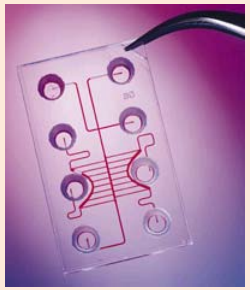
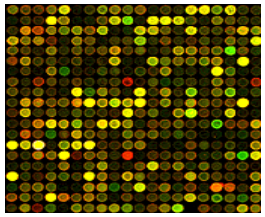
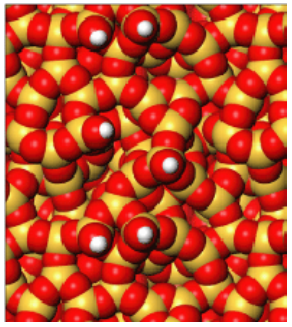
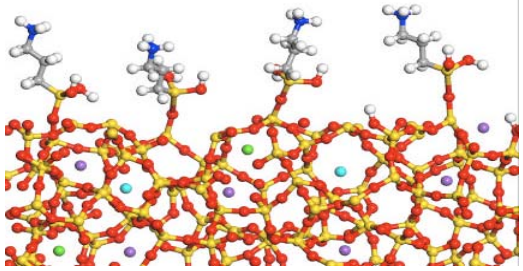


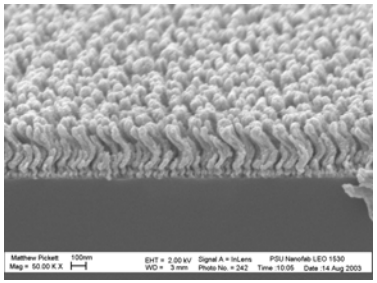
Glass Surfaces and Coatings for New Functionality

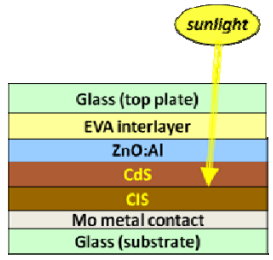
Carlo G Pantano
Department of Materials Science and Engineering
Materials Research Institute
Penn State University

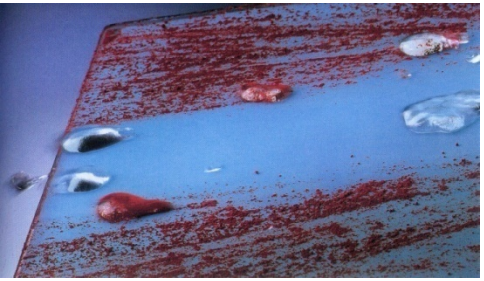












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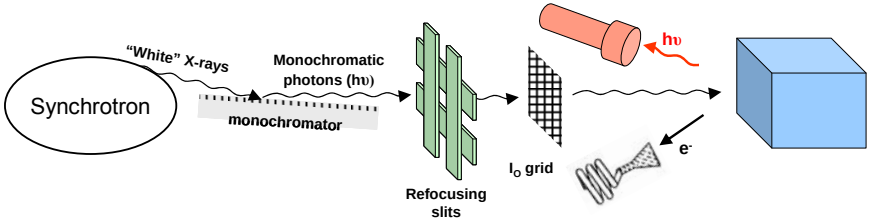
Materials Research Institute

Center for Glass Surfaces, Interfaces, and Coatings

IMI Winter School
Zhejiang University
January 2010

Important Roles for Glass Surfaces

- strength
- optical
- chemical defense
- substrate for coatings

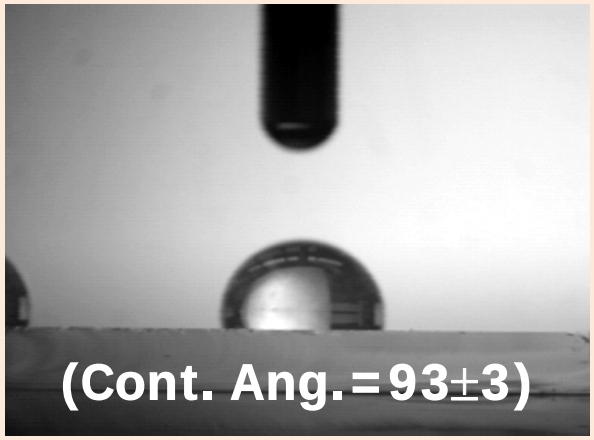


Methods of Characterization

- surface composition (XPS)
- depth profiling (SIMS)
- surface roughness (AFM)
- organic adsorbates (FTIR/Raman)
- chemical structure (NMR and NEXAFS)
- surface charge (streaming potential)
- contact angle tensiometry
- adhesion (CFM)

Characteristics and Properties of Glass Surfaces and Coatings

- surface composition
- chemical functionality
- contact angle/wettability
- surface charge and other surface forces
- porosity/roughness/specific surface
- cleanliness and chemical durability
- uniformity of ALL the above

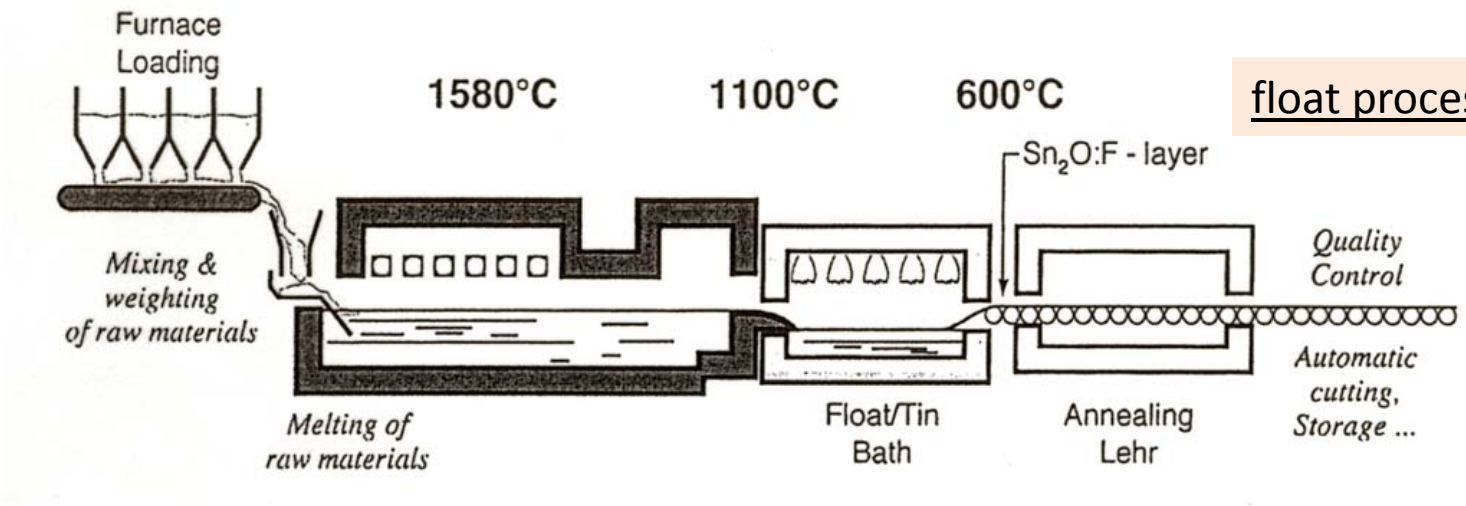


The composition, structure and properties of surfaces are determined by the process used to create the surface.

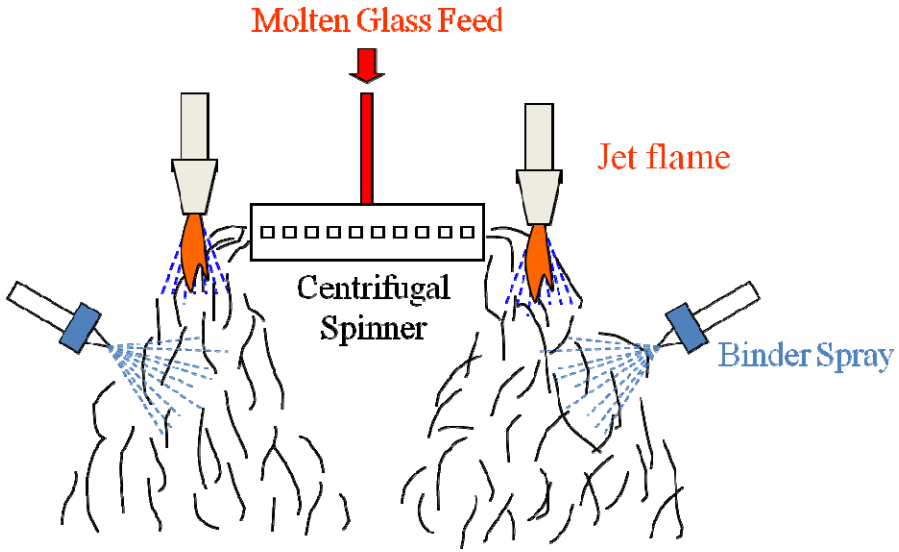
- Fracture surface
- Melt surface (frozen liquid)>> thermal history
- Ground and polished
- Chemically etched
- Plasma or ion-sputtered
- Vapor deposited

Manufacturing Flat Glass and Fiberglass>>> creating **SURFACE**

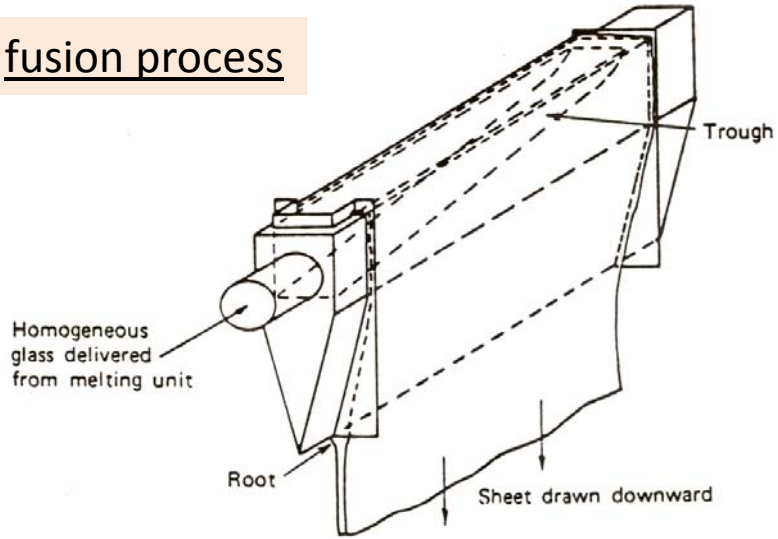
float process



fiberglass wool



fusion process



Outline

Part 1: Fundamentals

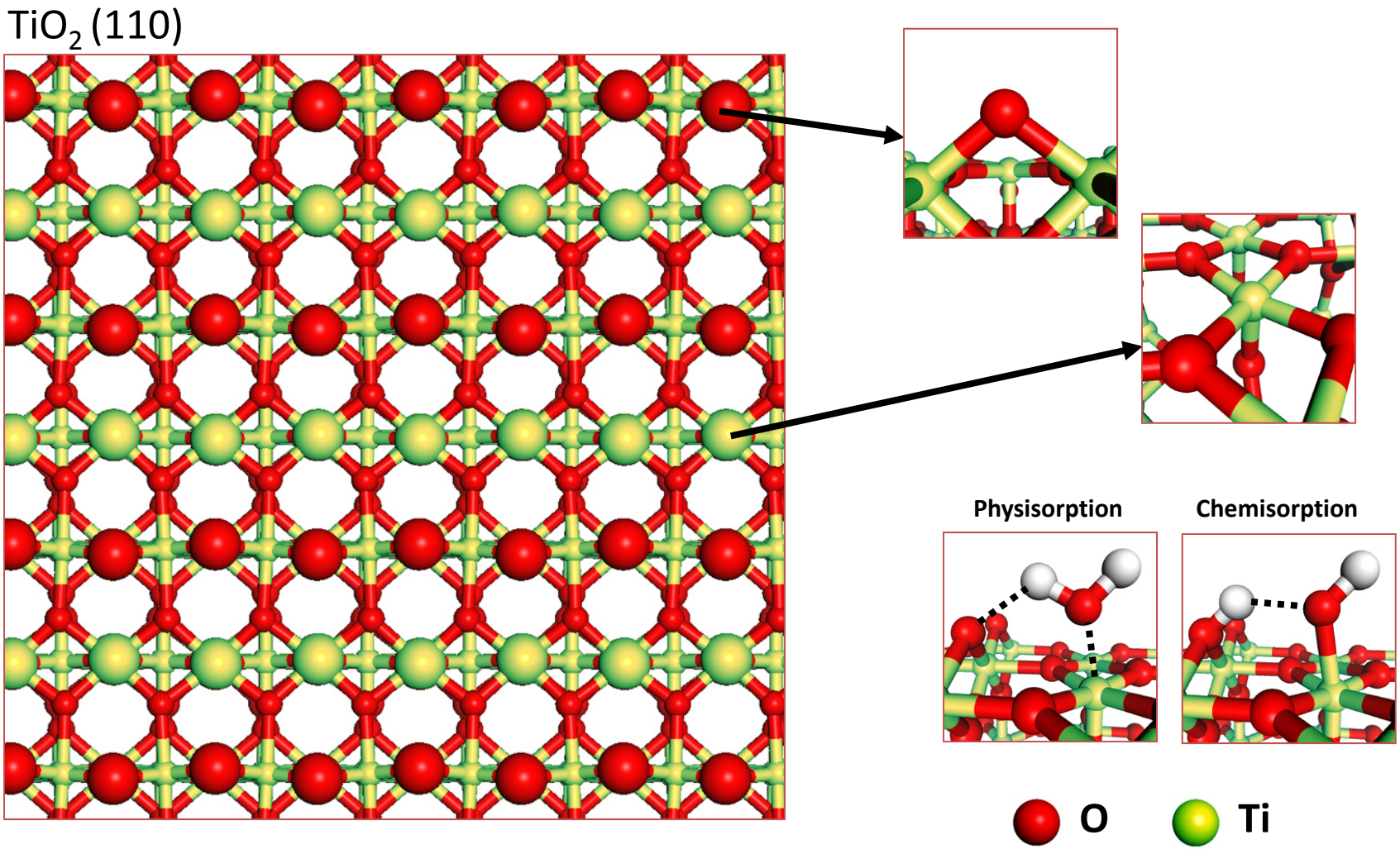
- **Surface Structure and Adsorption**
  - fracture surface vs melt surface
  - silica vs multicomponent
- **Surface and In-Depth Reactions**
- **Surface Functionalization**

Part 2: Functional Surfaces

- **DNA Microarray Substrates**
- **Semiconducting Glass Surfaces**
- **Nanoscale Carbon Coatings**
- **Glass-Polymer Interfaces**

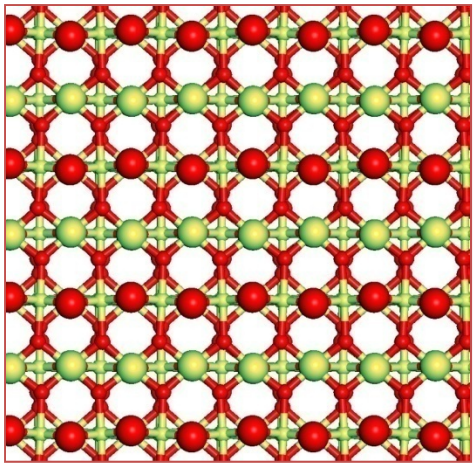
Crystalline Surfaces

Repeating arrays of nearly identical sites.

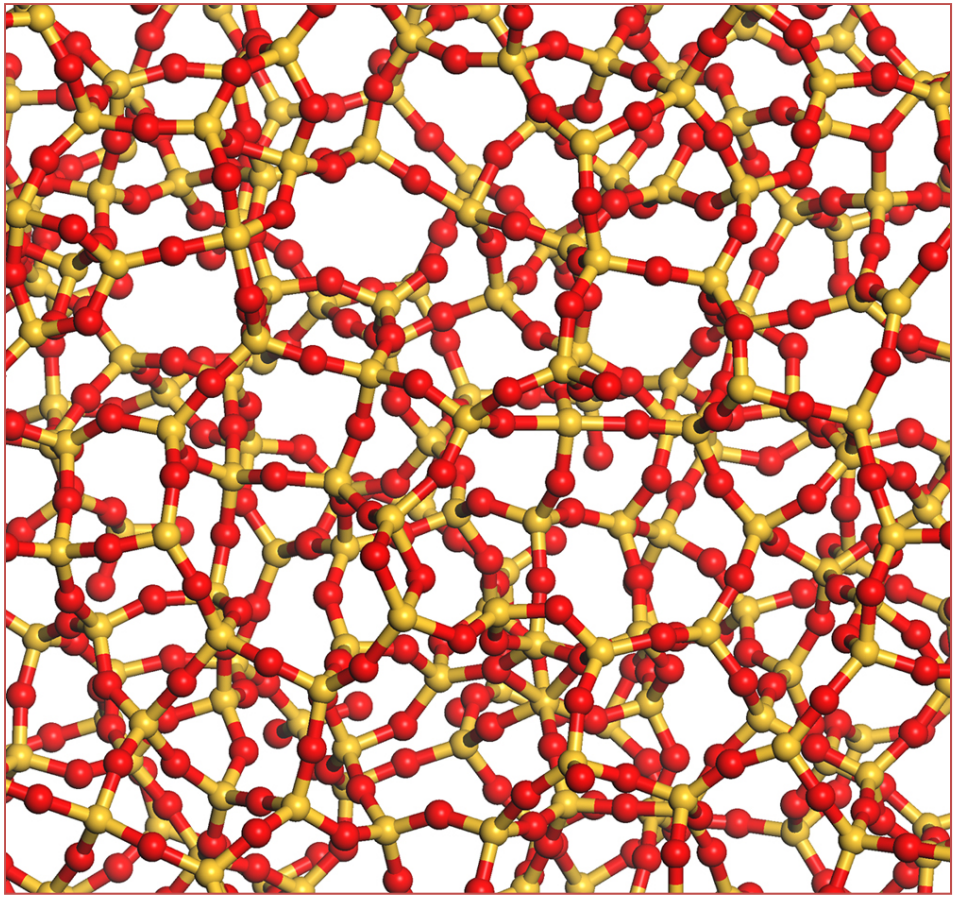


Glass Surfaces

glass surfaces contain a continuum of **heterogeneous adsorption sites**.



TiO_2 (110)



Silica glass

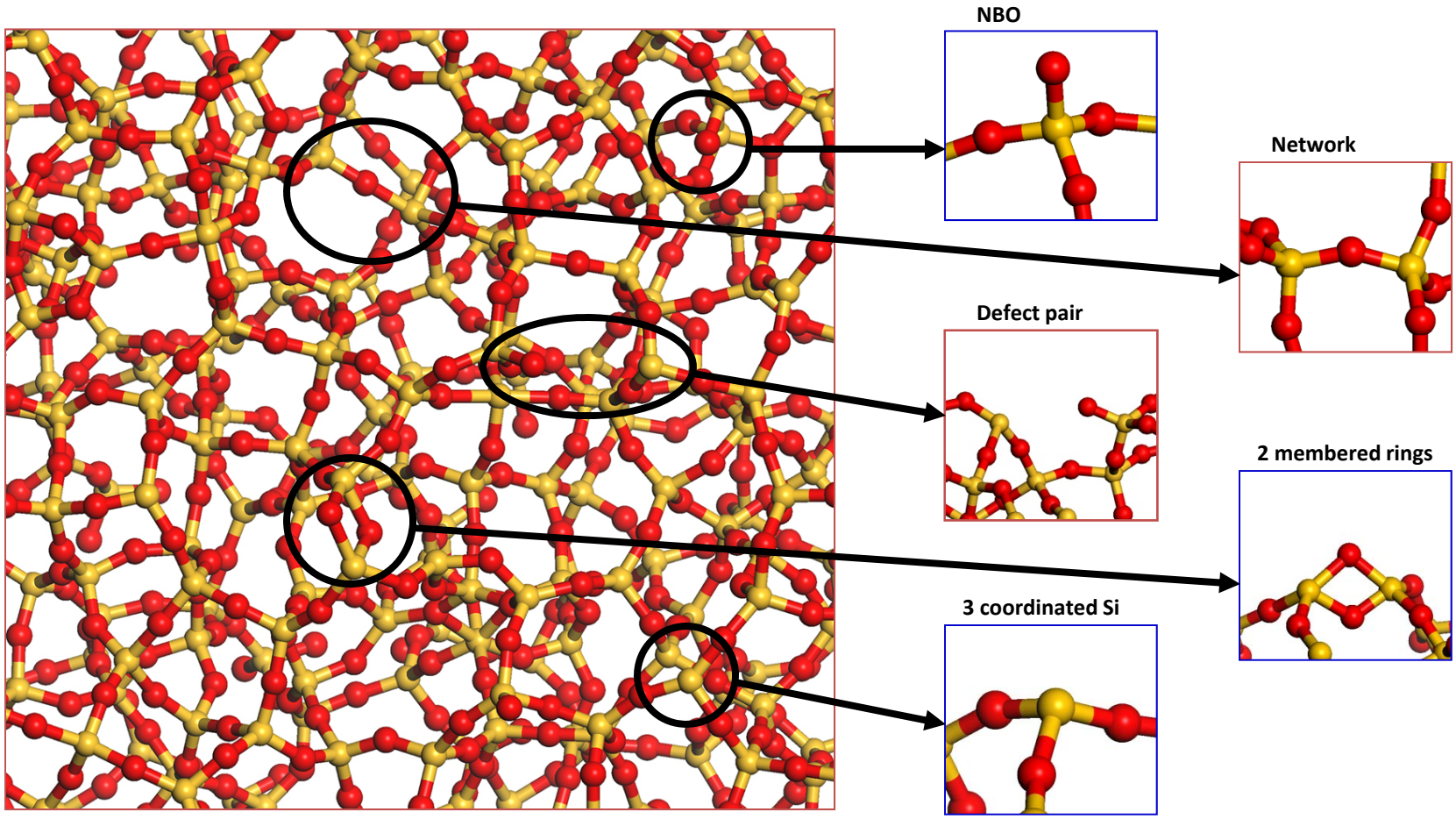
O

Si

Glass Surfaces

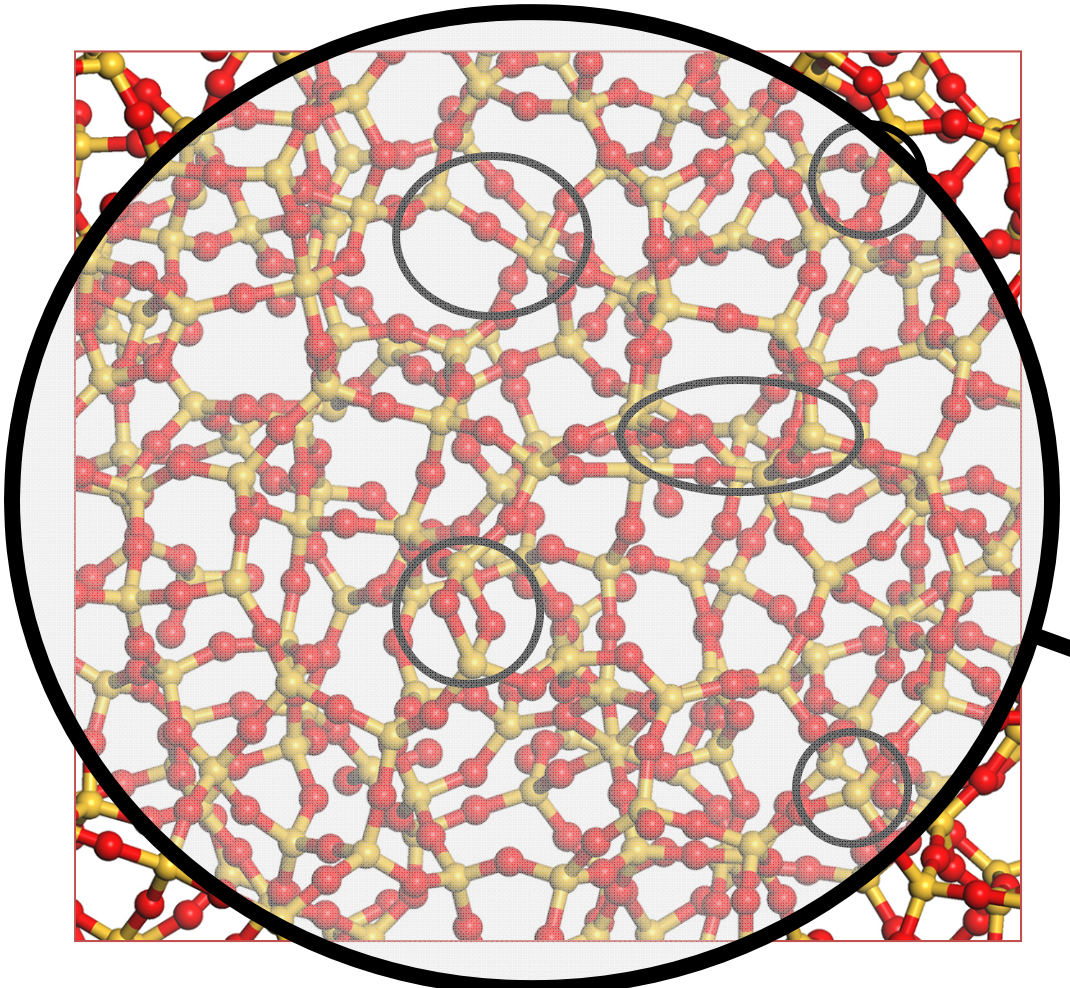
the continuum of heterogeneous adsorption sites can be broken down into

a set of distinct types of adsorption sites.

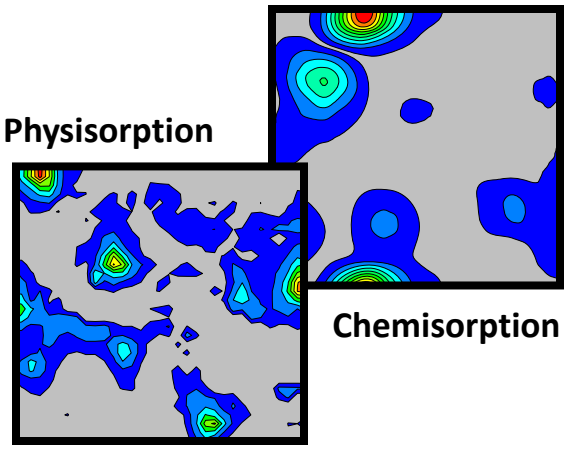


Glass Surfaces

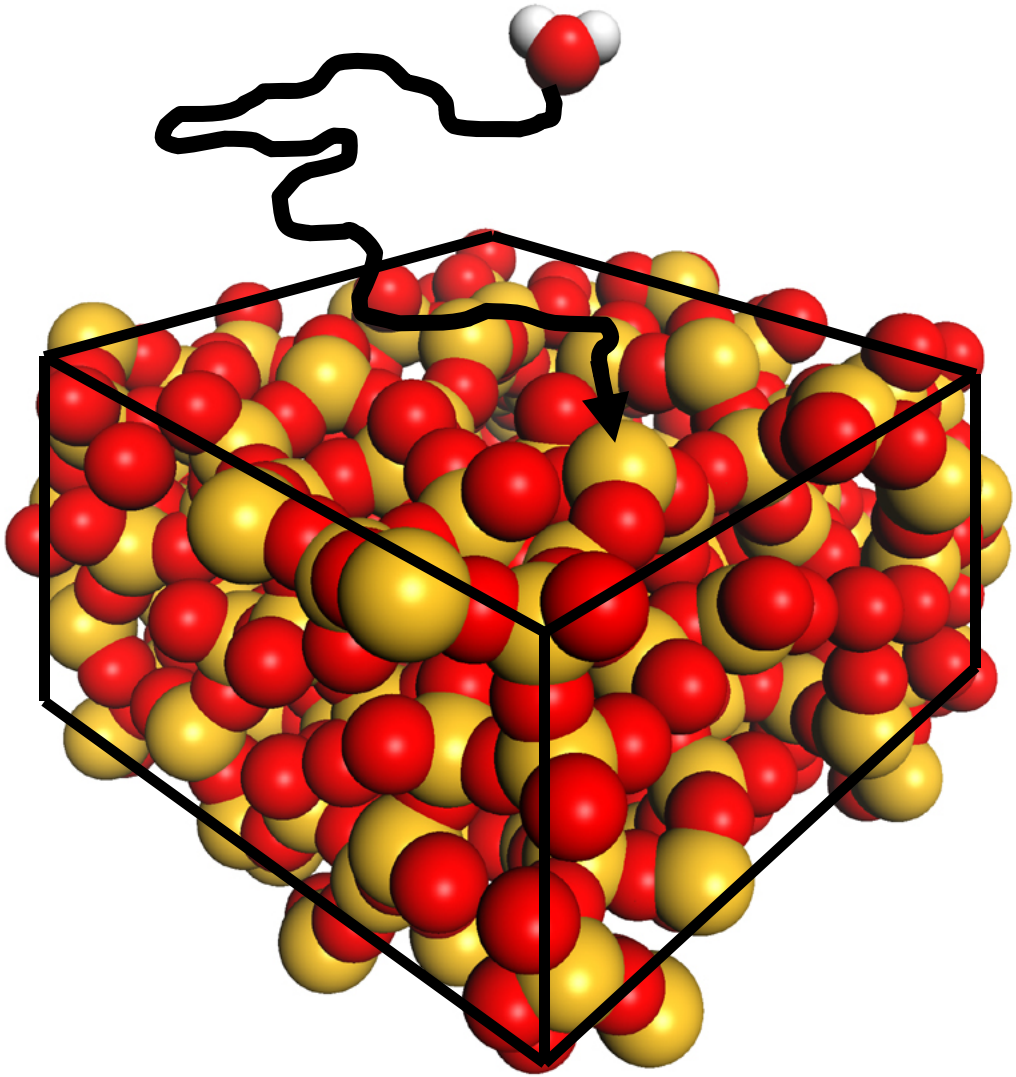
Glass surfaces are made up of a vast collection of **heterogeneous adsorption sites**.



Modeling Goal: Map the adsorption properties of the surface as a continuous network of heterogeneous sites.

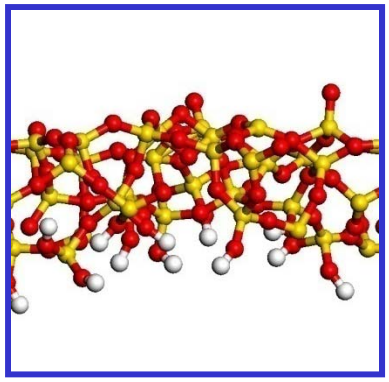


Modeling Surface Adsorption Sites Using Water (and other Polar PROBE Molecules)



Adsorption Investigated with DFT

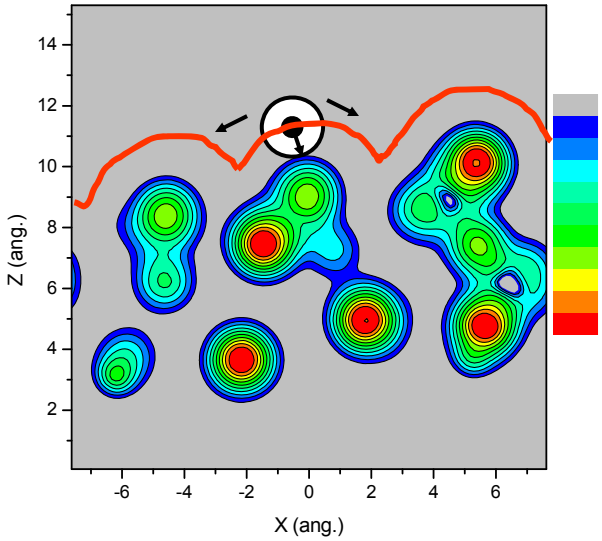
Start with a surface slab



(side views)

VASP

Create a surface profile



Calculate the electronic "softness" of the charge density

Find sites that are charge donor/acceptor pairs

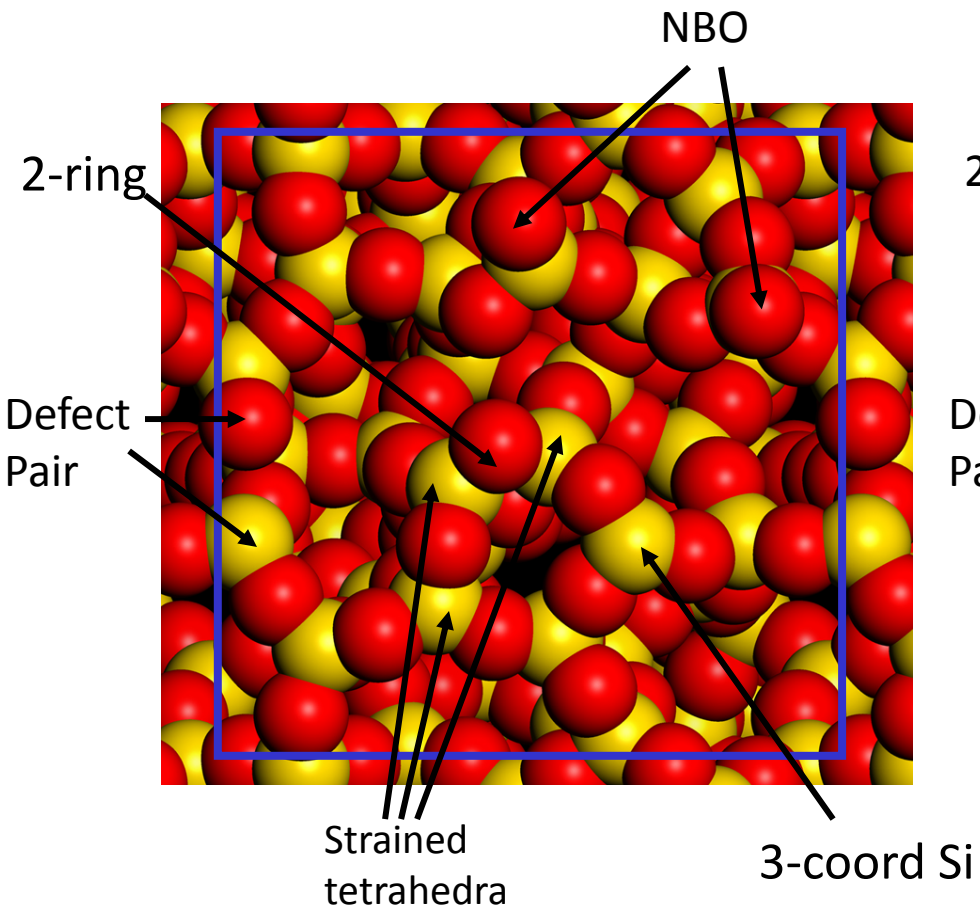
Chemisorption mapping

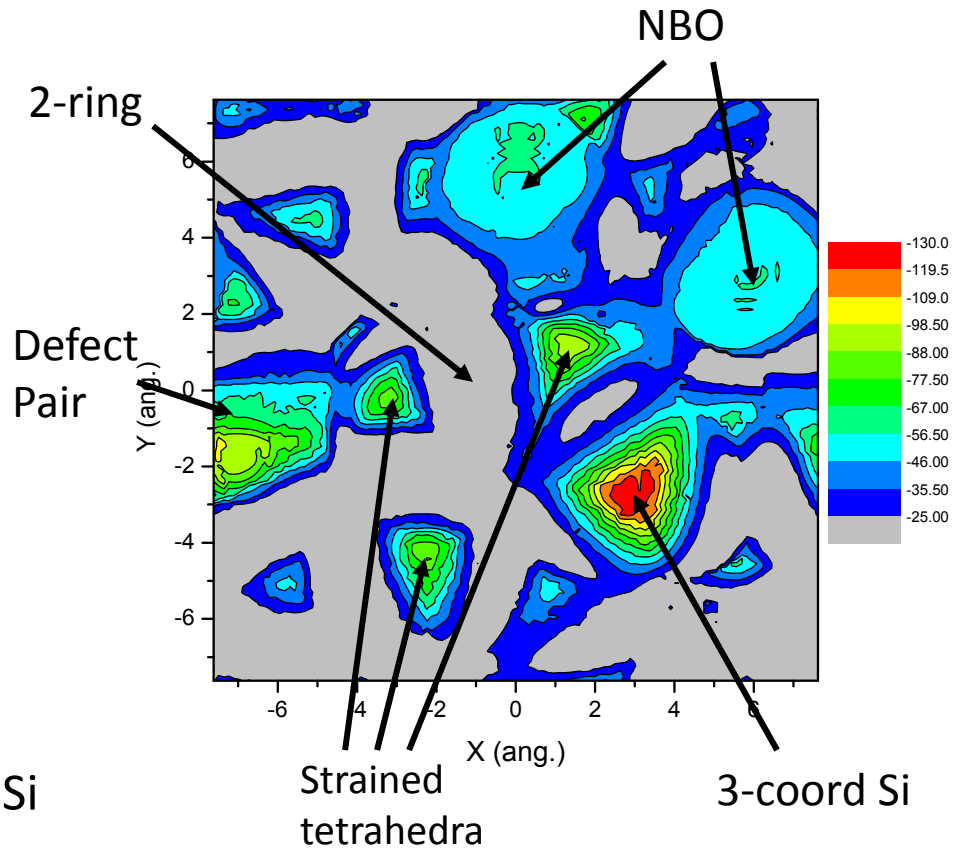
Multiply the gradient of the electric potential by the dipole moment of water (or any adsorbate)

