

## Nanometer-scale Science and Technology Division Room 19 - Session NS+SP+SS-ThA

### Advances in Scanning Probe Microscopy

**Moderator:** Sergei Kalinin, Oak Ridge National Laboratory

2:20pm **NS+SP+SS-ThA-1 Mapping Stress in Polycrystals with sub-10 nm Spatial Resolution**, *Celia Polop*, Universidad Autónoma de Madrid, Spain; *E Vasco*, *A Perrino*, *R Garcia*, Instituto de Ciencia de Materiales de Madrid, CSIC, Spain

From aircraft to electronic devices, and even in Formula One cars, stress is the main cause of degraded material performance and mechanical failure in applications incorporating thin films and coatings. Over the last two decades, the mechanisms responsible for stress generation during film deposition and processing have generated intense conjecture and scientific activity. However, no consensus has been reached so far. The main difficulty is that current models of stress generation, most of which are atomistic in nature, are only supported by data with at best sub-micron resolutions. For example, techniques such as curvature-based measurements, Raman spectroscopy, and x-ray diffraction cannot reveal the stress distribution in films on nanometer scales.

Here, we present a novel method for mapping the stress at the surface of polycrystals with sub-10 nm spatial resolution. This method consists of transforming elastic modulus maps measured by atomic force microscopy (AFM) techniques, such as force modulation method and bimodal AFM, into stress maps via the local stress-stiffening effect. The validity of this approach is supported by Finite Element Modeling simulations. By applying the method to Au polycrystalline films, we show that the intrinsic stress is heterogeneously distributed along the grain diameter, being concentrated in narrow strips adjacent and parallel to the grain boundaries (not directed inside the grain boundary, as is usually assumed). Stress gradients as intense as 100 MPa/nm are detected in these regions. Note that these gradients, which are undetectable by the standard techniques and tests used for stress analysis, are in the order of magnitude of the mechanical strengths required for many applications. The heterogeneous spatial distribution of the intrinsic stress along the grain diameter is the result of the Mullins-type surface diffusion towards the grain boundaries, and would be the probable cause of the kinetic compression that appears in polycrystals under conditions of high atomic mobility. Consequently, we demonstrate that the nanoscale stress mapping has great potential to disclose the nature and origin of the stress in solids.

[1] C. Polop, E. Vasco, A. P. Perrino and R. Garcia, "Mapping stress in polycrystals with sub-10 nm spatial resolution", submitted.

[2] E. Vasco, C. Polop, "The compressive intrinsic stress in polycrystals is not inside the grain boundary", submitted.

3:00pm **NS+SP+SS-ThA-3 XTIP – A Dedicated Beamline for Synchrotron X-ray Scanning Tunneling Microscopy**, *N Shirato*, *M Fisher*, *R Reininger*, *S Hla*, *Volker Rose*, Argonne National Laboratory

Recently, substantial progress was made on Argonne's Synchrotron X-ray Scanning Tunneling Microscopy (SX-STM) project. In particular, we demonstrated the power of SX-STM for elemental characterization and topography of individual Ni nano-islands on Cu(111) at 2 nm lateral resolution with single atom height sensitivity [1], tested a new probe tip concept based on carbon nanotubes [2], and demonstrated soft x-ray imaging of nanoscale magnetic domains of an iron thin-film by x-ray magnetic circular dichroism (XMCD) contrast [3]. Further substantial advances are expected using the new low temperature (LT) SX-STM system, which has been developed over the last 3 years and is currently under commissioning.

To fully exploit the special capabilities of the new LT x-ray microscope, XTIP, a dedicated beamline for SX-STM is under construction at the Advanced Photon Source. To meet the scientific objective of the nanoscience and nanomagnetism communities most effectively, we are going to build a soft x-ray beamline with full polarization control operating over the 500-1600 eV energy range.

