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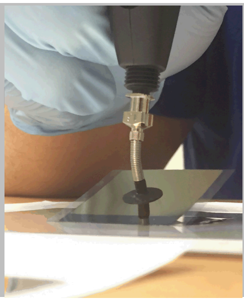

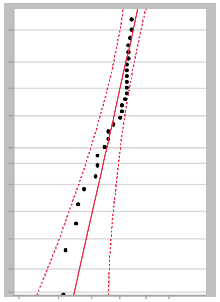

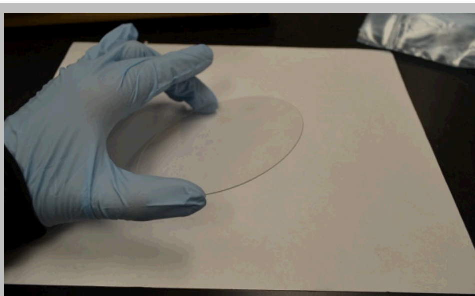

# Fabrication of Multilayer Glass Capacitors


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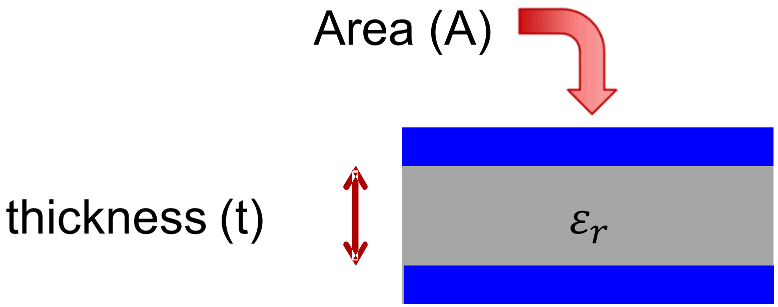
# Outline

