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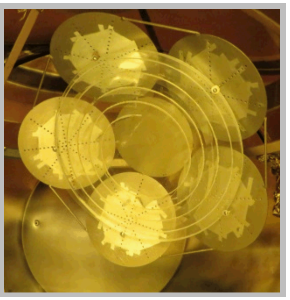

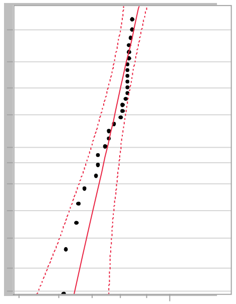

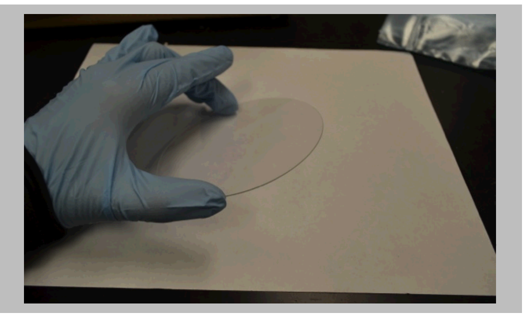

Processing of Alkali-free Glass for High Energy Density Capacitors

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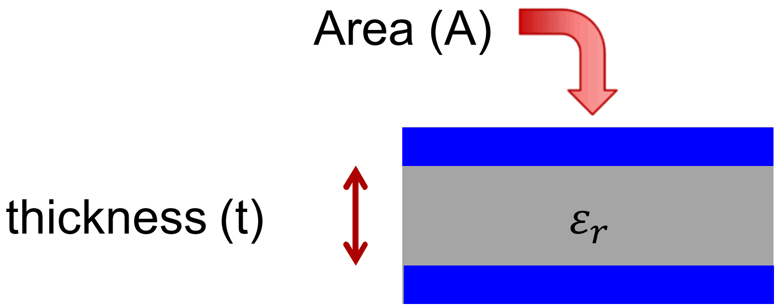
Outline

- Linear Dielectrics as Energy Storage Devices
- Glass as a Dielectric Material
- Alkali Free Glass
  - Properties of Thinned Glass
  - Wound Capacitor Demonstration
  - Multi-layer Glass Capacitor
- Conclusions

Energy Density of Linear Dielectrics

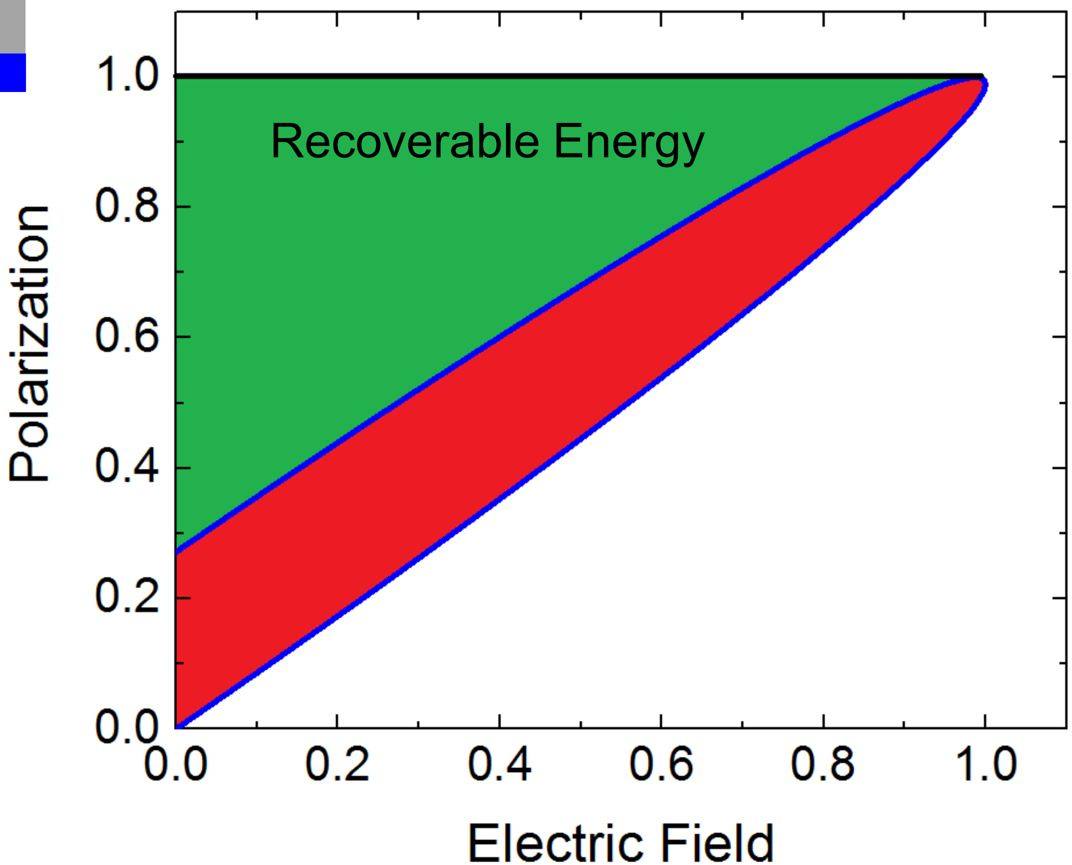


$$C = \varepsilon_r \varepsilon_0 \frac{A}{t}$$

$$W = \int PdE$$

$$W = \frac{1}{2} CV^2 = \frac{1}{2} \varepsilon_r \varepsilon_0 \frac{A}{t} V^2$$

