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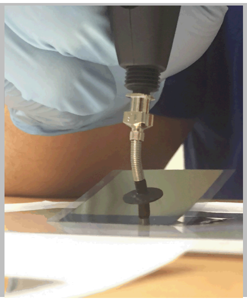

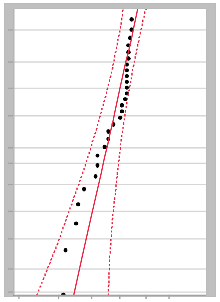

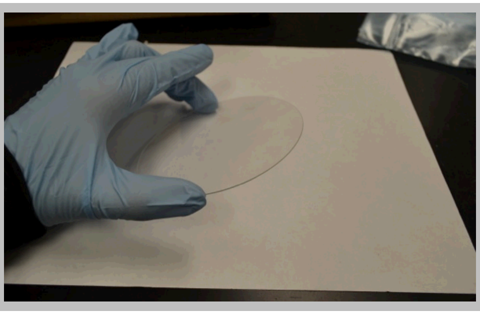

Towards High Energy Density Glass Capacitors

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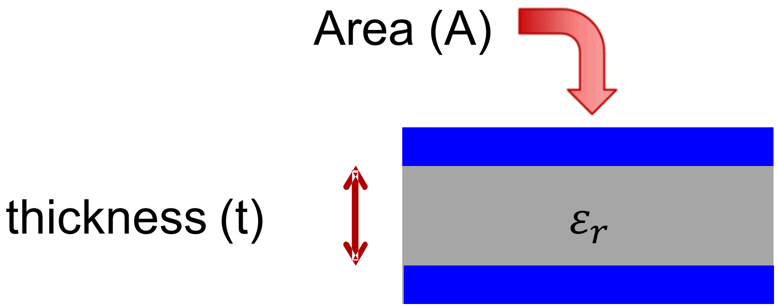
Outline

