

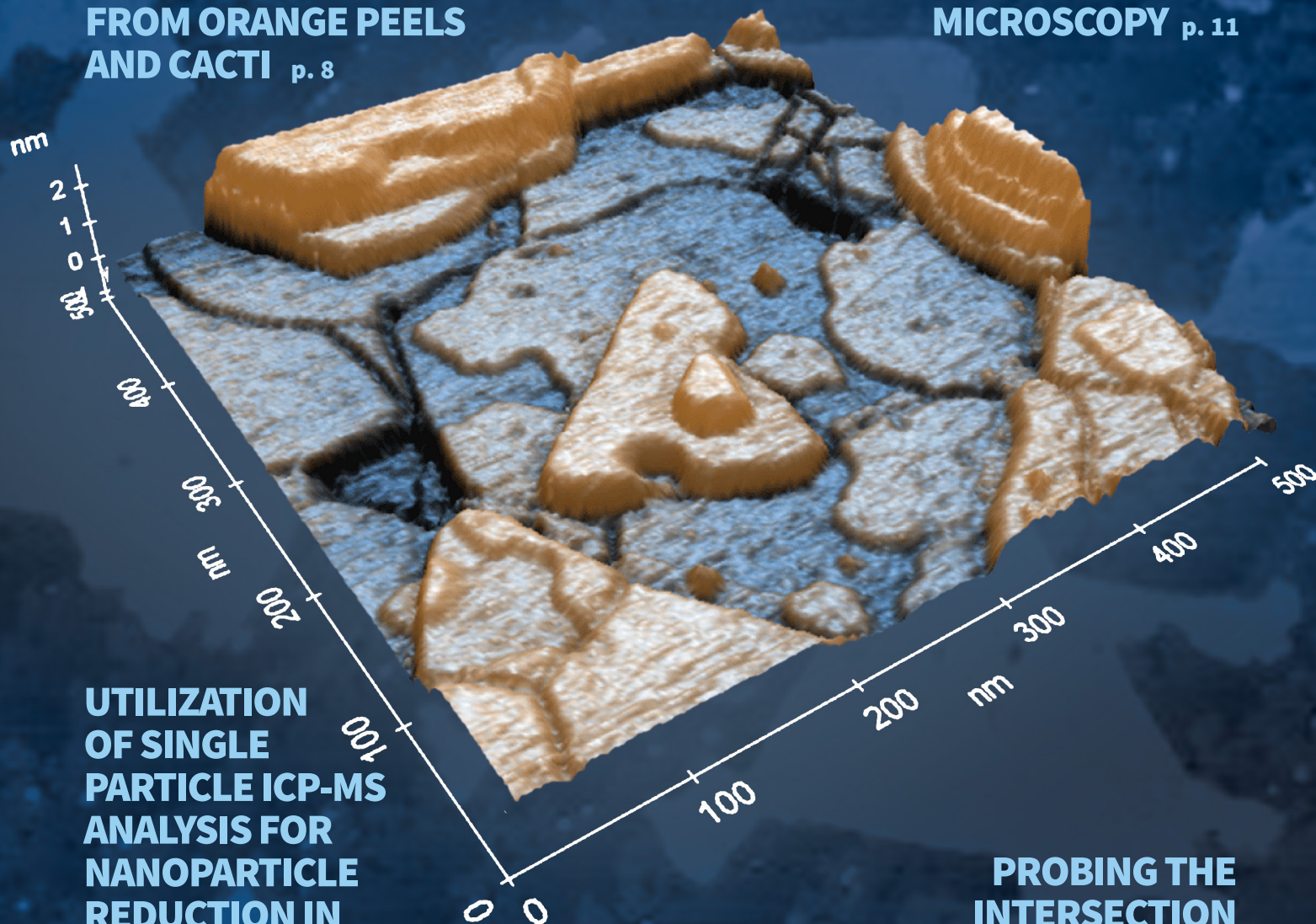
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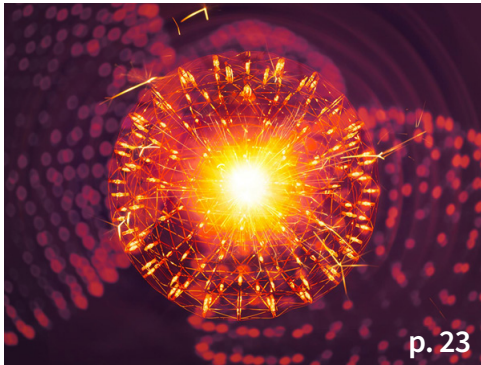
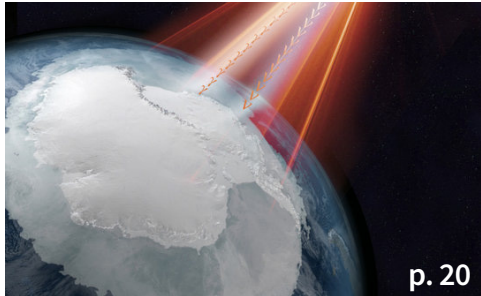
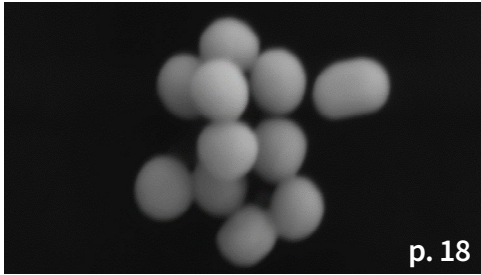
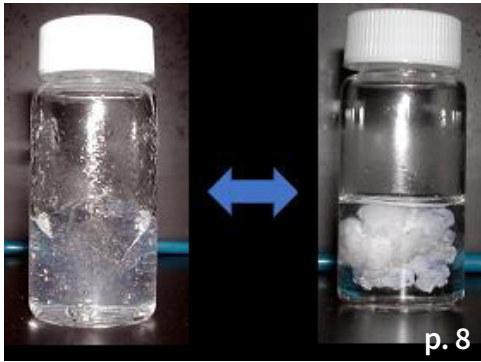


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MESSAGE FROM EDITOR

Welcome to our Summer Issue of NanoScientific.

With the start of summer, the natural world is buzzing with life. Baby birds are leaving the nest and you can spot colorful butterflies emerge from their chrysalis after just 10 to 14 days. The magnificence of biology in nature dumbfounds scientist to this day. Nanoscience technology can help put the puzzle pieces together of not just the biology we can see, but also the unknown actions of particles we have yet to image.

In this issue, we feature an article about OFI cactus who make pectin naturally that can teach us about responsive hydrogel coatings from Pectin Polysaccharides in research being done at the Department of Chemical and Biomedical Engineering, University of South Florida. This research explores pectin polysaccharides, complex and structurally diverse group of natural polymers that could lead towards replacing petroleum-based polymers with sustainable alternatives.

We also have an abstract from Prof. Cady, who obtained his Ph.D. in Microbiology and is currently a professor of nanobioscience in the College of Nanoscale Science at SUNY Polytechnic Institute, called “Probing the Intersection of Nanotechnology and Biology”.

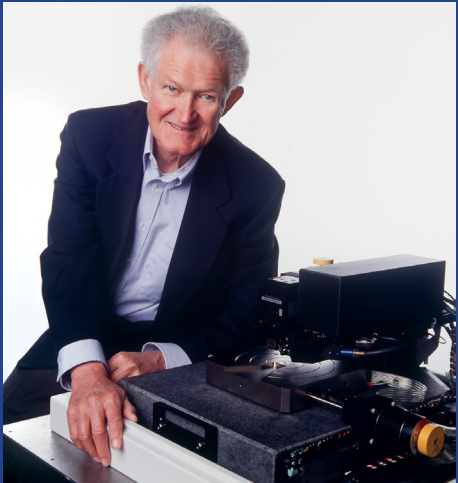
Dr. Cady will be presenting this entire lecture at the 2nd Annual NanoScientific Symposium at SUNY on Nov. 19, 2019.

This issue also offers an inside look into the next-generation underground neutrino detectors being built around the world and what they may tell us about the universe. We also share an article on ISO Standards being developed for Surface Chemistry Analysis and single particle inductively coupled plasma-mass spectrometry (SP ICP-MS). Our application note is focused on Hivac Advantages of High Vacuum for Electrical Scanning Probe Microscopy and in the column Materials Matter we examine Supramolecular Chemistry, Nanomachines, and AFM.

Lastly, we honor the legendary, Dr. Calvin Quate with a tribute from one of his colleagues, his contribution to nanoscience is far reaching and his love of science and new discoveries had a worldwide impact on so many and he was a true inspiration.

Keibock Lee
Editor-in-Chief

A TRIBUTE TO CALVIN F. QUATE (1923–2019)



Dr. Quate is best known for his role in co-developing the atomic force microscope (AFM) in the 1980’s with Gerd Binnig and Christoph Gerber, a pioneering nano metrology tool heralded as the milestone that led to decades of scientific advances and garnered them the Kavli Prize. The AFM established the ability to advance scientific research exponentially and his PhD student, Dr. Sang-il Park, who brought this unique tool to the public, still manufactures his innovative design today for scientists in fields ranging from semiconductor to life sciences.

My Memories of Dr. Quate

Franz J. Giessibl

It is impossible to forget the first time I met Calvin Forrest Quate. It happened at the Scanning Tunneling Microscopy conference at the University of Oxford in 1988, where a group of students from
(continued on page 6)



Franz J. Giessibl currently works at the Institute of Experimental and Applied Physics, University Regensburg where he does research in Condensed Matter Physics, Experimental Physics, Electronics and Mechanics.

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INSET PHOTO ON COVER:

Molybdenum disulfide (MoS₂) is two-dimensional (2D) layered material widely used for various research field both industry and academy for advanced semiconductor industry applications. The characterization and exploration of electrical and mechanical properties of 2D material are one of the most critical points in materials research field. The scanning probe microscope (SPM) allows to evaluate 2D materials in multidirectional viewpoints

using various imaging modes. High quality Scanning Tunneling Microscopy (STM) topography of a a multi-layer MoS₂ sample acquired in high vacuum without necessitating special sample prep/handling using Park NX-Hivac SPM is shown with high resolution visualization of islands and grain boundaries in the topography image.



Stanford University wore red sweatshirts that showed the face of a man in raster lines, with "the face of things to come" written on them.



I had just started to work on my PhD thesis with Gerd Binnig, who won the 1986 Nobel Prize in Physics together with Heini Rohrer for the invention of the scanning tunneling microscope (STM). STM was introduced at a time where personal computers and computer graphics were rudimentary at best. Accordingly, images were recorded trace by trace on chart recorders and a face was printed on the sweatshirts in that style. I wondered, "Who is this man, pictured on these shirts?" The face showed Calvin Forrest Quate, Edward Leland professor for Electrical Engineering and Applied Physics at Stanford University, born Dec 7, 1923. Professor Quate had been working on microwave technology and electron beam interactions at Bell Labs, and was a vice president and director of research at Sandia Labs before joining Stanford. At Stanford, he did pioneering work in microwave acoustics and introduced the acoustic microscope. At the age of almost sixty, he learned about vacuum tunneling and its potential use for microscopy on a flight to Europe. Professor Quate was on his way to a conference in London and extended his itinerary by a visit to the IBM Research Laboratory in Zurich to learn about scanning tunneling microscopy first hand⁽¹⁾. Calvin Quate ended his talk at the 1988 conference on STM discussing the many possibilities of scanning probe microscopy (SPM). I introduced myself and asked whether his ending about the perspective of SPM related to a magic chestful of endless possibilities, which he acknowledged with a witting smile.

He asked about the project I was working on, and immediately offered that I call him "Cal". After Binnig had applied for a patent for the atomic force microscope (AFM) in 1985, an extension of STM that should also be able to image insulators at very high resolution, Gerd Binnig, Calvin F. Quate and Christoph Gerber set out to build an AFM and published a seminal paper in Physical Review Letters⁽²⁾ about it. Cal realized that the cantilever of AFM that probes the forces between its tip and the sample was essential to the performance of the new microscope and set up a program to design micromachined cantilevers made from SiO₂, Si₃N₄ and later Si in the Stanford micromachining facilities. He supplied these cantilevers to our Munich IBM group that was started by Gerd Binnig and Christoph Gerber in 1987 where I became a member in 1988. After having obtained a PhD with Gerd, I joined Park Scientific Instruments (PSI), a company that was founded by Cal's former student Sang-il Park with Calvin Quate on the board of directors. While AFM at that time was mostly used in ambient conditions to image all types of samples on the nanometer scale, achieving atomic resolution in vacuum similar to STM was still not possible. My project at PSI was to design a room temperature UHV microscope that utilized the piezoresistive cantilevers that were invented in Cal's group. This microscope achieved atomic resolution on the reconstructed surface of Si(111)-(7x7), a feat that was important because atomic imaging of this surface by STM introduced this instrument into the toolbox of the thriving field of surface science. Cal frequently visited PSI - he had his way of looking deep into your eyes expressing his confidence in students and coworkers by gently saying, "you can do it".

He also supported me in publishing the successful imaging of Si(111)-(7x7) in Science in 1995. During a visit of Cal in my new affiliation at Jochen Mannharts chair at the University of Augsburg (Germany), Cal suggested to study graphite with our newly built low temperature AFM. Graphite was widely used in ambient STM and allowed even beginners to achieve atomic resolution easily, while exposing a few miracles such as giant corrugations and the appearance of only one of the two atoms per unit cell in the STM images. Cal was enthusiastically contributing to the

joint papers, writing in an email in 2006 "Wonderful stuff Franz. Thanks for including me. I have gotten a lot of mileage from the article by showing it to people who assumed that I was over the hill".