- 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

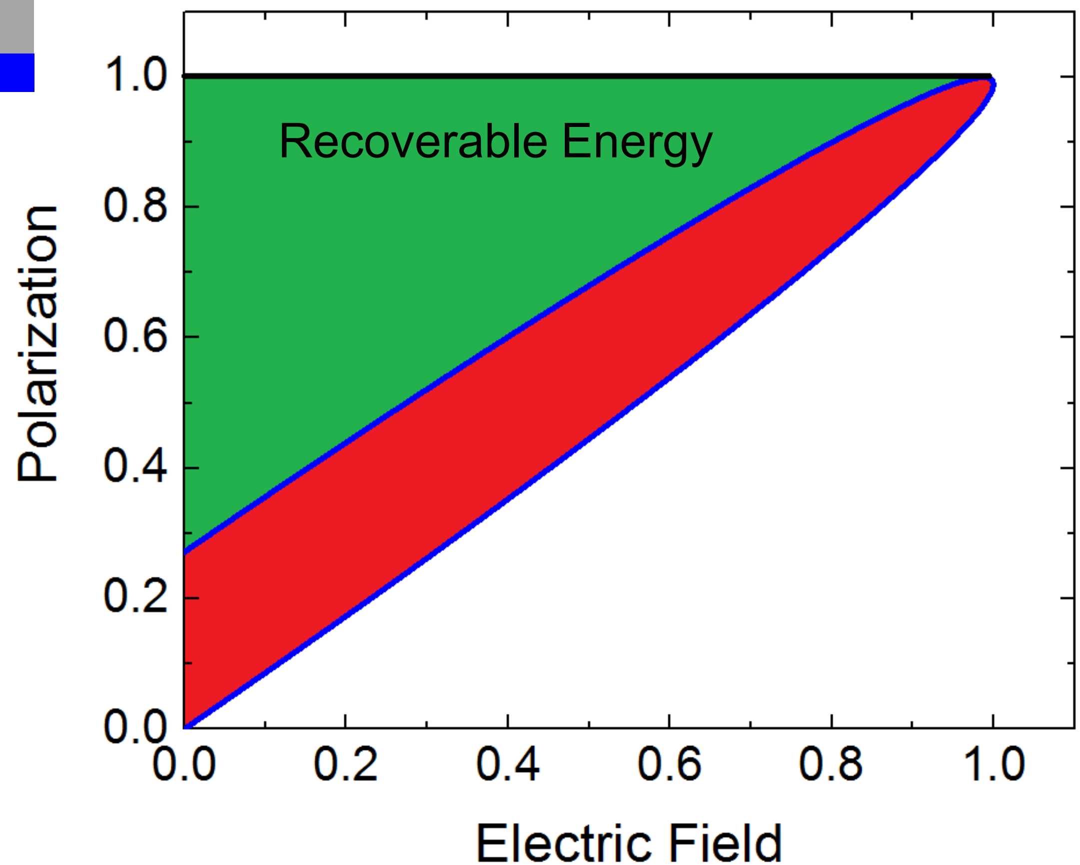



$$C = \varepsilon_r \varepsilon_0 \frac{A}{t}$$

$$W = \int P dE$$

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

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

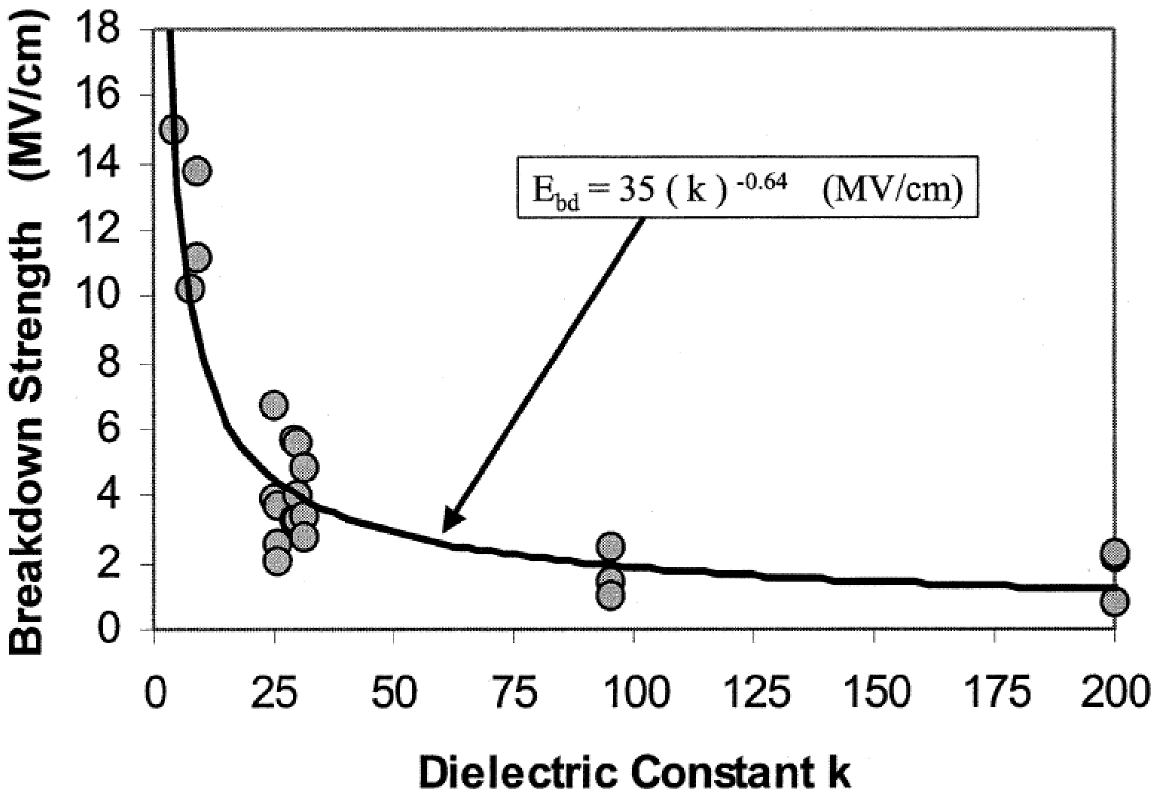


# Energy Density of Linear Dielectrics

Larger gains can be had by increasing breakdown strength

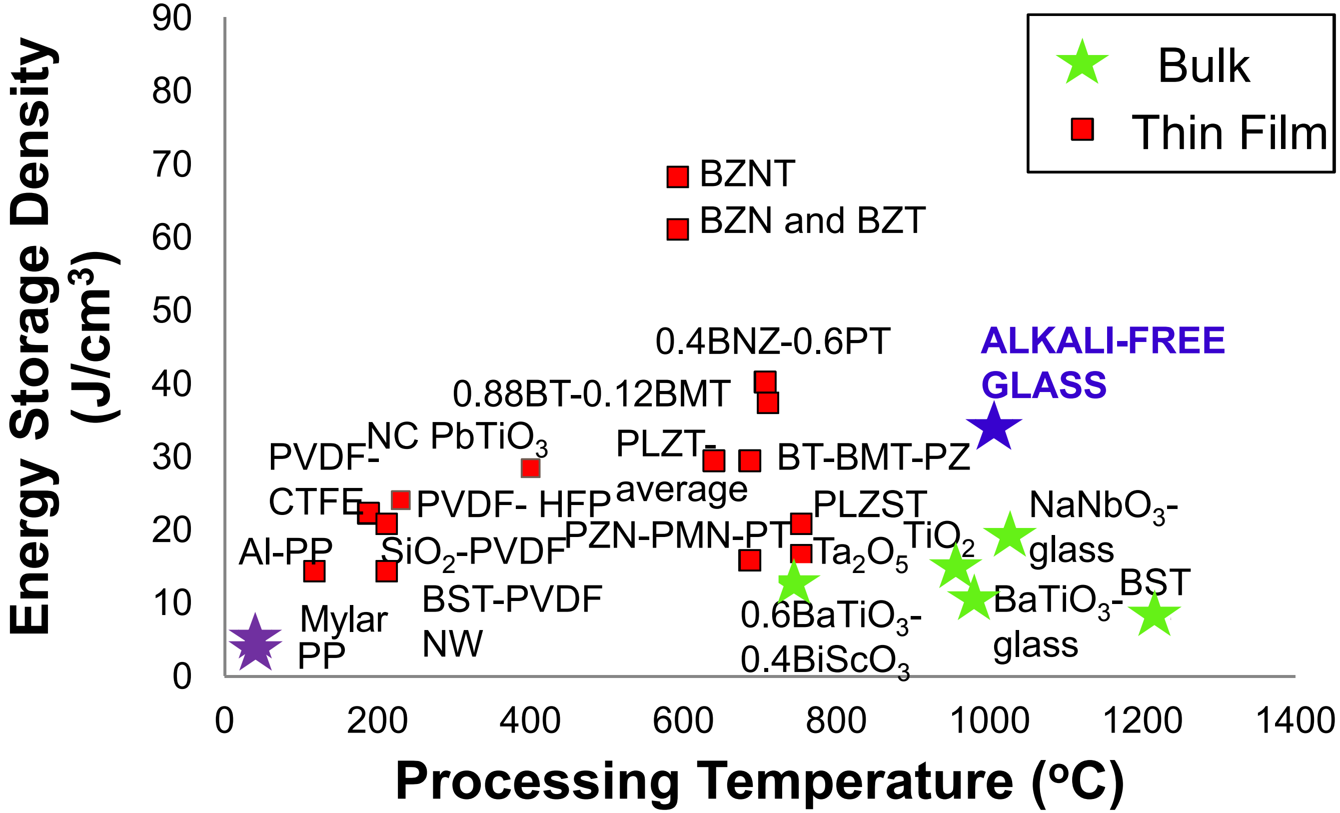
$$U = \frac{Energy}{Volume} = \frac{1}{2}\varepsilon_r \varepsilon_0 E^2$$

Limited value to tuning $\varepsilon_r$




McPherson et al. IEEE TED, 2003

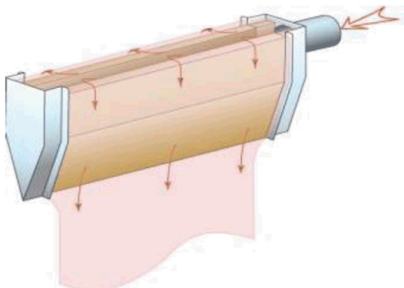
# Comparison of Capacitive Energy Storage Materials




- Alkali-free glass competitive with many emerging materials
- May have an advantage in manufacturing
- Packaged capacitors: 0.3-3 J/cc (depending on voltage rating)
  - Can we make 1 kV, 100 nF capacitors?

