Trends for Glass in Electrical Components and Systems

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Components and Systems

- Multilayer Ceramic Components
  - Low cost electrodes in Multilayer Ceramic Capacitors (MLCCs)
  - Lower sintering temperatures in Low Temperature Co-fired Ceramics (LTCC)
- High Temperature Power Electronics
  - Reliability
  - Graceful failure coatings
- Pulsed Power Dielectrics
  - Nanocrystals in an amorphous matrix
  - High breakdown strength
- Metamaterials
  - GHz to THz
  - Periodic structures

Role of Glasses in MLCC

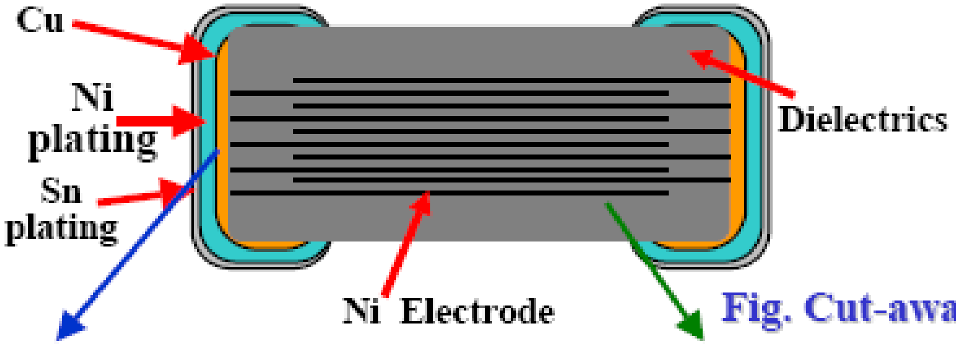
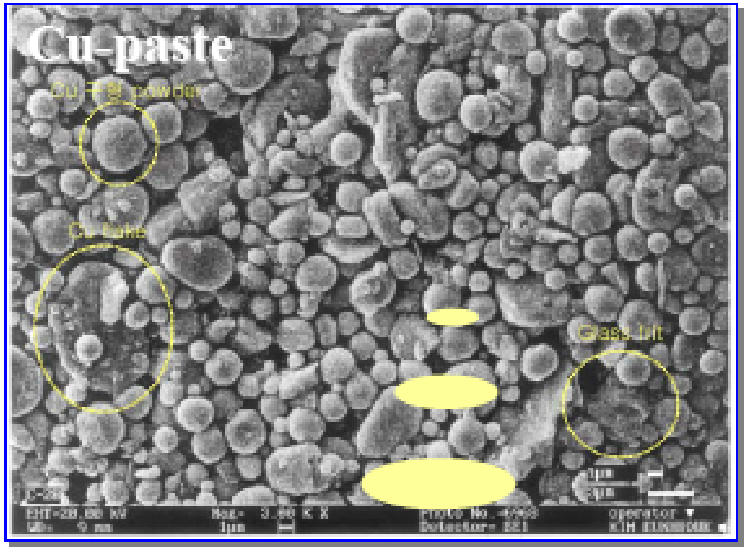
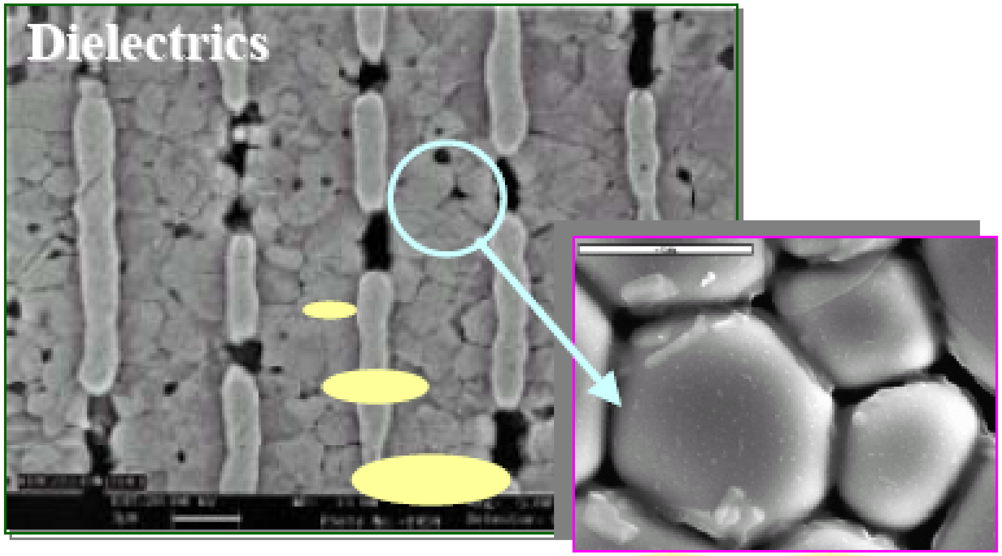


Fig. Cut-away view of MLCC





Glass is of major importance as an bond between ceramic and metal, and a filler.

Glass is of major importance as an additive to ceramics in order to promote sintering at low temperature.

Presented by Dr. Song Moon Song, Center for Dielectric Studies Fall Meeting

Key Challenges for Glass Additives in MLCCs

- Particles
  - Must be nanoscale
  - Well dispersed with BaTiO3 powder
  - Low volume fraction loading
- Scale-up challenges
  - Li-B-Si-O glass for reduced sintering
  - Li activity in large furnaces
- Glass wetting angle in microstructure

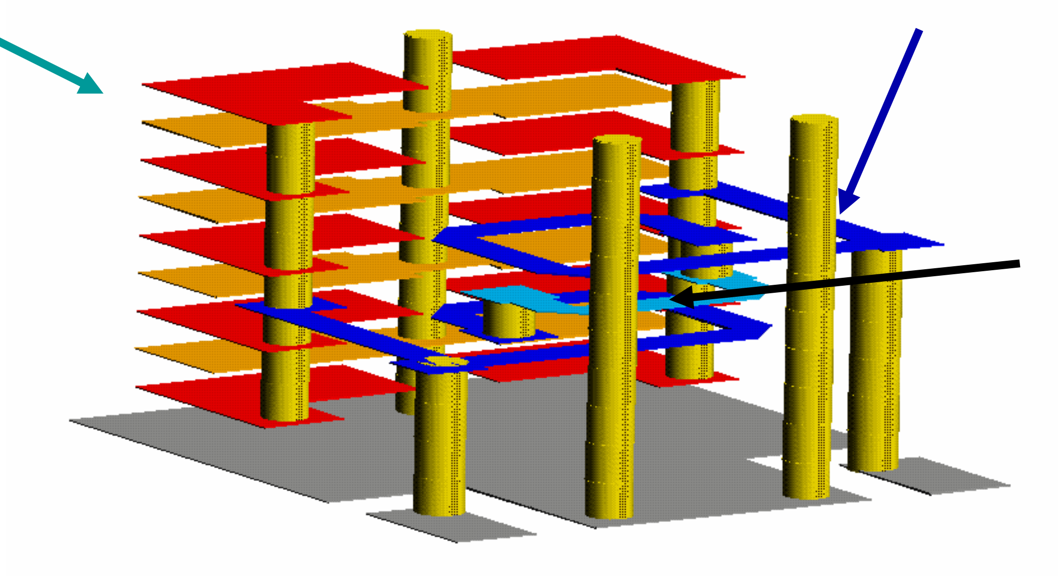
Vision for Device Integration for Low-Temperature co-fired Ceramics (LTCC)

Capacitors

high-permittivity dielectrics
high Q-factor
Low processing temperatures

Inductors & Transmission Lines

Low-permittivity dielectrics
High-tolerance line definition
Low resistivity in metal lines (Silver, Copper)



Resistors

high-tolerance
chemical compatibility
low fire

Requires chemical compatibility with other materials in the system.

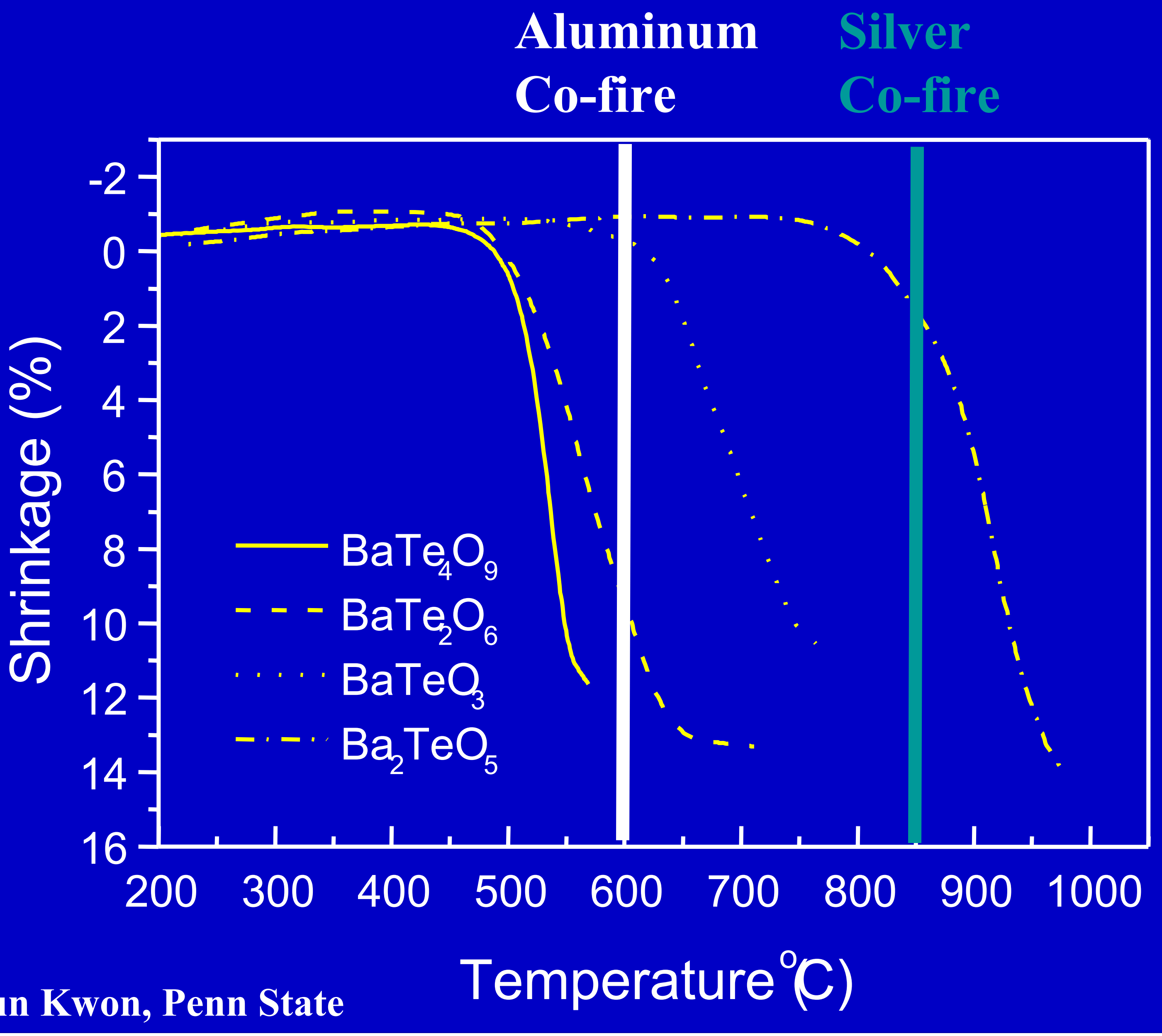
- Co-process dielectrics with high conductivity metal.
- Low sintering temperatures are required (T<930°C for Ag, T<660°C for Al).
- Glass is used to lower the sintering temperature