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

Energy Density of Linear Dielectrics

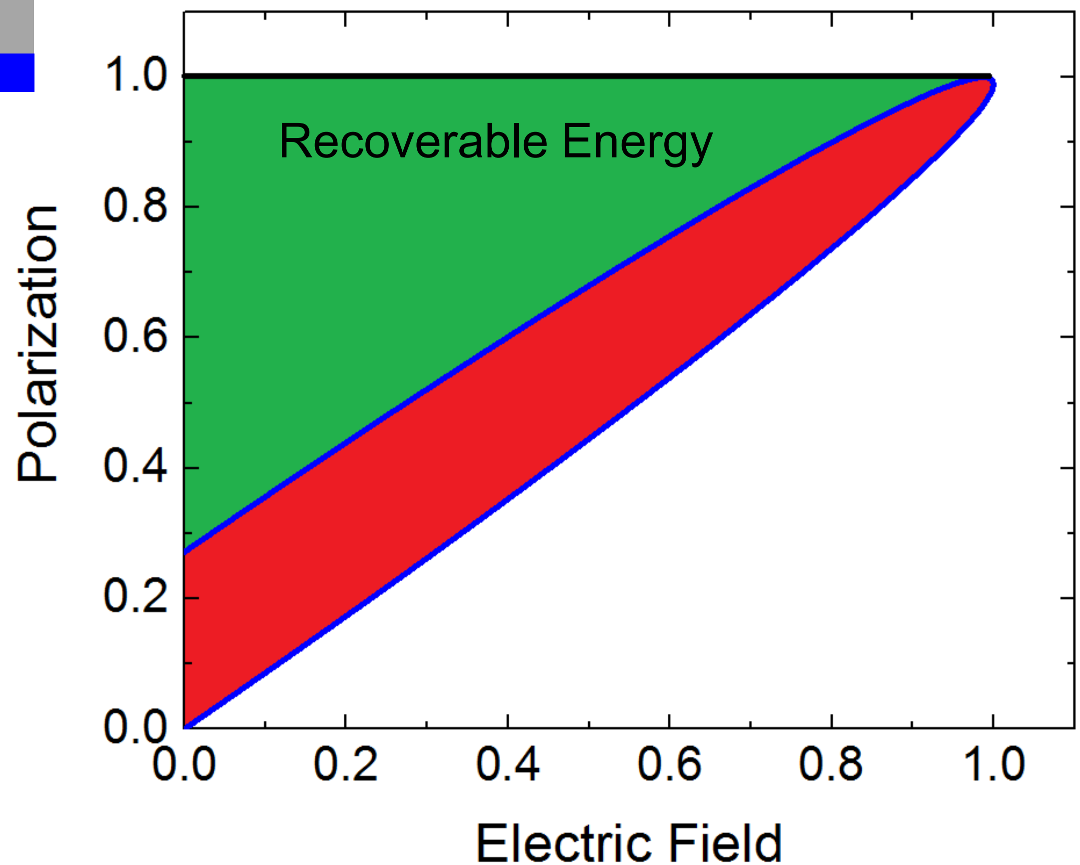


$$C = \varepsilon_r \varepsilon_0 \frac{A}{t}$$

$$W = \int P dE$$

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

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

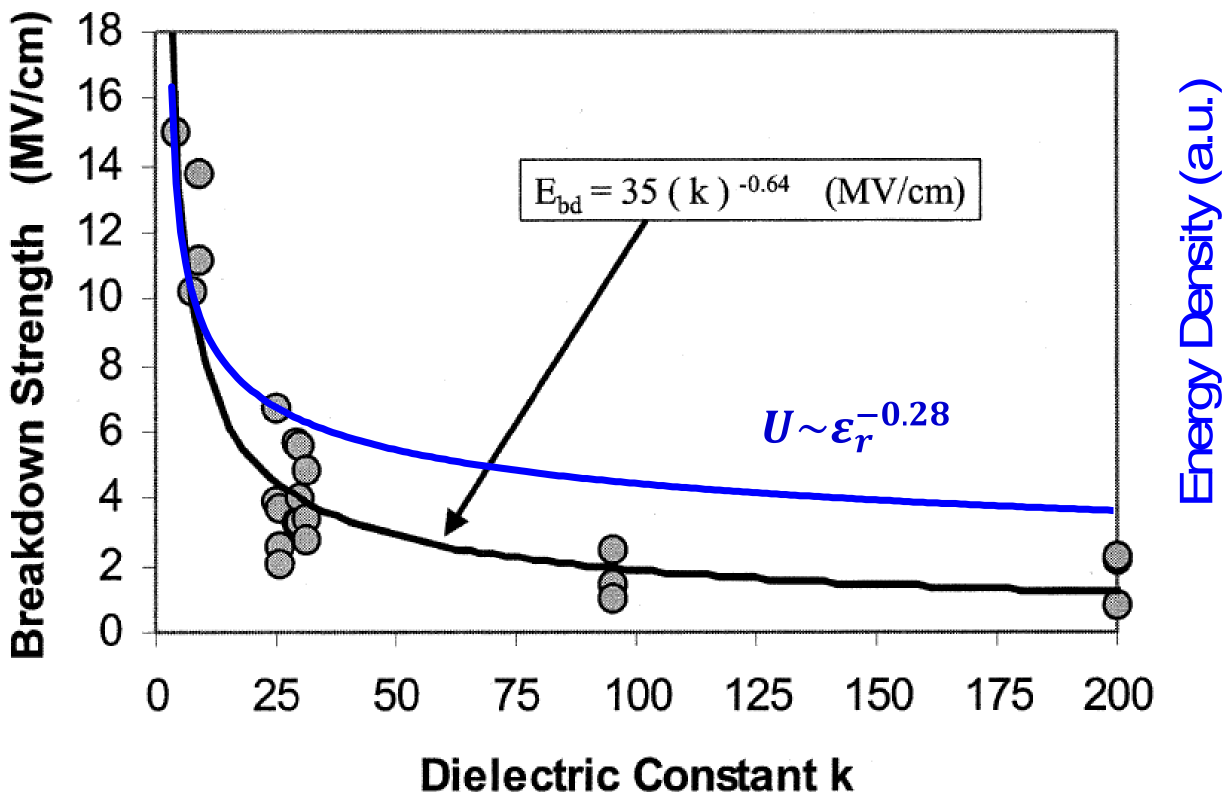


Trends in Breakdown Strength of Dielectrics

Larger gains from increasing breakdown strength

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

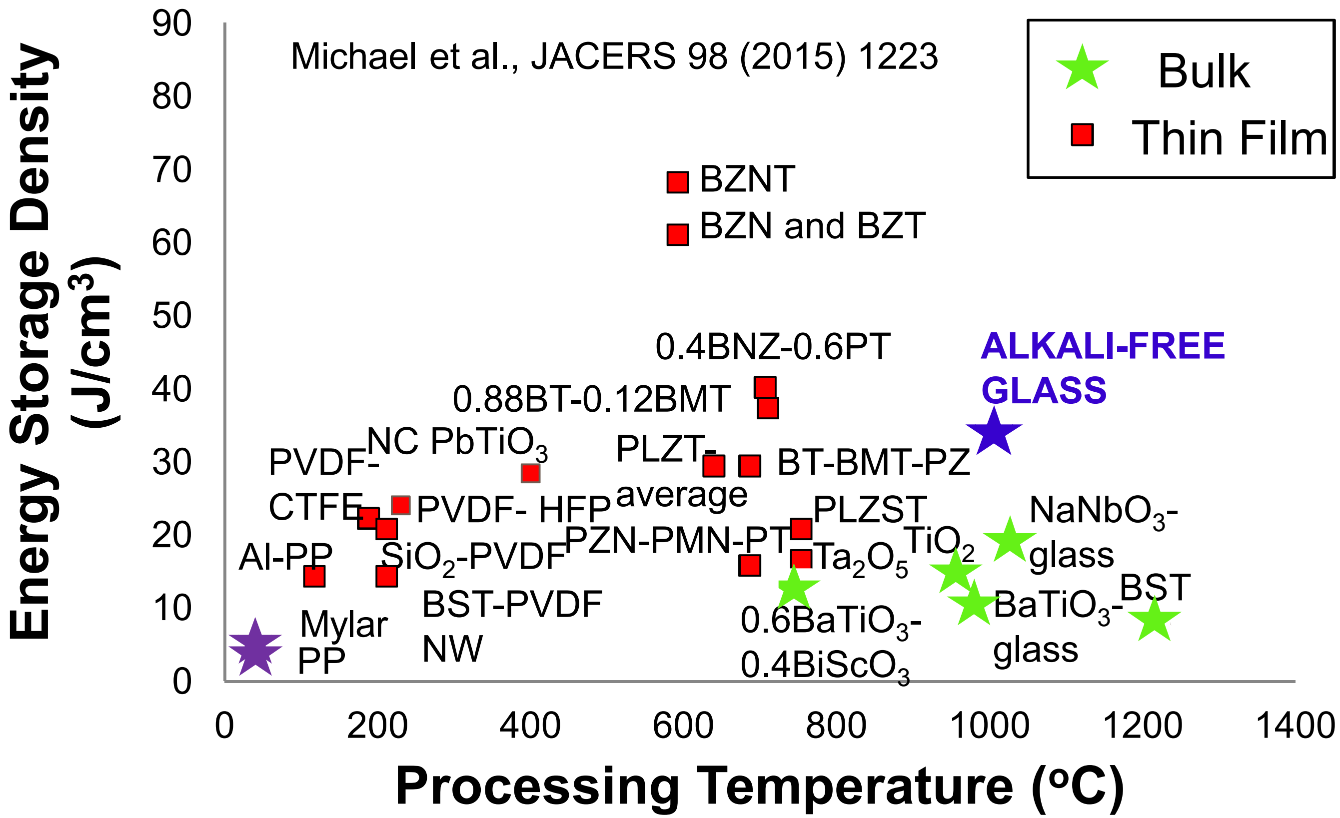
Limited value to tuning ε_r



McPherson et al. IEEE TED, 2003

- Thermochemical modeling suggests link between polarizability and bond strength
  - **Increasing permittivity in inorganic compounds will invariably lead to decrease in energy density due to drop in E_B**

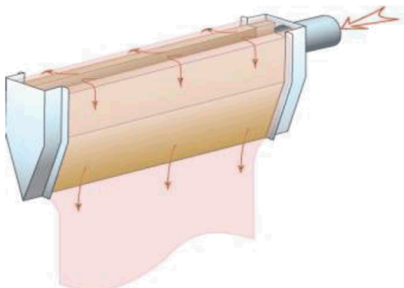
Comparison of Energy Storage Materials



- Alkali-free glass competitive with many emerging materials
- May have an advantage in manufacturing
- Packaged capacitors: 0.5-5 J/cc (depending on voltage rating)
  - Can we make 1 kV, 100 nF capacitors?

Laihonoen, IEEE TDEI 14 (2007) 275

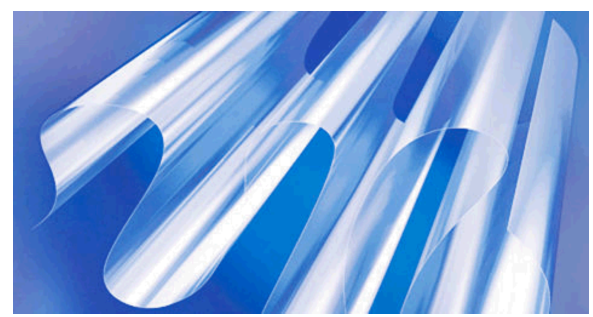
Alkali-Free Glasses



- "Overflow drawn down process"

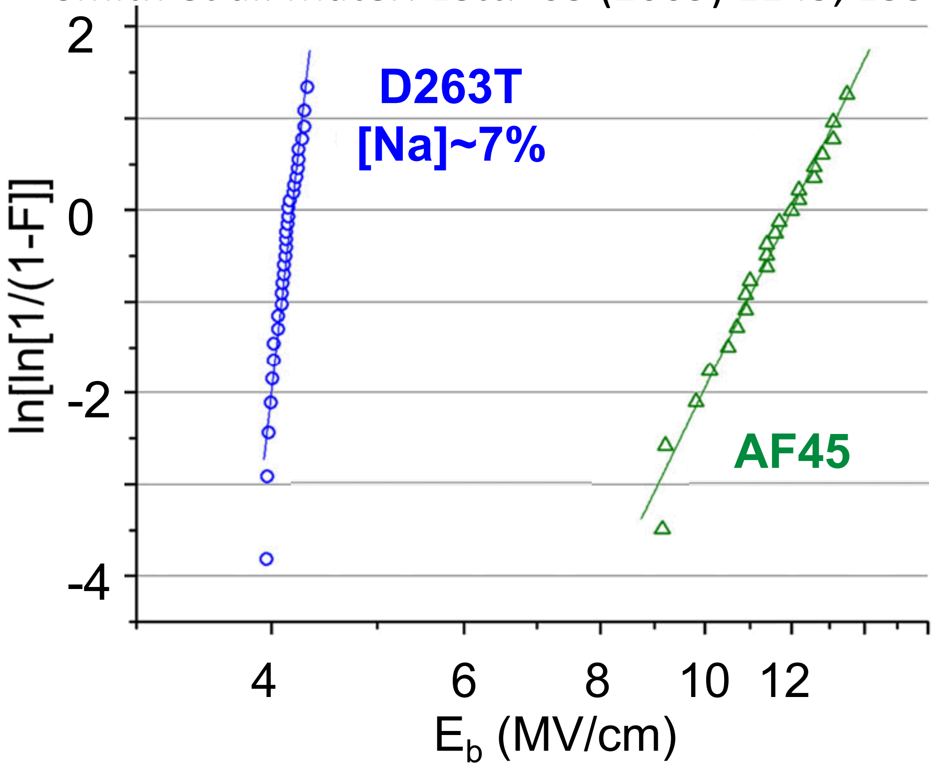
Parameter	Value
Density (g/cm^3)	2.3-2.5
Young's Modulus (GPa)	73-75
ε_r	5-6
tan δ	0.001
ρ (Ω*cm @ 250 °C)	$>10^{12}$
Strain Point	650-700 °C

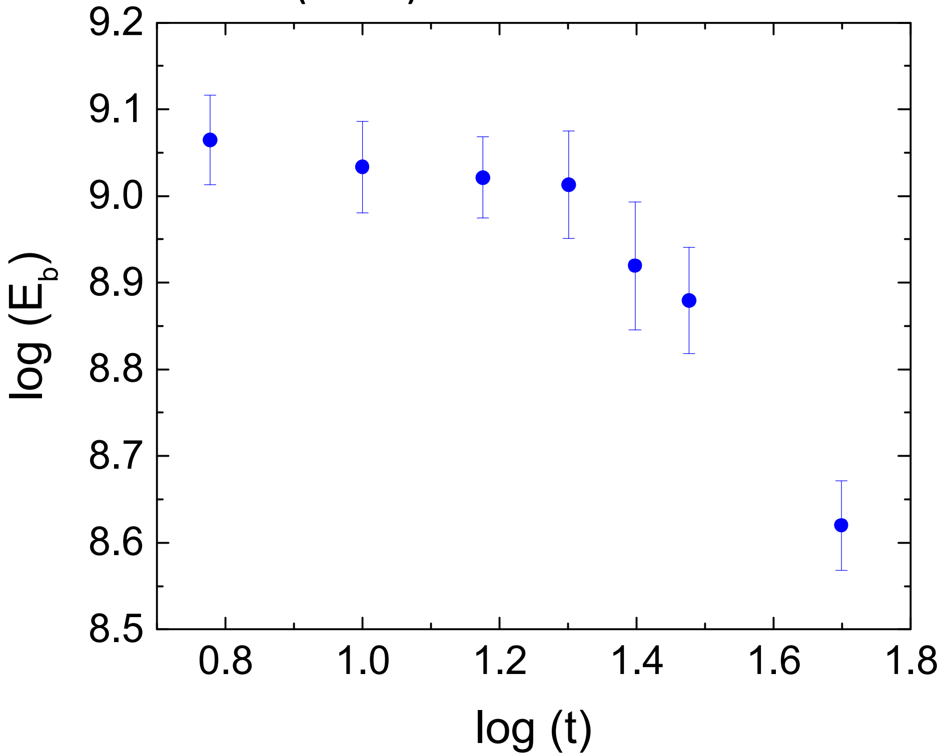
- Sold by many vendors world wide
- Boro-alumino-silicate glass category
- Sold in thicknesses ~ 100 – 200 µm
- [Na] < 350 ppm (typical)