The engineer in Cal always loved applications - I remember I once met Cal on the weekend in Fry's Electronics, a large electronic outlet, where he was looking at the new gadgets that had made it from laboratory to market to be inspired by them and spur his imagination. The visionary in Cal was a man who looked for progress in many places. He hired students from all over the world and interacted intensively with physicists, engineers, chemists, mathematicians and computer scientists. In his spare time, he loved to hike in nature with his students.

Cal passed away in his home in Menlo Park on July 6 2019⁽³⁾. His love for science and engineering radiated to many of his students and coworkers, and his gentle and humble ways made it natural for them to return this respect and admiration. When the Kavli Prize for Nanoscience was awarded to Gerd Binnig, Christoph Gerber and Calvin Quate in 2016, about a dozen of his former students and associates joined the ceremony in Oslo - a quarter of a century after their graduation. Calvin Quate received multiple other honors, including the IEEE Medal of Honor, the United States National Medal of Science, the Joseph F. Keithley Award For Advances in Measurement Science and others and was a member of both the National Academy of Sciences and the National Academy of Engineering.

His former students became officers and researchers in large Silicon Valley corporations such as IBM, KLA-Tencor and others. One of his former students founded a leading AFM company, one managed the US research station on the South Pole, some others became professors at distinguished universities around the world.

Cal is deeply missed, but he left a rich legacy.

1. Vacuum Tunneling: A New Technique for Microscopy, Calvin F. Quate, Physics Today 39(8), 26 (1986); <https://doi.org/10.1063/1.881071>
2. Atomic Force Microscope, G. Binnig, C.F. Quate, Ch. Gerber, Phys. Rev. Lett. 56, 930 (1986).
3. Calvin F. Quate, inventor of advanced microscopes, dies at 95, Andrew Myers, <https://news.stanford.edu/2019/07/10/calvin-f-quate-inventor-advanced-microscopes-dies-95/>
4. Photo by Thomas Albrecht, linescan rendering by Sang-il Park.



ISO FOR SURFACE CHEMICAL ANALYSIS USING SCANNING PROBE MICROSCOPY

DR. KEN NAKAJIMA PROFESSOR IN THE SCHOOL OF MATERIALS AND CHEMICAL TECHNOLOGY, TOKYO INSTITUTE OF TECHNOLOGY

The Nakajima Laboratory's expertise is polymer nanomechanics, in other words, investigating nano-scale structures and properties of polymeric materials, by which it connects knowledge in nano to macroscopic world. "No swallow written in textbooks" is our motto. The lab is currently involved in several national projects such as CAO SIP, CAO ImPACT, JST CREST.

At Tokyo Institute of Technology, Dr. Ken Nakajima is working with other institutions to create a new ISO Standard for using SPM for surface chemical analysis. This ISO is important to the rubber tire industry, where Dr. Nakajima works closely with all the leading manufacturers. He has pioneered methods for Nanorheological Mapping of Rubbers by AFM and AFM-based Nanomechanics rubber-filled interfaces. "We need to know the distribution and intervention of nanometer particles," comments Dr. Nakajima. "These properties can only be measured using AFM."

The importance of mechanical property mapping is evident by the top five tire manufacturers who work with Dr. Nakajima's group at the Dept. of Chemical Science and Engineering at the University of Tokyo.

The new ISO Standardization will have a significant impact on the rubber tire and other industries as they look at the value-added proposition and standards for integrating nanoparticles into their products. The tire industry specifically is very interested in the interfacial region because engineers know that the interface of the nanoparticles and rubber is important.

An example for the tire industry is to add carbon nanoparticles for durability and then measure the nanometer particles distribution and intervention. "Industry executives need qualitative measurements," adds Dr. Nakajima. His group consults and corroborates with industry and many of his students find industry jobs when they leave academics.

Dr. Nakajima works with many AFM manufacturers and sees a solution offered by every manufacturer based on that company's product and strengths. When specifically asked about Park Systems AFM, he replied, "Park Systems big advantage is in measurement accuracy because their AFM's biggest feature is having an accurate piezoelectric XY scanner, Park's XY scanner is wonderful and they are also strong in the semiconductor industry."

Summary of the ISO currently underway
ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

Surface chemical analysis
Scanning probe microscopy — Procedure for the determination of elastic moduli for compliant materials using atomic force microscope and the two-point JKR method.

Scope: This international standard describes a procedure for the determination of elastic modulus for compliant materials using atomic force microscope (AFM). Force-distance curves on the surface of compliant materials are measured and the analysis uses a two-point method based on Johnson-Kendall Roberts (JKR) theory[1,2]. This International Standard is applicable to the compliant materials of elastic moduli ranging from 100 kPa to 1 GPa. The spatial resolution is dependent on the contact radius between an AFM probe and the surface and is typically 10 nm.

Atomic force microscope (AFM) is a family of scanning probe microscope (SPM) used to image surfaces by mechanically scanning a probe over the surface. In AFM, a surface force is monitored as the deflection of a compliant cantilever, which has a probe at its free end in order to interact with surfaces. AFM can provide amongst other data: topographic, mechanical and chemical information about a surface depending on the mode of operation and the property of the probe tip. Accurate force measurements and sample deformation measurements are needed for a wide variety of applications, especially to determine the elastic moduli of compliant materials such as organics and polymers at surfaces. For quantitative force measurements, the adequate selection of contact mechanics used in calculating the elastic modulus and the appropriate calculation procedure are required. This International Standard describes a procedure for the determination of elastic moduli for compliant materials using AFM. Force-distance curves measured on the surfaces of compliant materials are used for the calculation based on Johnson-Kendall-Roberts (JKR) two-point method.

RESPONSIVE HYDROGEL COATINGS FROM PECTIN POLYSACCHARIDES EXTRACTED FROM ORANGE PEELS AND CACTI



Figure 1. Collapse of Poly(NIPAAm) hydrogel as temperature is increased above 32 °C

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Hydrogel coatings are a class of tethered or spatially-confined polymers capable of absorbing significant amounts of water. They are further divided into so-called stimuli-responsive hydrogels, which are materials that imbibe or expel water on demand allowing in situ control of properties and the capacity to generate work. The “stimuli-responsive” designation originates from the ability of the hydrogel to sense its physical and chemical environment, process data, and respond, often with strong amplification of the input signal. Thin films of stimuli-responsive polymers have been demonstrated in technologies that benefit from reversible modulation of surface properties, including drug delivery, separations, tissue cultures, and chromatography.¹⁻⁴

Most commonly, such stimuli-responsive hydrogels are derived from petroleum-based monomers that undergo changes in solubility with either pH or temperature. Poly(N-isopropylacrylamide), or poly(NIPAAm), is a well-known lower critical solution temperature (LCST) polymer that experiences a sharp phase transition when subjected to small perturbations in external stimuli.

For example, as shown in Figure 1, hydrogels of poly(NIPAAm) in water undergo a hydrophilic/hydrophobic transition at roughly 32°C.⁵⁻⁶

These types of polymers typically comprise moieties that have both hydrophobic and hydrophilic character, such that a small change in the environmental conditions cause a change in the balance between these two characters, either favoring the swollen “hydrophilic” state or the collapsed “hydrophobic” state. At low temperatures, solubility of the macromolecule is engendered through favorable mixing of the hydrophilic moieties and water. As temperature is increased, a point is reached where mixing can no longer stabilize hydrophobic interactions and the polymer phase-separates from solution, leading to a strong collapse in the volume of the hydrogel.

With a growing demand towards replacing petroleum-based polymers with sustainable alternatives, we have explored pectin polysaccharides to mimic such properties. Pectin polysaccharides are a complex and structurally diverse group of natural polymers that possess hydrophilic and hydrophobic functionality, which could have significant potential as

stimuli-sensitive hydrogels. Pectin is a heteropolysaccharide extracted from cell walls and intercellular regions of plants or their fruits (such as cactus mucilage or orange peels⁷⁻⁹) functioning as the hydrating component of the cellulosic network.¹⁰⁻¹¹ In general, the structure is mostly composed of D-galacturonic acid residues linked by α -1,4-glycosidic bonds, which are often interrupted with different sugars such as rhamnose, arabinans, galactose, xylose, etc. The carboxyl group associated with the D-galacturonic acid residue exists in two primary forms: The carboxylate salt and the neutral ester form.¹²⁻¹⁵ Depending on the pectin source and extraction technique, pectins can either have a low esterified content (LE, <50 % esterification) or high esterified content (HE, >50% esterification). This opens up non-synthetic routes to tune the response of the pectin coatings based solely on the source and method of extraction.

To illustrate this point, pectin was extracted from two sources: orange peels and *Opuntia ficus-indica* (OFI) cacti. The OFI cactus (commonly referred to as Nopal or prickly pear) is grown in semi-arid and arid regions as a food source.

The pectin polysaccharides extracted from both orange peels and OFI cacti have a high molecular weight and are capable of holding high volumes of water within the polysaccharide matrices, rendering hydrogels with a multitude of applications. However, the pectin from the orange peels is highly esterified with a degree of esterification near 70%, whereas the pectin from OFI cactus has a much lower degree of esterification (near 25 %).

Coatings of each type of pectin polysaccharide were fabricated by first spin-coating the pectin solution onto a solid surface followed by exposure to a calcium chloride (CaCl_2)/ethanol solution. Ethanol, a poor solvent for pectin, prevents dissolution of the coating while simultaneously allowing CaCl_2 diffusion in order to establish Ca^{2+} bridges between carboxyl groups to cross-link the pectin coating. The underlying mechanism is understood by the well-known ‘egg-box’ model, which describes the formation of networks through associations between Ca^{2+} and acidic regions of the pectin.¹⁶⁻¹⁹

Figure 2(a) shows a schematic of the cross-linked pectin coating and chemical composition. Figure 2(b) shows the attenuated total reflection Fourier transform infrared spectroscopy (ATR-FTIR) spectra of the two types of pectin coatings (extracted from the orange peels and OFI cactus). The two most relevant peaks with respect to the degree of esterification are centered at approximately 1610 cm^{-1} (corresponding to the carboxylate, or $-\text{COO}^-$ vibration of the non-esterified galacturonic acid residues) and 1740 cm^{-1} (corresponding to the carboxyl-ester, $-\text{COOR}$, vibration of the esterified galacturonic acid residues). The bands associated with the esterified residues in OFI cactus pectin are less distinct than the orange peel pectin indicating a lower degree of esterification. The resultant swelling profiles for 100 nm thick films are shown in Figure 2(c). The degree of swelling is defined as the swollen thickness divided by the dry thickness. Interestingly, both types of pectin have a prominent deswelling transition as temperature is increased above 30 °C, which we have shown to be driven by the dehydration of the

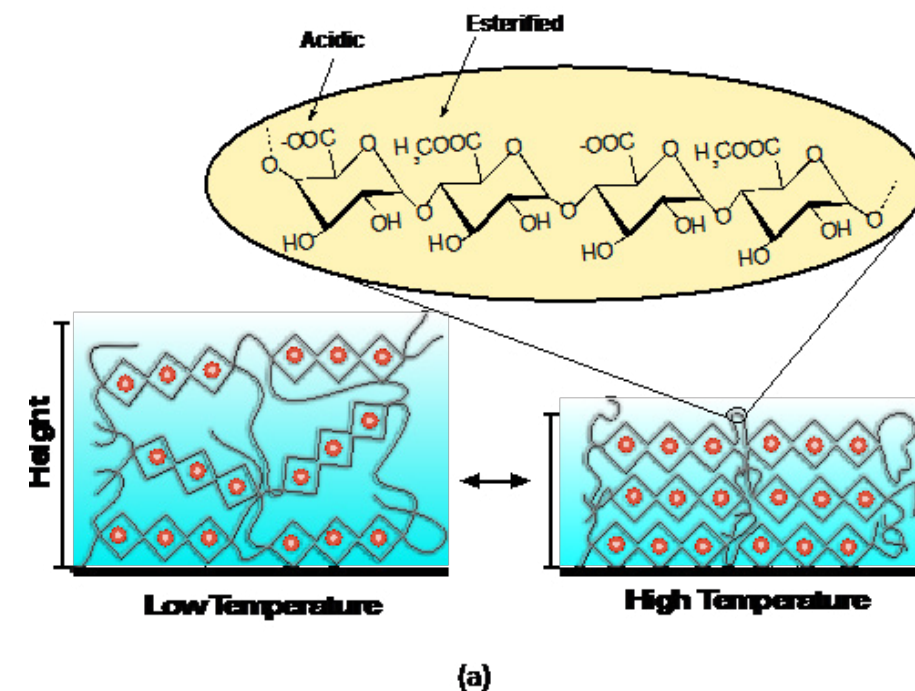
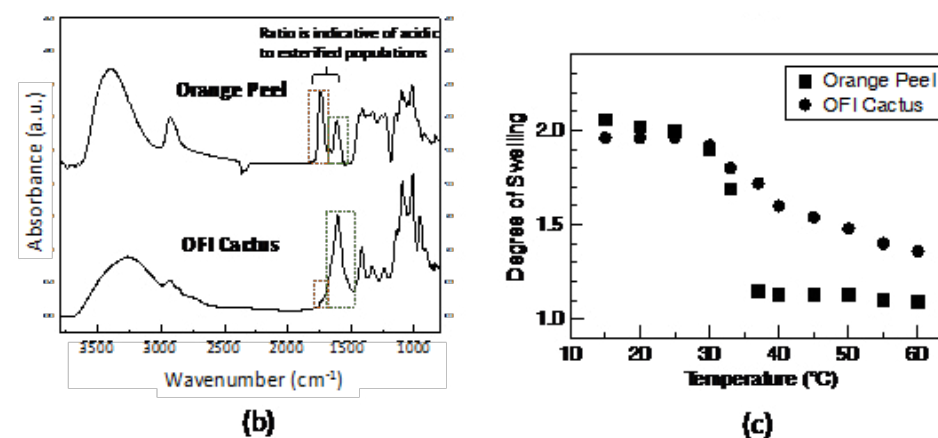


Figure 2. (a) Schematic of the cross-linked pectin coating; (b) ATR-FTIR spectra of the pectin coatings based on orange peels and OFI Cactus; (c) Swelling profiles of the pectin coatings as a function of temperature.



esterified galacturonic acid residues.²⁰ The transition is stronger in the orange peel pectin due to the higher degree of esterification, providing a mechanism to tune the transition depending solely on degree of esterification.