Physisorption mapping

DFT Physisorption Mapping

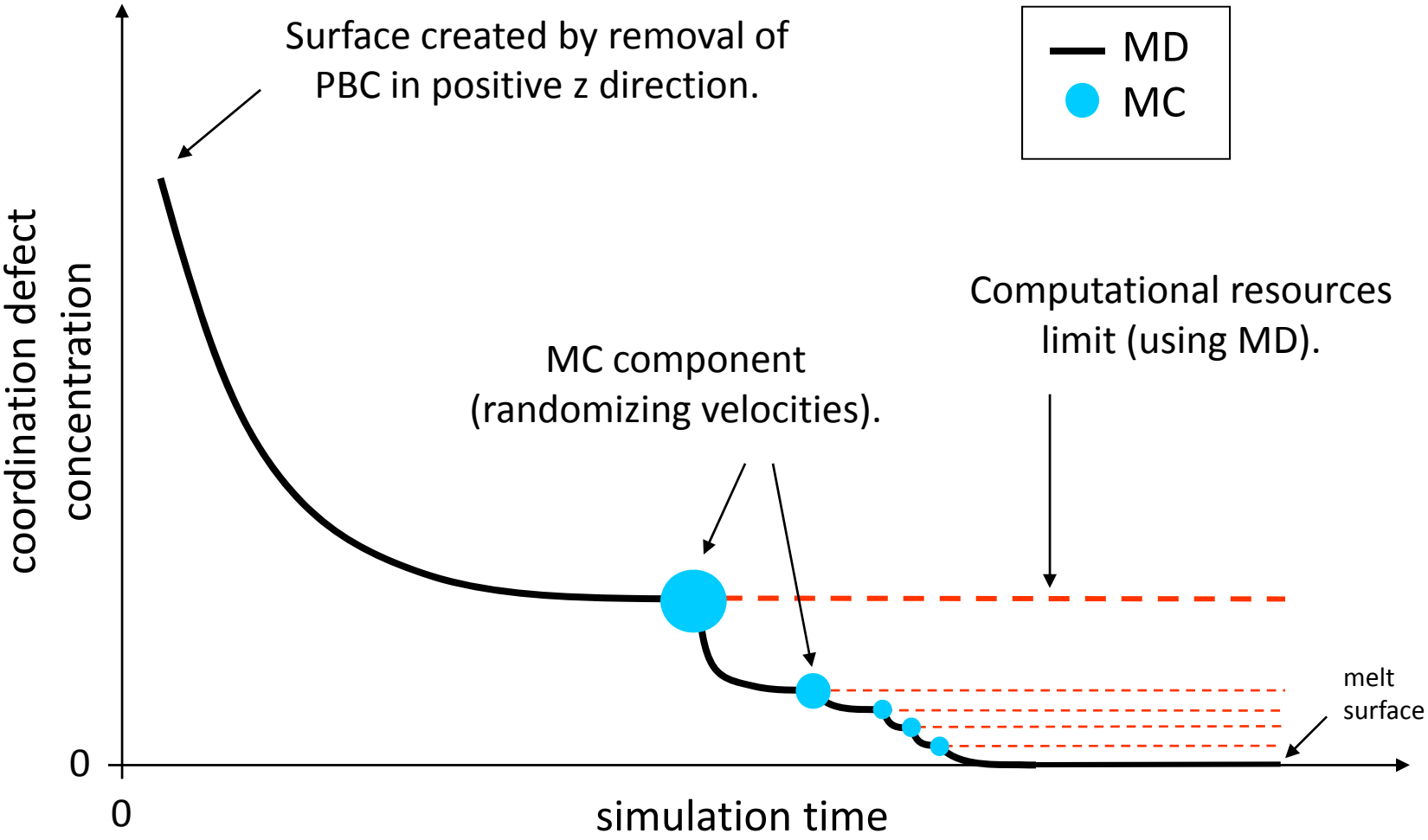
Silica fracture surface





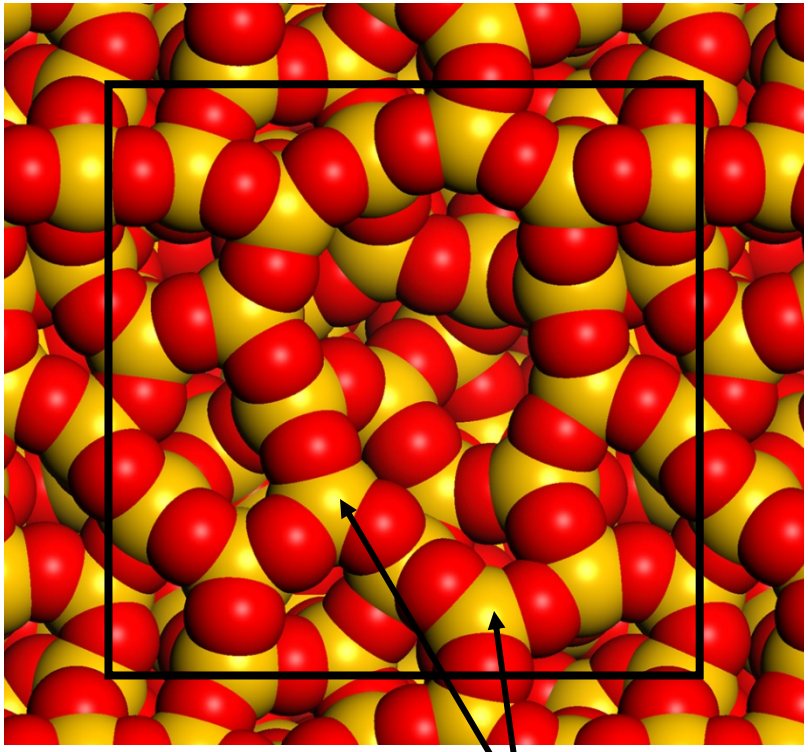
Modeling “Melt Surfaces”

Hybrid Monte Carlo / Molecular Dynamics (MC/MD) for simulating coordination-defect-free surfaces

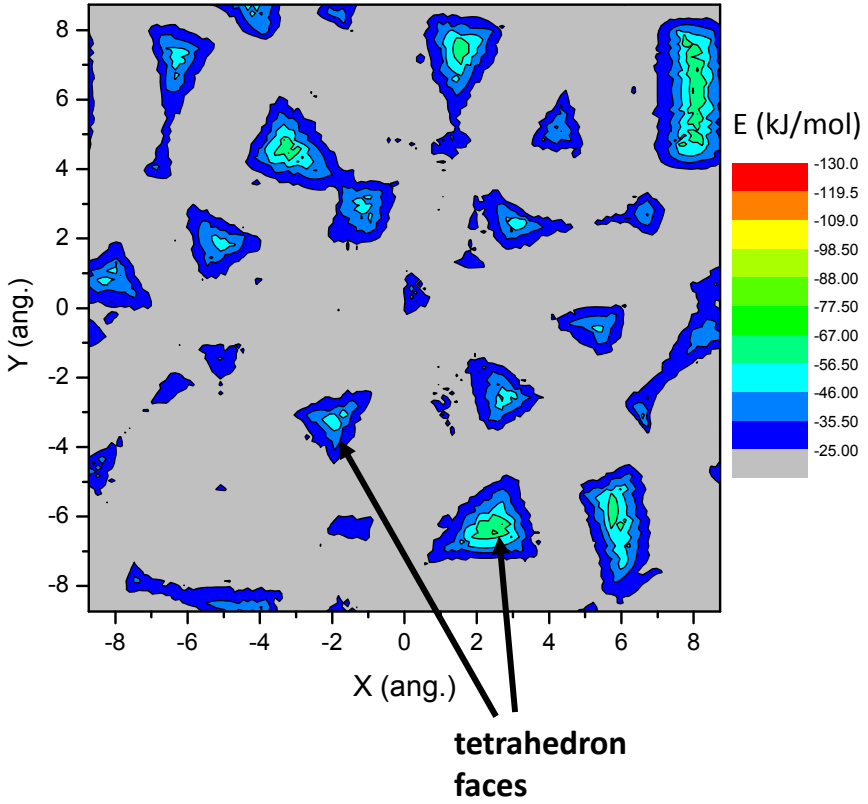


DFT Physisorption Mapping

silica melt surface… relaxed to eliminate dangling bonds

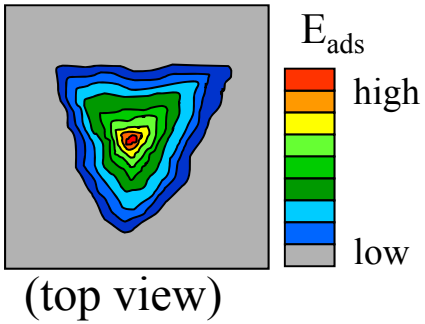


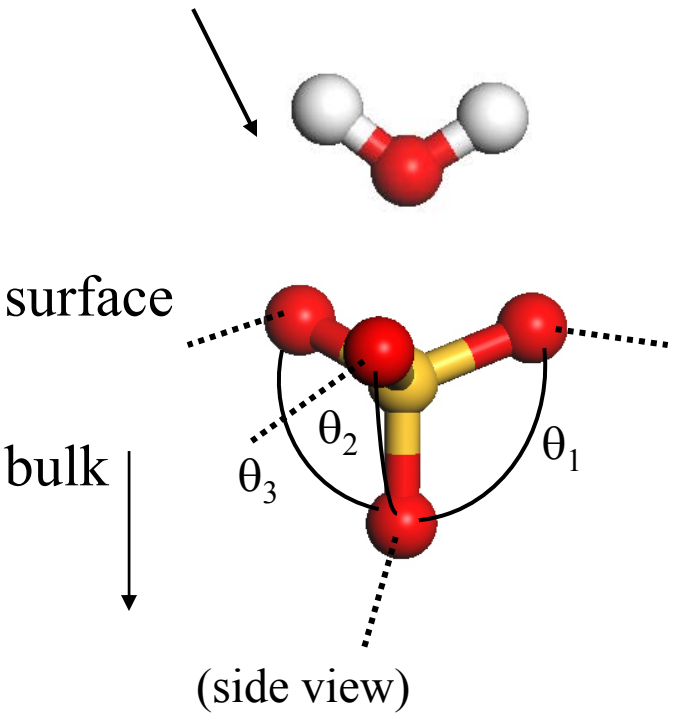
tetrahedron faces

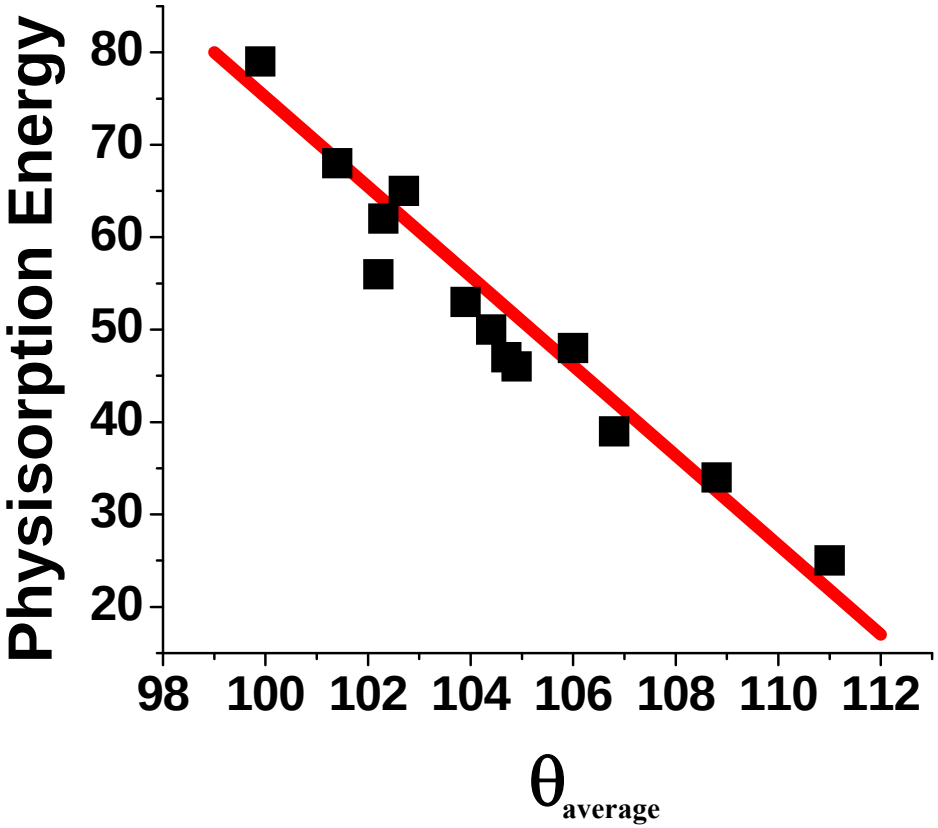


tetrahedron faces

DFT Physisorption Mapping

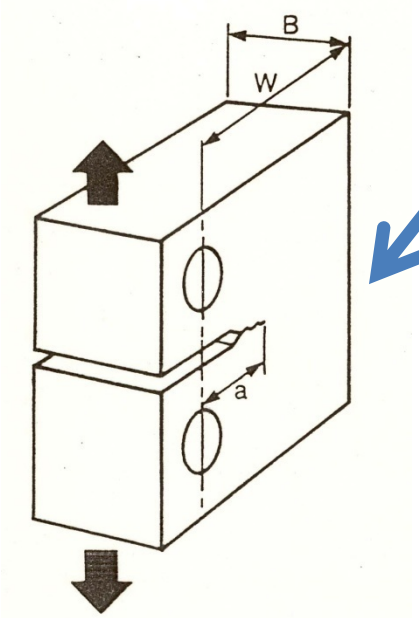


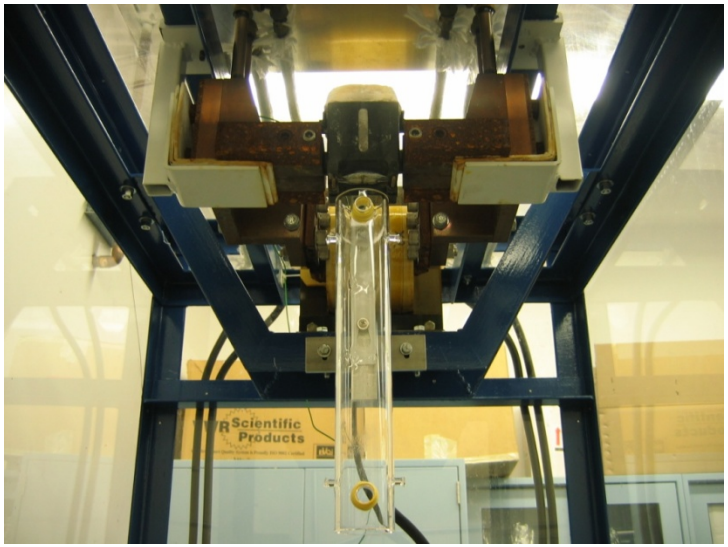


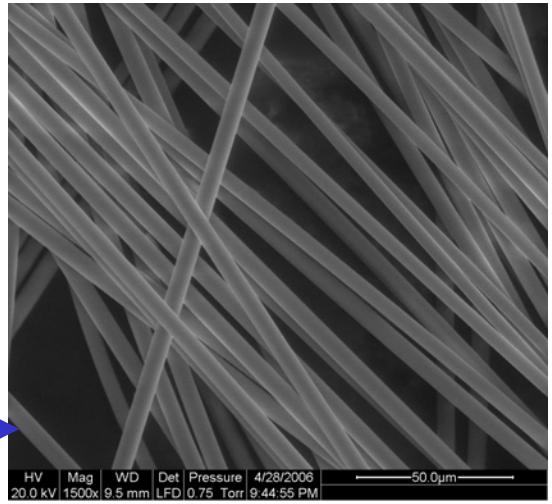


Glass Surfaces for Research

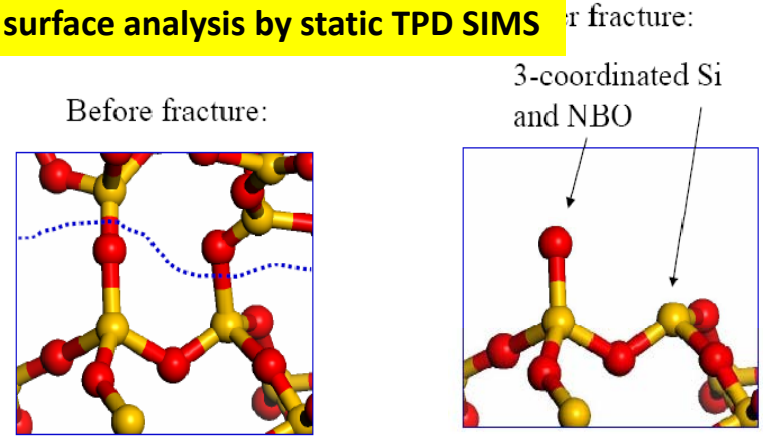
clean fracture surfaces and frozen melt surfaces

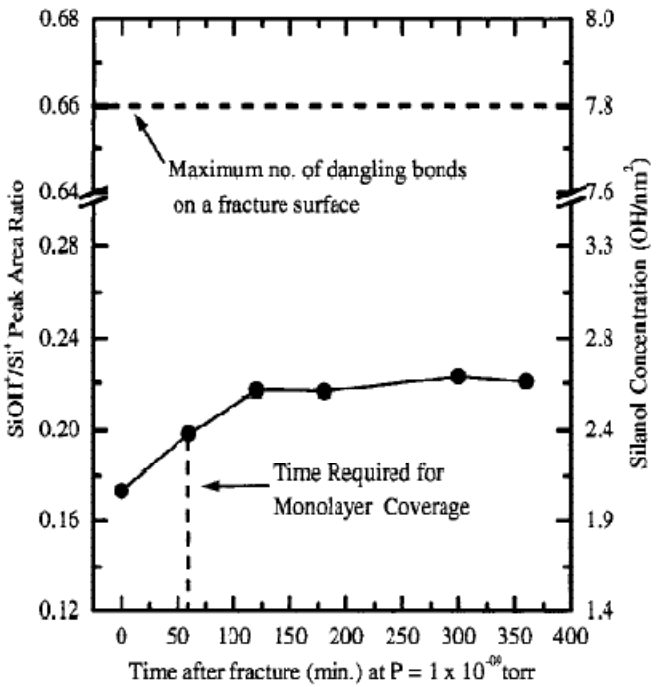






in-situ vacuum fracture surface analysis by static TPD SIMS



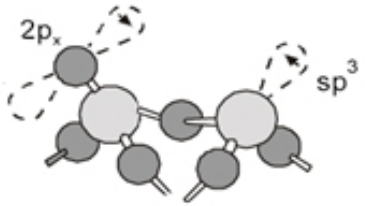


A. S. D'Souza, and C. G. Pantano, J. Am. Ceram. Soc. **82**, 1289 (1999)

in-situ vacuum fracture surface analysis by ESR

NBOHC (dangling oxygen bond)

Generic E'-center (dangling silicon bond)



G. Hochstrasser, and J. F. Antonini, Surface Science **32**, 644 (1972)

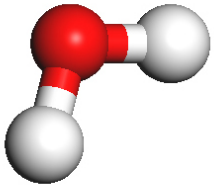
$$(\mathrm{Si + SiO})/\mathrm{nm}^2 = \left(\frac{N}{\nu(\mathrm{SiO_2})}\right)^{2/3}\left(\frac{1}{N}\right) = 7.8\ \mathrm{nm}^2$$

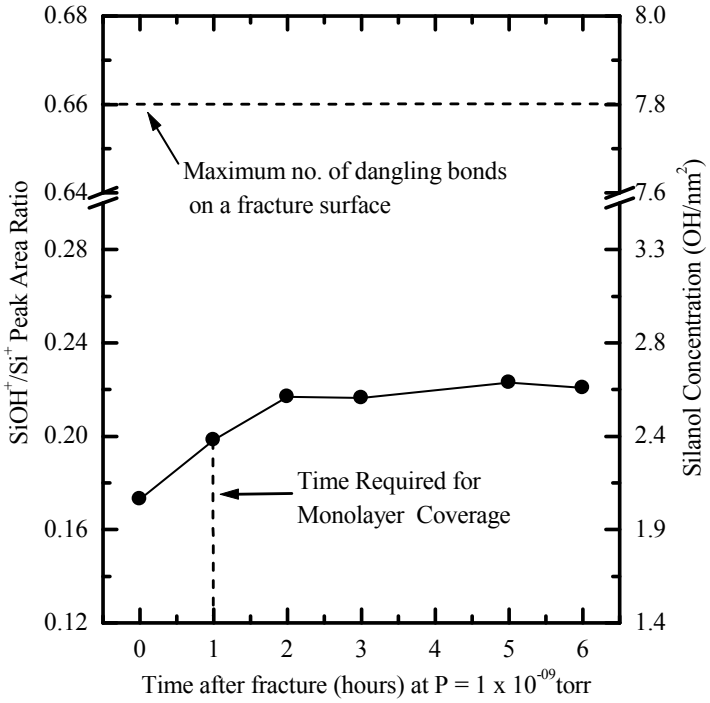
SIMS: 2.6SiOH/nm^2 (33%)

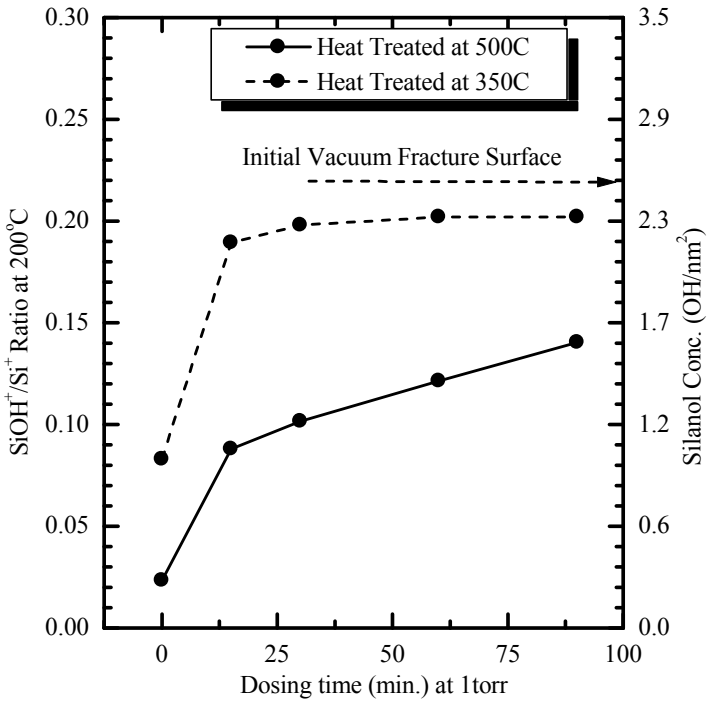
ESR: 0.01 E'$_s$/nm^2 dangling (0.12%)

~5.2 bonds/nm^2 re-constructed (66%)

•experimental work on clean silica fracture surfaces showed dependence of water vapor adsorption kinetics on thermal history.

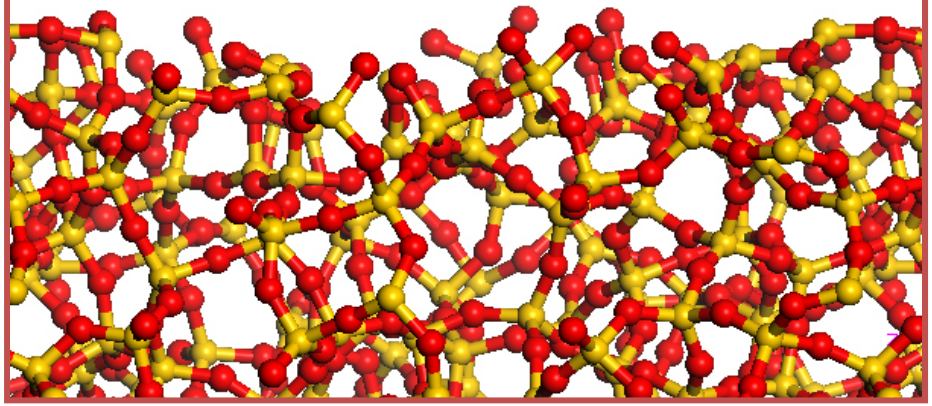




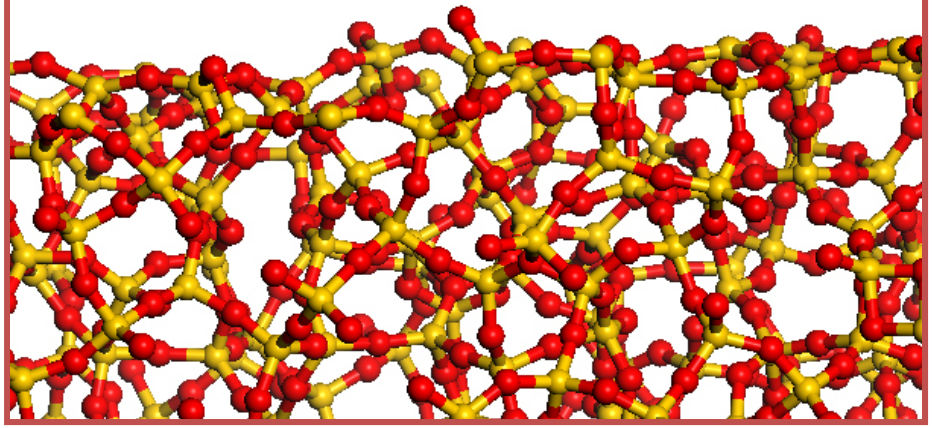


Glass Surface Structure Models

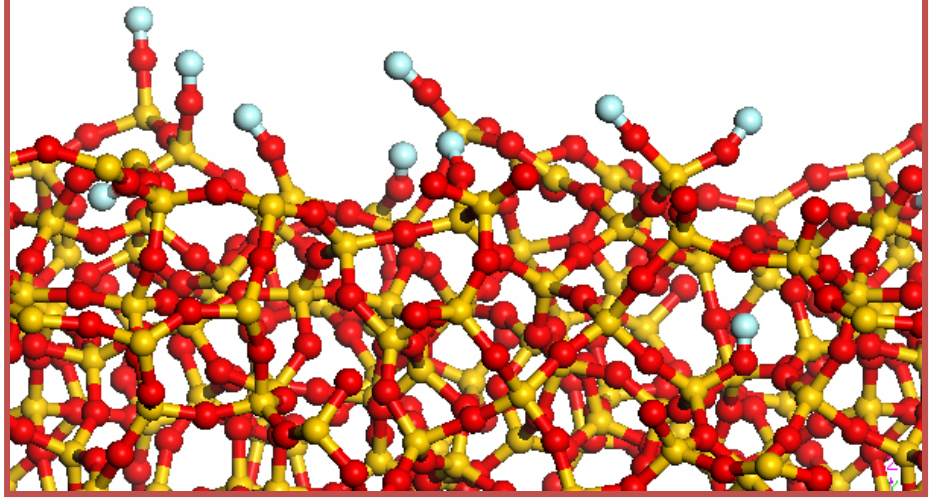
Silica at instant of fracture



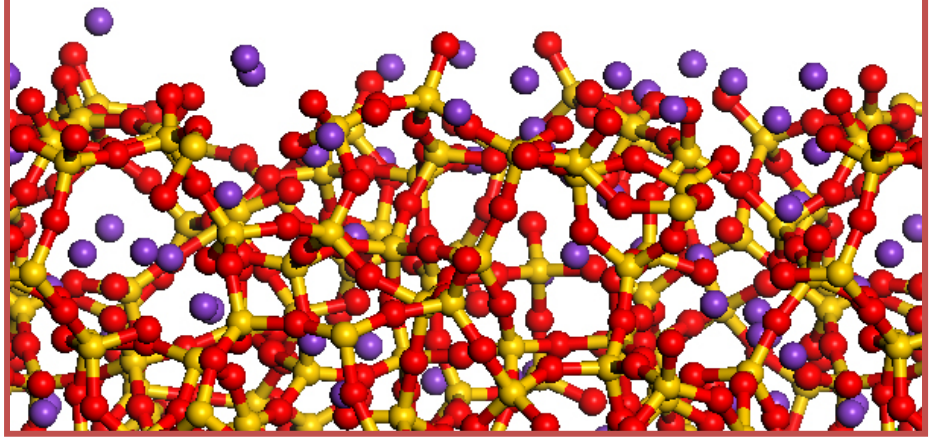
Relaxed silica fracture surface



Hydroxylated silica fracture surface



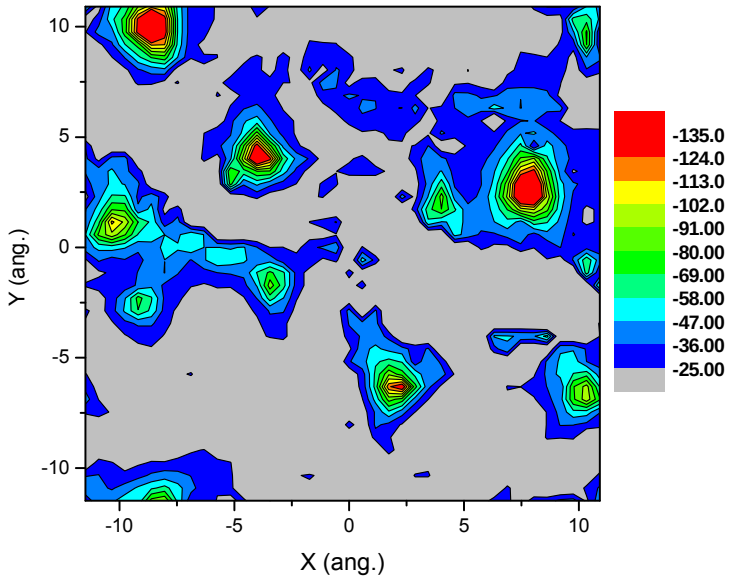
Relaxed sodium silicate fracture surface