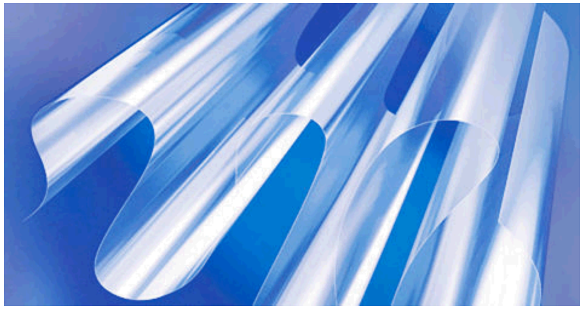
Michael et al., JACERS 98 (2015) 1223, Laihonoen, IEEE TDEI 14 (2007) 275

# Alkali-Free Glasses



- “Overflow drawn down process”

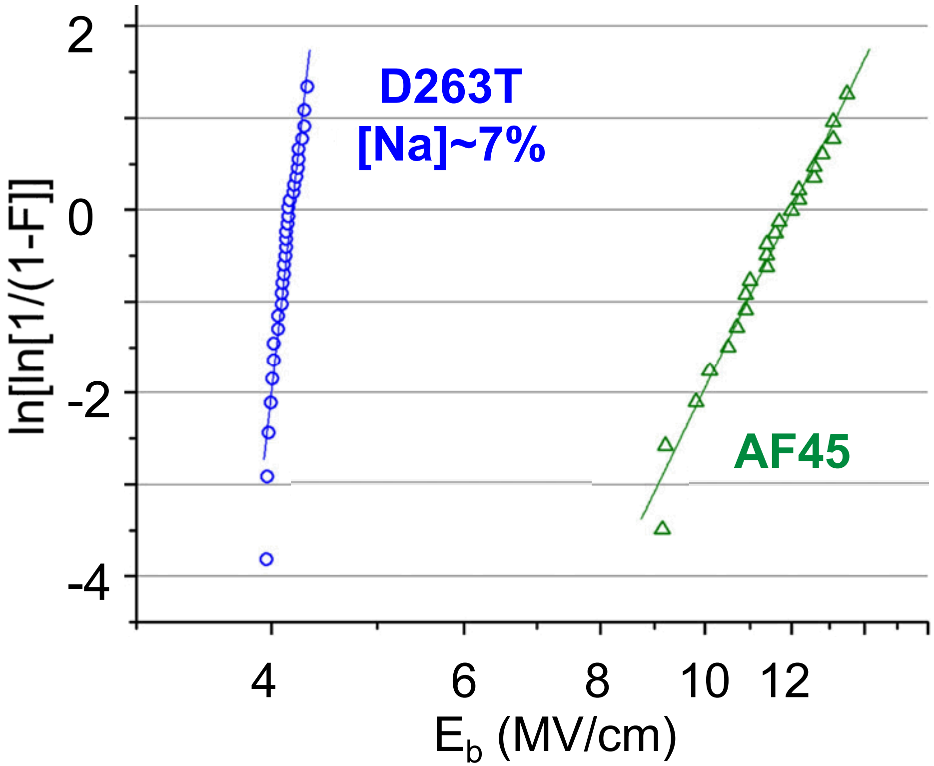
| Parameter | Value |
|---|---|
| Density (g/cm$^3$) | 2.3-2.5 |
| Young’s Modulus (GPa) | 73-75 |
| $\varepsilon_r$ | 5-6 |
| tan $\delta$ | 0.001 |
| $\rho$ ($\Omega$*cm @ 250 °C) | >$10^{12}$ |
| Strain Point | 650-700 °C |