As a demonstration of the thermal response of the pectin coatings, Figure 3 shows the ability of the orange peel pectin coating to culture and release NIH3T3 mouse embryonic fibroblast cells. When cultured at 37 °C, the coating is collapsed providing an adhesive surface for cells to attach and spread. Upon lowering the culture temperature to 20 °C, the coating

swells and releases the attached cells. After 60 min of incubation at 20 °C, the majority of the cells are detached from the coating.

In conclusion, pectin extracted from natural sources shows promise as responsive hydrogel coatings, which has the potential to replace petroleum-derived materials. The degree of esterification furthermore allows control over the response, which opens up avenues to control properties of the coating solely through the source and type of extraction process without having to resort to additional synthesis.

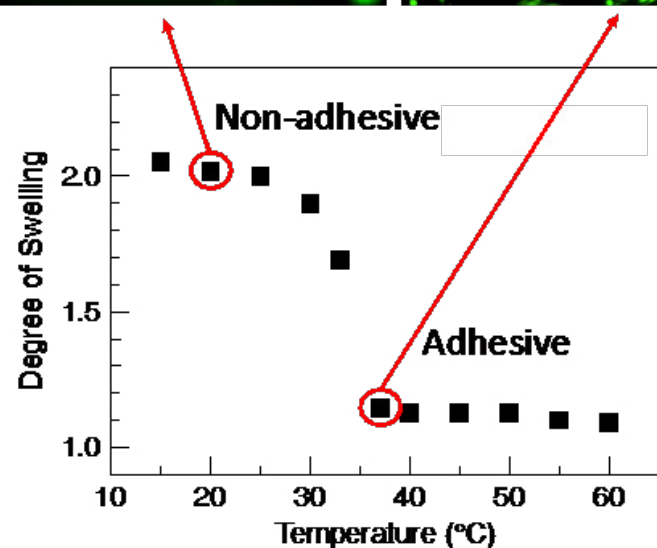
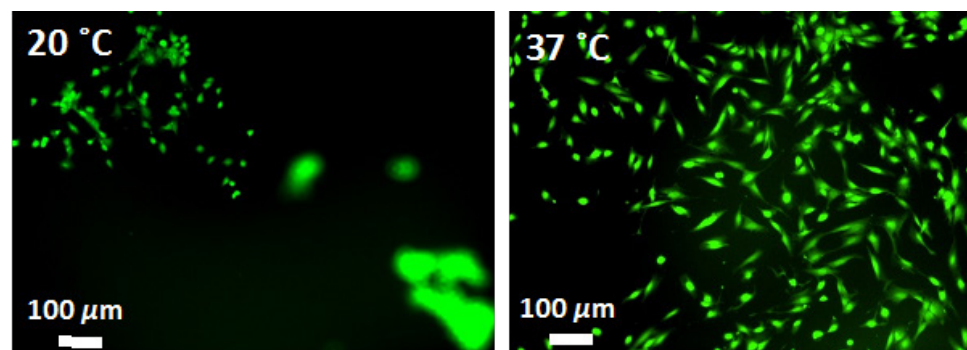


Figure 3. A pectin coating is adhesive to cells in the collapsed state (37 °C) and repulsive to cells in the swollen state (20 °C), functioning as an on-off tissue culture platform.

References

- (1) Hoffman, A. S., Environmentally Sensitive Polymers and Hydrogels - Smart Biomaterials. Mrs Bull 1991,16, 42-46.
- (2) Huber, D. L.; Manginell, R. P.; Samara, M. A.; Kim, B. I.; Bunker, B. C., Programmed Adsorption and Release of Proteins in a Microfluidic Device. Science 2003,301, 352-354.
- (3) Kikuchi, A.; Okano, T., Intelligent Thermoresponsive Polymeric Stationary Phases for Aqueous Chromatography of Biological Compounds. Progress In Polymer Science 2002,27, 1165.
- (4) Kushida, A.; Yamato, M.; Konno, C.; Kikuchi, A.; Sakurai, Y.; Okano, T., Decrease in Culture Temperature Releases Monolayer Endothelial Cell Sheets Together with Deposited Fibronectin Matrix from Temperature-Responsive Culture Surfaces. Journal of Biomedical Materials Research 1999,45, 355-362.
- (5) Schild, H. G., Poly (N-Isopropylacrylamide) - Experiment, Theory and Application. Progress in Polymer Science 1992,17, 163-249.
- (6) Shibayama, M.; Tanaka, T., Volume Phase-Transition and Related Phenomena of Polymer Gels. Adv Polym Sci 1993,109, 1-62.
- (7) Voragen, A. G.; Coenen, G.-J.; Verhoef, R. P.; Schols, H. A., Pectin, a Versatile Polysaccharide Present in Plant Cell Walls. Structural Chemistry 2009,20, 263.
- (8) Goycoolea, F. M.; Cárdenas, A., Pectins from Opuntia Spp.: A Short Review. Journal of the Professional Association for Cactus Development 2003,5, 17-29.
- (9) Maran, J. P.; Sivakumar, V.; Thirugnanasambandham, K.; Sridhar, R., Optimization of Microwave Assisted Extraction of Pectin from Orange Peel. Carbohydrate polymers 2013,97, 703-709.

(10) Thakur, B. R.; Singh, R. K.; Handa, A. K.; Rao, M., Chemistry and Uses of Pectin—a Review. Critical Reviews in Food Science & Nutrition 1997,37, 47-73.

(11) Burton, R. A.; Gidley, M. J.; Fincher, G. B., Heterogeneity in the Chemistry, Structure and Function of Plant Cell Walls. Nature Chemical Biology 2010,6, 724-732.

(12) Ridley, B. L.; O'Neill, M. A.; Mohnen, D., Pectins: Structure, Biosynthesis, and Oligogalacturonide-Related Signaling. Phytochemistry 2001,57, 929-967.

(13) Willats, W. G.; Knox, J. P.; Mikkelsen, J. D., Pectin: New Insights into an Old Polymer Are Starting to Gel. Trends in Food Science & Technology 2006,17, 97-104.

(14) Yapo, B. M., Pectic Substances: From Simple Pectic Polysaccharides to Complex Pectins—a New Hypothetical Model. Carbohydrate Polymers 2011,86, 373-385.

(15) Mohnen, D., Pectin Structure and Biosynthesis. Current opinion in plant biology 2008,11, 266-277.

(16) Powell, D.; Morris, E.; Gidley, M.; Rees, D., Conformations and Interactions of Pectins: Ii. Influence of Residue Sequence on Chain Association in Calcium Pectate Gels. Journal of molecular biology 1982,155, 517-531.

(17) Walkinshaw, M.; Arnott, S., Conformations and Interactions of Pectins: Ii. Models for Junction Zones in Pectinic Acid and Calcium Pectate Gels. Journal of Molecular Biology 1981,153, 1075-1085.

(18) Axelos, M.; Thibault, J., The Chemistry of Low-Methoxyl Pectin Gelation. The chemistry and technology of pectin 1991,6, 109-108.

(19) Grant, G. T.; Morris, E. R.; Rees, D. A.; Smith, P. J.; Thom, D., Biological Interactions between Polysaccharides and Divalent Cations: The Egg-Box Model. FEBS letters 1973,32, 195-198.

(20) Veisi, Z.; Gallant, N. D.; Alcantar, N. A.; Toomey, R. G., Responsive Coatings from Naturally Occurring Pectin Polysaccharides. Colloid Surface B 2019,176, 387-393.

APPLICATION NOTE

ADVANTAGES OF HIGH VACUUM FOR ELECTRICAL SCANNING PROBE MICROSCOPY

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Introduction

The discovery of graphene as the prototype of a new class of materials in 2004 has led to an enormous scientific interest in two-dimensional (2D) layered materials.¹ Since then, a wide variety of 2D materials have been synthesized and explored.²⁻⁶ Among them, the family of transition metal dichalcogenides (TMDs) has attracted specific interest from the semiconductor industry owing to an inherent band gap, a small dielectric constant, high mobilities, and ultrathin materials, which are heralded as promising candidates for scaling logic technology beyond the 5nm node. However, the integration of such materials in a 300mm compatible manufacturing environment still faces many challenges. As the praised properties have mostly been observed very locally, in flakes or single grains, the controlled growth, transfer and processing of high quality TMD layers remain a key hurdle.

Scanning probe microscopy, as an inherent high resolution 2D technique, is a powerful enabler for investigating the morphological and electrical properties of TMDs. In this technical note, we will illustrate the advantages of high vacuum for electrical measurements utilizing the capabilities of the Park NX-Hivacatomic force microscopy system (Park Systems) using MoS₂ as an example material.

Investigation: Material and Methods MoS₂

A series of MoS₂ samples with varying layer thickness were grown by metal organic chemical vapor deposition (MO-CVD) on sapphire substrates.

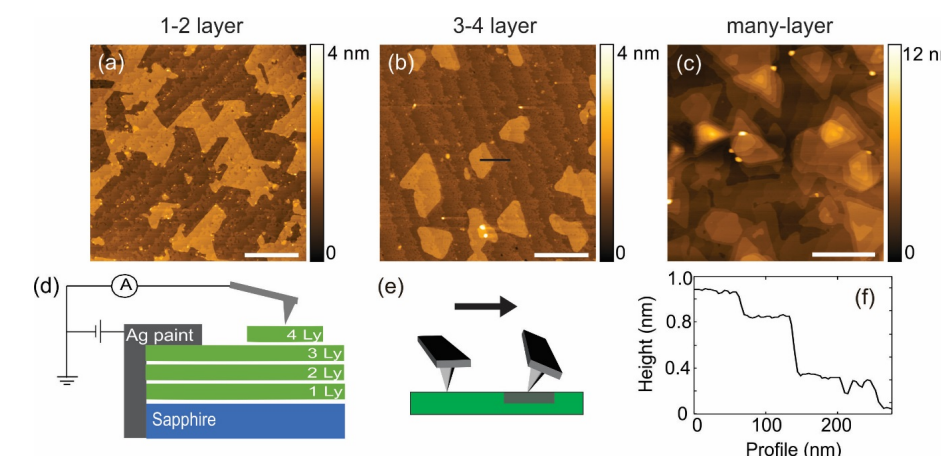


Figure 1: (a-c) AFM topography images of the samples studied. (d) Schematic of C-AFM setup used to measure multilayer MoS₂ on a sapphire. (e) Cartoon showing how the cantilever twists as it scans over a high friction region. (f) Cross section of topography corresponding to black line in (b) showing 0.6nm step at the MoS₂ island edge and 0.2nm step at the sapphire terrace. All images are plotted in Gwyddion. Scale bar is 500nm.

All measurements are performed on the as-grown, un-transferred MoS₂/sapphire. The room temperature mobility for devices made from the same material are found to be up to $\mu\text{m} \sim 30 \text{ cm}^2/\text{Vs}$, with higher average mobilities for thicker samples.¹²

Atomic force microscopy (AFM) images of all the samples measured are shown in figure 1. In total, three samples were measured with layer thicknesses of 1-2 layers, 3-4 layers, and one with pyramid structures, referred to here as multi-layered MoS₂. The 1-2 layer sample consists of a completely closed monolayer MoS₂ film with additional monolayer islands forming on top. These monolayer islands constitute the beginning of the growth of the second layer and can be identified as the light-colored regions in the topography image. Similarly, the 3-4 layer sample consists of a completely closed tri-layer MoS₂ film with additional monolayer islands.

An example of the sample structure for the 3-4 layer sample is shown in figure 1(d). Here, each green layer represents one layer of MoS₂. In addition to MoS₂ islands, we also see diagonal lines running across each sample. These are terraces from the sapphire substrate, which can be seen through the 2D film. The sapphire terraces can be unambiguously distinguished from MoS₂ layers by the step height, 0.2nm for c-plane sapphires. 0.6nm for a monolayer MoS₂ step, as can be seen from the cross section in figure 1 (f).^{13,14} The multi-layer sample differs from the other two in that the MoS₂ surface is characterized by 3D pyramid-like structures. These pyramids sit on a completely closed tri-layer, and their formation is due to a change in the growth mechanism from layer-by-layer to 3D with increasing layer thickness. Details of the growth can be found in ref.12.

Conducting Scanning Probe Microscopy

Here we employ two conducting scanning probe microscopy (SPM) techniques to characterize the electronic properties of MoS₂: Conductive Atomic Force Microscopy (C-AFM) and Scanning Tunneling Microscopy (STM). In C-AFM, the cantilever is in contact with the surface of the material and we simultaneously record topography and current. To measure the electrical current, a bias is applied to the sample chuck and current is measured by an external current amplifier connected to a conducting AFM probe. Electrical contact to the material is made by applying silver paint to the top and sides of the material. We use commercially available Pt-Ir coated probes, such as PPP-CONTSCPT or PPP-NCSTPt, with nominal spring constants in the range of 0.2 to 7 N/m. Since C-AFM is a contact-based AFM technique, it also allows the lateral force to be recorded along with the other C-AFM channels. Lateral force microscopy (LFM) measures the lateral deflection of the laser on the PSD due to torsion, or twisting, of the cantilever as it scans across the surface, as depicted in figure 1(e). The difference between the forward and reverse LFM images is proportional to the friction of the material and differs from C-AFM in that a conductive wire, cut Pt-Ir in our case, is used to measure the tunneling current between the probe and the sample when the probe is a few angstroms above the surface. STM can be performed by either keeping the height constant and recording the current (referred to as constant height mode) or using the feedback to keep the current level constant and recording the height (constant current mode). In constant current mode, the height image contains both topographic and electronic information.