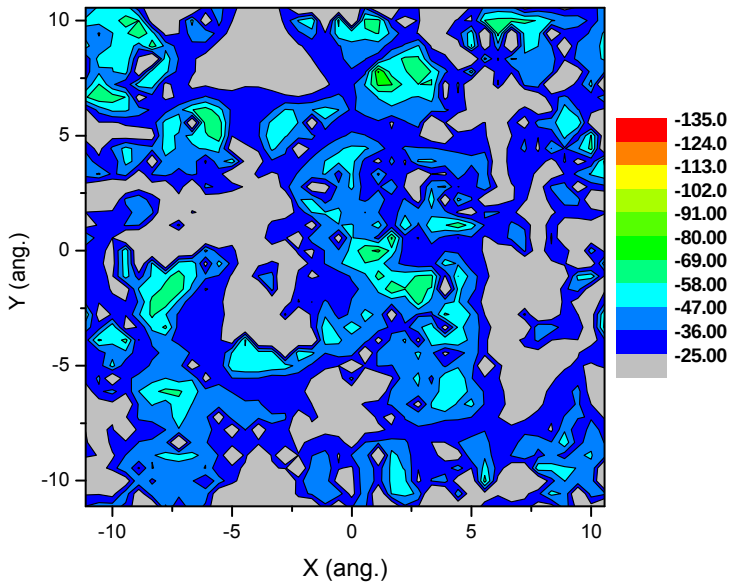


Silica

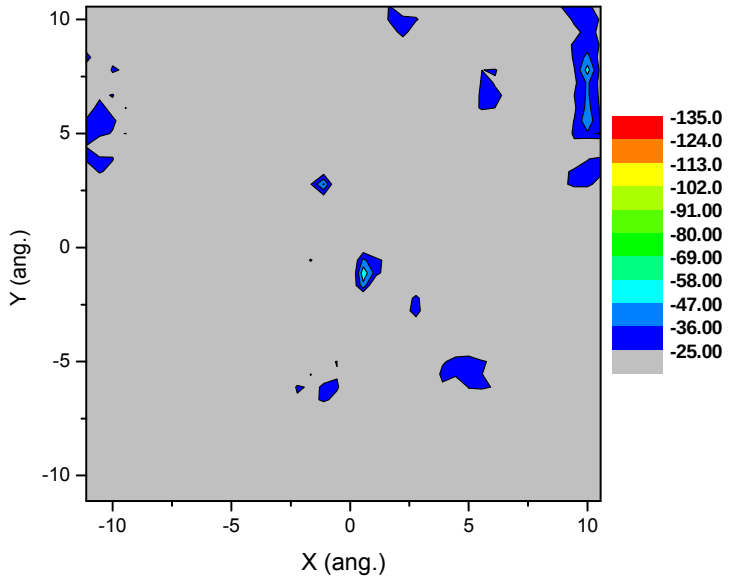
25 Na_2O – 75 SiO_2

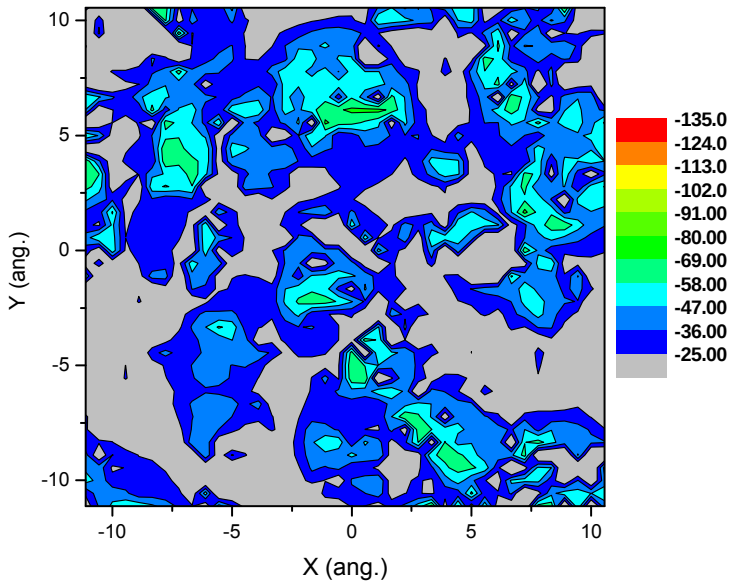
Fracture Surface





Melt Surface

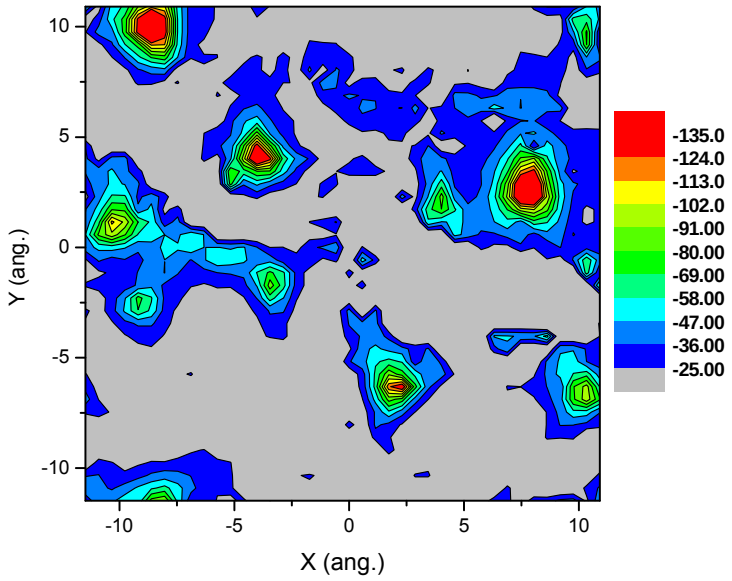


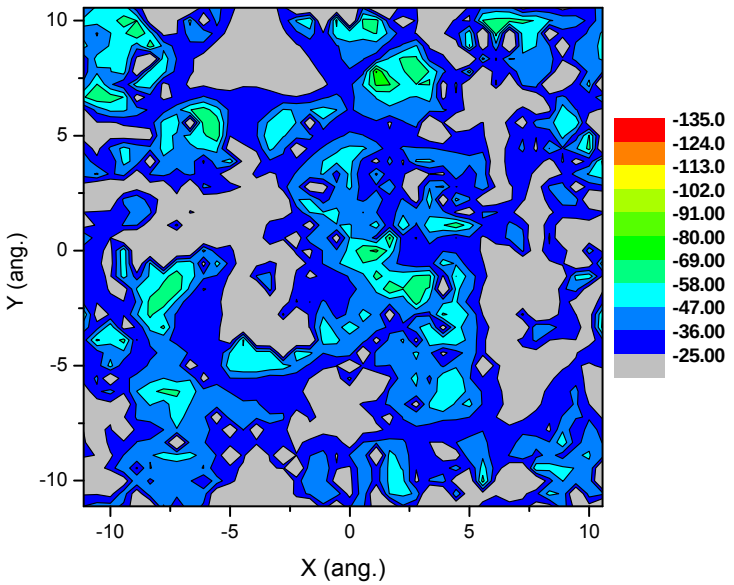


Silica

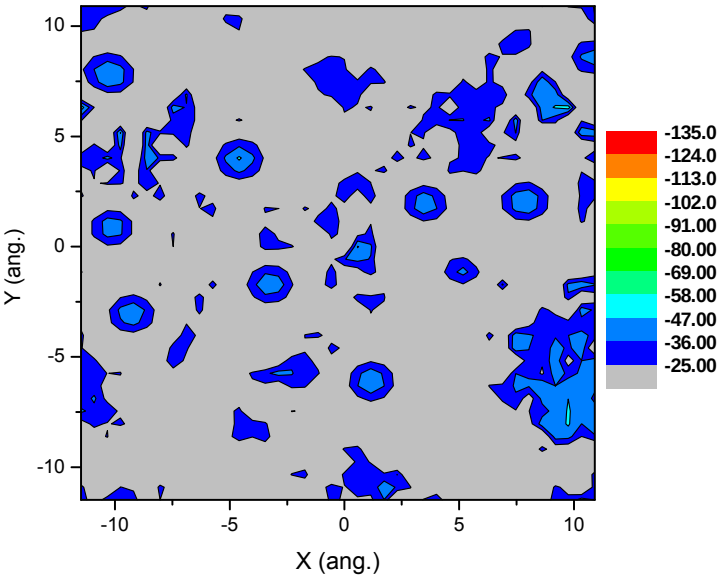
$25\ Na_2O - 75\ SiO_2$

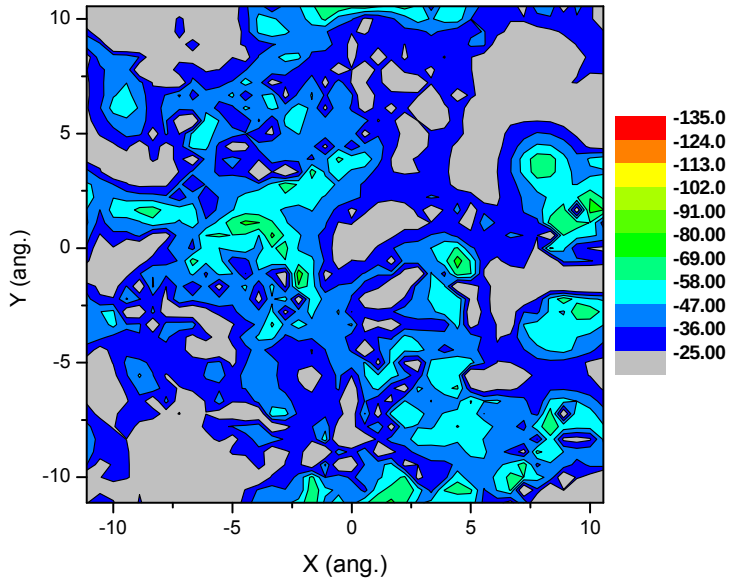
Fracture Surface





Hydroxylated FS





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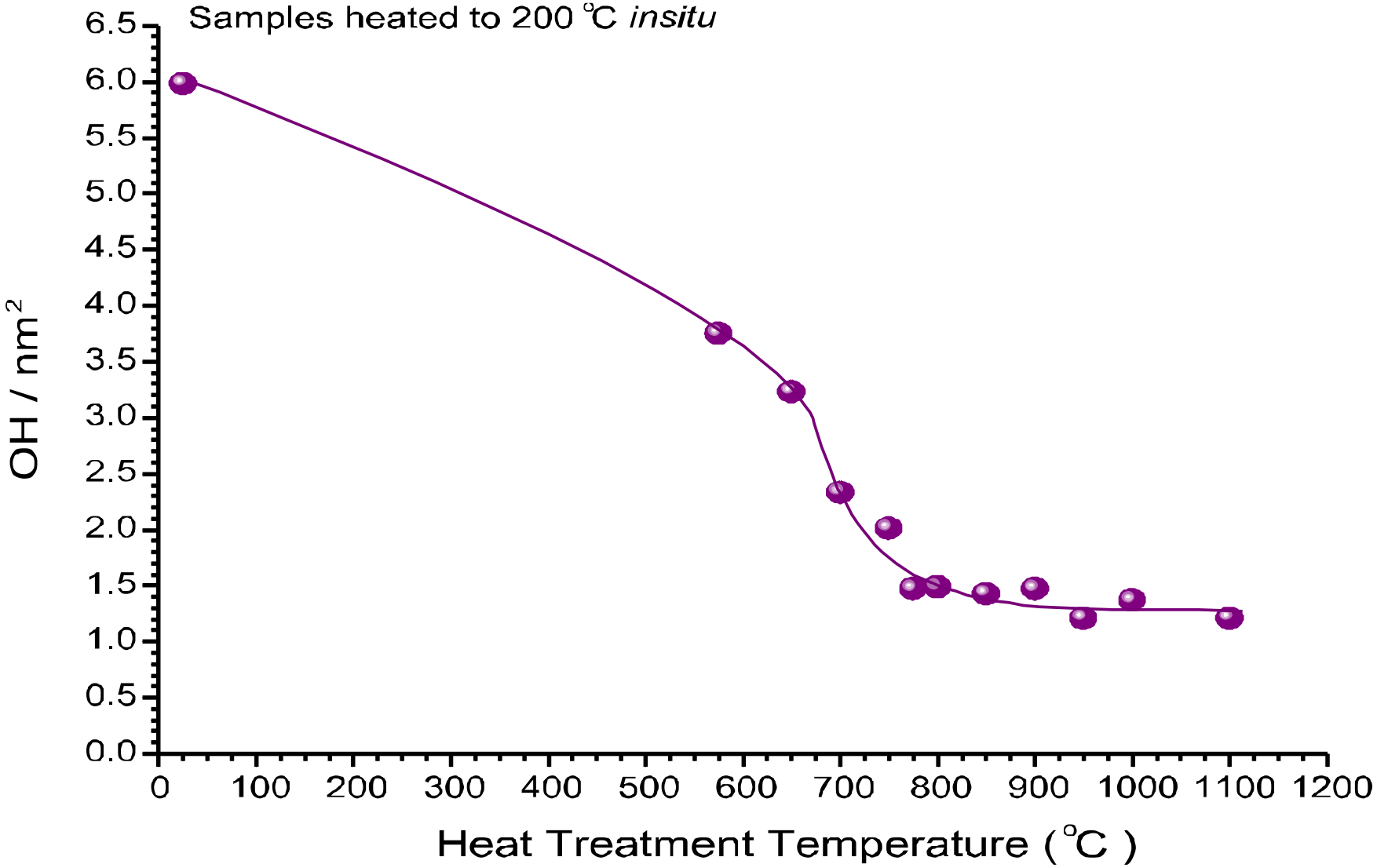
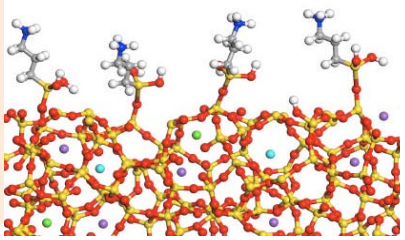
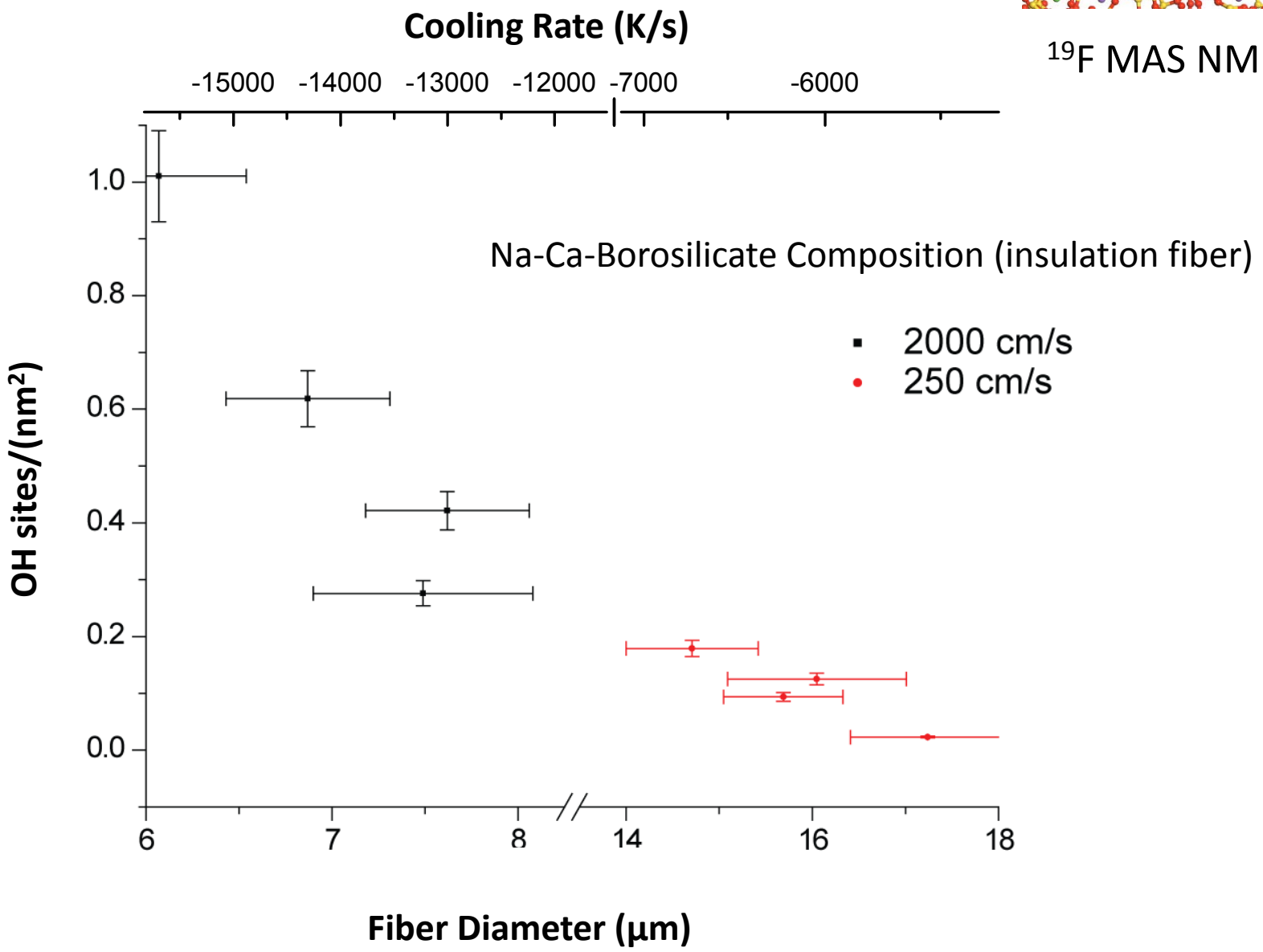
Dehydroxylation During Heat Treatment of SK6-Cleaned 1737GW



Surface Hydroxyl Concentration

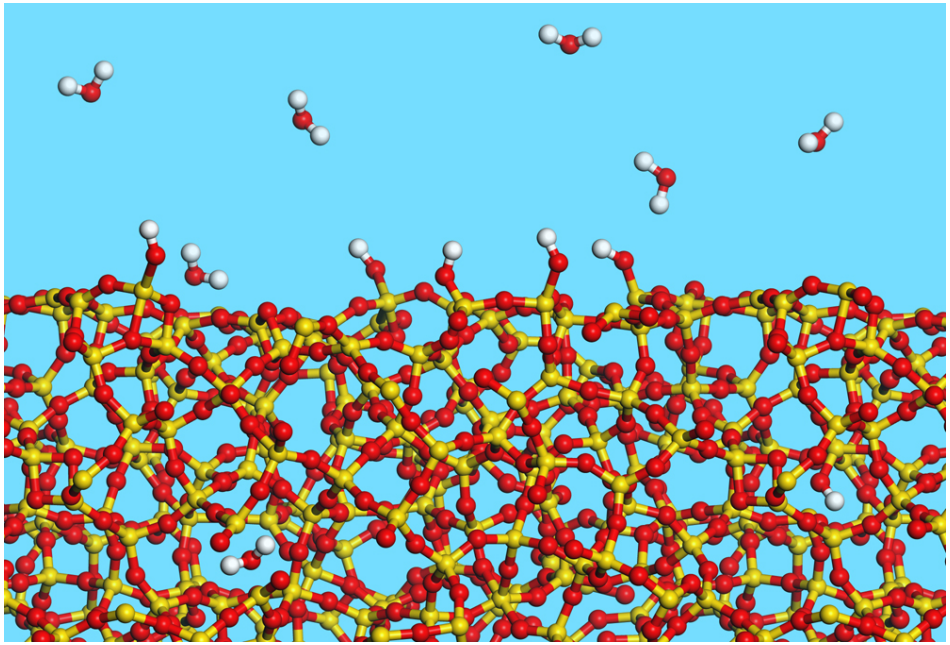


^{19}F MAS NMR

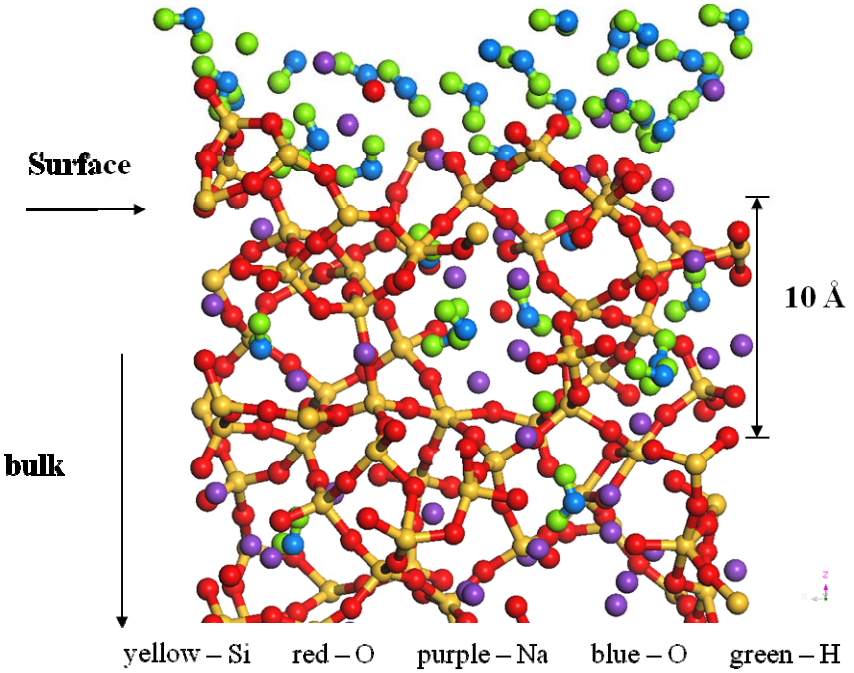


Inorganic Oxide Glass Surfaces

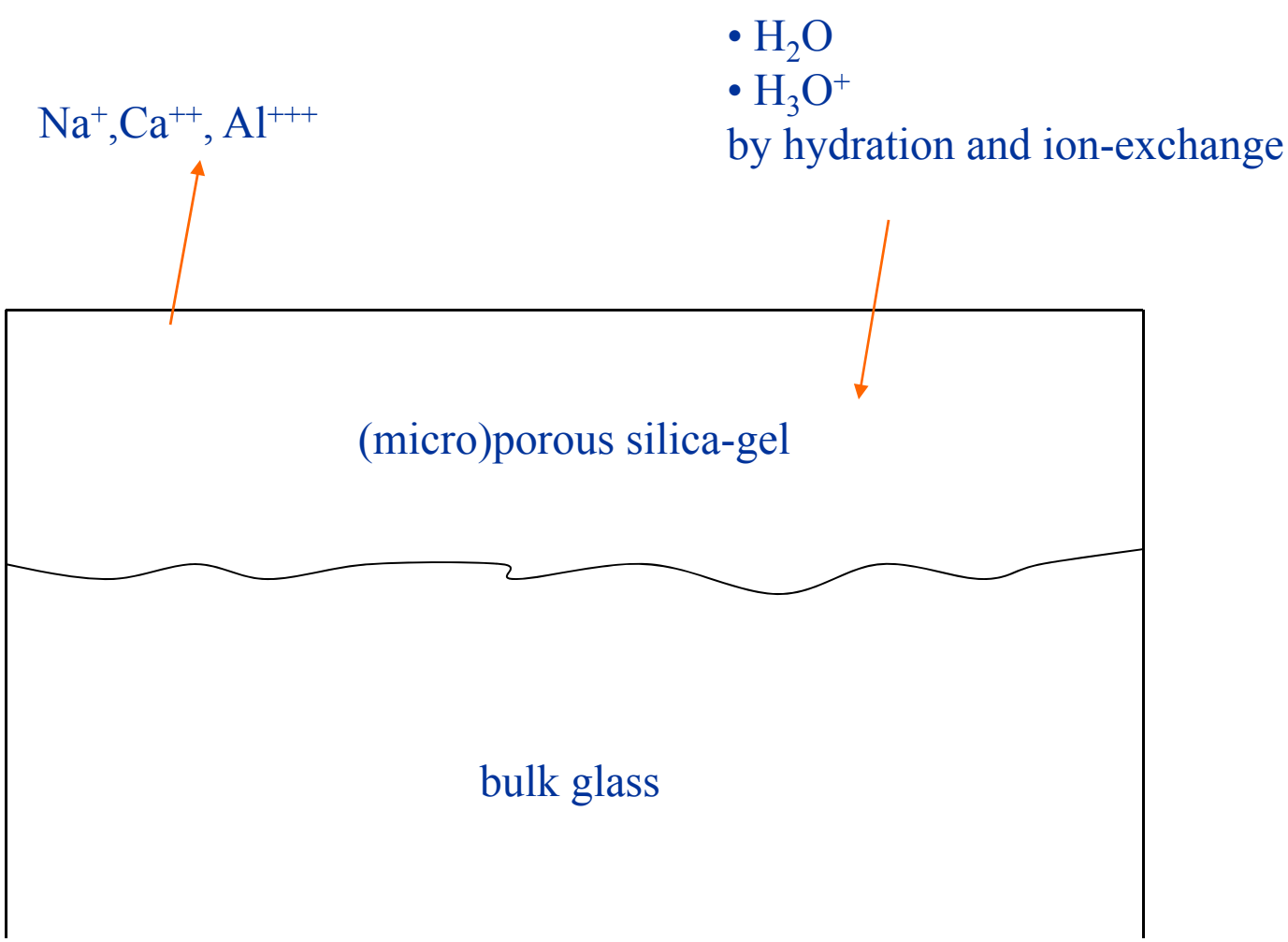
Silica (SiO_2) Glass



Multi-Component Silicate Glass



Surface Layer Formation



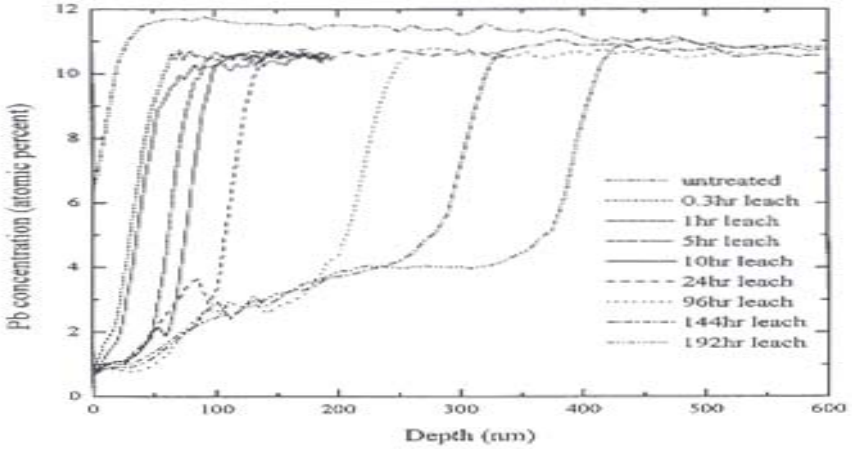
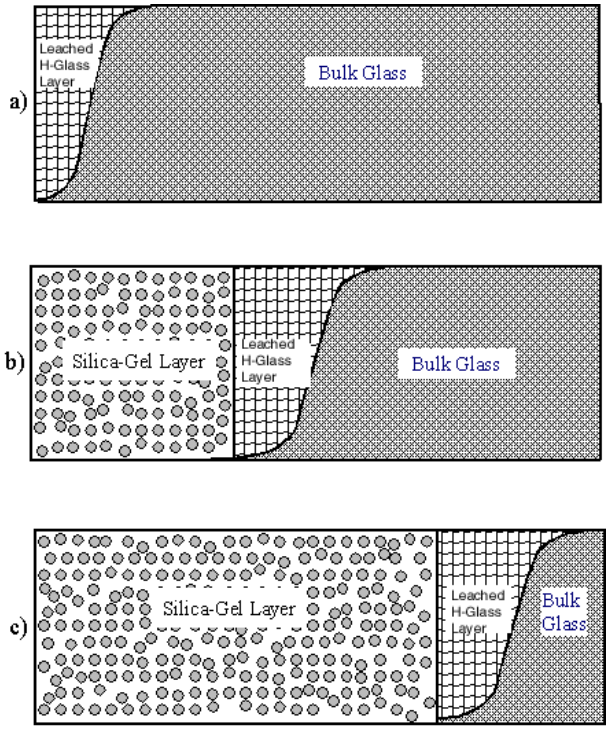
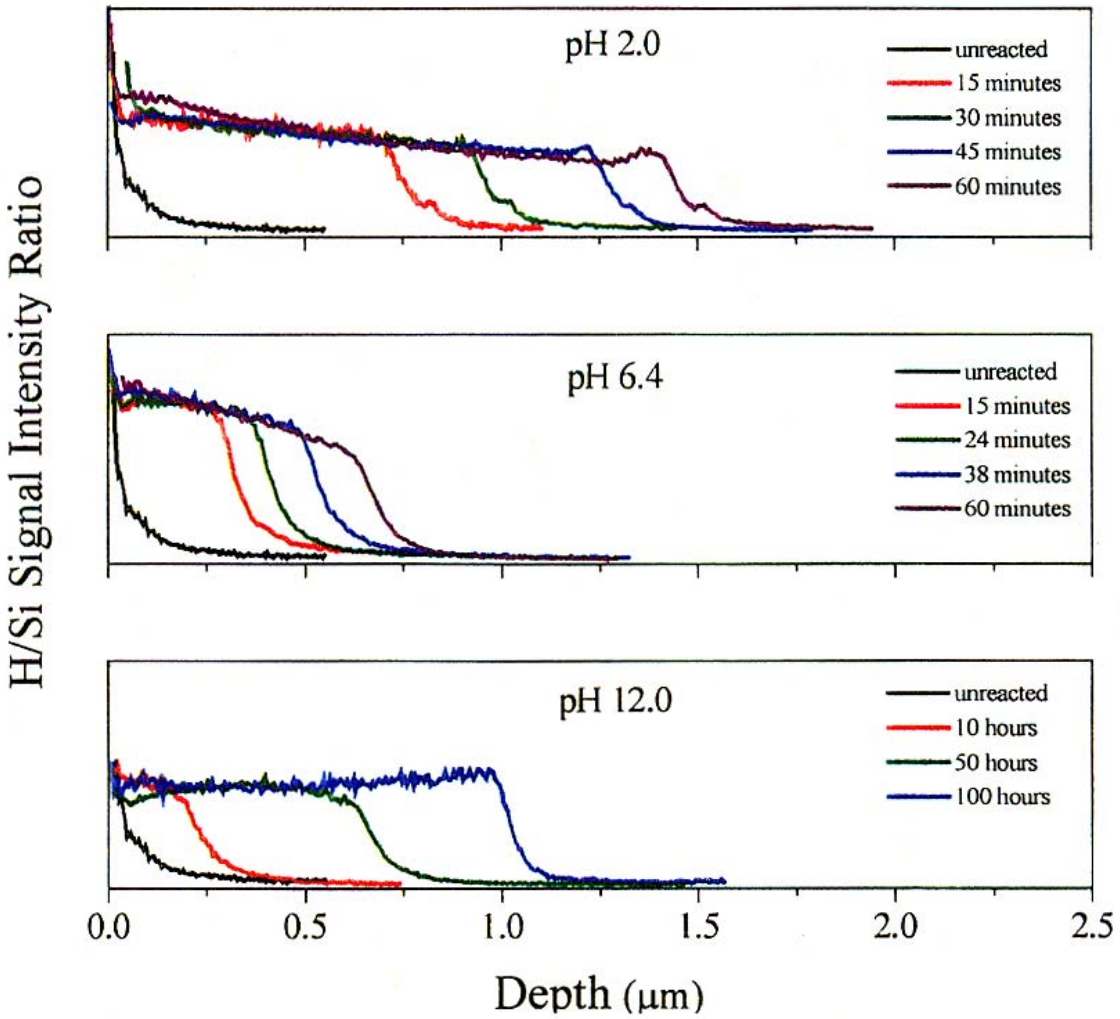


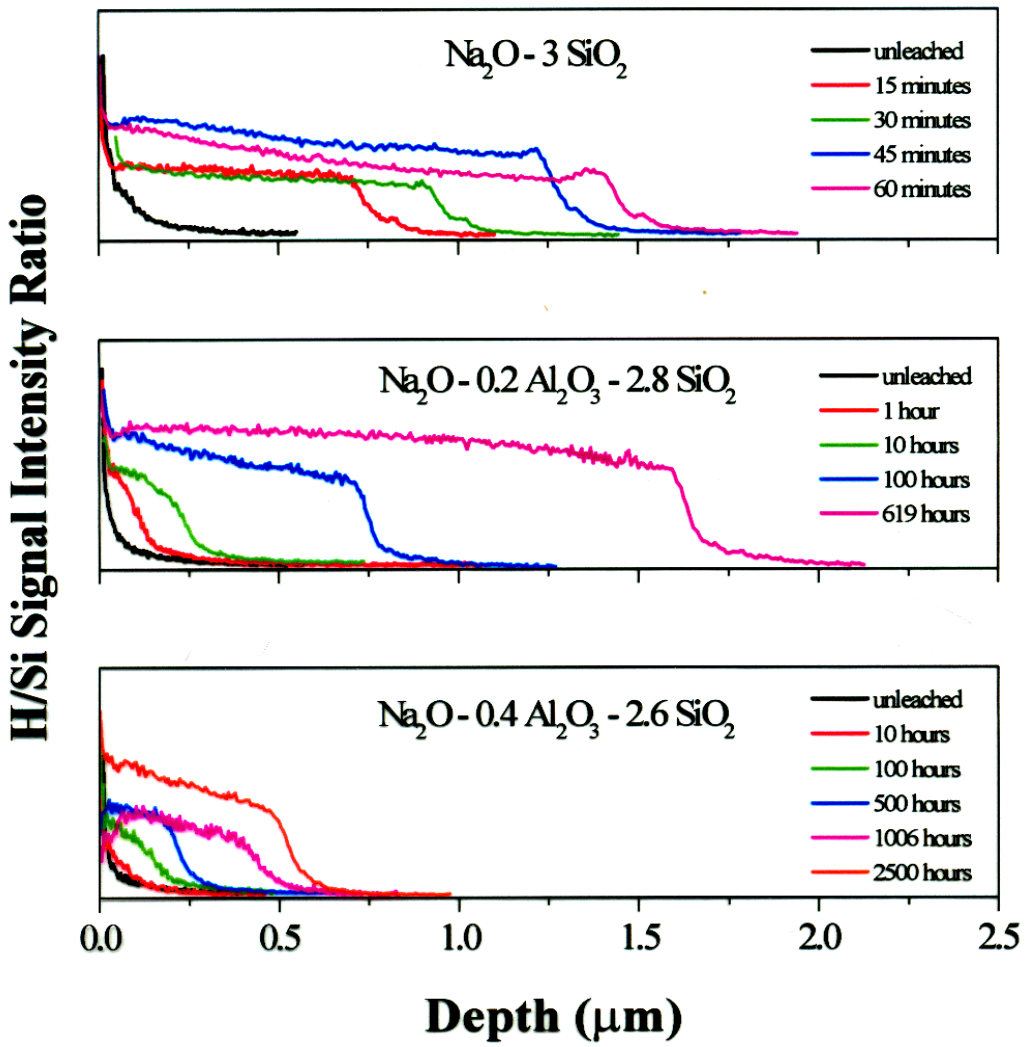
FIGURE 8. Lead depth profiles (obtained with SIMS) as a function of leaching time in 1N Hcl



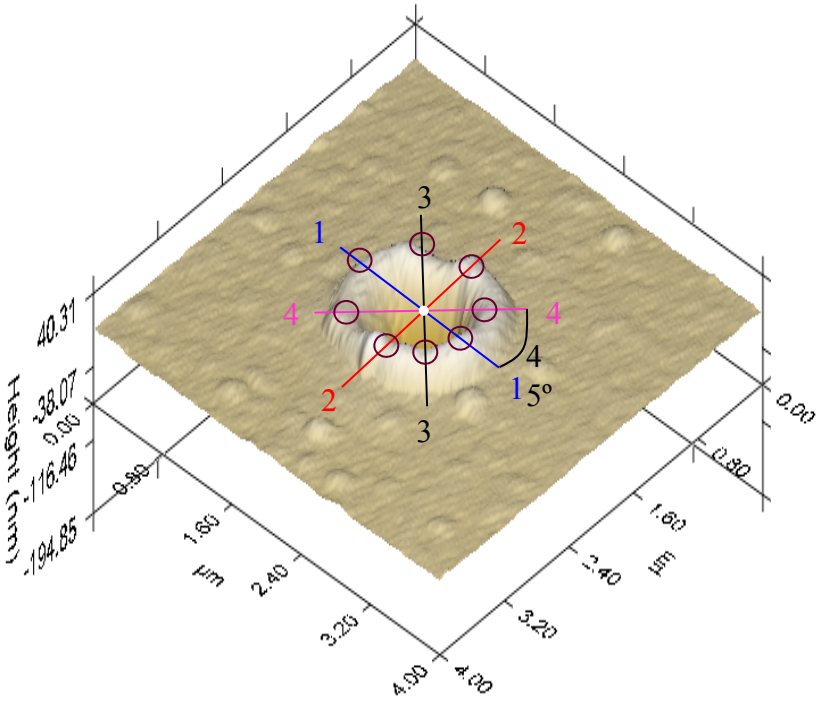
Sodium-Trisilicate Glass

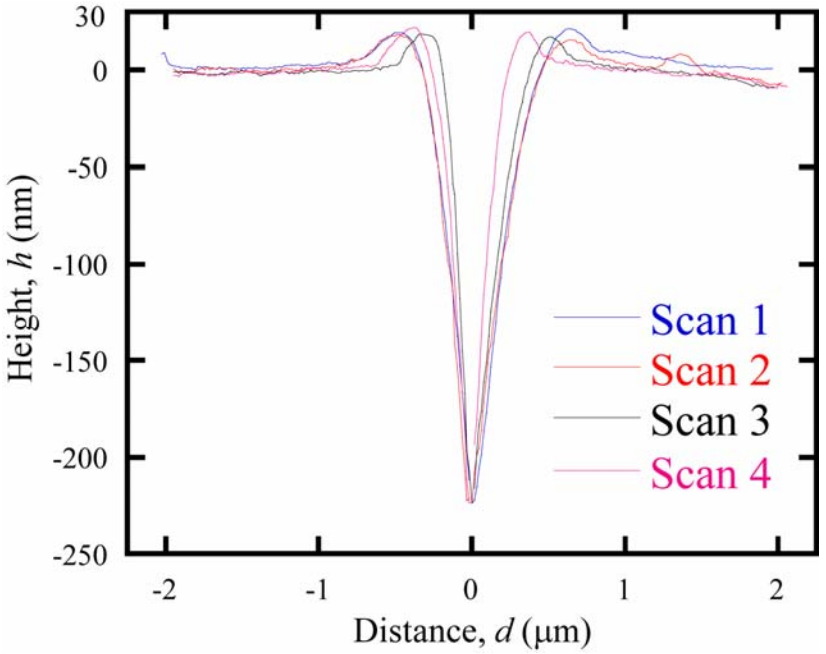


pH 2

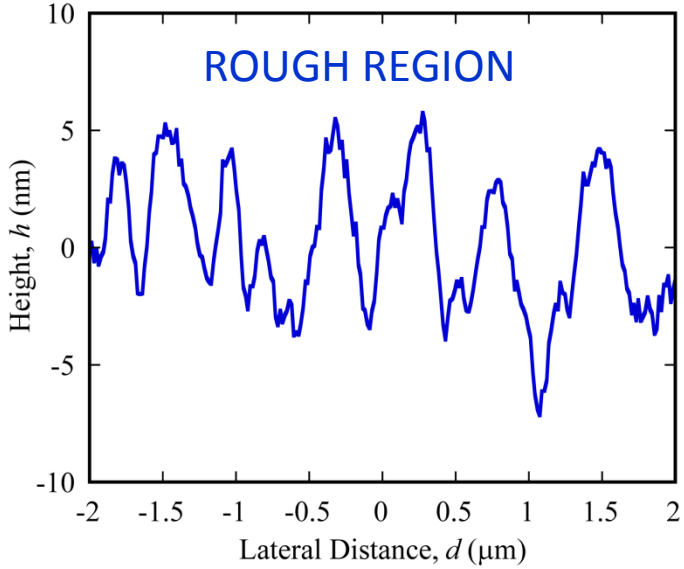

$Na_2O - 3\ SiO_2$
unleached
15 minutes
30 minutes
45 minutes
60 minutes
$Na_2O - 0.2\ Al_2O_3 - 2.8\ SiO_2$
unleached
1 hour
10 hours
100 hours
619 hours
$Na_2O - 0.4\ Al_2O_3 - 2.6\ SiO_2$
unleached
10 hours
100 hours
500 hours
1006 hours
2500 hours
H/Si Signal Intensity Ratio
0.0
0.5
1.0
1.5
2.0
2.5
Depth (μm)