Breakdown Strength of Alkali-free Glass

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



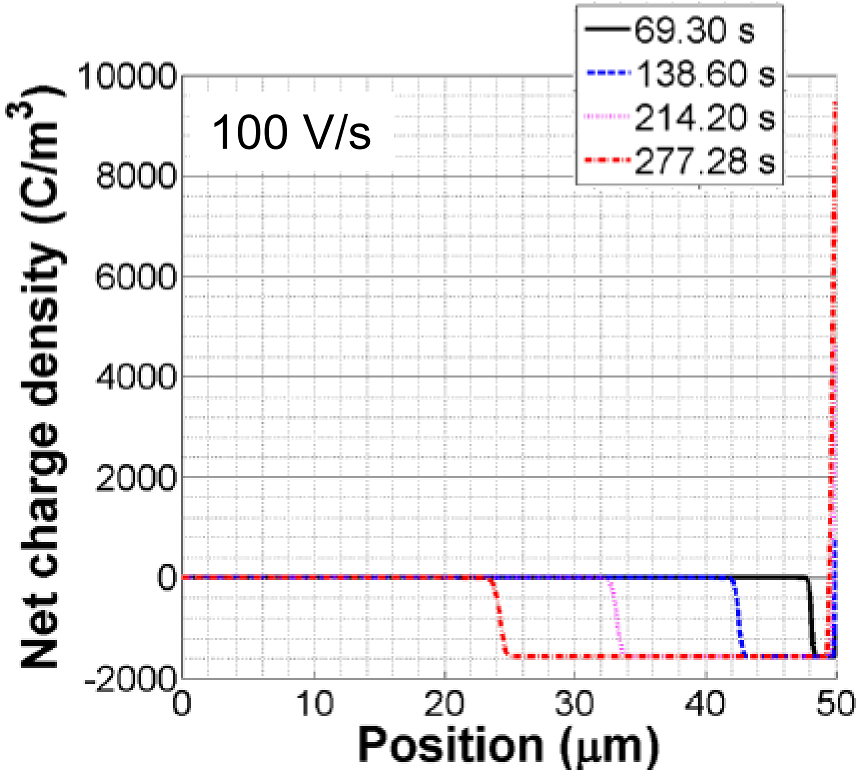


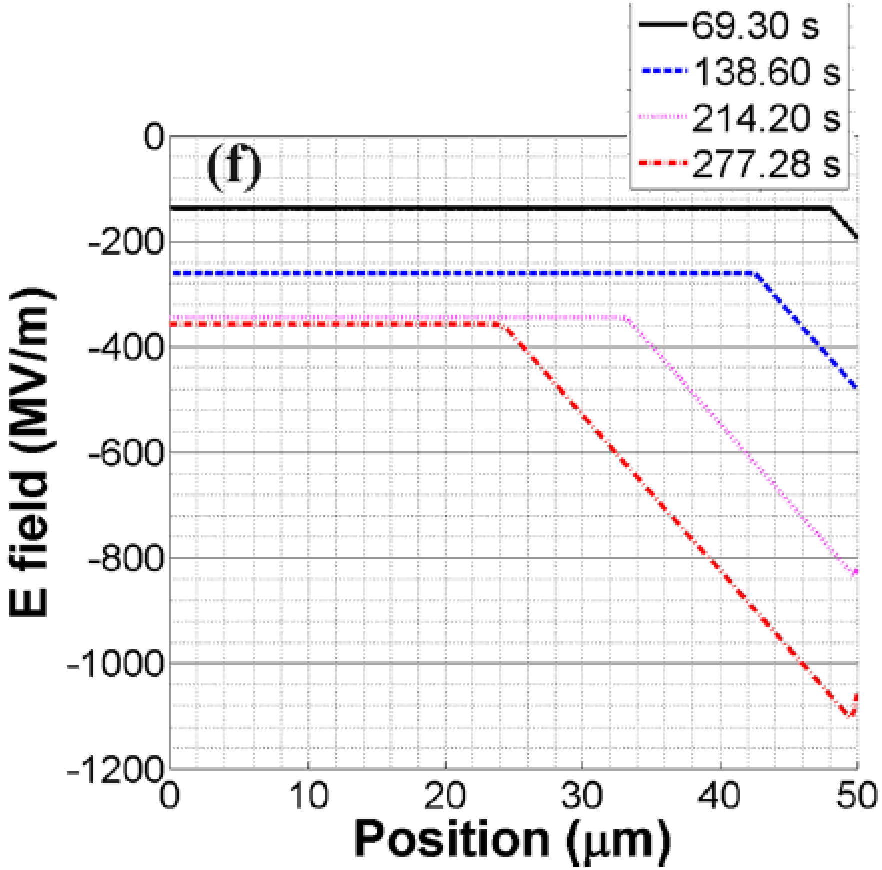
Parameter	D263T	AF45
t (μm)	30	19
E_b (MV/cm)	4.2	12
β	47.9	10.7

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

Breakdown Governed By Residual Na Content

Choi et al. JAP 118 (2015) 084101

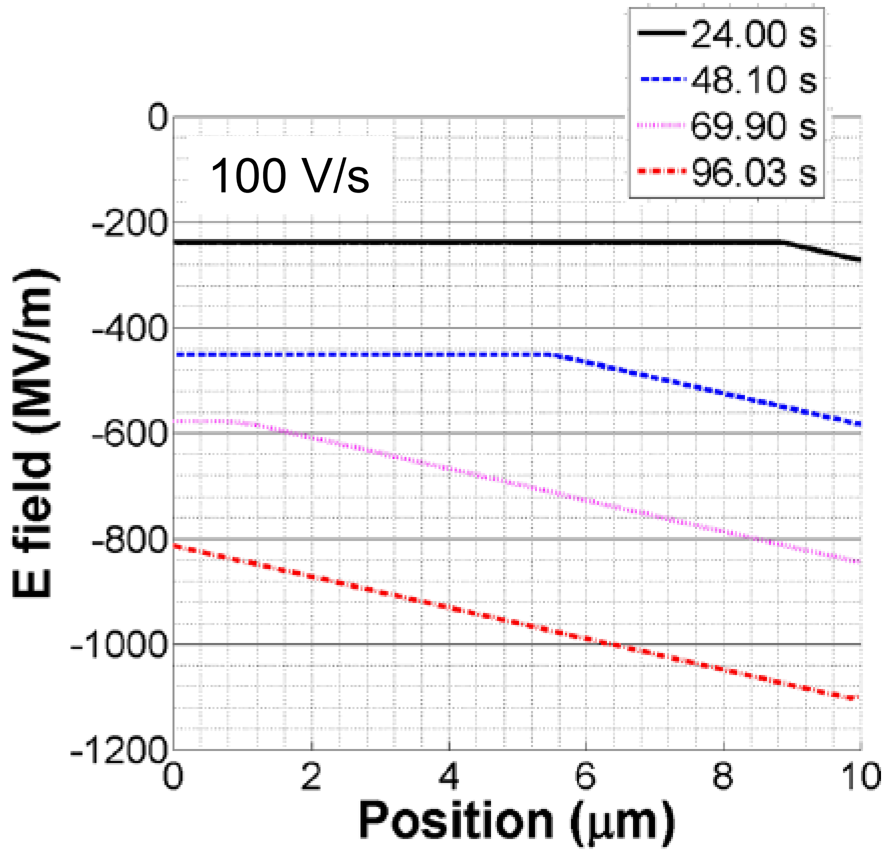


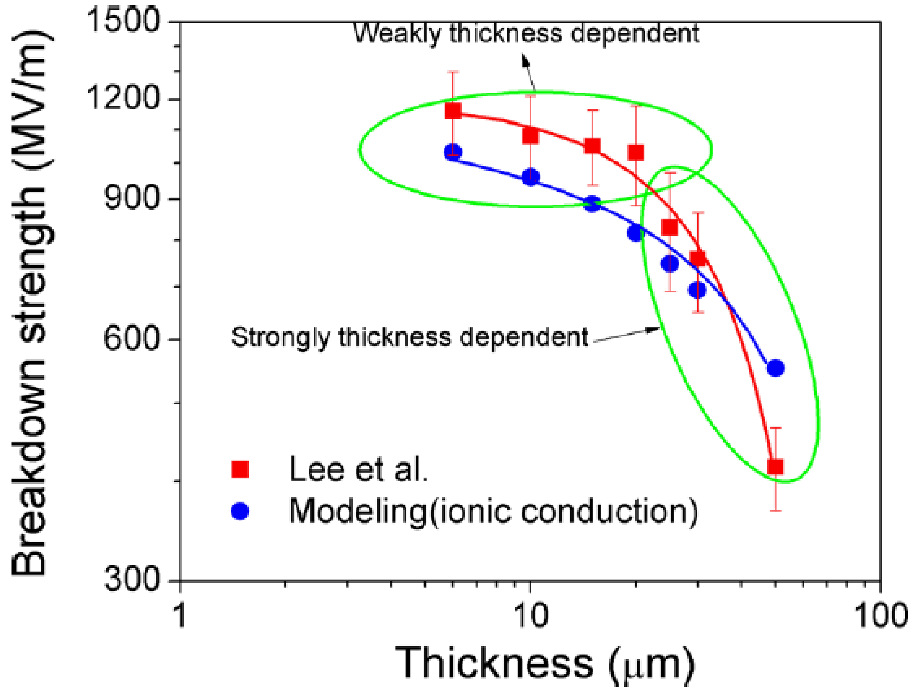


- Mobile ions (Na^+) depleted from anode, giving rise to field enhancements that can lead to breakdown

