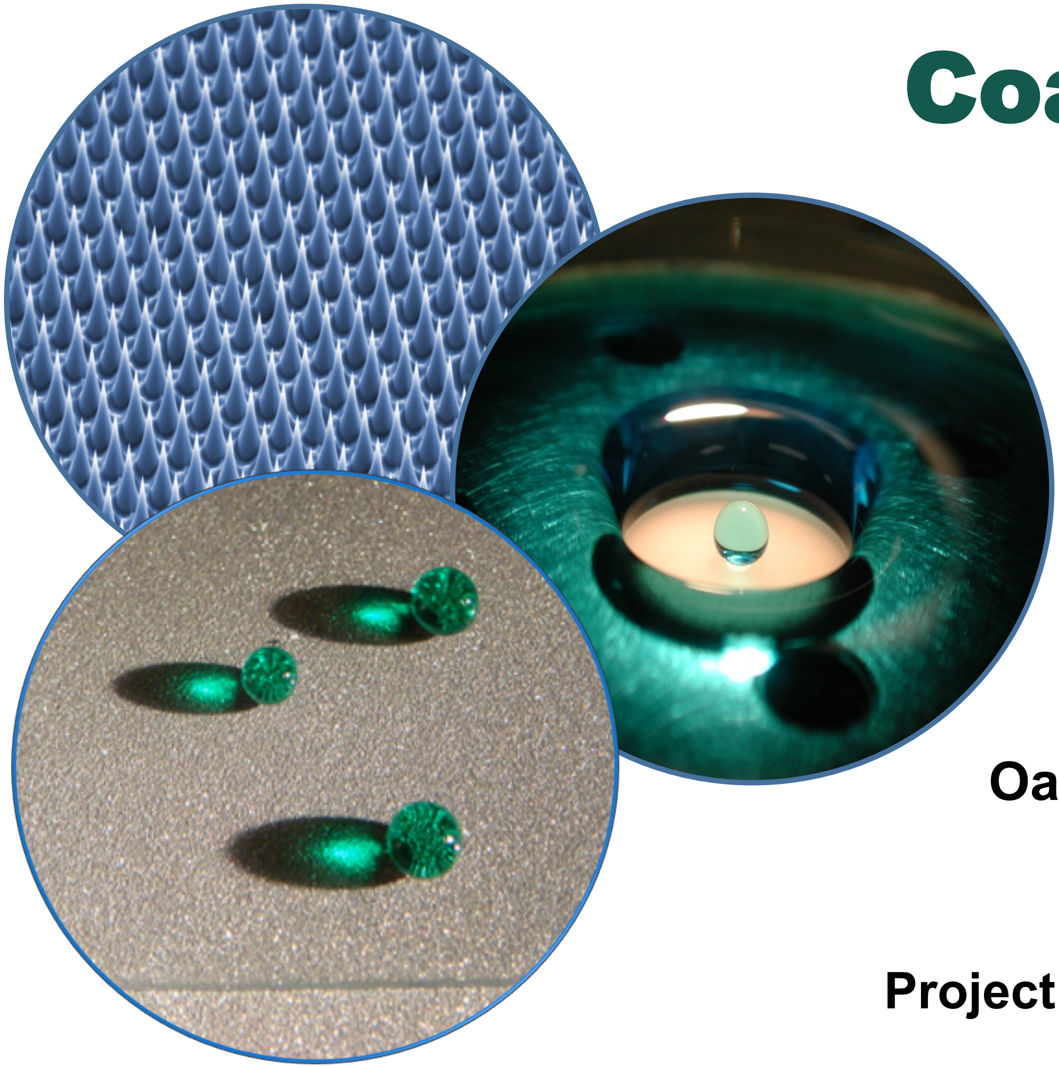
Low-Cost Self-Cleaning Coatings for CSP Collectors



PI: Scott Hunter

Oak Ridge National Laboratory

Project Start Date: November 1, 2012

SunShot
U.S. Department of Energy

SunShot CSP Program Review
April 23-25, 2013

OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

Project Description

Background

- One of the most significant maintenance problems and costs associated with CSP solar collectors is the soiling of the first surface of the solar radiation reflectors by the accumulation of sand, dust and other pollutants
- Typical cleaning methods use clean de-ionized water that is applied to the mirror surfaces using cleaning systems that incorporate jet nozzles with and without brushing - manual cleaning is labor intensive and costly

Project Description

- Develop, test and implement low-cost durable multifunctional (self-cleaning and anti-reflecting) nanostructured collector surface coatings that will significantly enhance the reliability and efficiency of CSP collectors, while reducing collector cleaning and maintenance costs

Project Objectives

Goals and Objectives:

- Reduce CSP heliostat and collector first mirror surface maintenance (washing, scrubbing and removal of loose debris) by 90% compared to uncoated mirror surfaces
- Improve average amount of reflected solar radiation by up to 20%
  - Highly innovative nano-silica based superhydrophobic coatings
  - No loss in optical transparency or increased scattering
  - Low cost, large surface area, simple one coat spray application
  - Coating durability is the key

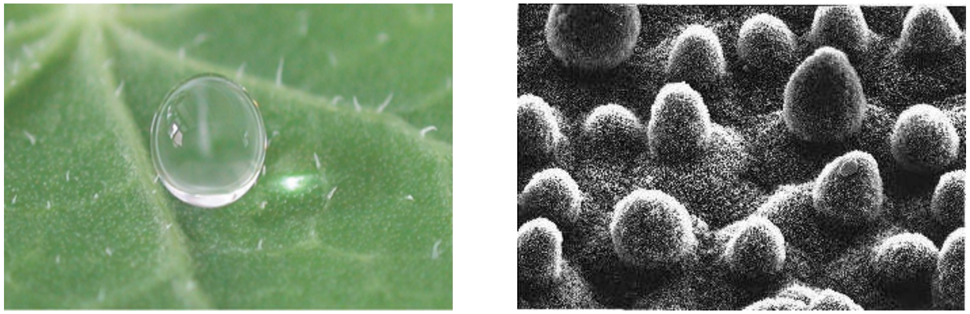
Project Objectives

Innovation:

