High Temperature Dielectric Materials and Capacitors for Transportation Power Electronics

Eugene Furman and Mike Lanagan
Materials Research Institute
Penn State University

Presented at the 2015 APEC Meeting

Outline

- Overview of capacitor technology
- Capacitors in power electronics
- New high temperature materials with high energy and power densities
- Summary

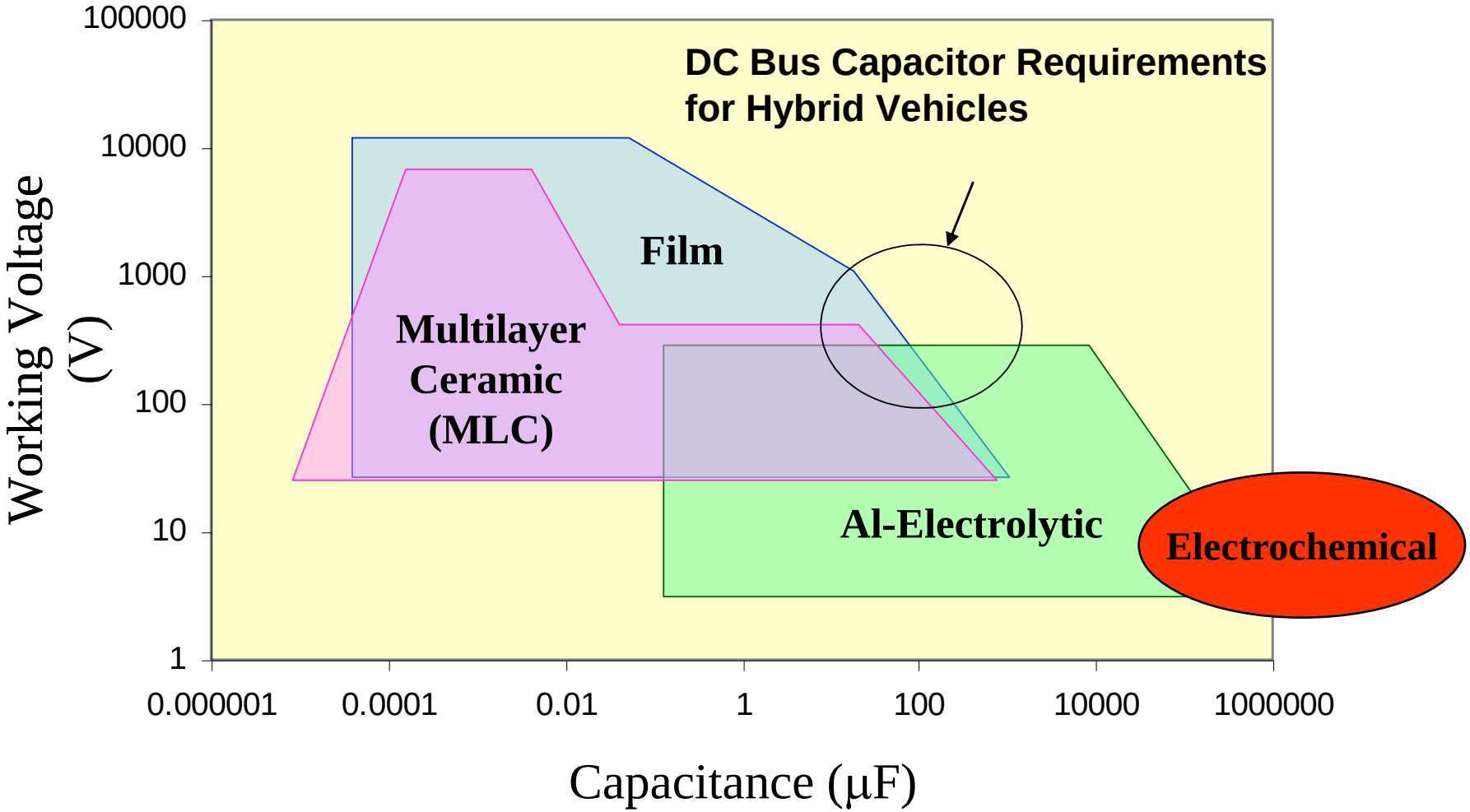
Impact of trends in power electronics on Capacitor development