Breakdown Governed By Residual Na Content

Choi et al. JAP 118 (2015) 084101

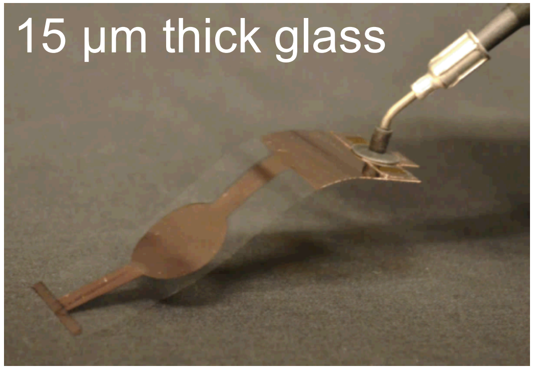




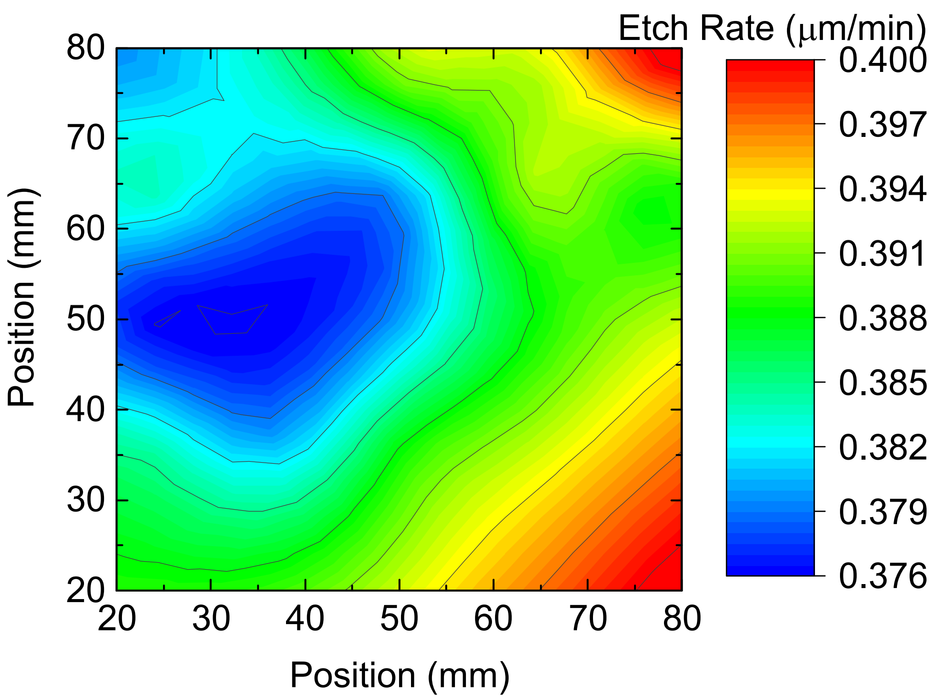
- For dielectric layers <20 µm, depletion extends across entire layer ⇒ E_B less thickness dependent

What do we want?

- Goal is to make high energy density capacitors in the 100-1000 nF size
  - Need thin glass!
    - $C = \frac{\varepsilon_0 \varepsilon_r A}{t}$
    - Breakdown field higher for t<20 µm
  - Need a way to take hundreds of sheets of glass and connect them mechanically and electrically
    - Thin glass is NOT very robust.
    - Targeting temperature range of -55 to +65 °C
  - We really need thin glass

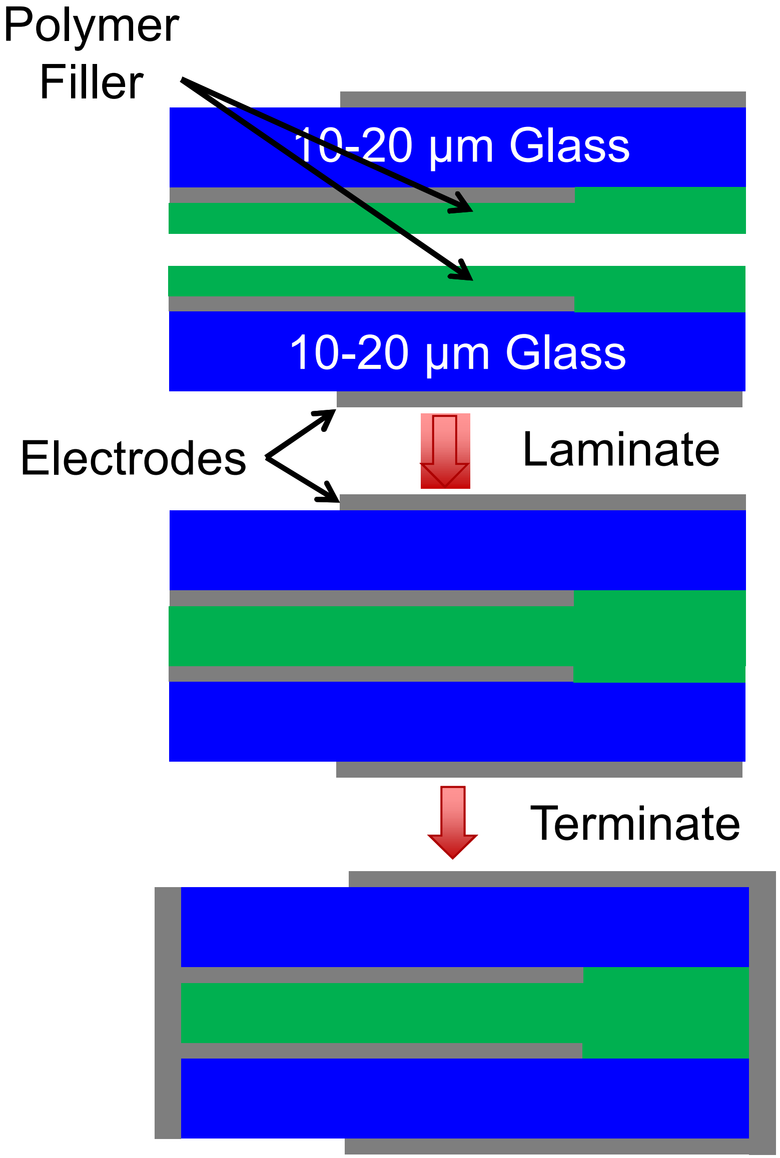


Thinning of Glass has been Demonstrated



- Glass is masked on edges – provide mechanical structure for thinned samples
- Etched in 2.5% HF solution using μ-Fab recirculating HF tank
- Reproducibly thin to from 30 μm to 10 μm (±3%)

Approach for Bonding Metallized Glass



- Thinned glass is manufactured “layer by layer”
- Need approach to physically and electrically connect multiple layers to form final capacitor
- Bonding Approach – laminate using high breakdown strength Epon 828/Jeffamine T403
  - Analogies to epoxy impregnated mica-paper capacitor construction