C-AFM in Air vs High Vacuum

In order to demonstrate the importance of the water layer on the surface on 2D materials, we performed C-AFM on the same MoS₂ sample in air and high vacuum (HV), figure 2 (a-b) and (c-d), respectively. While the topography images for the scan in air and HV are quite similar, the C-AFM images differ considerably. Most notably, the measured current increases by three

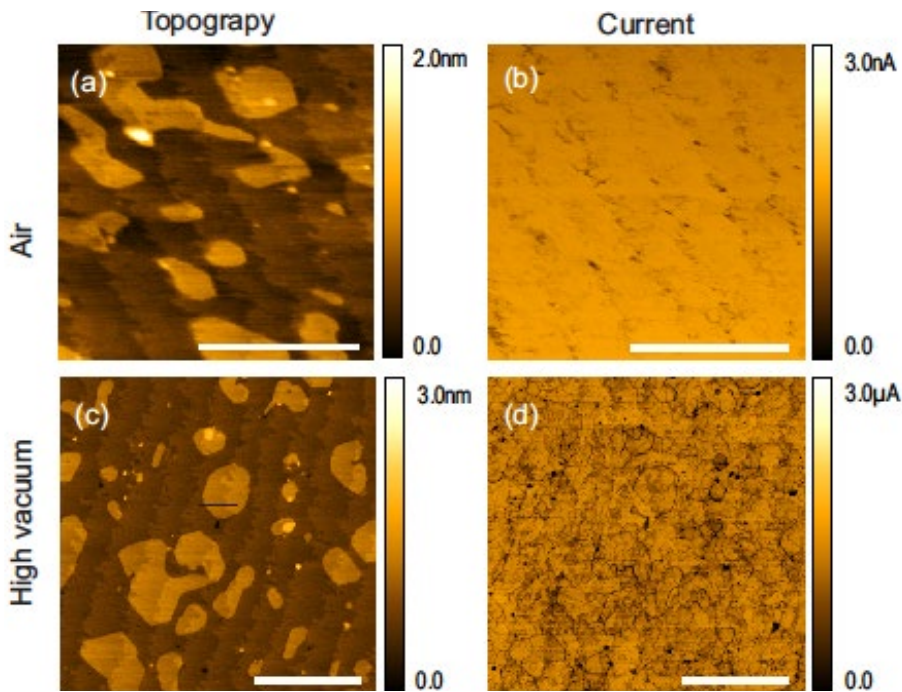


Figure 2: C-AFM from the same 3-4 MoS₂ sample showing the increased current level and sensitivity under high vacuum. (a) Topography and (b) current images in air at 5V bias. (c) Topography and (d) current images taken immediately after pumping to high vacuum at 0.5V bias. The data taken in air and high vacuum was acquired using identical parameters: same probe with spring constant k of 7N/m, set point of 10nN, and 1Hz scan rate. Scale bar is 500nm.

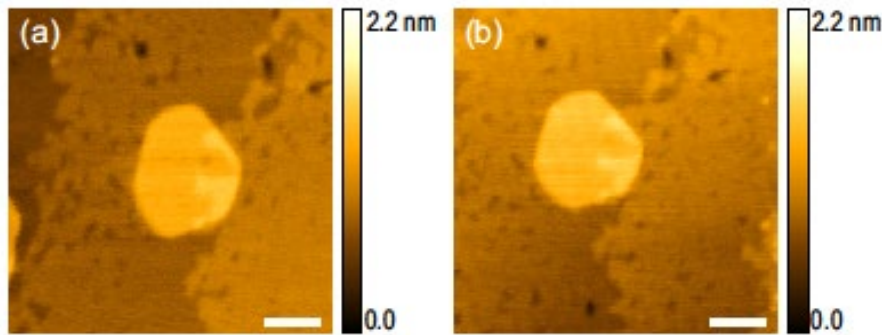


Figure 3: Topography image of a 3-4 layer MoS₂ (a) initially and (b) after 5 successive scans at 0.1V set point using a PPP-NCSTPt probe with spring constant of ~7N/m. Scale bar is 50nm.

orders of magnitude in HV. The average current level in air is 1.4nA at 5V bias, while in HV it is 1.1μA. The increase in current level is due to the removal of the thin water layer that is always present on the surface of the sample in air. This water layer is particularly problematic for MoS₂ as it p-dopes the material, effectively turning it off electrically. From electrical transport of similar CVD grown MoS₂ devices, the on state current is severely degraded and mobility decreases by 40% after exposure to DI water for two hours.¹⁵

Besides just an increase in current, the C-AFM image in HV shows much more

detail. From the image in air, it appears that current is relatively homogeneous. Other than the current level, not much information can be extracted for the C-AFM in air on this sample. From the current map taken in HV, in contrast, we can clearly see the grain boundaries in the MoS₂ layers.

Despite the fact that the C-AFM probe is in direct contact with the material, the low force applied results in no removal of MoS₂ material over the repeated scans. Figure 3 shows the topography image from the same sample after 5 scans in HV at ~30nN force with a probe with nominal spring constant at ~7N/m.

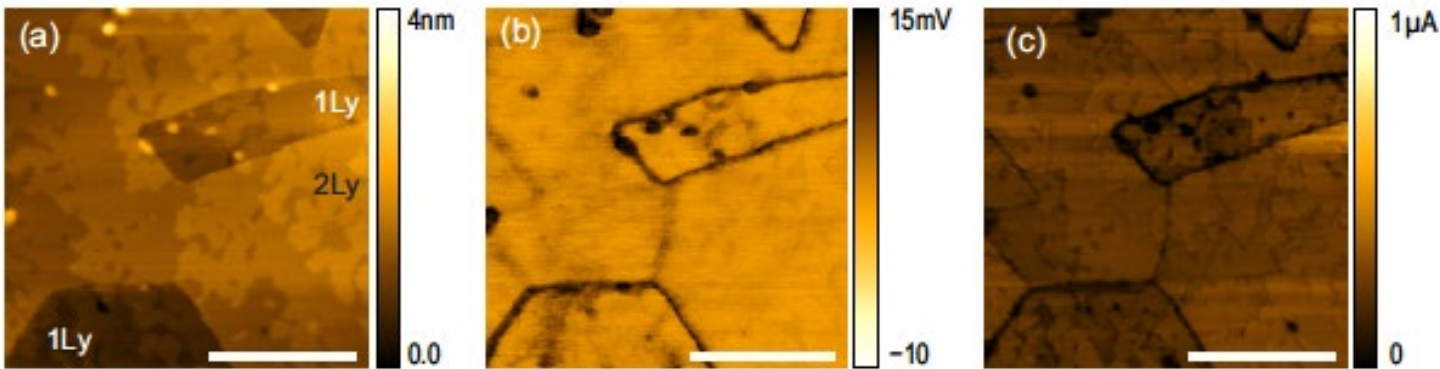


Figure 4: (a) Topography, (b) Friction, and (c) current acquired simultaneously on an 1-2 layer as-grown MoS₂/sapphire sample. The layer thickness of each region is indicated in (a). Scale bar is 200nm.

C-AFM + LFM for Grain Boundary Analysis

When imaging with a low spring constant probe, such as PPP-CONTSCPT with nominal spring constant of 0.2N/m, we can acquire frictional data simultaneously with C-AFM, allowing for correlation between topographic, electrical, and material properties. Figure 3 shows the height, friction, and current images from a 1-2 layer MoS₂ sample. The 1st layer and 2nd layer regions are labeled as 1Ly and 2Ly, respectively, in figure 3(a). The friction at grain boundaries is higher than the pristine regions, so that they show up as dark lines in the friction. By comparing the current and friction, we can see that the dark lines in the friction image match the dark lines in the current. However, the current image shows additional features due to the influence of the substrate on the local conductivity of the 2D film.

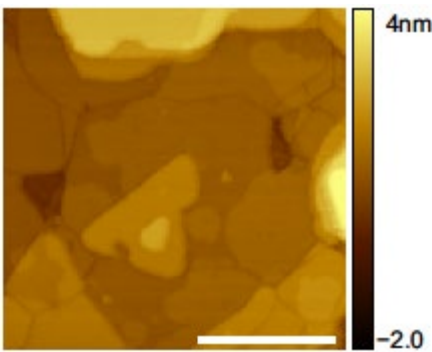


Figure 5: STM image of multilayer MoS₂/sapphire. Cut Pt-Ir wire in constant current mode. I_{set} =0.5nA, V_{bias} =1V. Scale bar is 200nm.

Scanning Tunneling Microscopy on MoS₂

With the ParkNX-Hivac, we were able to also acquire high quality STM images without the need for complicated UHV

systems and special sample prep/handling. Figure 4 shows a 500nm scan of the multi-layer MoS₂ sample imaged in constant current mode, with I_{set} =0.5nA and V_{bias} =1V. Since STM gives a convolution of topography with electronic structure, we see both islands and grain boundaries in the height image.

Conclusion

In this study, molybdenum disulfide (MoS₂), one of the highly interesting 2D materials of transition metal dichalcogenides (TMDs) family, was investigated on morphological and electrical aspects using Park NX-Hivac AFM (Park Systems). The differences between single and multi-layer was observed on AFM topography images. Furthermore, the details of 3D pyramid-like structures due to layer-by-layer growth mechanism was determined at multi-layer image.

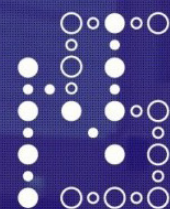
Using conducting SPM (C-AFM and STM), electrical properties of MoS₂ were studied both in ambient and high vacuum (HV) condition. Despite the presence of oxide layer, clear, homogeneous and higher current signal was measured while in HV condition. Lastly, topographical, electrical, and mechanical information were obtained for grain boundary analysis using combination of C-AFM and LFM. This approach allowed the finding of more specific and detailed structures on grain boundary.

2D layered material is widely used for various research field both industry and academy. The characterization and exploration of electrical and mechanical properties of 2D material are one of the most critical points in materials research field. The atomic force microscope, a

versatile imaging and measurement tool, allows us to evaluate 2D materials in multidirectional viewpoints using various imaging modes. This study underlines the improving strategy of material analysis. Moreover, these results emphasize the importance of multidirectional and multichannel analysis on 2D materials, including the transition metal dichalcogenides that are of high interest by the semiconductor industry.

References

1. K. S. Novoselov, A. Geim, S. V. Morozov, D. Jiang, Y. Zhang, S. V. Dubonos, I. V. Grigorieva, & A. A. Firsov. Electric field effect in atomically thin carbon films. *Science* 306, 666–669 (2004).
2. A. K. Geim & I. V. Grigorieva. Van der Waals heterostructures. *Nature* 499, 419–425 (2013).
3. K. F. Mak, C. Lee, J. Hone, J. Shan, & T. F. Heinz. Atomically Thin MoS₂: A New Direct-Gap Semiconductor. *Phys Rev Lett* 105, 136805 (2010).
4. H. Liu, A. T. Neal, Z. Zhu, Z. Luo, X. Xu, D. Tománek, & P. D. Ye. Phosphorene: an unexplored 2D semiconductor with a high hole mobility. *ACS Nano* 8, 4033–4041 (2014).
5. J. Zhao, H. Liu, Z. Yu, R. Quhe, S. Zhou, Y. Wang, C. C. Liu, H. Zhong, N. Han, J. Lu, Y. Yao, & K. Wu. Rise of silicene: A competitive 2D material. *Prog Mater Sci* 83, 24–151 (2016).
6. C. R. Dean, A. F. Young, I. Meric, C. Lee, L. Wang, S. Sorgenfrei, K. Watanabe, T. Taniguchi, P. Kim, K. L. Shepard, & J. Hone. Boron nitride substrates for high-quality graphene electronics. *Nat Nanotechnol* 5, 722–726 (2010).
7. X. Xu, W. Yao, D. Xiao, & T. F. Heinz. Spin and pseudospins in layered transition metal dichalcogenides. *Nat. Phys.* 10, 343–350 (2014).
8. G. Fiori, F. Bonaccorso, G. Iannaccone, T. Palacios, D. Neumaier, A. Seabaugh, S. K. Banerjee, & L. Colombo. Electronics based on two-dimensional materials. *Nat Nanotechnol* 9, 768–779 (2014).
9. X. Xi, L. Zhao, Z. Wang, H. Berger, L. Forró, J. Shan, & K. F. Mak. Strongly enhanced charge-density-wave order in monolayer NbSe₂. *Nat. Nanotechnol.* 10, 765–769 (2015).
10. S. Manzeli, D. Ovchinnikov, D. Pasquier, O. V. Yazyev, & A. Kis. 2D transition metal dichalcogenides. *Nat. Rev. Mater.* 2, 17033 (2017).
11. W. Choi, N. Choudhary, G. H. Han, J. Park, D. Akinwande, & Y. H. Lee. Recent development of two-dimensional transition metal dichalcogenides and their applications. *Mater. Today* 20, 116–130 (2017).
12. D. Chiappe, J. Ludwig, A. Leonhardt, S. El Kazzi, A. Nalin Mehta, T. Nuyten, U. Celano, S. Sutar, G. Pourtois, M. Coymox, K. Paredis, W. Vandervorst, D. Lin, S. Degendt, K. Barla, C. Huyghebaert, I. Asselberghs, and I. Radu. Layer-controlled epitaxy of 2D semiconductors: bridging nanoscale phenomena to wafer-scale uniformity. *Accepted Nanotechnology* (2018).
13. E. R. Dobrovinskaya, L. A. Lytvynov, & V. Pishchik. *Sapphire: material, manufacturing, applications*. Springer Science & Business Media, 2009.
14. B. Radisavljevic, A. Radenovic, J. Brivio, V. Giacometti, & A. Kis. Single-layer MoS₂ transistors. *Nat Nanotechnol* 6, 147–150 (2011).
15. A. Leonhardt, D. Chiappe, I. Asselberghs, C. Huyghebaert, & I. Radu. Improving MOCVD MoS₂ Electrical Performance: Impact of Minimized Water and Air Exposure Conditions. *IEEE Electron Device Lett* 38(11) 1606–1609 (2017).