Metals for Co-processing with Ceramics

High Conductivity Metal Electrodes

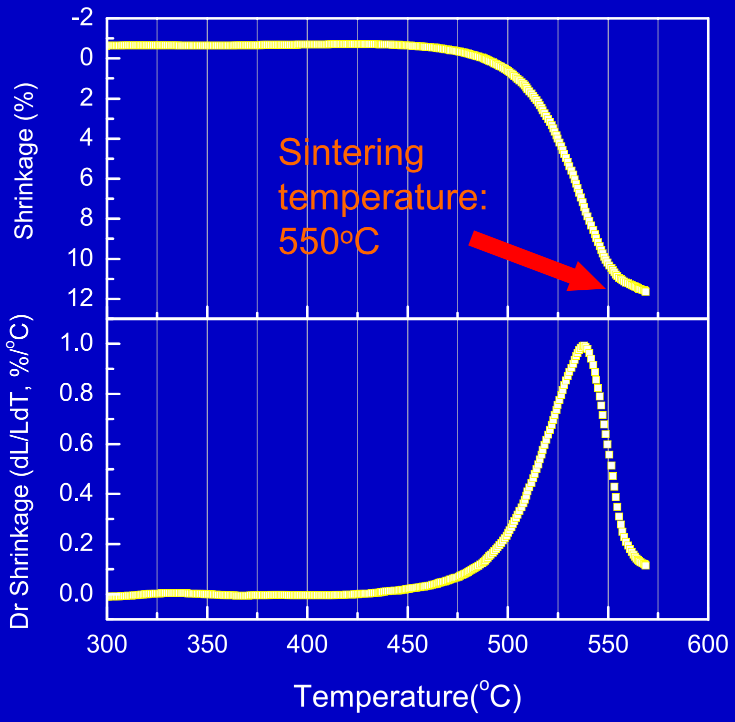
Metal	Electrical Resistivity (μΩ·cm)	Melting Point (°C)	Application
Cu	1.7	1083	LTCC
Au	2.3	1063	
Ag	1.6	960	
Al	2.7	660	ULTCC
Pd	10.3	1552	-
Pt	10.6	1769	-
Ni	6.9	1455	-
W	5.5	3410	HTCC
Mo	5.8	2610	

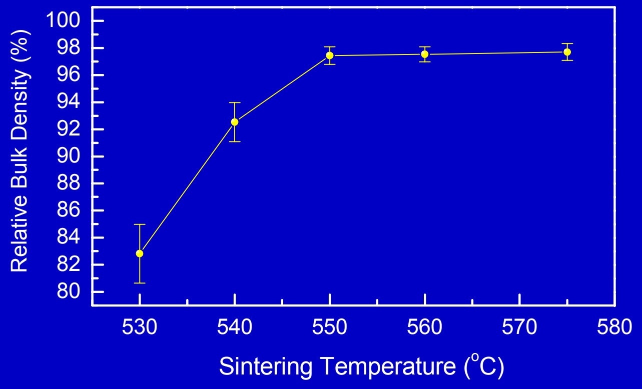
Densification (Sintering)



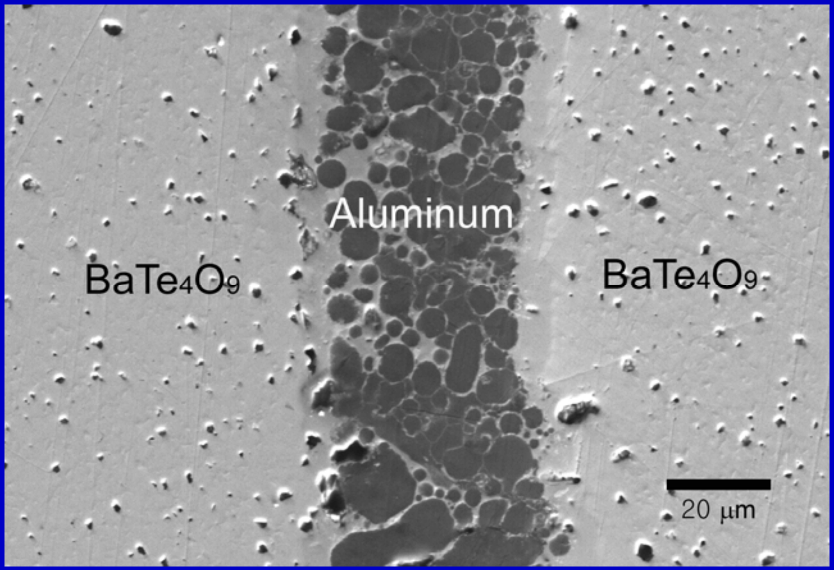
Do-Kyun Kwon, Penn State

Co- Sintering of $BaTe_4O_9$ with Glass/Aluminum





- Co-firing Aluminum and $BaTe_4O_9$



Aluminum paste courtesy of ESL Corporation

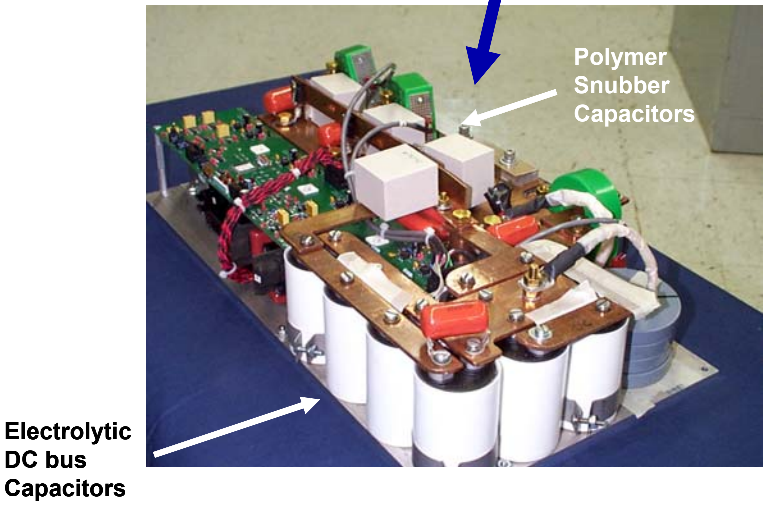
D.-K. Kwon*, M.T. Lanagan, and T.R. Shrout, 2005, "Microwave Dielectric Properties and Low Temperature Co-Firing of BaTe4O9 with Aluminum Electrode," *J. Am. Ceram. Soc.* 88 (12):3419-3422 (Dec 2005).

Key Challenges for Glass Additives in LTCCs

- Lower sintering temperatures to be compatible with Ag, Cu, and Al.
- Chemical compatibility with other dielectrics.
- Control glass migration by viscosity and wetting
- Dielectric properties for low loss

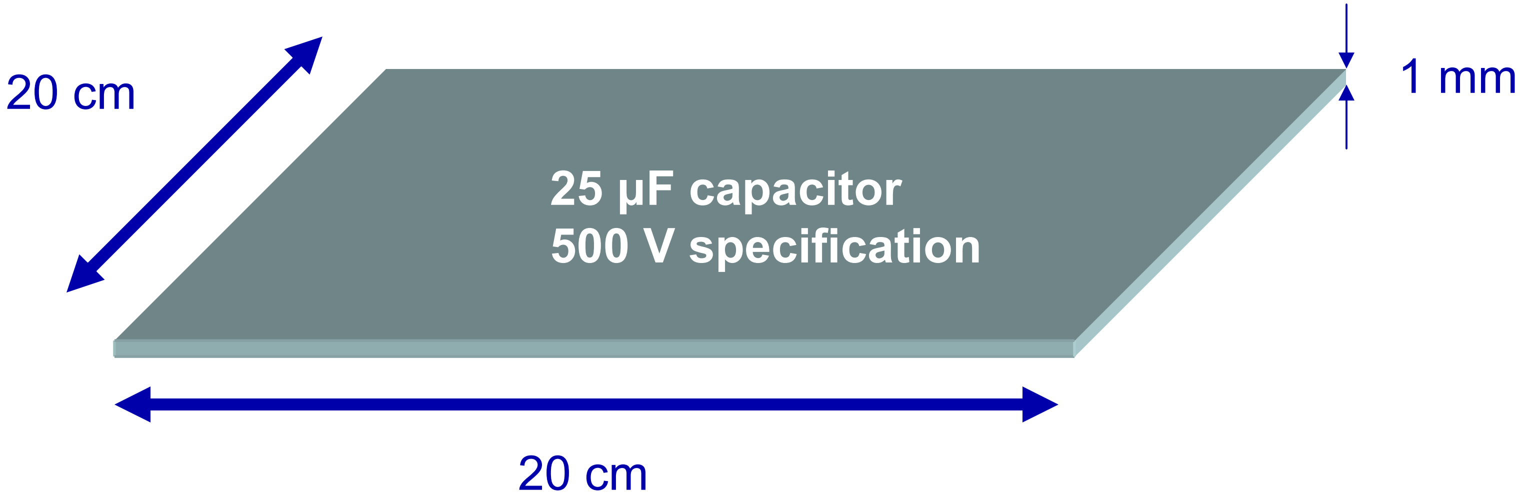
Glass for High Temperature Power Electronic Components

- Replace polymer components with glass for high temperature operation?