Indentation Pile-up



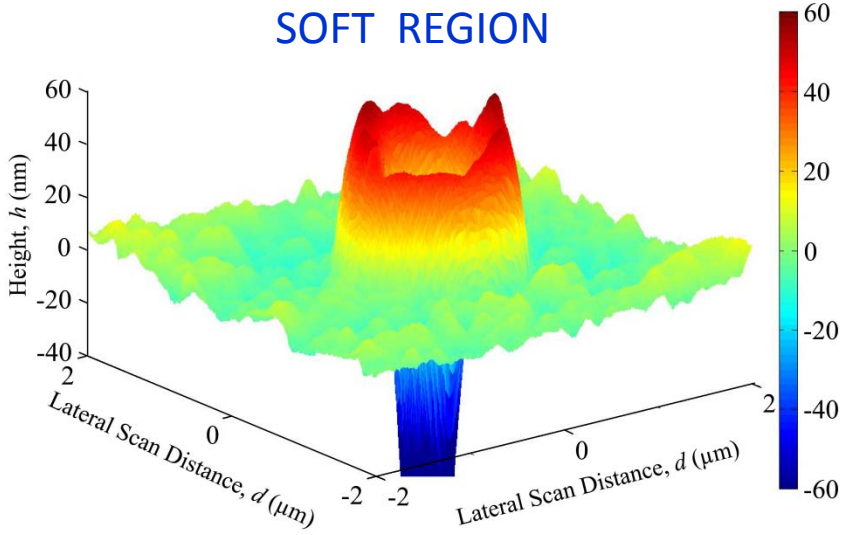


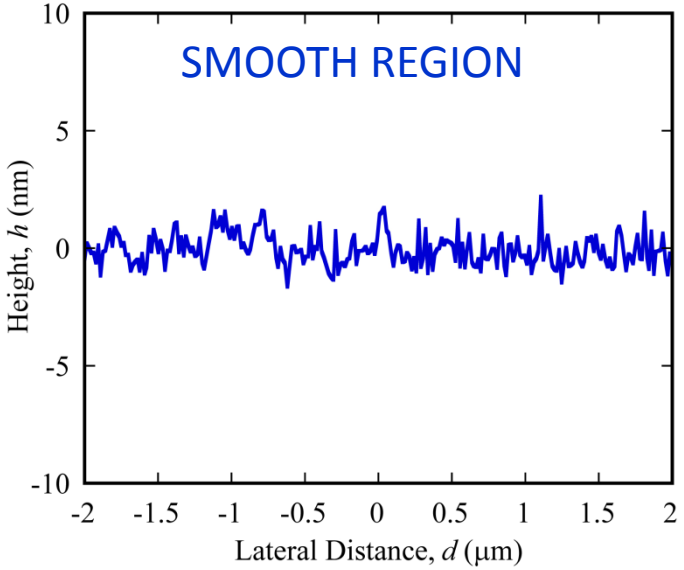
Soft and Hard Regions of Float Glass



6500 μN

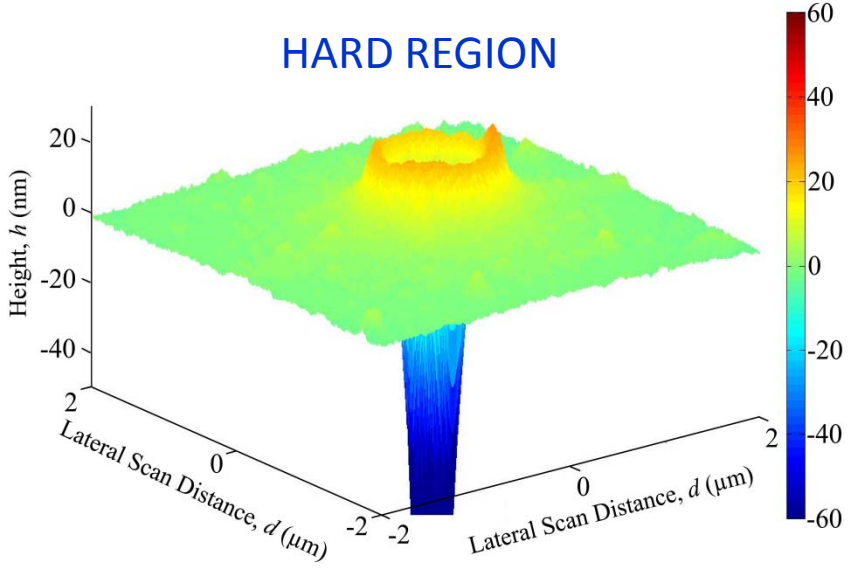
E_r = 72.0 GPa
H = 7.34 GPa





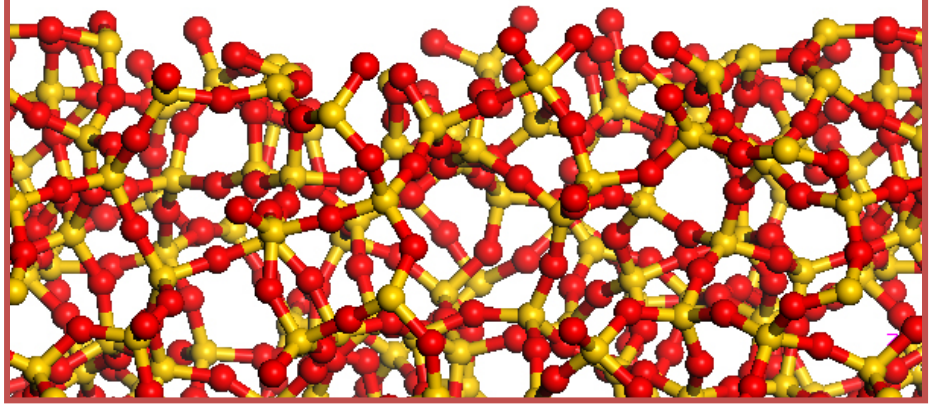
6500 μN

E_r = 78.0 GPa
H = 8.16 GPa

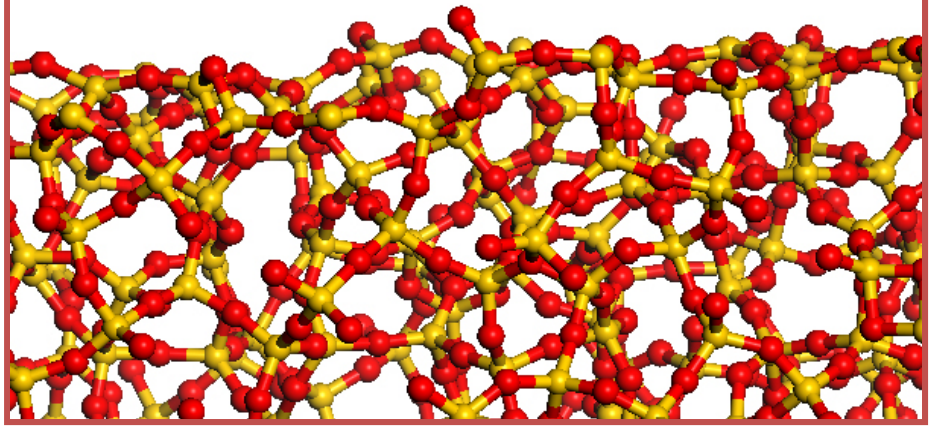


Glass Surface Structure Models

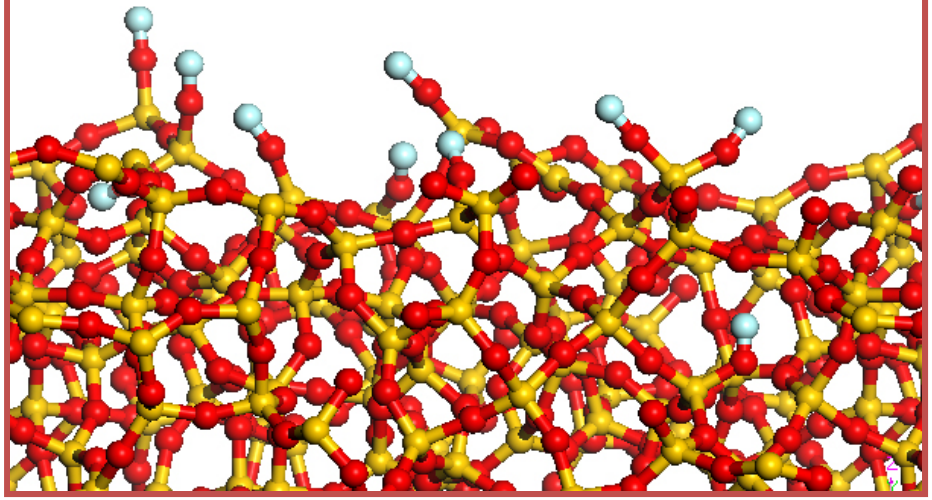
Silica at instant of fracture



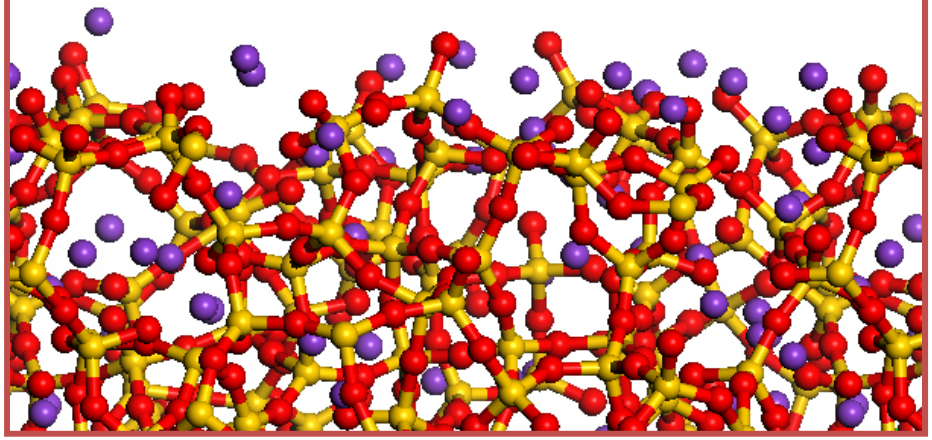
Relaxed silica fracture surface



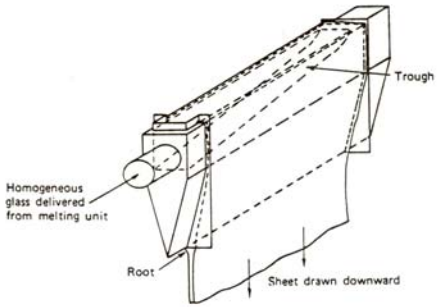
Hydroxylated silica fracture surface



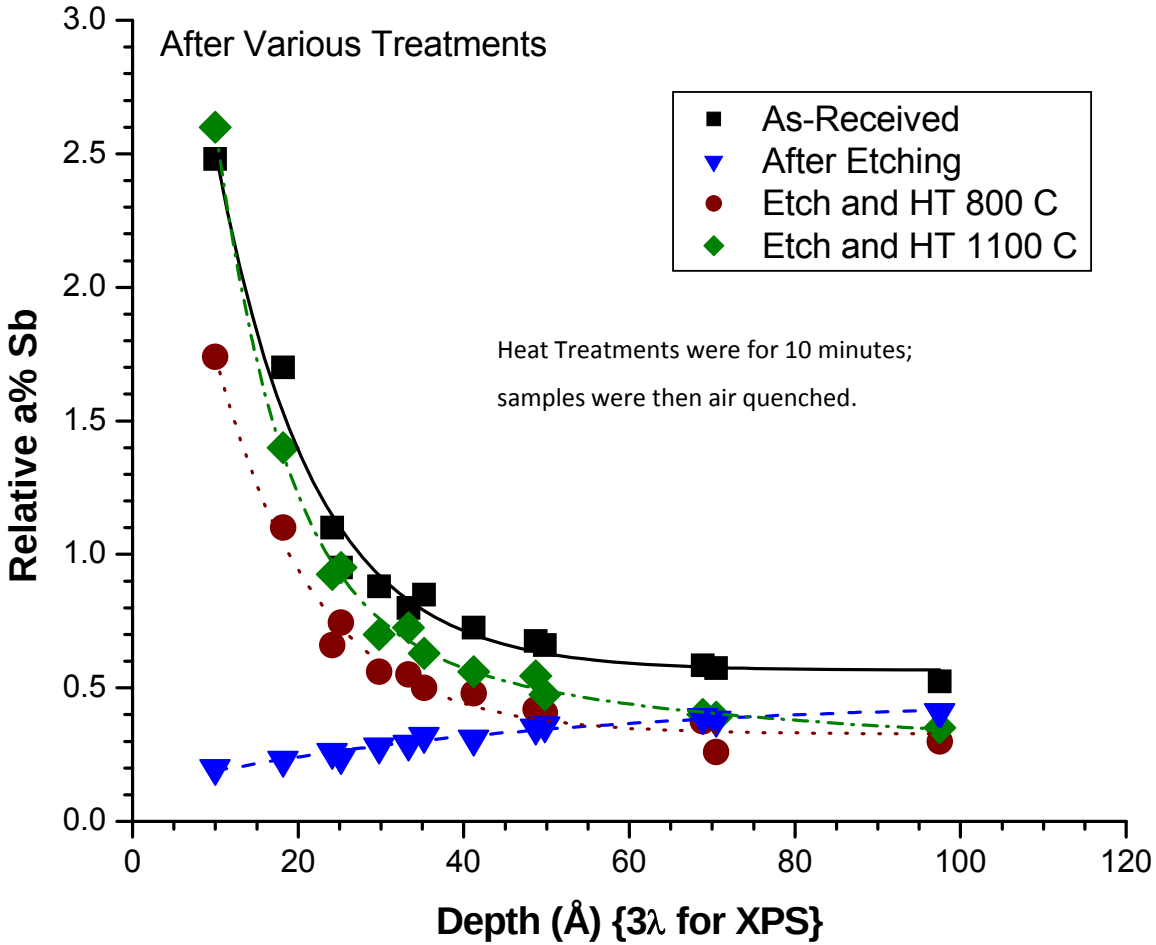
Relaxed sodium silicate fracture surface

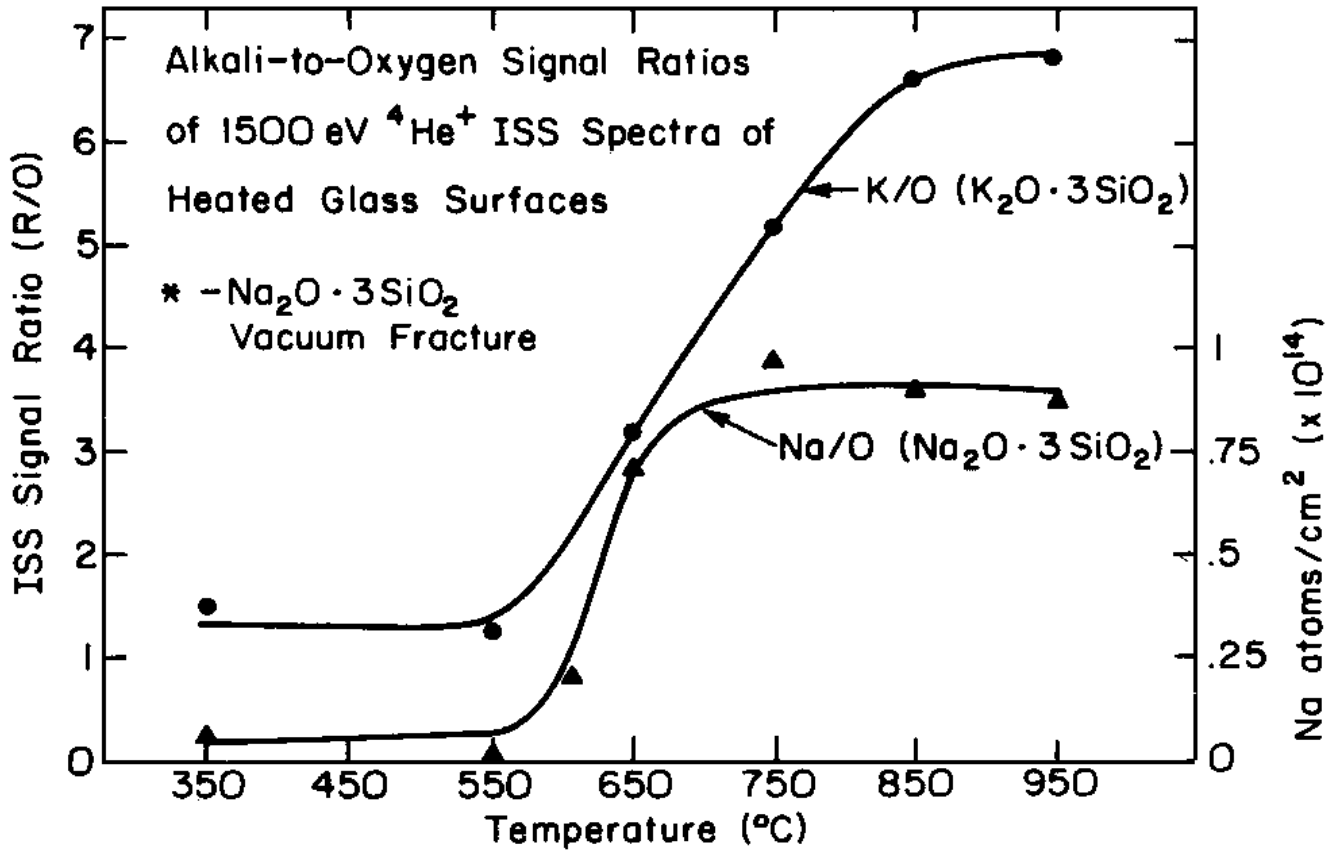


Antimony Depth Distribution by Angle-Resolved XPS and FAB-Static SIMS

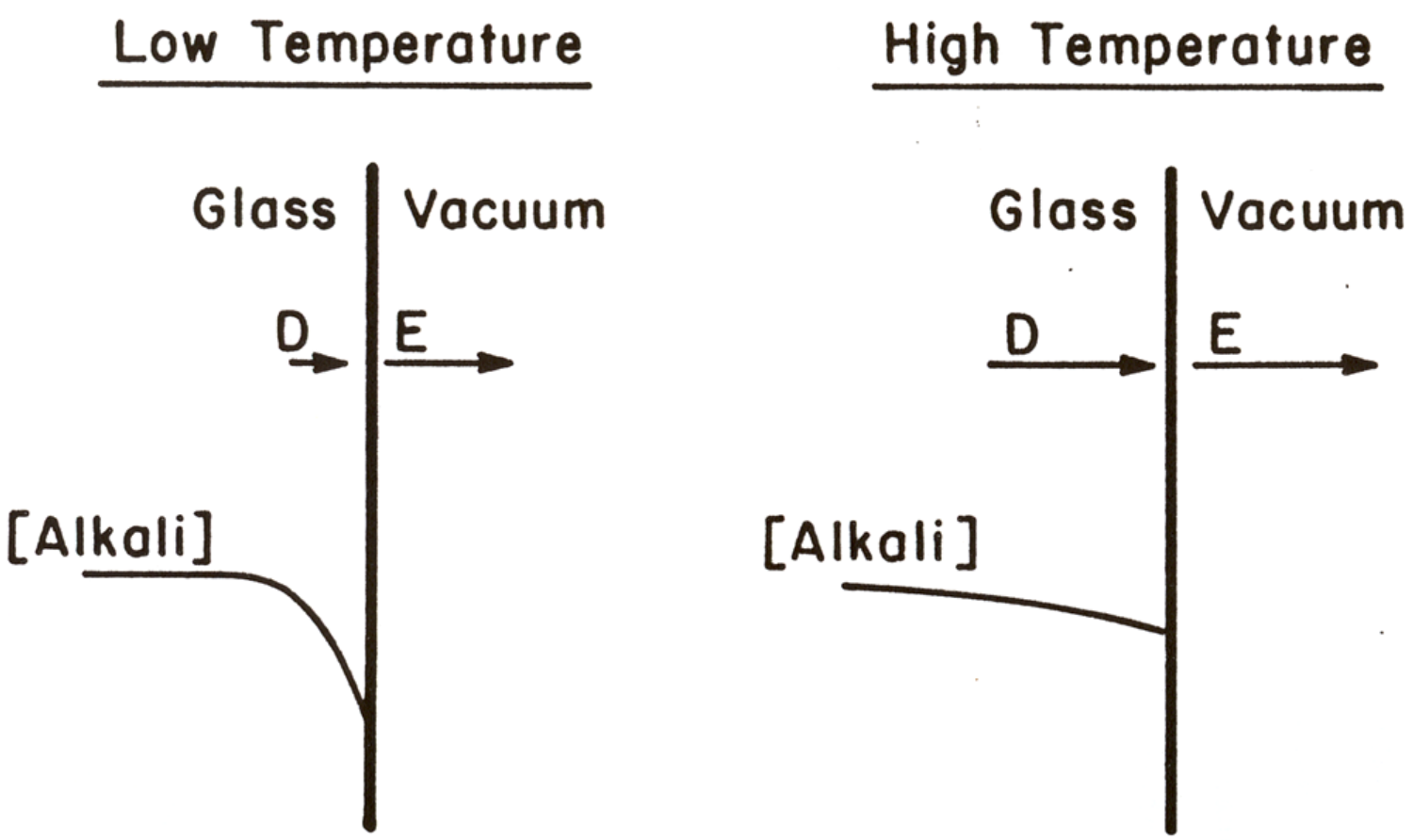


Alkaline-Earth Boroaluminosilicate Display Glass

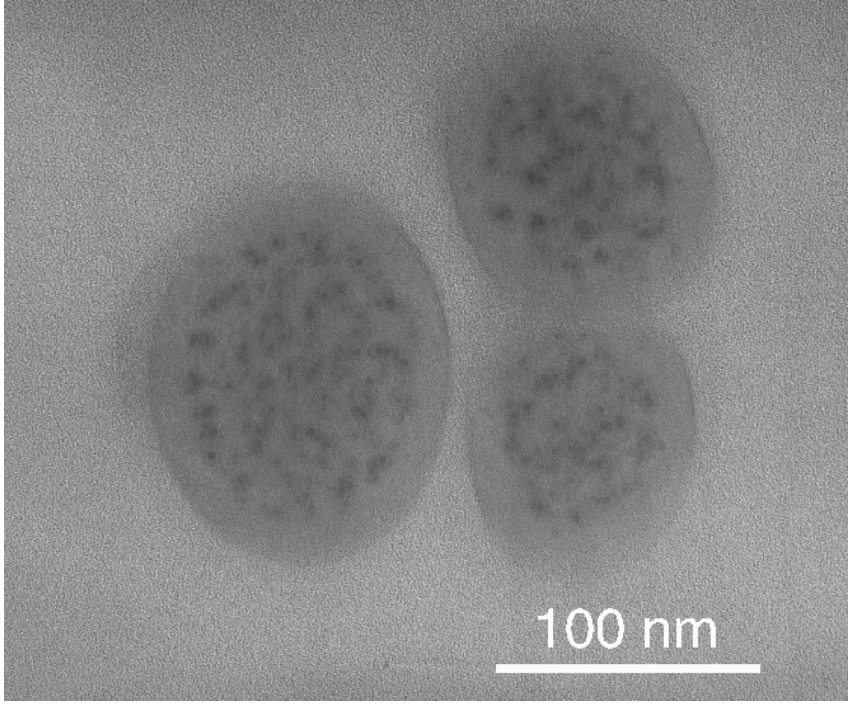


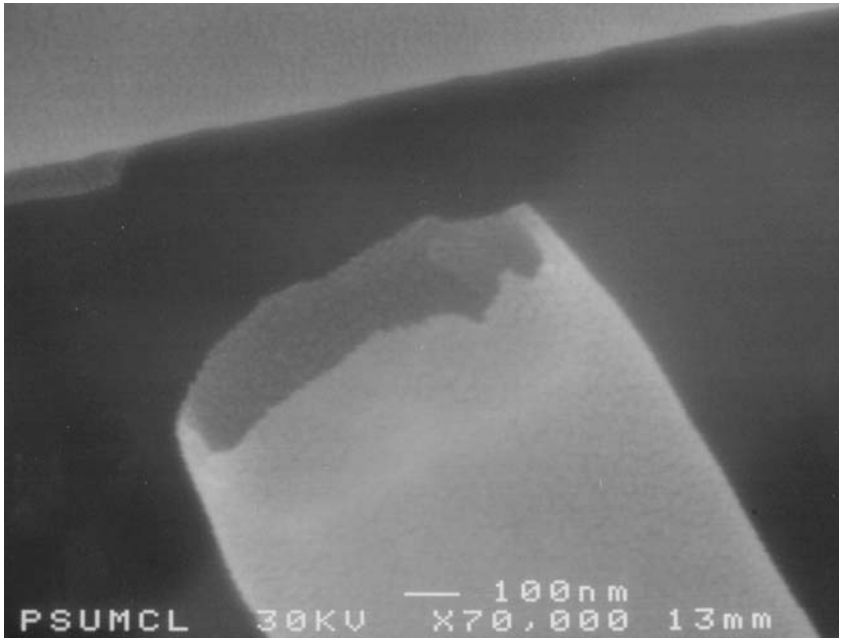


J. F. Kelso and C. G. Pantano: Spectroscopic examination of clean glass surfaces

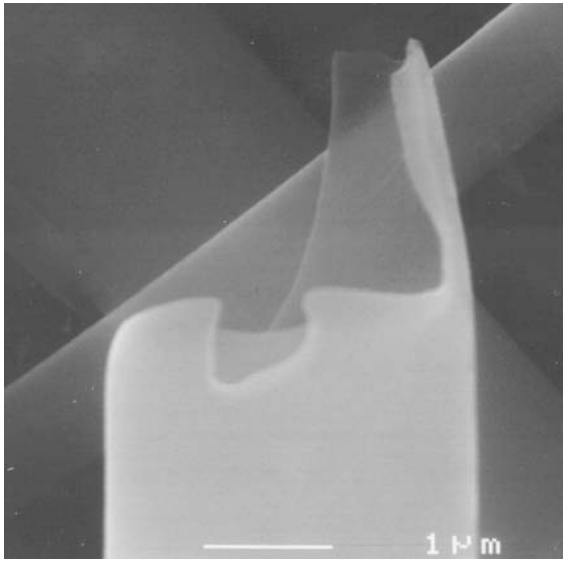

Low Temperature
Glass
Vacuum
D
E
[Alkali]
High Temperature
Glass
Vacuum
D
E
[Alkali]

Fiber Surface Layer by TEM and SEM

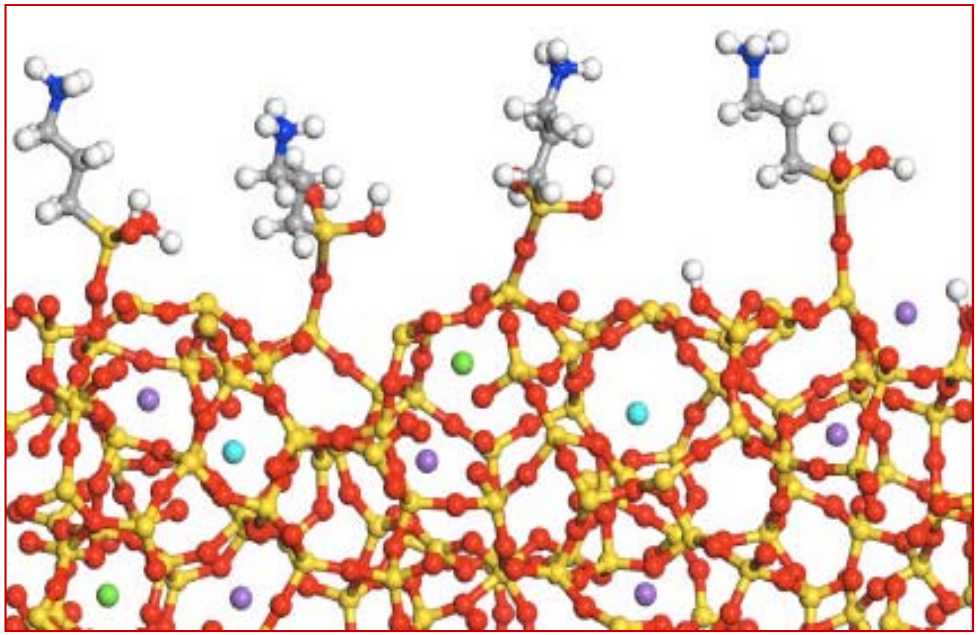




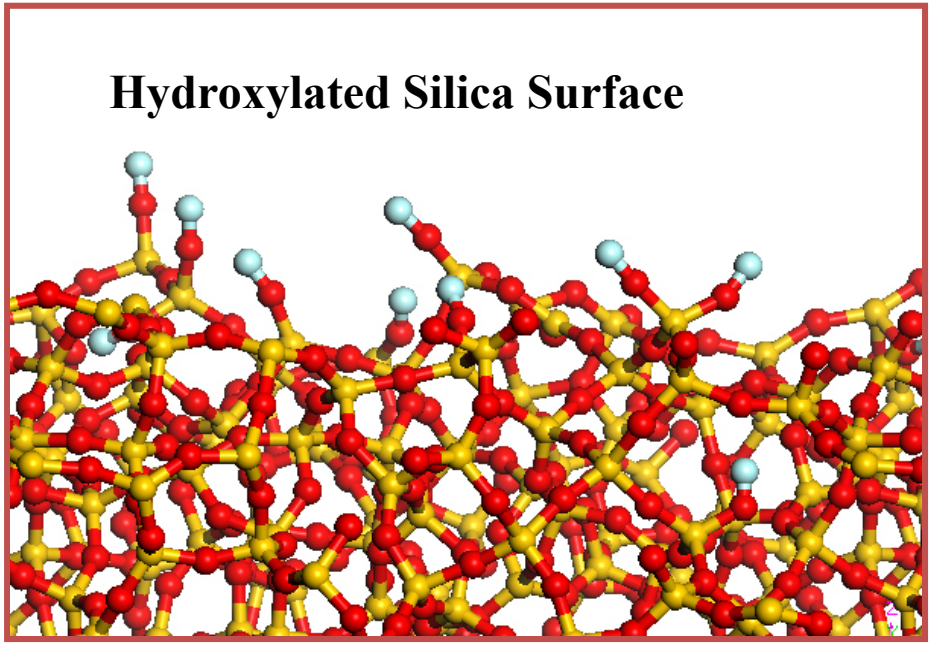
FA fiber corroded by simulated body fluid



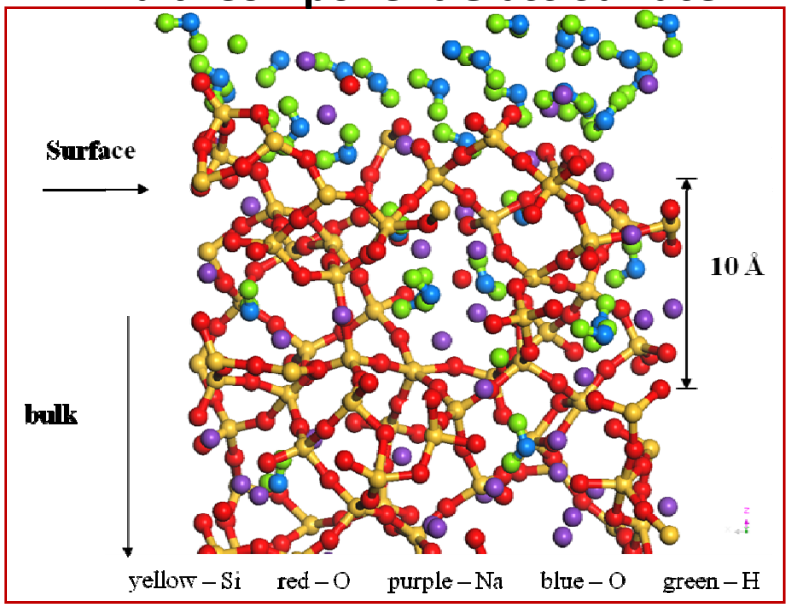
Organo-Functionalization of Glass Surfaces



Hydroxylated Silica Surface



Multi-Component Glass Surface



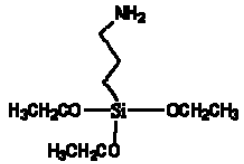
"chemical" water barriers ?

coupling agents

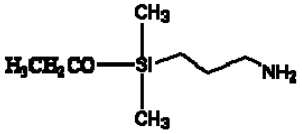
Silanes

hydrophobic

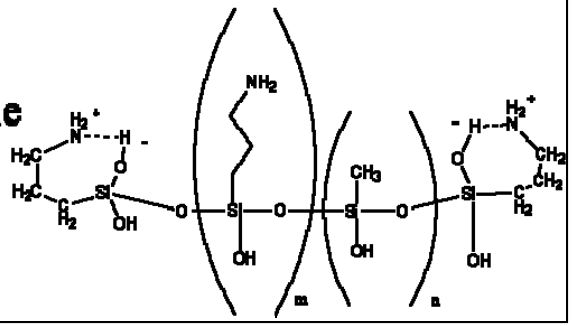
- γ-aminopropyltriethoxysilane
  (trifunctional)

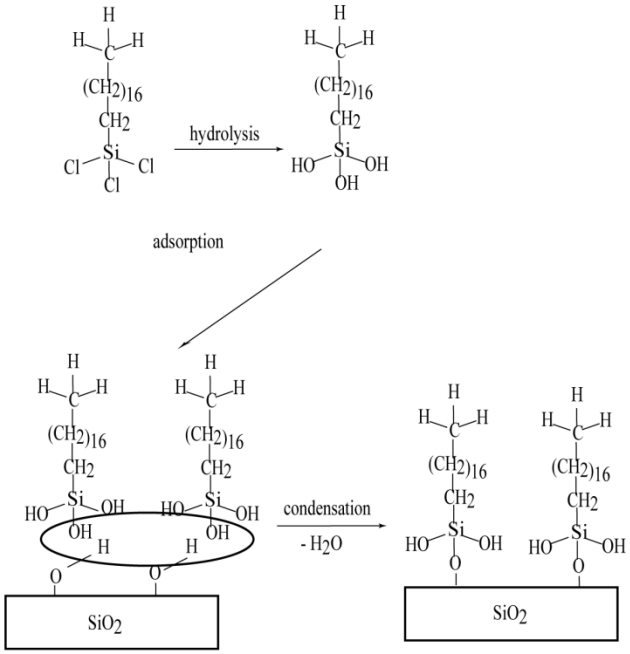


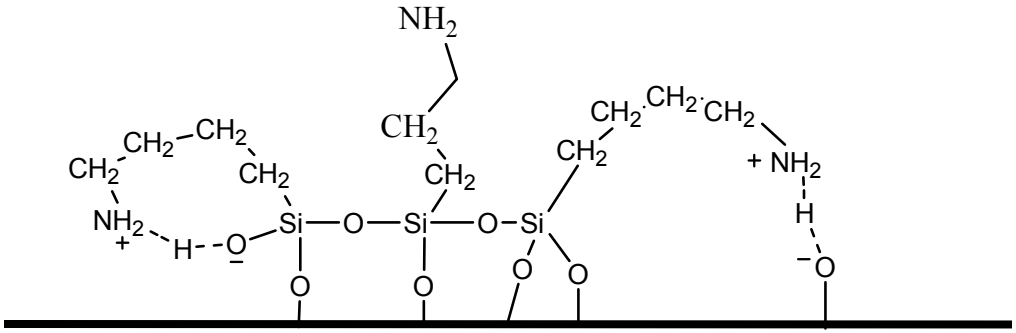
- 3-aminopropyldimethylethoxysilane
  (monofunctional)

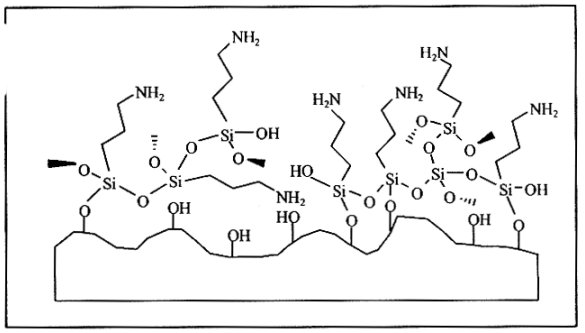


- Aminoalkylsilsesquioxane
  (oligopolymeric)