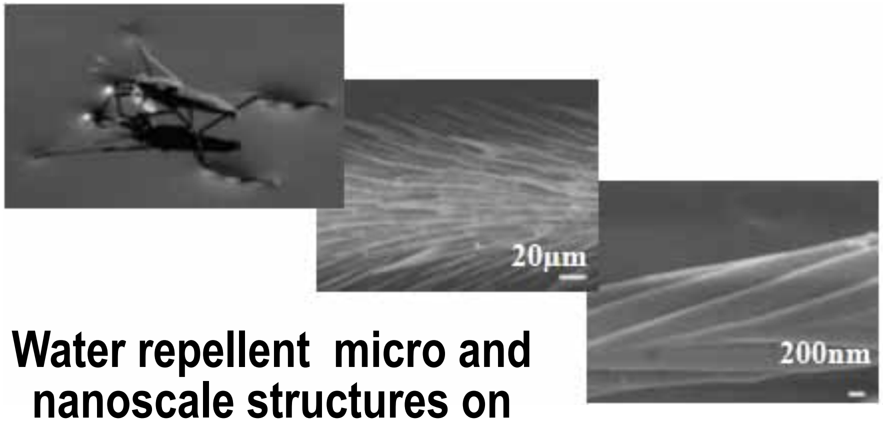
- **Hydrophobic and superhydrophobic coatings have been researched for several years:**
    - Glass surfaces – low surface energy coatings, polymer based
    - Not durable, require surface etching or photolithography (expensive, not scalable to large surface areas)
    - Most anti-soiling solutions to date are only partial solutions – only reduce soiling – surfaces still need washing
- **Unique properties of ORNL coatings:**
    - Very optically transparent, minimal optical scattering, can be anti-reflective
    - Made from robust, UV degradation resistant auto industry clearcoats
    - Applicable to most surfaces (glass, metals, polymers)
    - Completely scalable - very low cost, simple application techniques (used in the paint industry)
    - Amenable to retrofitting and refinishing in the field

Natural Superhydrophobic Surfaces

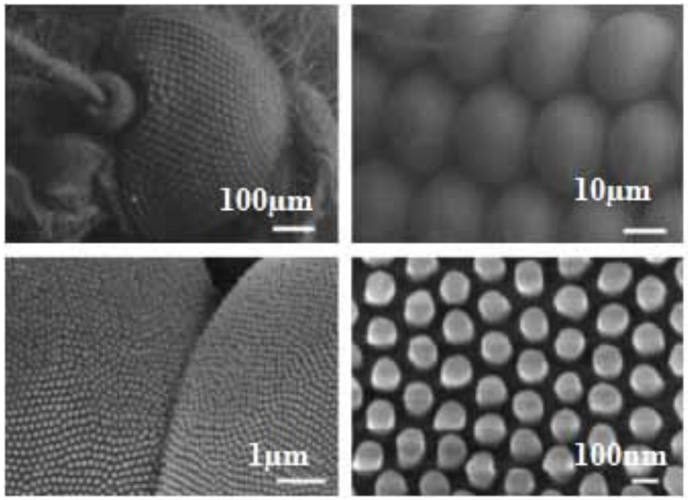
Lotus leaves and insect surfaces can be superhydrophobic



