Dielectric Breakdown in Filled Silicone Elastomers

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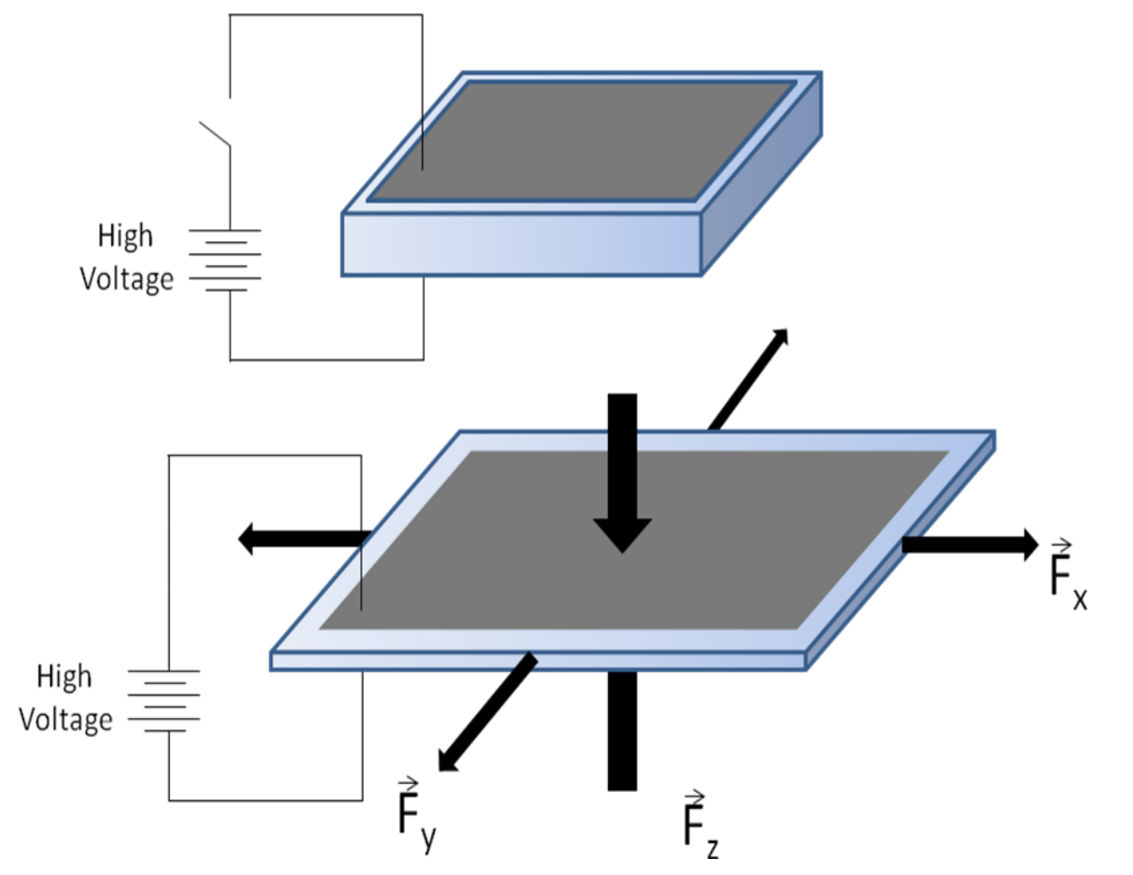
Motivation: Dielectric Elastomer Actuators and Sensors

Dielectric elastomer actuators and sensors are an emerging class of electroactive materials with potential for producing large area, large strain, conformal devices at low cost. The potential applications of such devices include energy efficient pumps and valves, conformal ultrasound transducers, endoscopic camera autofocus apparatus, and structural health monitoring transceivers. Dielectric elastomer actuators have achieved strains over 100%, which puts them in a wholly different class from typical piezoelectric actuators, which produce strains of approximately 0.2%. The energy density storage (Joule/cc) of dielectric elastomer devices is approximately eight times that of typical piezoelectric and electromagnetic devices [1].



Dielectric elastomer actuator device in non-activated (top) and activated (bottom) states. Flexible electrodes (grey) expand with the device under bias.

The Importance of Dielectric Breakdown Strength

Dielectric elastomer actuators are essentially compliant capacitors, where a thin slab of elastomer, coated with flexible electrodes on each face, is subjected to a potential difference applied over the thickness direction. The resulting buildup of electrostatic charge on each electrode surface causes a compressive strain in the thickness direction and tensile strain in the perpendicular plane. The electrostatic stress driving the deformation, known as the Maxwell Pressure, is dependent on the dielectric constant of the elastomer and the applied electric field