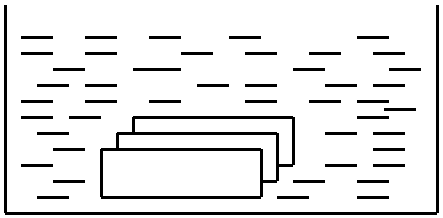


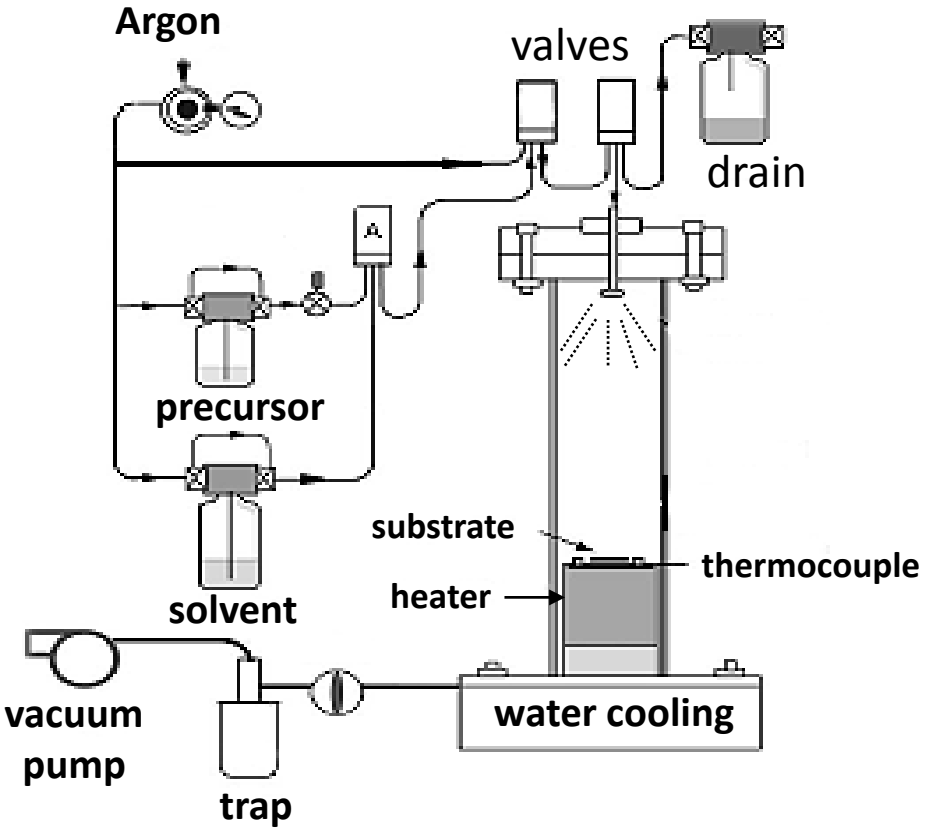
Scheme 2.5: *Schematical representation of the APS multilayer obtained by Method 2, the gasphase silanization procedure of Haller [20].*

Silanization process:

Dipping

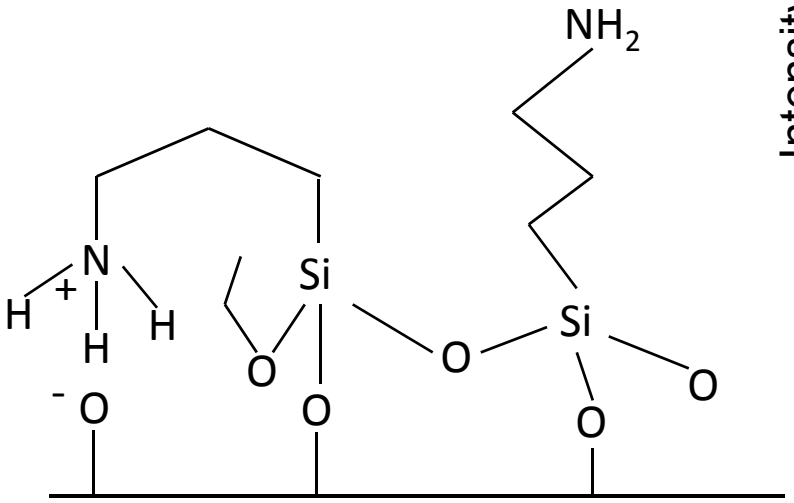
CVD

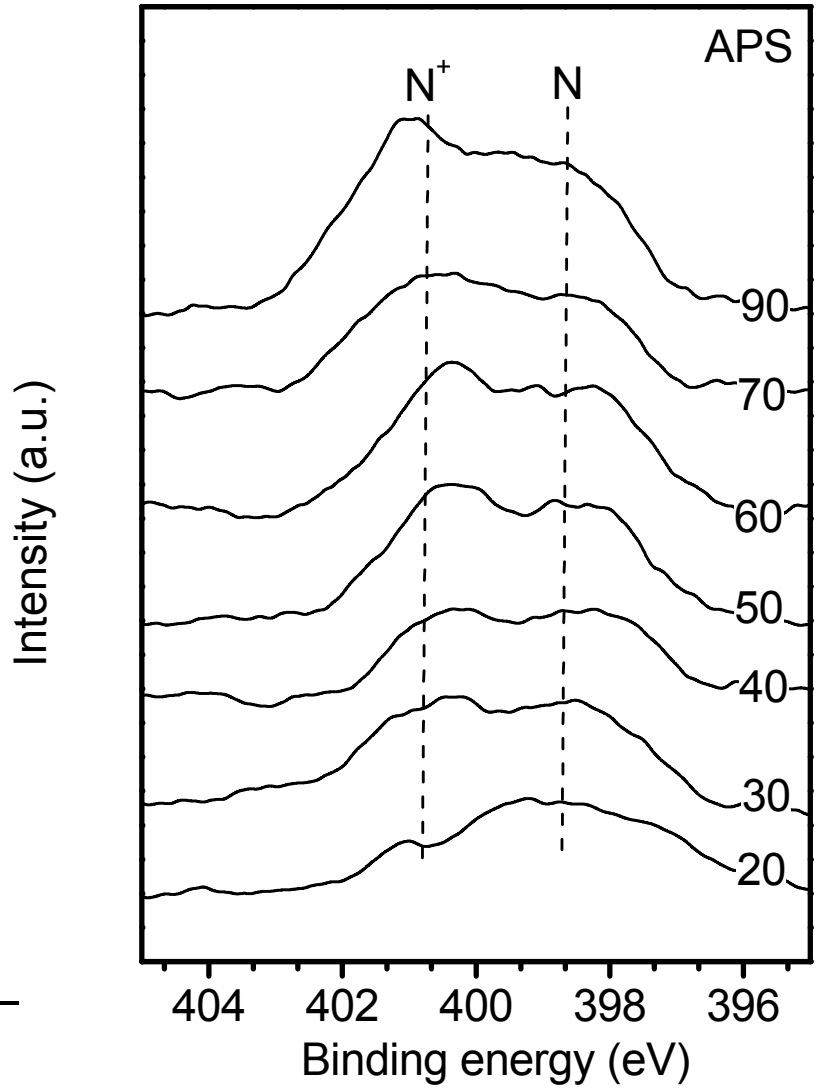




Angle dependent XPS results

A preference for the protonated amine to be oriented towards the glass surface and the non-protonated ones to be oriented away from the surface is suggested.





Composite fracture surface: azide functional silane on silica beads in polyethylene

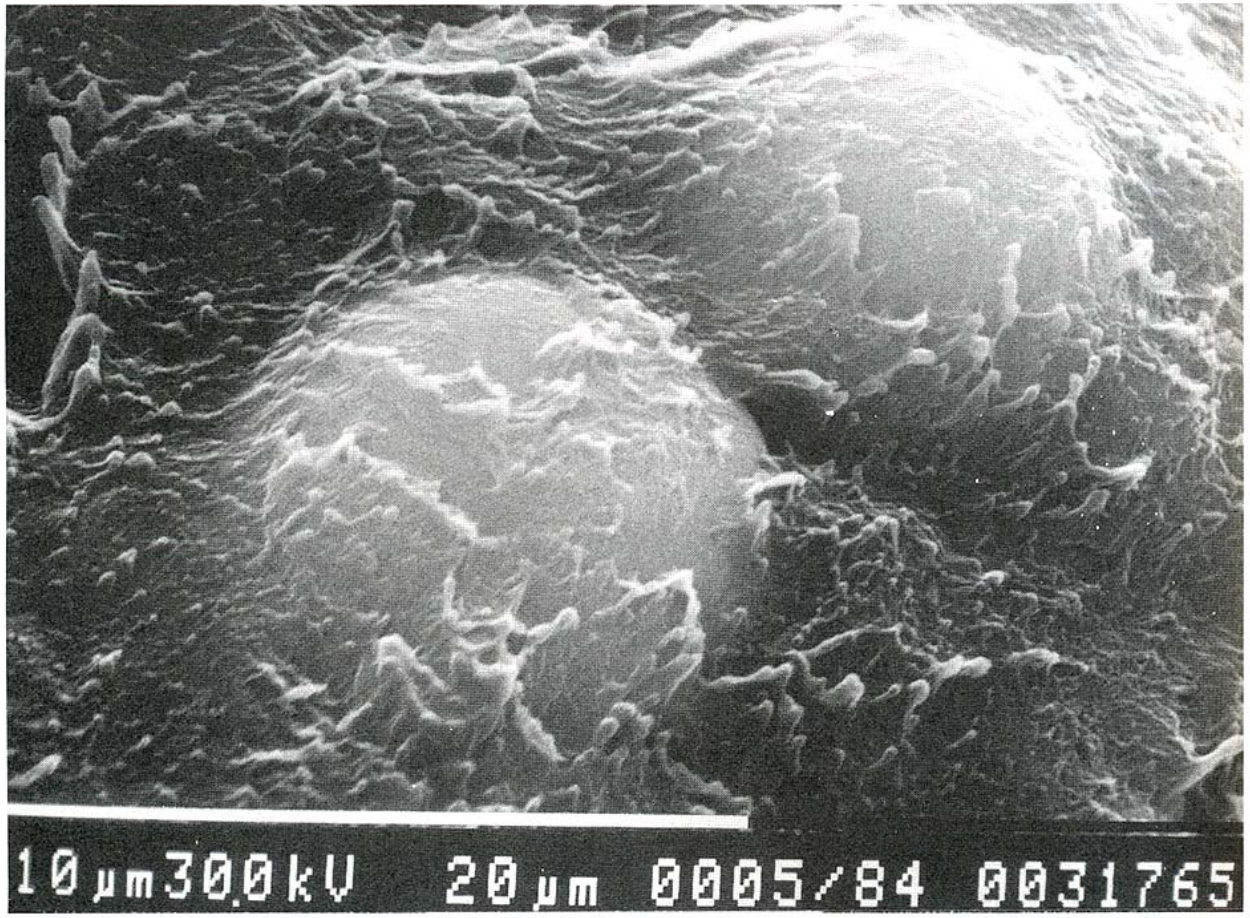
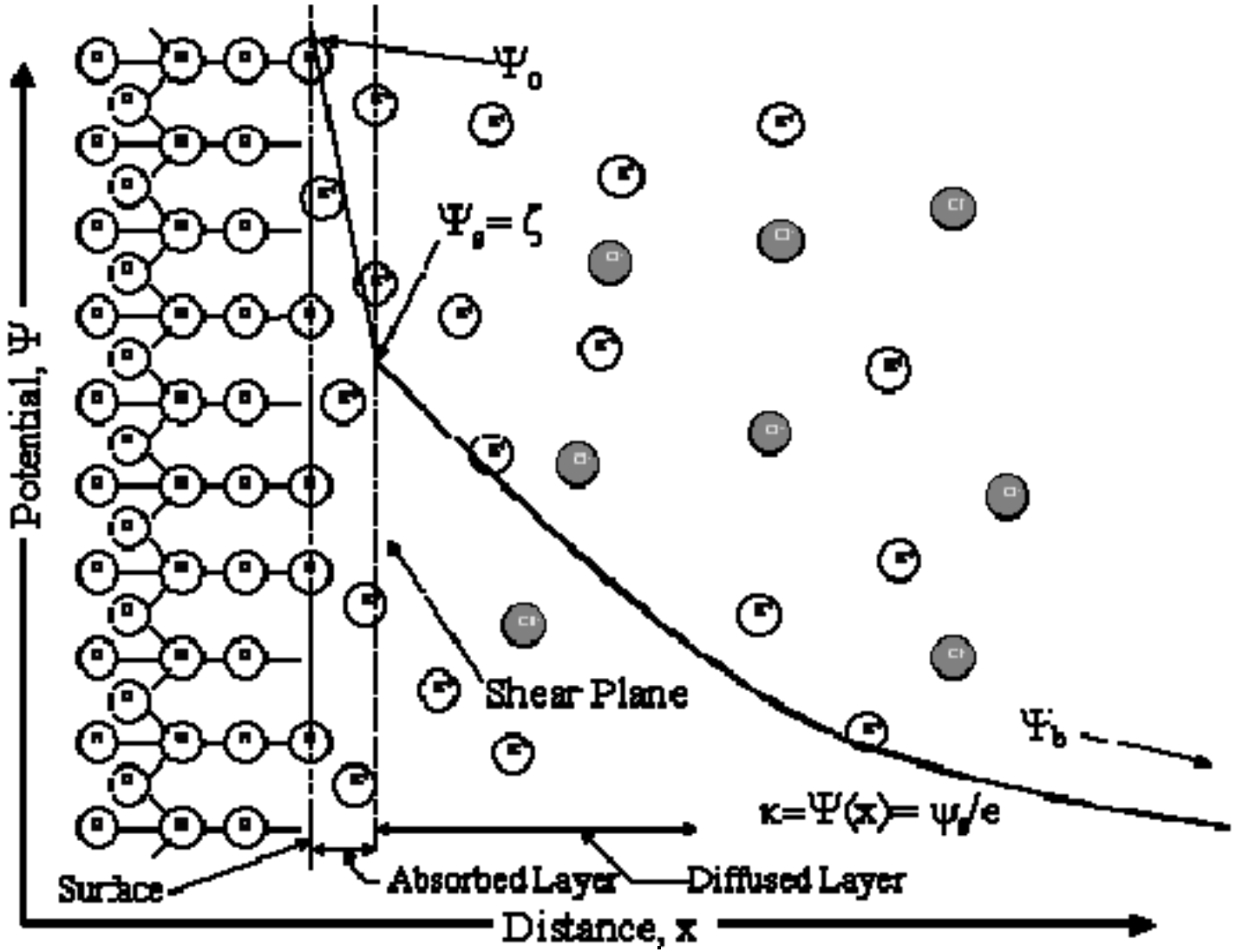
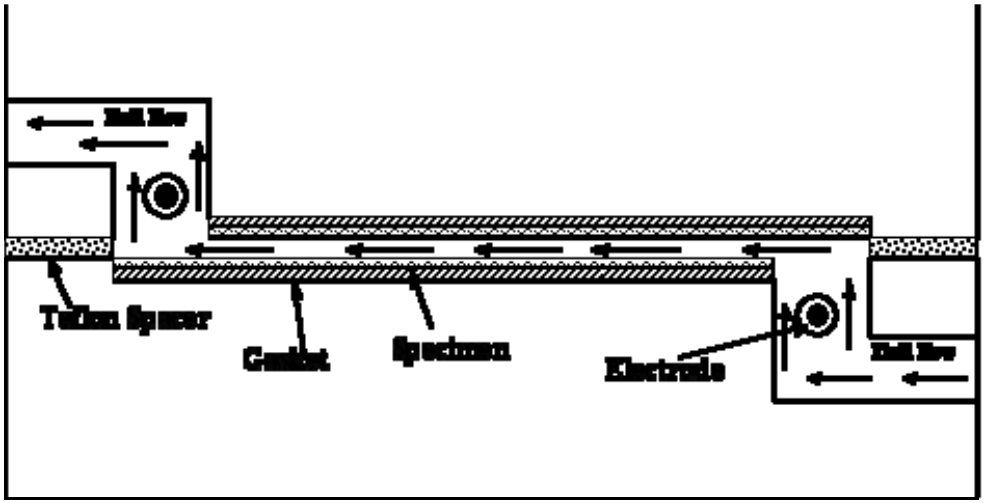


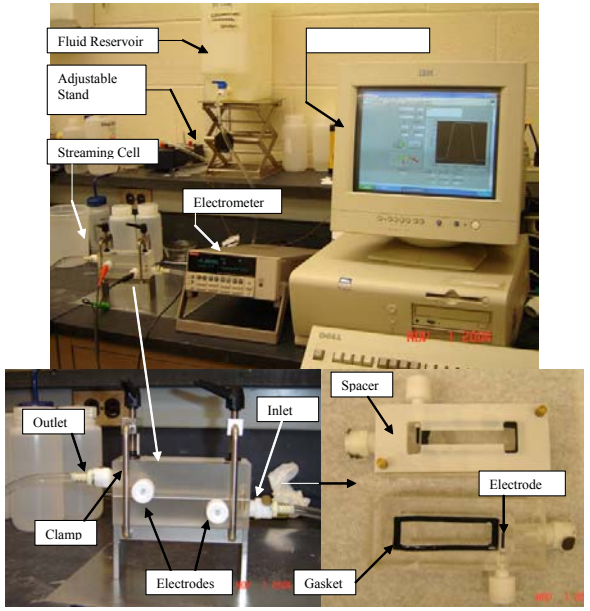
FIGURE 5. Scanning electron micrograph of the fracture surface of a glass-sphere-filled high-density polyethylene where the glass has been modified with an azide-functional silane.

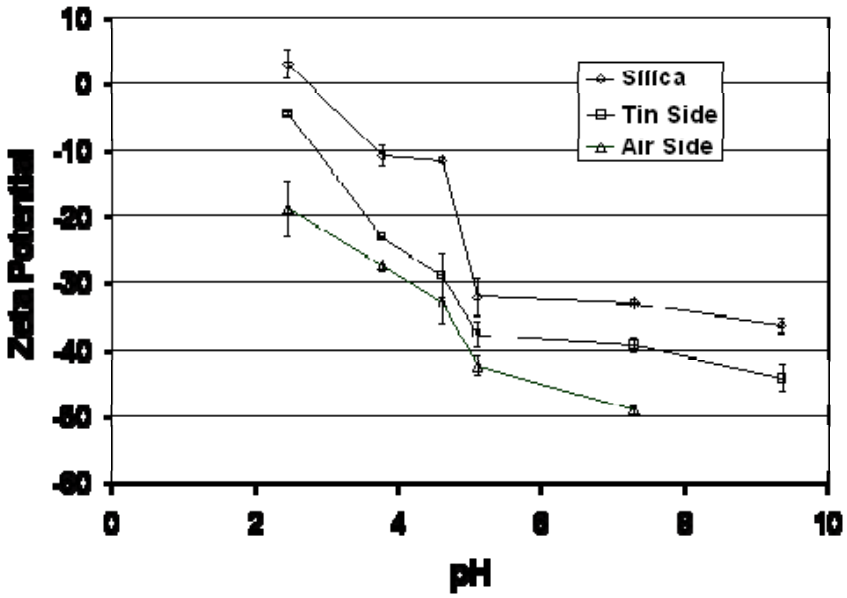
Electrical double layer at the glass-water interface

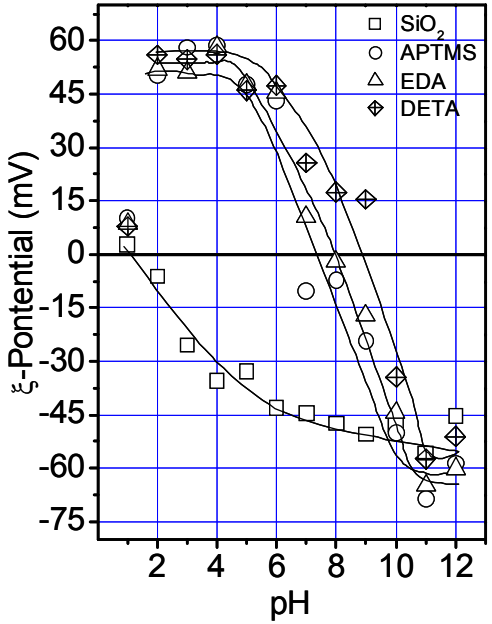


Characterizing surface charge by streaming potential

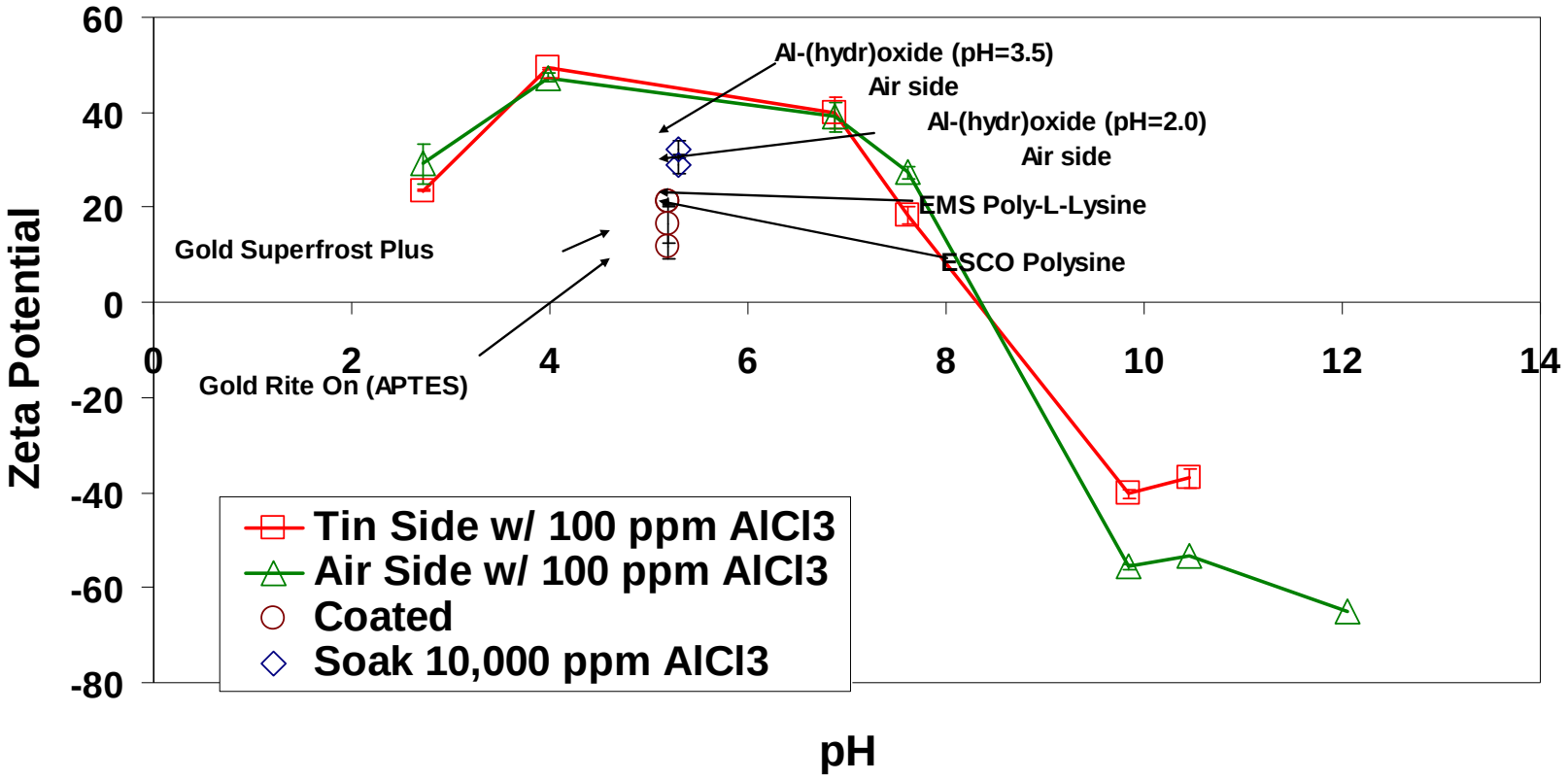




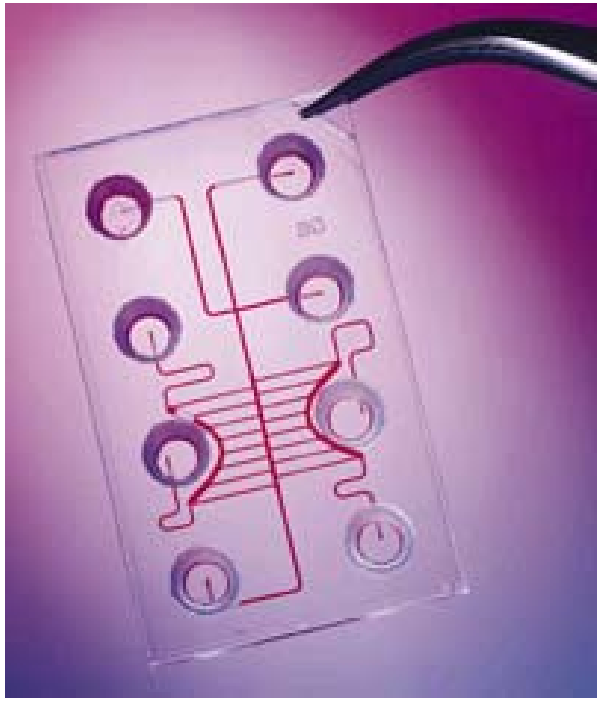




Glass surface modification using inorganic and organic coatings



Glass Surfaces and Coatings for Biotechnology



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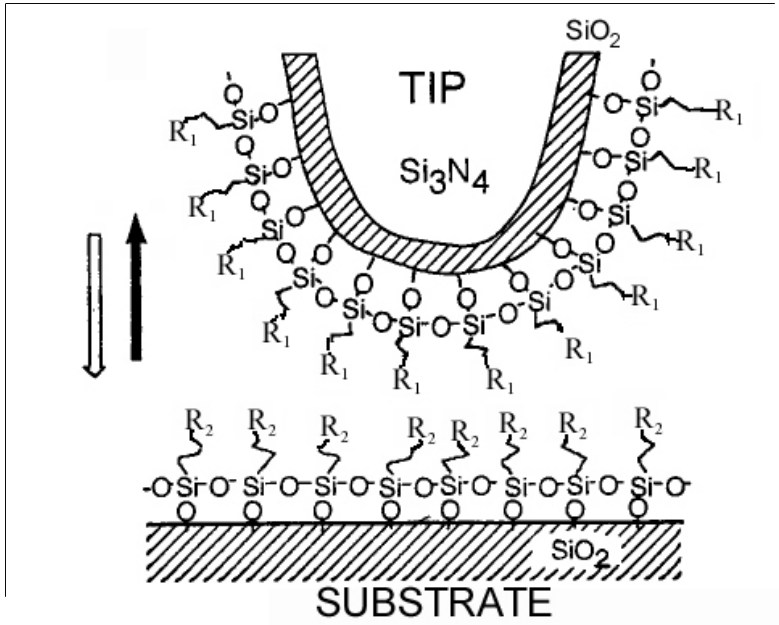
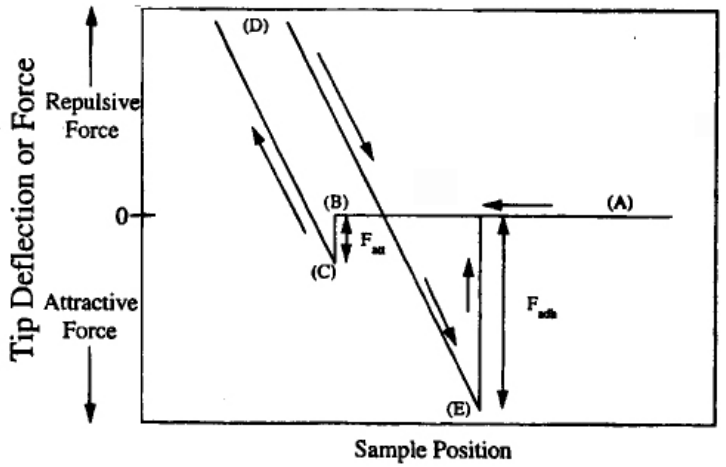
Center for Glass Surfaces, Interfaces, and Coatings

Adhesive Force Studies by Chemical Force Microscopy (CFM)

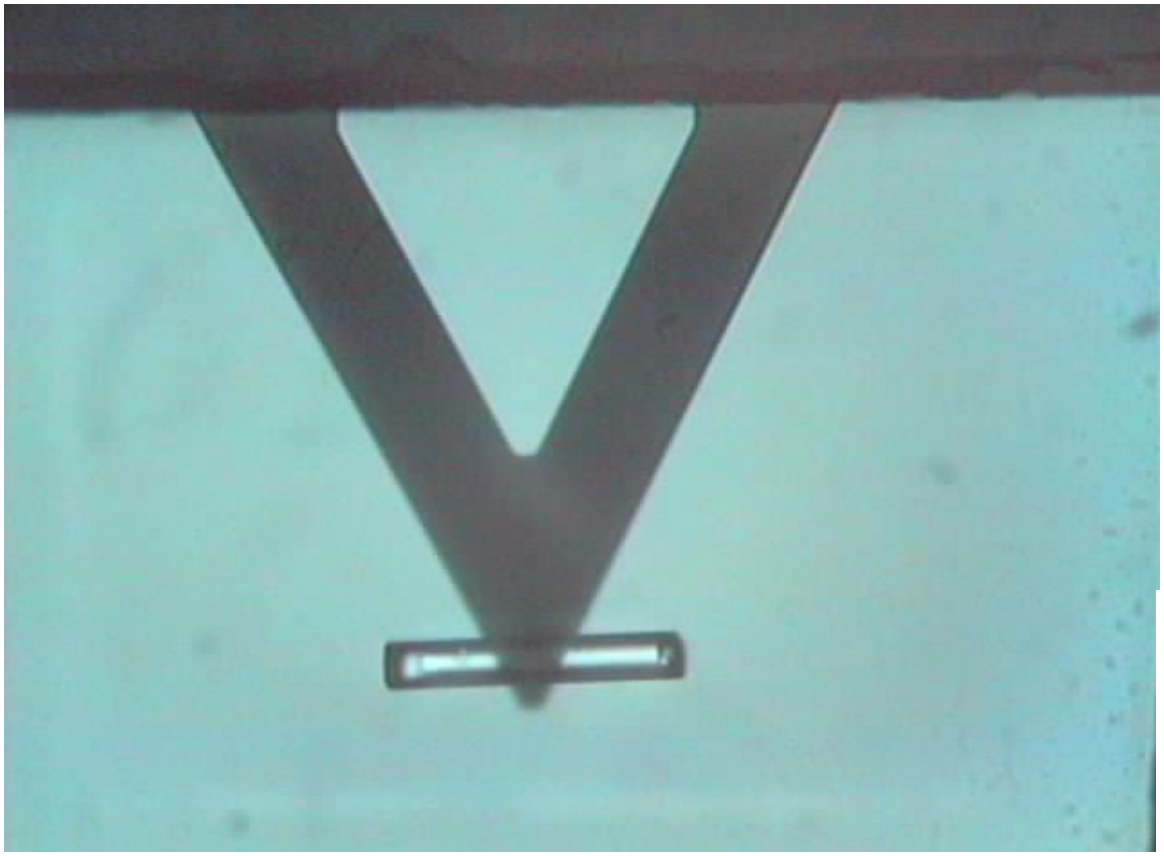
Functionalized Si_3N_4 Tip

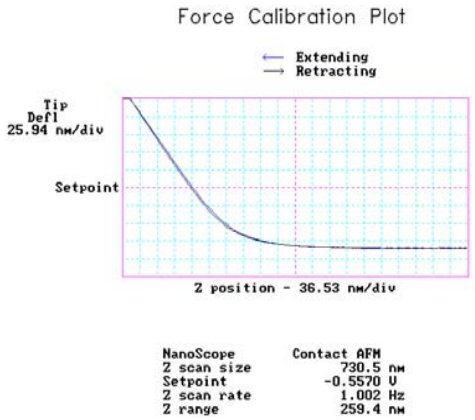


Force-Distance Measurements

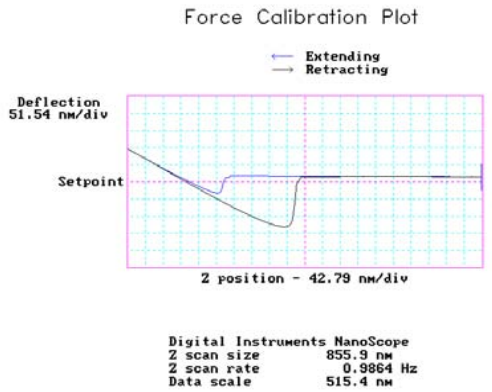


fiber probe for AFM/CFM (glass fiber diameter 10 μm)

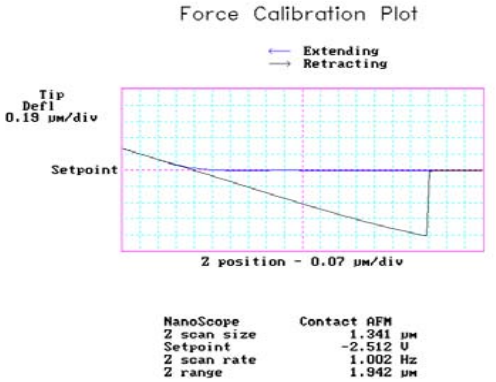




DI water



Silane solution



Silane coated

vic.020

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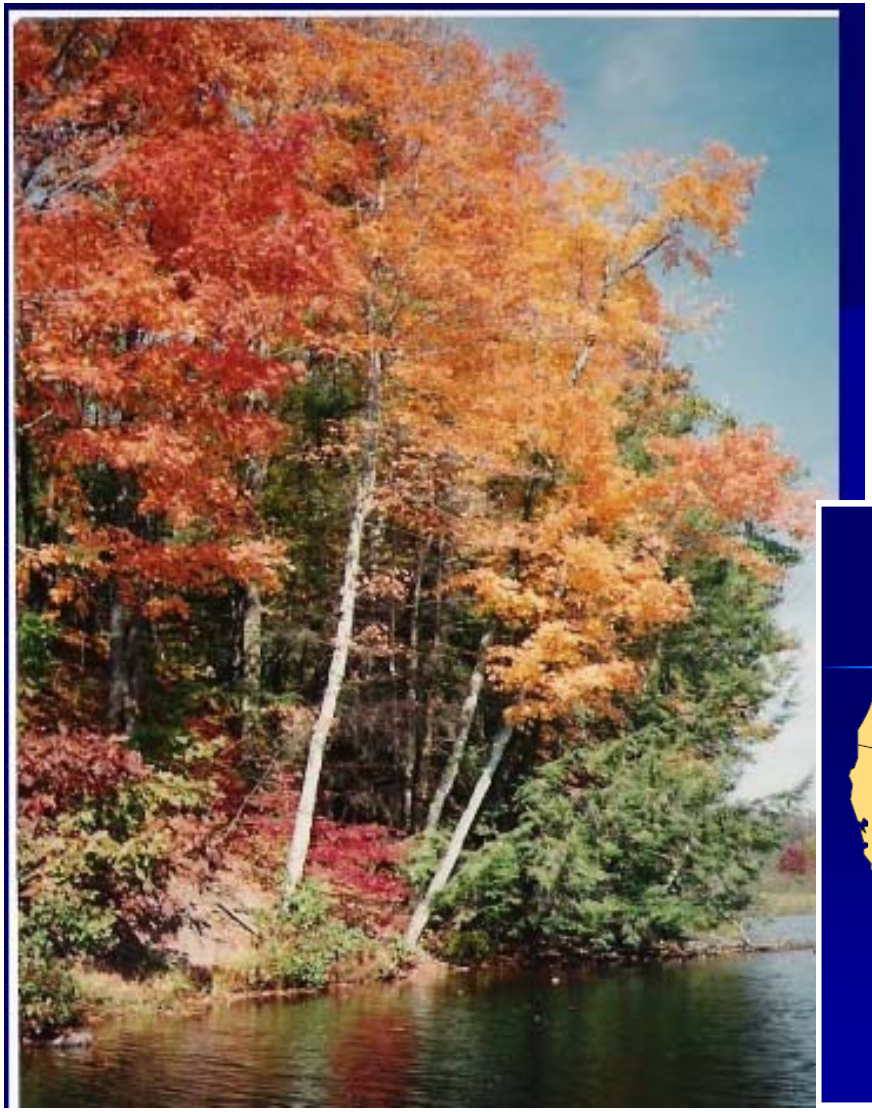
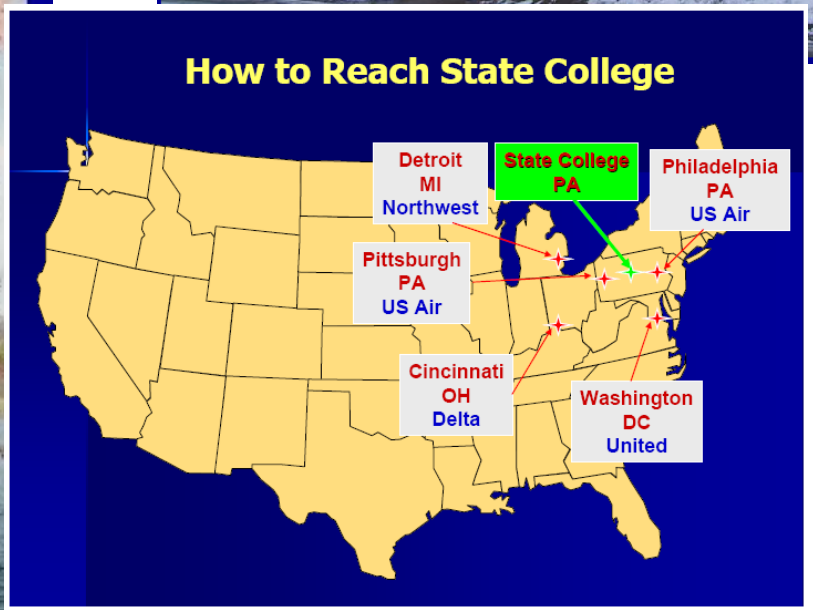