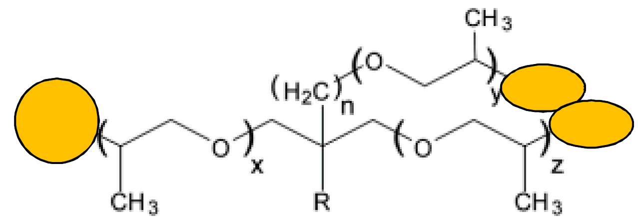
http://machinedesign.com

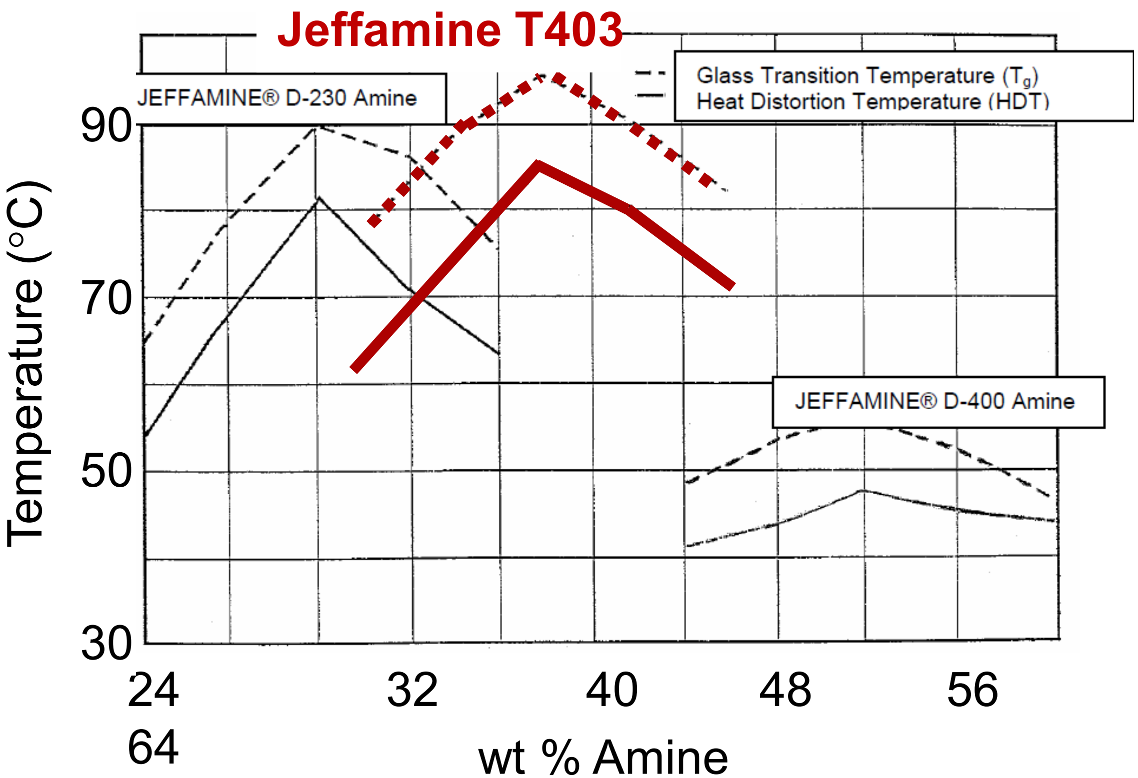
Selection of Epoxy

Epon 828 with Jeffamine T403

Epon 828

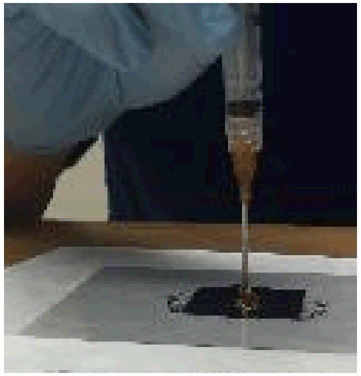
Triamine

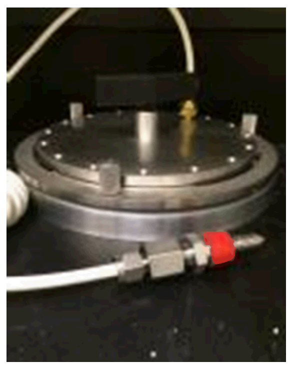


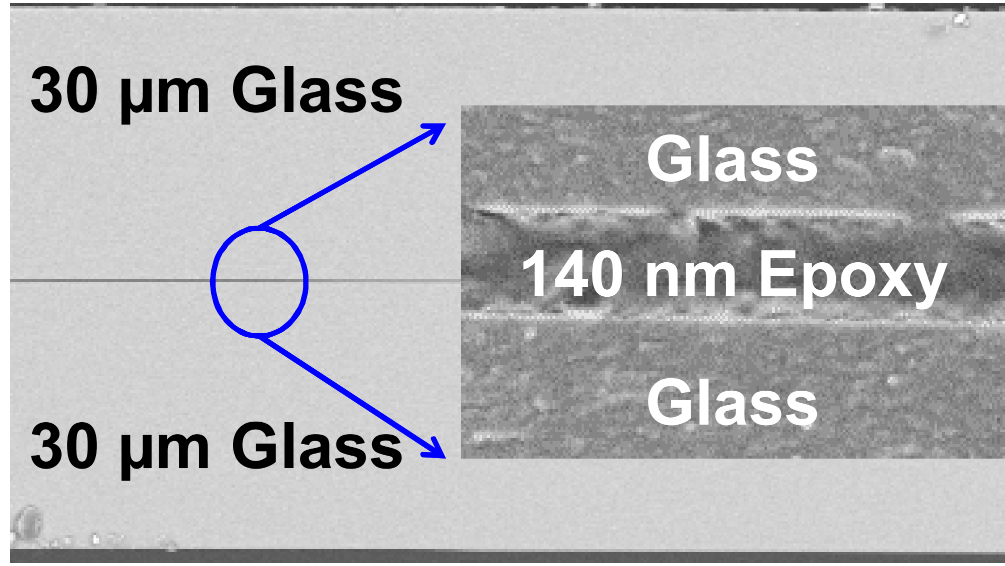


- Lack of solvent means no solvent evacuation needed
- T_g>90 °C for 42 wt% Jeffamine T403
- Volume contraction during curing ~5%

Demonstration of Bonding under Pressure

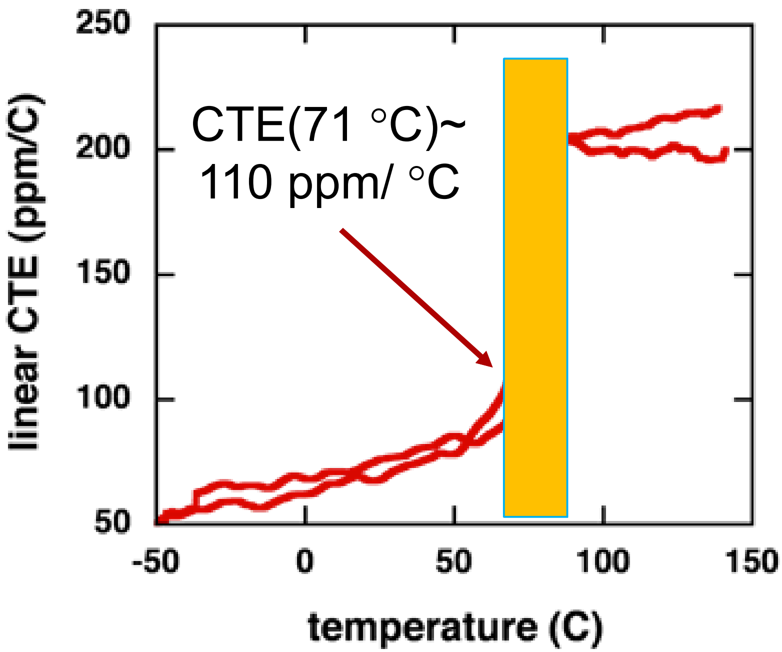




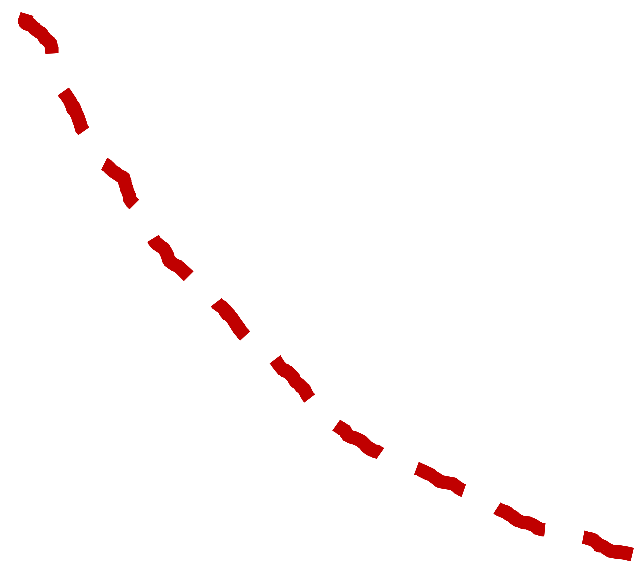


- Epoxy cured at 100 °C under uniaxial pressure of 4.2 kPa
- Uniform thickness of 138±4 nm across 1” test piece