$$P = \epsilon_r \epsilon_o E^2$$

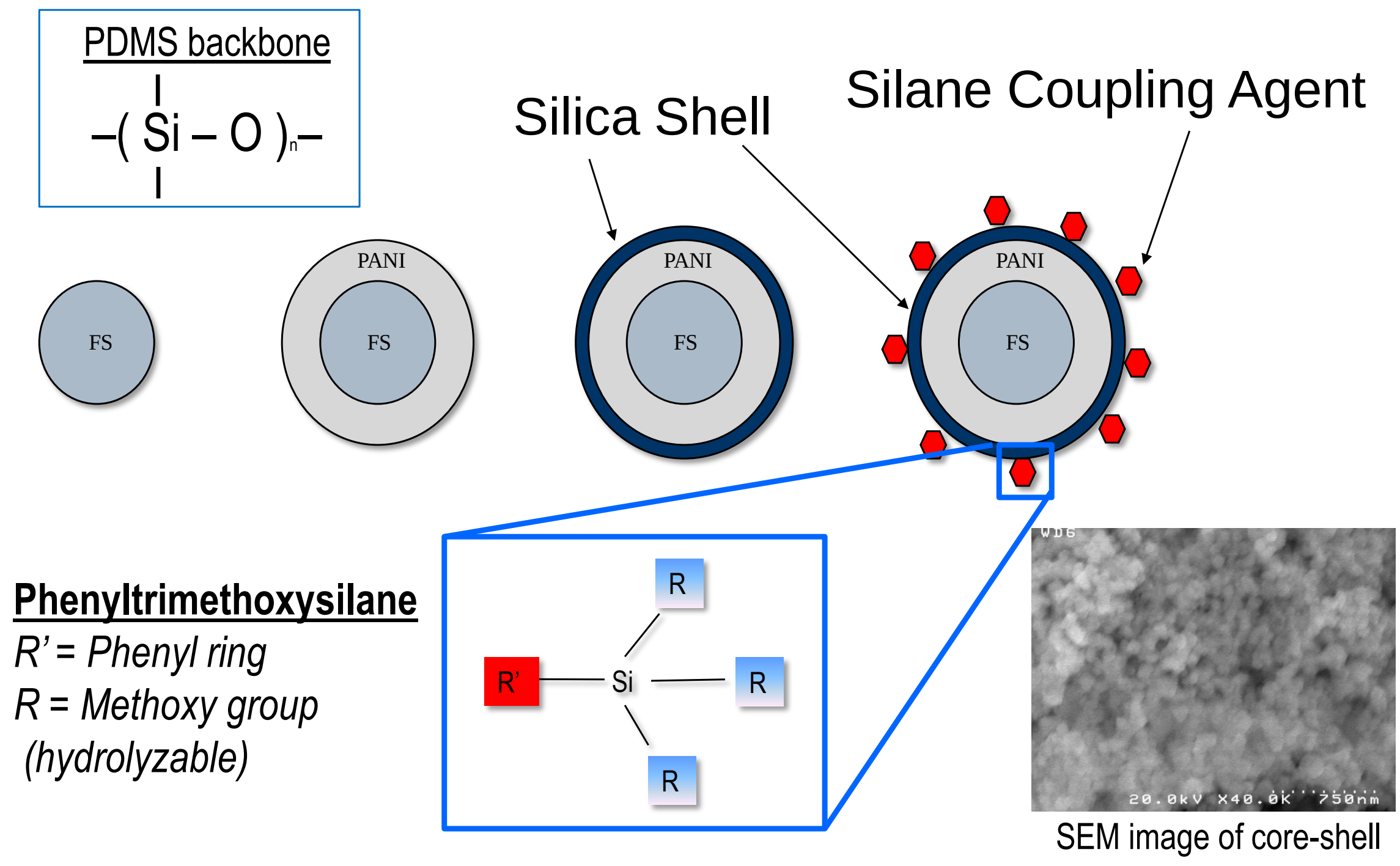
where P is the electrostatic pressure exerted over the thickness direction, ε is the relative dielectric constant of the elastomer, ϵ_o is the permittivity of a vacuum, and E is the applied electric field [2]. However, what is often of interest is the strain exhibited by the material. The thickness strain S_z is inversely related to the elastic modulus, Y, assuming isotropic values of Y and ε

$$S_z = \frac{\epsilon_r \epsilon_o E^2}{Y}$$

The dielectric breakdown strength is the most influential parameter involved as it inherently limits the applied bias over the dielectric. Devices capable of high strain are achieved using materials which exhibit high dielectric constant and dielectric breakdown strength as well as low elastic modulus. Nanoparticle fillers have been synthesized to improve the strain performance of such dielectric elastomer devices.

Designing Nanoparticulate Fillers

Polyaniline (PANI) coated fumed silica (FS) nanoparticles have been synthesized for dispersal within a polydimethylsiloxane (PDMS) matrix. The FS core (~20nm diameter) was used as a scaffold on which highly polarizable PANI could be coated. An outer silica shell was produced using Stober synthetic methods [4]. Phenyltrimethoxysilane (silane coupling agent) was applied to the outer silica surface to disperse the nanoparticles evenly.