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Dr. Nathanial Cady, Professor of NanoBioscience, SUNY Polytechnic Institute

Prof. Cady obtained his Ph.D. in Microbiology from Cornell University in Ithaca, NY. He is currently a professor of nanobioscience in the College of Nanoscale Science (SUNY Polytechnic Institute). Prof. Cady has active research interests in the development of novel biosensor technologies and biology-inspired nanoelectronics, including novel hardware for neuromorphic computing.

PROBING THE INTERSECTION OF NANOTECHNOLOGY AND BIOLOGY

Biology and nanotechnology may appear to exist at distant ends of the spectrum, within the world of science and technology. At its core, however, biology is a nanoscale science, one in which molecular events govern how cells grow, how organisms function, and how organisms interact with each other. On the other hand, we can gain helpful insights and inspiration from the biological world as we develop engineering solutions at the nano, micro and macro size scale. In my research group, we leverage nanotechnology to improve our understanding of biological systems, and leverage biological innovations to design and fabricate unique nanotechnologies. As part of this work, we often need to measure the size, shape, and mechanical properties various systems. In the field of microbiology, we have developed microfluidic platforms that enable us to grow cells in controlled environments and then monitor their morphological and physical properties using integrated confocal microscopy and atomic force microscopy. We have extended this technology to the study of higher

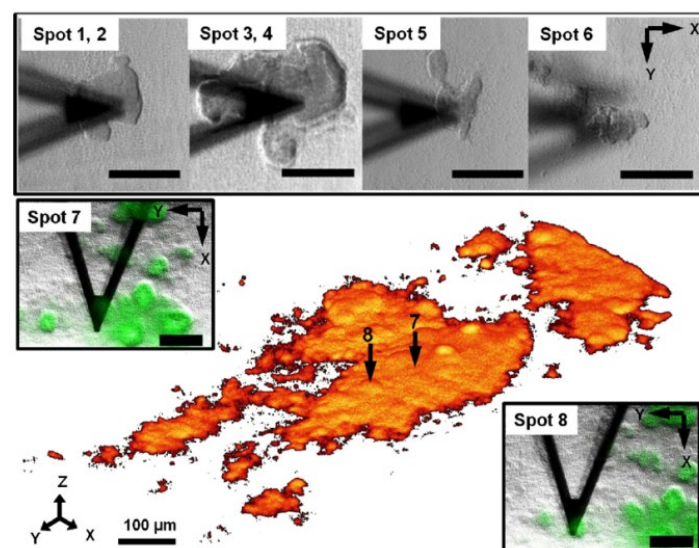


Figure 1. Integrated confocal microscopy / atomic force microscopy based measurement of bacterial biofilms (Mosier, Cady et al. Journal of Microbiological Methods, 2012).

organisms, including measuring the mechanical properties of mammalian tissues and tissue development. These projects demonstrate the power of using nano and micro technologies for the study of biological phenomena. Beyond this work, we are also exploring how

biological systems can be emulated in nanoelectronics. We are developing nanoscale electronic devices called memristors that mimic the function of neural synapses in the human brain. As part of that work, we perform extensive characterization of materials and devices,



Presenter at NanoScientific Symposium at SUNY Polytechnic Nov. 19-20, 2019

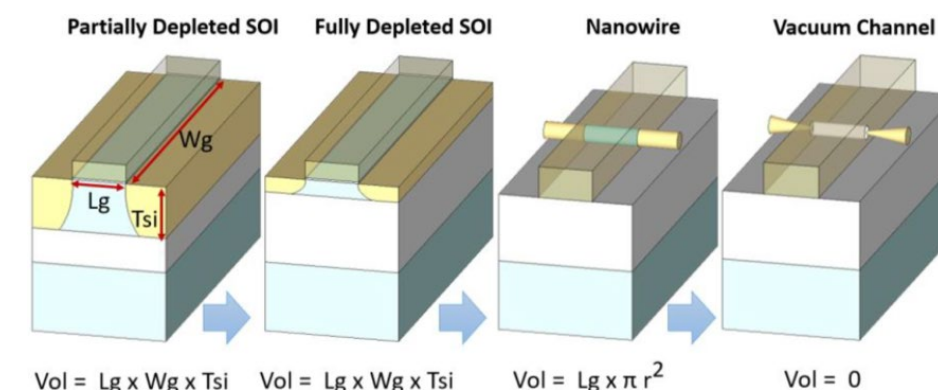
Dr. Jin-Woo Han, Senior Research Scientist at the Center for Nanotechnology, NASA Ames Research Center

NANOSCALE VACUUM CHANNEL TRANSISTOR ON SILICON AND SILICON CARBIDE

Jin-Woo Han is a Senior Research Scientist at the Center for Nanotechnology, NASA Ames Research Center, Moffett Field, California, USA. He currently leads a research team composed of USRA personnel responsible for developing nanoscale vacuum transistor for next generation nanoelectronics and printed electronics. He has received the NASA Ames Honor Award, the IEEE Electron Device Society Early Career Award, Outstanding Engineering Achievement Merit Award from Engineers' Council, the 2015 Mike Sargeant Award from the Institute of Engineering and Technology, IET, UK), IEEE Nanotechnology Council Early Career Award and the Presidential Early Career Award for Scientists and Engineers (PECASE) Award in 2016. He has published over 140 articles in peer-reviewed journals and given numerous invited talks on his subject areas in national and international conferences and universities. He is also active in the IEEE Electron Devices Society (EDS) serving in various technical committees including IEDM.

Nanoscale Vacuum Channel Transistor on Silicon and Silicon Carbide

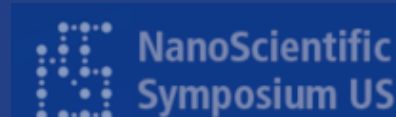
Long-term operation in the harsh environment becomes increasingly less sustainable due to several device aging mechanisms. Total ionizing dose (TID) and displacement damage (DD) degradation limits the new class of missions including long term (> 20 years) deep-space exploration, nano-spacecraft, Europa mission, and so on. In order to tackle such challenges, in this talk, we propose a nanometer scale vacuum channel transistor that combines the advantages of both vacuum and solid-state electronics, providing compactness as well as high performance.



Our fabricated vacuum channel transistor is introduced and the radiation immunity is experimentally assessed. Incident radiation needs to traverse some distance in the channel to release its energy and liberate electrons from the semiconductor for device degradation to occur. Therefore, the only approach to completely avoid the radiation effects is to utilize a vacuum channel.

Unfortunately, as long as the electron emitter and collector structures exist, the vacuum transistor faces mechanical reliability issue associated with the electrode material rupture and degradation in the long term. Our latest results on SiC-based nanoscale vacuum channel transistor suggest them to be a robust alternative to silicon-based vacuum devices.

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UTILIZATION OF SINGLE PARTICLE ICP-MS
ANALYSIS FOR NANOPARTICLE REDUCTION IN
SEMICONDUCTOR FABRICATION



Lisa M. Mey-Ami, Jinjin Wang and Fuhe Li
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Introduction

Nanoparticles are defined as ultrafine particles with at least one dimension in the nano-scale (1-100nm) range. Naturally occurring nanoparticles, present as unwanted contaminants in all aspects of the semiconductor manufacturing processes, are increasingly important to characterize. As the world of electronics become smaller approaching 5 nm technical node, nanoparticles are crucial contaminants that need to be monitored and then removed from the processes to avoid device failure.

This paper describes single particle inductively coupled plasma-mass spectrometry (SP ICP-MS). With the technique, we have evaluated ultrapure water (UPW), process chemicals and the surface of various original equipment manufacturer (OEM) parts. Figures of merit presented include particle concentration (particles/mL or particles/cm²), median particle size (nm), size distribution, and background equivalent diameter (BED). BED is related to the smallest particle size that can be detected and often as low as single digit nm.

Background

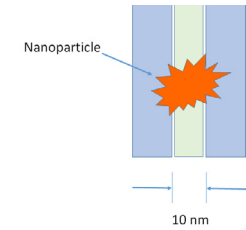


Figure 1: Nanoparticle Studies: Why Needed? Single nm -100 nm particles are now critical. Monitoring & controlling single near 1 nm particles will soon be required.

Figure 1 illustrates the importance of currently being able to detect particles between single nm and 100 nm as sub 10-nm scale devices have been in production since 2018. Soon it will be necessary to monitor near 1 nm particles as the semiconductor technical node continues to scale down.

ICP-MS is routinely used for the determination of trace elements in UPW, process chemicals and extraction solutions for OEM tool parts ¹⁻³. The detection limits are often as low as sub parts per trillion (ppt). Since the analytes dissolve completely and aspirate into the ICP plasma continuously, producing a constant signal intensity, only total elemental concentration is determined. Using time resolved data acquisition with short dwell times (a data point is collected every 0.1 ms), the transient signal of each individual nanoparticle can be differentiated from the steady-state ICP-MS signal generated by the dissolved species. This unique feature, coupled with the assumption of spherical particle size, enables ICP-MS to characterize nanoparticles down to single nm sizes producing various results: particle concentration, particle median size, size distribution information, elemental composition and background equivalent diameter (BED). There is no other analytical methods to date, which can provide all these parameters simultaneously for nanoparticles.

Results and Discussion

In order to validate that SP ICP-MS is suitable and reliable for the analysis of nanoparticles, a nanoparticle standard with a known size and particle concentration was prepared and studied.

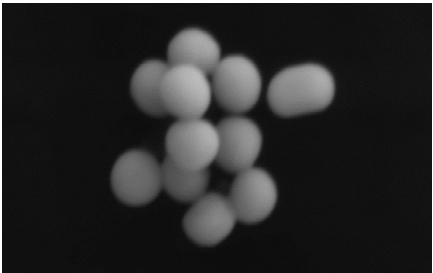


Figure 2: Au (60nm) NP Standard SEM image

Figure 2 shows a scanning electron microscope (SEM) image of a 60 nm commercial Gold (Au) nanoparticle standard. Figures 3 and 4 show the time-resolved particle signal profile and the particle size distribution of the Au standard by SP ICP-MS, respectively. As can be seen, the particle size distribution clearly shows that the median Au particle size is centered at 60 nm with a narrow distribution.

Element	Pre Filtration Particle Concentration	Post Filtration Particle Concentration	BED (nm)
Al	98	*	8
Mg	180	*	6
B	120	40	15
Zn	110	*	11
Ti	65	*	6
Fe	800	110	4
Cr	*	*	3
As	*	*	5
V	60	*	5

* = not detected

Table 1: Results of a UPW Sample in Particles/mL

Table 1 shows SPICP-MS results for a UPW sample, pre and post 10 nm in line filtration. The samples were analyzed for a variety of elements that commonly form nanoparticles in an aqueous solution and also critical to semiconductor manufacturing. The ICP-MS instrument parameters (e.g. reaction gases) were optimized to combat the molecular and isobaric interferences

associated with ICP-MS (e.g. 56Fe vs 40Ar16O). Many of the element's BED values were single nm as the result of the optimization. The analysis revealed that the nanoparticles found in the “pre” sample were successfully removed by the 10 nm inline filter employed. The results demonstrate the effectiveness of SP ICP-MS for monitoring nanoparticle filtration efficiency.

Element	70% Nitric Acid	96% Sulfuric Acid	25% TMAH	30% H2O2	IPA	PGMEA
Mg	200	390,000	NA	8000	2000	NA
Al	7000	1,800,000	NA	56,000	950,000	NA
Cu	3500	NA	NA	14,000	NA	81,000
Fe	5000	640,000	800,000	20,000,000	23,000	2,500,000
Ti	4800	500	600,000	400	6100	2150
Zn	200	17,000	NA	1000	83,000	NA
Cr	200	21,000	40,000	22,000,000	15,000	58,000
Sn	150	NA	NA	70,000,000	NA	9500
Ni	400	NA	200,000	25,000,000	NA	NA
Ta	NA	NA	12,000,000	NA	NA	NA

NA = not available

Table 2: Results of Various Chemical Samples in Particles/mL

SP ICP-MS has also been used to characterize various process chemicals. Table 2 shows SPICP-MS nanoparticle concentrations for various analytes in acid samples (e.g. 70% nitric acid and 96% sulfuric acid), base samples: (e.g. 25% tetramethylammonium hydroxide; TMAH), oxidizers: (e.g. 30% hydrogen peroxide; H2O2), and organic solvents: (e.g. isopropyl alcohol; IPA and propylene glycol methyl ether acetate, PGMEA). These are all common process chemicals used in semiconductor manufacturing processes such as cleaning, developing, etching, planarizing and photoresist stripping. Again, ICP-MS parameters were optimized to eliminate interferences (e.g. 48Ti vs 32S16O in a sulfuric acid matrix) and enhance overall analysis sensitivity. A large amount of nanoparticles was found in the process chemicals, although the elemental composition of nanoparticles varied. Some of the nanoparticle contaminants were likely introduced during the chemical manufacturing process. For example, Tantalum (Ta) nanoparticles found in TMAH were the direct result from using Ta electrodes in the electrochemical synthesis of TMAH. The Tin (Sn) nanoparticles found in H2O2 were due to the addition of an inorganic Sn-based stabilizer. The decomposition of the Sn compound caused the formation of Tin nanoparticles in H2O2. The precision of SP ICP-MS analysis was studied and the relative

standard deviation (RSD) was found to be approximately +/-10%, depending on the element. The consistency of the results have enabled process engineers to develop nanoparticle specifications in order to achieve quality control of incoming process chemicals. Furthermore, material suppliers can use the results to guide their efforts in reducing and removing nanoparticles from various chemicals they produce. Monitoring nanoparticles on a solid part surface is a more challenging task. There hasn't been a suitable technique thus far. Water extracts of OEM parts used in etching and deposition chambers (quartz part, ceramic part and Aluminum coupon) were evaluated for nanoparticles by SPICPMS. Figure 5 shows SP ICP-MS concentration results for a variety of analytes for these three parts expressed in particles/cm2 (surface area).