Capacitor Design with thin Glass Sheet

Assumptions: 10 µm thick glass layer
100 layers
Operating Field 0.5 MV/m
Operating Temperature 140°C



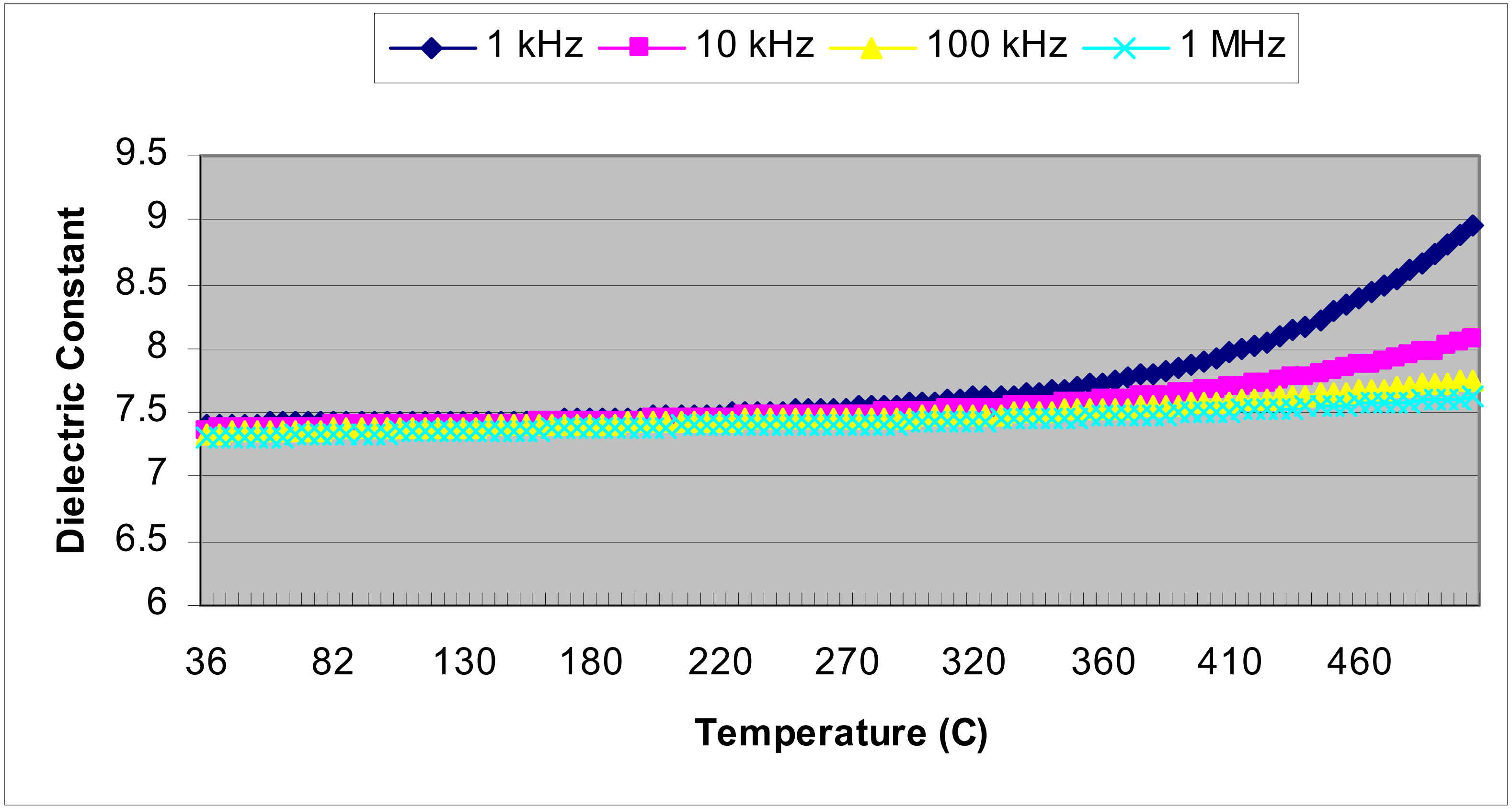
Commercial Multilayer Ceramic Capacitor (16 µF, 400V, 125°C) cost is $ 20.

Data based on ORNL report by Robert Staunton

DOE goal is (2000 µ F, 600V, 140°C) and cost is $ 30.

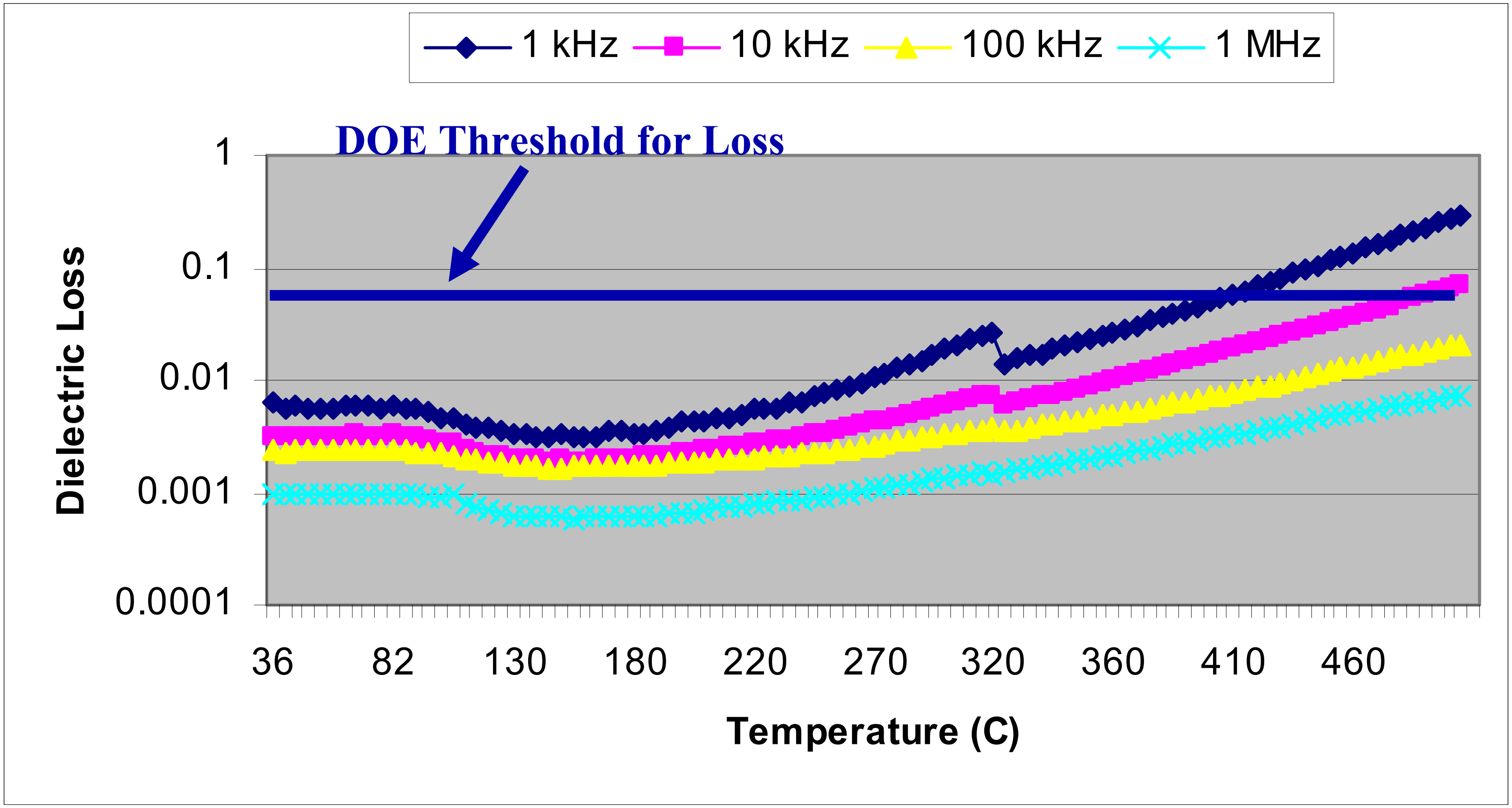
Data based on DOE FreedomCar report

Dielectric Properties of Commercial Flat Panel Glass



- Dielectric Constant of commercial glass is twice that of commercial polymers
- The capacitor size will be reduced to 50% of the polymer film capacitors.

Dielectric Properties of Commercial Flat Panel Glass



- Meets DOE specifications for dielectric loss up to 270 °C
- Low dielectric loss will translate to a low ESR for large capacitors

Key Challenges for High Temperature Glass Power Capacitors

- Can we achieve 10 µm layers?
- Need to develop a graceful failure electrode system

Glass for Pulsed Power Systems

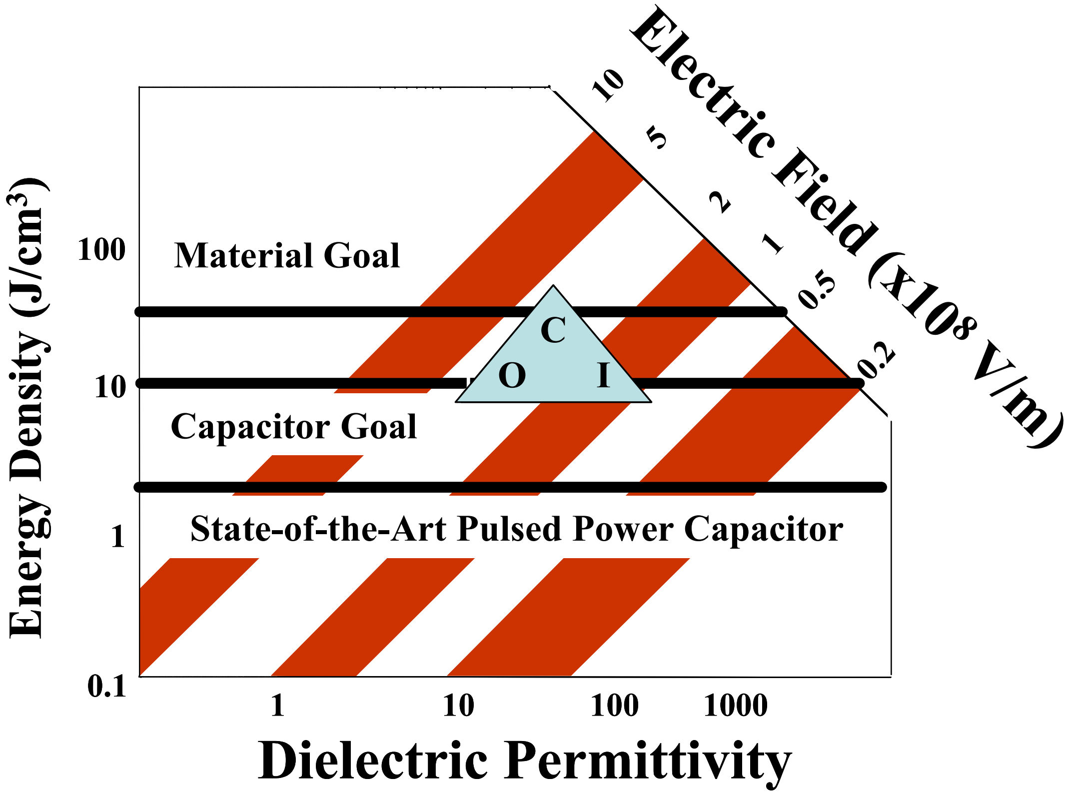
Biomedical, automotive, and military systems require high energy density dielectrics.