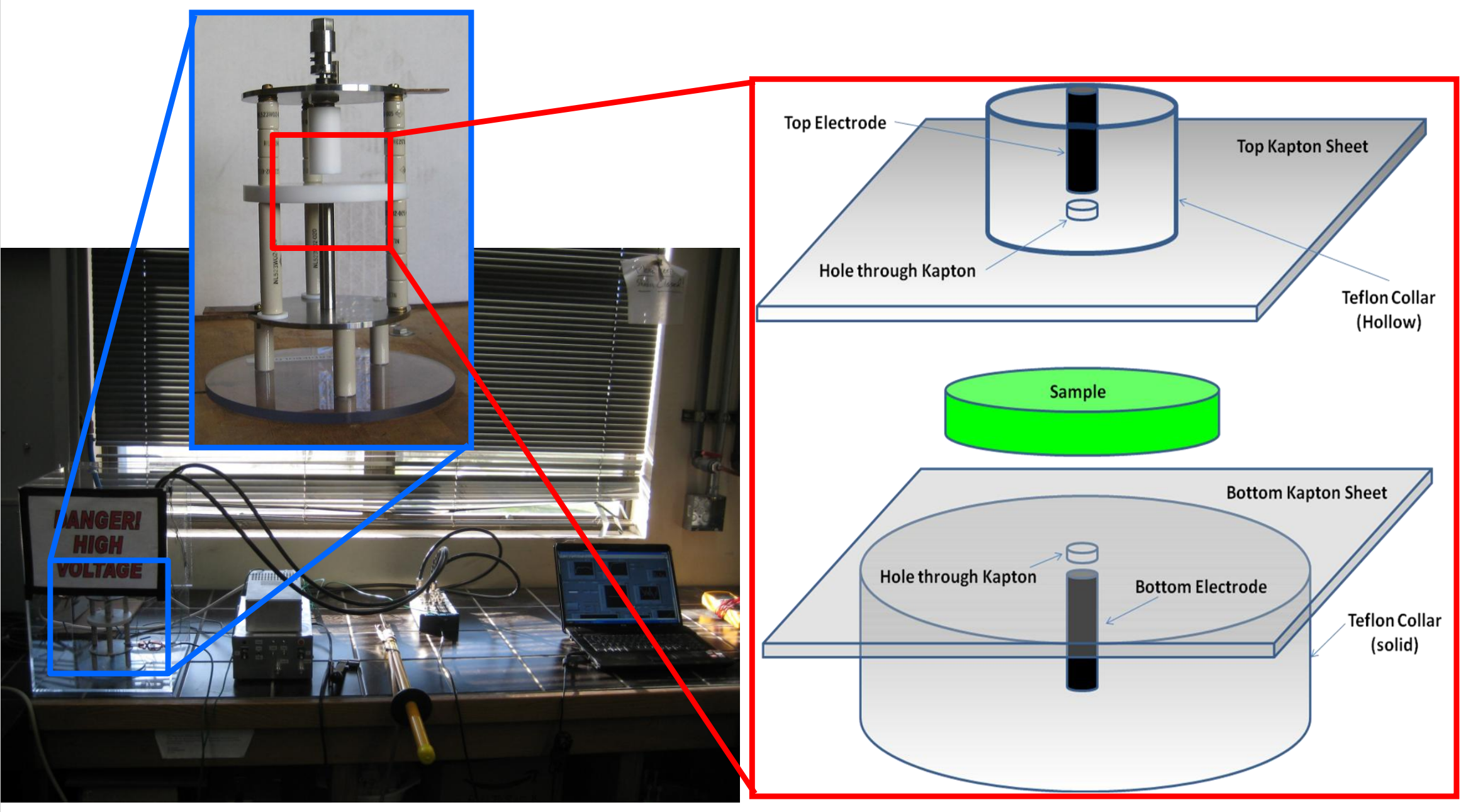


Phenyltrimethoxysilane
R' = Phenyl ring
R = Methoxy group (hydrolyzable)