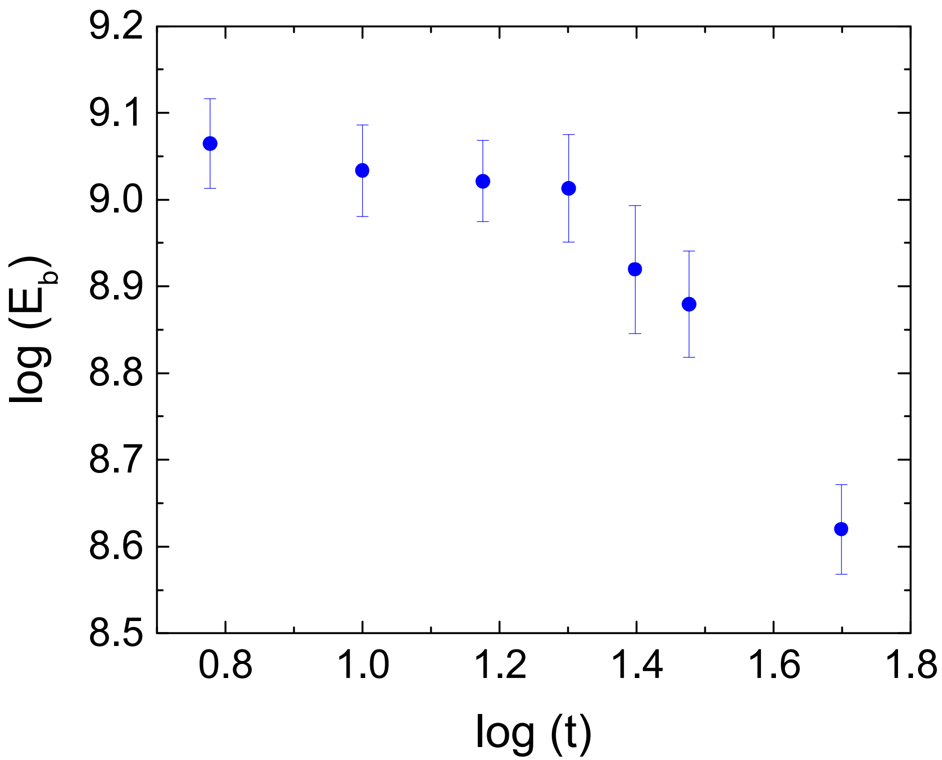


- Sold by many vendors world wide
- Boro-alumino-silicate glass category
- Sold in thicknesses ~ 100 – 200 µm
- [Na] < 350 ppm (typical)