- 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

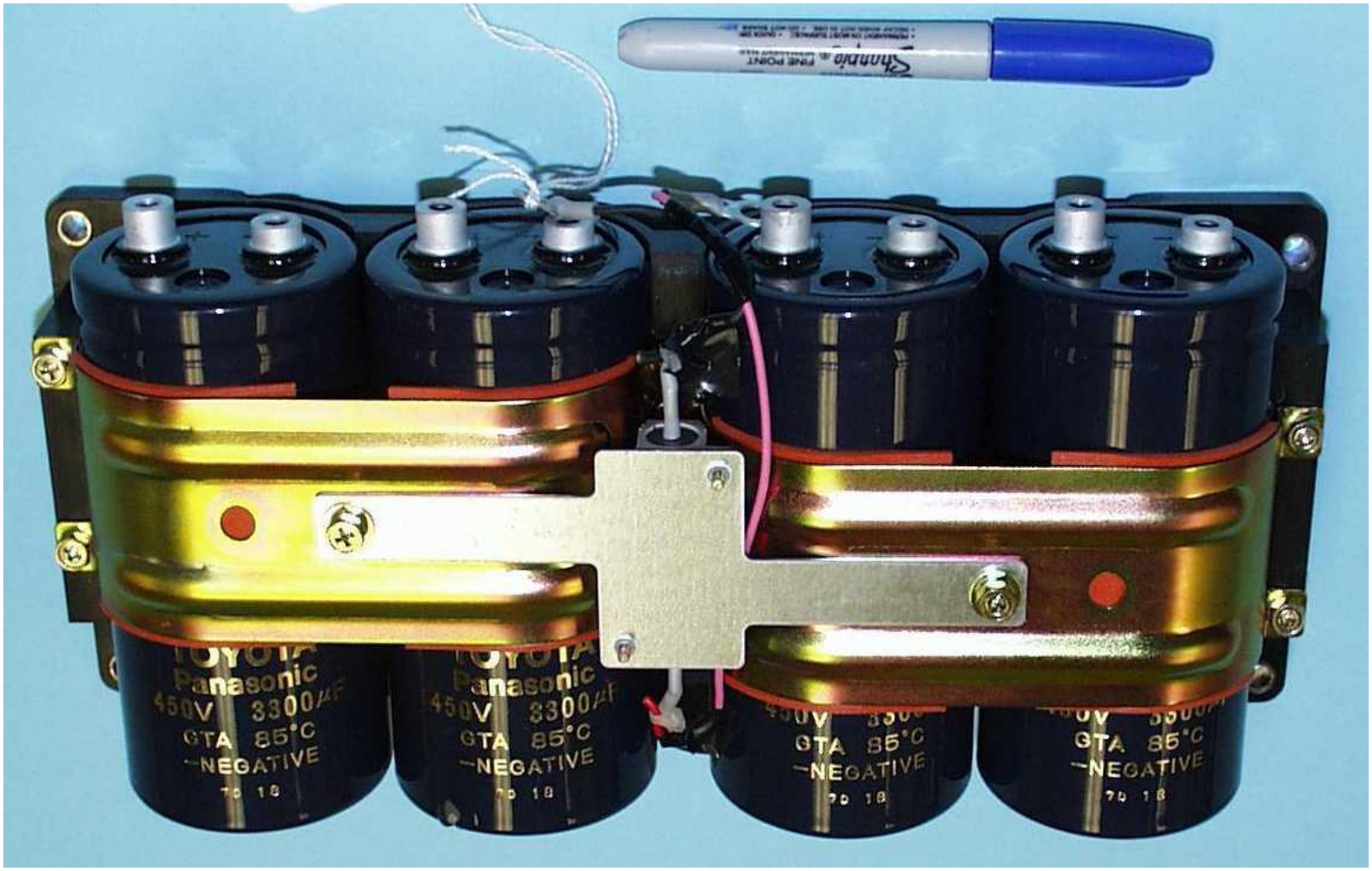
Commercial Capacitor Ranges



Electrolytic Capacitors

- **Electrolytics – Formed by Metal Anodization**
  - Al_2O_3 (ε_r=9) or Ta_2O_5 (ε_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_{rms} at 75ºC is 70% lower than I_{rms} at 25ºC**

AVX film capacitor: 525V 240 µF

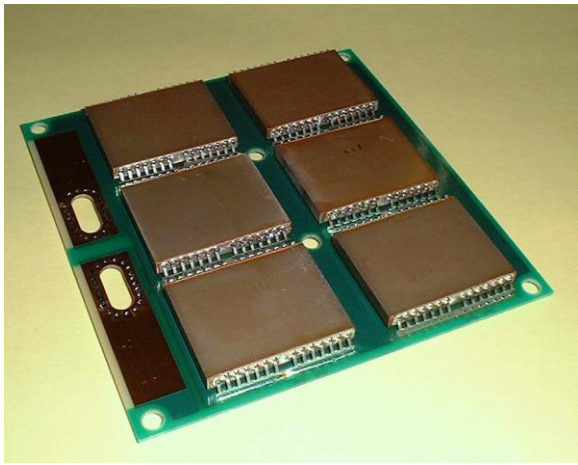
Multilayer Ceramic Cap.

Advantage

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

Disadvantage

- **Non-graceful failure mode**

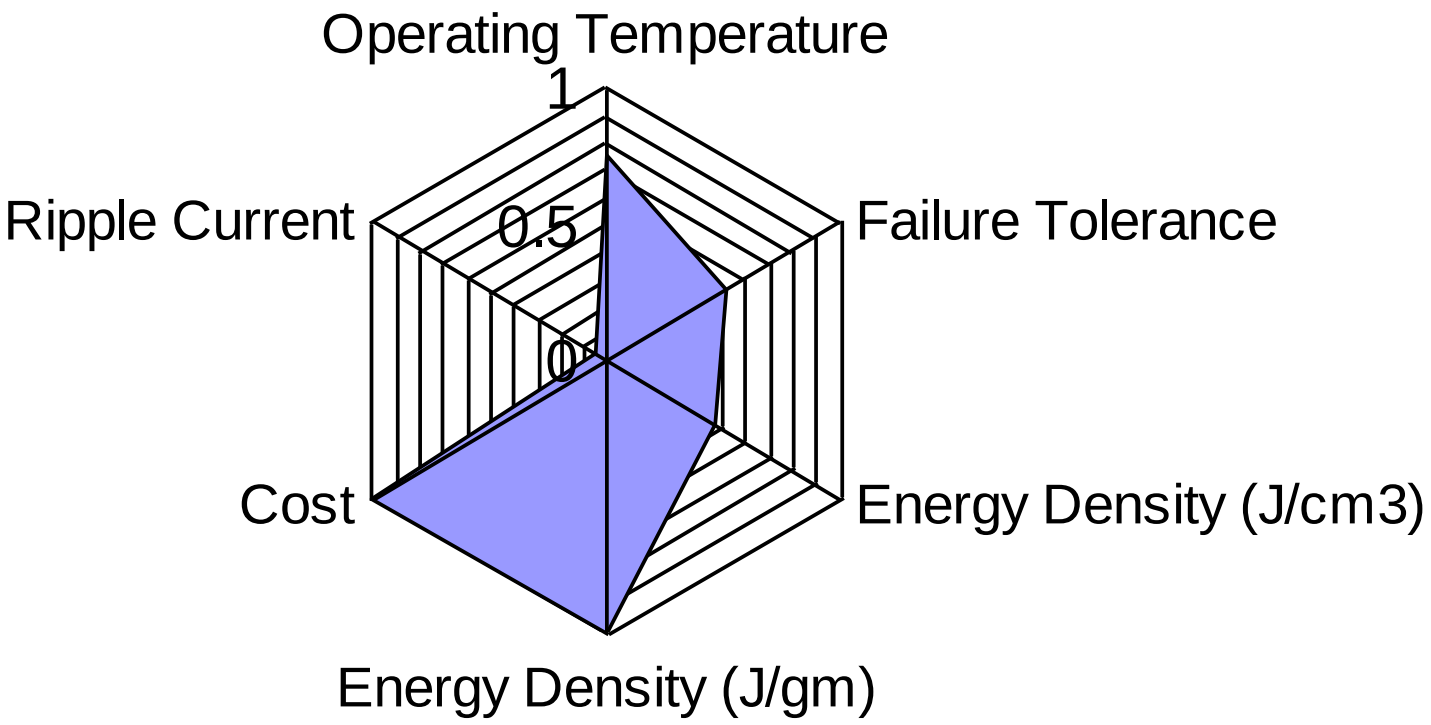


Murata MLCC capacitor 250V 270 µF
See (www.powerelectronics.com)