The dedicated XTIP beamline will provide researchers access to a one-of-a-kind instrument. Among the potential breakthroughs are "designer" materials created from controlled assembly of atoms and molecules, and the emergence of entirely new phenomena in chemistry and physics.

This work was funded by the Office of Science Early Career Research Program through the Division of Scientific User Facilities, Office of Basic

Energy Sciences of the U.S. Department of Energy through Grant SC70705. Use of the Advanced Photon Source and the Center for Nanoscale Materials was supported by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences, under contract DE-AC02-06CH11357.

[1] N. Shirato et al., Nano Letters 14, 6499 (2014).

[2] H. Yan et al., J. Nanomaterials 2015, 492657 (2015).

[3] A. DiLullo et al., J Synchrotron Rad. 23, 574 (2016).

3:20pm **NS+SP+SS-ThA-4 Kelvin Probe Force Microscopy for High-Resolution Imaging of Hydrogen in Steel Alloys**, *Joy McNamara*, *P Korinko*, *M Morgan*, *A Duncan*, Savannah River National Laboratory

Understanding the mechanism of hydrogen interactions in metals is continually a topic of interest for those exploring the use of hydrogen as an alternative fuel source and for other applications which involve the long term storage of hydrogen. Atomic hydrogen in stainless steel alloys segregates to regions of extended defects, such as grain and phase boundaries, and can cause stress and premature cracking in a process known as hydrogen embrittlement. The presence of hydrogen can have serious consequences on the structural integrity and lifetime of hydrogen containers and piping, making it essential to understand the effect of hydrogen on the microstructural properties of stainless steel alloys. The migration of hydrogen through the crystal structure depends on the diffusion rate and solubility of hydrogen in a given phase which gives rise to varying hydrogen concentrations between phases. Hydrogen segregated at the surface of stainless steel specimens and particularly at defect sites changes the local work function of the material and can be measured by Kelvin probe force microscopy (KPFM). By co-locating the presence of hydrogen with extended defects at the surface using KPFM, it may be possible to predict the long term storage properties of a container. KPFM produces nanoscale surface potential (i.e., voltage) images, and is capable of measuring the local change in work function of materials with very high spatial resolution compared to current methods of optically imaging the microstructures of stainless steel. In this work, stainless steel specimens were fabricated by forging techniques and laser engineered net shaping (LENS), a directed energy deposition method of additive manufacturing, and were hydrogen charged at high pressure and temperature for approximately 2 weeks. The samples were then cut and polished to produce smooth surfaces and were imaged using KPFM. The resulting surface potential images show concentration differences of hydrogen at twin boundaries, phase boundaries and other defects as evidenced by a reduction in the local contact potential difference (CPD). Differences in CPD between the forged and LENS samples were observed and will be discussed. This work has potential to elucidate the effects of hydrogen on stainless steel components.

4:00pm **NS+SP+SS-ThA-6 Video-Rate Atomic Force Microscopy**, *Roger Proksch*, Asylum Research

We present results from a new, video rate AFM (Cypher VRS) capable of imaging delicate samples in air and fluid up to 625 lines/second (or >10 frames per second). This is about 300x faster than typical AFMs and 10x faster than current "fast scanning" AFMs. We will describe the architecture of this new AFM, and demonstrate the advantages of its unique design. Some recent specific examples are shown, including: (1) real time observation of the cleavage of a DNA molecule with the DNase1 enzyme. (2) a variety of high resolution examples including Bacteriorhodopsin molecules, the DNA double helix and single atomic point defects, all acquired at frame rates in excess of 1 frame per second, (3) the self-assembly of type I Collagen molecule into fibrils. Collagen molecules were injected on a bare mica surface and let spontaneously polymerize to form fibrils in a phosphate buffer. The typical banding pattern of 67 nm appeared as early as 1 min after introduction of the molecules, and, finally, (4) the dynamics of CTAB hemi-micelles at the solid-liquid interface (HOPG and aqueous buffer). These long molecules spontaneously form micelles in aqueous solutions and hemicylindrical structures upon adsorption onto HOPG. AFM can image these structures with high resolution but with the VRS the kinetics of the formation can now be followed in real time.