$$U = \frac{Energy}{Volume} = \frac{1}{2} \varepsilon_r \varepsilon_0 E^2$$

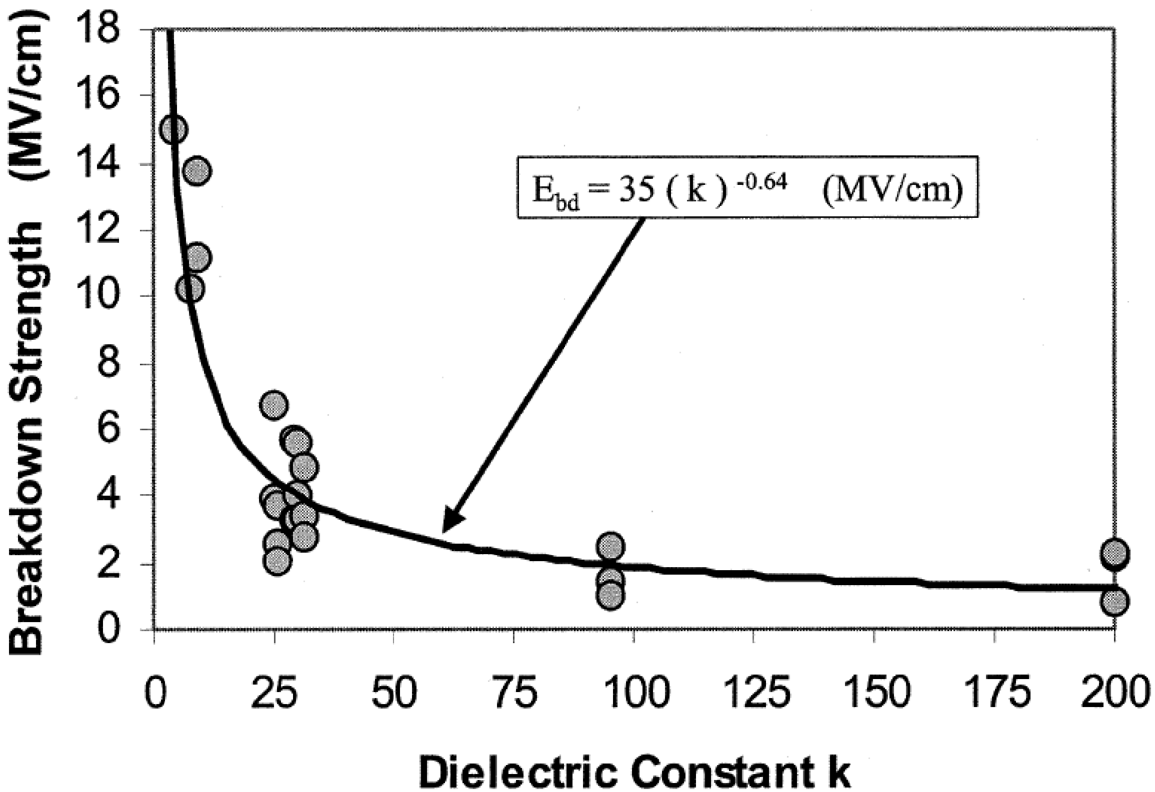


Energy Density of Linear Dielectrics

Larger gains can be had by increasing breakdown strength

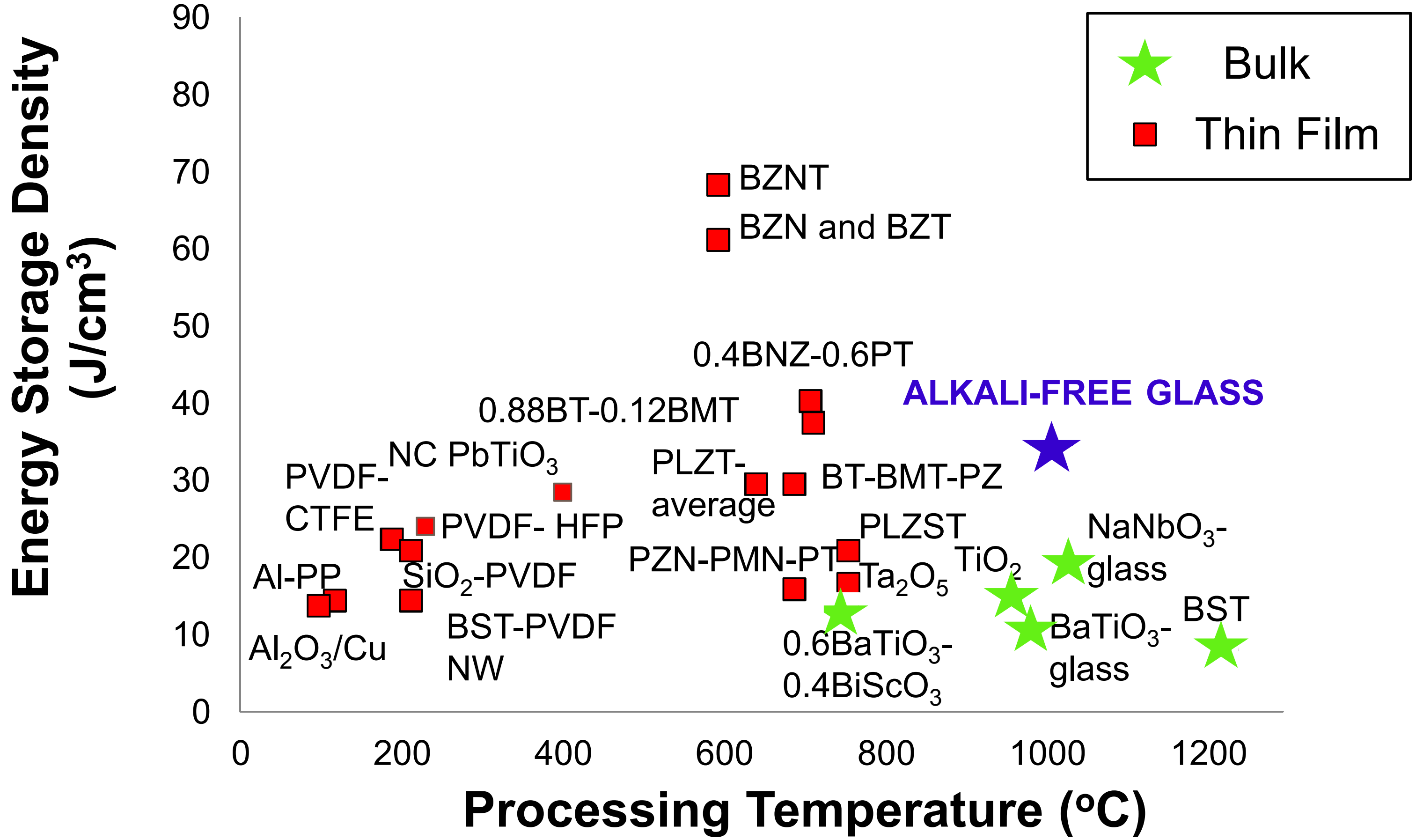
$$U = \frac{Energy}{Volume} = \frac{1}{2}\varepsilon_r \varepsilon_0 E^2$$

Limited value to tuning ε_r



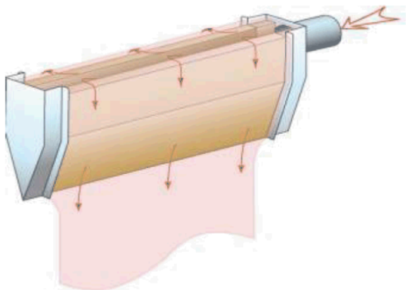
McPherson et al. IEEE TED, 2003

Comparison of Capacitive Energy Storage Materials



- Alkali-free glass competitive with many emerging materials
- May have an advantage in manufacturing

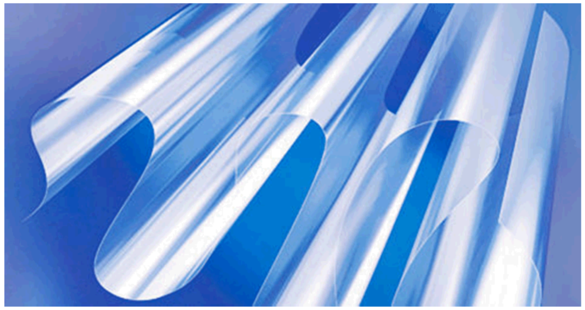
Alkali-Free Glasses



- "Overflow drawn down process"

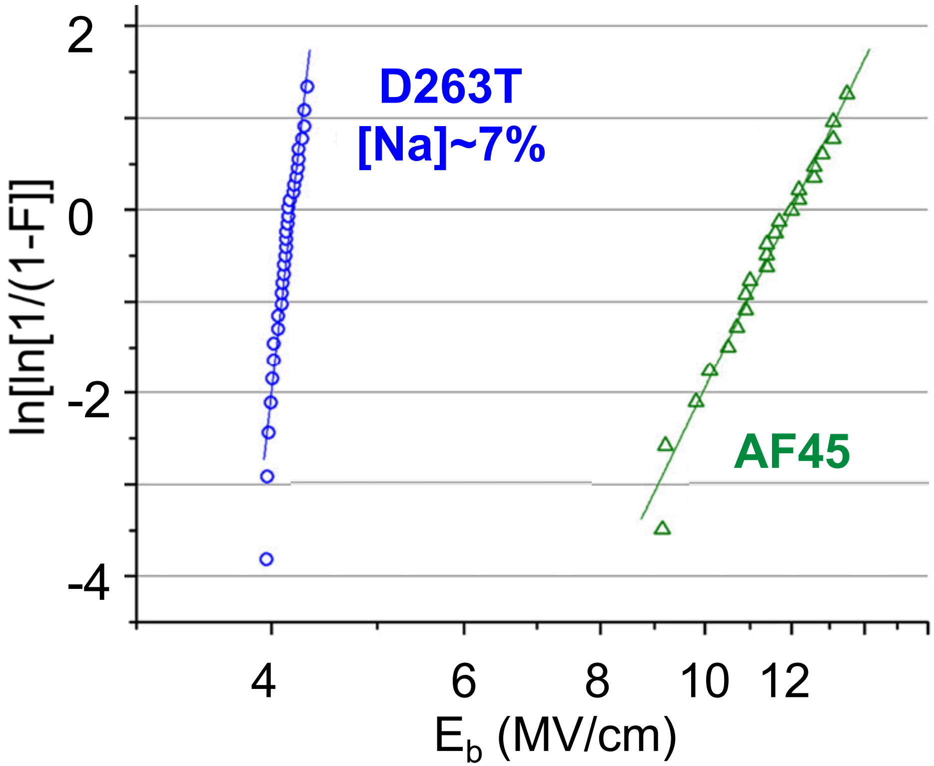
Parameter	Value
Density (g/cm^3)	2.3-2.5
Young's Modulus (GPa)	73-75
ε_r	5-6
tan δ	0.001
ρ (Ω*cm @ 250 °C)	>10^{12}
Strain Point	650-700 °C