Setting of Curing Temperature



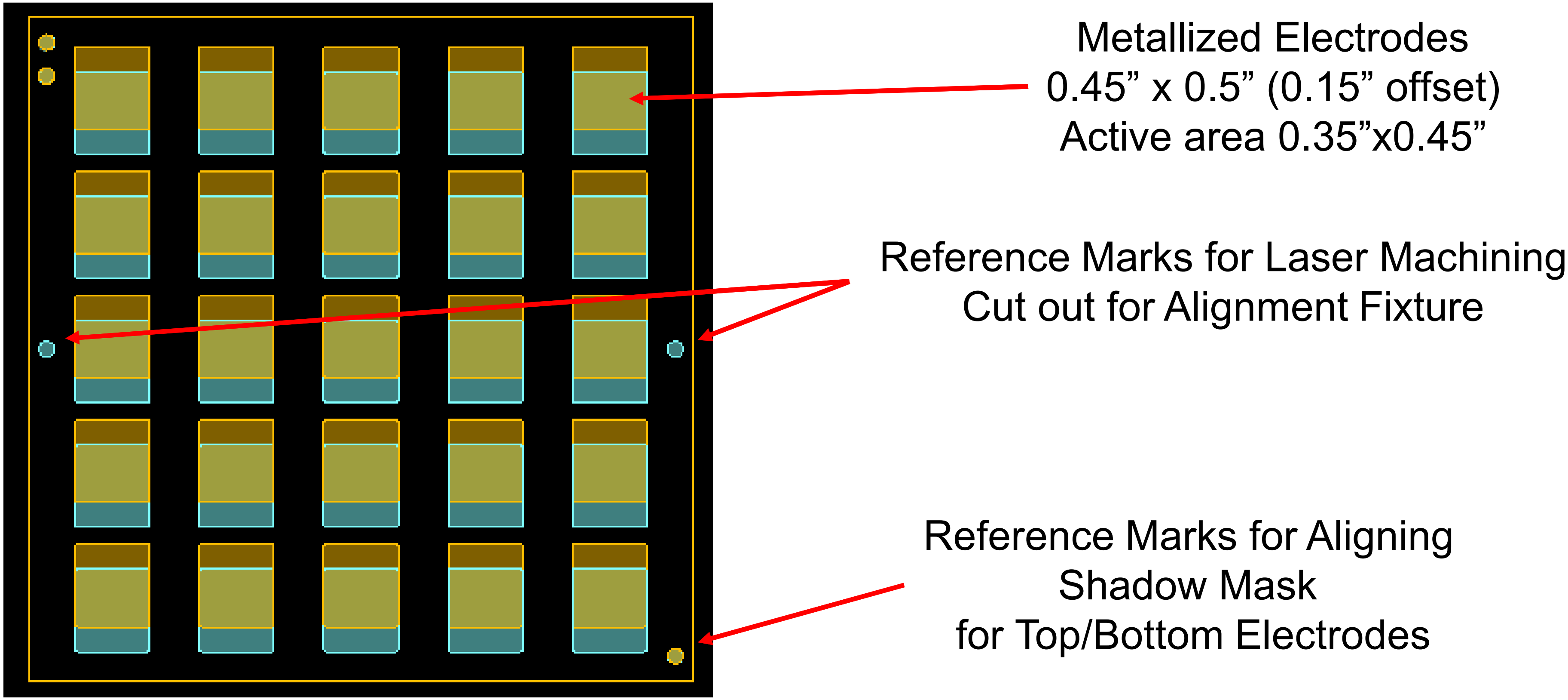
Huntsman, 2005



$\alpha_{(Lin)} = \frac{1}{L}\left(\frac{\partial L}{\partial T}\right)$ $\sigma = E\frac{1}{L}\left(\frac{\partial L}{\partial T}\right)dT$

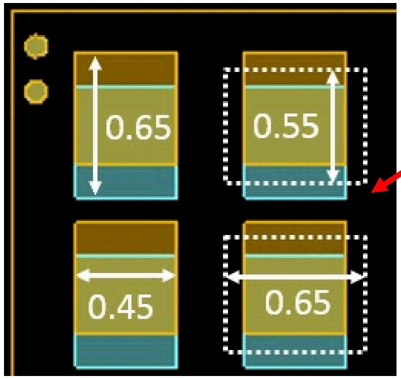
- CTE of glass is 4.5 ppm/°C
- Curing at 100 °C induces significantly more stress than staying below T_g
- Cure at 65 °C requires higher pressure for similar thickness epoxy layer

Aligning Electrodes

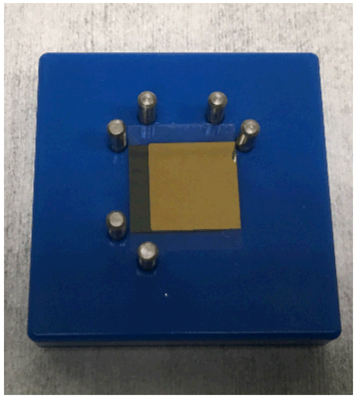


- Alignment between subsequent layers is crucial for minimizing dead volume/maximizing energy density
- Shadow mask designed for metallizing glass – providing alignment markings
- Glass sheets subsequently cut

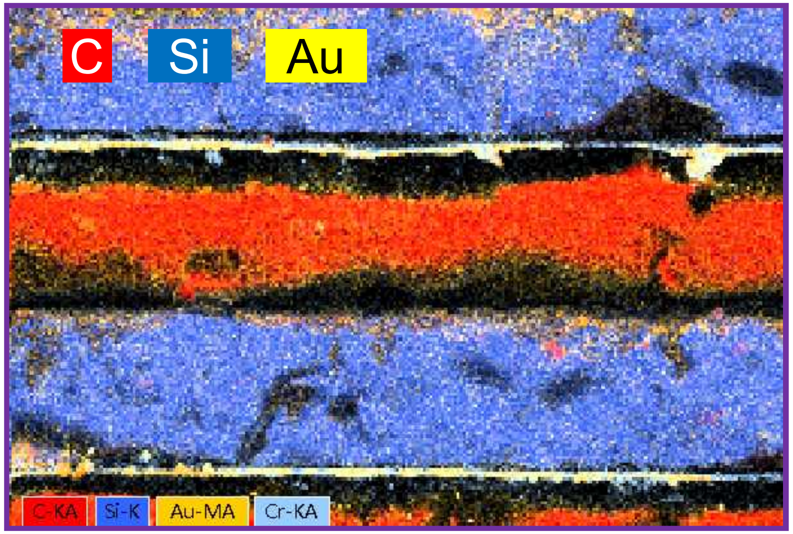
Fabricating Capacitor using 3D Printed Fixture



Laser cut (0.1" edge margins)



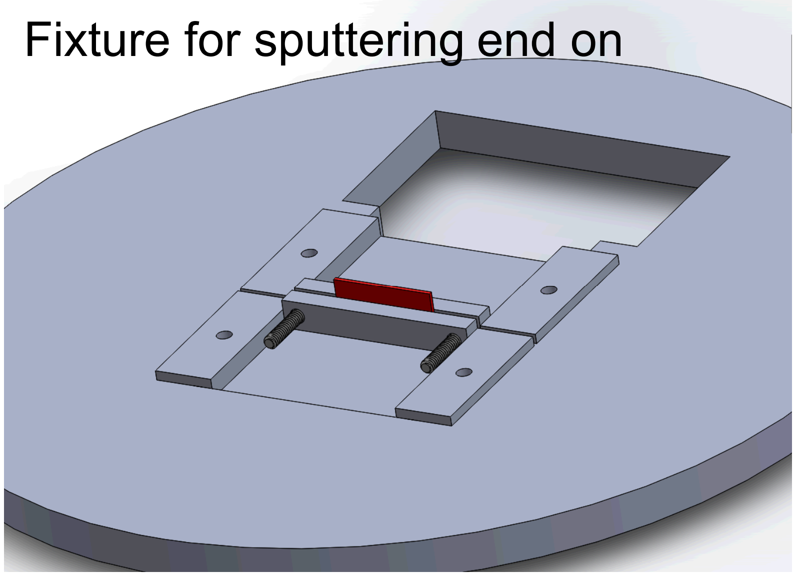
Bond/Polish ends

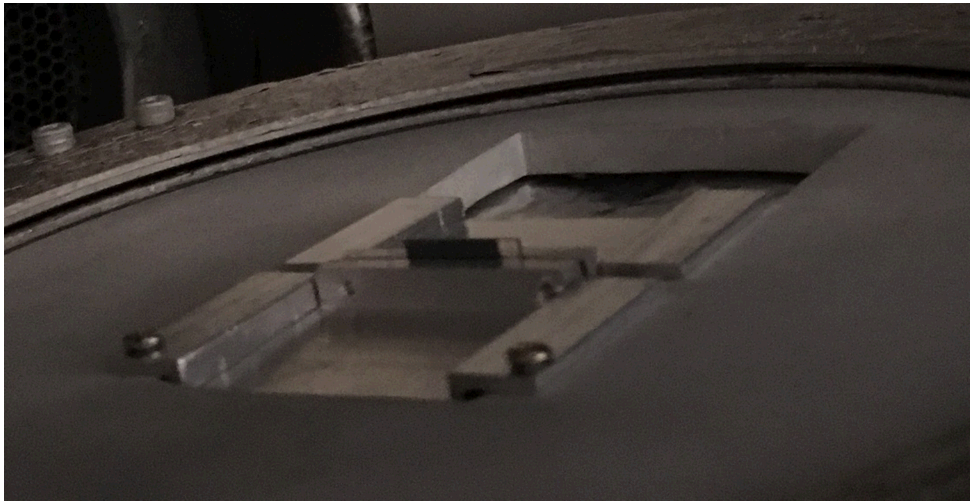


- Active area of capacitor is 0.35"x0.45" (Total area 0.55"x0.65")
  - 10 µm glass provides 500 pF per layer
  - Long term goal is 5 µm (990 pF per layer)