4:40pm **NS+SP+SS-ThA-8 Novel AFM Probes Enable Highly Sensitive Chemical and Thermal Characterisation at the Nano Scale**, *Georg Ramer*, *J Chae*, *S An*, NIST Center for Nanoscale Science and Technology / University of Maryland; *V Aksyuk*, *A Centrone*, NIST Center for Nanoscale Science and Technology

Photothermal induced resonance (PTIR) - a hyphenated technique of optical spectroscopy and scanning probe microscopy - allows to perform

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chemical imaging at nanoscale resolution [1,2]. The signal generation in PTIR consists of illuminating the sample with a pulsed tunable laser and transducing the local thermal expansion using a conventional AFM tip. The rapid expansion of the sample induces a ring down motion in the cantilever with amplitudes proportional to the absorption coefficient. Absorption images can be collected by moving the AFM tip across the sample, local absorption spectra can be collected by keeping the tip still and tuning the laser. PTIR works at ambient conditions and is non-destructive, making for a wide range of possible applications.

PTIR has been successfully applied to range of different samples, from life sciences, to photonics, material science and quality control [1,2]. Recently, PTIR sensitivity down to a monolayer has been demonstrated by using optical field enhancement between a gold tip and gold substrate as well as a mechanical enhancement by resonant excitation of the AFM cantilever.

Here, we present latest advances in improving the sensitivity of PTIR. Our novel AFM tips based on a nanosized picogram scale micromechanical cantilever as a displacement sensor and an optical resonator based near field read out achieve a thermal noise limited deflection measurement in the low fm Hz<sup>-0.5</sup> range. Through the high sensitivity and low noise detection of these new probes we obtain PTIR spectra of monolayer samples with high signal to noise ratio, without the need for optical field enhancement or resonant excitation.

Furthermore, low detection noise across the large bandwidth achieved by these probes enables the direct measurement of the sample thermal expansion dynamics after each laser pulse. Leveraging a simple model, the fitting of the thermal expansion dynamics yields the local thermal conductivity at unprecedented, nanoscale lateral resolution.

1 Centrone, A.: 'Infrared Imaging and Spectroscopy Beyond the Diffraction Limit', Annual Review of Analytical Chemistry, 2015, 8, pp. 101-126

2 Dazzi, A., and Prater, C.B.: 'AFM-IR: Technology and Applications in Nanoscale Infrared Spectroscopy and Chemical Imaging', Chem Rev, 2016

5:00pm **NS+SP+SS-ThA-9 Photoinduced Thermal Desorption Coupled with Atmospheric Pressure Chemical Ionization Mass Spectrometry for Multimodal Imaging**, *Matthias Lorenz*, C Brown, University of Tennessee; R Proksch, M Viani, A Labuda, Oxford Instruments; S Jesse, O Ovchinnikova, Oak Ridge National Laboratory

The key to advancing materials is to understand and control their structure and chemistry. However, thorough chemical characterization is challenging since existing techniques characterize only a few properties of the specimen, thereby necessitating multiple measurement platforms to acquire the necessary information. The multimodal combination of atomic force microscopy (AFM) and mass spectrometry (MS) transcends existing analytical capabilities for nanometer scale spatially resolved correlation of the chemical and physical properties of a sample surface. The combination of AFM and MS using resistively heated cantilever tips for thermal desorption has been demonstrated as a promising pathway for multimodal imaging. However, the nano-TA heated probes limit the ability to carry out more standard AFM measurements such as PFM, KPFM and cAFM. To enable a more general application of chemical imaging into an AFM platform we have developed a novel closed cell sampling on an Oxford Instruments Cypher ES for in situ surface sampling/imaging analysis using photothermal heating of the AFM tip for thermal desorption (TD) coupled to a Thermo Orbitrap Velos Pro with inline ionization by atmospheric pressure chemical ionization (APCI). This approach takes advantage of the blueTherm cantilever heating technology developed by Oxford Instruments for localized thermal desorption, and demonstrates its applicability to multimodal chemical imaging using mass spectrometry. The ability to use photothermal heating of an AFM probe versus conventional resistive heating nano-TA technology opens up the possibility for carrying out multiple AFM measurement approaches on a single AFM cantilever, for a true multimodal imaging approach to link chemical composition with material functionality. We show the use of photothermal heating as a means for thermal desorption surface sampling mass spectrometry. We illustrate the application of the AFM-MS coupling for the analysis of small molecules, i.e. pigment yellow 74 as a test substrate to show 500 nm achievable lateral resolution as well as show the application to pharmaceuticals and polymer films. Additionally, the ability to introduce fast heating rates for the TD through ps laser pulsing reduces the melting of sample material and improves the access to intact molecules.