- Nano and microscale structures
- Waxy low surface energy hydrophobic material

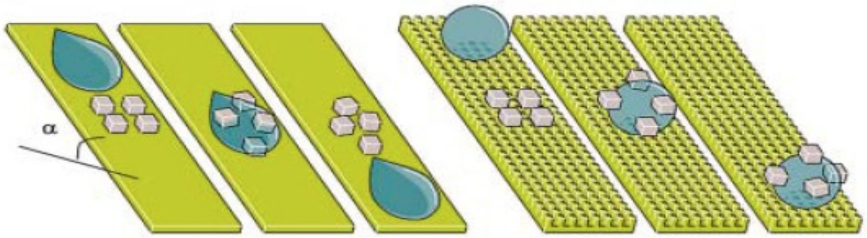


Water repellent micro and nanoscale structures on pond skater's legs



Compound mosquito eye

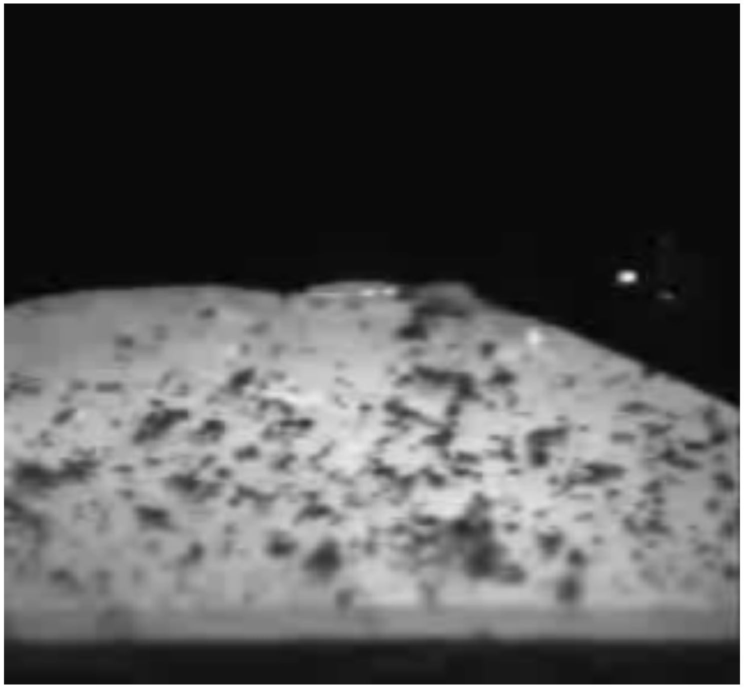
Self-Cleaning Superhydrophobic Surfaces



Dirt particles remain on
a normal surface

Water drop collect surface dirt on
a superhydrophobic (SH) surface

Water drops falling on to a
superhydrophobic surface in
slow motion



Light wind or rain will remove most dirt, sand and dust from these surfaces

Technical Approach

Superhydrophobic coating development and optimization

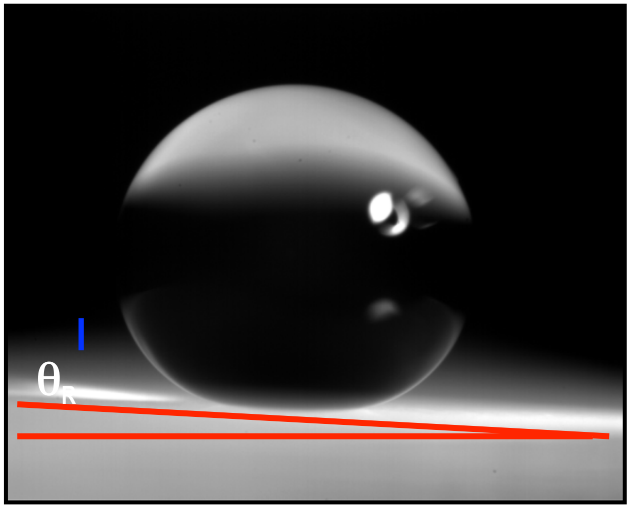
- Develop low cost techniques for functionalizing the silica nanoparticles using environmentally-friendly solvents and techniques
- Optimize nanosilica particle size to provide the required optical transmission and solar radiation scattering specifications
- Develop polymer and epoxy based bonding agents for high surface bonding, optical clarity, water repellency and minimal UV degradation

Coating characterization and testing

- AFM, SEM and optical microscope characterization measurements to determine coating surface uniformity and roughness
- Static and dynamic water contact angle and rolling angle measurements to estimate coating water repellency
- Optical transmission measurements over the wavelength range 250 nm to 3.0 microns
- Specular and hemispherical reflectance measurements on coated samples over the range 250 nm to 3.0 microns

Technical Approach

Extreme water and dirt repellent optically transparent surfaces

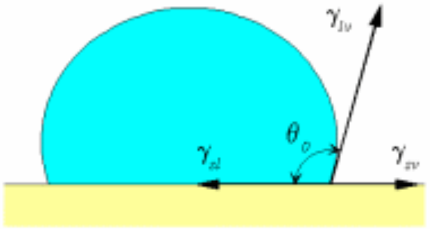


Rolling Angle Measurement

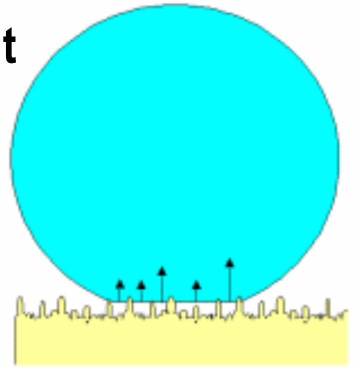
Two measures of superhydrophobicity:

- **Contact Angle**
  - $\theta_0 < 90^0$ surface is hydrophilic
  - $\theta_0 > 90^0$ surface is hydrophobic
  - $\theta_0 > 150^0$ surface is superhydrophobic
- **Rolling Angle**
  - $\theta_R < 5.0^0$ surface does not wet

Contact Angle Measurement

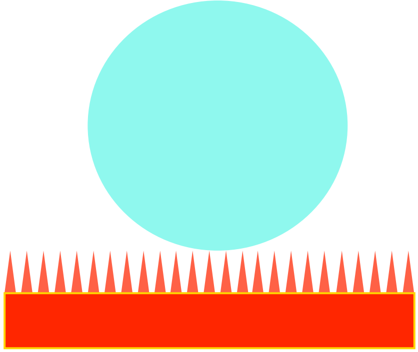


Droplet on normal hydrophobic surface



Droplet on superhydrophobic surface

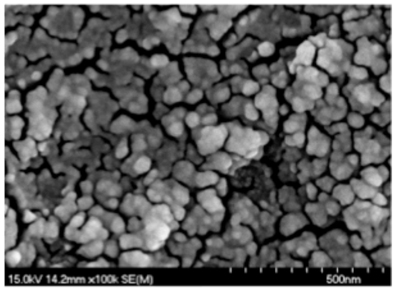
Nanostructured, low energy surfaces can give water contact angles approaching 180^0