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



Electrolytics

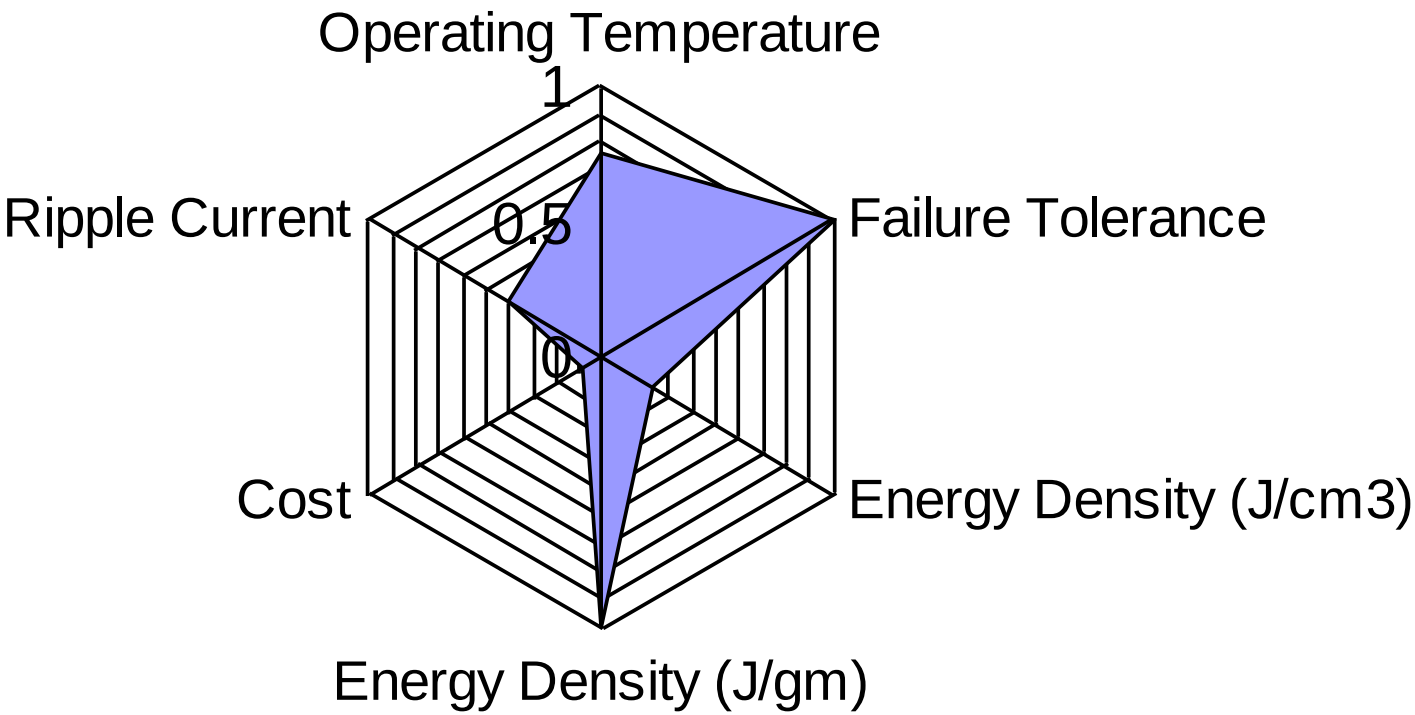
ADVANTAGES

- 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



Film Capacitors

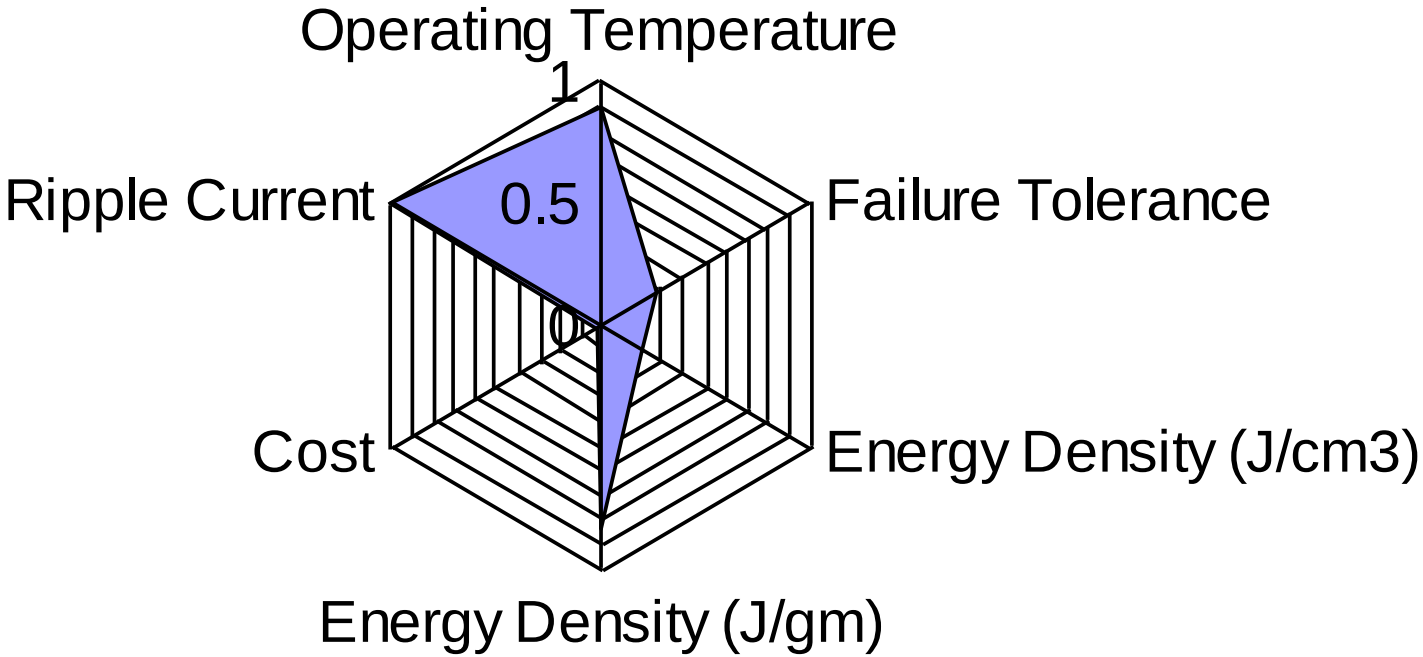
ADVANTAGES

- 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



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 Reguirements
  - $/µF too high
  - $/Amp ripple current may be another metric

Assessment Conclusions (Continued)

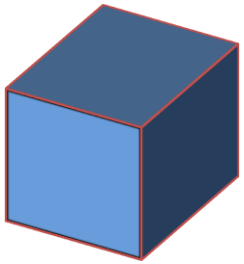
- Improvement in volumetric efficiency
  - Related to de-rating factors
    - Graceful failure, reliability, materials
  - Ripple current as a function of Temperature
- Lower costs
  - Improve volumetric efficiency
  - Present performance and cost targets will be difficult to meet (450V,1000µF,<3mΩ ESR,100A 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)

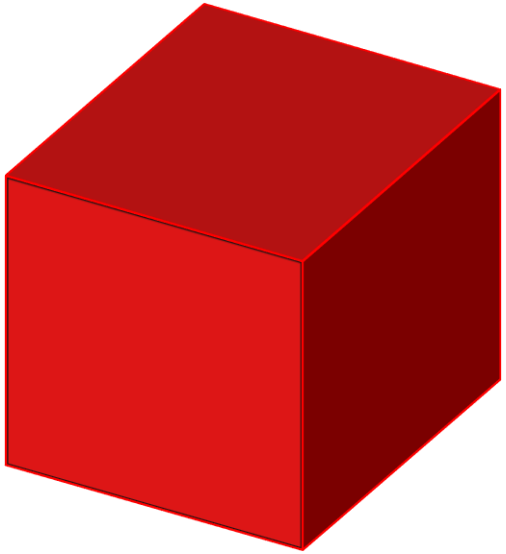
Volume of 1000 µF 600V capacitors in a Hybrid Electric Power Inverter

Current Capacitor
Wound polymer film
(polypropylene)