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

# Breakdown Strength of Alkali-free Glass



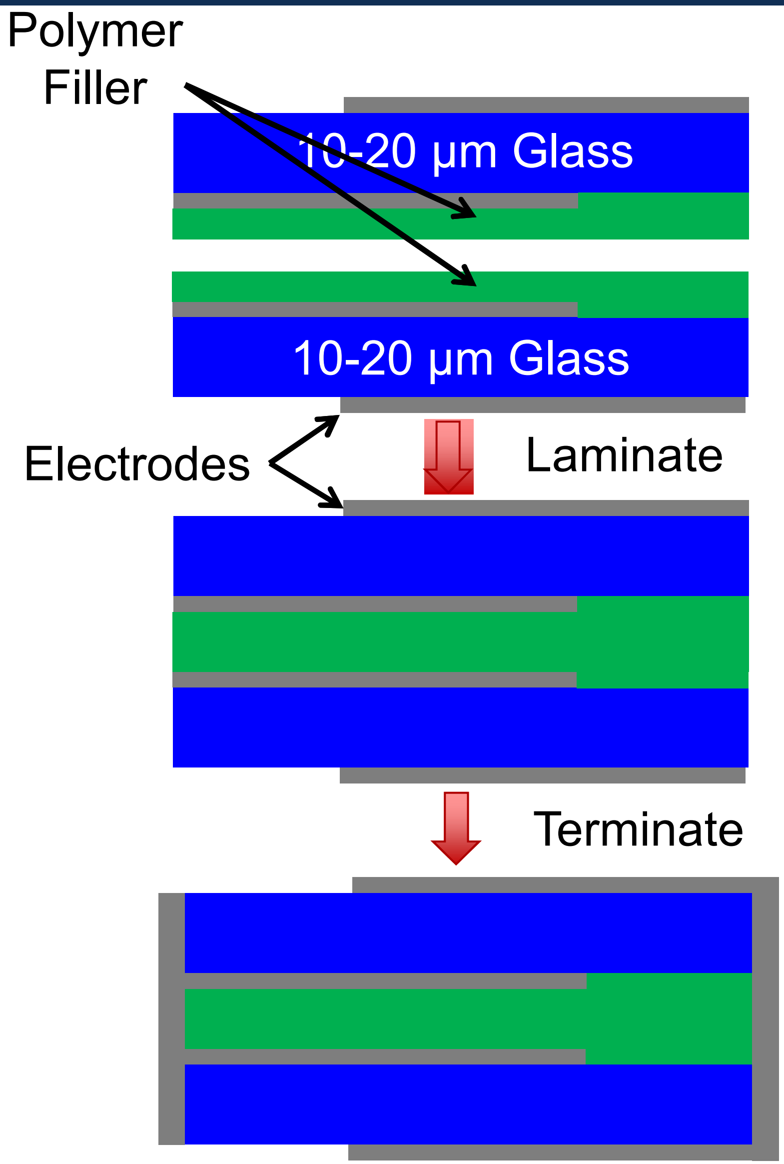




| Parameter | D263T | AF45 |
|---|---|---|
| t (μm) | 30 | 19 |
| $E_b$ (MV/cm) | 4.2 | 12 |
| β | 47.9 | 10.7 |

- 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

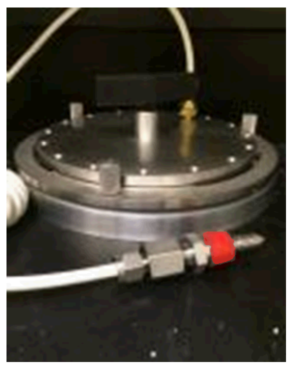
# Approach for Bonding Metallized Glass

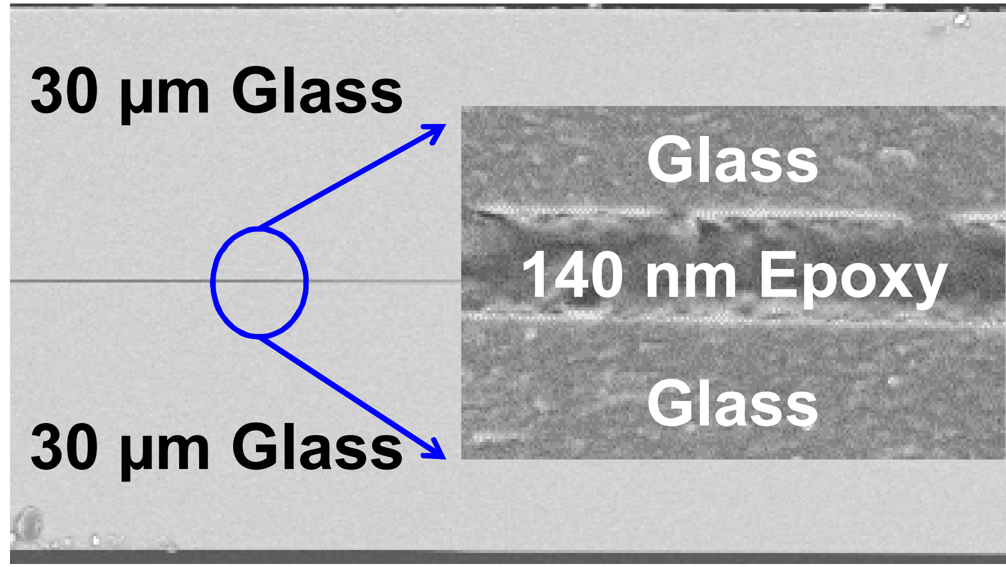



- Thinned glass is manufactured "layer by layer"
- Need approach to physically and electrically connect multiple layers to form final capacitor
- Bonding Approach – laminate using high breakdown strength Epon 828/Jeffamine T403
  - Analogies to epoxy impregnated mica-paper capacitor construction