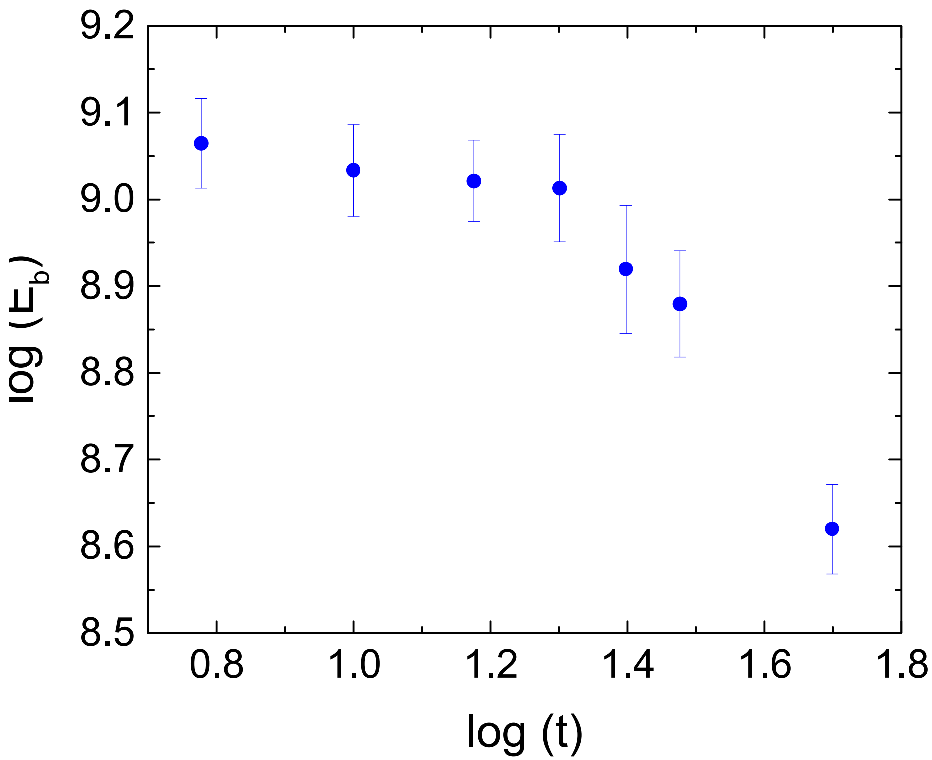
- Sold by many vendors world wide
- Boro-alumino-silicate glass category
- Sold in thicknesses ~ 100 – 200 µm
- [Na] < 350 ppm (typical)



http://www.neg.co.jp/JP/technology/pdf/idw11.pdf

Breakdown Strength of Alkali-free Glass





Parameter	D263T	AF45
t (µm)	30	19
E_b (MV/cm)	4.2	12
β	47.9	10.7

- Schott AF45 glass etched via sonicating in HF
- For t < 20 µm, E_b > 10 MV/cm
- $U_{dielectric}$~35 J/cc

- Smith et al. Mater. Lett. 63 (2009) 1245, Lee et al. JACERS 93 (2010) 2346

Temperature Stability of "Flexible" Capacitor Materials

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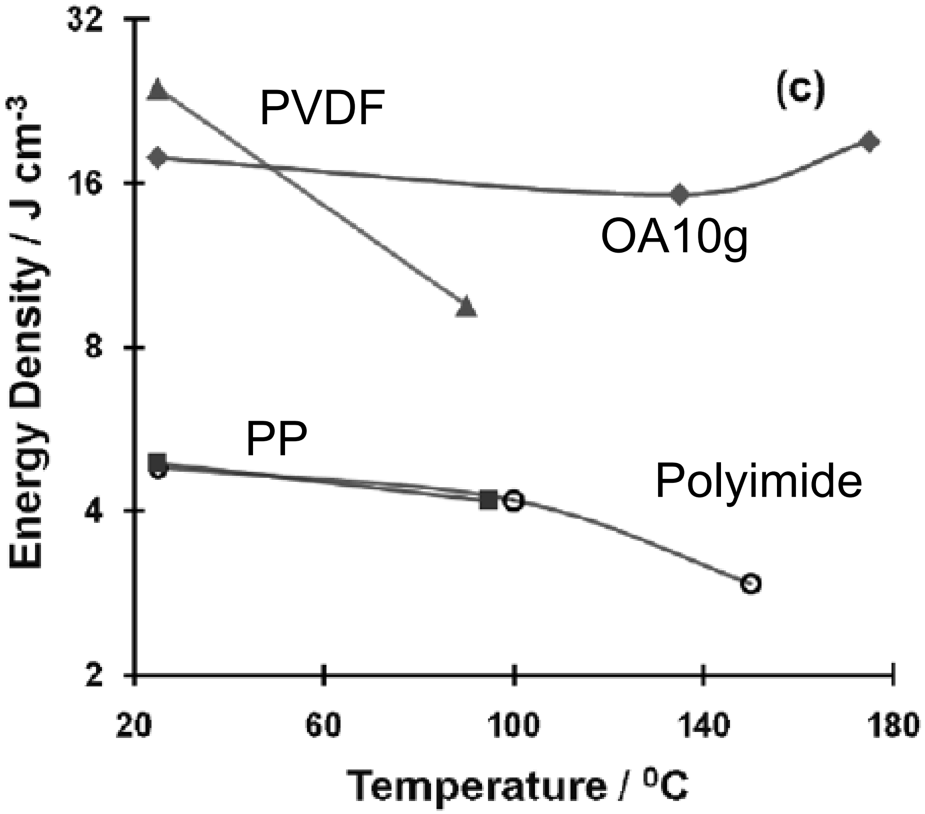
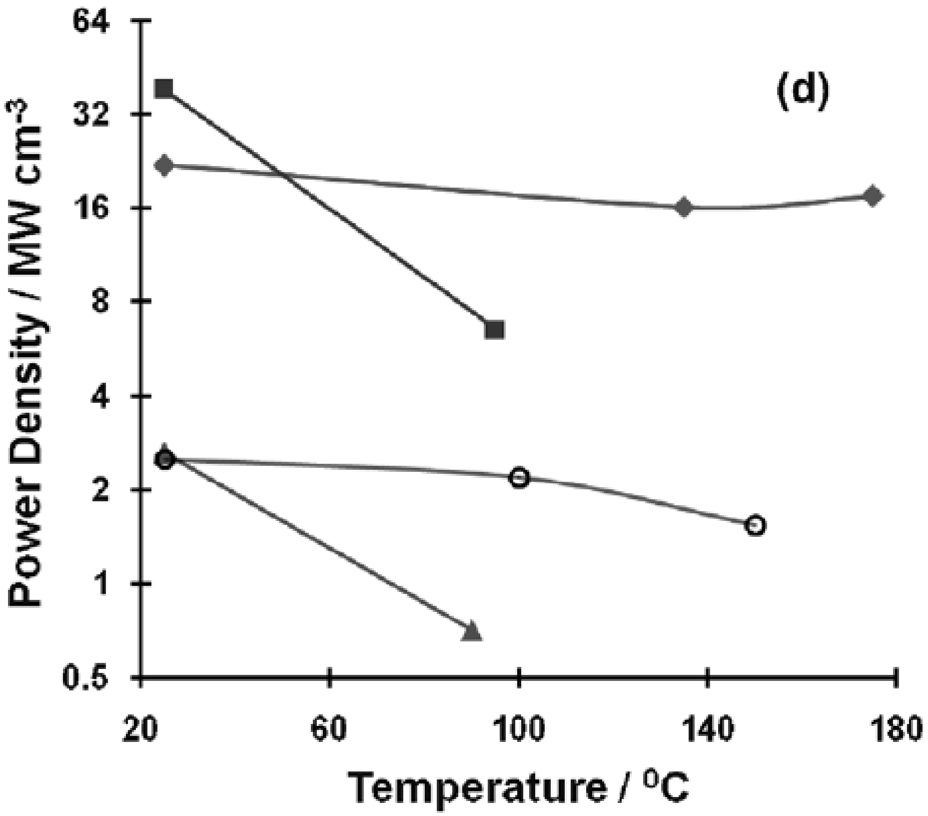