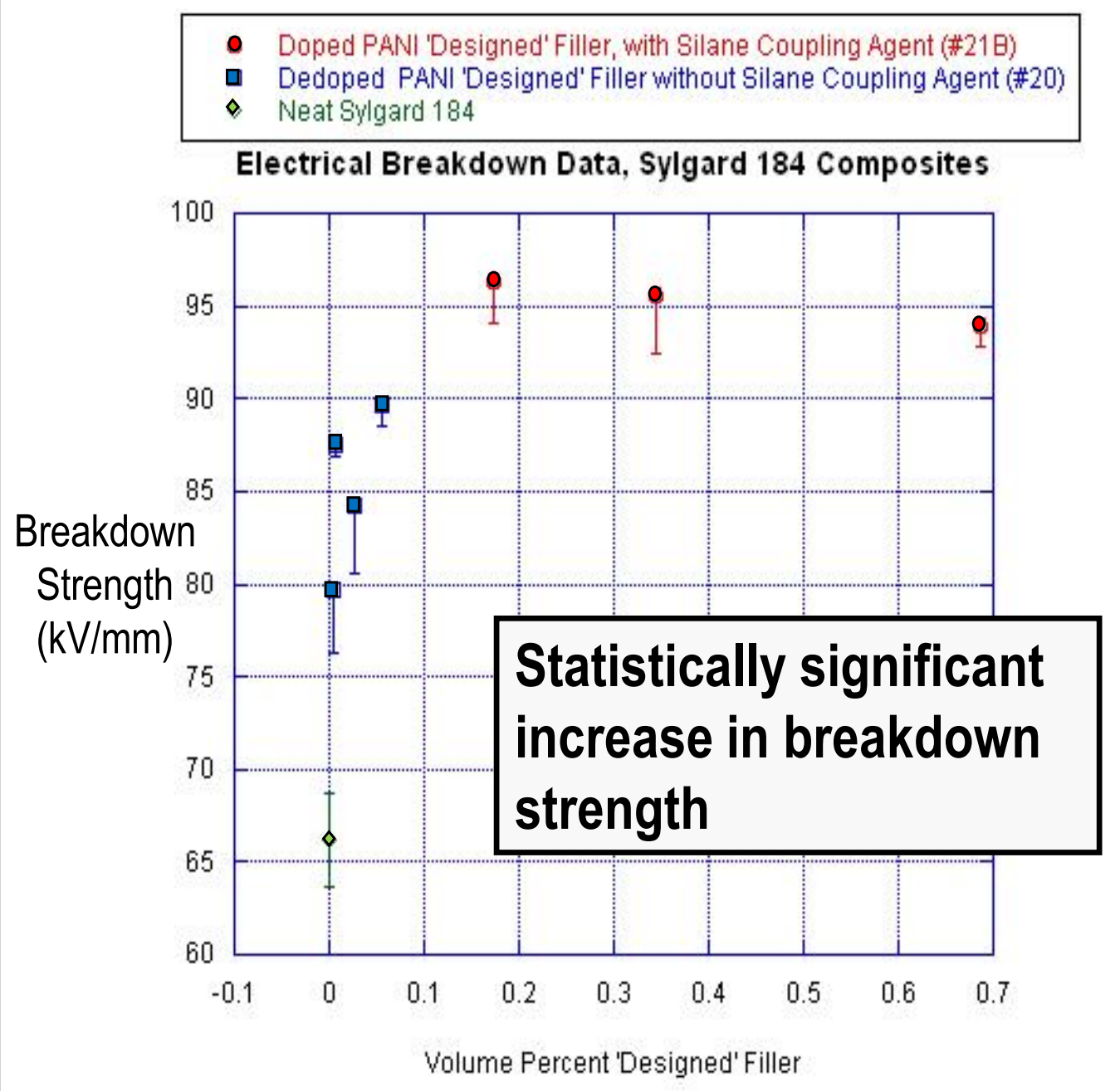
SEM image of core-shell nanoparticles

Materials Characterization

A custom hipot system capable of delivering 60kV (at 1mA) has been constructed along with a sample holder designed specifically to prevent surface flashover. This LabVIEW controlled system is highly effective in inducing electrical failure directly through the thickness of the specimen under test.



Macro Breakdown Results and Conclusions



Statistically significant increase in breakdown strength

- <u>Possible explanation:</u> Reduction of dielectric constant mismatch between matrix and filler with intermediate shell material [3]. This lowers electrical stress concentrations which act as defects which ican nitiate breakdown events.

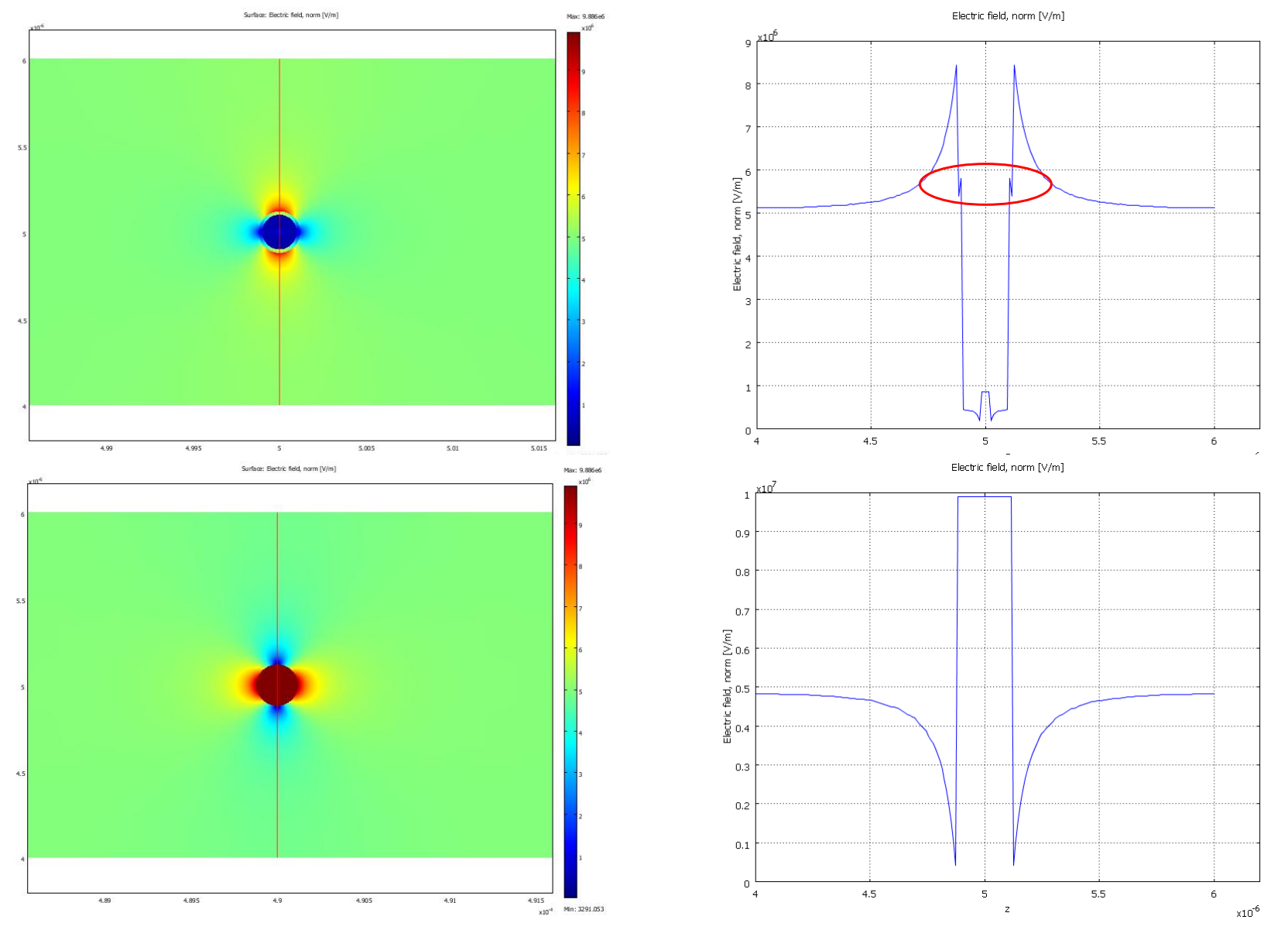
- More data is necessary to fully understand the effect of the silica shell, PANI, and silane coupling agent on the composite breakdown strength.