Superhydrophobic Surface Coatings

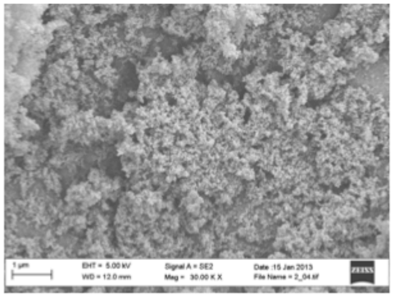
Approach – Initial Studies

Particle Size Characterization



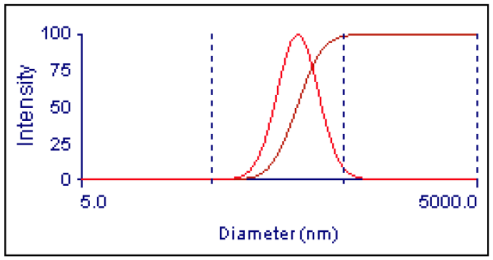
Aerogel
commercially
functionalized

Particle size 50-100 nm
Prior measurements

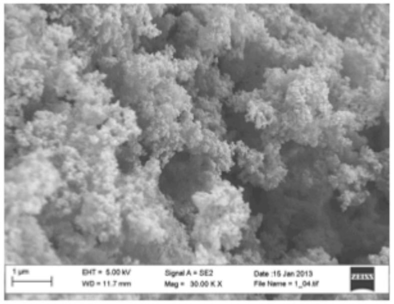


Aerosil
commercially
functionalized

Particle Size: 221.5 ± 81.3 nm

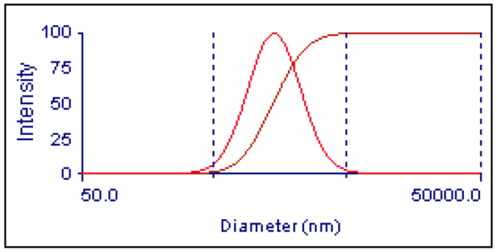


Lognormal Distribution



Fumed Silica (SiO_2)
functionalized w/ methyl
and alkyl groups

Particle Size: 1417.3 ± 677.1 nm



Lognormal Distribution

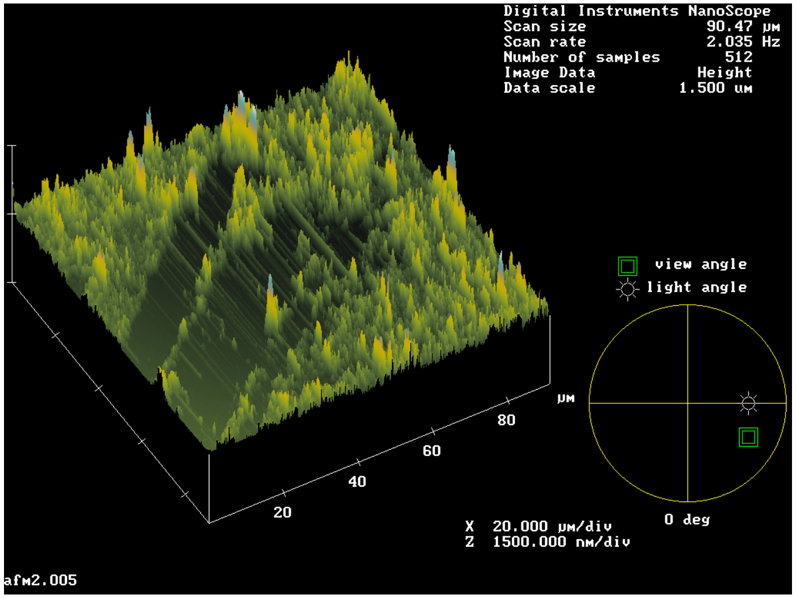
Three component mixtures of silica particles allow a range of particle sizes for good hydrophobicity and coating durability

Superhydrophobic Surface Characterization

AFM imagery of coated glass slide

Image Statistics

Ra: 56.5 nm
Rmax: 750.4 nm



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Digital Instruments NanoScope
Scan size              90.47 µm
Scan rate              2.035 Hz
Number of samples        512
Image Data             Height
Data scale           1.500 um
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100 x 100 µm image size

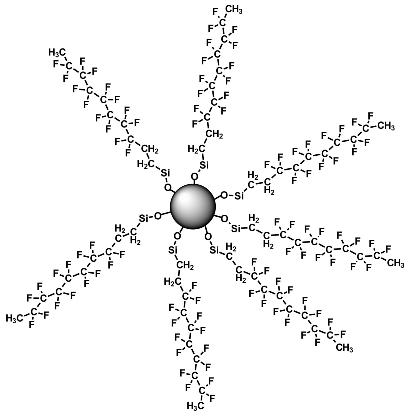
A mixture of particles functionalized with low energy self-assembled monolayers of paraffinic- and fluoro-silanes

- Mixture of Aerogel, Aerosil and flouro silanated silica
- The mixture components were immiscible – not compatible with solvents leading to poor surface coverage

Silica Particle Functionalization

Functionalization

- ✧ Covalently bond self-assembled monolayers (SAM) on the nanosilica surface
- ✧ Functionalized silica nanoparticulates exhibit superhydrophobic properties with water contact angles up to 175°

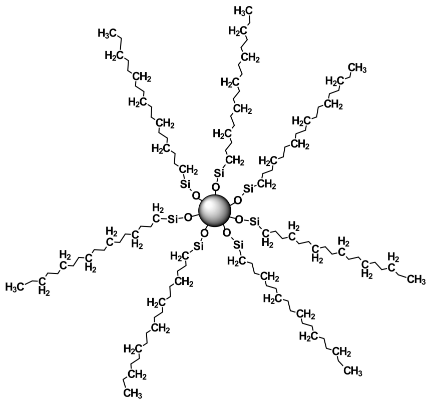


Initial Studies

Silica (SiO_2) nanoparticles
functionalized with fluoro-silanes

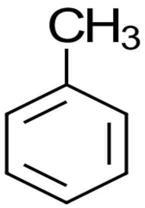
Subsequent Studies

Silica (SiO_2) nanoparticles
functionalized with alkyl-silanes



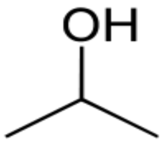
Dispersed in ➔

Toluene ≈ 50%
C_6H_5-CH_3



and

IPA ≈ 50%
C_3H_8O



- ✧ Toluene is hydrophobic and is a good dispersant for functionalized particles
- ✧ IPA (Isopropyl Alcohol) is miscible with toluene and has good wetting properties on glass substrates

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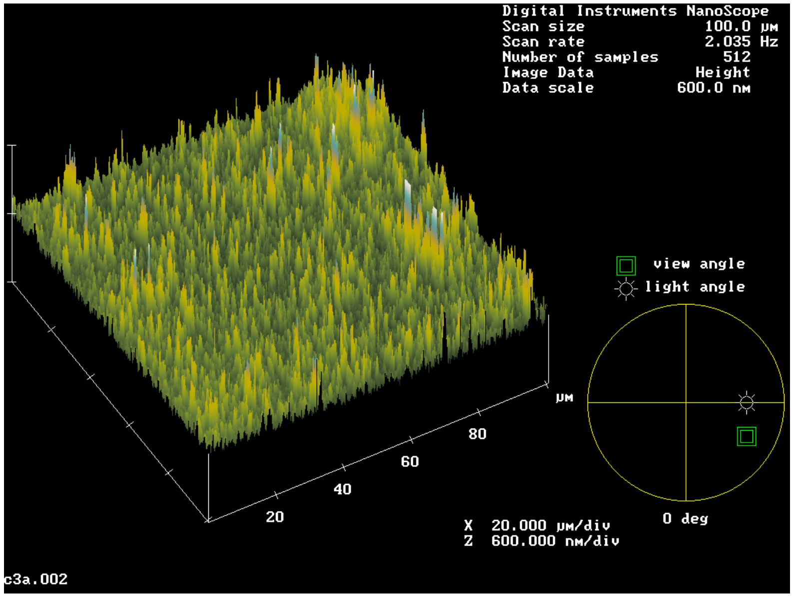
Superhydrophobic Surface Characterization