- Temperature stable HV properties beyond range achievable by most polymers
- $BaTiO_3$-$BiScO_3$ shows 2-3 J/cc out to 300 °C
- Concentration of Alkali-elements key to minimizing loss at high temperatures

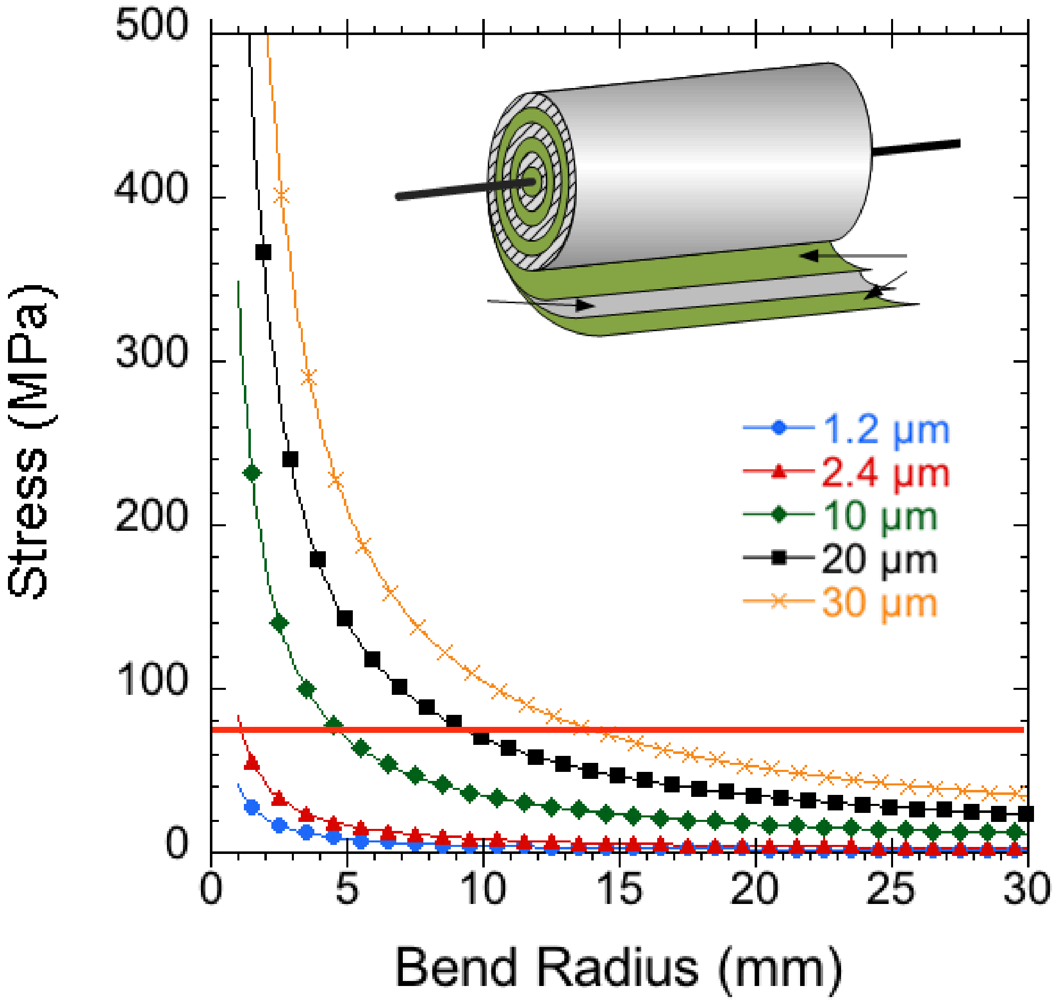
Manoharan et al. *E. Tech.* 2013, Petay et al. *MRS Proc.* 2014, Ogihara et al. JACERS 2009

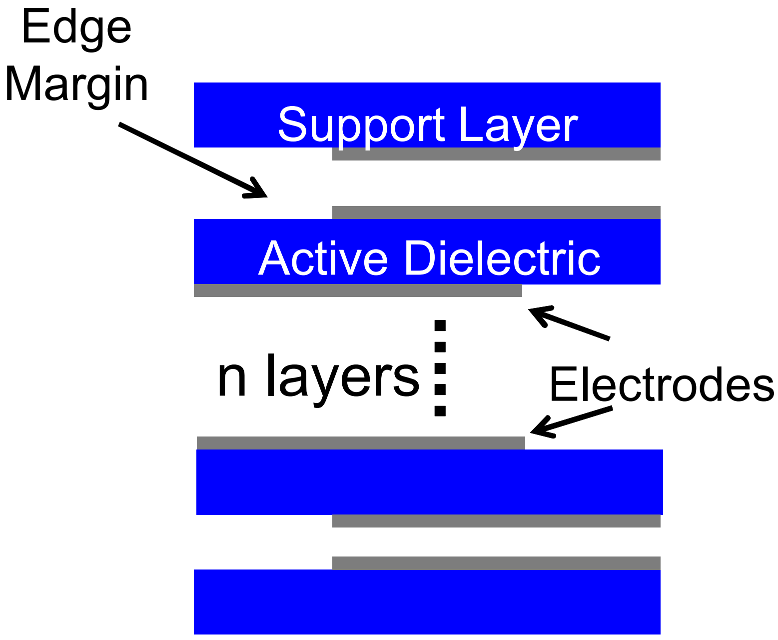
Thinning of Glass - Motivation

5 µm thick, 8 mm diameter

- Alkali-free glass has found wide use in cell phone, display applications
- Commercially sold in thickness > 100 µm (1.3 x 300 m rolls)
- ε_r ~ 5-6 $\Rightarrow$ Need massive area (>20 cm^2) to achieve 1 nF capacitance