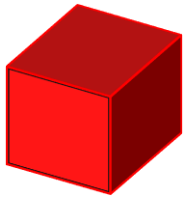
Volume = 1.4 Liters
85ºC Rating

Current High Temperature Capacitor
Wound polymer film capacitor



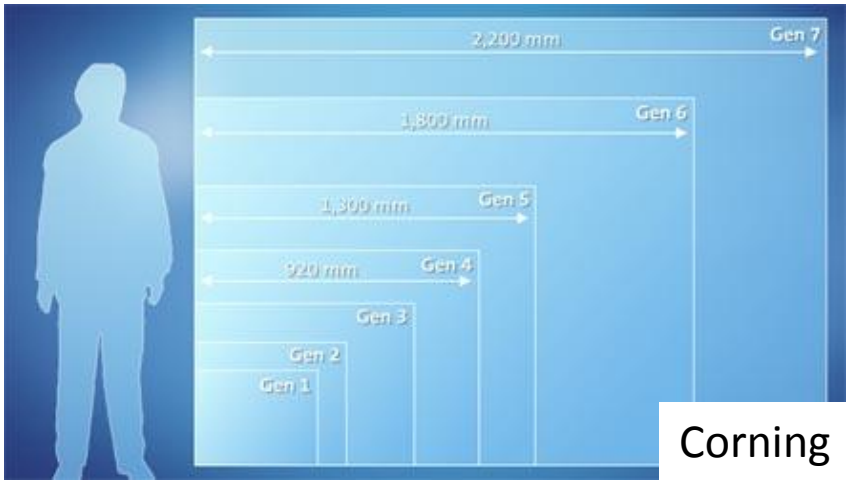
Volume = 21.6 Liters
125ºC Rating

Future Glass Capacitor



Volume =1.2 Liters
140ºC Rating

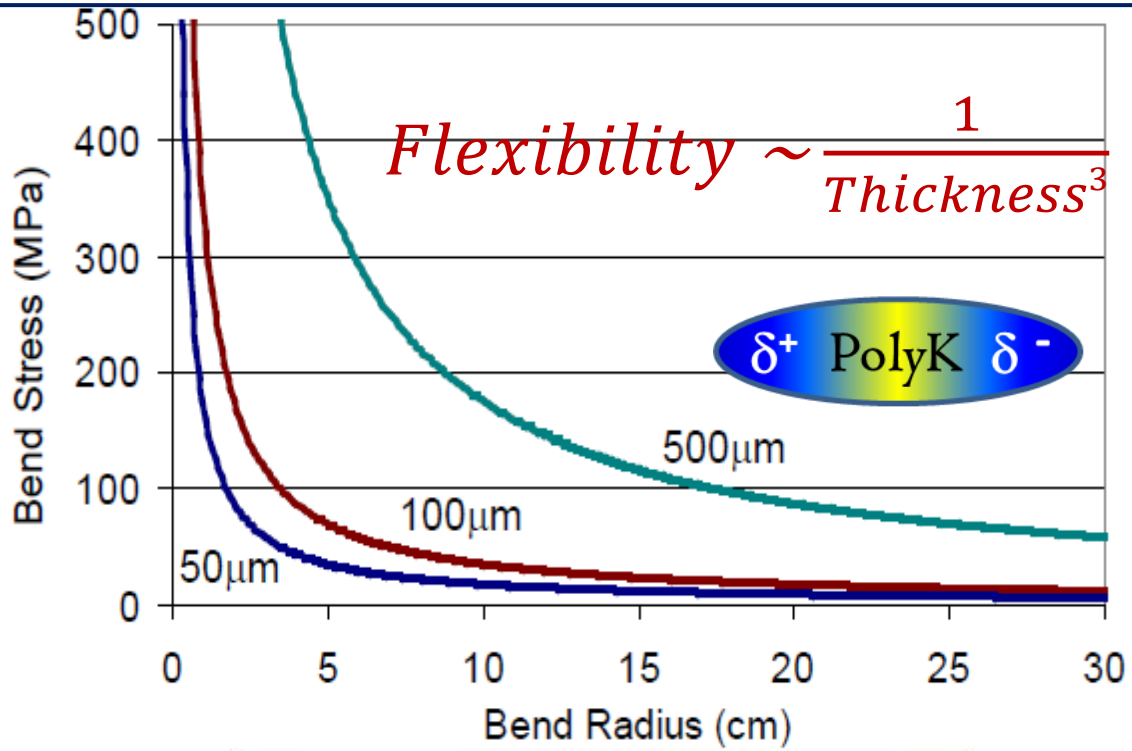
$30B Investment in Glass Manufacturing

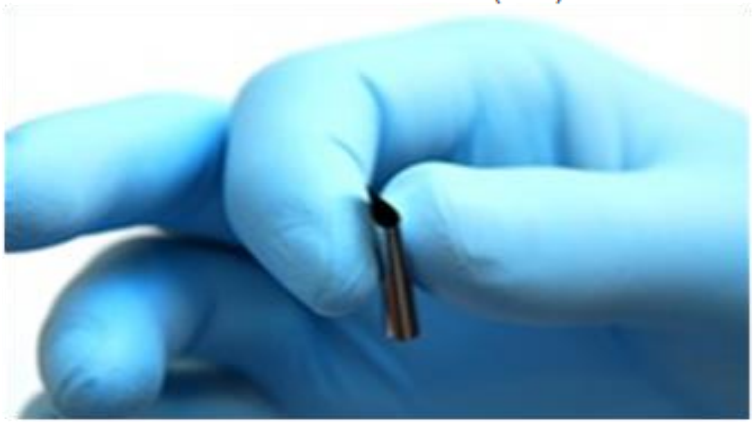


Corning

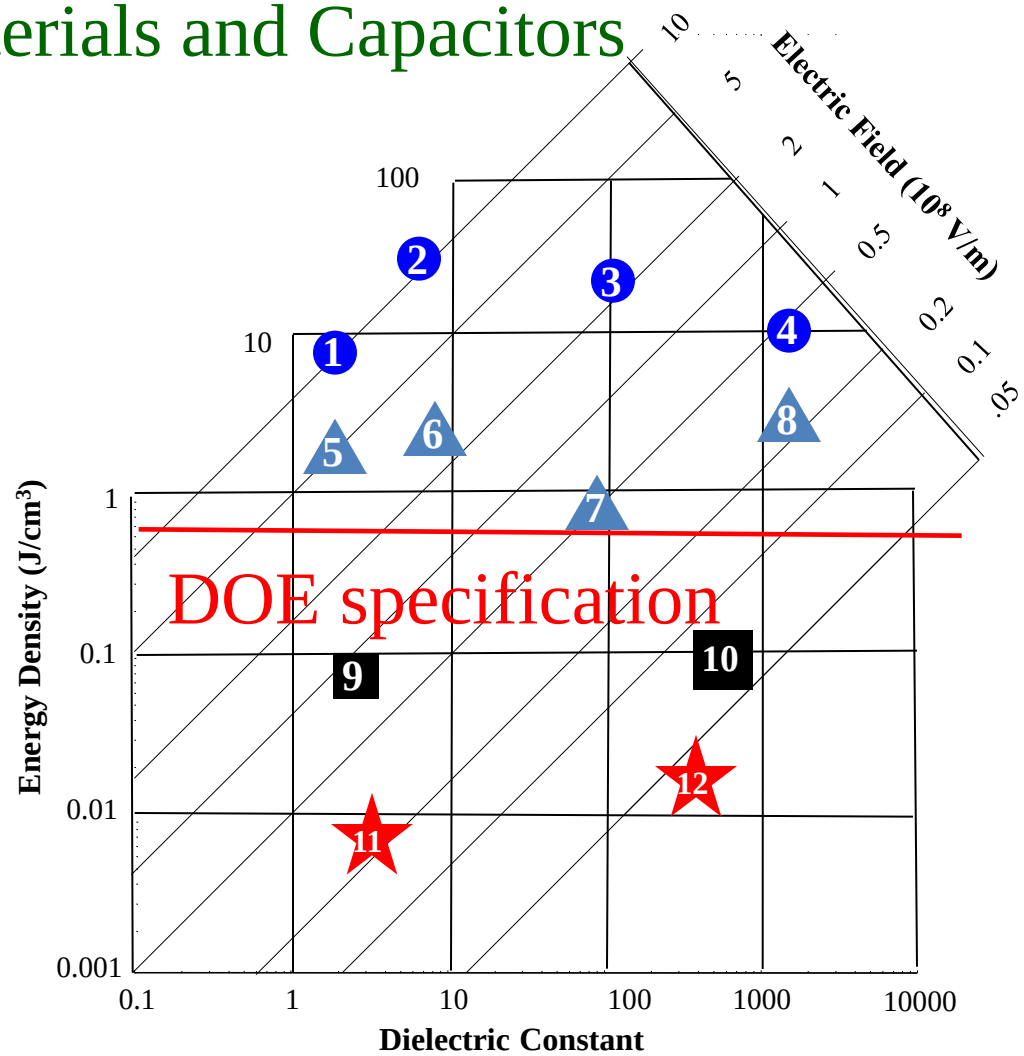
- Glass is inorganic material with significantly higher thermal stability (>500 °C).
- Traditional glass sheets are thick (> 1mm) and are rigid.
- Recent development in display industry (large screen TV, smart phones, iPad, etc.) enabled the commercial production of ultrathin glass sheet with thickness 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