Energy Density

$$U = \varepsilon_o \varepsilon_r E^2$$

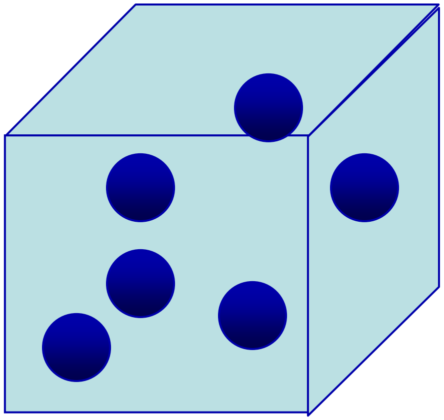
Permittivity

Electric Field



“O” =Organics, “I”= Inorganics
“C”=Composites

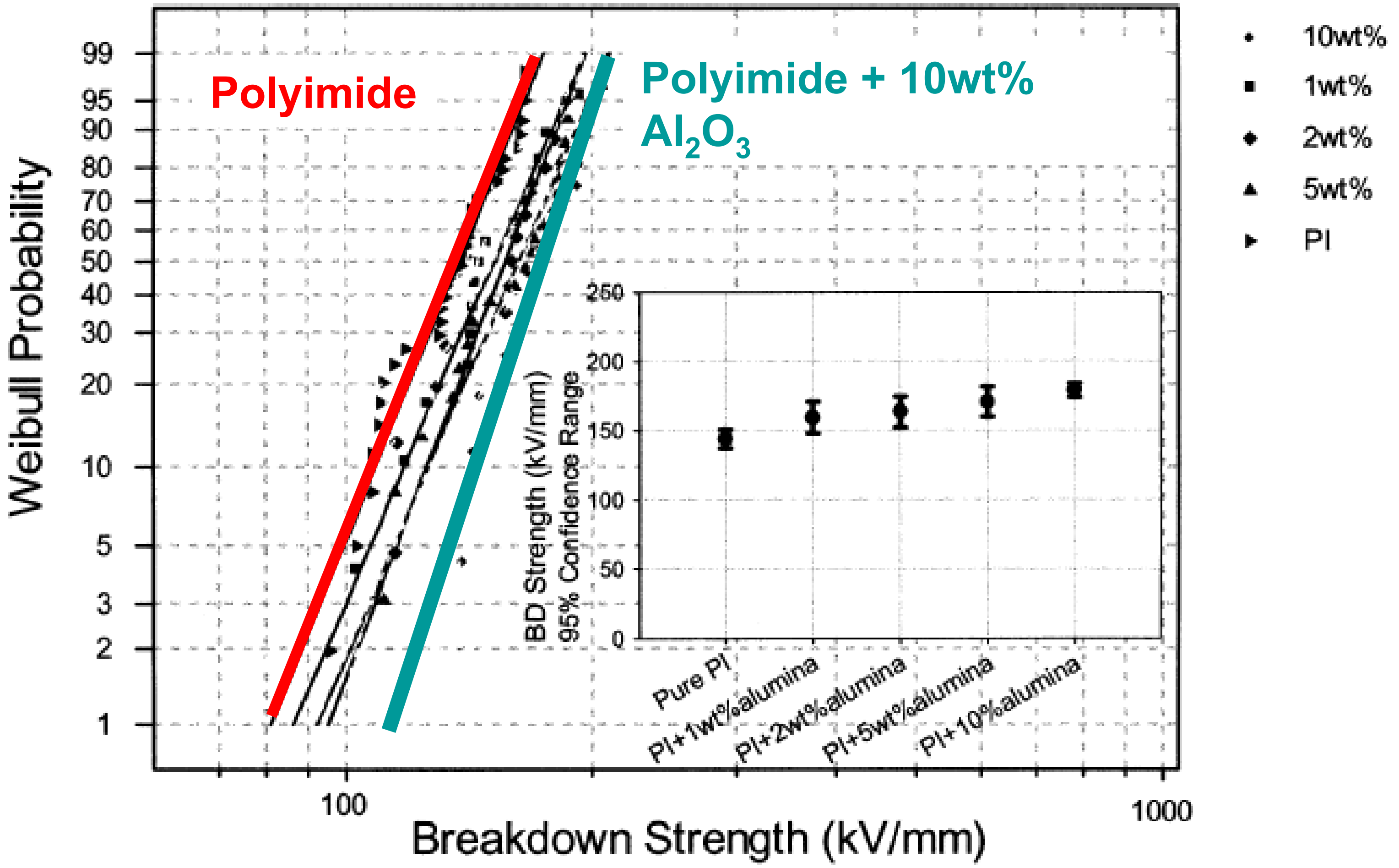
Particles in an amorphous matrix



- Dielectric contrast
  - difference between matrix and particles
- Role of interfaces
  - Increased breakdown strength
  - Reduction of space charge
- Interparticle distance

- Matrix Dielectric
  - BOPP, PVDF, Glass?
- Particulates
  - Low ε_r: SiO_2, Al_2O_3
  - Med ε_r : ZrO_2, Nb_2O_5
  - High ε_r : TiO_2, $BaTiO_3$