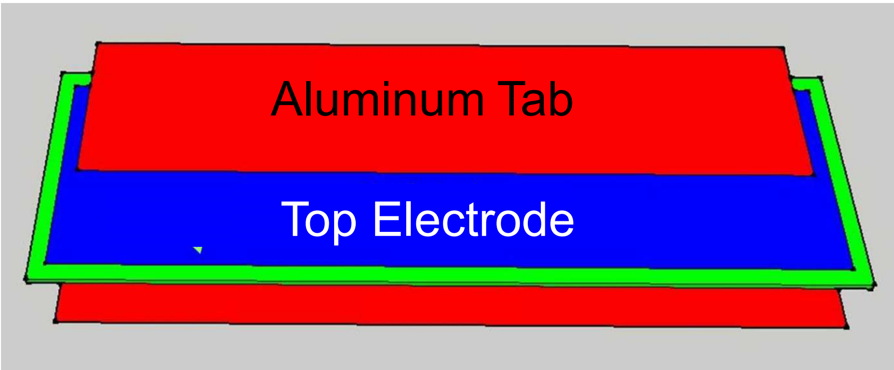
Thinned Glass Capacitors Designs



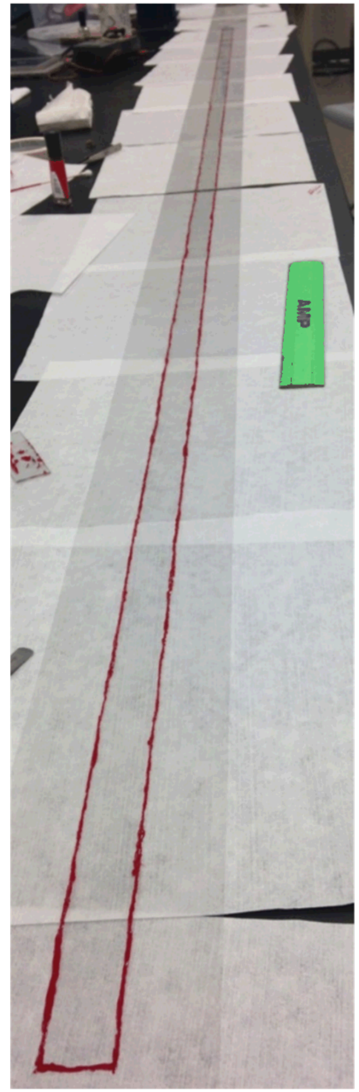


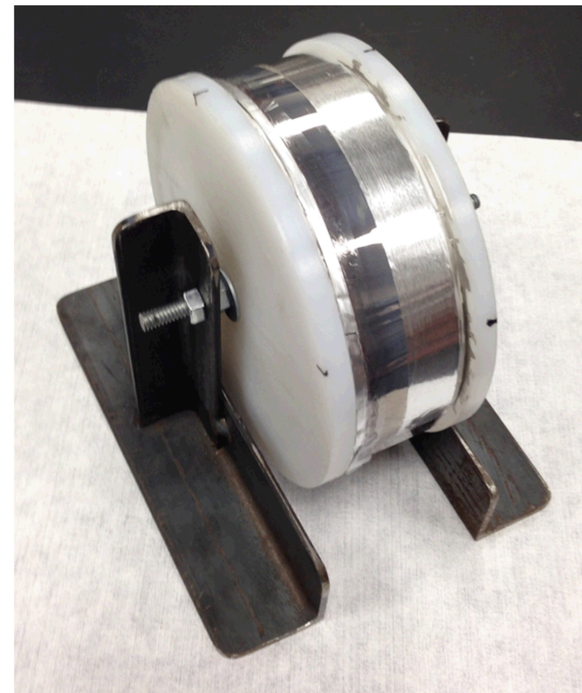
- Top/Bottom sheets for physical support
- Edge margin to avoid flashover
  - Needs insulating fluid to avoid triple points

Fabrication of a Wound Capacitor

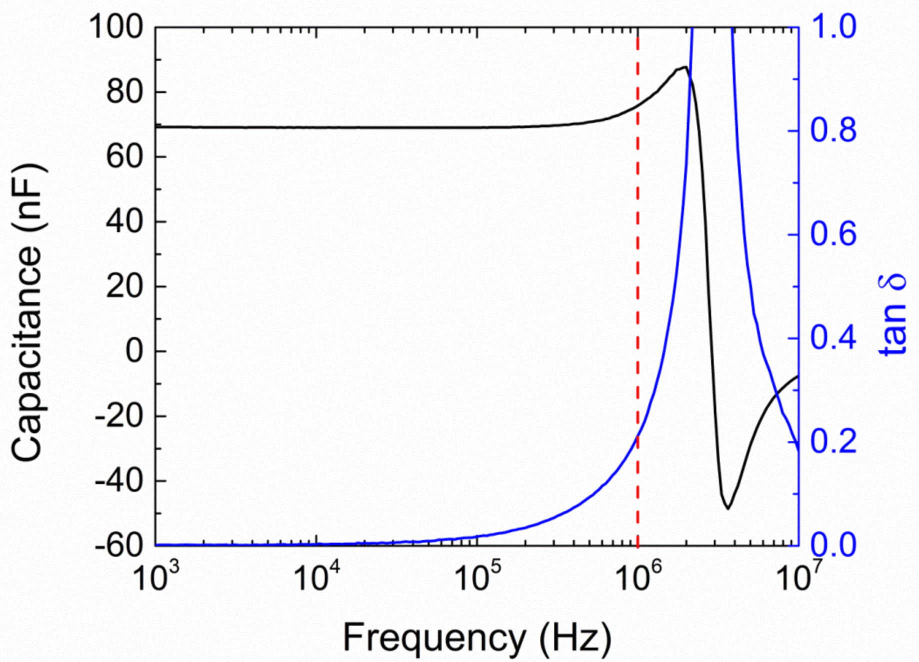


- 2.7 m long piece of 50 µm thick NEG Glass
- Designed to have electrode tabs to limit electrode resistance and inductance effects
- 12 µm polypropylene sheet glued around edges to prevent flashover
- Wound around 5.5 inch diameter spool

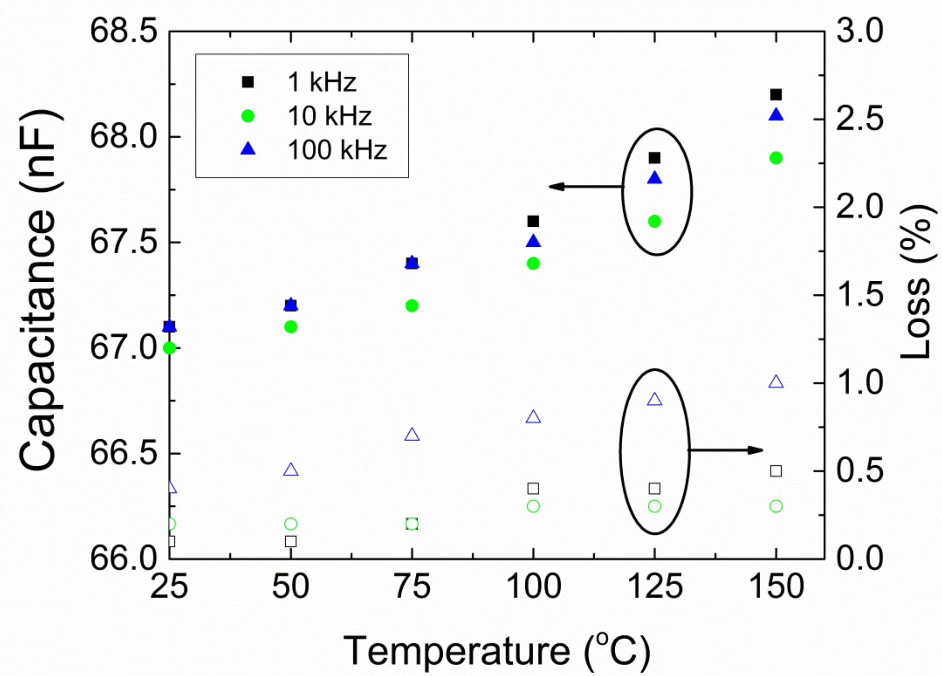




Electrical Properties of Wound Capacitor



- Self-resonance above 1 MHz
- L~90 nH



- Show good temperature stability to 150 °C (low frequencies)
- $U_{dielectric}$~10 mJ/cc, $U_{capacitor}$~0.5 pJ/cc