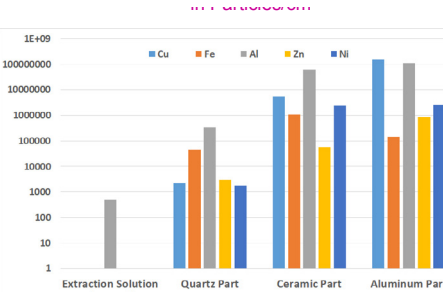


Figure 5: Nanoparticles Found From the Surface of Various OEM Parts in Particles/cm2

Conclusion

SPICP-MS methods have been developed in our laboratory and regularly applied to water, chemicals and OEM parts used throughout semiconductor manufacturing processes. The processes include wafer surface cleaning and preparation, chemical mechanical planarization (CMP), deposition, etching, implantation, and lithography. The analytical results produced have been used by chipmakers, OEM's and raw material suppliers in monitoring nanoparticles in their processes. The results we obtained showed that a large number of nanoparticles was present in various process chemicals and on the surface of OEM plasma etch and deposition equipment parts. The presence of these nanoparticle contaminants can cause random device defects and would have a detrimental impact on current and next generation semiconductor manufacturing. A strategy

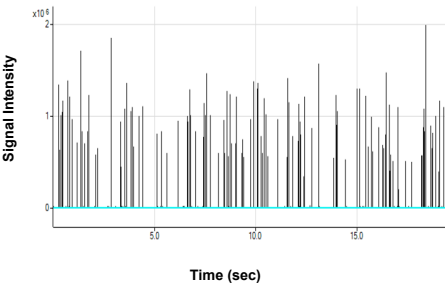
needs to be in place soon to begin reducing the number of nanoparticles in the process before the semiconductor manufacturing yield can be improved markedly.

Acknowledgement

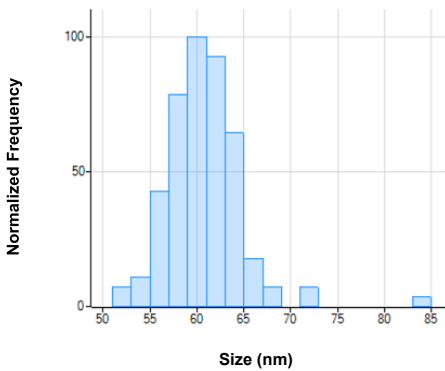
The authors would like to thank Dr. Amir Tavakoli and Ms. Laura Jackson for their contributions.

References

- 1) Mey-Ami, L., Wang, J., Gotts, H and Li, F., “Single Nanoparticle ICP-MS Analysis of Process Chemicals and UPW Used in Surface Cleaning and Preparation”, Proceedings of International Surface Preparation and Cleaning Conference (SPCC), Cambridge, MA, April 2018.
- 2) Mey-Ami, L., Wang, J and Li, F., “Optimization of Single Nanoparticle ICP-MS Analysis for Controlling Nanoparticles in Process Chemicals and UPW used in Wet Surface Cleaning,” Proceedings of International Surface Preparation and Cleaning Conference (SPCC), Portland OR, April 2019.
- 3) Wang J., Mey-Ami, L. and Li, F., “A Novel ICP-MS Metrology for Analysis of Nanoparticles in UPW”, Ultrapure Micro, Phoenix, AZ, June 2019



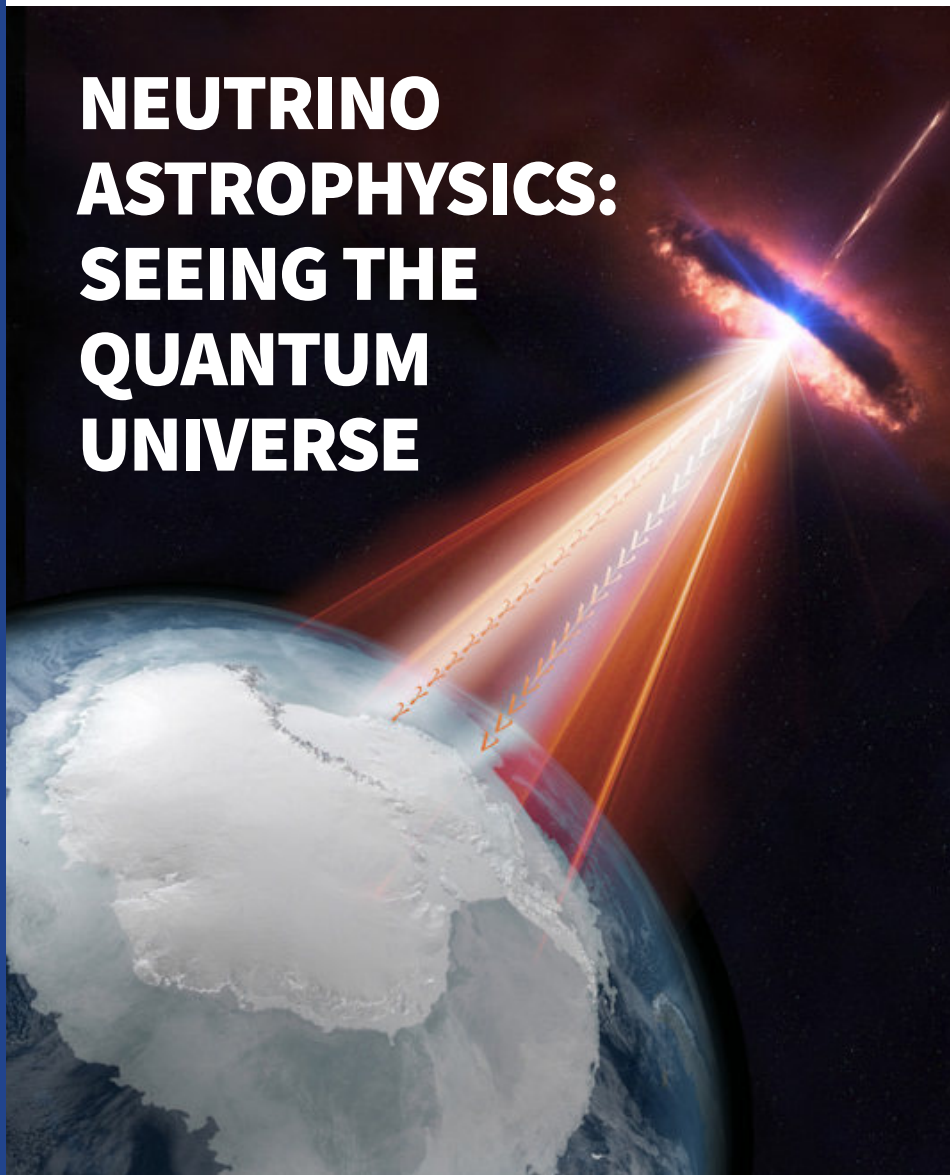
60 nm Au Particle Standard: SP-ICP-MS



60 nm Au Particle Standard: SP-ICP-MS

NEUTRINOS ARE AMONG THE MOST ABUNDANT PARTICLES IN THE UNIVERSE, A BILLION TIMES MORE ABUNDANT THAN THE PARTICLES THAT MAKE UP STARS, PLANETS AND PEOPLE. NEUTRINOS ARE PRODUCED IN UNIMAGINABLE QUANTITIES BY THE SUN AND STARS. COULD THEY BE THE DARK MATTER THAT CONTROLS THE FATE OF THE UNIVERSE OR EXPLAIN WHY WE LIVE IN A UNIVERSE OF MATTER AND NOT ANTIMATTER? WORLD-CLASS, MULTIPURPOSE DETECTORS DESIGNED TO SOLVE THE PUZZLE ABOUT NEUTRINOS ARE DISCUSSED IN THIS ARTICLE ALONG WITH FIRST HAND UPDATES FROM TWO OF THE PHYSICISTS WORKING IN THIS AREA. THE DETECTOR RESEARCH AIMS TO GET A CLEARER PICTURE OF THE UNIVERSE, CREATING A NEW ERA OF SCIENCE: NEUTRINO ASTROPHYSICS.

NEUTRINO ASTROPHYSICS: SEEING THE QUANTUM UNIVERSE



Blazar emitting neutrinos and gamma rays. Photo Credit Ice Cube/NASA

Super-Kamiokande is the large water Cherenkov detector located in Gifu Japan. The construction was started in 1991 and the observation began on April 1st, 1996

The Super-Kamiokande detector consists of a stainless-steel tank, 39.3m diameter and 41.4m tall, filled with 50,000 tons of ultra pure water. About 13,000 photo-multipliers are installed on the tank wall. The detector is located at 1,000 meter underground in the Kamioka-mine, Hida-city, Gifu, Japan.

One of the purposes of the Super-Kamiokande experiment is to reveal the neutrino properties through the observation of solar neutrinos,

atmospheric neutrinos and man-made neutrinos. In 1998, from the observation of atmospheric neutrinos we discovered the neutrino oscillations which neutrinos are changing their types in flight. In 2001, solar neutrino oscillations were discovered by the observation of solar neutrinos. In 2011, the third neutrino oscillation mode was discovered by man-made neutrino observation.

Neutrinos move at or very near the velocity of light, have no electric charge, and have so little mass that until very recently scientists were not sure if neutrinos have any mass at all. Until recently, when in 1988 neutrino oscillation was discovered by the Super-Kamiokande experiment.

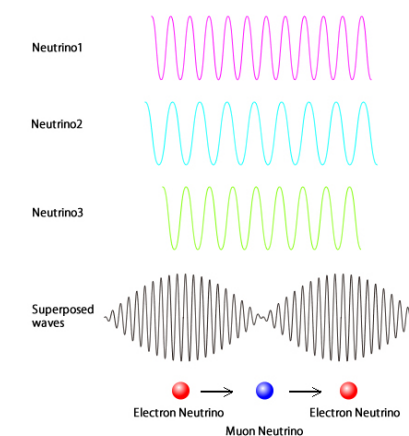


SUPERNOVA 1987A, WHICH OCCURRED ON FEBRUARY 23, 1987. THE RIGHT FIGURE SHOWS BEFORE EXPLOSION. (Anglo-Australian Observatory/ David Malin)

A supernova explosion happens when a star at least 8 times more massive than the sun collapses. An enormous amount of energy (more than 99% of energy emitted from the Sun for 4.5 billion years) is released primarily in the form of neutrinos in just 10 seconds. A supernova explosion is expected to occur inside our galaxy once every 10 to 50 years. If such an explosion occurs, Super-Kamiokande is expected to detect about 8,000 neutrinos. and be able to reveal the mechanism of supernova explosions by analyzing the information of the energy and the arrival time of these neutrinos.

“SINCE NEUTRINOS INTERACT ONLY WEAKLY WITH MATTER THEY CAN BE USED TO INVESTIGATE BOTH THE DEEP INTERIOR OF STARS AND THE FAR REACHES OF THE UNIVERSE. FOR EXAMPLE, WE CAN OBSERVE NOT ONLY THE CORE OF OUR SUN, WHOSE NUCLEAR FUSION CREATES THE LIGHT THAT POWERS THE EARTH, BUT ALSO THE MOMENT WHEN THE CENTRAL CORE OF A MASSIVE STAR COLLAPSES AS A SUPERNOVA BURST USING THE NEUTRINOS THESE PROCESSES CREATE.” DR. MASAYUKI NAKAHATA, DIRECTOR, SUPER-KAMIOKANDE COLLABORATION

They plan to “dissolve gadolinium in the tank around the end of this year or the beginning of next year in order to enter a new phase of observation. “We can detect supernova neutrinos from the beginning of the universe, improve pointing accuracy for galactic supernova, reduce background for nucleon decay searches, and etc.,” explains Dr. Nakahata.



Pictured Neutrino oscillation was discovered by the Super-Kamiokande experiment in 1998. Neutrinos exhibit the properties of a particle as well as a wave. Therefore, neutrino1, neutrino2 and neutrino3, each with different mass eigenstates, travel through space as waves that have a different frequency. The flavor of a neutrino is determined as a superposition of the mass eigenstates. The type of the flavor oscillates, because the phase of the wave changes. This phenomenon is called neutrino oscillation. Neutrino oscillation occurs when neutrinos have mass and non-zero mixing.

The next phase in this project is the proposed Hyper-Kamiokande (HK), to be constructed in Kamioka, Hida City, Gifu Prefecture, expected to start sometime in 2020 with eight times larger fiducial mass than Super K.

Hyper K will be equipped with newly developed high-sensitivity photosensors. The aim of HK is to elucidate the Grand Unified Theory and the history of the evolution of the universe through an investigation of proton decay and CP violation (the difference between neutrinos and antineutrinos), as well as the observation of neutrinos from supernova explosions. Seed funding for Hyper-Kamiokande (HK) has already been allocated for the current Japanese fiscal year, and 12 countries, including Japan, expressed interest in the project.