Interdisciplinary Materials Research, Science and Engineering at Penn State

Core Competencies:

- nanoscience, nanomaterials and nanostructures
- electronic materials, devices and systems
- functional polymers and ceramics
- synthesis, processing and manufacture
- materials characterization and surface science
- computational modeling and simulation

Glass Research at Penn State

Faculty:

- David Green (mechanical)
- John Hellman (struct/proppants)
- Seong Kim (polymer coatings)
- Mike Lanagan (dielectric props)
- Karl Mueller (NMR/surface chem)
- Chris Muhlstein (nanomechanics)
- Carlo Pantano (surfaces/coatings)

Opportunities:

- Coatings: processing and properties
- Mechanical properties and strength
- Corrosion and weathering
- Glass for capacitors
- Microwave processing

- High performance buildings
- Solar for pv and fuel
- Composites

the Art and Science of Glass

PENNSTATE

Outline

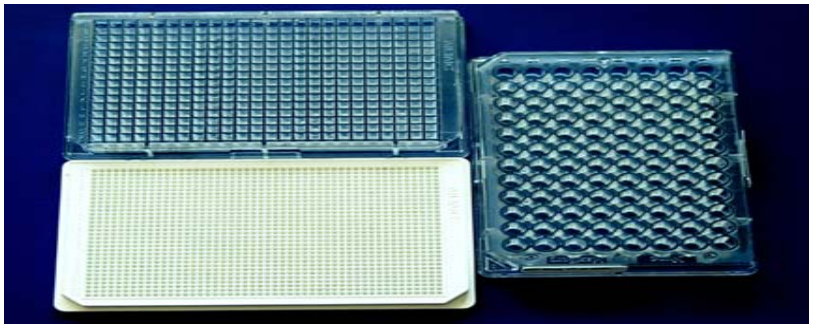
Part 1: Fundamentals

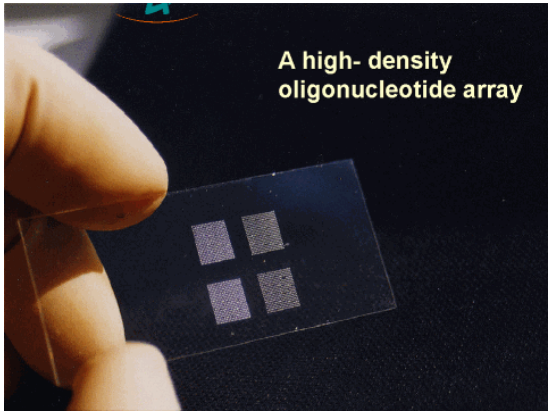
- **Surface Structure and Adsorption**
  - fracture surface vs melt surface
  - silica vs multicomponent
- **Surface and In-Depth Reactions**
- **Surface Functionalization**

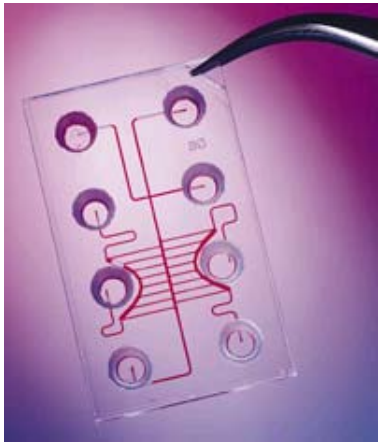
Part 2: Functional Surfaces

- **DNA Microarray Substrates**
- **Semiconducting Glass Surfaces**
- **Nanoscale Carbon Coatings**
- **Glass-Polymer Interfaces**

Glass Surfaces and Coatings for Biotechnology





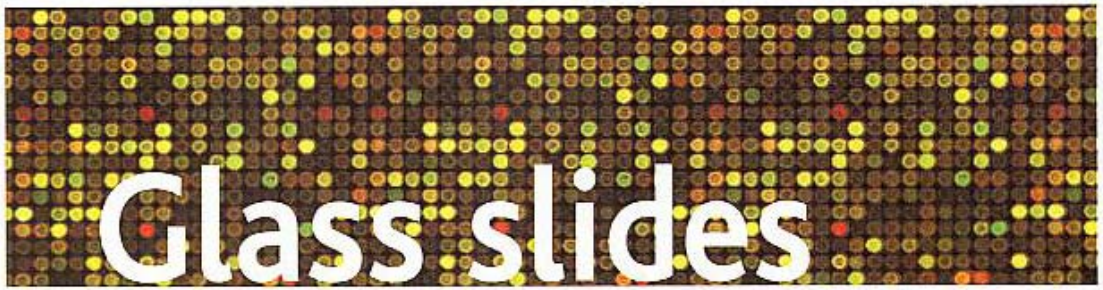


PENNSTATE

1855

Materials Research Institute

Center for Glass Surfaces, Interfaces, and Coatings



Glass slides to DNA microarrays

by Samuel D. Conzone* and Carlo G. Pantano†

A tremendous interest in deoxyribonucleic acid (DNA) characterization tools was spurred by the mapping and sequencing of the human genome. New tools were needed, beginning in the early 1990s, to cope with the unprecedented amount of genomic information that was being discovered. Such needs lead to the development of DNA microarrays; tiny gene-based sensors traditionally prepared on coated glass microscope slides. The following review is intended to provide historical insight into the advent of the DNA microarray, followed by a description of the technology from both the application and fabrication points of view. Finally, a description of the unmet challenges and needs associated with DNA microarrays will be described to define areas of potential future developments for the materials researcher.

*Director R&D-Schott Nextorion AG, Ma/086, Otto-Schott-Str. 7, D-55127 Mainz, Germany
E-mail: sam.conzone@schott.com

†Director, Materials Research Institute, The Pennsylvania State University, 199 Materials Research Institute Building, University Park, PA 16802-6809 USA
E-mail: pantano@ems.psu.edu

Most individuals, outside of academic circles focused on genomics, became aware of the potential commercial, technical, and social importance of the human genome project during the late 1990s. The human genome project was formally initiated in 1990[1] and was expected to last 15 years. It had the major goals of identifying all of the genes in human DNA, determining the sequences of those genes, and storing the information in public databases. However, the project moved quickly from the onset and, by 1998, the Department of Energy (DOE) and the National Institutes of Health (NIH) predicted that the human genome project would be completed by 2003.

The big buzz about biotech

The tremendous success in rapidly mapping and sequencing the human genome (a working draft sequence of the human genome was completed in 2000), has lead many commentators to predict that similar achievements would follow on the applications side, leading to unprecedented discoveries related to human health[2,3]. Gaudy promises of high-tech clinics with the ability to prescribe drugs based on the genetic make-up of the patient were well ahead of their time. This normal lag from discovery (the sequenced human genome) to true applications (genetically engineered drugs) is partially attributable to the lack of tools, which could enable researchers to utilize effectively the tremendous amount of information that was generated during the human genome project.

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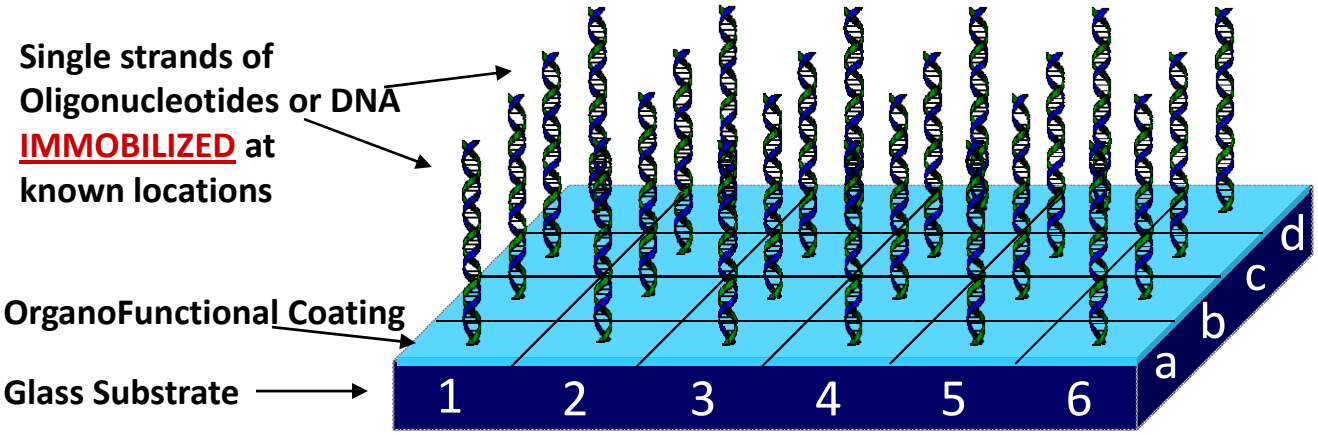
DNA Microarray: a glass-based biological sensor

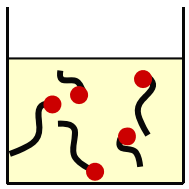


glass substrates provide:

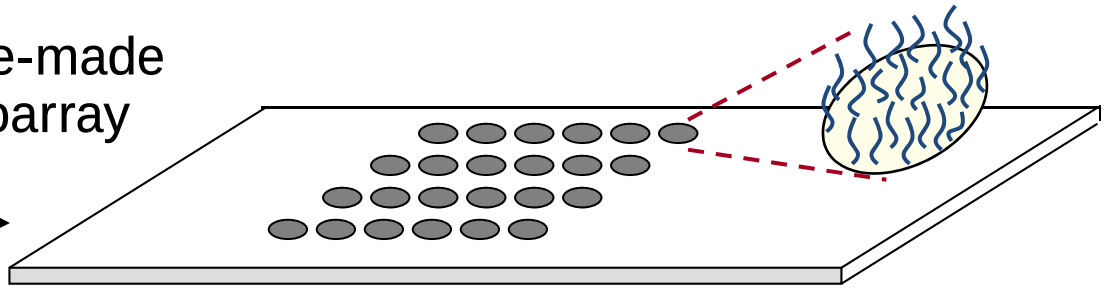
- chemical inertness
- optical platform
- low fluorescence background
- flatness and smoothness
- low cost!

Biomaterials and Bionanotechnology

DNA Microarrays (Gene Chips for sequencing)



Apply to pre-made
DNA Microarray

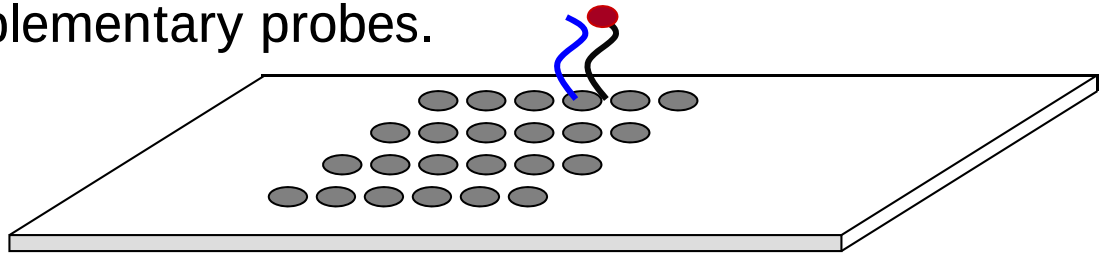


Unknown DNA solution
with fluorescent dyes.

Each spot contains identical DNA
probes of different known sequence.

Laser Confocal Scan

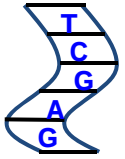
Unknown DNA molecules attach
to their complementary probes.

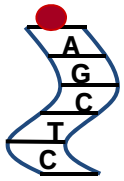


The sequence of the unknown
strand is now determined.

i.e.

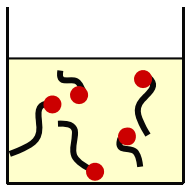
Array
probe



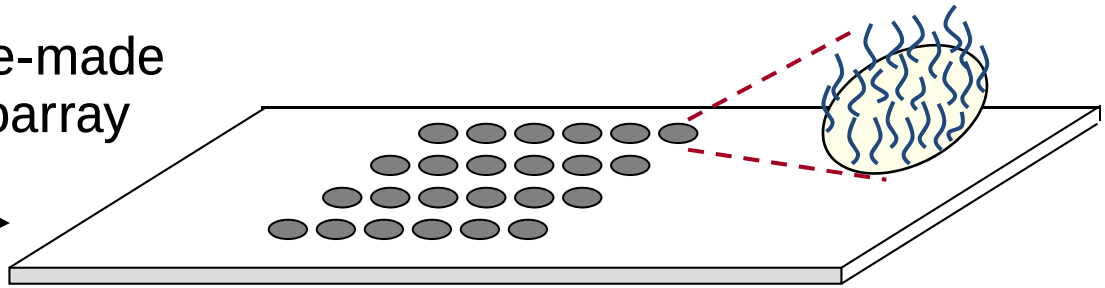


Unknown
probe

DNA Microarrays (Gene Chips for sequencing)



Apply to pre-made
DNA Microarray



Unknown DNA solution
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Each spot contains identical DNA
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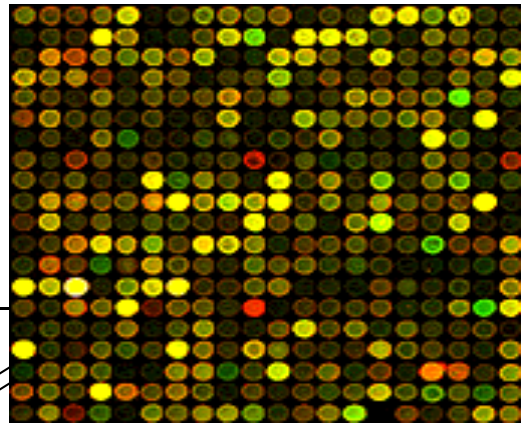
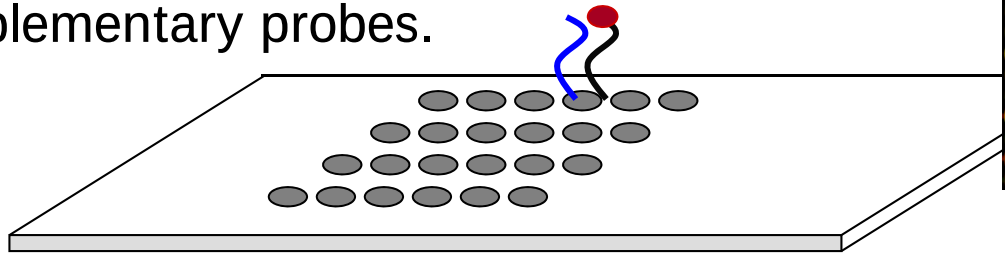


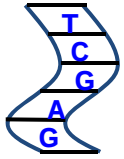
Unknown DNA molecules attach
to their complementary probes.

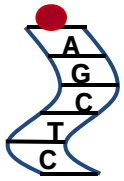


The sequence of the unknown
strand is now determined.

i.e.

Array
probe





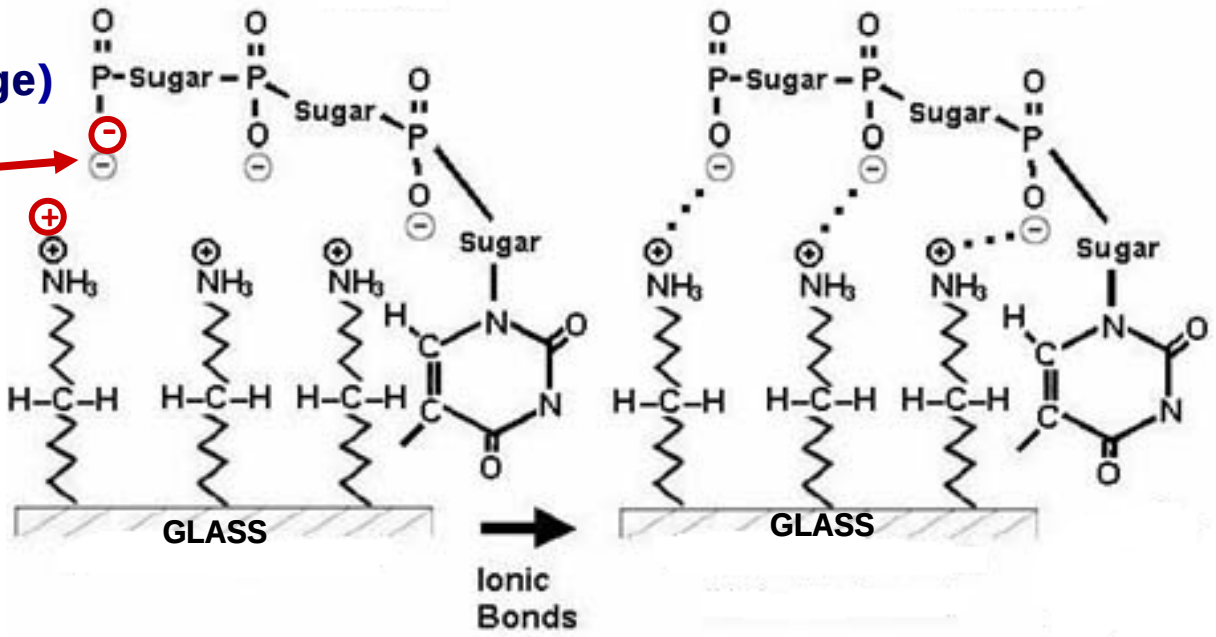
Unknown
probe

Immobilization of Unmodified DNA to glass substrates

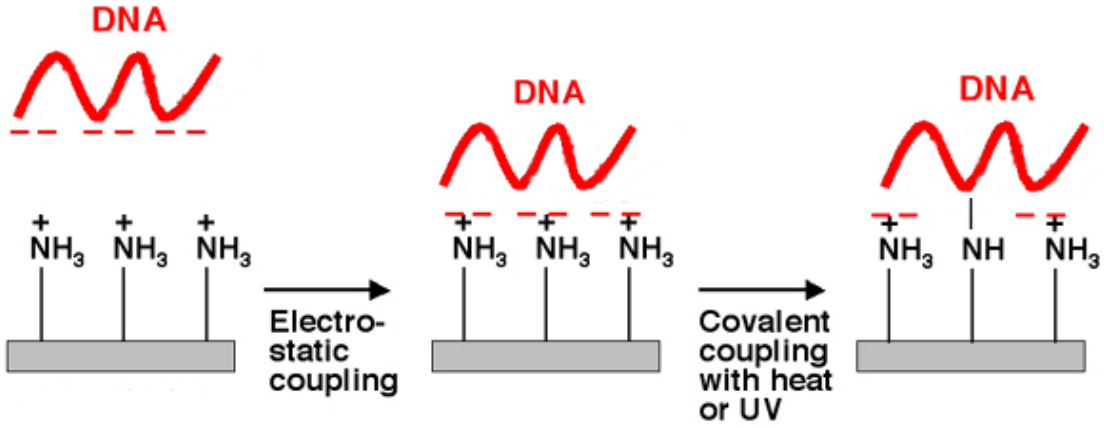
Phosphate-Sugar DNA backbone (carries negative charge)

electrostatic attraction

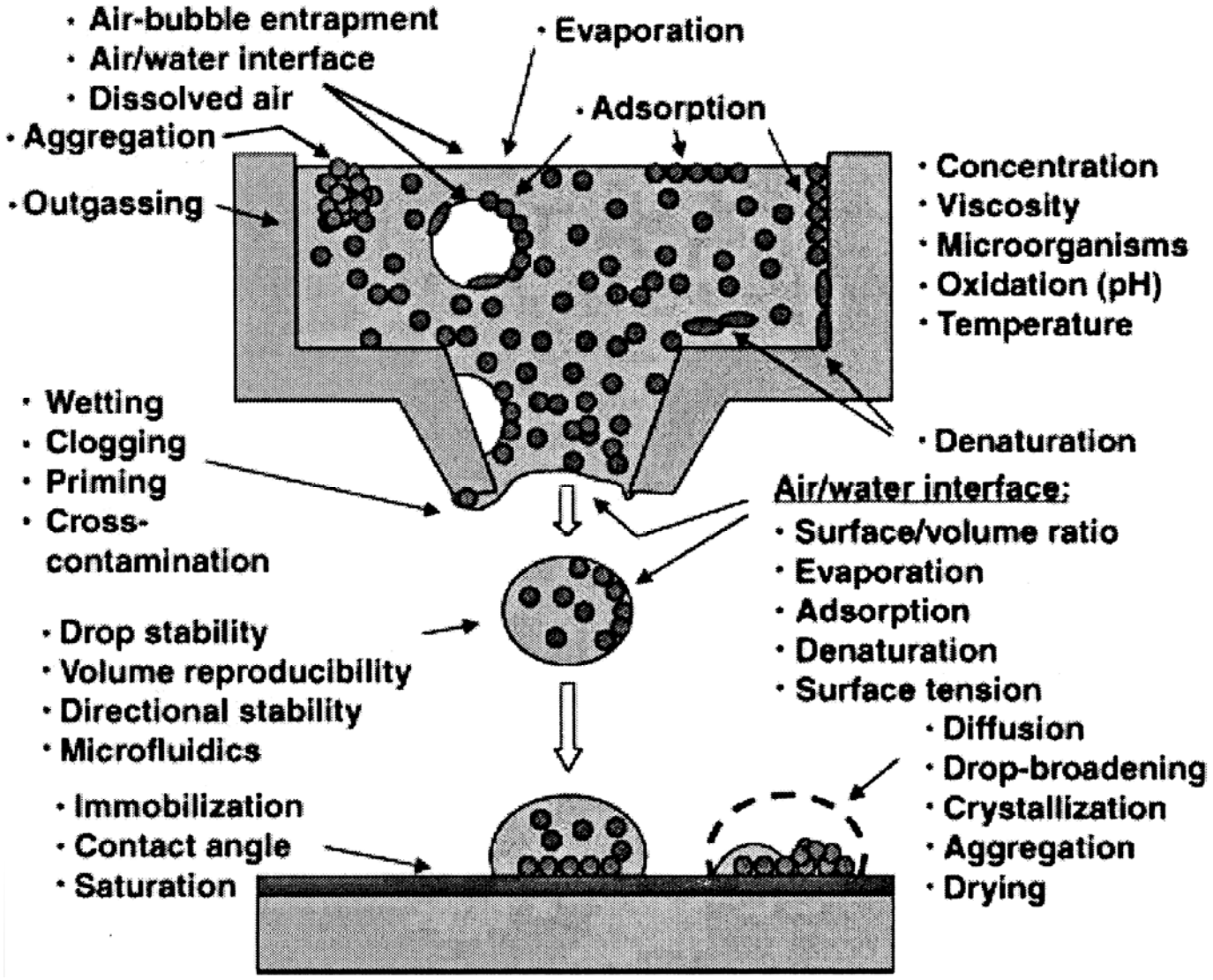
functional amine group-NH_3^+



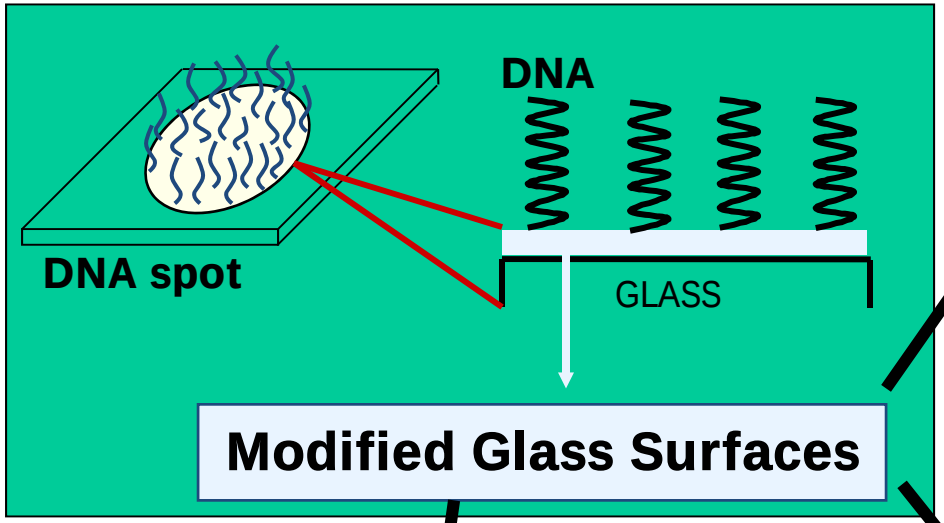
Unmodified DNA strands carry intrinsic $(PO_4)^{3-}$ groups; glass surfaces functionalized with protonated amino groups (NH_2) can be used for their initial immobilization.



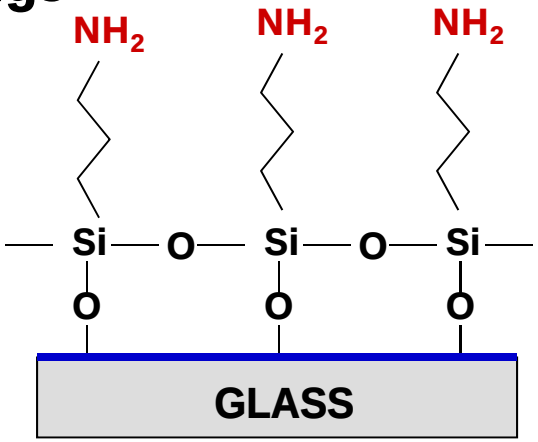
Physical Chemistry / Engineering of the Microspotting Process



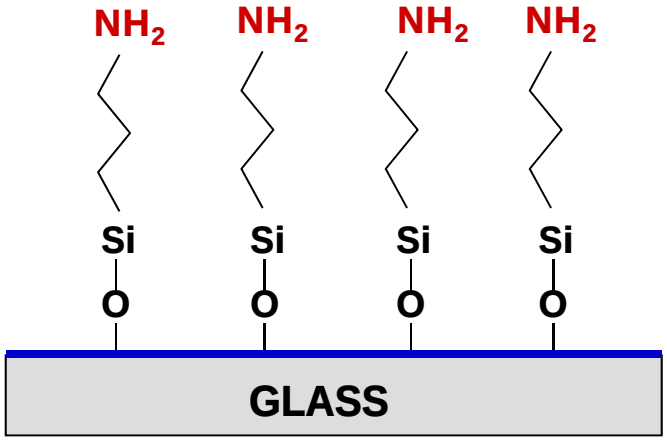
MODIFICATION of GLASS for DNA ATTACHMENT



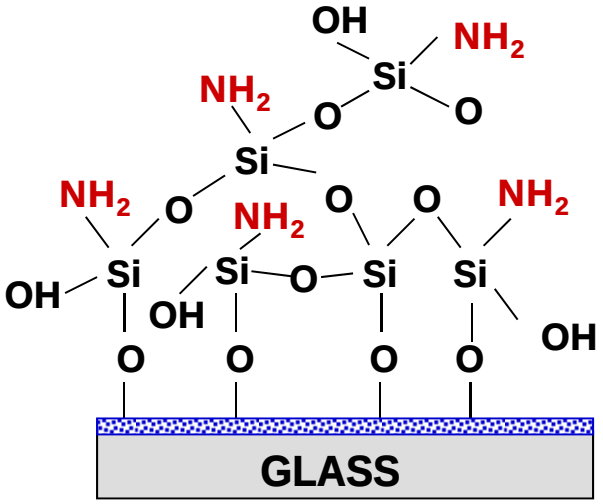
Functionalized Monolayer Coatings



Self Assembled Monolayers (SAMs)



Functionalized Porous Oxides



Aminosilane (APS)

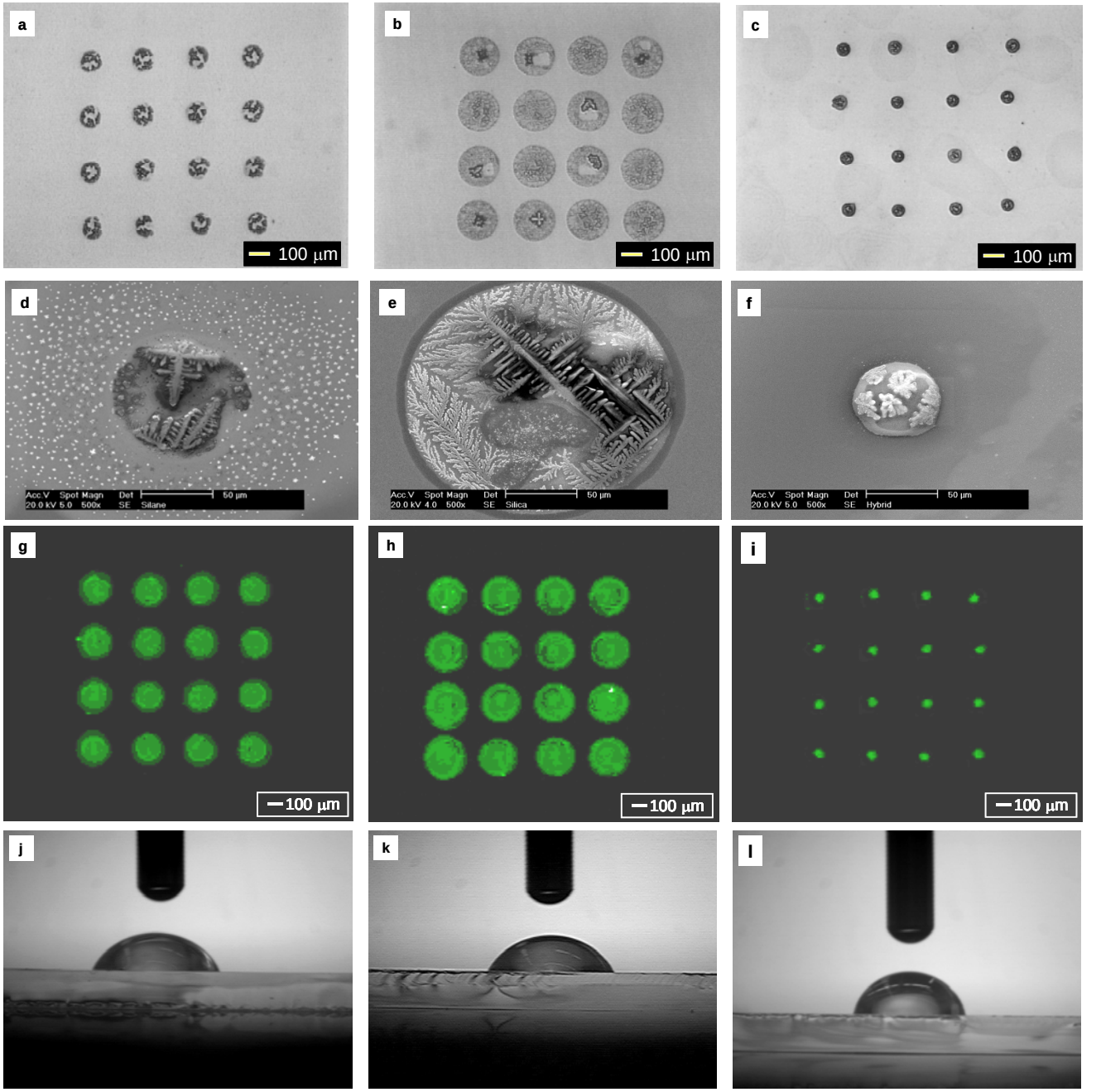
APS-treated sol/gel derived porous silica

Hybrid sol/gel derived APS-functionalized silica

Optical microscopy

SEM

Confocal Laser Scanning

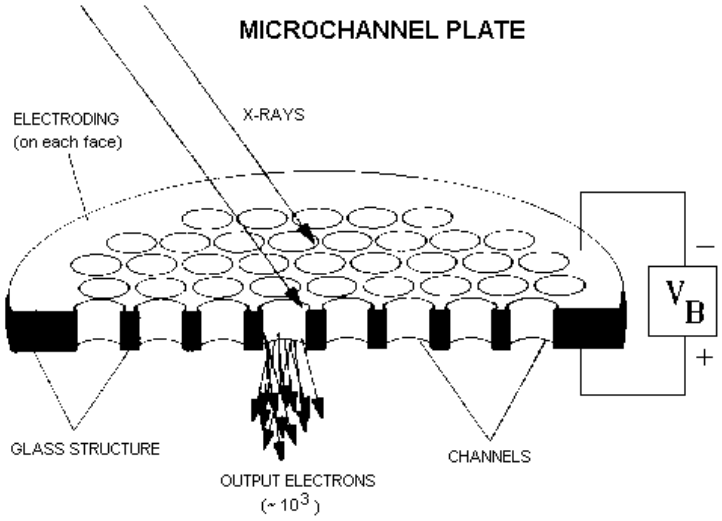


Code 8161 - 52% PbO, 39% SiO 2, 5% K20, 2% Rb20 and 2% BaO.

Electron Emission Glasses

The acid etch was brief and utilized an 0.10 N HC1 solution. The hydrogen reduction took 10 h at 450-500°C.

These surface layers can exhibit resistivity of ~ an ohm-cm and secondary electron yields up to 3.5.



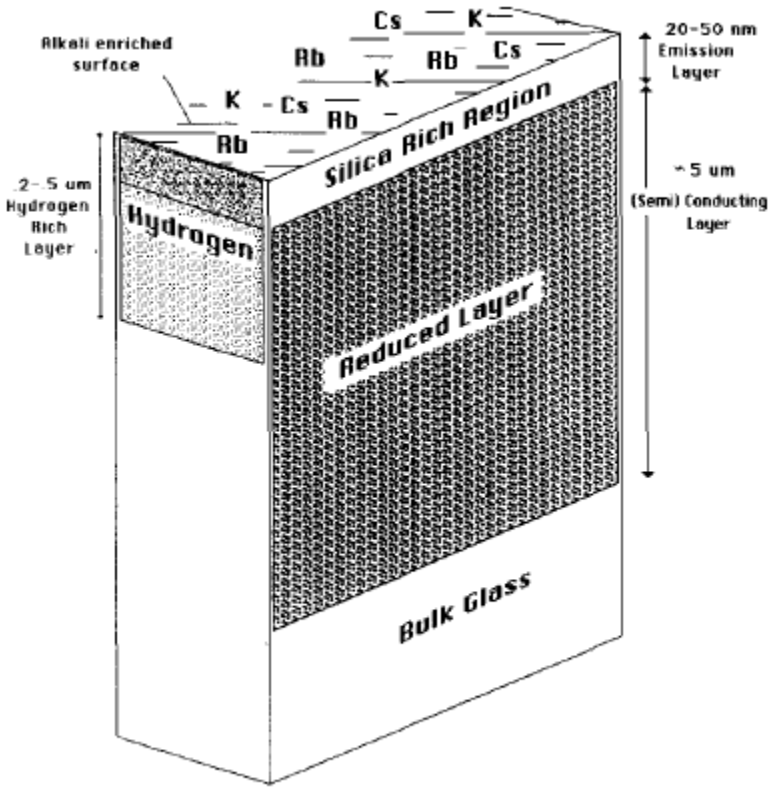


Fig. 5. Schematic representation of a typical acid-etched and reduced alkali–lead silicate glass surface; not to scale.