Pulsed Discharge of Wound Capacitor

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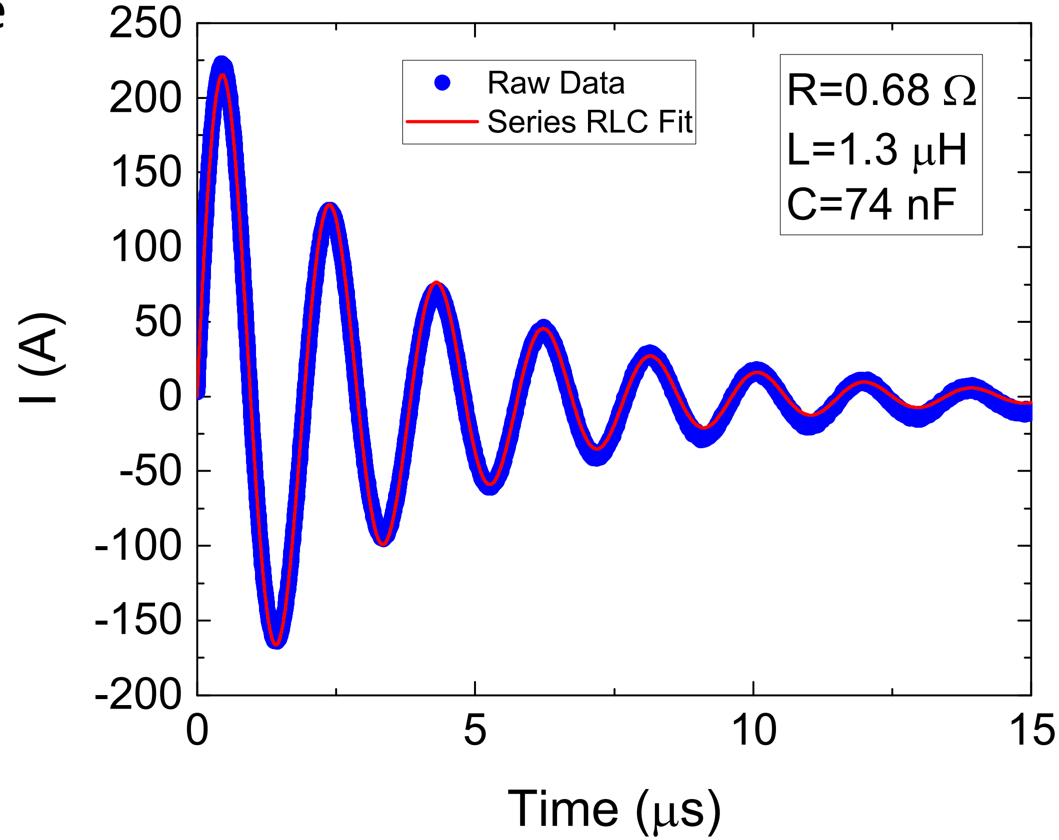
- Underdamped RLC discharge

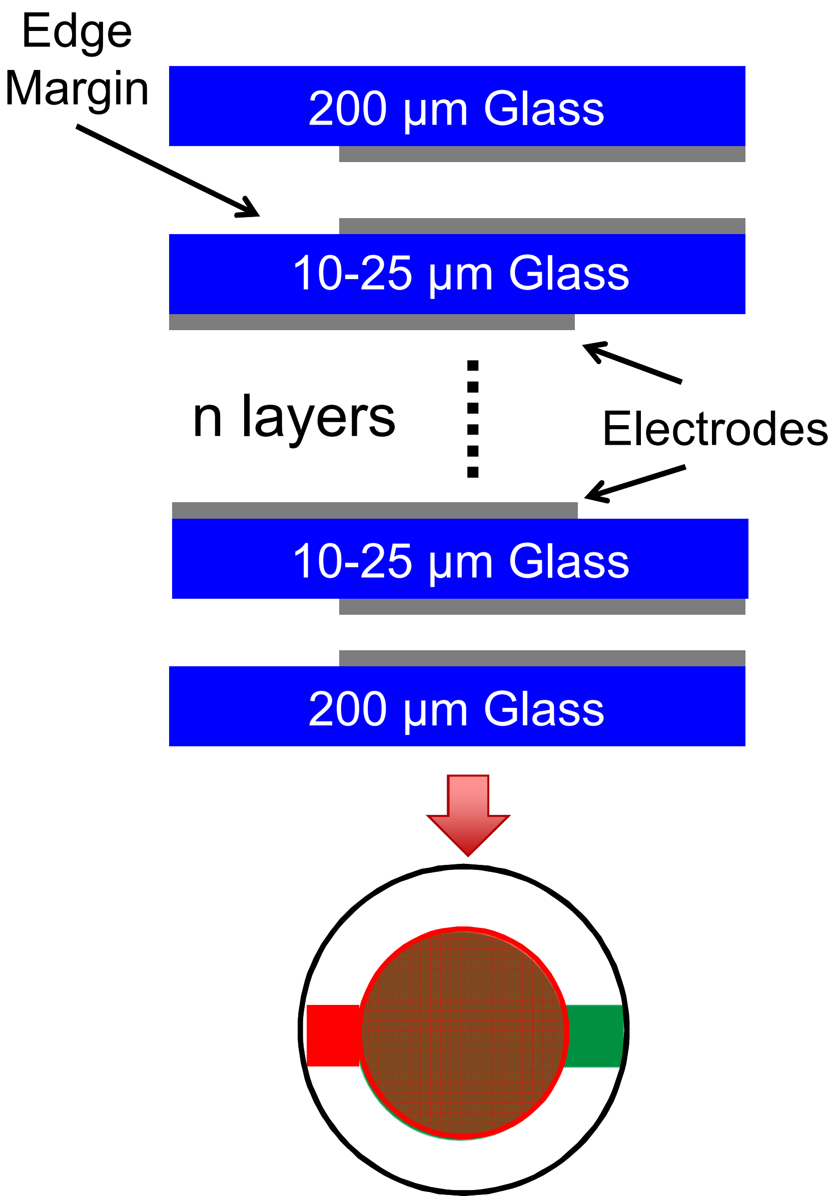
$$I(t) = \frac{V_0}{\omega_0 L} e^{\left(-\frac{Rt}{2L}\right)} \sin(\omega_0 t)$$

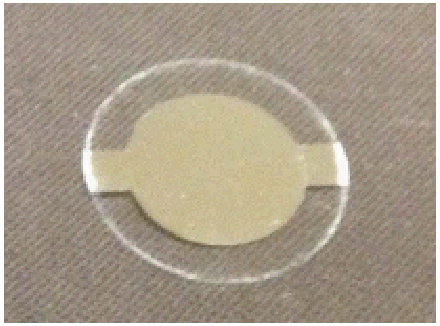
$$\omega_0 = \sqrt{\frac{1}{LC} - \left(\frac{R}{2L}\right)^2}$$



- Charged to 1000 V
- Could not compensate for lead inductance.

Fabrication Approach for Multi-layer Glass Capacitor





- Pattern 0.75” diameter electrode with edge tab
  - Electrode deposition top and bottom – rotated 180°
- Laser cut glass to form individual capacitor layer
  - Edge margin is 0.125” (~10 kV hold off voltage in air)