5:40pm **NS+SP+SS-ThA-11 Synchrotron X-ray Scanning Tunneling Microscopy Investigations of Magnetic and Electronic Properties of Nanoscale Metal-Clusters**, *Hao Chang*, Ohio University and Argonne National Laboratory; N Shirato, M Cummings, Argonne National Laboratory; H Kersell, Ohio University and Argonne National Laboratory; D Rosenmann, J Freeland, V Rose, Argonne National Laboratory; S Hla, Ohio University and Argonne National Laboratory

Synchrotron X-ray scanning tunneling microscope (SX-STM) [1,2] combines two of the most powerful materials characterization techniques, synchrotron X-rays and scanning tunneling microscopy. SX-STM has a great potential revolutionize material characterizations with simultaneous elemental, magnetic and topological contrast down to the atomic scale. Here, we will present our recent SX-STM results of nanoscale materials measured at the Advanced Photon Source of Argonne National Laboratory. Using SX-STM X-rays absorption spectroscopy (XAS) technique, we are able to determine the X-ray absorption cross-section of a single nickel and cobalt nanoclusters on a Cu(111) surface. By employing circular polarized synchrotron X-rays, we are also able to demonstrate X-ray magnetic circular dichroism (XMCD) of the Fe L<sub>2</sub> and L<sub>3</sub> edges of a thin iron film deposited on Cu(111) [3] as well as LSMO/LNO superlattices in room and lower temperatures. Here, polarization dependent x-ray absorption spectra have been obtained through a specially fabricated tip that captures photoelectrons. Unlike conventional spin-polarized STM, x-ray excitations provide magnetic contrast even with a non-magnetic tip. Intensity variations in the photo-excited current indicate chemical variations within a single magnetic Fe domain. Moreover, using a hard X-ray nanoprobe beamline, we have successfully detected element specific X-ray induced electron emissions from a single cobalt nanocluster at room temperature. Here, varying the incident x-ray energy across the Co electron binding K-edge enables the detection of elementally sensitive electrons. As the tip scans across the single Co nanocluster- Au(111) surface boundary, atomic spatial dependent changes in the x-ray absorption cross section are directly measured by taking the x-ray induced current as a function of x-ray energy. In addition to presenting the recent results, we will also discuss potential future research directions using SX-STM.

[1] V. Rose, K. Wang, T.U. Chien, J. Hiller, D. Rosenmann, J.W. Freeland, C. Preissner, and S.-W. Hla. *Adv. Funct. Mater.* **23**, 2646-2652 (2013).

[2] N. Shirato, M. Cummings, H. Kersell, Y. Li, B. Stripe, D. Rosenmann, S.-W. Hla, and V. Rose. *Nano Lett.* **14**, 6499-6504 (2014).

[3] A. Dilullo, N. Shirato, M. Cummings, H. Kersell, H. Chang, D. Rosenmann, D. Miller, J.W. Freeland, S.-W. Hla, and V. Rose. *J. Synchrotron. Rad.* **23**, 574-578 (2016).

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