Effect of Nanoparticle Addition on Breakdown Strength in Amorphous Polymer



Y. Cao et al., Trans. Diel. Elec. Insul. 2004

Enhanced Breakdown Strength of Polyimide with 5wt% Nanoparticle fillers

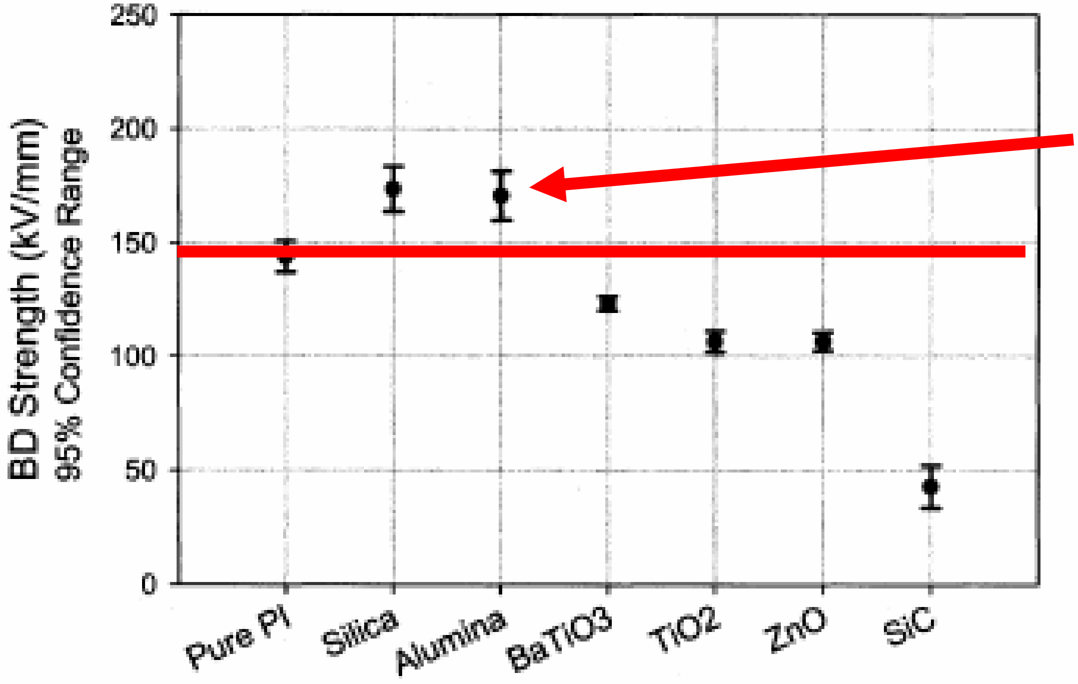


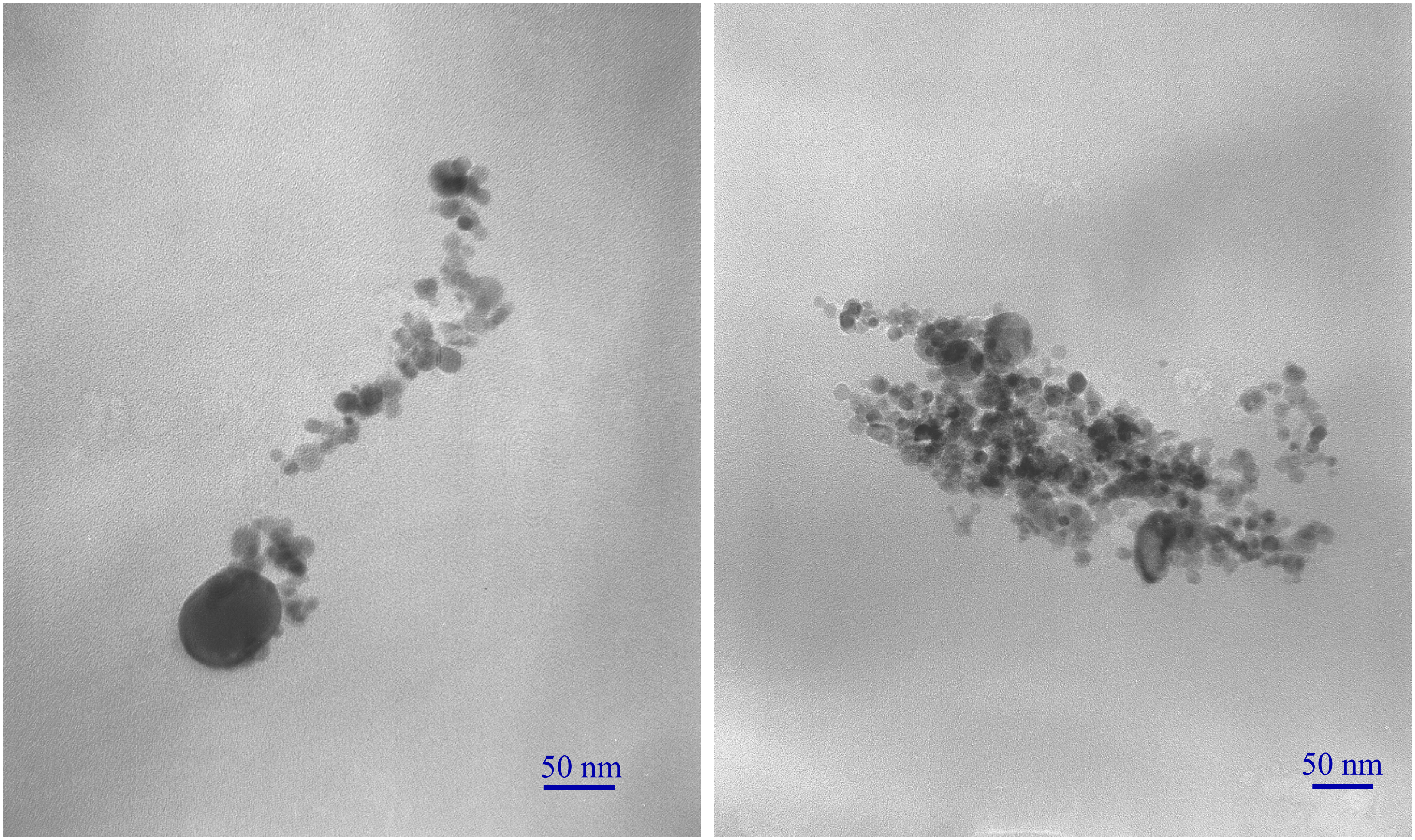
Figure 6. ac breakdown strengths for PI with various nanofillers at 5wt% loading. The tests were performed with 500 v/s ramp rate on samples of 25 μm thick. The remarkably low breakdown strength of SiC nanocomposites may be caused by the aggregation of SiC nanoparticles.

Why better than unloaded polymer and other nanoparticle species?

- **Particle Dispersion**
- **Lower ε_r**
- **Lower Conduction**

Y. Cao et al., Trans. Diel. Elec. Insul. 2004)

Particle dispersion in 0-3 composites



Enlarged TEM images showing the distributions of ZrO_2 particles in PVDF matrix

B. Neese, Q. Zhang, GaiYing Yang and Clive Randall, Penn State

Nanoparticulates in Vycor glass were previously studied for optical properties

- Process was demonstrated for iron oxide in Vycor
- Disperse Particles
- Uniform matrix
- 10 nanometer particle diameter.

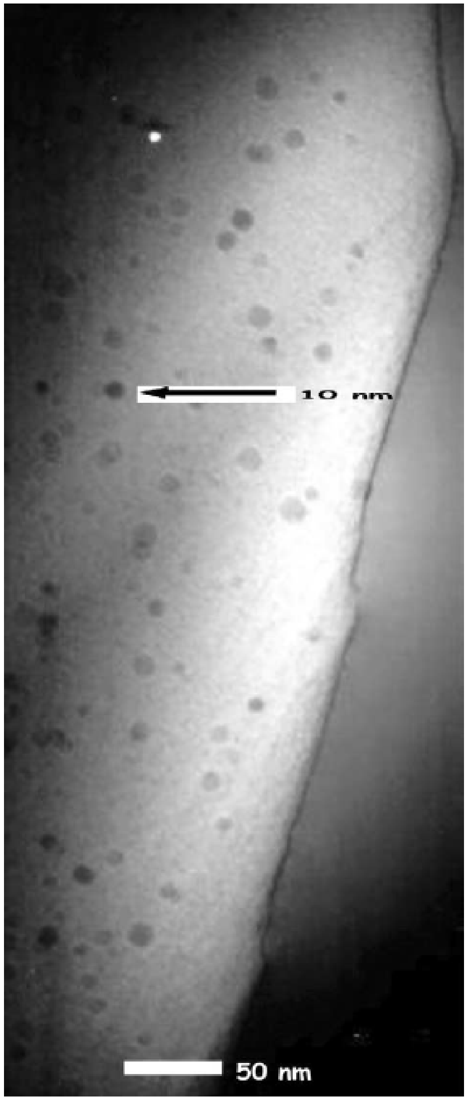
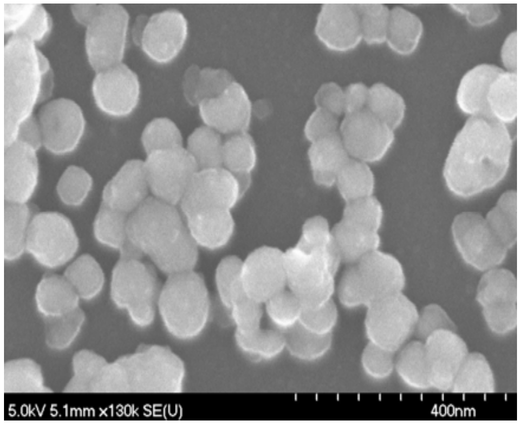


Fig. 2. TEM micrograph of photolyzed sample after cor dating the glass at 1200 °C.

D. Sunil et al. / Journal of Non-Crystalline Solids 319 (2003) 154–162

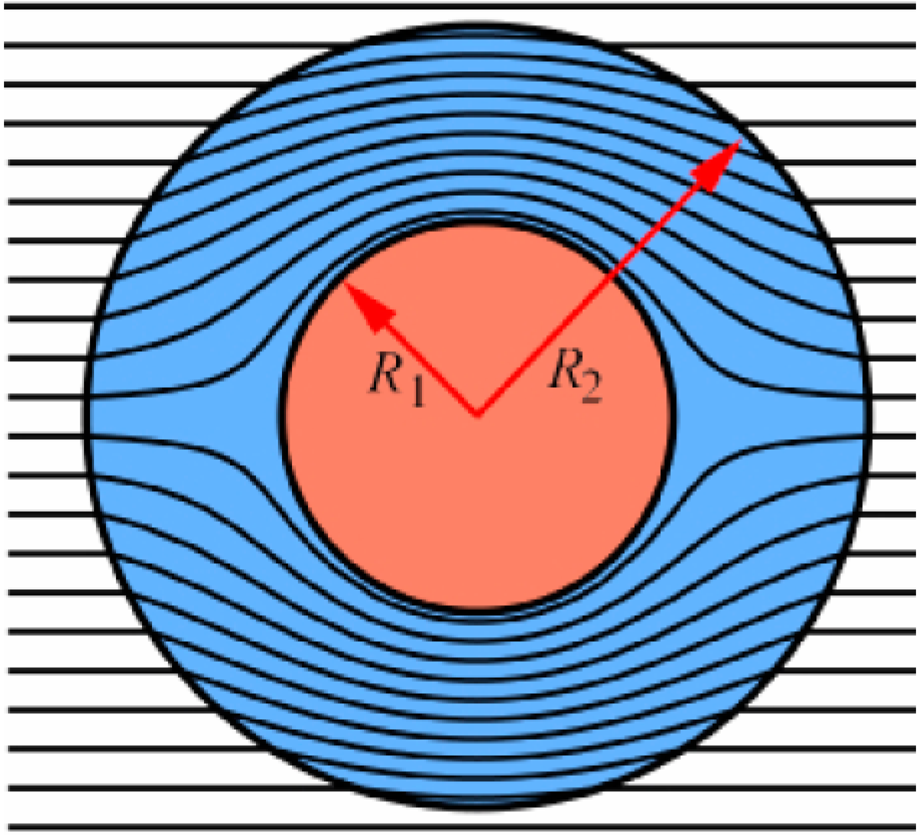
Key Challenges for Glass in High Energy Dielectrics for Pulse Power

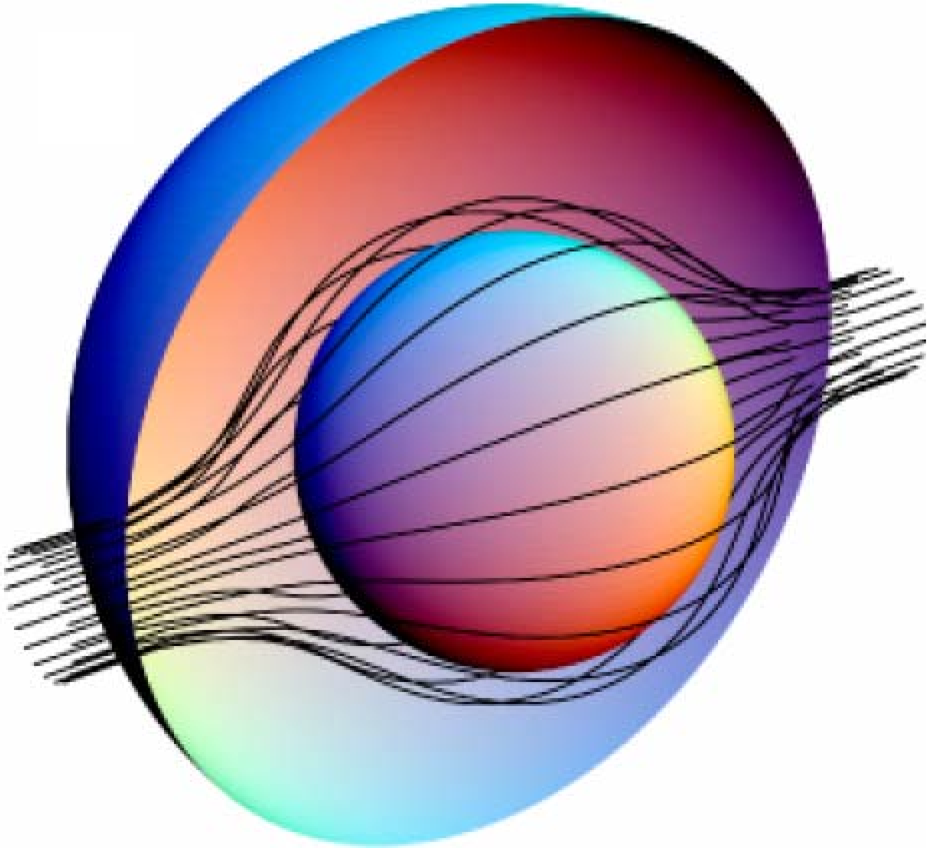
- Particles
  - Must be nanoscale
  - Well dispersed
  - Controlled interface
- Glass Matrix
  - Intrinsically low conductivity
  - High breakdown strength