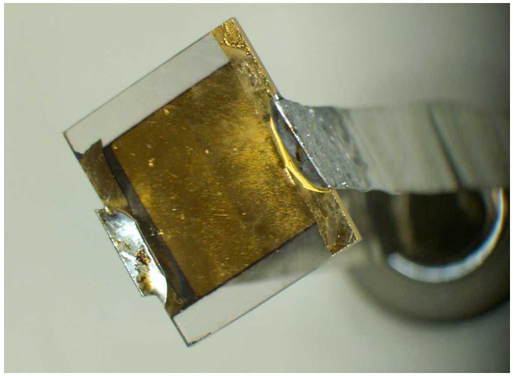
End Terminations

Fixture for sputtering end on

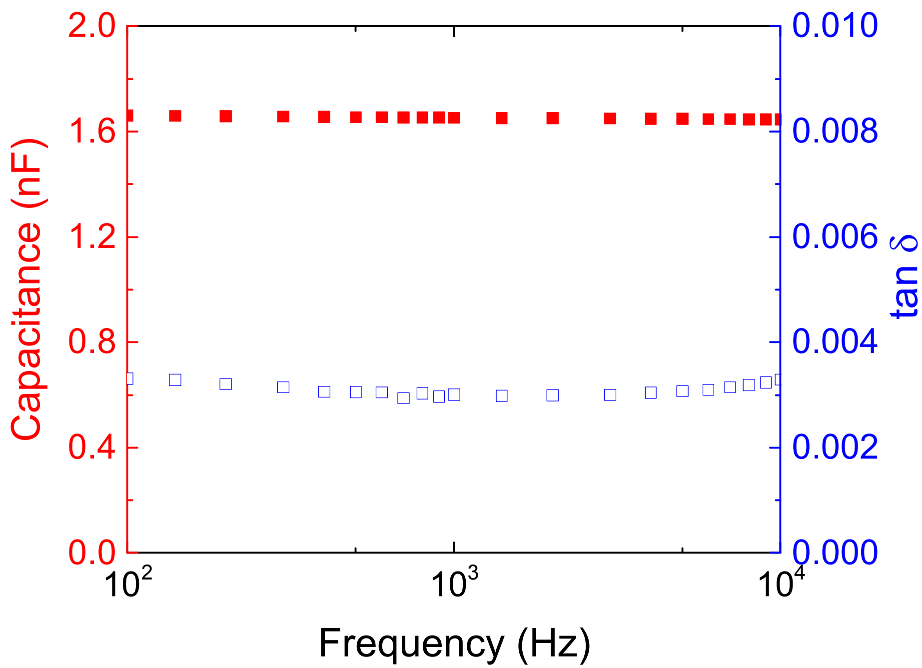


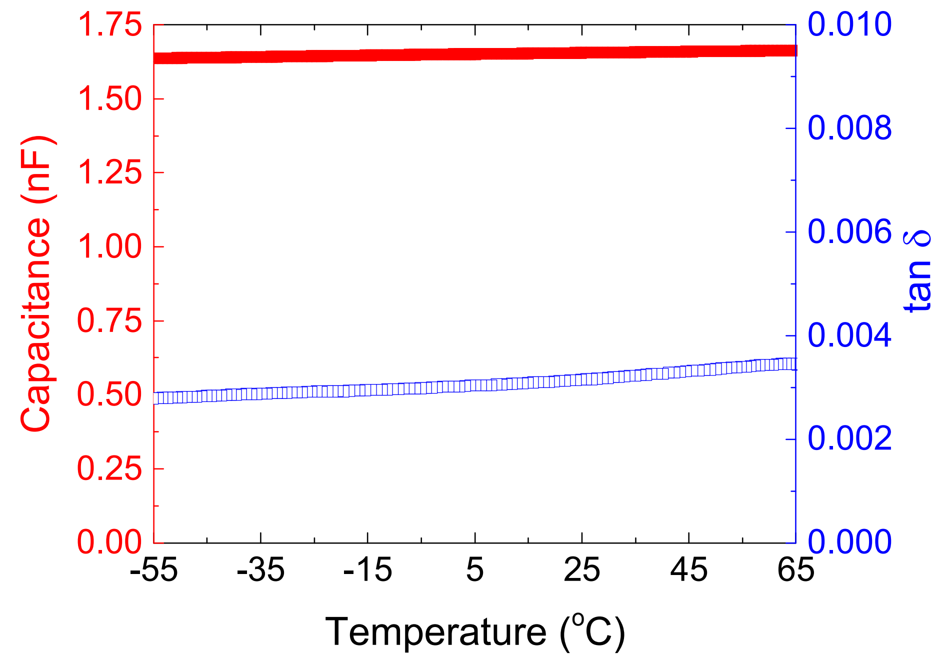


- Sputter deposit Ti (200 nm)/Pt (100 nm)/Au (200 nm)
  - Non-directional nature of deposition ensures contact to inner electrodes
- Solder leads for electrical testing



Capacitor from 30 µm Glass



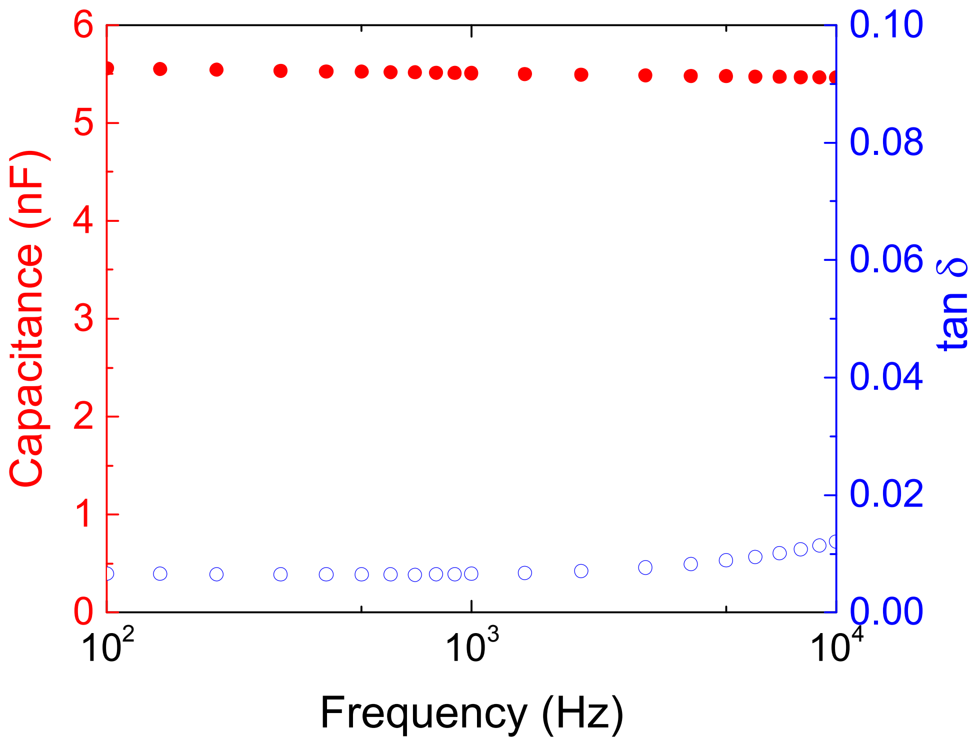


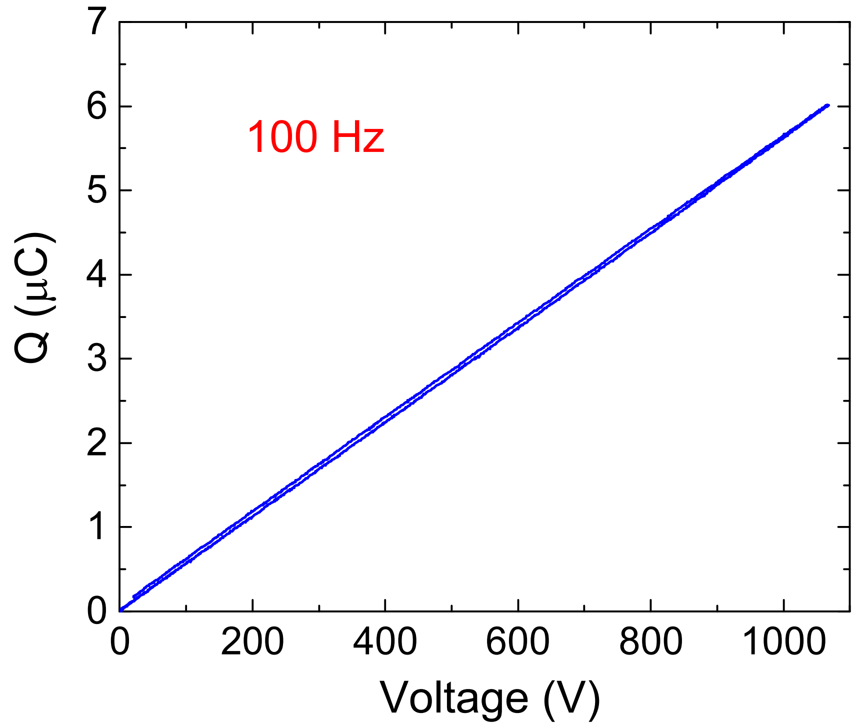
- 10 layers - 1.65 nF (indicates all layers electrically active)
- Shows better than ±1% stability over -55 °C to +65 °C (exceeds X4A classification)
- $R = 2.81 \times 10^{13}\ \Omega$ @ 65 °C ($RC = 4.7 \times 10^{4}\ s$)
- $V_{Breakdown}$=9.74 kV (dielectric ⇒ 2.8 J/cc, package ⇒ 0.4 J/cc); need more samples for Weibull analysis
- 150x increase in area vs. Lee report:

$$\frac{E_{b1}}{E_{b2}} = \left(\frac{Area_2}{Area_1}\right)^{1/\beta} \Rightarrow V_B(MLGC) \sim 12kV$$

