High Temperature Dielectric Materials and Capacitors for Transportation Power Electronics

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Outline

- Overview of capacitor technology
- Capacitors in power electronics
- New high temperature materials with high energy and power densities
- Summary
Impact of trends in power electronics on Capacitor development

• SiC power semiconductors enable miniaturization of automotive power control units, higher operating frequencies, and higher operating temperatures.

• DC link capacitors capable of high temperature and frequency operation, high ripple current, low ESR and ESL at operating conditions, and high volumetric energy and power storage are being developed.

Ref. Toyota 2014 http://www.greencarcongress.com/2014/05/20140520-sic.html
Commercial Capacitor Ranges

DC Bus Capacitor Requirements for Hybrid Vehicles

- Film
- Multilayer Ceramic (MLC)
- Al-Electrolytic

Electrochemical

Capacitance (μF)

Working Voltage (V)
Electrolytic Capacitors

- Electrolytics – Formed by Metal Anodization
  - $\text{Al}_2\text{O}_3 \ (\varepsilon_r=9)$ or $\text{Ta}_2\text{O}_5 \ (\varepsilon_r = 28)$
  - Advantages – high cap, low cost
  - Disadvantages – high ESR, liquid electrolyte
- Applications
  - Electronics, Implantable heart defibrillators
Electrolytic Capacitor Bank in Toyota Prius Power Inverter (prior to 2010)
Ceramic And Polymer Capacitors

**Polymer Film Capacitor**

**Advantage**
- Benign failure mode
  - self clearing

**Disadvantage**
- Poor High-Temp. Ripple Current
  - $I_{\text{rms}}$ at 75°C is 70% lower than $I_{\text{rms}}$ at 25°C

**Multilayer Ceramic Cap.**

**Advantage**
- Excellent High-Temperature and high frequency dielectric and ripple current capabilities

**Disadvantage**
- Non-graceful failure mode

AVX film capacitor: 525V 240 μF

Murata MLCC capacitor 250V 270 μF
See (www.powerelectronics.com)
GAP Analysis for DC Bus Capacitors

• Comparison of DC bus capacitor needs with commercial capacitors

• Major Parameters
  – Energy density – determined by dielectric constant and operating electric field
  – Ripple Current – strong temperature dependence
  – Reliability including graceful failure
  – Cost
Electrolytic Capacitors
Gap Analysis

Operating Temperature
Ripple Current
Cost
Energy Density (J/cm³)
Energy Density (J/gm)
Failure Tolerance
Electrolytics

ADVANTAGES
• High Capacitance Density
• Low Cost

DISADVANTAGES
• Non-benign failure mode
• Low ripple current capability
• High ESR
• Large size
• Limited voltage range
• High dissipation factor
• Limited temperature range
• Dryout-limited life
• Limited vibration
• Polarized
• High leakage current
• Temperature dependent properties
Polymer Film Capacitors
Gap Analysis

Operating Temperature
Failure Tolerance
Energy Density (J/cm³)
Energy Density (J/gm)
Cost
Ripple Current
Film Capacitors

ADVANTAGES
• High ripple current capacity
• Benign failure mode
  – self clearing
• Low ESR at low frequency
• Wide voltage range
• Low dissipation factor
• Non polarized
• Low leakage current
• Good overvoltage and shape compatibility

DISADVANTAGES
• Cost
• Medium to low volumetric energy density
• Low dielectric constant
• High ESR at high frequency
Multilayer Ceramic Capacitors
Gap Analysis

Operating Temperature
Failure Tolerance
Energy Density (J/cm³)
Energy Density (J/gm)
Cost
Ripple Current
Ceramic Capacitors

ADVANTAGES
• High ripple current
• Low ESR
• Low dissipation factor
• Wide temperature range
• Low leakage current
• Non polarized

DISAVANTAGES
• Cost
• Weight
• Low density
• Non-benign failure mode
• Process sensitive
• Limited voltage range
• Susceptible to vibration
Assessment Conclusions

• There are technology gaps for all commercial capacitors
  – Operating temperature for polymer film caps
  – ESR for electrolytics
  – Graceful failure for ceramics

• Capacitor Cost Requirements
  – $/\mu F$ too high
  – $$/Amp$ ripple current may be another metric
Assessment Conclusions (Continued)

• Improvement in volumetric efficiency
  – Related to de-rating factors
    • Graceful failure, reliability, materials
  – Ripple current as a function of Temperature

• Lower costs
  – Improve volumetric efficiency
  – Present performance and cost targets will be difficult to meet (450V, 1000μF, <3mΩ ESR, 100A ripple current, 140°C, benign failure)
Why is energy density important?