Modeling of Core-Shell PANI/Silica Nanoparticles

Silica shell reduces electric field gradient at particle boundary

Core-shell PANI/silica nanoparticle (120nm diameter) (PANI modeled as Aluminum)

Silica nanoparticle - Traditional filler material (120nm diameter)



2D Plane-Plane electrodes, 10V potential, 2μm PDMS matrix
COMSOL Multiphysics

Micro Breakdown Studies

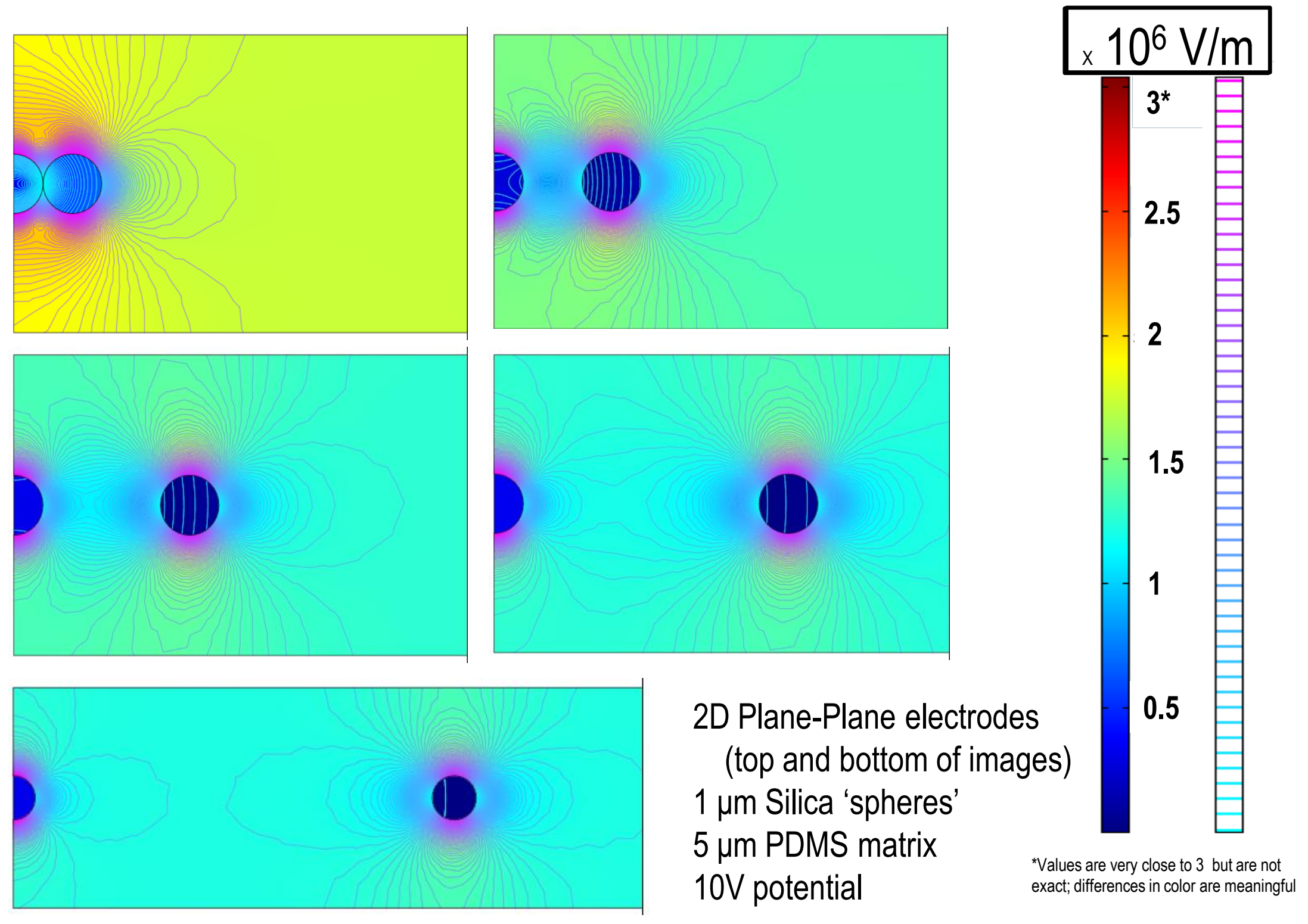
When considering composite material properties, surface interactions between the filler and matrix become increasingly important as the size of the filler decreases towards the nanoscale. ***However, it is currently unclear what effect filler particle surface chemistry has on the dielectric breakdown properties of polymer composites.*** Therefore, it has been proposed to study dielectric breakdown of matrix/filler interfaces on the nanoscale using conductive atomic force microscopy (CAFM) to elucidate these effects.