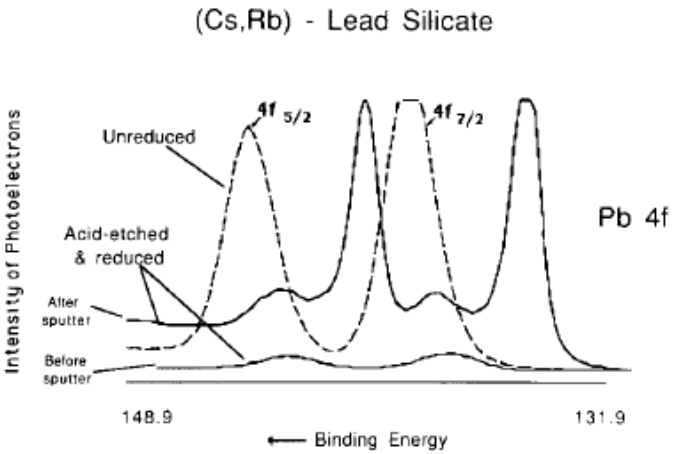


Fig. 4. High-resolution XPS spectra of the Pb 4f line after treatment of the (Cs, Rb)-glass; the spectra of a clean fracture surface is shown for reference.

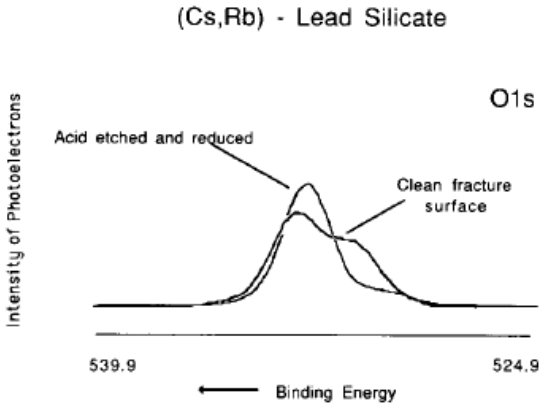
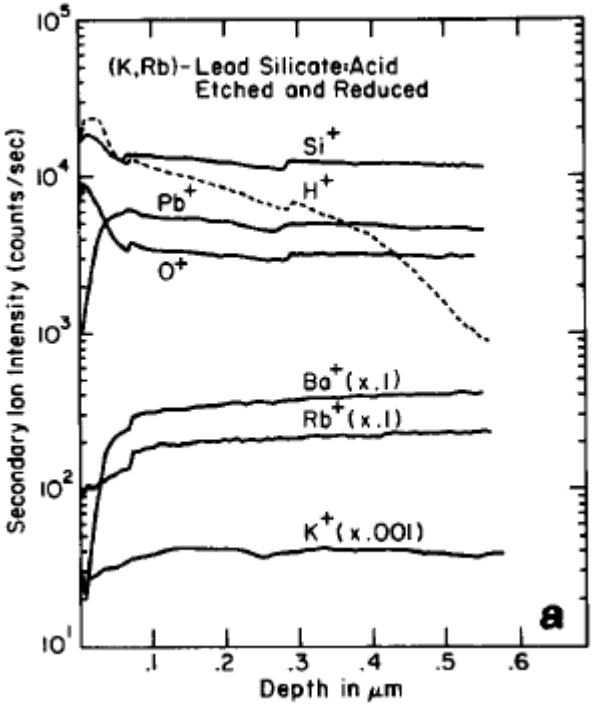
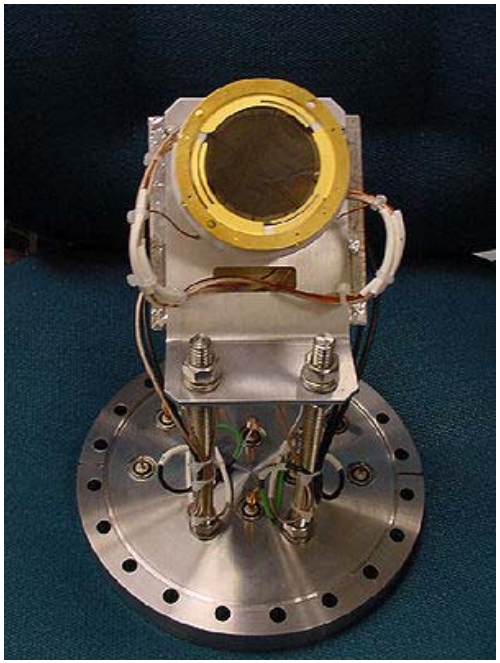
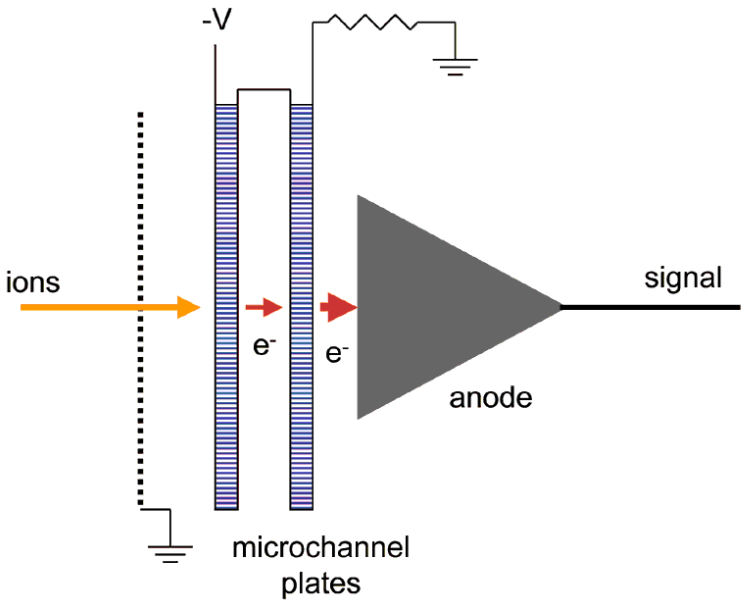


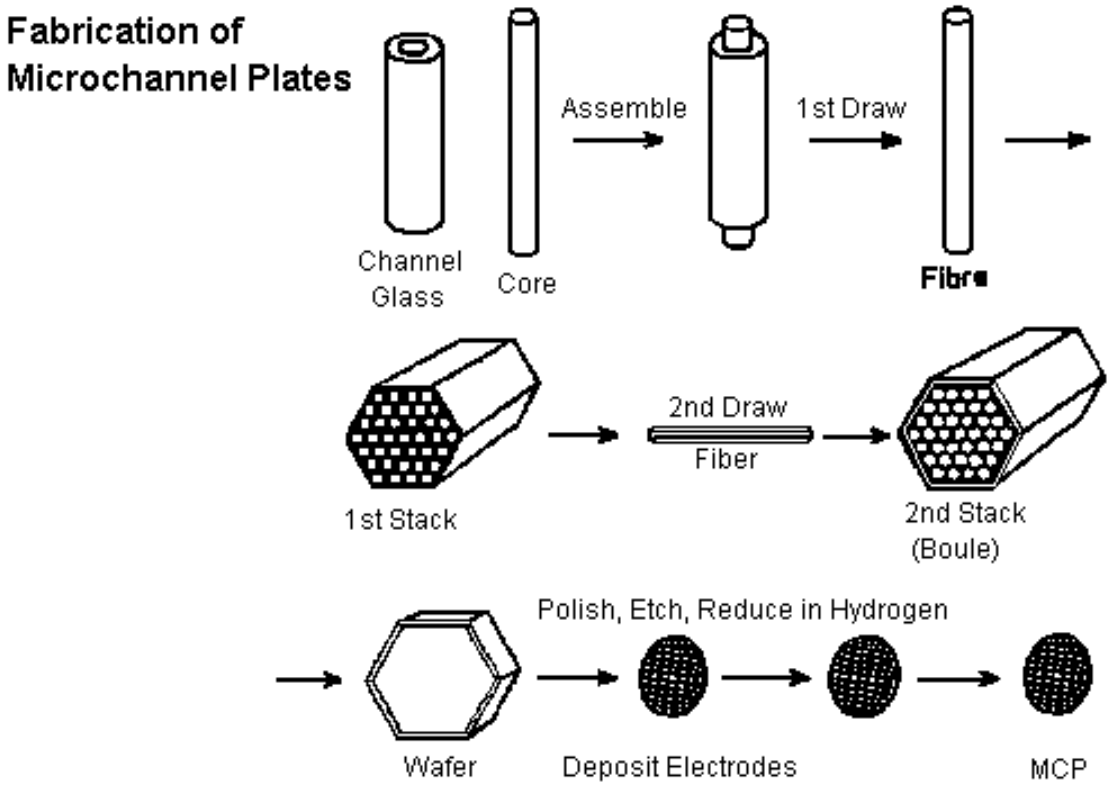
Fig. 3. High-resolution XPS spectra of the O1s line after treatment of the (Cs, Rb)-glass; the reference spectra of a clean fracture surface shows a shoulder at lower binding energy due to non-bridging oxygen.



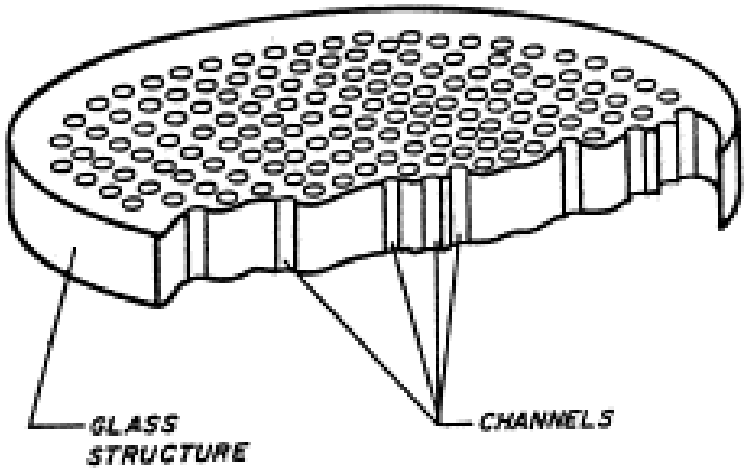


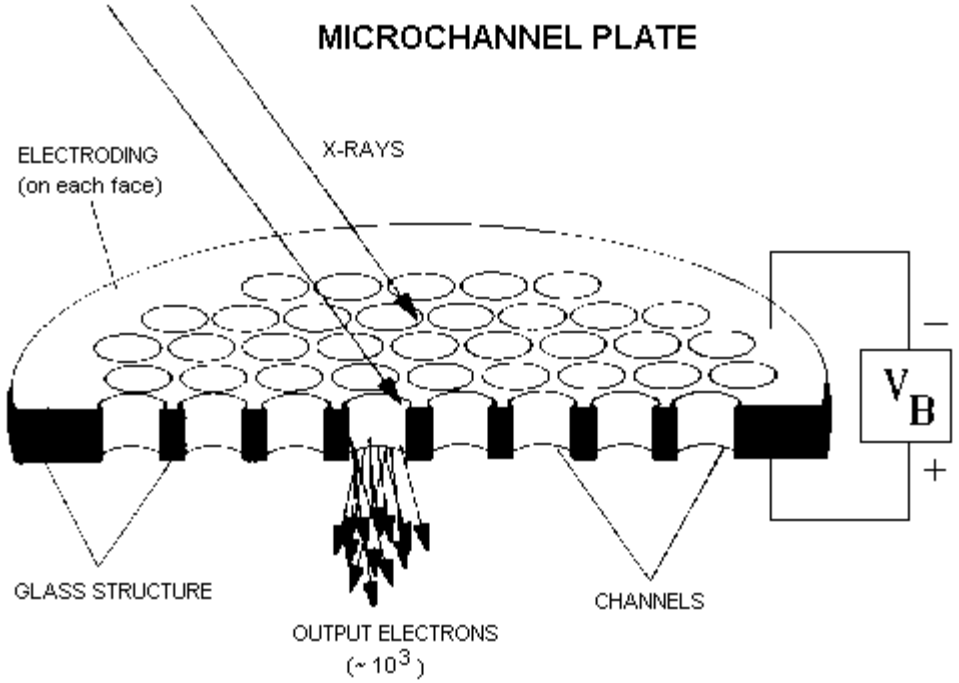

-V
ions
e-
e-
signal
anode
microchannel
plates

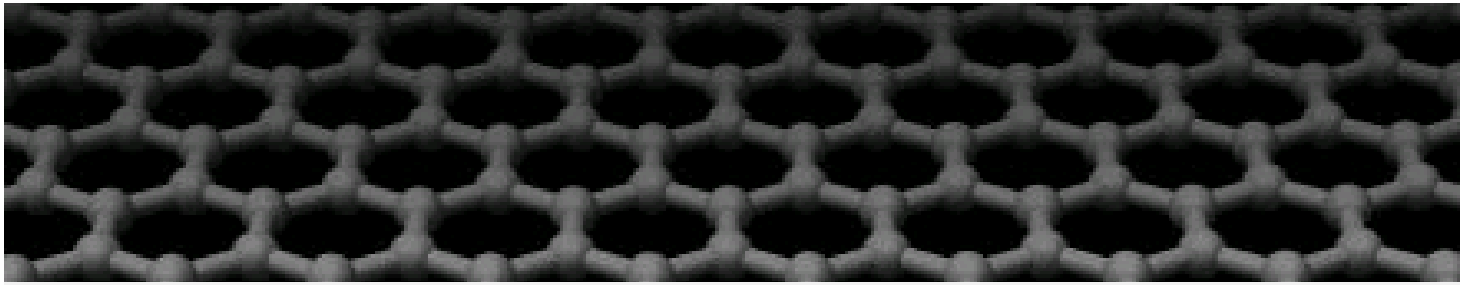
A hollow billet of lead oxide cladding glass is mechanically supported by the insertion of a rod of etchable core glass and then pulled through a vertical oven, producing a "first draw" fiber of approx. 1 mm diameter. Lengths of first draw fiber are then stacked (usually by hand) in a hexagonal array which is itself drawn to produce a hexagonal "multifiber".
Lengths of multifiber are stacked in a boule and fused under vacuum. The boule is sliced and polished to the required thickness and shape. The solid core is then etched away, leaving the channel array to be fired in a hydrogen oven to produce a semiconducting surface layer with the desired resistance and secondary electron yield. (Source: Philips Photonics)



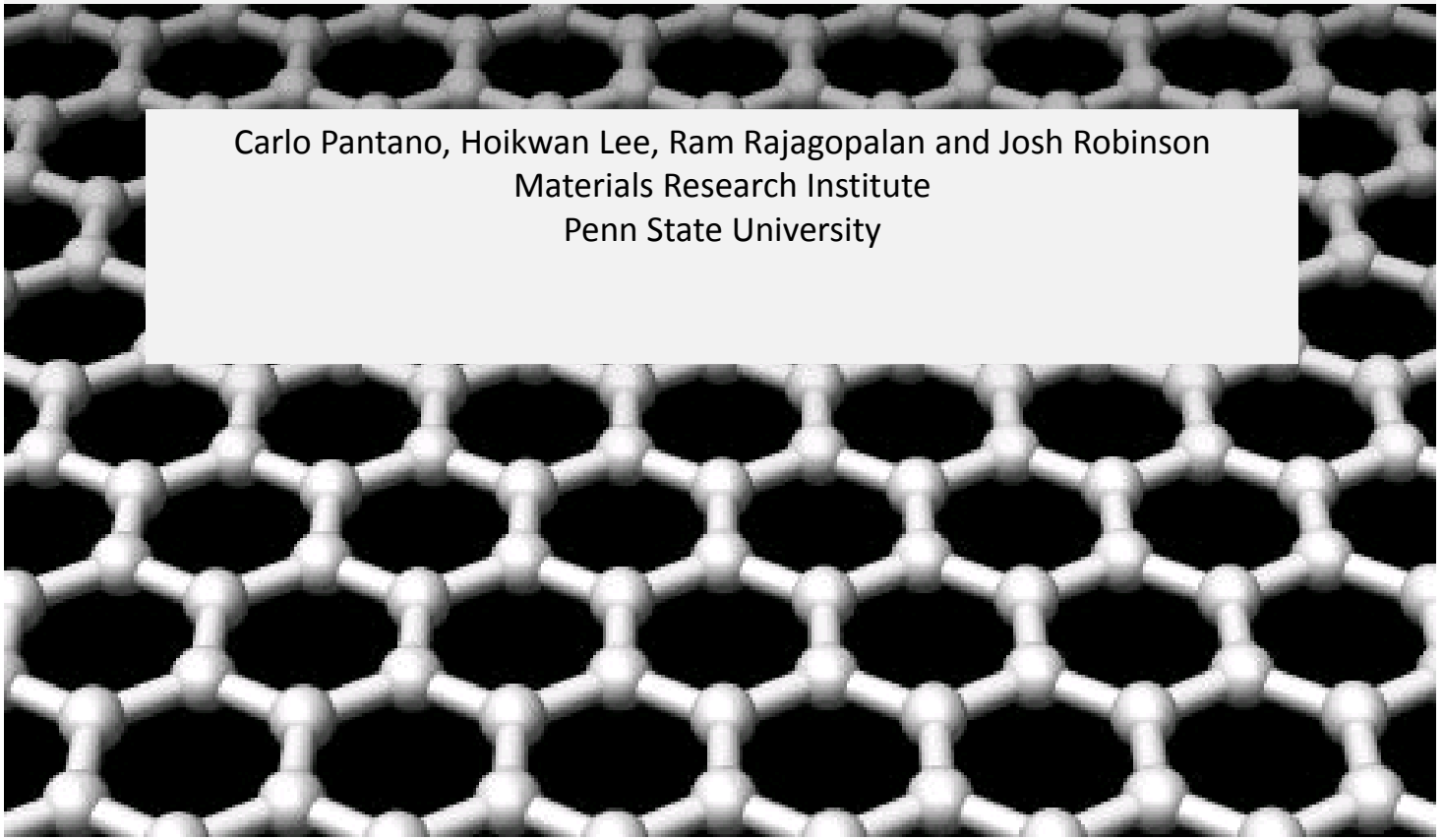
A single x-ray photon interacting in a channel of the MCP produces a charge pulse of about 1000 electrons that emerge from the rear of the plate. Since the individual tubes confine the pulse, the spatial pattern of electron pulses at the rear of the plate preserve the pattern (image) of x-rays incident on the front surface. When coupled to an additional MCP and an electronic readout and display the MCP becomes an x-ray image intensifier. The same microchannel plate technology is used to make visible light image intensifiers for night vision goggles and binoculars.





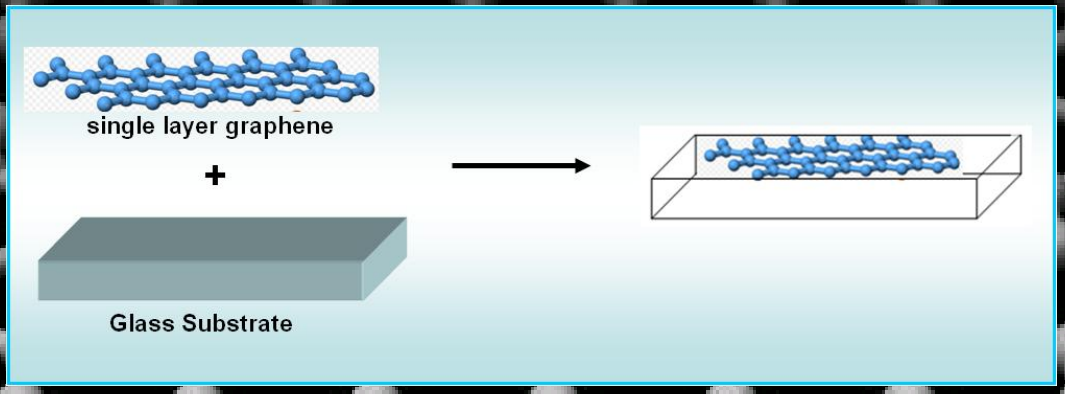


Nanoscale Carbon Coatings for Glass



Carlo Pantano, Hoikwan Lee, Ram Rajagopalan and Josh Robinson
Materials Research Institute
Penn State University

Nanoscale Carbon Coatings for Glass



a potentially multi-functional coating

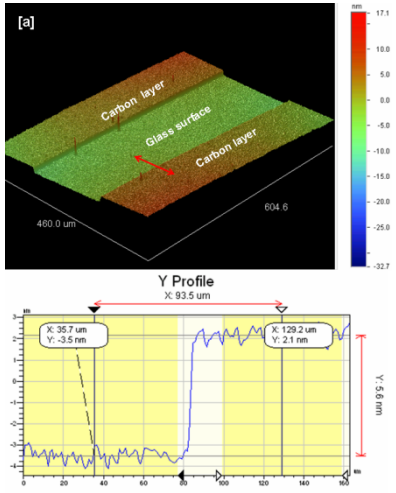
- water barrier
- low friction
- electrical conductivity
- high contact angle

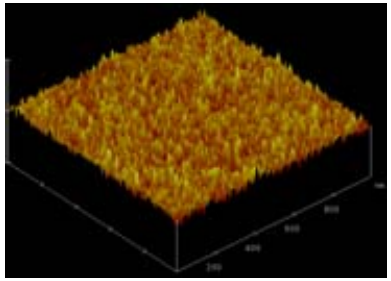
The long-range goal is to deposit or grow this layer on glass to enhance surface properties and add functionality.

Hoikwan Lee, Ramakrishnan Rajagopalan, Joshua Robinson and Carlo Pantano, "Processing and Characterization of Ultrathin Carbon Coatings on Glass", Applied Materials and Interfaces, Vol 1 No. 4, 927-933 (2009).

Organic Precusors		Before Pyrolysis (nm)	After Pyrolysis at 800°C (nm)	After Pyrolysis at 700°C (nm)
Polyfurfuryl Alcohol (PFA)	0.5wt%	9.60±0.15	3.28±0.04	5.7
	1wt%	12.88±0.08	3.38±0.06	
	5wt%	53.31±0.17	10.04±0.05	
Coal-Tar-Pitch (CTP)	0.5wt%	16.68±0.15	3.27±0.13	3.6
	1wt%	20.94±0.81	4.60±0.18	
	5wt%	81.66±1.69	5.77±0.15	
Photoresist (1805)	(10:1)	13.39±0.18	2.68±0.05	4.6
Thickness Measurement		Ellipsometry		Optical Profilometry

Thin carbon layers on the order of 3 – 6 nm in thickness were formed on glass substrates





SURFACE ROUGHNESS

Polymer Content (wt%)	PFA (nm)	CTP (nm)	Photoresist(1805) (nm)
0.5/(10:1)	0.182±0.017	0.341±0.110	0.180±0.021
1	0.190±0.027	0.257±0.136	
5	0.225±0.028	0.293±0.036	

Contact angle measurements

Precursor	Contained FPA (wt%)	Contact Angle (degrees)
Polyfurfuryl Alcohol	0.5	80.78±2.55
	1	80.55±3.92
	5	79.96±2.39
Coal-Tar Pitch	0.5	79.56±4.22
	1	77.34±1.75
	5	
Photoresist	10:1	85.33±2.19
AF45 Glass	-	47.56

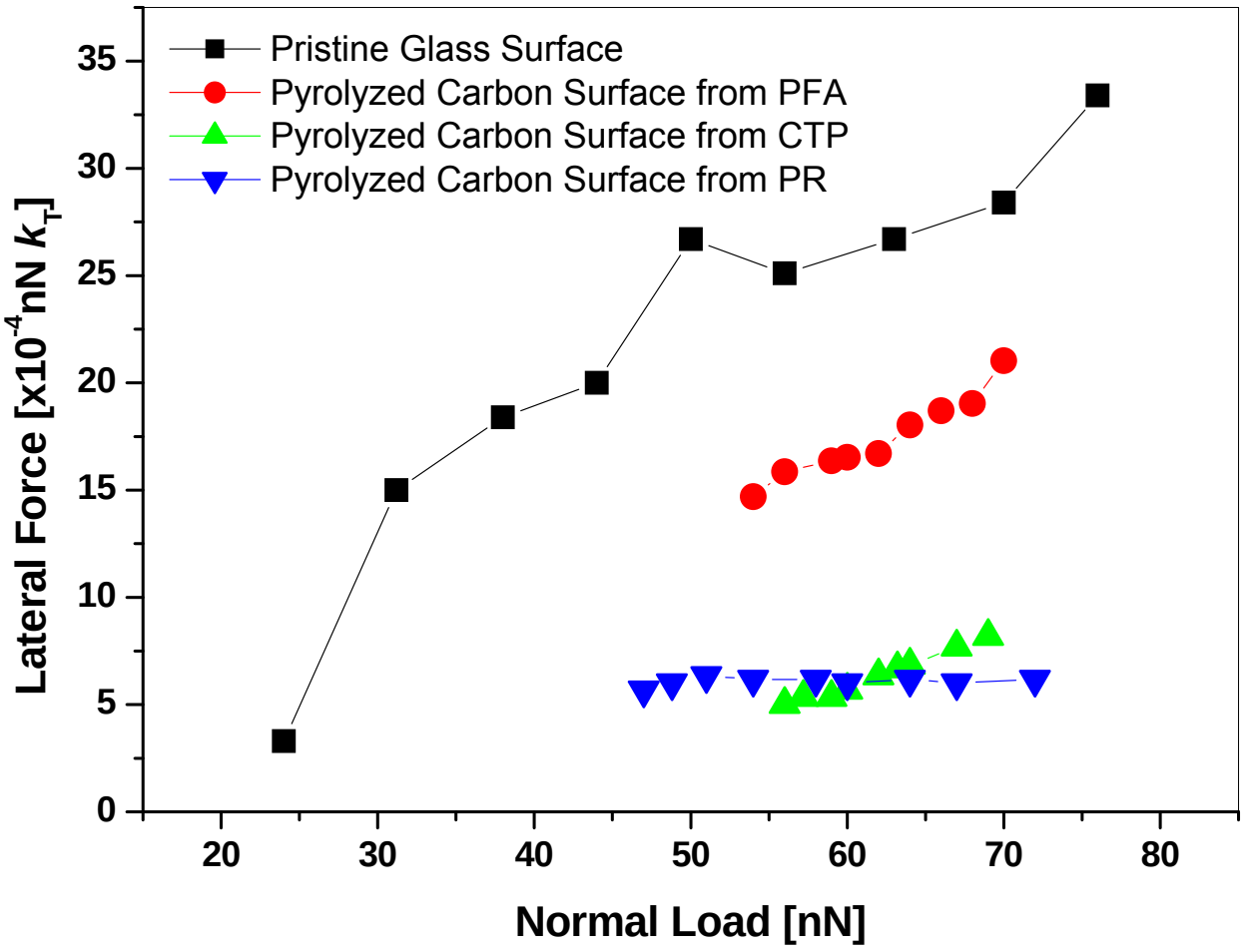
Contact angle of water on pristine AF45 glass

[a]

Contact angle of water on carbon coated AF45 glass

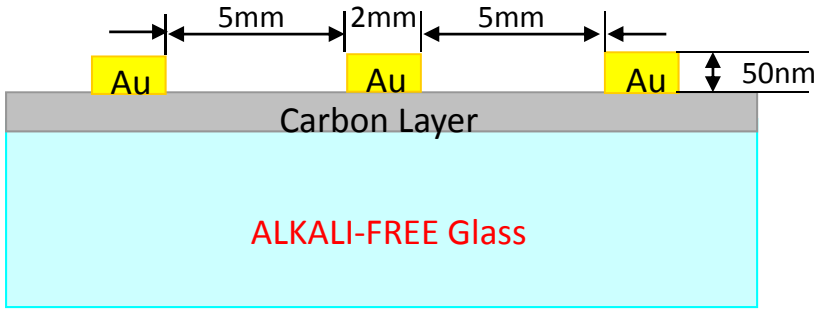
[b]

Measurement of frictional force using AFM



Measured frictional force of carbon coated glass was five times lower than the pristine glass surface

Electrical Properties



Temperature (oC)	Electrical Properties	
(2:1) 1805 at 700°C with vacuum	Rs (sheet resistance)	1.3×10^{-1} Ω/square
	P(Bulk resistivity)	1.3×10^{-6} Ω cm
	Electric conductivity	7.69×10^{5} Scm
(2:1) 1805 at 800°C with vacuum	Rs (sheet resistance)	6×10^{-2} Ω/square
	P(Bulk resistivity)	6×10^{-7} Ω cm
	Electric conductivity	1.67×10^{6} Scm
1803 at 800°C with Argon gas atmosphere Reference (thickness :440nm)	Rs (sheet resistance)	5.03x10 Ω/square
	P(Bulk resistivity)	2.2×10^{-3} Ω cm
	Electric conductivity	4.54×10^{2} Scm

Investigating the effect of sodium near the glass/polymer interface

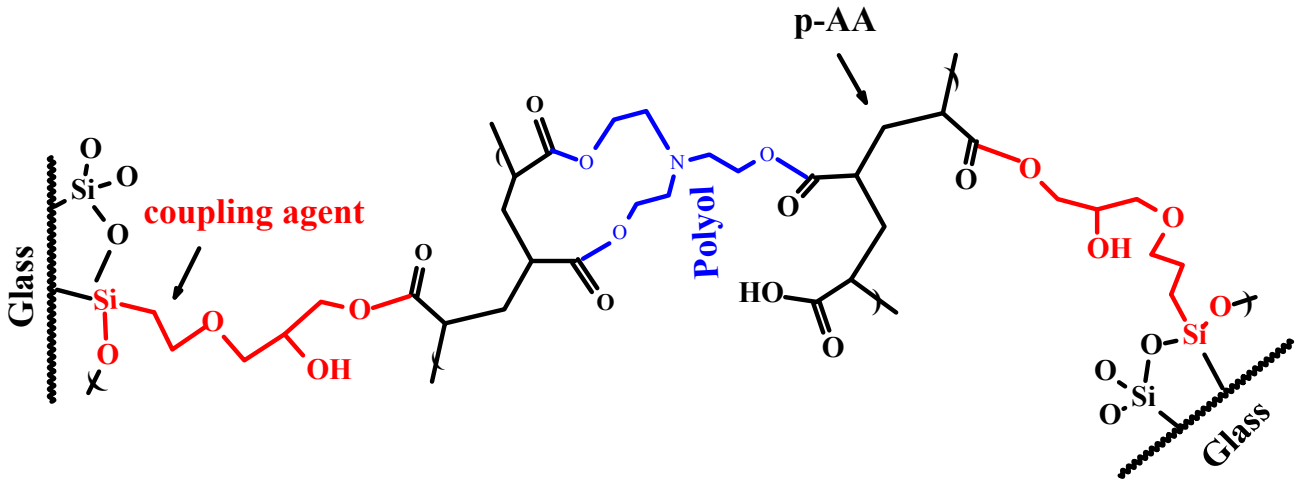
Joy Banerjee, Carlo Pantano (Penn State)

James Hamilton (Johns Manville)

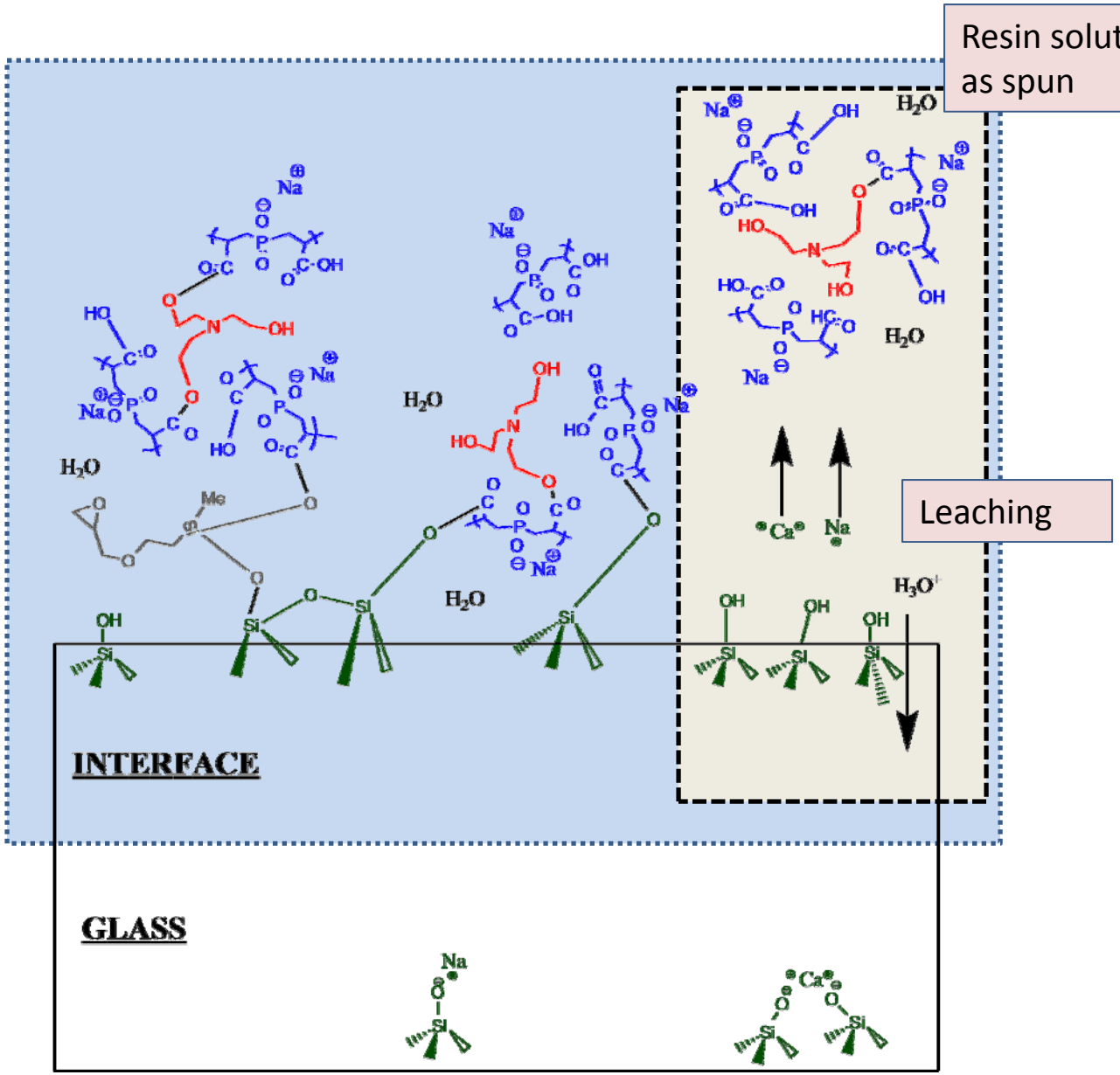
Scope

Interfacial chemistry

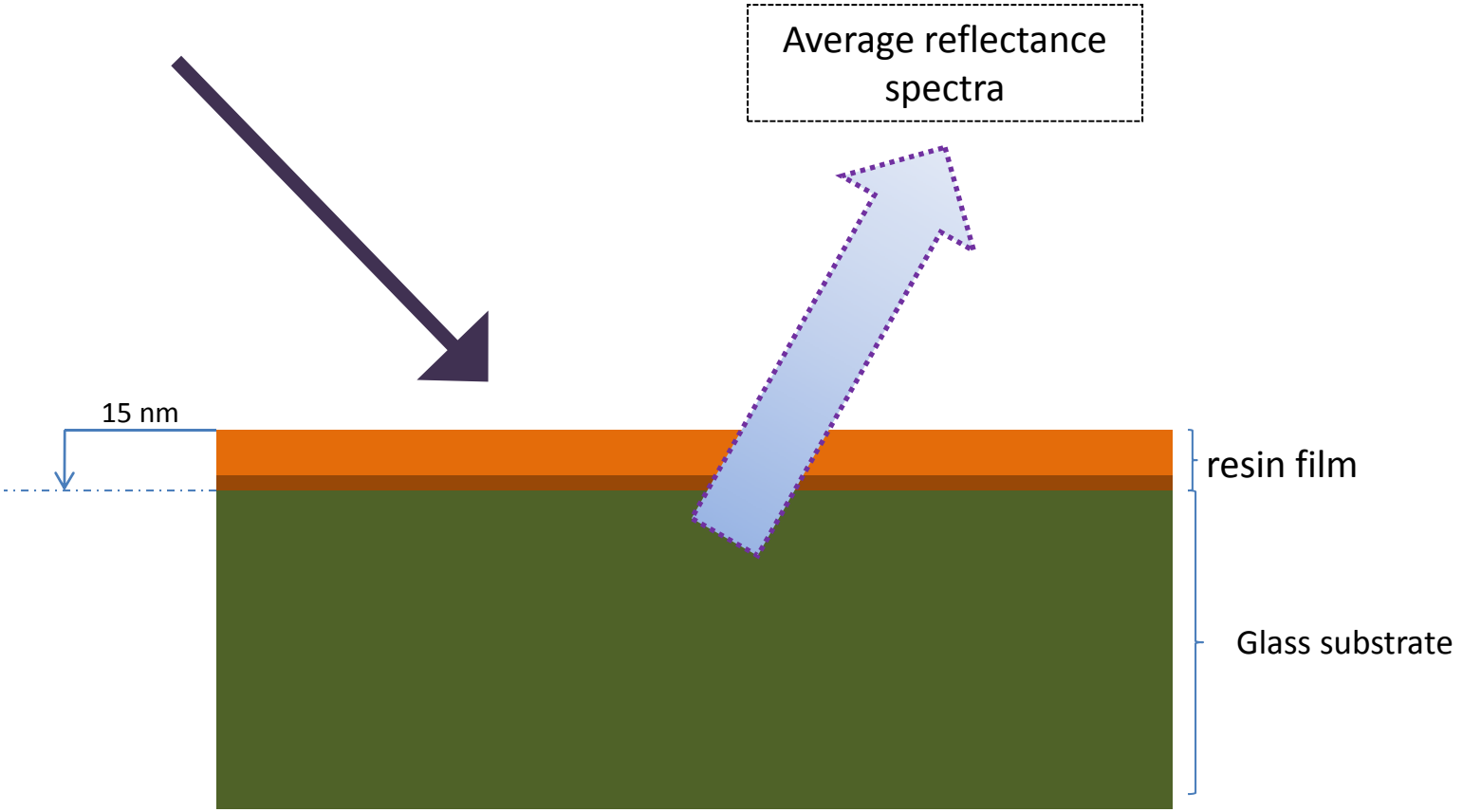
- Between glass surface and "green"(water-based) polymers
- Effect of bulk/surface glass composition
- Effect of polymer pH and processing conditions