MASAYUKI NAKAHATA

is the Director, Kamioka observatory, ICRR the University of Tokyo and Spokesperson for the Super-Kamiokande Collaboration in Gifu-ken, Japan. The Super-Kamiokande is operated by an international collaboration of about 150 people and about 40 institutes from Japan, the United States, Korea, China, Poland, Spain, Canada, UK, Italy and France.



In January, Super -K was restarted after work was done in 2018 to stop a water leak in the tank. “The very precise test done in early February showed that water leak is completely fixed,” explained Dr. Nakahata, “We filled pure water to the tank from last October to January. In this time, we recirculated water even filling phase. Because of this new scheme, water transparency has been very good even just after the tank was full and we have been taking good data in SK-V.”

AN INTERVIEW WITH DR. KATE SCHOLBERG



KATE SCHOLBERG is a Professor of Physics at Duke University where her broad research interests include experimental elementary particle physics, astrophysics and cosmology. Her main specific

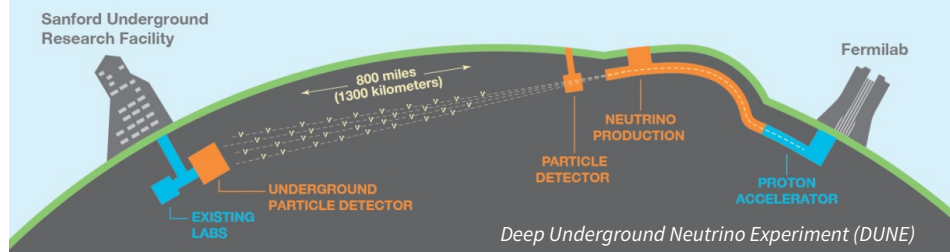
interests are in neutrino physics. Dr. Scholberg studies neutrino oscillations with the Super-Kamiokande experiment where her primary involvement is with the atmospheric neutrino data analysis, which in 1998 yielded the first convincing evidence for neutrino oscillation (implying the existence of non-zero neutrino mass).

Why do you think understanding Neutrinos is so important and how might it help us understand the universe? How is Neutrino research impacting physics?

Neutrinos are fundamental particles, like electrons and quarks, and we need to understand the properties of the fundamental constituents of matter if we are to understand the “big picture” of Nature. Neutrinos also played a role in the early Universe. It is very likely that neutrinos were important in the generation of matter at very early times in the Universe’s history. One of the huge questions out there is why we have an enormous excess of matter today, rather than antimatter, given that the properties of matter and antimatter are almost symmetric. Neutrinos were probably involved in the generation of the matter-antimatter imbalance. Therefore we need to understand the properties of neutrinos in order to figure out how the Universe became so matter-heavy.

Can you explain how SNEWS gathers information about Supernovas? And do you have any theory on when the next event might occur?

SNEWS (Supernova Early Warning System) is a network of large underground neutrino detectors. Any one of these detectors would see an intense burst of neutrinos within about 10 seconds if a star’s core collapses in the Milky Way. Any of the detectors, if they see such a



burst, will send a datagram to the central SNEWS computer. If this computer receives at least two datagrams indicating bursts within 10 seconds of each other, it sends out an alert message. Individual experiments, if they have really clean signals, can also send individual alerts, but two or more at the same time will mean we are sure that something happened.

Unfortunately the kind of core-collapse supernova burst that would result in a SNEWS alert is really rare— it will happen only about every 30 years or so in the Milky Way. We have no good way of predicting when or where it happens next, although we can keep an eye on some red giant stars, like Betelgeuse, which might blow up any minute (or 10,000 years from now-- it’s hard to tell for an individual star). Some stars, in the months and days before they blow up, may produce extra neutrinos, and we will be watching for that too, but such a presupernova neutrino signal would be so faint that we could only see it for very nearby stars (Betelgeuse is one of them). The rarity of such a stellar blowout does mean that it’s especially important to be prepared, so that we can capture all possible information, in neutrinos, photons, and other astrophysical messengers, like gravitational waves.

Do you think the Hyper K proposal will be approved and why is it important?

It can be harder to make funding predictions than supernova ones! Hyper-K is certainly a good prospect. It will see a truly enormous number of neutrinos (actually, mostly antineutrinos) from a supernova. The Deep Underground Neutrino Experiment (DUNE) in the U.S. is also a good future prospect. It will see fewer neutrinos than Hyper-K, but because it’s made of argon rather than water, it will see mostly neutrinos, whereas Hyper-K will see antineutrinos. This will bring us unique information

about, for example, the star’s collapse into a neutron star. JUNO in China is another future large detector, to be made of hydrocarbon, which will see antineutrinos. Deep Underground Neutrino Experiment (DUNE), will be the largest particle physics project ever to be built in the United States. Hosted by the U.S. Department of Energy’s Fermilab, this international project brings together more than 1,000 scientists from more than 30 countries around the world, all dedicated to unraveling the mysteries of ghostly particles called neutrinos. To do this, Fermilab will send its world-leading particle beam 800 miles (1,300 kilometers) through the earth to four gigantic detectors built a mile beneath the surface at the Sanford Underground Research Facility in South Dakota. A liquid-argon neutrino detector, pre-excavation work is in full swing at the site in Lead, South Dakota.

Can we create images of the Elusive Neutrinos Using AFM/SPM?

“Well, I think AFM, SEM, etc. won’t be of much use, I’m afraid,” says Dr. Scholberg. “One cannot directly see a neutrino. What one does see is the tracks or other evidence of charged particles that result from the rare interaction of the neutrino with matter, and one can make images out of this information. There are a lot of different detector technologies. Usually the images are electronic: for example, the charged particles make Cherenkov light, and then photo sensors capture and digitize the photons, making lovely ring images. In other detectors, like DUNE (a “time projection chamber”), the charged particles from the interaction ionize liquid argon, and the ionization charge is drifted in a high electric field placed on the argon, and then collected to make an image in the projected shape of a track. The time at which the charge arrives on an anode plane gives the third dimension.

TWO SCIENTISTS FROM THE TANDEN SCHOOL OF ENGINEERING NEW YORK INTERESTED IN NEUTRINO MASS DETECTION USING AFM



LORCAN M. FOLAN,
Department Chair,
Applied Physics, NYU
Tandon School
of Engineering



VLADIMIR TSIFRINOVICH
Industry Professor,
Sr. Lecturer, Applied
Physics, NYU Tandon
School of Engineering

Their paper titled “*Generation of a directed mono-energetic neutrino beam and measurement of the neutrino mass*” was a proposal for a method to measure the rest mass of the neutrino emitted in electron capture beta decay. We study generation of a directional mono-energetic neutrino beam in electron capture beta-decay and analyze the recoil force exerted by neutrinos. We consider the influence of the neutrino rest mass on the recoil force and discuss the opportunity for neutrino mass measurement using an atomic force microscopy (AFM). We compute the enhancement of the signal-to-noise ratio due to signal accumulation (averaging), find the optimal time for signal accumulation and formulate conditions

for measurement of neutrino mass with AFM.

“My collaborator, Vladimir Tsifrinovich and I are very interested in neutrinos. Of the fundamental particles, they are perhaps the most enigmatic. Subsequent work indicates that the sensitivity required to make a measurement is beyond current technology, but we are still working on finding a method that will work.” Lorcan M. Folan, Department Chair, Applied Physics, NYU Tandon School of Engineering. “Our opinion is that every proposal, including our AFM proposal, should be pursued further.”

Why is the Neutrino particle the most enigmatic of the fundamental particles?

According to the Standard Model neutrinos do not have rest mass. However oscillation experiments show that they do have a mass. Thus, neutrino is the only fundamental particle which cannot be described in the scope of the Standard Model. There are believed to be three neutrino types or flavors (electron, muon and tau) and three neutrino masses, but there is not a one to one correspondence between the flavors and the masses. And the mass ordering and flavor mixings are still unknown.

Can you explain why the current technology was not capable of the image?

As the first step to the AFM neutrino mass experiment, one should detect the recoil force produced by neutrino radiation.

In our proposal, a sample containing 5x10⁻¹⁰ kg of radioactive antimony atoms must be attached to an AFM tip in order to produce a 1 pN recoil force at a temperature of 25 mK. If this force could be detected, we could discuss the use of AFM for the neutrino mass measurement. So far, even this initial experiment has not been implemented.

What/how does technology need to advance to make this measurement?

We believe that the first step could be achieved with current AFM technology. If it is done, one will need to increase the sensitivity of the measurement in order to measure the neutrino mass.

Why is a method for this measurement important and is it possible for AFM (if improved) to make this measurement?

There are currently a few proposals for the neutrino mass measurement. None of them has succeeded. Our opinion is that every proposal, including our AFM proposal, should be pursued further.

How are discoveries about Neutrino likely to change physics as we understand it today? What do you think it might explain about the universe?

Discoveries about neutrinos could generate a new theory of baryonic matter beyond the standard model. It could also help to understand the mysterious dark matter and asymmetry between matter and antimatter in our Universe.



Liliang Huang is from The Mirkin Research Group at Northwestern University which has pioneered the use of nanoparticle-biomolecule conjugates as synthons in materials science and the development of many nanoparticle-based extra and intracellular biondiagnostic and therapeutic tools.

Research summary

Hydrogen is widely used as a clean, renewable alternative to fossil fuels, while water electrolysis represents an increasingly important method for industrial hydrogen manufacturing (~5% of the market). Currently, platinum is extensively used as a hydrogen evolution reaction (HER) electrocatalyst for water electrolysis; however, its scarcity and high cost limits practicality in electrolyzers. The key motivation of my graduate studies is focused on developing novel strategies to discover, design and fabricate cost-effective HER electrocatalysts.

Nanoparticles are emerging as attractive HER electrocatalysts for researchers due to their enhanced activity when compared to their bulk counterparts. Pt-based multimetallic nanoparticles are particularly interesting because alloying Pt with earth abundant transition metal elements (e.g. Cu) is found to be favorable for activity and stability enhancement, in addition to the apparent cost savings. A series of multimetallic nanoparticle synthesis methods (e.g. coreduction and thermal decomposition) have been used to prepare targeted multimetallic nanocrystals with specific elemental compositions and size. These methods, however, are usually system-specific and lack in generalizability. Recently, the Mirkin group reported a novel synthesis method termed scanning probe block copolymer lithography (SPBCL), which allowed for the synthesis of a library of multimetallic

nanoparticles of up to five elements (Au, Ag, Cu, Co, and Ni) by using a simple two-step thermal annealing treatment. This synthetic route forms a versatile platform for studying the catalysis-related properties of the nanoparticles. In this work, by effectively utilizing SPBCL in combination with density functional theory (DFT) calculations, we introduced a novel strategy to design and discover cost-effective HER electrocatalysts. Through this exercise, we have identified a homogeneous alloy PtAuCu nanoparticle as a more efficient and stable HER catalyst than the commercial Pt/C catalyst.

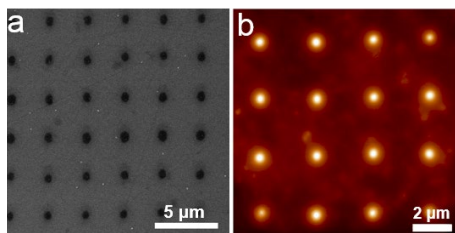


Fig. 1. (a) An SEM image of uniformly patterned polymer nanoreactor arrays synthesized with a modified AFM instrument. (b) AFM image of the nanoreactor arrays.

In an acidic electrolyte, the catalyst hydrogen binding energy (HBE) is the sole reaction descriptor for HER activity and an optimal HER catalyst should have an HBE that is neither too strong nor too weak. We first used density functional theory (DFT) calculations to evaluate the HBE for a series of multimetallic nanoparticles and identified PtAuNi and PtAuCu alloy nanoparticles as promising HER catalysts. Then SPBCL was used to accordingly synthesize these nanoparticles (Fig. 1), followed by characterization of their catalytic properties towards HER. Through this process, we confirmed PtAuCu alloy nanoparticles as excellent HER catalysts and highlighted the phase structure as a key parameter in determining the HER performance of the nanocatalysts, where the phase separation within PtAuNi heterodimer particles (PtNi forms one phase domain and Au forms another domain) results in poor HER catalytic activities.

Finally, a bulk synthetic method was used to scale up the discovered PtAuCu

catalyst, which was determined to be 7 times more active on a Pt-to-Pt basis than the “gold standard” commercial Pt catalyst. Herein, this work is a proof-of-concept for a powerful tool used to discover new catalysts. We believe that more variables could be explored with this technology, leading to catalysts that will likely even exceed in performance than the one we identified here through preliminary efforts.

How do you use Park AFM in your research?

Park AFM instrument is quite important for my research. I not only use it as a multimetallic nanoparticle synthesis instrument, but also employ it to characterize the size and height of the patterned polymer nanoreactor features. Specifically, I synthesize nanoparticles through a process called SPBCL, where polymer pen arrays were placed into a modified AFM instrument and brought into contact with a flat substrate to pattern uniform polymer nanoreactors. These nanoreactors can further be thermally treated to produce nanoparticles. During the nanoparticle synthesis process, I will also use Park AFM to characterize the size uniformity of the patterned polymer features. Furthermore, the height and size ratio information of the patterned polymer features obtained from AFM measurements can also give me an idea of the hydrophobicity of the substrate, which is an important concern for this nanoparticle synthesis process.

Why do you think Park AFM is a valuable tool for researchers?

Nanotechnology has provided additional opportunities for researchers to address existing energy, environmental, and biological-related problems that are difficult to be solved with conventional bulk materials. Park AFM, as a flagship AFM instrument, has enabled researchers to obtain precise topographical information about the nanostructures, which is highly important for nanofabrication and its applications.