Lee et al., JACERS 23 (2010) 2346

Capacitors from thinned Glass



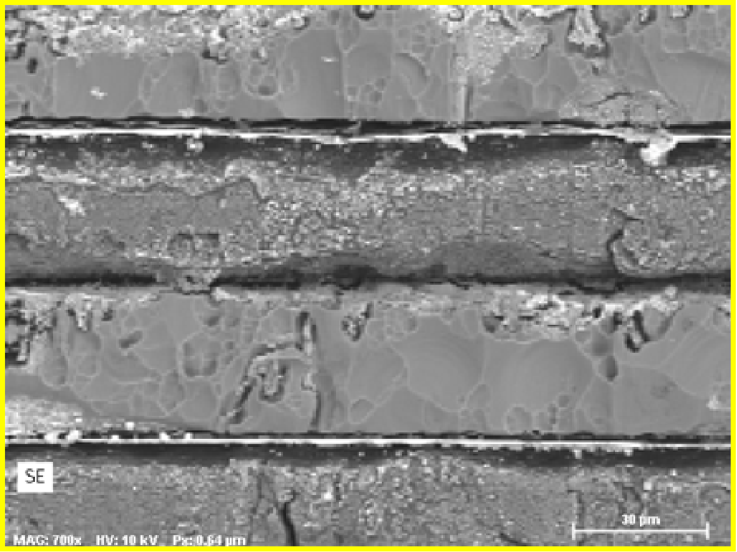


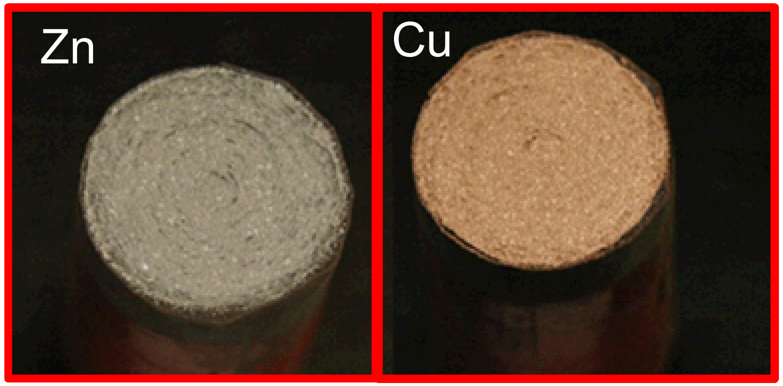
- 10 Layers – 5.5 nF @ 1 kHz
- Tested to 1 kV
  - $E = 3.2\ mJ, U = 0.09\ \frac{J}{cc}$
  - 66% value of NovaCap at ceramic

- 50% of volume was from epoxy bonding layer
  - Need to optimize bonding process to reduce inactive volume

What's Next?

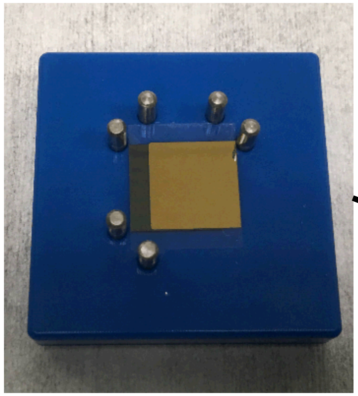
- Decrease dead-space to improve energy density
- Demonstrate more commercially viable processing

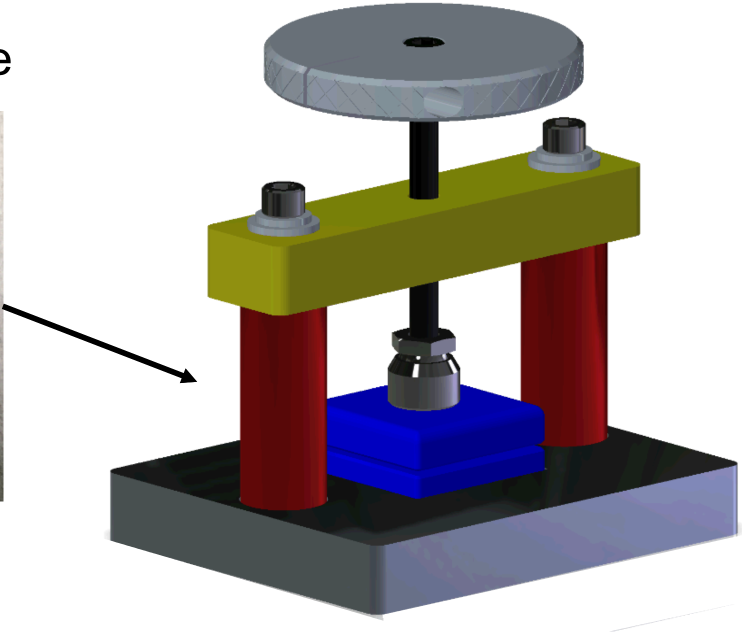




New Fixture for Controlling Pressure

Alignment Fixture

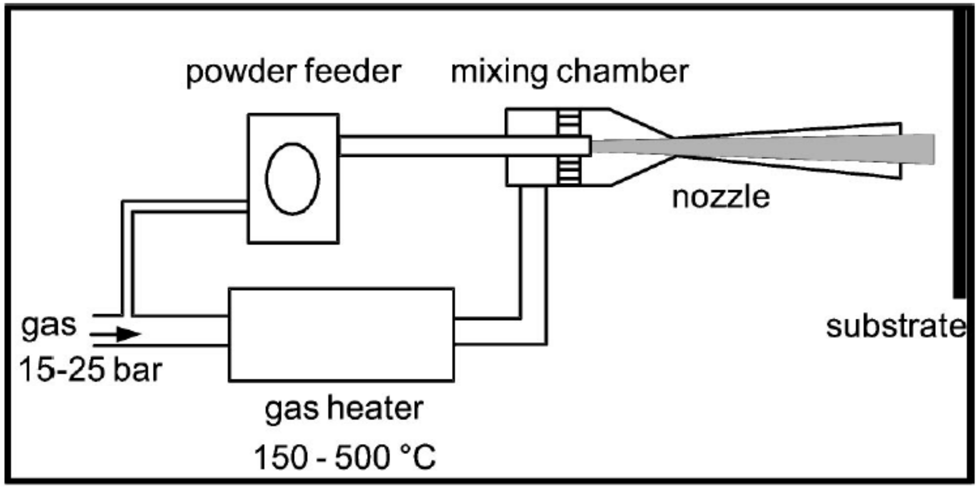




- SS construction allows fixture to be place in oven
- Applied pressure can be controlled by torque wrench or large thumb screw

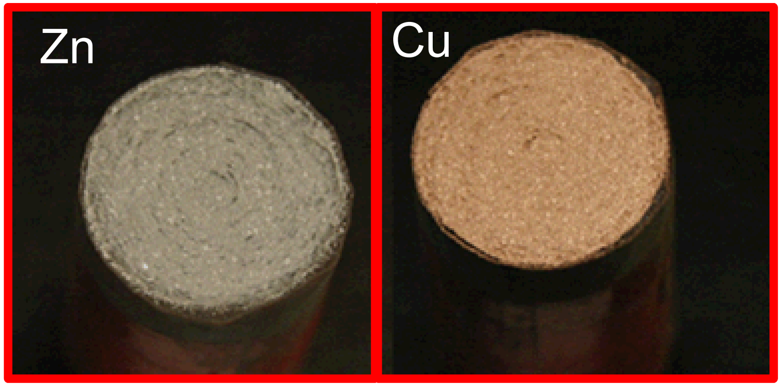
- Can “pre-cure” glass @ 65 °C for 1 hour under controlled pressure to control thickness of epoxy layer
- Remove glass from alignment fixture, clean, then proceed to final cure

Investigate Arc-Spray as Route to Apply End Terminations

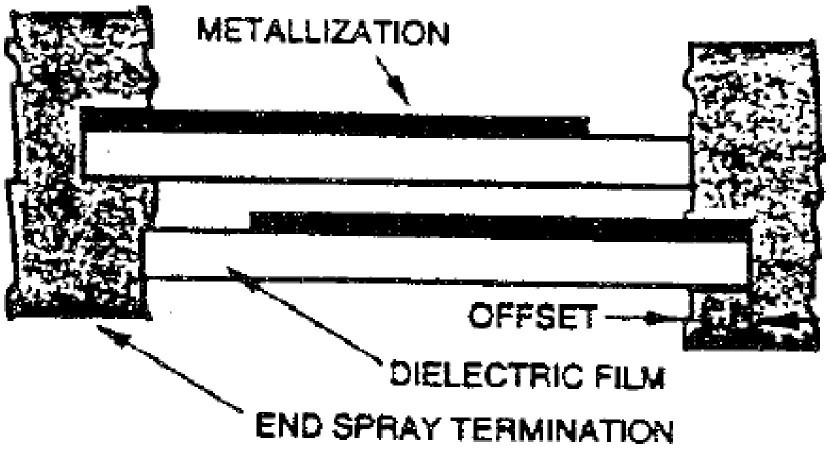


Borchers et al., JAP 2003

- Zn/Cu arc-spray on polymer capacitors
- Low temperature process – won't damage epoxy/glass structure
- Rapid deposition for thick films (>10 µm)
- Resistivity of Cu films 40-400 µΩ∗cm (bulk 1.7 µΩ∗cm)



Pylin Sarobol, Andrew Miller



Ennis et al., Pulsed Power 1997

Conclusions

- Successfully demonstrate route to make solid state multi-layer glass capacitors
- Temperature range of operation determined by bonding material (Epon 828/Jeffamine T403 -55 °C to + 65 °C)
- Breakdown data suggests area scaling of Weibull data applies
  - Need to proof test glass sheets prior to incorporation to maximize energy density
  - Working on “mass production” to demonstrate Weibull statistics on packaged capacitors
- End terminations in the works.....