Energy Density of Dielectric Materials and Capacitors



Dielectric

Pulsed power capacitor

Power electronic capacitor

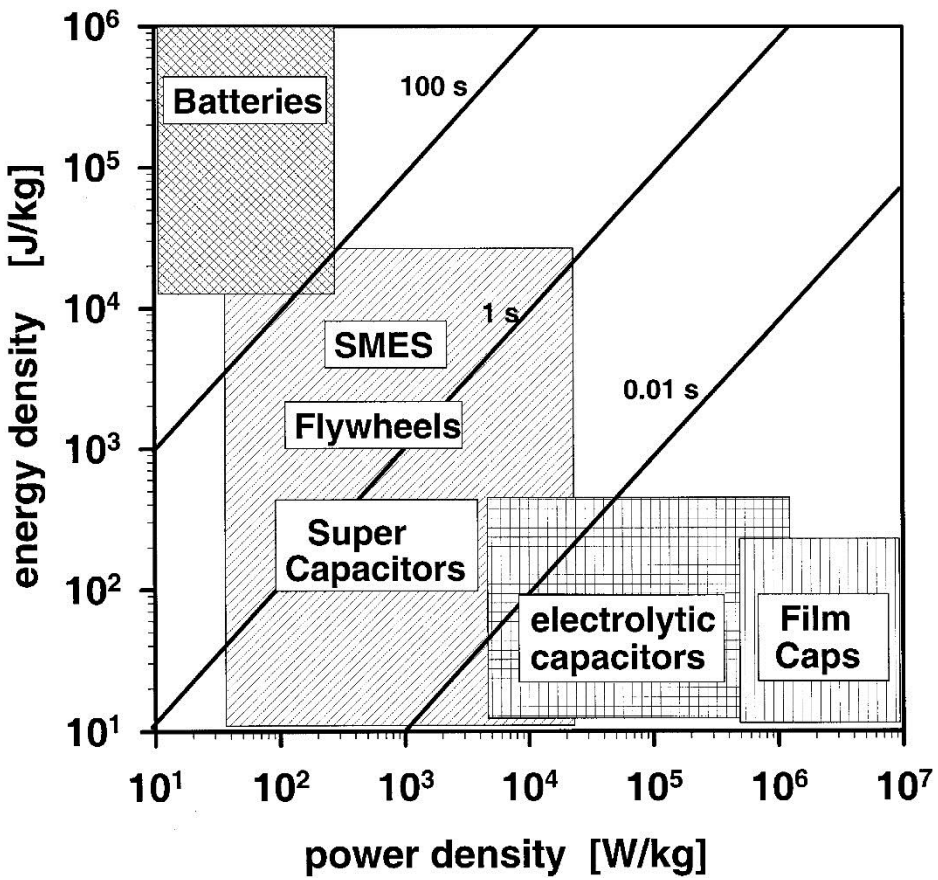
High Temperature capacitor

Energy density decreases because of higher reliability requirements

(1)Polypropylene, (2) glass, PSU Material (3) Titania, (4) PZT Ceramics, PSU Material , (5) Polypropylene Capacitor (6) High-k Polymer Capacitor, (7) NPO MLCC, (8) X7R based MLCC , (9) Polypropylene film capacitor, (10) X7R MLCC, (11) High Temperature, 125ºC, Polymer Capacitor, (12) High Temperature, 200ºC, MLCC.

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.



T. Christen and M. Carlen, J. Power Sources. 91, 210, (2000).

Theory of Ragone Plots

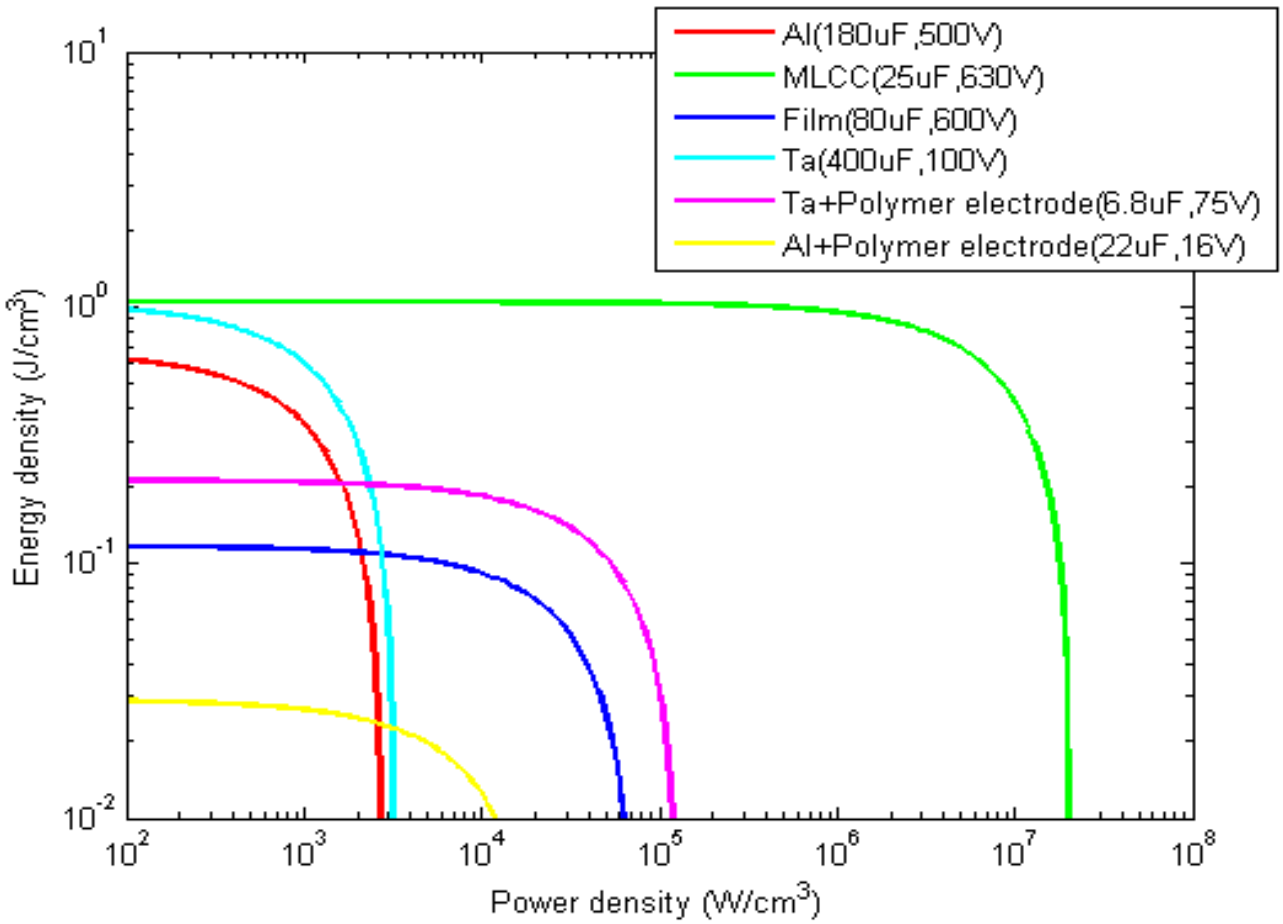
- Solution to 2nd order differential equation with unique charge conditions