PROBIOTIC BACTERIA TOPOGRAPHY AND NANOMECHANICAL PROPERTIES ANALYSIS USING ATOMIC FORCE MICROSCOPY

GABRIELA MENDOZA, BYONG KIM AND KEIBOCK LEE, PARK SYSTEMS, INC., SANTA CLARA, CA, USA

Introduction

Probiotics are living microorganisms that provide numerous health benefits to the host when supplied in adequate amount as well as improve the intestinal microflora of the host. Probiotics are mainly administered to humans combined with food and are widely used in food products. From in vivo and in vitro studies of host intestinal epithelial or immune cell responses to probiotic strains, it has been reported that adhesion of probiotic strains to the intestinal surface and the subsequent colonization of the human gastrointestinal tract are important prerequisites for probiotic action [1]. This study looks into the topography and adhesion properties of those microorganisms to determine the shape and form that adheres well to the colon by means of using commercially available probiotics and the PinPoint nanomechanical mode of an atomic force microscopy (AFM) instrument from Park Systems.

Experimental

To isolate probiotic bacteria, 1 mL samples of a commercial product were put into microcentrifuge tubes and centrifuged (BioLab centrifuge) for 15 min at 10000 rpm to separate the biomass pellet. The supernatant was discarded and the biomass was recovered in a test tube. Serial dilutions (1 mL of biomass in 9 mL of sterile saline solution) from 10⁻¹ to 10⁻⁵ were performed [2]. From the 10⁻⁵ dilutions, 0.1 mL drops were placed onto a silicon wafer chip (Ted Pella, Inc. 16007) and allowed to air dry. For bacteria characterization, a Park NX10 AFM from Park Systems was used; measurements were performed in air using an AC160TS cantilever. PinPoint™ Nanomechanical Mode from Park Systems can be used to study surface topography as well as determine quantitative nanomechanical properties (i.e., modulus, adhesion force, adhesion energy) [3]. In this study, topography, adhesion energy and

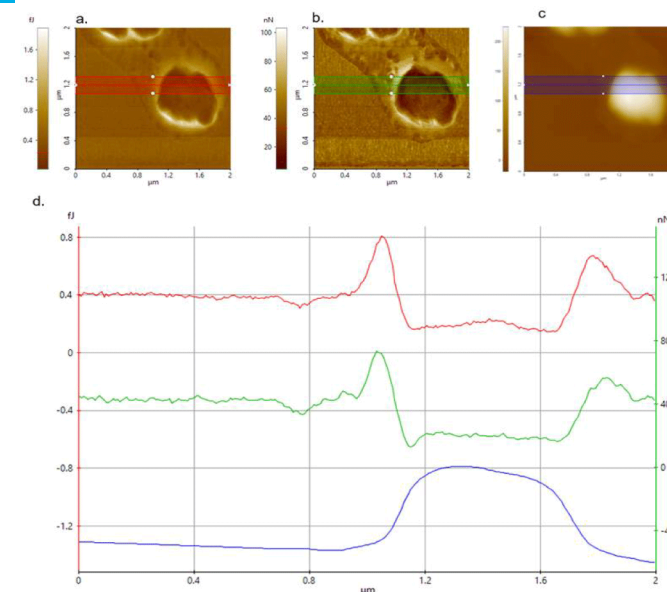


Figure 1. a) Adhesion energy, b) adhesion force and c) height images taken with AC160TS cantilever. d) Corresponding overlaid topography, adhesion energy and force line profiles.

adhesion force images were acquired using the PinPoint Nanomechanical Mode. Images obtained were 256 x 256 pixels and 2 μm x 2 μm sizes.

Result

Figures 1a, b and c are the adhesion energy, adhesion force and topography images, respectively, of isolated Streptococcus chains from a 10⁻⁵ dilution. Figure 1d shows the corresponding overlaid topography, adhesion energy and force line profiles. The adhesion energy (Figure 1a) and adhesion force (Figure 1b) behaved in a similar manner; smaller values were observed for the bacteria compared with the substrate where they were attached.

The adhesion energy on the silicon wafer chip was 400 aJ, but just 200 aJ on the probiotic bacteria. Similar results were obtained for the adhesion force (Figure 1d); 20 nN for the bacteria but 45 nN on the silicon wafer chip and clearly indicates that less force was required on the bacteria. The isolated bacteria in air is observed to be relatively less adhesive than that of the underlying Si substrate. Bacterial adhesion is based on physical interactions between two or more surfaces. There were

three different surfaces identified in this study: the cantilever tip (surface 1), the bacteria (surface 2) and the silicon wafer (surface 3). All three surfaces have different physicochemical properties: surface area, surface energy, surface roughness size and shape, which affect the adhesion force and energy.

Conclusion

The test results show that probiotic bacteria under study were less adhesive to the Si cantilever tip compared to the Si substrate. This phenomenon can be correlated with the adhesion of probiotic strains to the site of action, an important prerequisite for probiotic action. We found from nanomechanical measurements that the adhesion force and adhesion energy are affected by the physicochemical characteristics from each substrate. Therefore, adhesion force and adhesion energy values were lower when the measurement was on the bacteria compared to that done on the silicon wafer.

References

- [1] Saarela M et al., *Journal of Biotechnology*. 2000; (84) 197-215.
- [2] Mendoza M AG et al., *Revista Mexicana de Ingeniería Química*. 2017; 16(1): 159-168.
- [3] Park Systems's PinPoint™ Nanomechanical mode <https://www.parksystems.com/index.php/en/park-afm-modes/nanomechanical-modes?i=0>

SUPRAMOLECULAR CHEMISTRY, NANOMACHINES, AND AFM

MATERIALS MATTER

Column Highlighting Topics Presented in Dr. Advincula's Monthly Webinars on Advancements in Material Science



Dr. Rigoberto Advincula, Professor, Macromolecular Science & Engineering Case Western Reserve University

NANOTECHNOLOGY REQUIRES THE USE OF TOOLS NEEDED TO UNDERSTAND PHENOMENA AND MANIPULATE MATERIALS ALL THE WAY TO THE ATOMIC LEVEL. ATOMIC FORCE MICROSCOPY (AFM) IS ONE OF THE MOST IMPORTANT METHODS FOR PROBING AND HARNESSING THE POTENTIAL OF NANOTECHNOLOGY.

The Nobel Prize in Chemistry 2016 was awarded to Sauvage, Stoddart, and Feringa for their work in supramolecular chemistry and it highlighted the need for nanomanipulation and probes to demonstrate stimulation response and motion to molecular and nanomachines. AFM is one of the few methods available to directly visualize and manipulate these nano-objects by investigating topology and field response in flat surfaces and using specific cantilever-tip to molecule interactions. AFM techniques based on contact and non-contact modes including scanning tunneling microscopy (STM) as well as field-responsive methods have enabled quantitative and visualized experiments to correlate with the dynamics of macromolecular and supramolecular chemist.

This column summarizes a webinar on AFM imaging of knotted polymers. This is a summary of the complete webinar given by Dr. Advincula. To view this webinar and other webinars, go to: www.parksystems.com/supramolecular

Can you describe Supremolecular Chemistry?

When we talk about molecules, synthesizing new types of complexes, macromolecular systems that involve metal-to-ligand interaction or even protein assemblies in enzymes, what is fascinating is that you can use the different types of non-covalent and covalent interactions to create larger molecules with varying complexity or structures that are beautiful and at the same time functional. What opens the door for different types of modular approaches in chemistry is that you can take these building blocks and assemble them in terms of different geometries, taking molecular precursors into different architectures that then can be complex, let's say, in guest host systems that will allow you to look at binding kinetics or self-assembly towards higher ordered structures. You have a molecular approach to prepare the building blocks that can then result into higher complexity based on the synthesis of these building blocks with finite covalent structures, however, you can prepare different types of non-covalent structures or complexation to build larger macromolecules or supramolecular structures that then can have function for recognition, transport and catalysis.

What are Supramolecular Chemistry Molecule Knots?

You can actually have these intricate cyclic structures, polycycles, macrocycles, different types of order where the building of these structures can be achieved through ion complexation, hydrogen bonding, or donor-acceptor systems.

The ability to put this together to form larger structures with finite geometry such as a trefoil knot or a Borromean ring or Solomon link has been a fascination of a lot of organic chemistry aficionados, scientists, who would like to be the first to report this type of architecture using these different building blocks. There's a whole world there of organic chemists who are fascinated with building this supramolecular structures or even trying to observe their formation of extended and higher ordered structures.

What are Synthetic Strategies for Polymer Catenation?

A basic strategy usually involves the use of a more template-directed catenation or binding whereas in the statistical catenation or threading, you don't have that yield that allows you to isolate a higher yields of specific cyclic structures or catenation whereas by templating it, one can bias the system such that that particular precursor structure can be formed followed by the final step which is in this case ring closure. This basic dichotomy between statistical and templated direction actually is the key towards higher yields or isolation of specific geometries based on molecular bias. That is why templates such as transitional metal, donor-acceptor, hydrogen bonding, or other types of ligand complexation is quite effective in locking or preparing this interlock structure where the final step can be used to close the ring or prepare different types of extended structures such as tubes, calixarene rings, chalice-type of structures, or different geometries that are geometrically feasible.

What are Programmed Knots and Knot Theory?

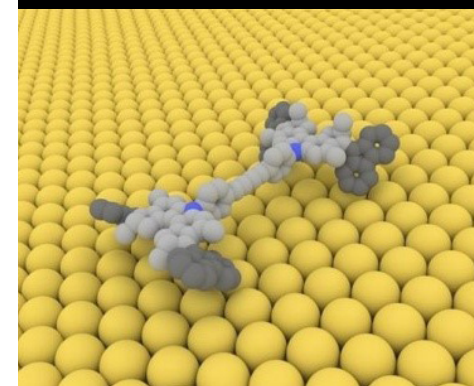
You can actually program the links to give specific catenated or knotted structures based on the degree of complexation and ligand-to-metal interaction such as it was popularized by Sauvage during the 1990s. You can create metal-to-ligand interactions with one metal, two metals, three metals, four metals, and five metals, by closing the ring, let's say connecting A and B or X and Y, you will end up actually with a catenated structure of two rings by demetalation.

On the other hand, if you take a bidentate ligand and complex two metals within this ligand and close the ring, you can actually demetalate that and form the simplest knot or a trefoil knot. What you can see here as you go with an odd and even number of chelation, you can go from a cyclic to a knot, cyclic to a knot, cyclic to a knot, and so on. What's fascinating here is that this is a programmable method based on knot theory to create interlinks structures that are defined based on the template that they originated with.

This has to be designed properly or programmed properly in order to get the design cyclic structure or supramolecular molecule. You can simulate or even calculate the type of interactions and the degree of interaction to result in that particular geometry. Even higher orders of assembly including proteins, a double helix can result in long range ordering of these structures to result in rods or particle complexes such as micelles, vesicles, and nanoparticles. These are the building blocks to go from molecular to nanomolecular and then mesoscopic. So for example cyclodextrin, cucurbiturils, calixarines are rings that are hydrophobic inside and hydrophilic outside, therefore, making them efficient complexing agents that can render organic molecules more soluble in aqueous or more polar solvents.

Can AFM be used to observe nanomachines or molecular cars?

AFM is a possible tool to actually visualize this supramolecular structure based on the interaction of the cantilever



A model of a single-molecule car that can advance across a copper surface when electronically excited by an STM tip.

Credit: Courtesy of Ben Feringa, co-winner Nobel Prize

and tip and the assembly or adsorption of the supramolecular structures in flat surfaces. AFM actually plays the key role in observing some of these movement or motion on what we call nanomachines or molecular cars.

Nanocars, when adsorbed on flat surfaces such as mica where the movement of the axle and the rod or wheel and the tire rods show movement over a particular space that can be tracked by atomic force microscopy.

What is the Interest in Polymer Physics about Molecular knots?

The interesting thing is if knots are formed in your DNA during replication, you're probably be dead. The reason is that cyclic structures or knots are unnatural systems that can mess up your DNA or cause diseases. The fortunate thing is the human body has what we call DNA polymerases that actually correct these structures and destroy them before they can do more harm. In polymer physics, knots and entanglements are a particular interest because chain entanglement as observed with high molecular weight polymers result in changes in the thermo-mechanical, physical, chemical properties of polymers in solution or melt or other real logical parameters or even reptation to tubes or narrow geometries or channels.

Can you explain Knotty Polymers by a Ring-Expansion Strategy

It is possible to make a knotty polymer by ring-expansion strategy. A true knot,

the simplest one, the trefoil knot is based on a 3-1 structure. The question is how can we prepare this and can we observe this indirectly and directly. Synthetically, we just extended the catenated structures into this bidentate ligand and the bi-functional ligand was then closed and then finally, the caprolactone was polymerized form a polycaprolactone system. Of course, demetalation when unfolded should give a trefoil knot.

Just to confirm that we can observe this by UV-Vis spectroscopy, NMR, or even x-ray photoelectron spectroscopy to confirm the presence of copper and tin on the molecules showed that we have a good correspondence with the drone structures and the empirical proof. GPC was used to look at the changes in the hydrodynamic volumes. Let me emphasize that a ring structure compared to a linear polymer will have a lower hydrodynamic volume even though they have the same molecular weight. For example, here in this GPC trace, you will see a linear polymer equivalent of a knotted polymer of the same molecular weight but the knotted polymer has a higher retention volume indicating that even though the molecular weight is the same, the hydrodynamic volume of the knotted macromolecule is lower or smaller. The proof is on the AFM. Actually, this was the first report of a trefoil knot synthetic polycaprolactone that was observed on mica and then upon closer examination of that adsorbed macromolecule indeed the trefoil knot structure was confirmed.



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