The advantages of using CAFM over traditional breakdown methods include:

Fewer defects in test volume
Large amount of data able to be collected
Closer approximation of intrinsic breakdown strength
Removal of particle-particle interactions

COMSOL Multiphysics Model: Particle-Particle Interactions

Electric field line models predict the locations of high electrical stresses. When designing experimental test structures, it is useful to know the distance between two dielectric spheres where lines of equipotential do not impinge upon each other such that particle-particle interactions can be avoided.

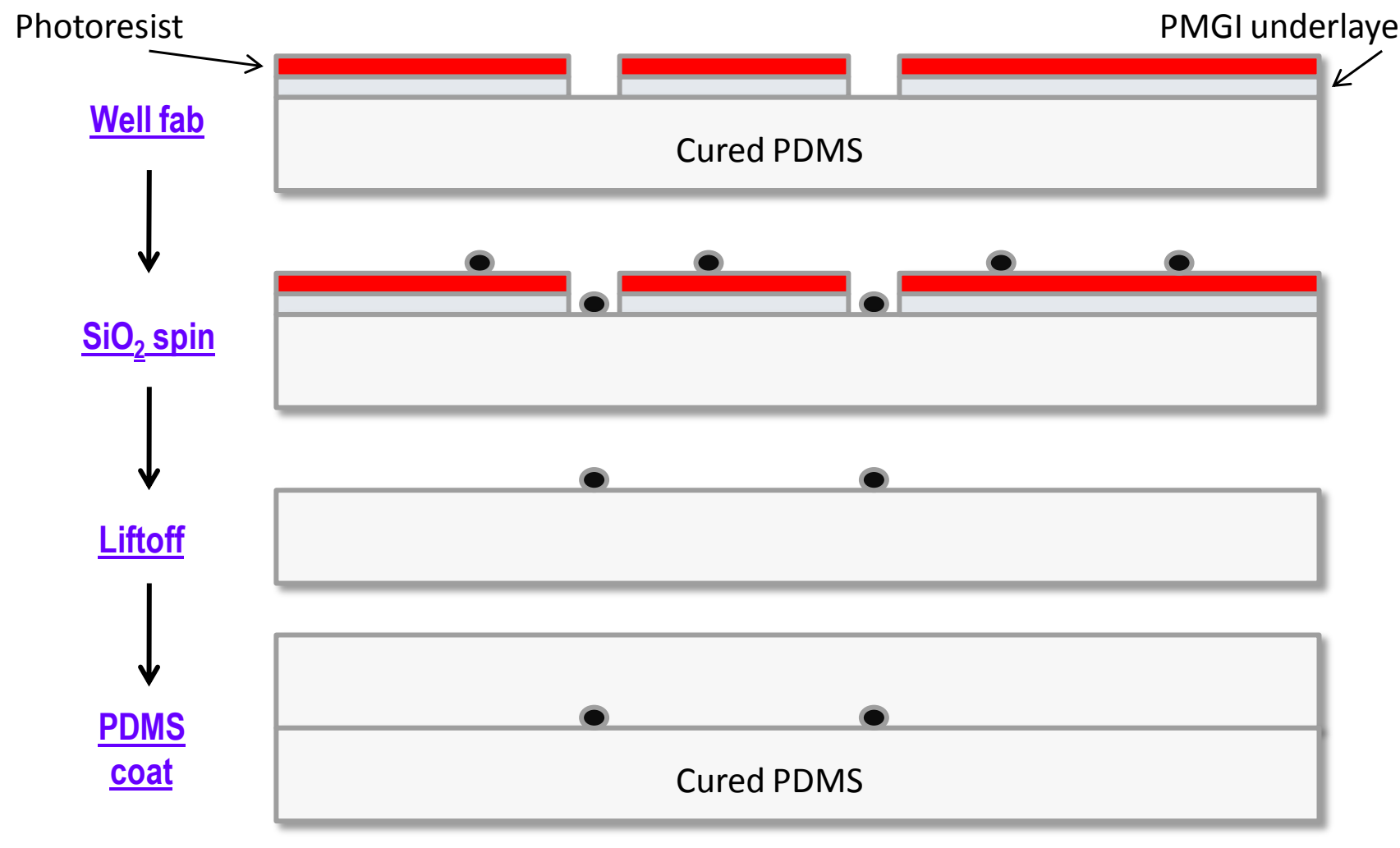


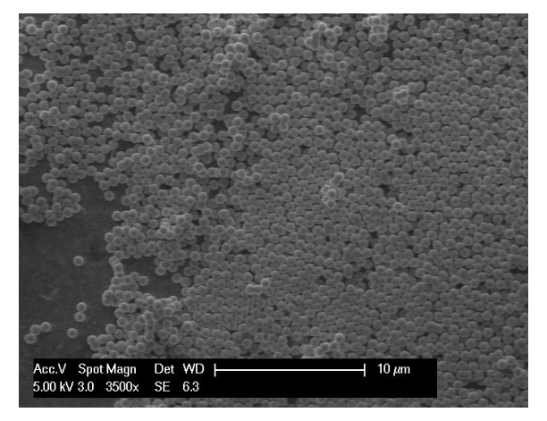
2D Plane-Plane electrodes
(top and bottom of images)
1 μm Silica 'spheres'
5 μm PDMS matrix
10V potential

*Values are very close to 3 but are not exact; differences in color are meaningful

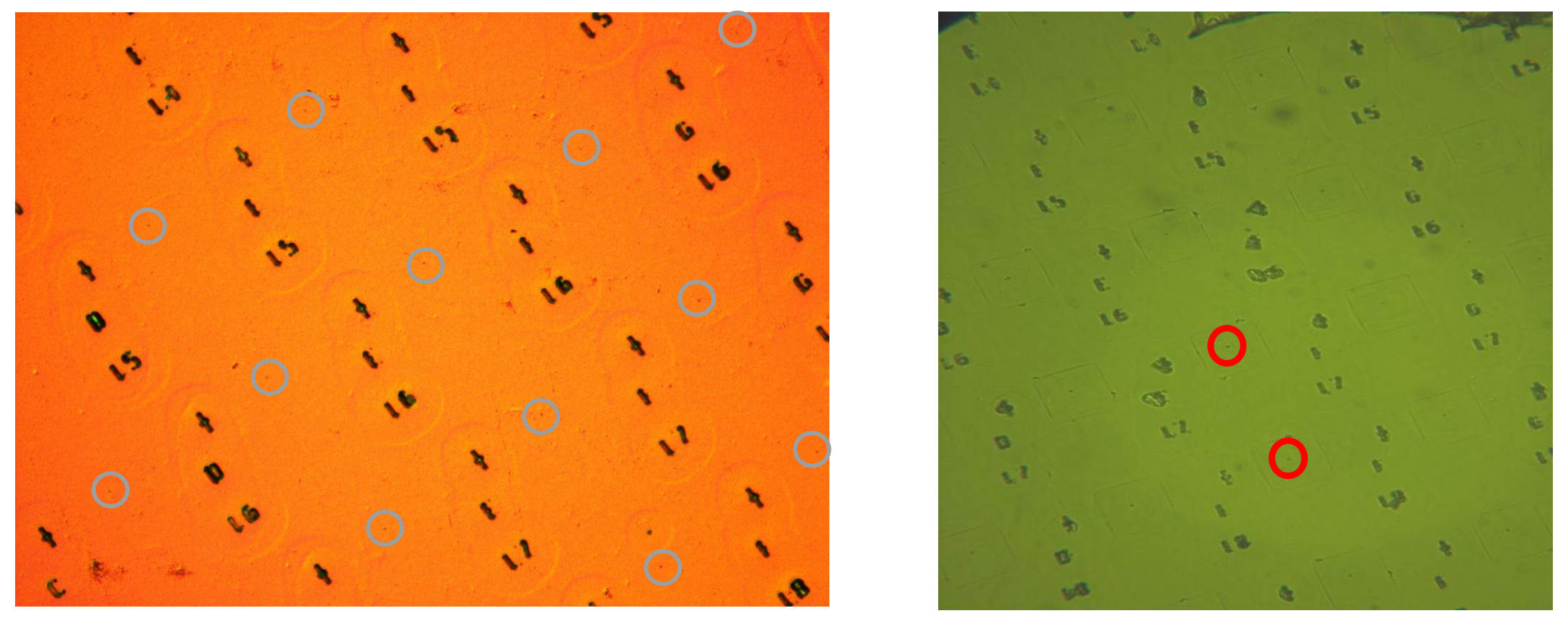
Micro Breakdown Experimental Setup

Single silica particles have been localized in PDMS thin films using optical lithography. Unfortunately, the reproducibility of this fabrication process is low, and is not amenable to vastly different filler surface chemistries.