Glass Metamaterials

Cloaking Devices

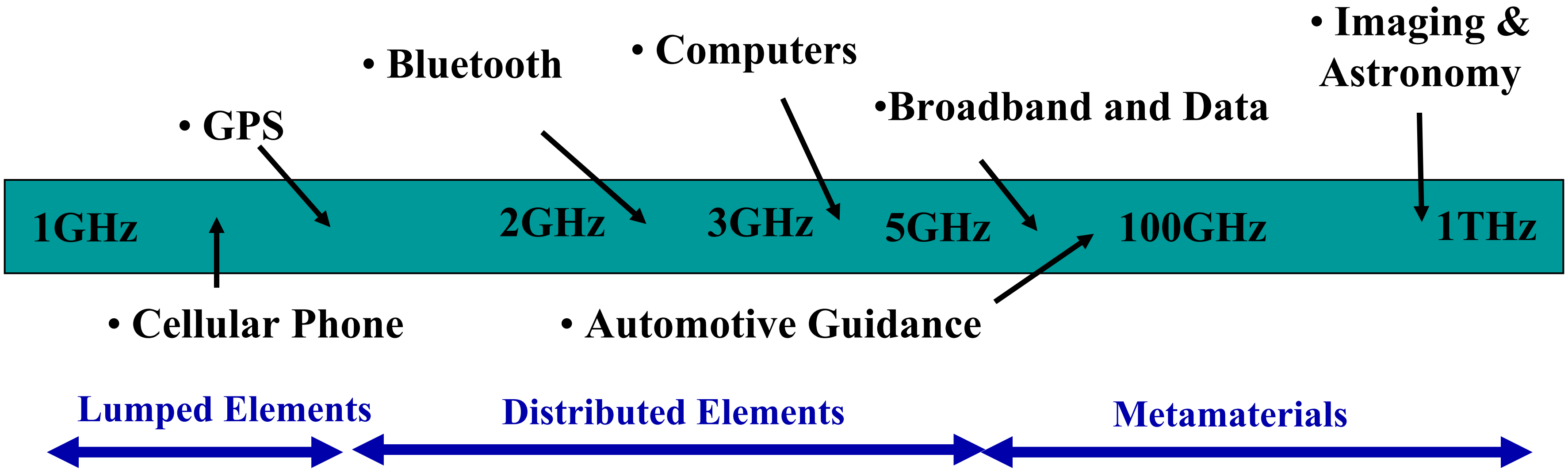




*J.B. Pendry *et al.*, *Science* **312**, 1780 (2006).

Moving Toward THz Applications

- **Materials Trends**
  - Lower permittivity (dielectric constant) and lower loss (higher Q)
  - All dielectric (no metal?) structures
- **Design and Process Implications**
  - More compact designs
  - Dimensional control becomes more critical



• Imaging & Astronomy

• Computers

• Bluetooth

•Broadband and Data

• GPS

1GHz

2GHz

3GHz

5GHz

100GHz

1THz

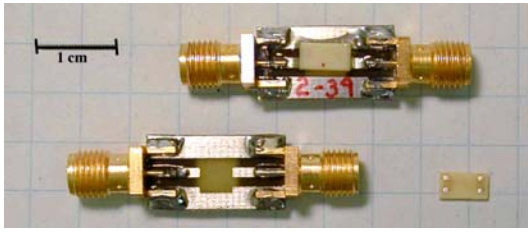
• Cellular Phone

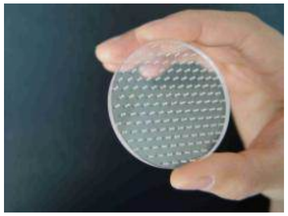
• Automotive Guidance

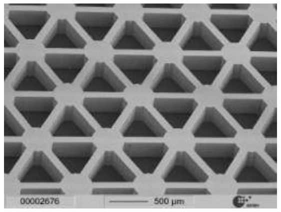
Lumped Elements

Distributed Elements

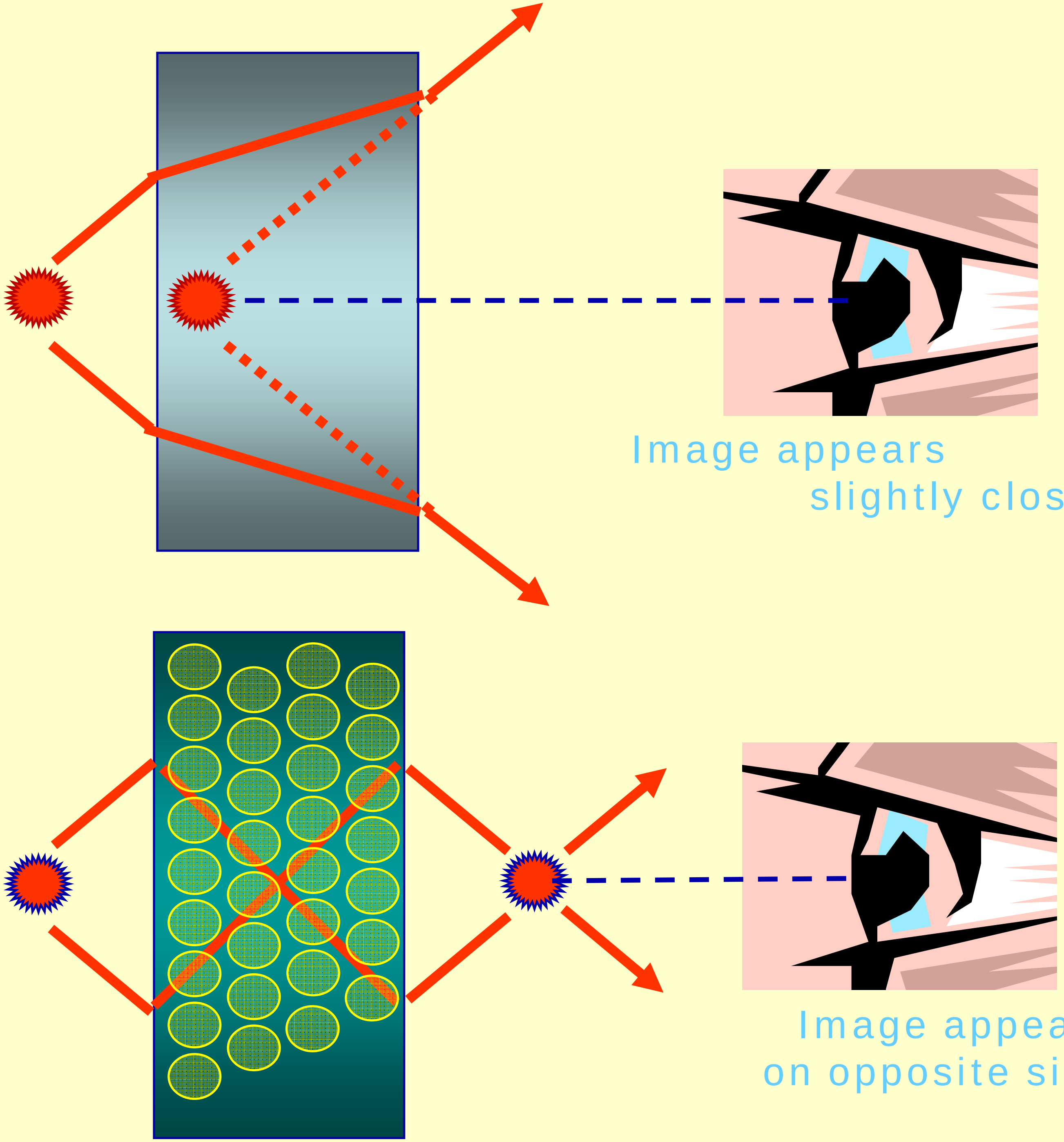
Metamaterials







*http://www.fz-juelich.de/isg/isg2/isg2-sh/ebg_materials.htm


Natural Material

Positive
Index of
Refraction

Image appears
slightly closer

Meta-Material

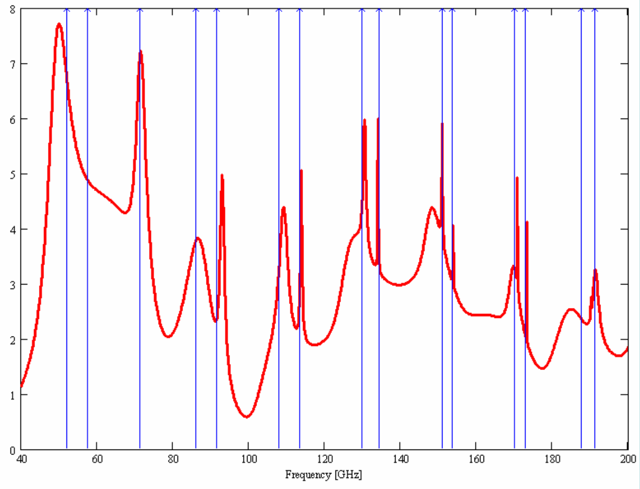
Negative
Index of
Refraction

Image appears
on opposite side

THz measurements

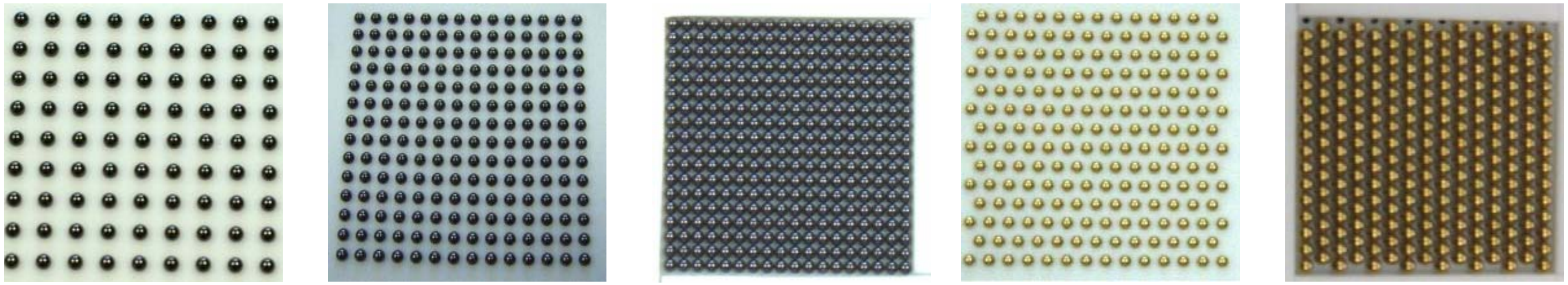
- Materials:
  - Silicon Nitride, Si_3N_4 $\varepsilon_r \approx 8.9$
  - Brass
- Lattices:
  - Square
  - Hexagonal
- Unit cells:
  - 4mm
  - 3mm
  - 2mm