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

Where Q = Charge
L = Inductance
R = Series Resistance
P = Power
V = Voltage

T. Christen and M. Carlen, J. Power Sources. 91, 210, (2000).

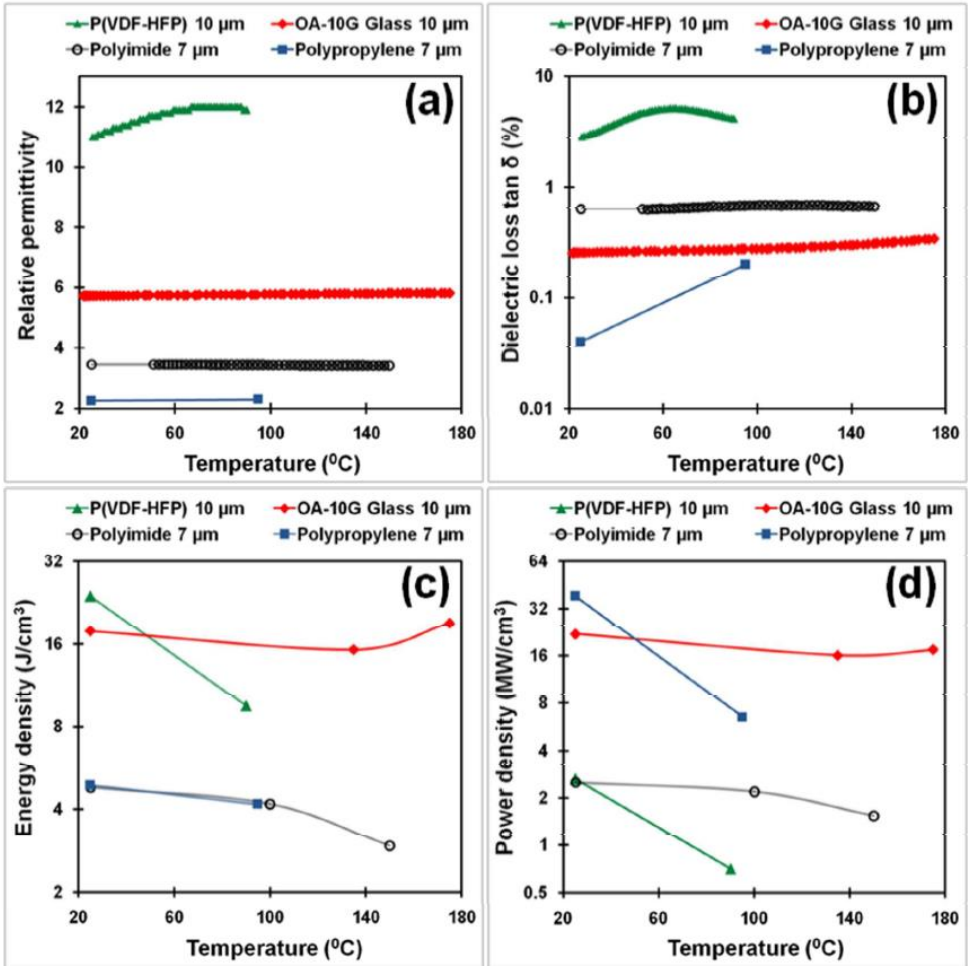
Comparison of Capacitor Technologies



Doo Hyun Choi Thesis Chapter 1 (2013)

Energy and Power Density Comparison for Dielectrics

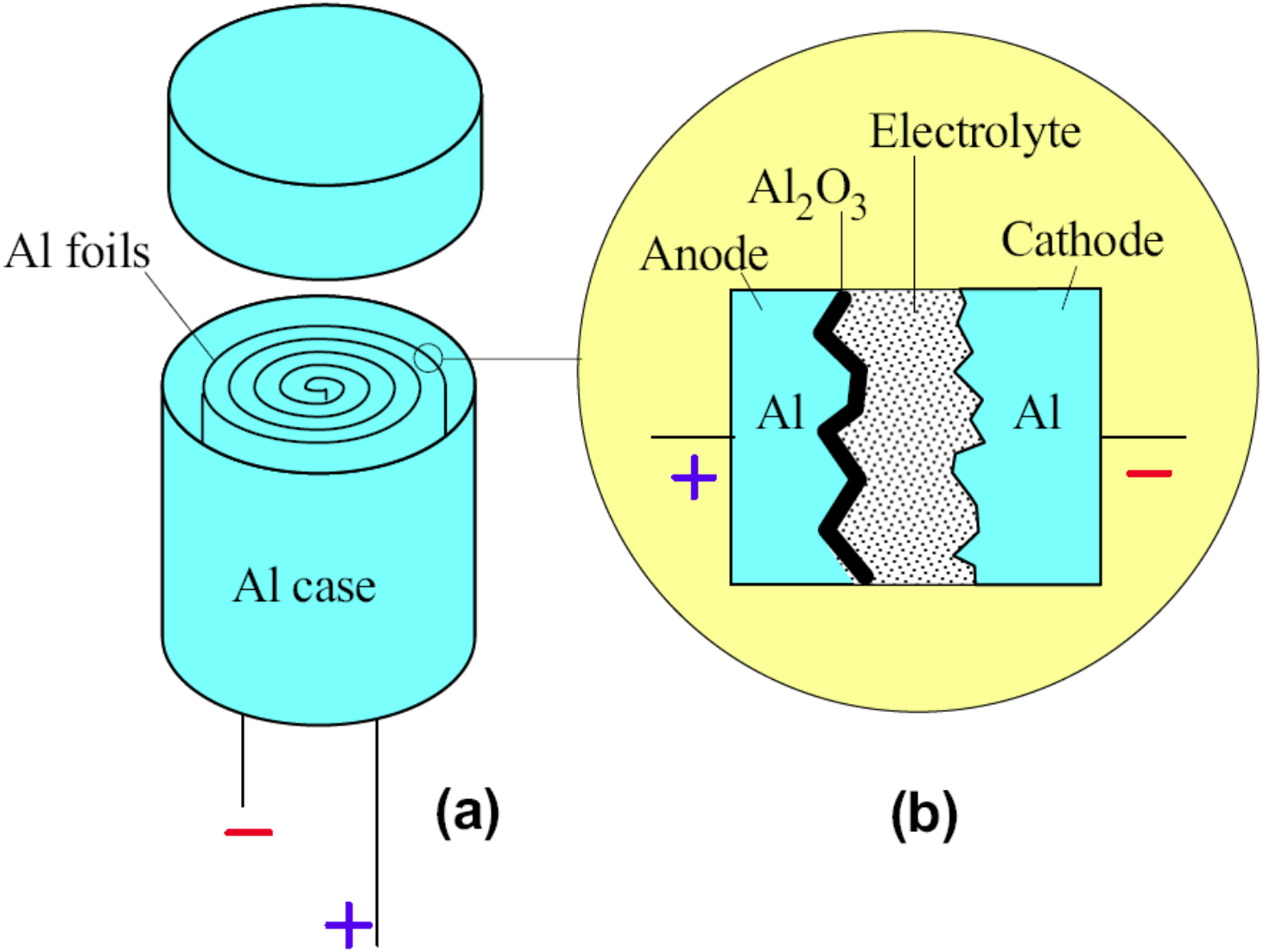
- PVDF based polymers have high energy density but poor power density.
- PP's power density decreases significantly with temperature.
- Flat panel display glass has the best combination of energy and power density at high temperature.