AFM imagery of coated glass slide

Image Statistics

Ra: 34.9 nm
Rmax: 771.6 nm



100 x 100 µm image size

Particles functionalized with paraffinic-silanes (n-octadecyltrichlorosilane) and were dispersed in paraffinic-based solvent (Toluene)

- Miscibility of paraffinic monolayer and solvent leads to well-dispersed particles
- Improved superhydrophobic properties due to multimodal particle size distribution

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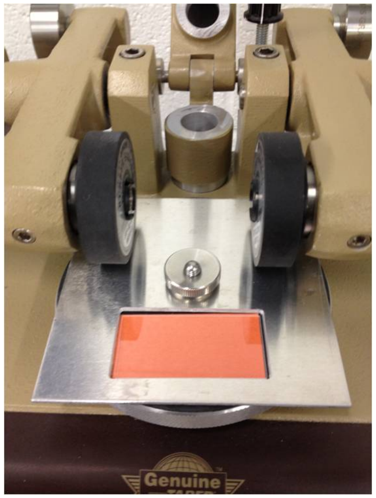
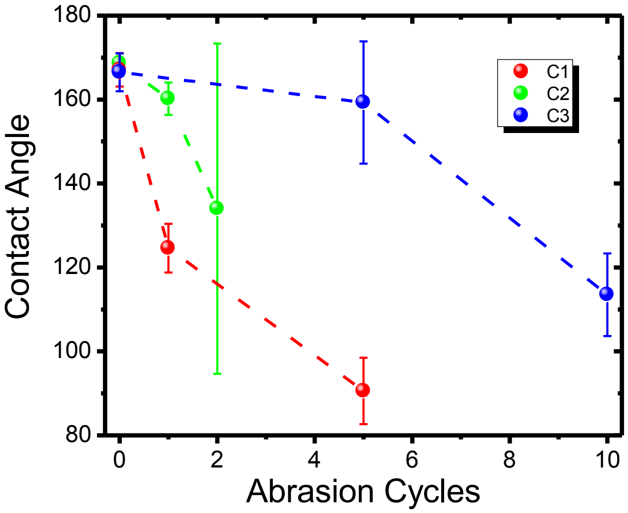
Superhydrophobic Coating Durability

Taber Abrasion Tester

Superhydrophobic coated glass slides are mounted in a metal plate holder and rotated under each standard abrasion wheel





Mixtures

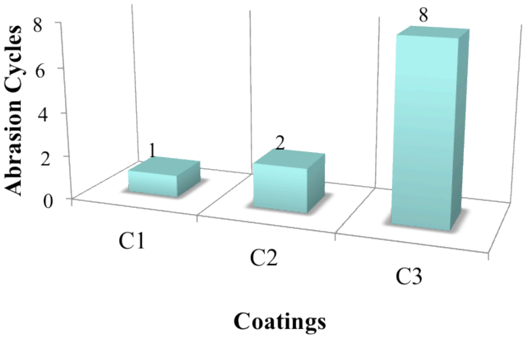
C1: Teflon®-AF + Aerogel

C2: Mixture of paraffinic- and fluoro-functionalized particles (SiO_2/Aerosil/Aerogel)

C3: Mixture of paraffinic-functionalized particles (SiO_2/Aerosil/Colloidal)

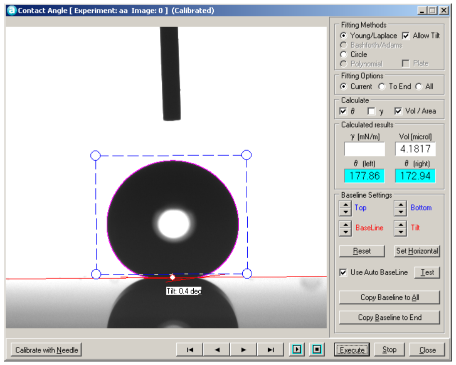
Binder - a commercially available polyurethane clearcoat

Taber™ Abrasion Durability Improvement



Project Goal – Coatings will have < 10% reduction water repellency defined by CA and RA measurements after a 25 Taber abrasion cycle test

Superhydrophobicity and Optical Transmission


Contact Angle [Experiment: aa Image: 0] (Calibrated)

Fitting Methods
● Young/Laplace ☑ Allow Tilt
○ Bashforth/Adams
○ Circle
○ Polynomial ☐ Plate

Fitting Options
● Current ○ To End ○ All

Calculate
☑ θ ☐ γ ☑ Vol / Area

Calculated results
γ [mN/m]:
Vol [microl]: 4.1817
θ (left): 177.86
θ (right): 172.94