http://machinedesign.com

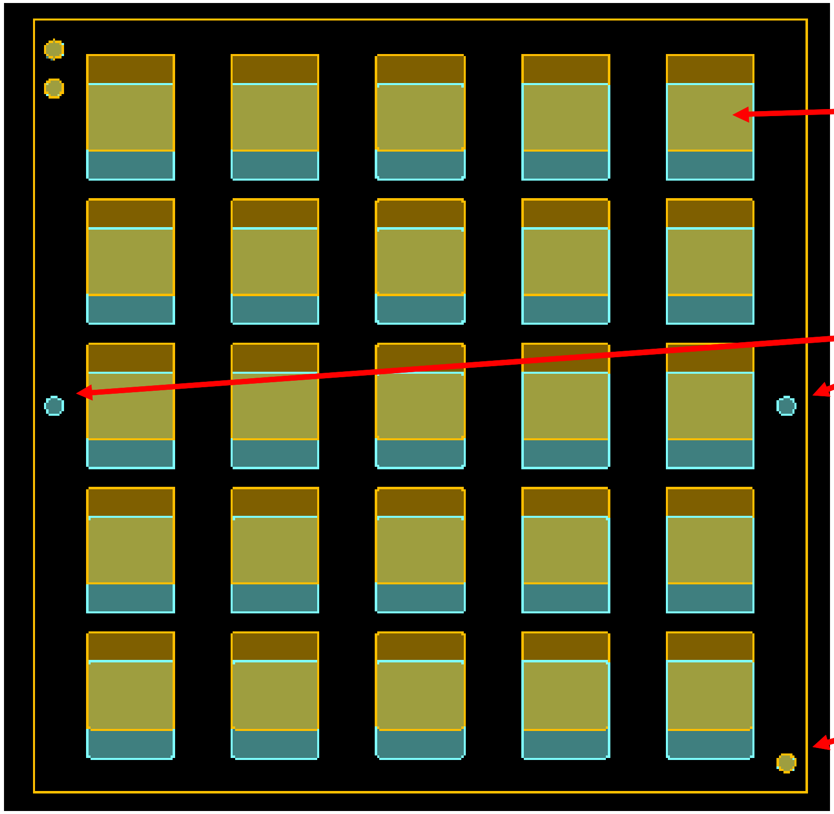
# Demonstration of Bonding under Pressure






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

# Aligning Electrodes



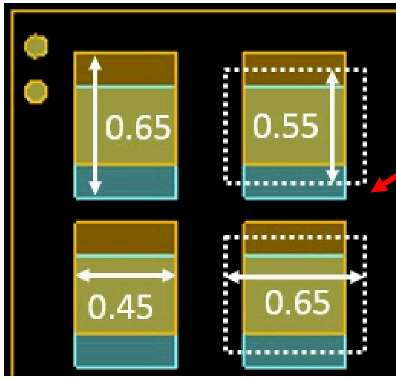
Metallized Electrodes
0.45” x 0.5” (0.15” offset)
Active area 0.35”x0.45”

Reference Marks for Laser Machining
Cut out for Alignment Fixture

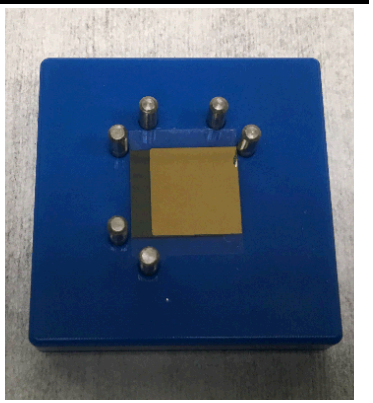
Reference Marks for Aligning
Shadow Mask
for Top/Bottom Electrodes

- 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

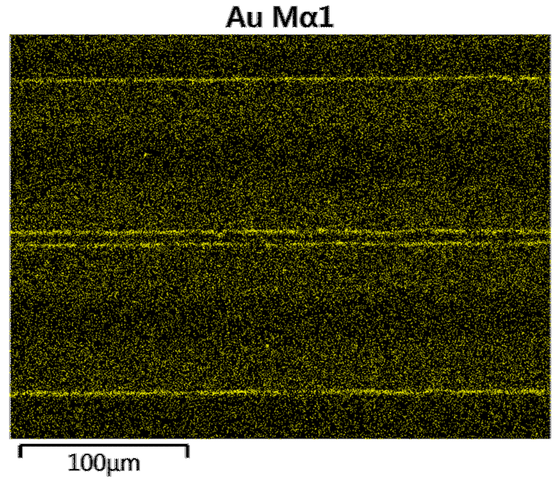
# Fabricating Capacitor using 3D Printed Fixture




Laser cut (0.1” edge margins)