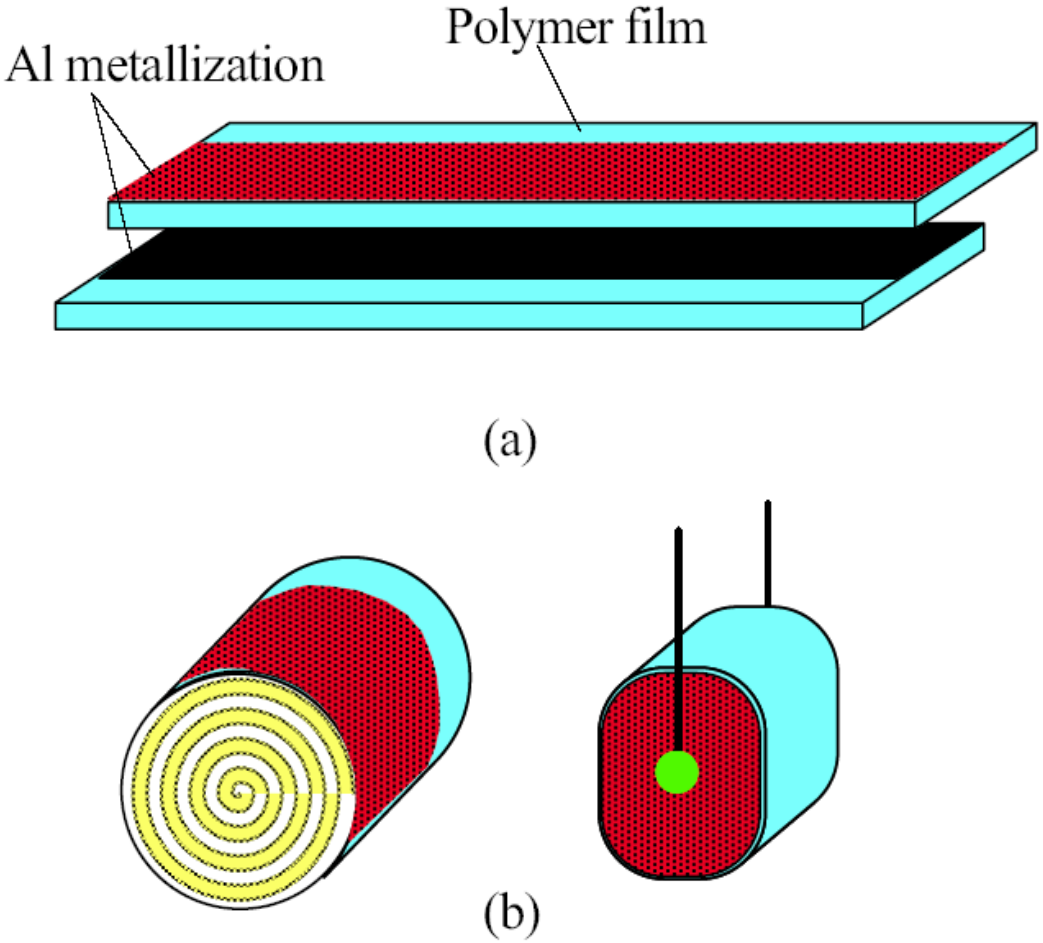
M. Manoharan, "Flexible Glass for High Temperature Energy Storage," Energy Technology

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.



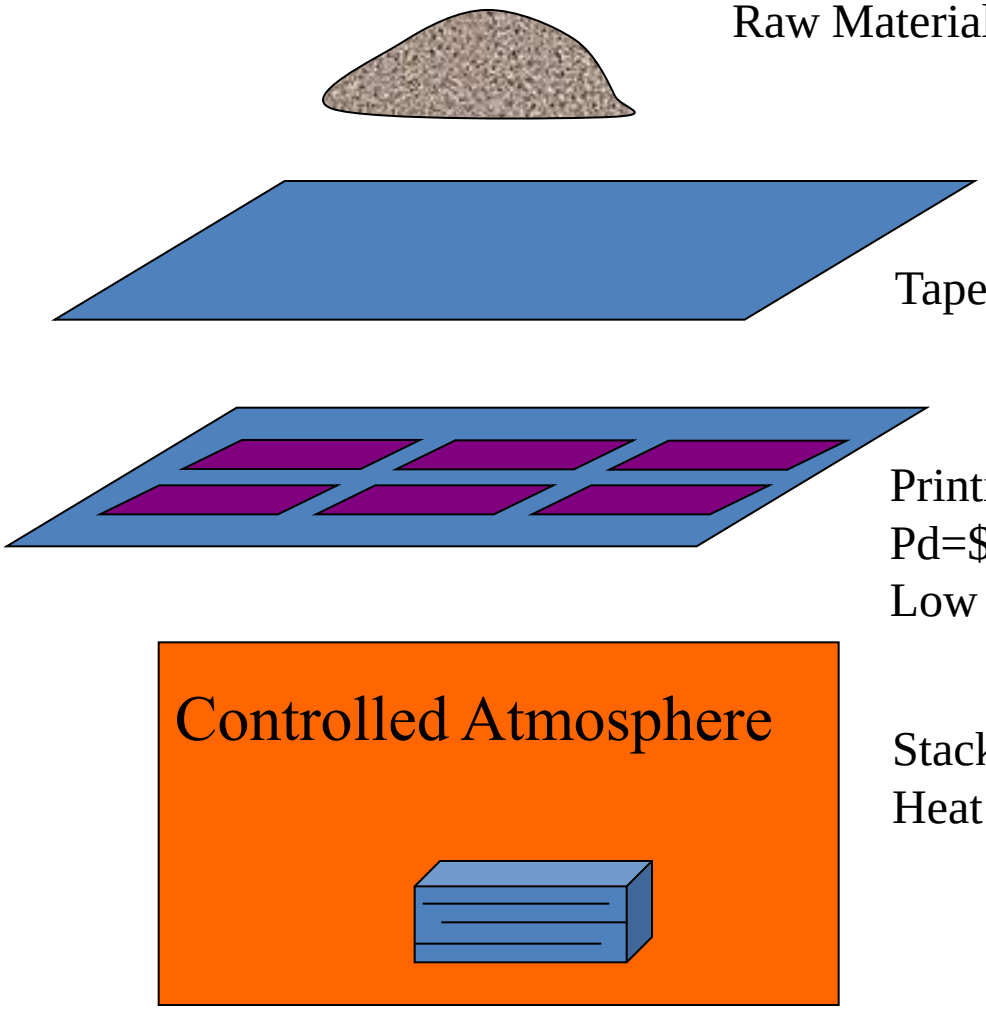
Aluminum electrolytic capacitor.