Thinning of Glass - Process

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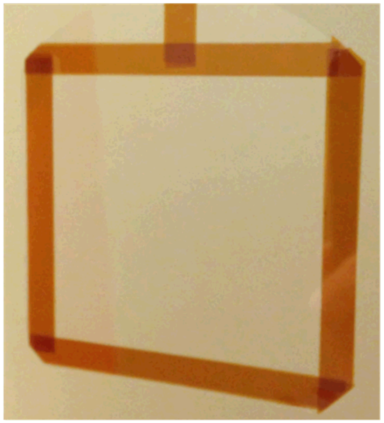
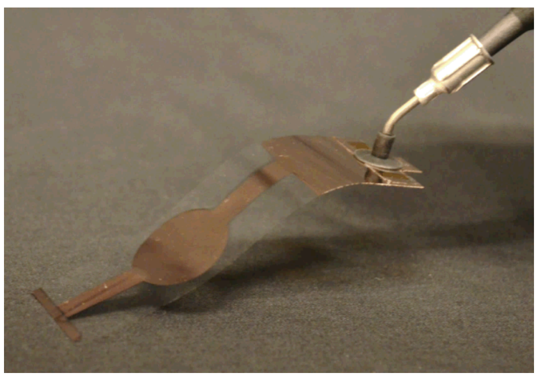
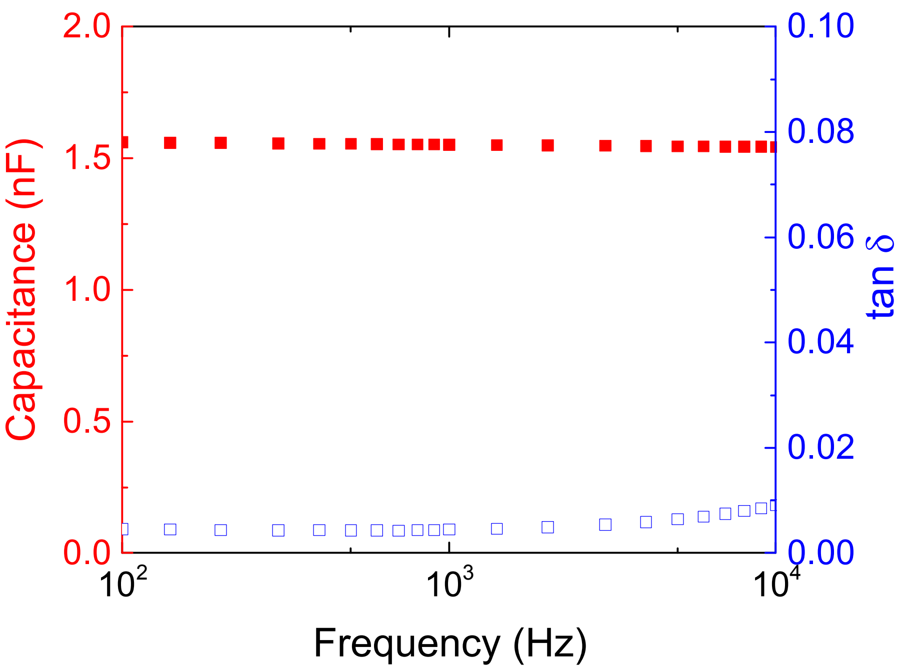
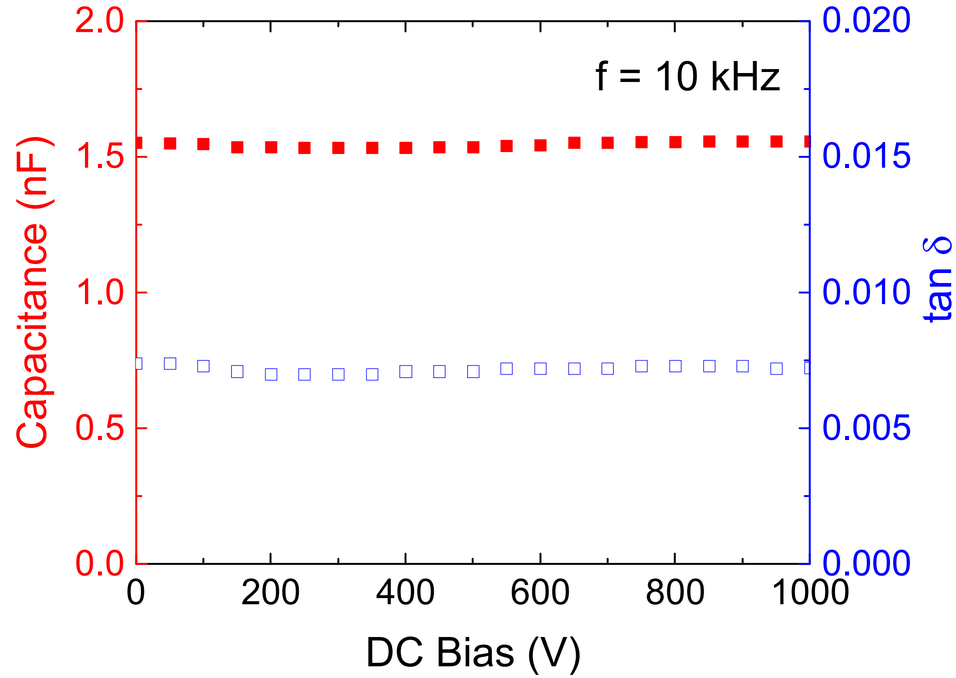




- Glass is masked on edges – provide mechanical structure for thinned samples
- Etched in 2.5% HF solution (0.01 ${}^{\mu m}/_{s}$)
- Ti/Pt contacts

Electrical Properties of nF Sized "Bulk" Capacitors





- Corning Willow thinned to ~ 25 µm thickness
- Electrode size = 1 inch (5.07 cm^2)
- Flat frequency response with no tunability at 1 kV
- $\rho > 10^{15}$ Ω*cm

Breakdown Characteristics of Thinned Corning Willow Glass

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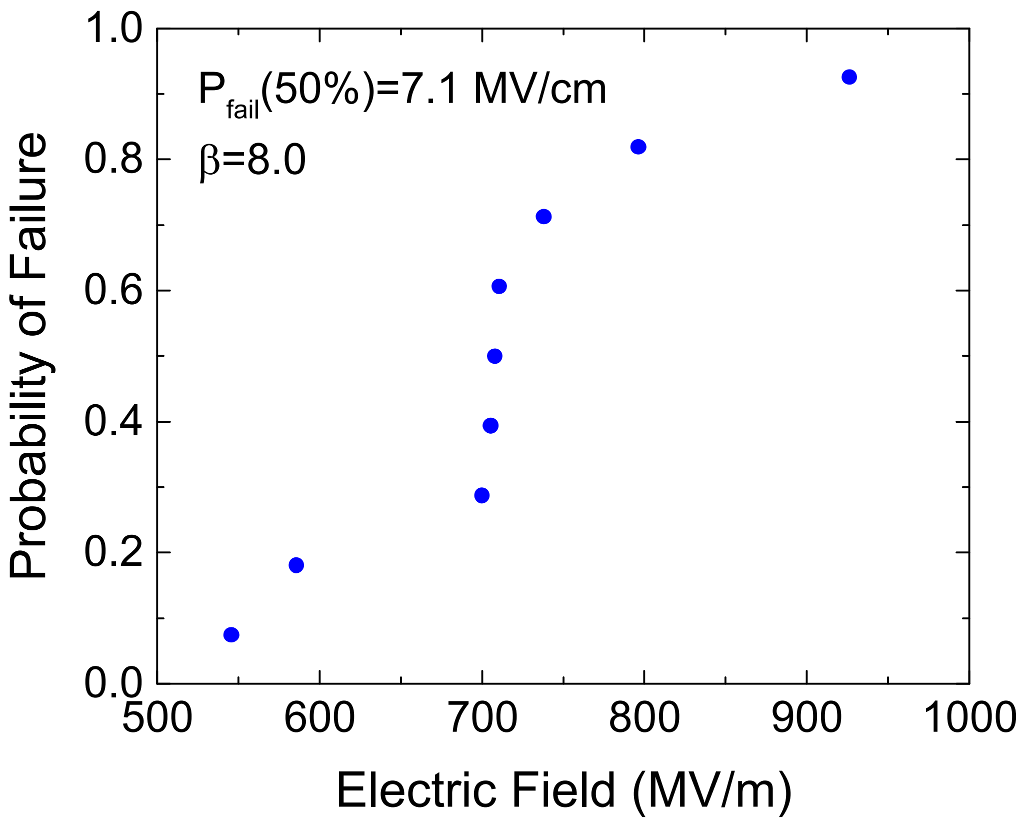