Mie theory (single sphere) and loosely coupled (unit cell = 4mm) array



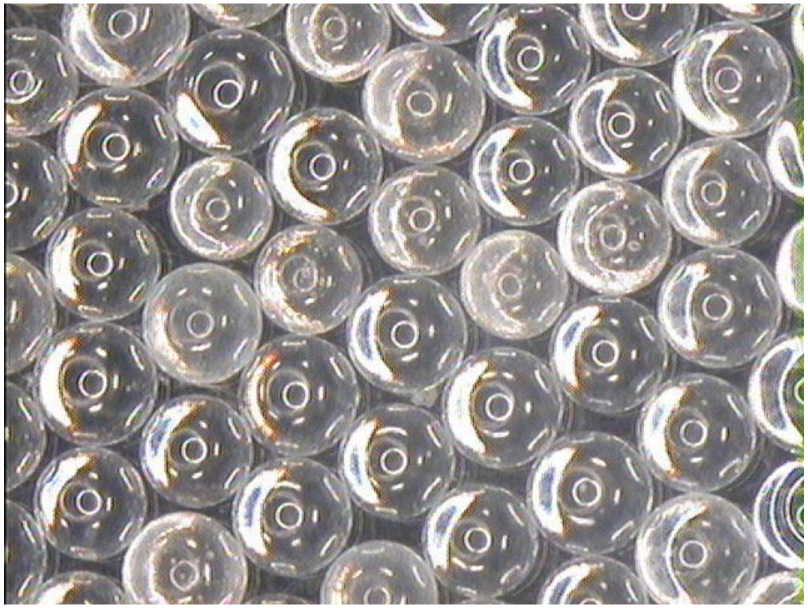
Blue – Measured resonant frequencies

Red – Scattering cross-section (Mie)



What’s Next for Metamaterials?

- Higher Frequencies pushing into the THz range
- All dielectric structures
- Free space optical testing.



1 mm diameter silica spheres.
Fabricated by Amanda Baker

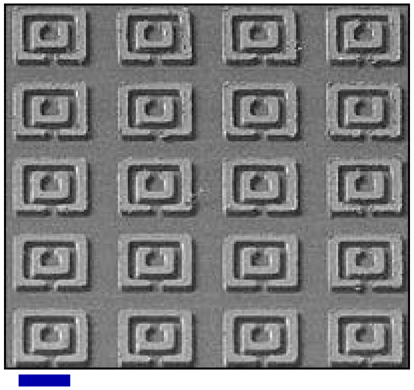
Extra Slides

Metamaterials at THz*

New designer materials and THz technology could eventually lead to:

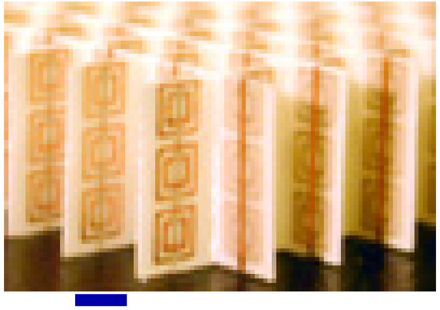
- **Noninvasive imaging for security and medical**
- **Compact and high speed communications transceivers**
- **Phased array radar and Broad Band antenna**
- **Waveguide and signal routing for high speed signals**

THz array



50 µm

10 GHz array



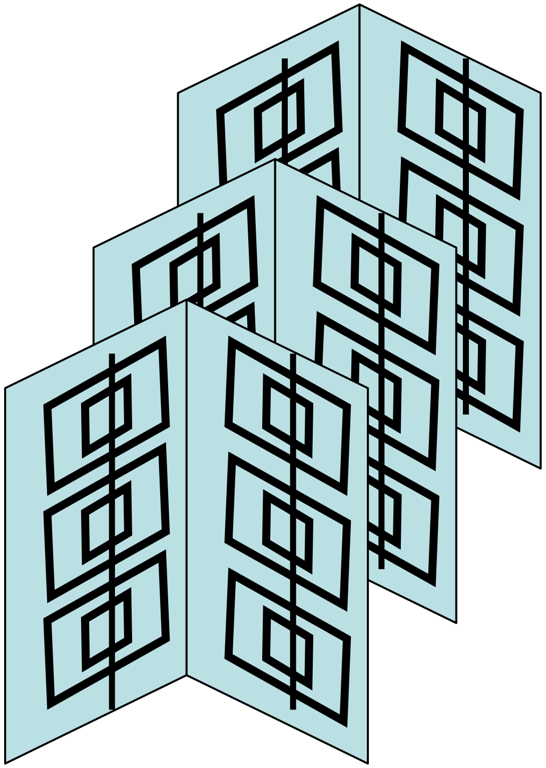
3 mm

Split ring resonator arrays
UC San Diego

* Science: March 2004 Issue and http://news.bbc.co.uk/2/hi/science/nature/3537161.stm

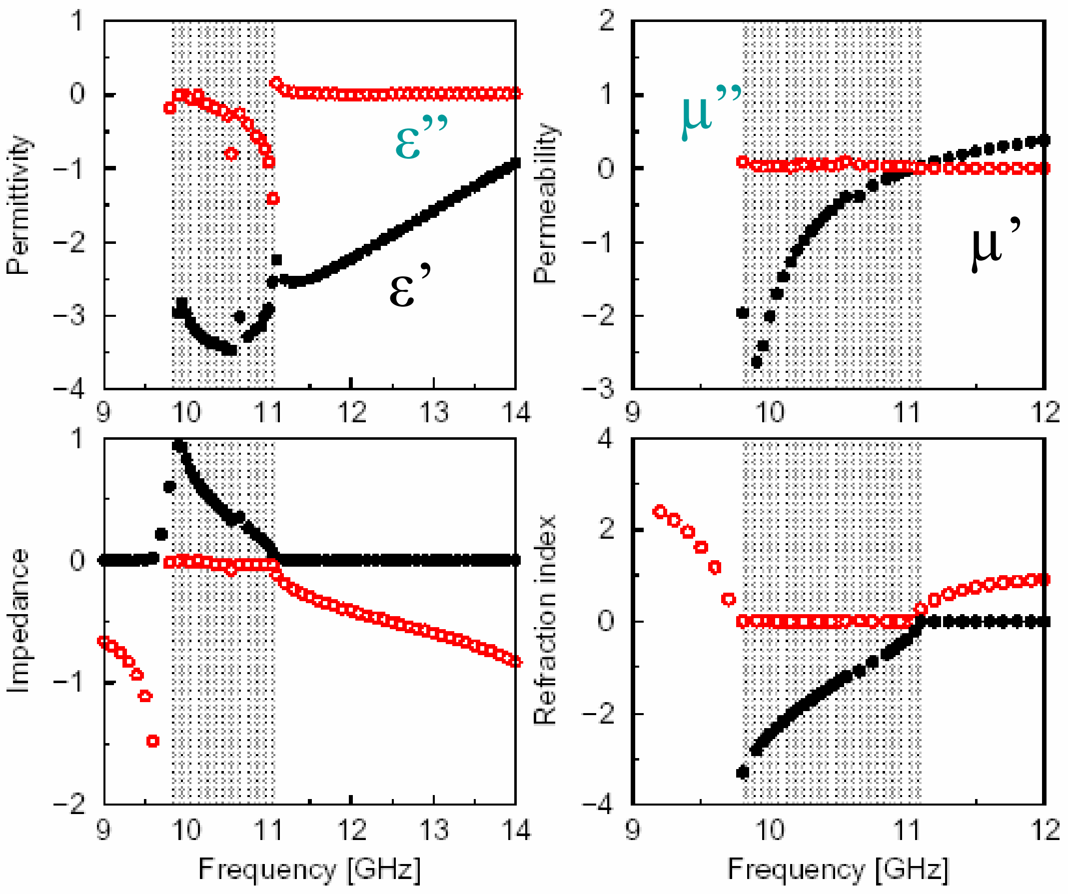
Future Materials Research Microstrip Meta-materials (1-20 GHz)

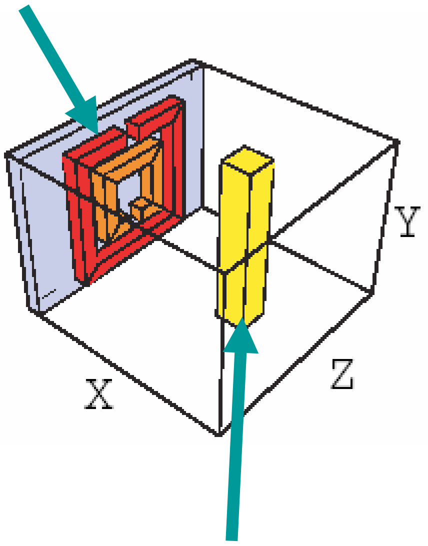
- Periodic Array of Resonators
  - Ring Resonators (H-field)
  - Line Resonators (E-field)
- Resonator “plasma” frequency
  - Negative μ and ε terms
  - Optical Index $n^2 = (\varepsilon\mu / \varepsilon_o\mu_o)$
- Resonators are coupled
  - Coupling is directional
  - Potential for beam steering



V. G. Veselago, Soviet Phys. Vol. 10, p. 509 (1968)
R. A. Shelby et al., Appl. Phys. Lett., p. 489 (2001)
http://physics.ucsd.edu/~drs/left_home.htm