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

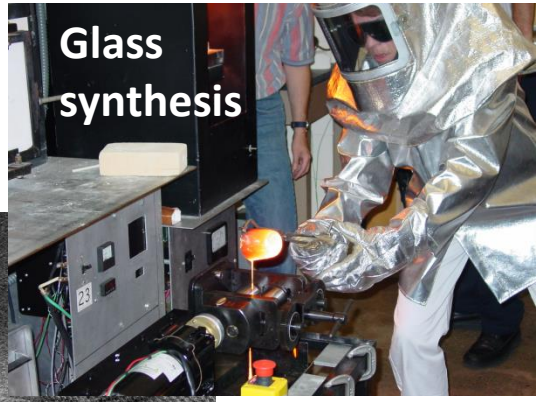
Tape cast layer < 2 µm

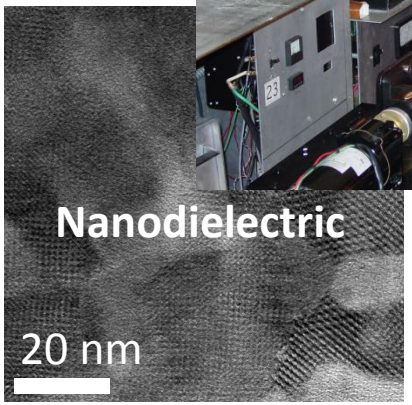
Printing Metals
Pd=$600/oz
Low cost Ni

Stacking > 500 layers
Heat treating

Capacitor Research

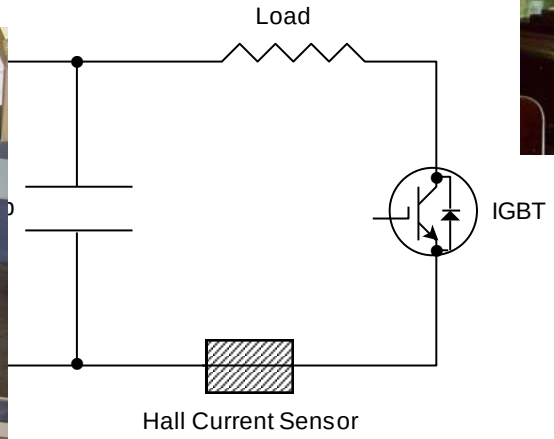
Materials Development

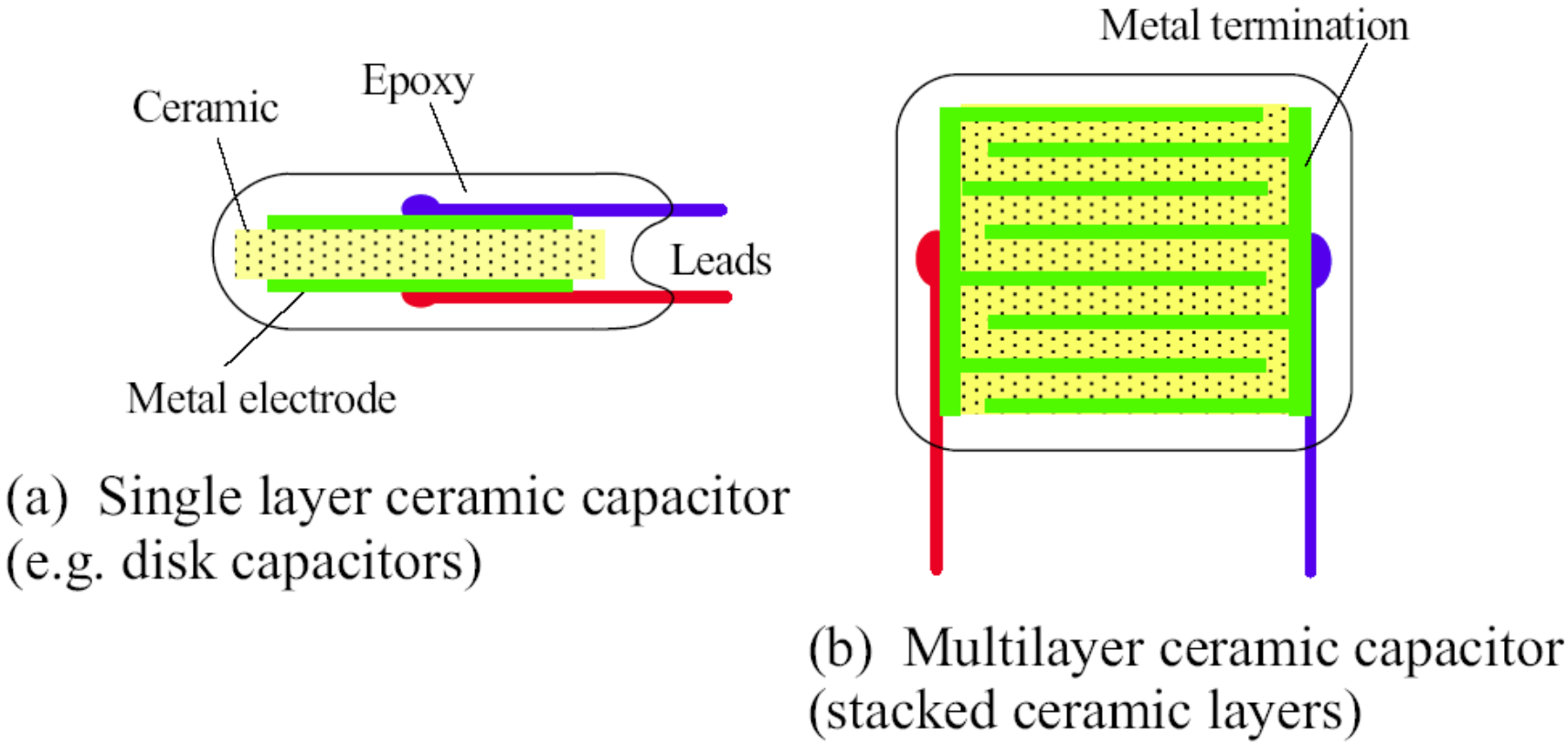




Collaboration with Component Manufacturers

Performance and Reliability Testing





Single and multilayer dielectric capacitors.