Baseline Settings

☑ Use Auto BaseLine

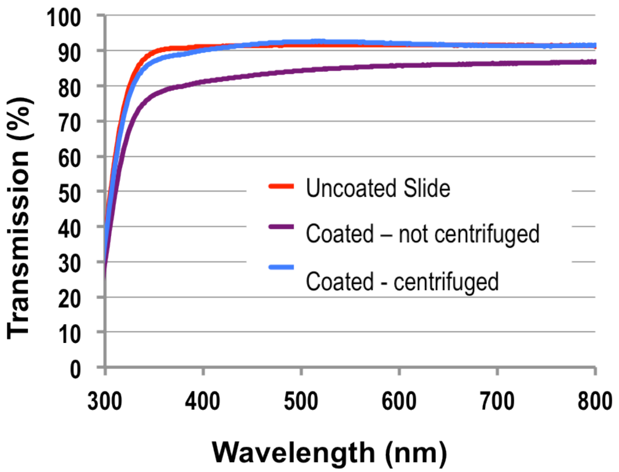
Tilt: 0.4 deg

Surfaces are highly water repellent
contact angles = $165\text{-}175^0$

Mixtures

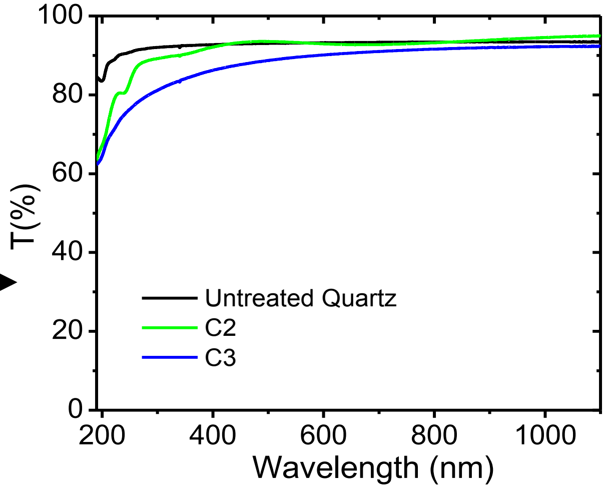
C1: Teflon®-AF + Aerogel
C2: Mixture of paraffinic- and fluoro-functionalized particles (SiO_2/Aerosil/Aerogel)
C3: Mixture of paraffinic-functionalized particles (SiO_2/Aerosil/Colloidal)

Binder - a commercially available polyurethane clearcoat



C1-Initial studies

C2,C3-Present measurements



- Improved durability without loss in coating optical transmission
- Optical transmission in UV still needs to be improved

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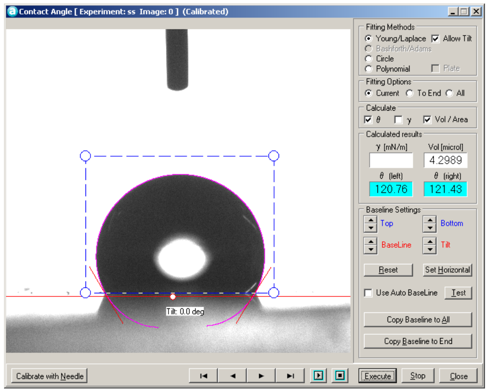
Ongoing Studies

Improved Surface Bonding



Contact Angle [Experiment: ss Image: 0] (Calibrated)

Fitting Methods: ● Young/Laplace ☑ Allow Tilt

Fitting Options: ● Current

Calculate: ☑ θ ☐ γ ☑ Vol / Area

Calculated results: γ [mN/m] — Vol [microl] 4.2989; θ (left) 120.76; θ (right) 121.43

☐ Use Auto BaseLine

Tilt: 0.0 deg

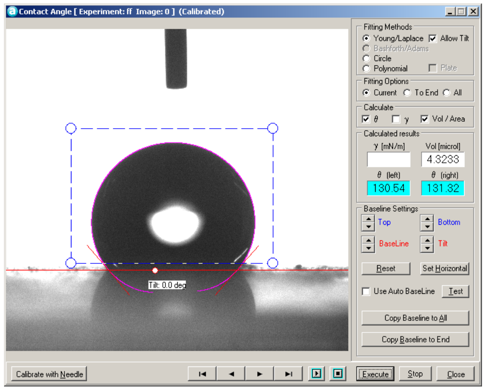
New Binder Study

RTV Epoxy

Initial C.A.= $121.9^{0} \pm 2.1^{0}$

After 10 Taber abrasion cycles

C.A. = $130.3^{0} \pm 1.1^{0}$



Contact Angle [Experiment: ff Image: 0] (Calibrated)

Fitting Methods: ● Young/Laplace ☑ Allow Tilt

Fitting Options: ● Current

Calculate: ☑ θ ☐ γ ☑ Vol / Area

Calculated results: γ [mN/m] — Vol [microl] 4.3233; θ (left) 130.54; θ (right) 131.32

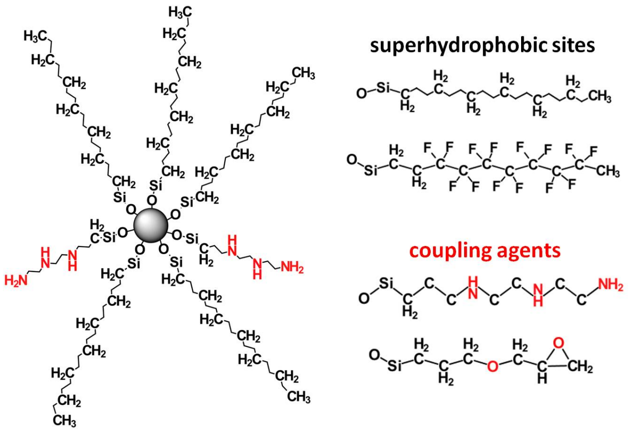
☐ Use Auto BaseLine

Tilt: 0.0 deg

Excellent hydrophobicity (similar to fluorinated epoxy surfaces) and durability

Improved silica particle functionality by adding hydrophilic amine groups (in red) which covalently bonds to surface

All particles, solvents and binders are compatible in this scheme with good bonding to substrate