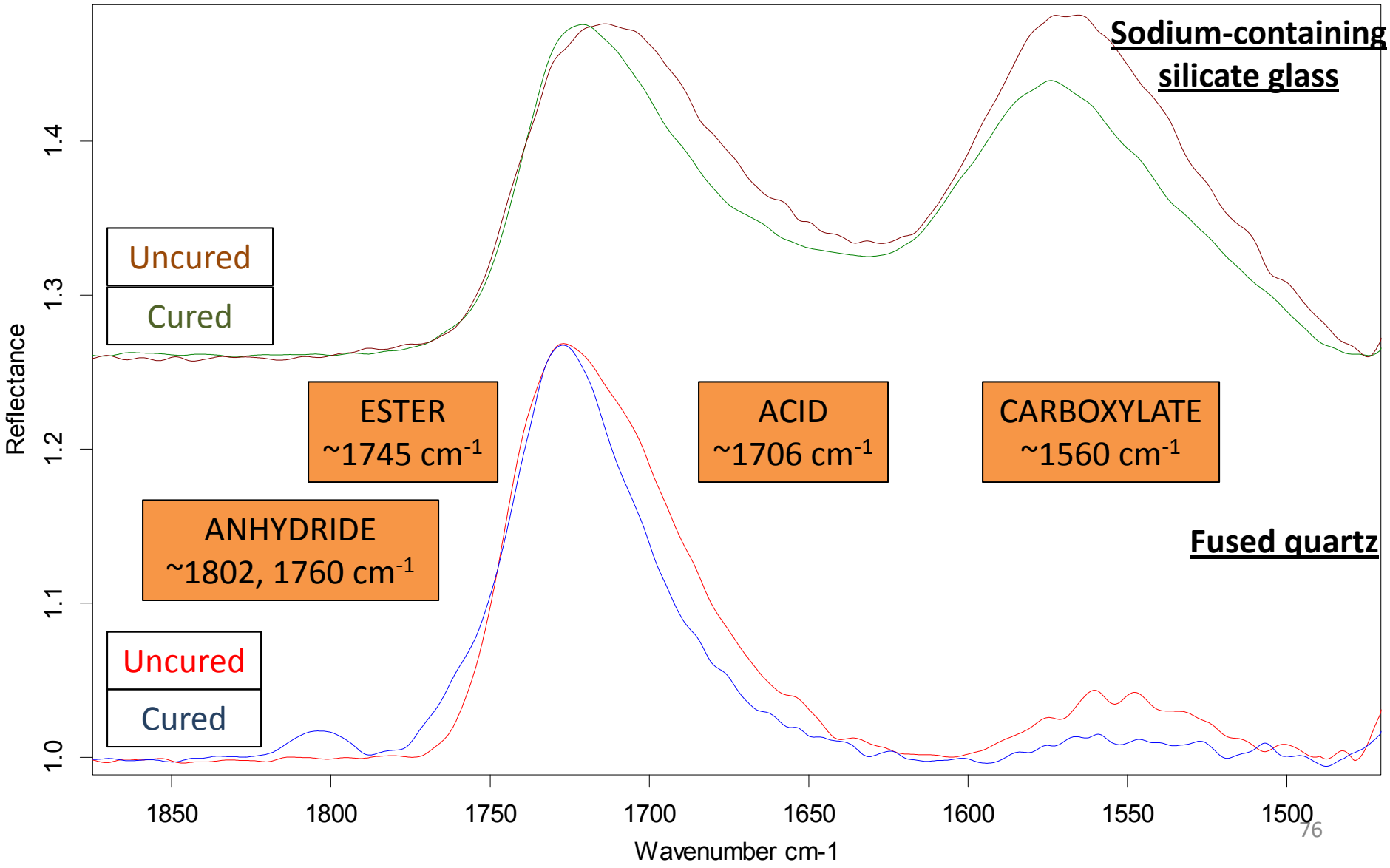
Resin on sodium-rich glass as-spun



Infrared Reflectance Spectroscopy of thin films

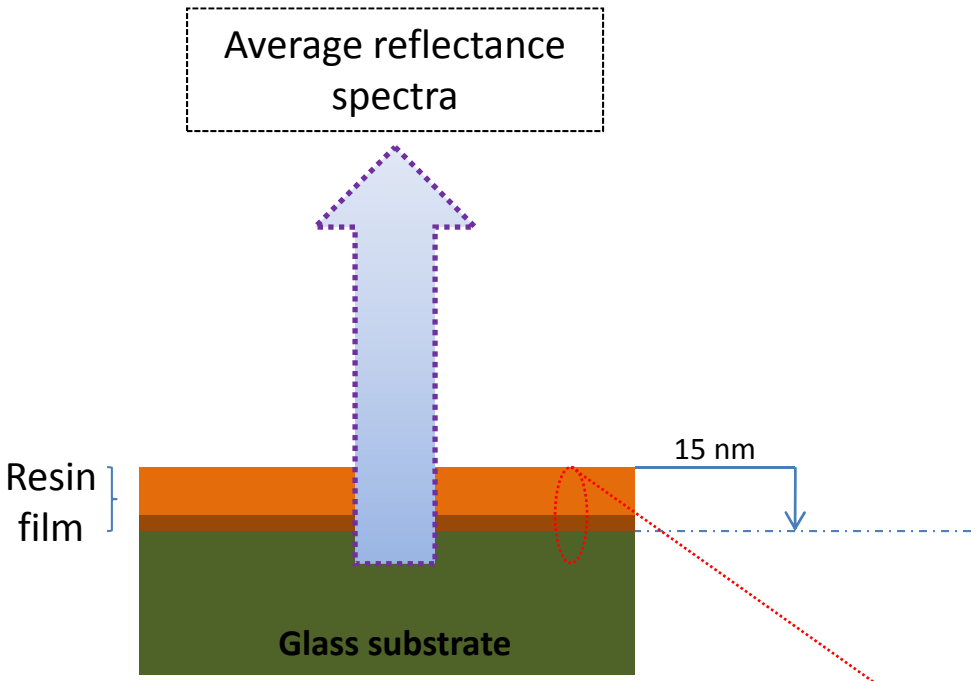


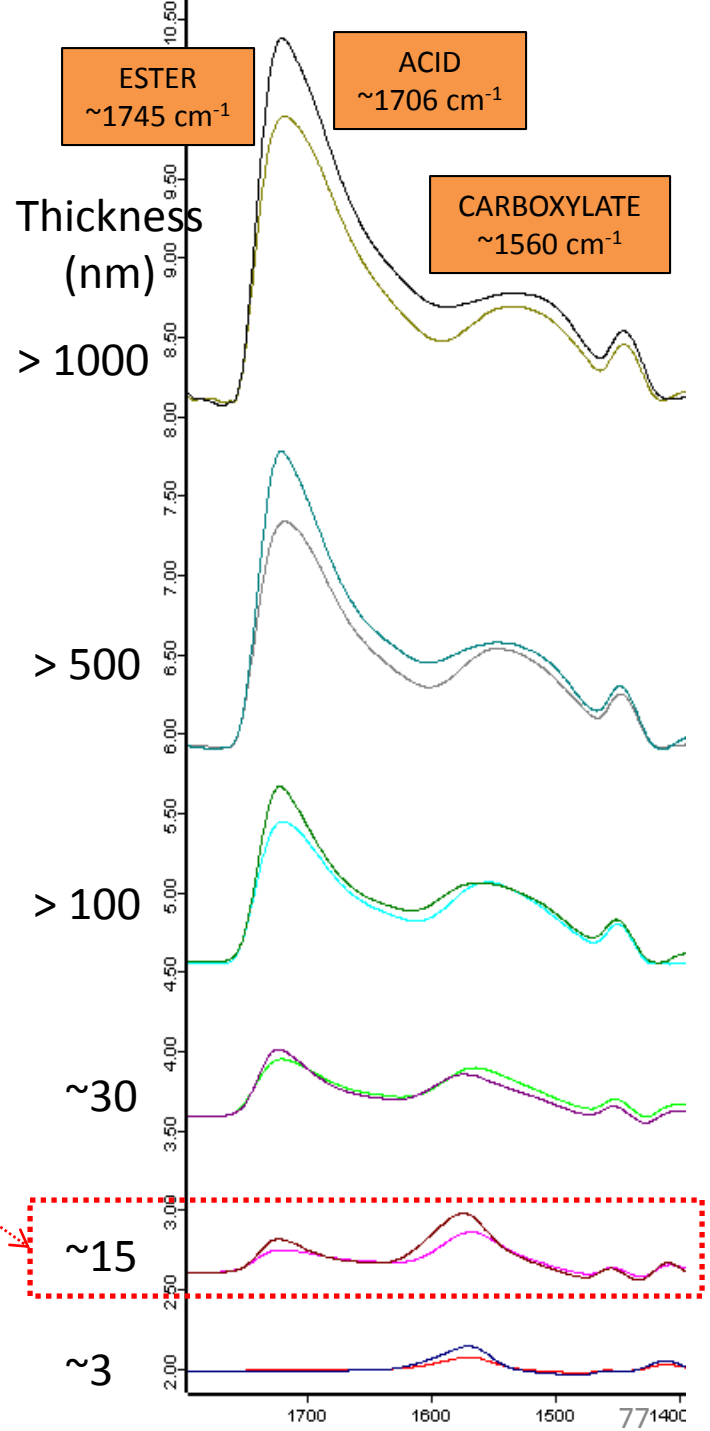
Resin thin film on glass (film thickness: 15nm)



- Resin interacts differently with JM901 versus fused quartz, primarily with carboxylate formation

Resin on JM901 (varying thickness)

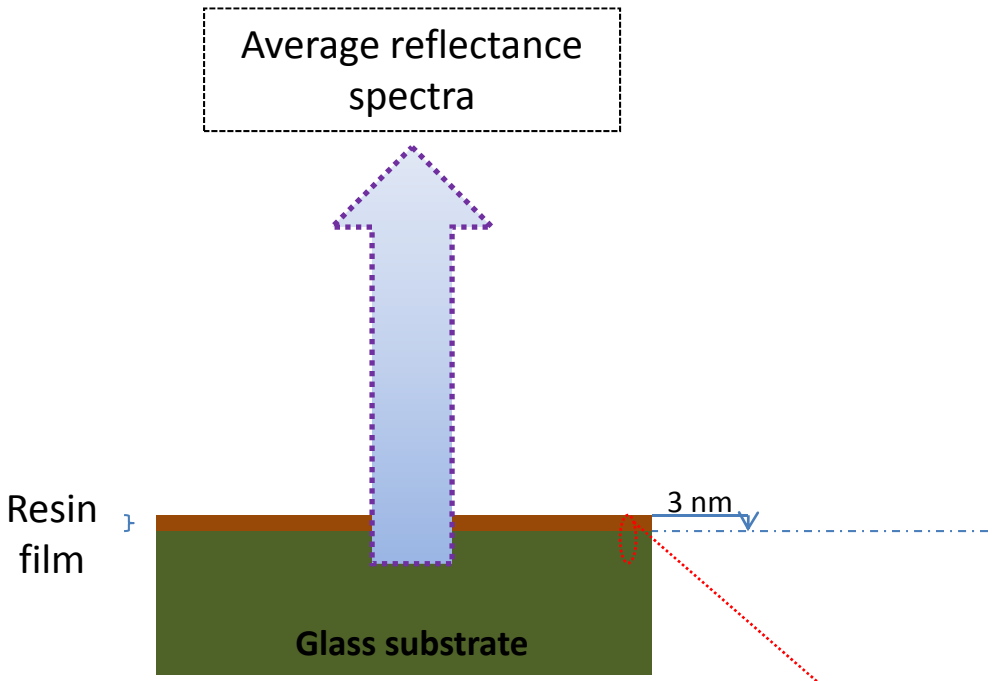


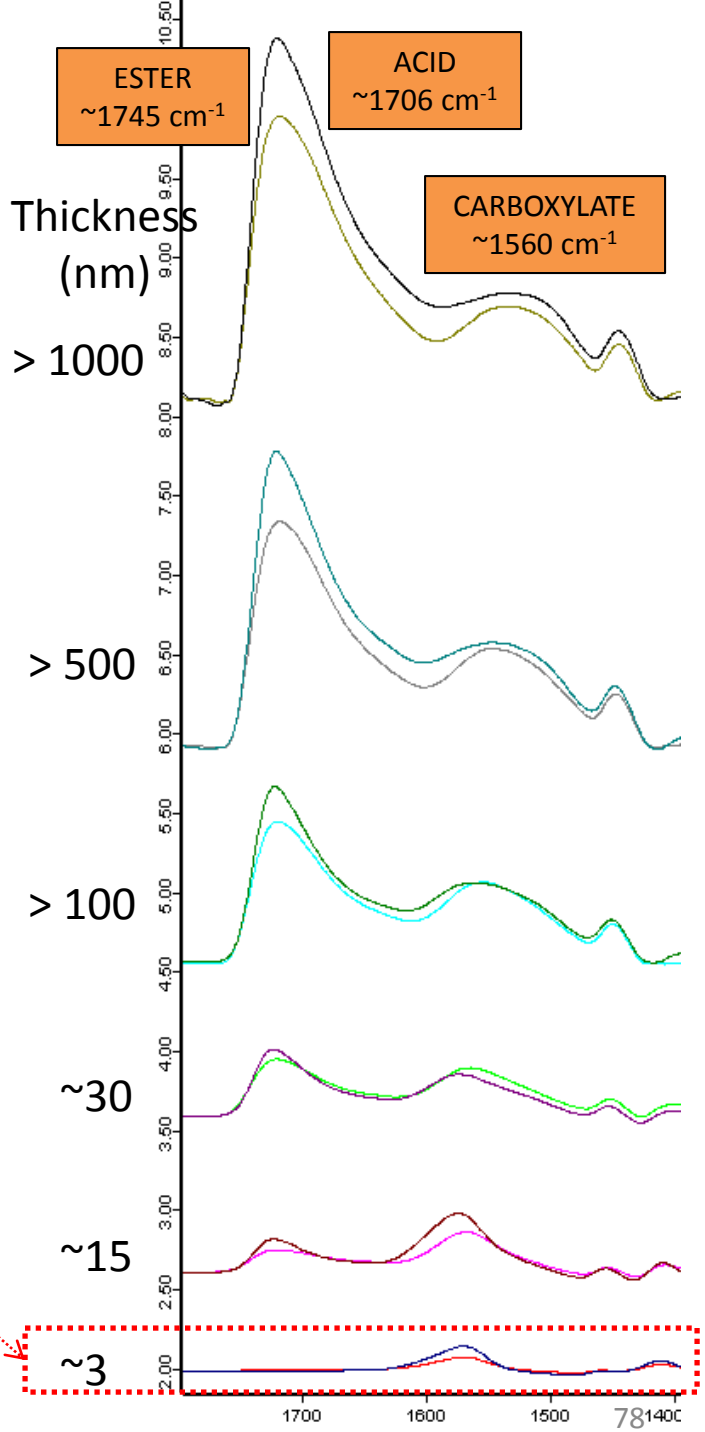


Higher intensity at acid/ester peak: cured 190C/1h

Lower intensity at acid/ester peak: dried 15h

Resin on JM901 (varying thickness)

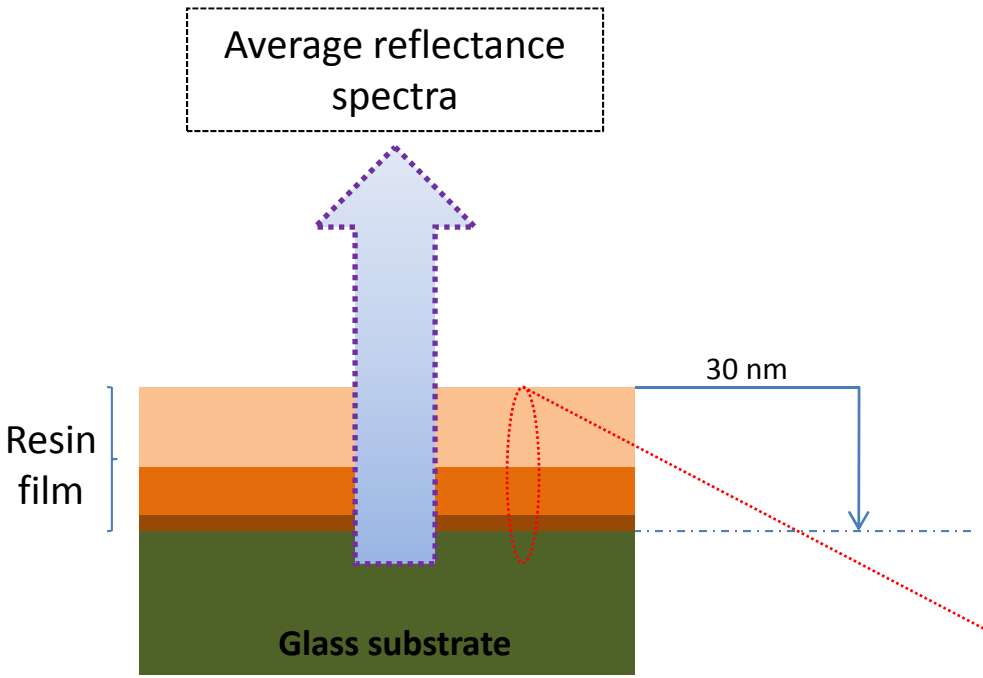


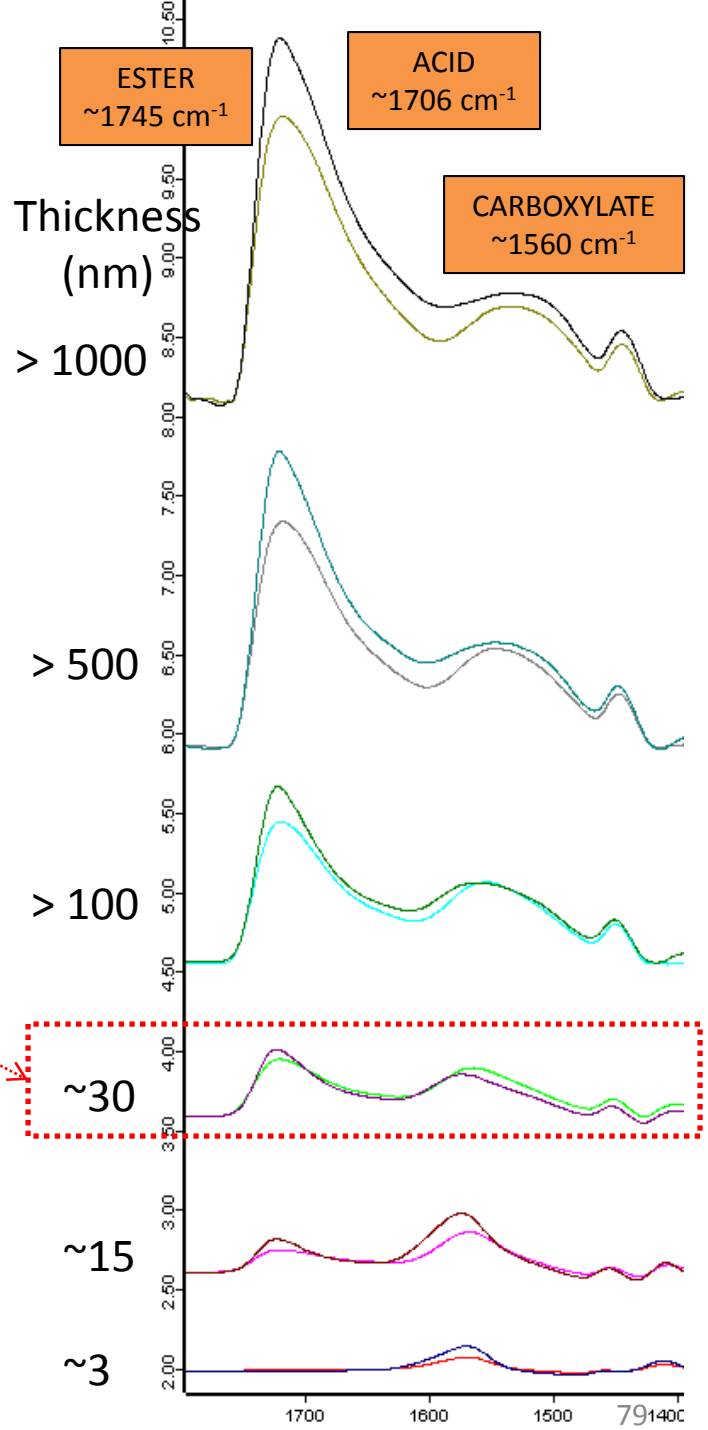


Higher intensity at acid/ester peak: cured 190C/1h

Lower intensity at acid/ester peak: dried 15h

Resin on JM901 (varying thickness)

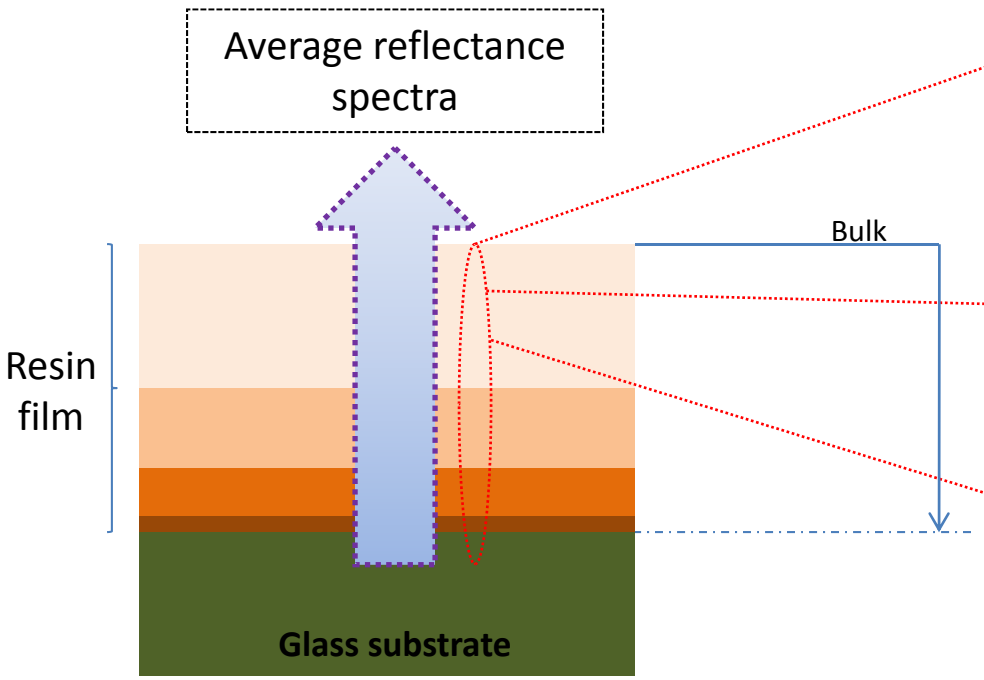


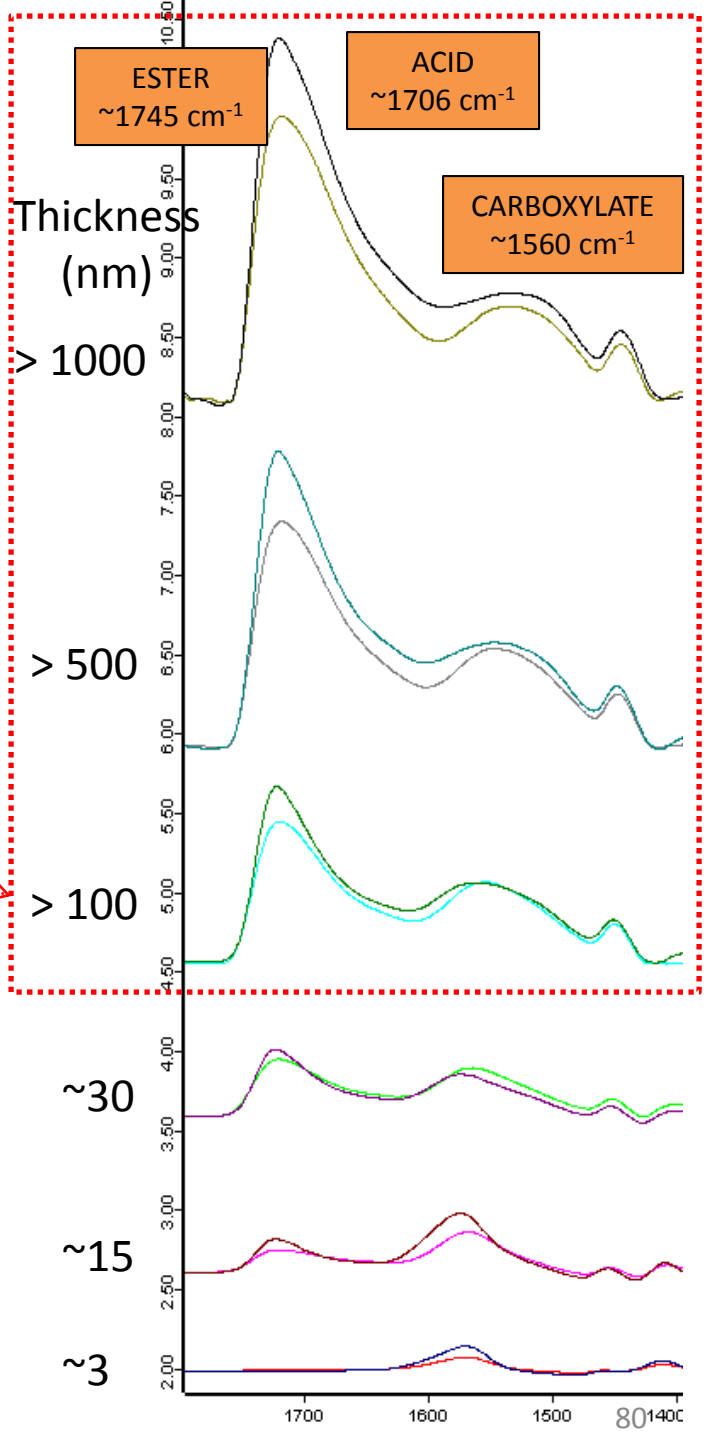


Higher intensity at acid/ester peak: cured 190C/1h

Lower intensity at acid/ester peak: dried 15h

Resin on JM901 (varying thickness)

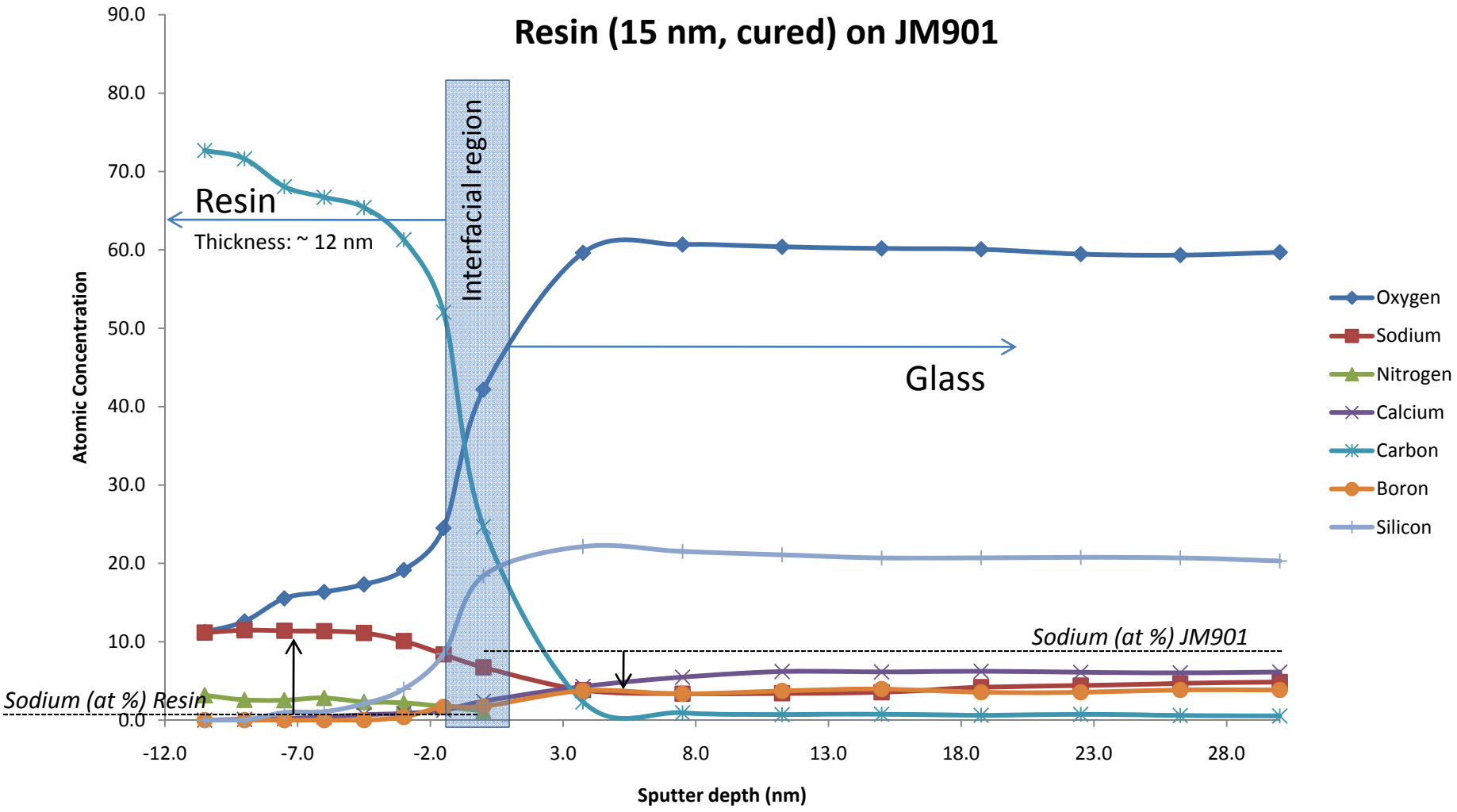




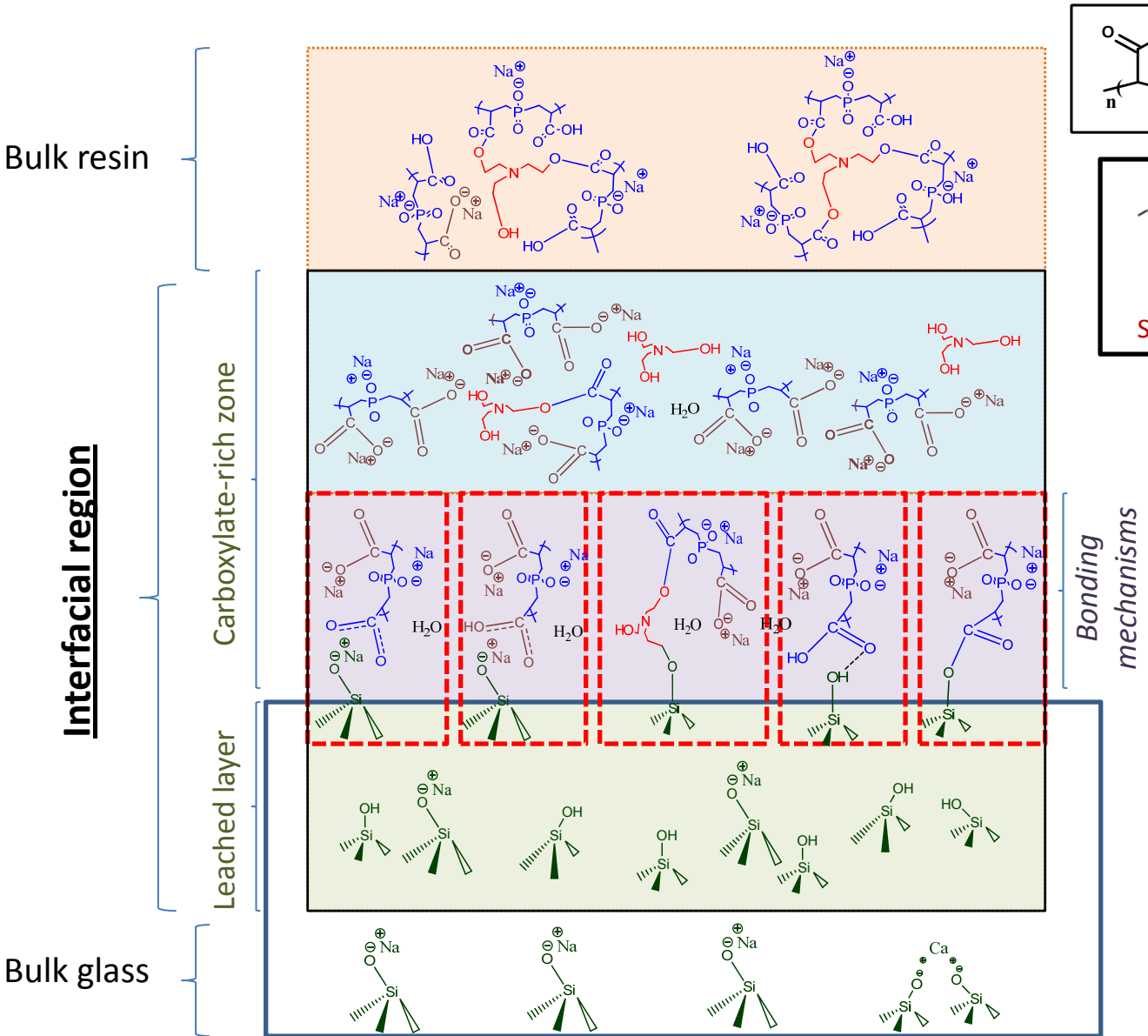
Higher intensity at acid/ester peak: cured 190C/1h

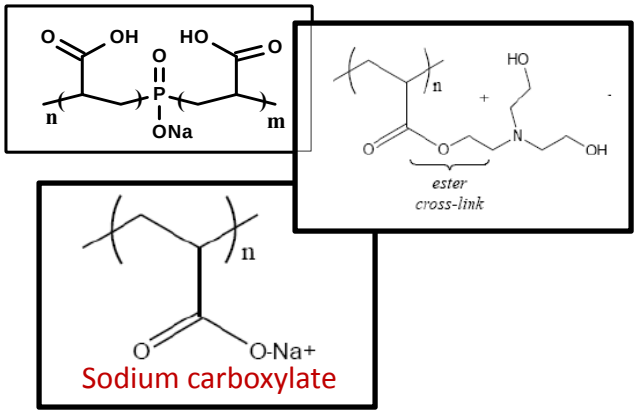
Lower intensity at acid/ester peak: dried 15h

Does sodium transfer from glass into the resin?



What is going on near the interface?





- The aqueous resin solution causes leaching of mobile cations such as calcium and sodium from the glass substrate into the thin film
- Leaching can lead to disruption of the resin cross-link network, and alter adhesion at the resin/glass interface due to formation of carboxylates

Our current interface model with proposed bonding sites