Double Negative Materials*



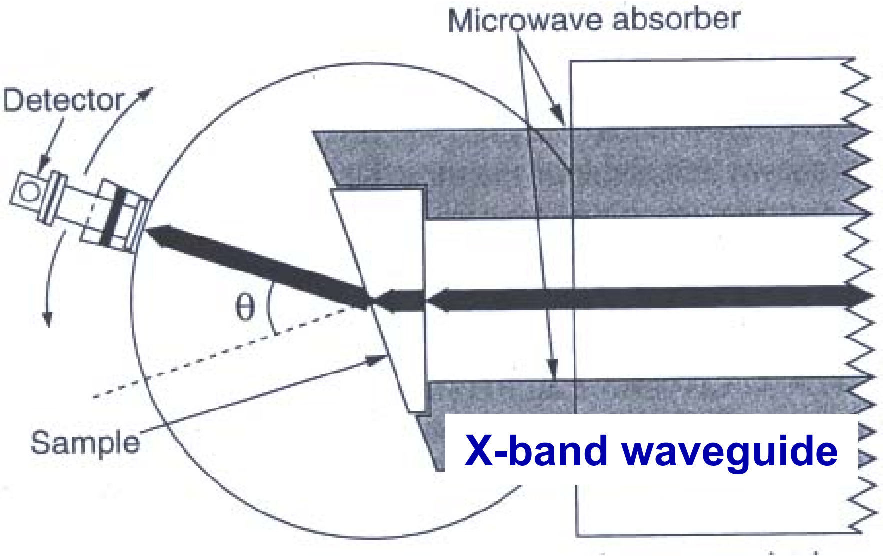


Magnetic Element

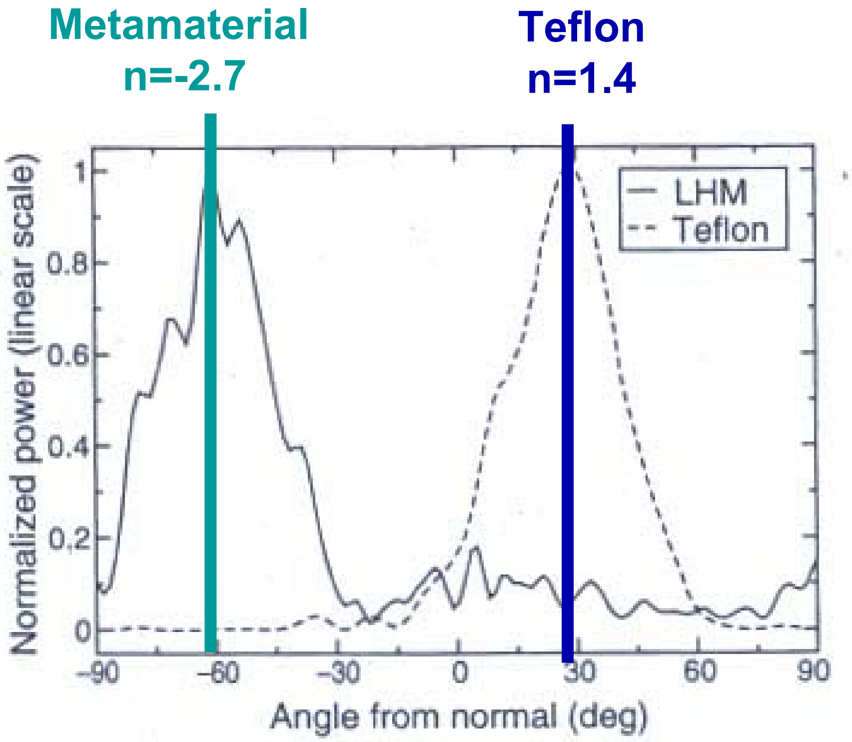
Electric Element

P.M. Markos and C. M. Soukoulis, Opt. Exp., p. 649 (2003)

Experimental Confirmation of a Meta-material*



X-band waveguide

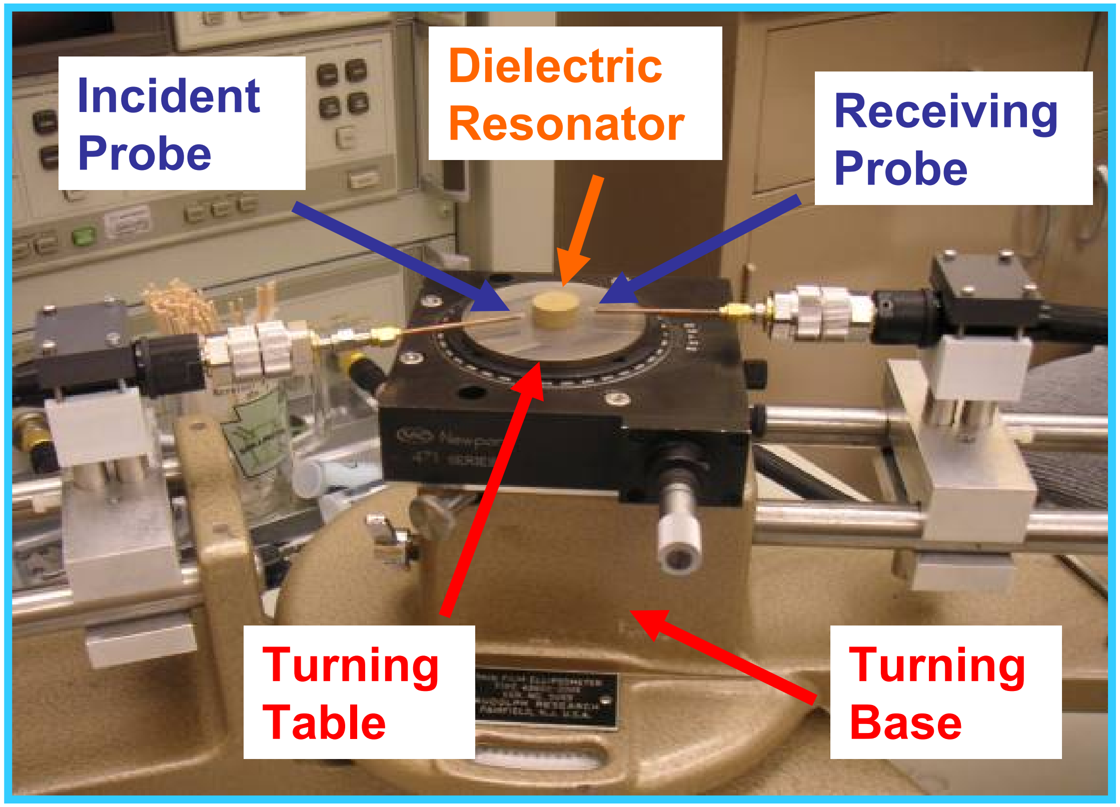


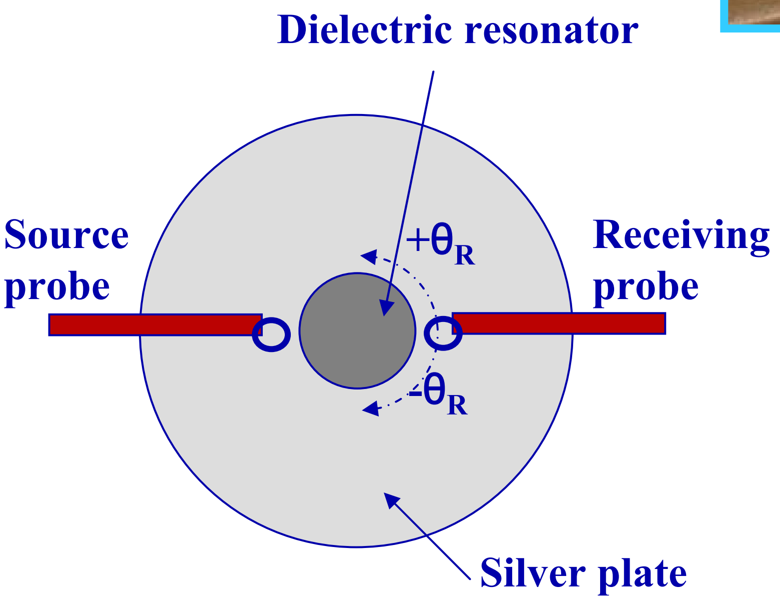
Metamaterial
n=-2.7

Teflon
n=1.4

R. A. Shelby et al., Science, pg. 77 (2001)

Metamaterial Characterization at Microwave Frequency





Measure the microwave power output at receiving probe as a function of angle.

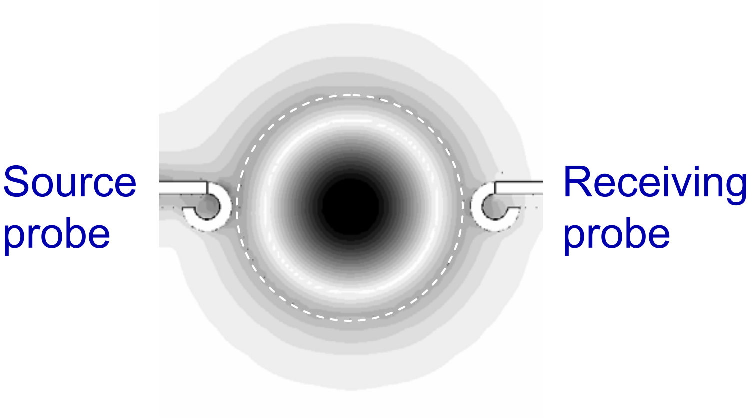
M. Iwasaki

M. Iwasaki

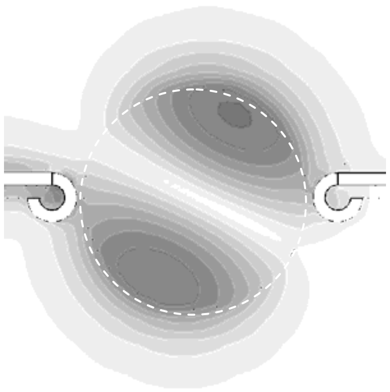
Equatorial field distribution of single DR

-By simulation results, magnetic field distributions were drawn in longitudinal direction at the half height of DR.

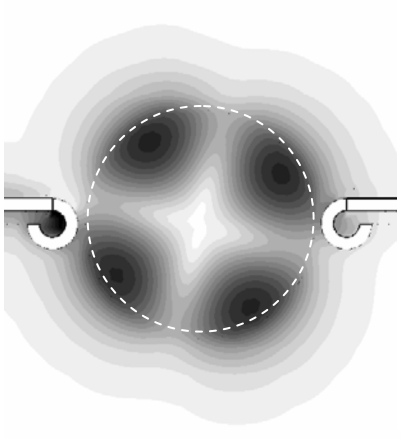
(a) TE$_{011}$ mode



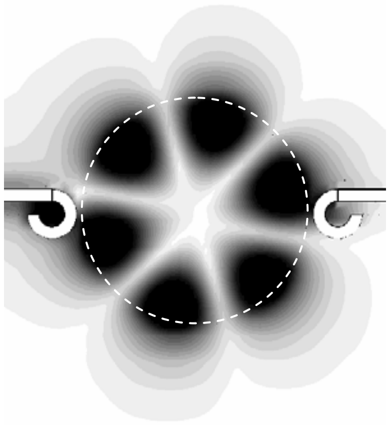
(b) HEM$_{111}$ mode



(c) HEM$_{211}$ mode



(d) HEM$_{311}$ mode



M. Iwasaki