Patent Application submitted

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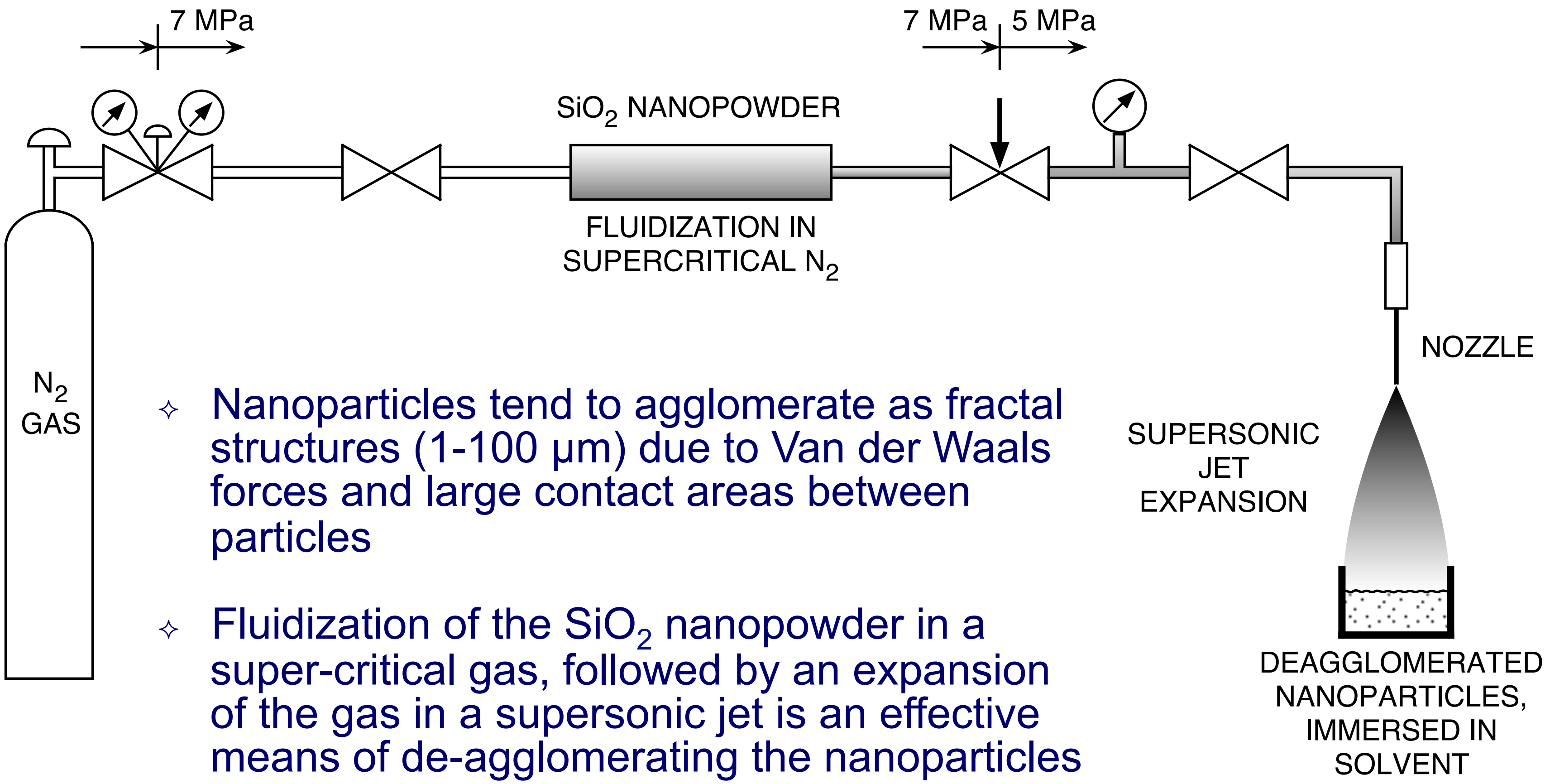
Ongoing Studies

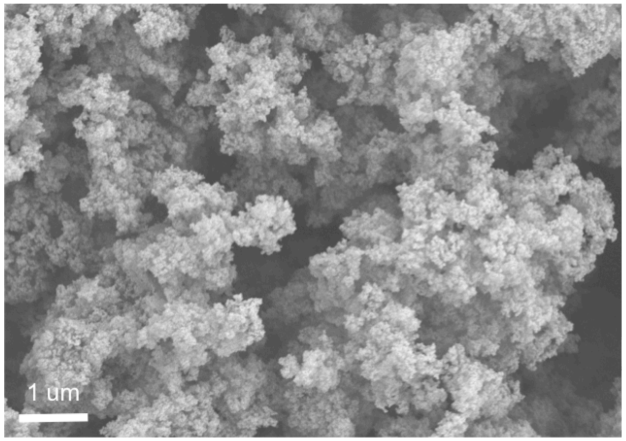
Reduced Silica Particle Size



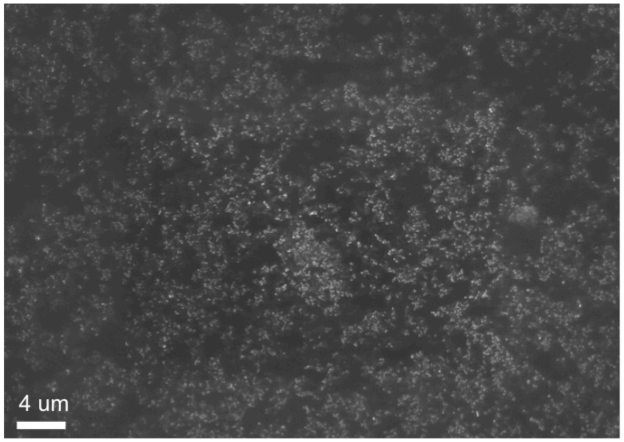
- Nanoparticles tend to agglomerate as fractal structures (1-100 μm) due to Van der Waals forces and large contact areas between particles
- Fluidization of the SiO_2 nanopowder in a super-critical gas, followed by an expansion of the gas in a supersonic jet is an effective means of de-agglomerating the nanoparticles before immersion in the solvent

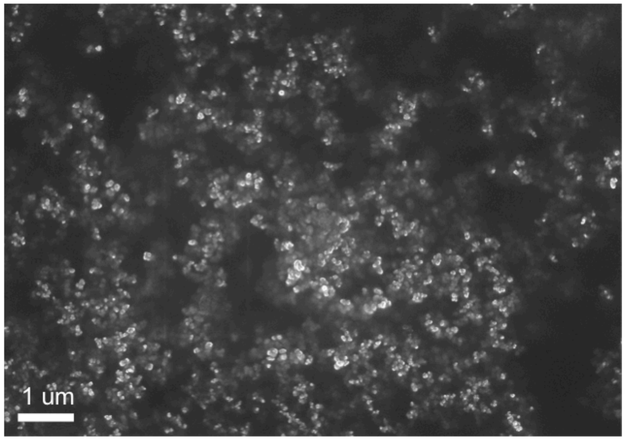
Ongoing Studies

De-agglomeration of Silica



SiO_2 nanopowder (fumed silica, as-received) is comprised of large agglomerates that must be de-agglomerated to provide SH coatings with the required durability and optical performance