- Example: capacitors for hybrid vehicle power inverter
- Directly related to volume (30% of inverter)

Volume of 1000 μF 600V capacitors in a Hybrid Electric Power Inverter

Current Capacitor
Wound polymer film (polypropylene)

Volume = 1.4 Liters
85ºC Rating

Current High Temperature Capacitor
Wound polymer film capacitor

Volume = 21.6 Liters
125ºC Rating

Future Glass Capacitor

Volume = 1.2 Liters
140ºC Rating
Glass is inorganic material with significantly higher thermal stability (>500 °C).

Traditional glass sheets are thick (> 1mm) and are rigid.

Recent development in display industry (large screen TV, smart phones, iPad, etc.) enabled the commercial production of ultrathin glass sheet with thickness of 5 um to 100 um (with >$30B global investment in glass manufacturing).

Global glass manufacturers: Corning, NEG, Schott

Ultrathin glass sheet enabled high capacitance and energy density
Flexible Glass

Flexibility $\sim \frac{1}{\text{Thickness}^3}$

NEG Corporation

5 um thick
Energy Density of Dielectric Materials and Capacitors

Energy density decreases because of higher reliability requirements.

Breakdown Field Controls Energy and Power Density

- Ragone plots are typically generated for electrochemical energy storage sources.
- Adapt mathematical formalisms to dielectrics and electrostatic energy storage.

Theory of Ragone Plots

• Solution to 2\textsuperscript{nd} order differential equation with unique charge conditions

\[ L\ddot{Q} + R\dot{Q} + V(Q) = -\frac{P}{Q} \]

Where

\begin{align*}
\text{Q} &= \text{Charge} \\
\text{L} &= \text{Inductance} \\
\text{R} &= \text{Series Resistance} \\
\text{P} &= \text{Power} \\
\text{V} &= \text{Voltage}
\end{align*}

Comparison of Capacitor Technologies

![Graph comparing energy density vs. power density for different capacitor technologies.](image-url)
Energy and Power Density Comparison for Dielectrics

- PVDF based polymers have high energy density but poor power density.

- PP’s power density decreases significantly with temperature.

- Flat panel display glass has the best combination of energy and power density at high temperature.

M. Manoharan, “Flexible Glass for High Temperature Energy Storage,” Energy Technology
Summary

• The most common capacitor technologies for power electronic applications are electrolytic, polymer and ceramic.

• A gap analysis was carried out to show specific areas of strength and weakness for each of the capacitor technologies.

• Ragone analysis provides for a coherent representation and comparison of electrostatic energy storage materials and capacitors.

• New dielectric materials and capacitors will need to be developed to satisfy the cost and performance requirements of power electronic systems.
Aluminum electrolytic capacitor.
Two polymer tapes in (a), each with a metallized film electrode on the surface (offset from other), can be rolled together (like a Swiss roll) to obtain a polymer film capacitor as in (b). As the two separate metal films are lined at opposite edges, electroding is done over the whole side surface.

MLCC Process

- Understanding the process is key for cost analysis.
- Process and materials improvements.
- Capital investment linked to market size.

Raw Materials: Oxide Powder Metals

Tape cast layer < 2 µm

Printing Metals
Pd=$600/oz
Low cost Ni

Stacking > 500 layers
Heat treating

Controlled Atmosphere
Capacitor Research

Materials Development

Glass synthesis

Nanodielectric

20 nm

Collaboration with Component Manufacturers

Performance and Reliability Testing

Load

IGBT

Hall Current Sensor
(a) Single layer ceramic capacitor  
(e.g. disk capacitors) 

(b) Multilayer ceramic capacitor  
(stacked ceramic layers) 

Single and multilayer dielectric capacitors.