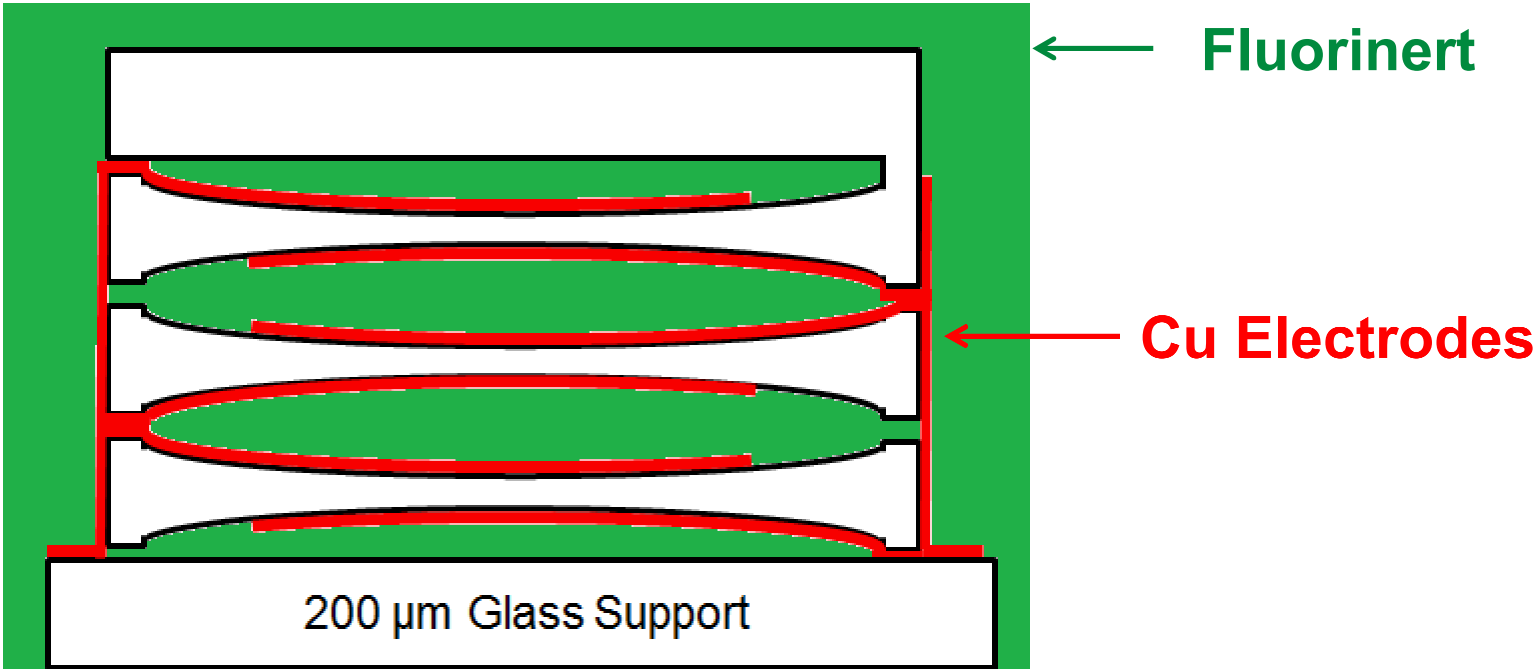
- t~19 µm (estimated from capacitance)
- Area~9.6 mm^2 (Lee et al. Area~1.6 mm^2)

$$\frac{E_{b1}}{E_{b2}} = \left(\frac{Area_2}{Area_1}\right)^{1/\beta}$$

- Breakdown strength scales with area (greater probability of sampling defects)
- Weibull Statistics prediction of E_b of AF45 = 8.0 MV/cm

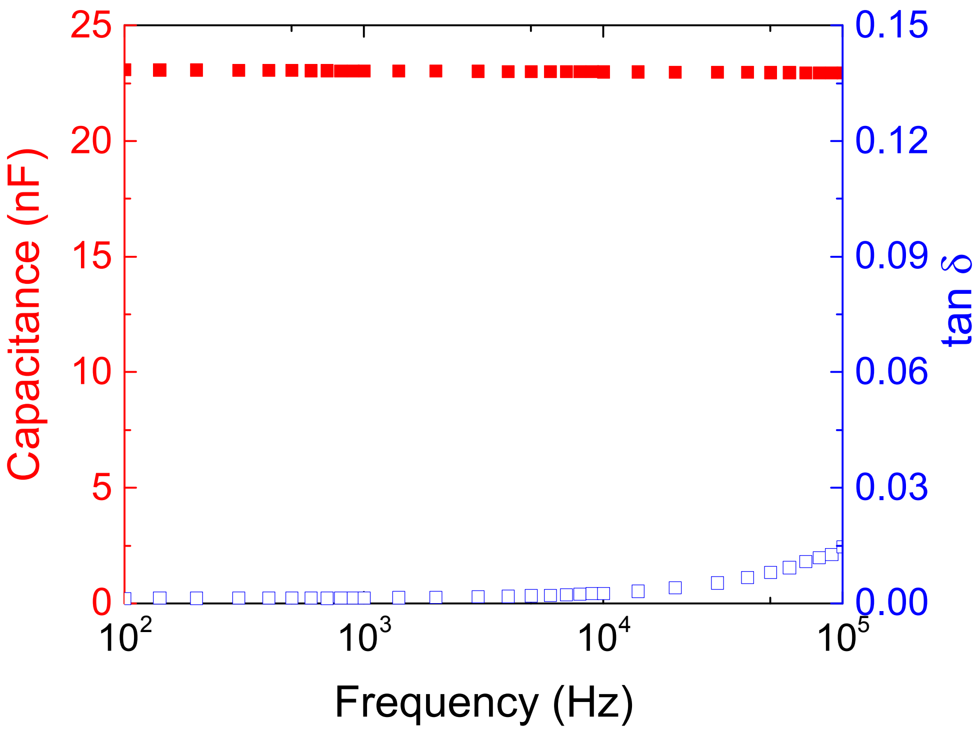
Lee et al. JACERS 93 (2010) 2346

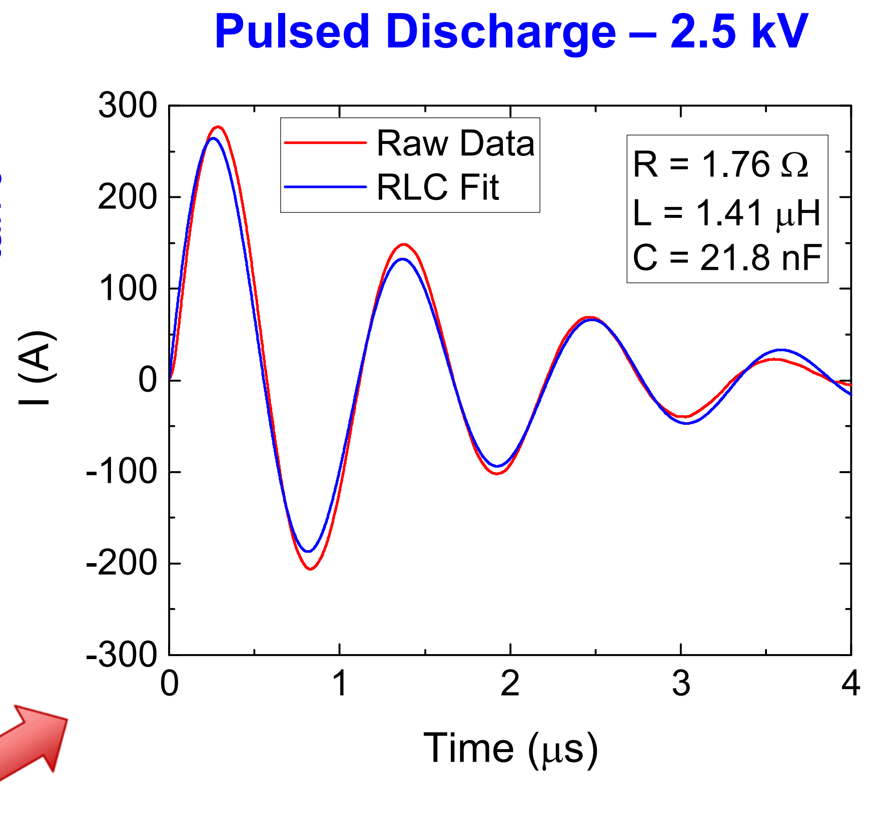
Fabrication of Large Area/Multi-Layer Capacitor



- Left 200 µm thick support frame around 25 µm thick thinned glass (60 mm × 60 mm)
- Immersed in Fluorinert for measurement
- Layers bonded together using air dried silver paint

Properties of Multi Layer Glass Capacitor





- C (1 kHz) = 23.0 nF, tan δ=0.001
- $U_{dielectric}$~0.24 J/cc – need to improve end termination to push $E_{applied}$
- $U_{capacitor}$~70 mJ/cc - can increase by increasing n, decreasing edge margin, using thinner support layers

Conclusions

- Alkali-free glasses show great promise for high energy density capacitors
  - Literature reports of
    - $E_b > 1$ GV/m
    - $U_{dielectric} \sim 35$ J/cc
    - Alkali content is crucial for high energy density and temperature stability
  - Challenging to make and handle!
    - With sufficiently thin glass, wound capacitors are possible
    - Our approach – thin and build multi-layer capacitor
      - Have process for thinning to 10 µm (1-2 nF per layer)
      - Have process to electrode and cut individual layers
      - Stacking:
        - » Demonstrate 23 nF on 3 layer stack with 36 cm^2 electrodes
        - » Next step: stack laser cut layers to build 10-100 nF capacitor

Acknowledgements

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Extra