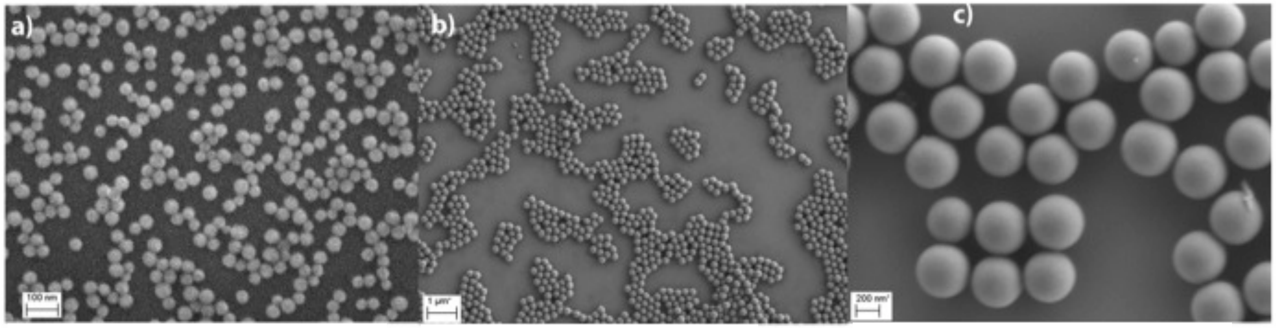




De-agglomerated SiO_2 following fluidization and rapid expansion in a supersonic jet with particles in the 50-200 nm size range

Ongoing Studies

In-house colloidal silica (SiO_2) synthesis



Scale bar = 100 nm

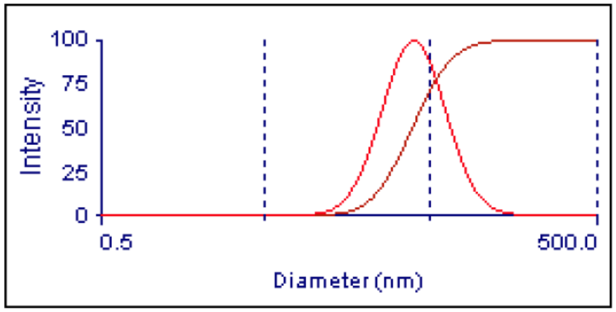
Particle Size
65 nm

Scale bar = 1 µm

Particle Size
225 nm

Scale bar = 200 nm

Particle Size
425 nm



Lognormal Distribution

Smallest size particle batch made so far
Particle Size Distribution
39.3 ± 17.9 nm

We can manufacture monodisperse silica particles with a range of particles sizes from 10-20 nm up to several hundred nm for good optical transmission and superhydrophobicity

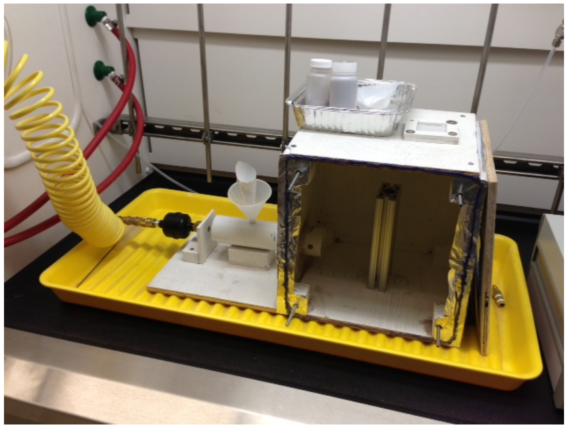
Accomplishments and Breakthroughs

- Developed multimodal, functionalized silica particle size distributions with improved superhydrophobic properties
- Demonstrated an 8 fold increase in surface durability with no loss in hydrophobicity and optical transmittance from initial coatings
- This has been achieved by improving particles, solvents and binder compatibility leading to excellent particle dispersion and coating uniformity
- Demonstrated the ability to fabricate monodisperse silica particles over a range of particle sizes in a scalable, repeatable process
- Demonstrated improved surface durability and high hydrophobicity (not superhydrophobicity) with RTV silicone epoxy in Taber abrasion tests
- Developed a new silica functionalization scheme to improve bonding to silicone based epoxies – patent applied for

Future Work

Next 6 months

- Complete development of anti soiling coatings
- Perform long term (18 months) durability tests on promising coating formulations
- The goal is to understand the durability issues and any possible failure mechanisms of the proposed coatings under simulated environmental conditions:
  - Standardized Taber tests – milestone is 25 cycles without significant loss of hydrophobicity
  - UV exposure – 30 year simulated solar UV in QUV Accelerated Weathering Tester
  - Coatings will be studied for salt fog, rain and humidity durability in an Autotechnology Salt Fog Chamber in accordance with salt fog standard ASTM B-117
  - Controlled sand and dust blasting in custom made wind tunnel
  - Ongoing optical characterization of tested samples


Custom made wind tunnel for sand blasting studies

Future Work

FY 2014

- Setup small scale coating demonstration
- Partnering with a mirror manufacturer or CSP facility operator
- Field trial data collection and analysis
- Demonstration of 18 months field and laboratory endurance

Milestones

- Demonstrate that mirror maintenance will be reduced 90% compared to uncoated mirrors
- Demonstrate that the anti-soiling coated mirror surfaces have an average increase in reflectivity ≥ 5% higher as compared to uncoated mirror surfaces exposed to the same environmental conditions

Acknowledgments

I wish to acknowledge my colleagues at the
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Dr. George Polyzos
Mr. Daniel Schaeffer
Dr. Dominic Lee

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