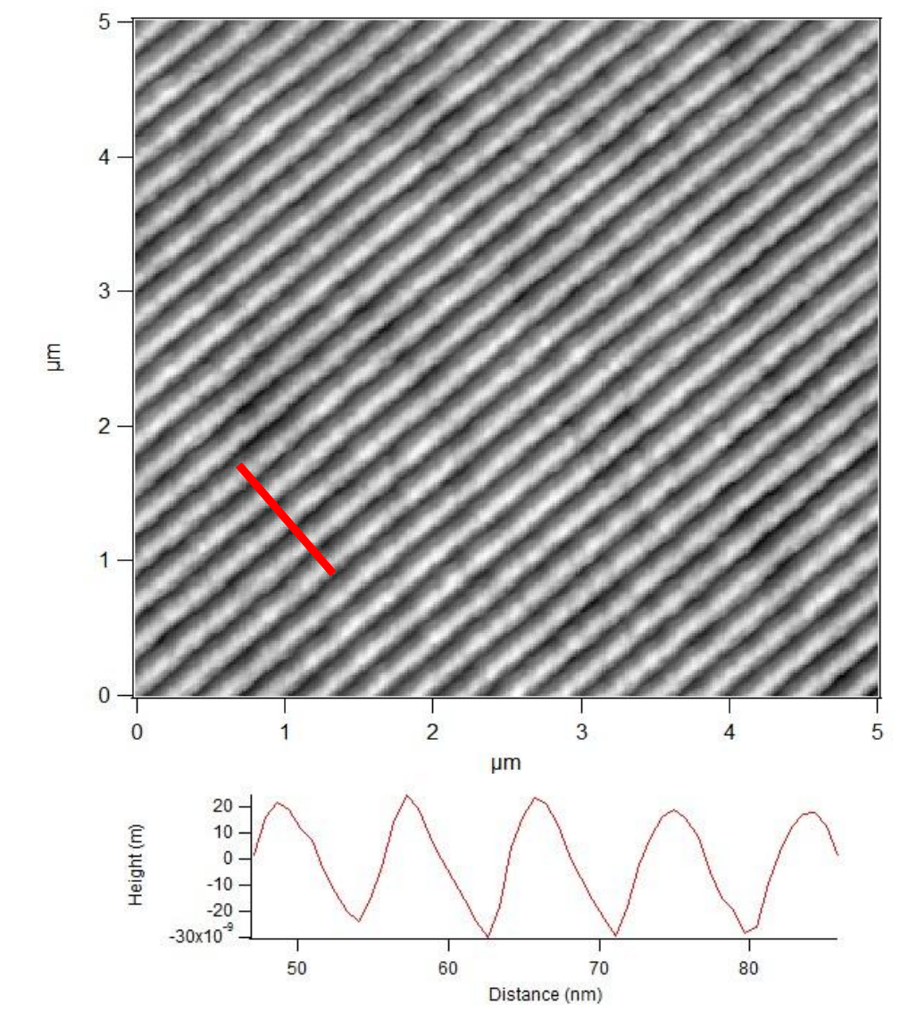
Monodisperse Stober silica particles



Optical microscope images of localized silica particles on PDMS coated substrate. Left image is after resist liftoff, right image is after PDMS coat (squares). Both images have circles drawn to aid the eye. Black letters/numbers are Ti registration marks. Major axis of registration mark cross is 30μm.

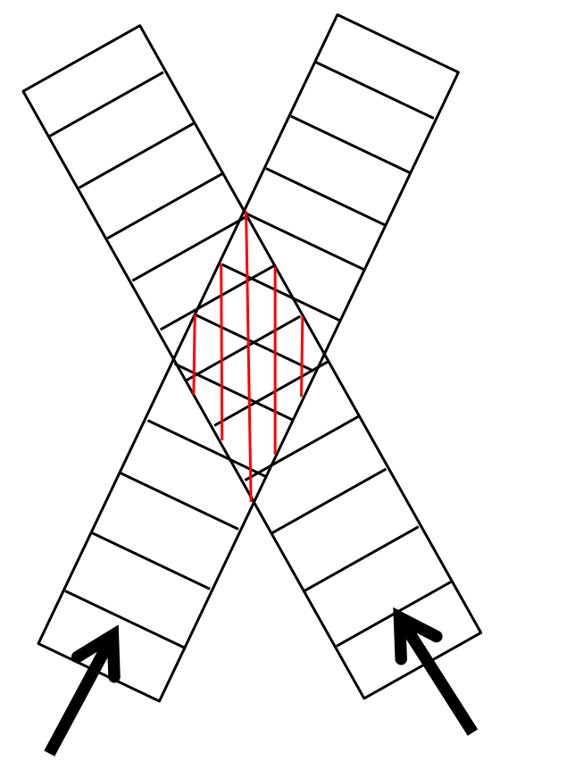
Micro Breakdown Conclusions and Current Work

Although much time has been devoted to localizing single filler particles within a PDMS matrix for probing with CAFM apparatus, recent efforts have been directed towards fabricating nano scale structures using interference lithography. Current-voltage characteristics will be recorded from CAFM probes placed along a PDMS/silica interface which can be chemically modified.



Tapping mode AFM image of developed photoresist on a silicon wafer after undergoing interference lithography processing.

Two lasers recombined at an angle to create an interference pattern which can be used to expose photoresist lines.



References and Acknowledgements

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