Bond/Polish ends

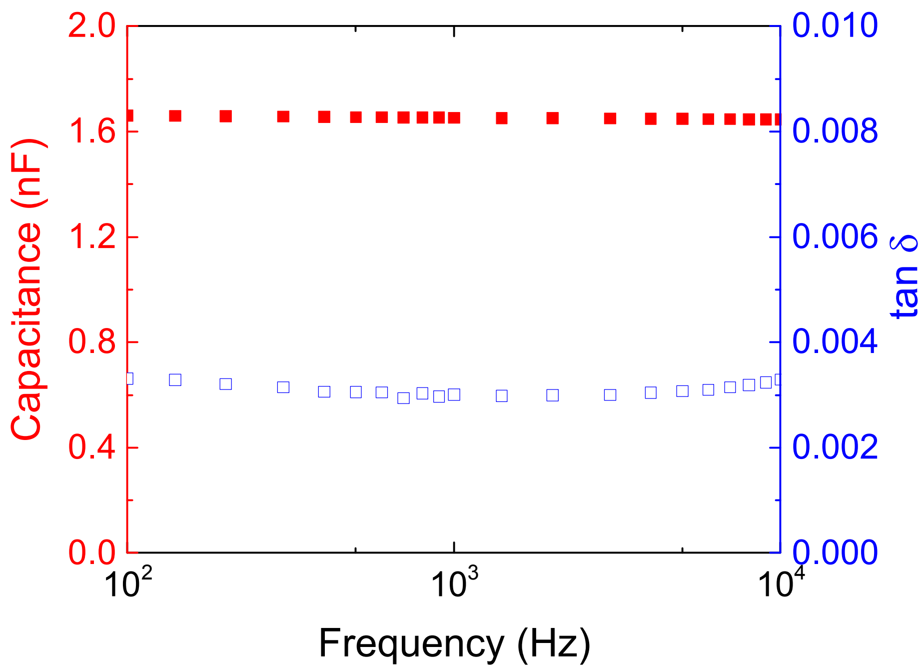


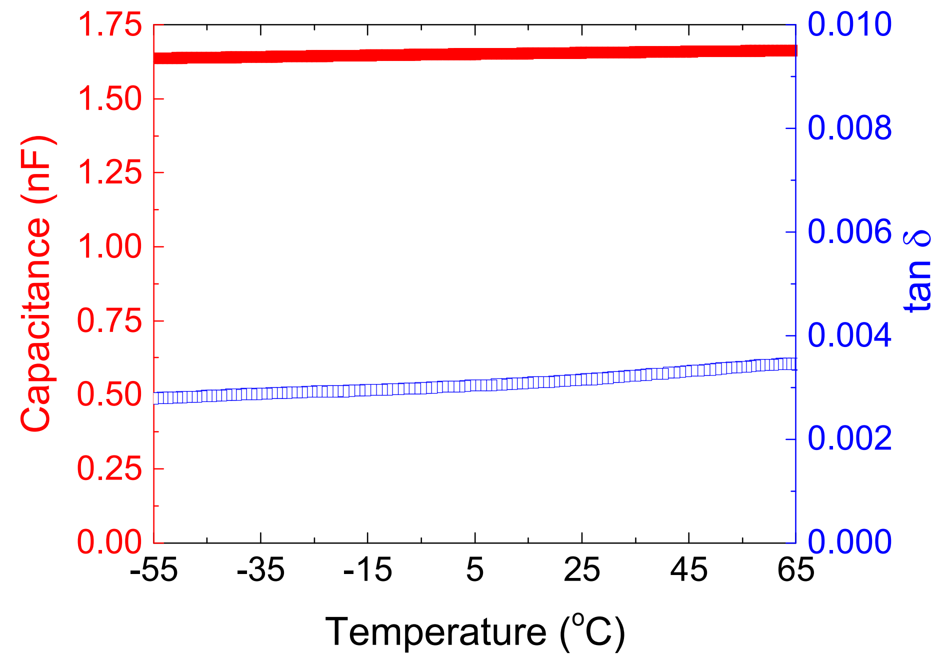

Terminate

Sputter Deposited End Terminations

- Active area of capacitor is 0.35”x0.45” (Total area 0.55”x0.65”)
  - 160 pF per layer for 30 µm thick glass
  - Have process to thin to 10 µm (500 pF per layer)
  - Long term goal is 5 µm (990 pF per layer)

# Electrical Properties of 10 layer Capacitor




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

# 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