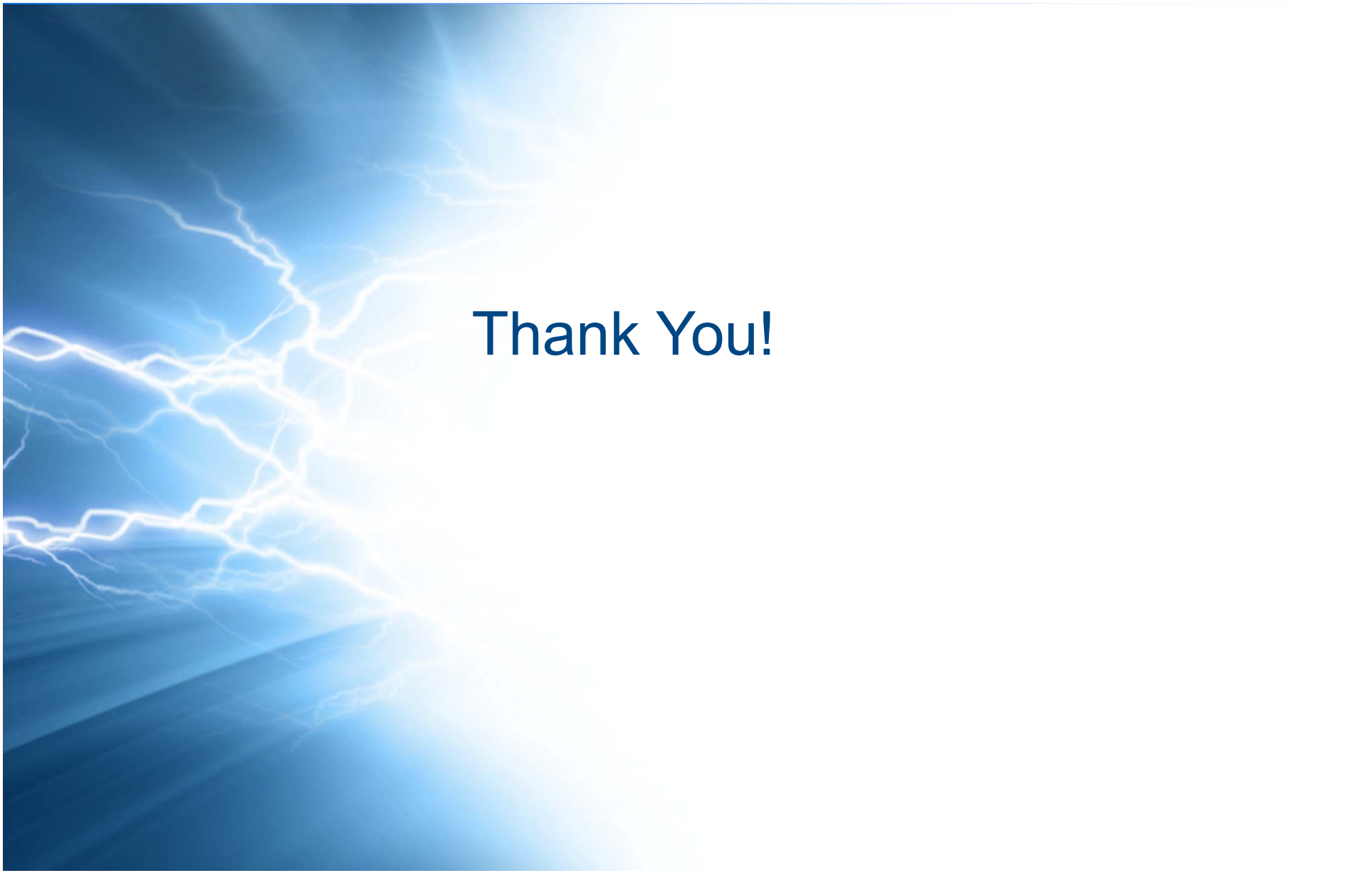


Vertical Orientation:

- More even heating
- Lower Temp. @ Steady State ≈ - 5°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!