Tuesday Afternoon, October 22, 2019

Vacuum Technology Division
Room A213 - Session VT-TuA

Advanced Applications of Vacuum Technology

Moderators: Julia Scherschligt, National Institute of Sandards and Technology (NIST), Alan Van Drie, TAE Technologies

2:20pm **VT-TuA1 Single Atom and Single Electron Transistors for Quantum Technologies***, **Richard Silver**, X.Q. Wang, R.V. Kashid, J. Wyrick, P. Namboodiri, K. Liu, M.D. Stewart, G. Bryant,* National Institute of Standards and Technology (NIST) **INVITED**

Atomically precise fabrication has an important role to play in developing atom-based electronic devices for use in quantum information processing, quantum materials research and quantum sensing. Atom by atom fabrication has the potential to enable precise control over tunnel coupling, exchange coupling, on-site charging energies, and other key properties of basic devices needed for solid state quantum computing and analog quantum simulation. Using hydrogen-based scanning probe lithography we deterministically place individual dopant atoms with atomically aligned contacts and gates to build single electron transistors and single or few atom transistors.

We have developed robust lithography, device relocation, and contact processes that enable routine electrical measurement of atomically precise devices with an emphasis on minimizing process-induced dopant movement. Our low temperature palladium silicide contact process provides low-resistance ohmic contacts with yield better than 98%. Fabrication at the atomic scale requires exceptional vacuum and sample cleanliness. Our STM and sample preparation vacuum systems operate in the low $1x10^{-11}$ torr regime and we are implementing several hardware upgrades to achieve < 10^{-12} torr vacuum.

This presentation will cover the design, fabrication, and characterization of multiple STM patterned single electron transistors that demonstrate stable coulomb blockade oscillations. We will report measurements of the electronic properties and tunnel coupling in single electron transistors where the tunnel gap is varied at the dimer row scale. Shrinking single electron transistors to the atomic limit, we demonstrate single dopant atom and few dopant cluster devices - essential building blocks in silicon-based donor dot qubits and proposed solid state analog quantum simulators. This presentation will include spectroscopic transport measurements and modeling of atomically precise single and few atom transistors.

3:00pm **VT-TuA3 Turbomolecular Pump for Achieving Ultra-high Vacuum in a High-power Proton Accelerator Vacuum System***, **Junichiro Kamiya**, M. Kinsho,* Japan Atomic Energy Agency, Japan*; N. Ogiwara,* KEK, Japan*; M. Sakurai, T. Mabuchi,* Osaka Vacuum, Ltd., Japan*; K. Wada,* Tokyo Electronics Co., Ltd., Japan

Challenges for achieving an ultrahigh vacuum (UHV) region in J-PARC 3 GeV rapid cycling synchrotron (RCS), which produces proton beam with 1 MW power, come from the large static and dynamic outgassing. In the RCS vacuum system, turbomolecular pumps (TMP) have been used as main pump because it can evacuate such continuous and additional outgassing with a large pumping speed in the wide pressure range. TMP also has the advantage of not causing pressure instabilities like ion pumps. The more than 10 years operation of the RCS vacuum system showed that the UHV was rapidly obtained from the atmospheric pressure. It was also shown that the large additional outgassing during the high-power beam operation was promptly evacuated by the TMP due to its constant pumping speed in the wide pressure rage. The future operation with more high-beam power requires the vacuum system for the lower pressure region. The pumping speed and compression ratio of the standard TMP is limited by the rotational speed of the rotor. We have developed a TMP with the rotor of titanium alloy, which have much higher mechanical strength than aluminum alloy for the normal rotter. When the rotational speed increase by a factor of 1.3, the pumping speed and compression ratio increase by a factor of 1.3 and 12.5, respectively. The increase of the compression ratio is especially effective for hydrogen, which is the main outgas component in the UHV region. Challenges in the development comes from the difficulty of the machining performance and the weightiness of the titanium alloy comparing with the aluminum alloy. We report the signification and the status of the development of the TMP with titanium alloy.

3:20pm **VT-TuA4 US Contributions to ITER Vacuum Auxiliary System***, **Charles Smith**,* Us Iter

This paper gives an overview of the ITER Tokamak Vacuum Auxiliary System (VAS) with a focus on the design challenges, solutions, and validation unique to a reactor-scale fusion vacuum system.

US ITER, the United States Domestic Agency for US contributions to the ITER project, is responsible for the final design, procurement, and acceptance testing for the Vacuum Auxiliary System (VAS) to be used in support of over 5000 clients of the ITER machine. The VAS system consists of more than six kilometers of pipework used in the vacuum roughing headers, more than 100 high-vacuum stations to support specific plant needs, and the Service Vacuum System (SVS) which is used to connect the roughing system to the end-use clients. VAS is a key element to the world's first vacuum system rated for a licensed nuclear fusion facility.

ITER received a nuclear construction authorization decree from the French Ministry of Environment in 2012, as its goal is to demonstrate the feasibility of fusion energy and produce a reactor-scale deuterium/tritium fueled plasma. ITER's VAS will utilize ASME B31.3 piping with a minimum schedule 10 wall thickness. In most large vacuum systems, commercially available vacuum fittings, flanges, and other standard components are designed around tubing. The requirement for schedule 10 piping and B31.3 design criteria has resulted in US ITER designing and certifying the components as opposed to procuring commercial off-the-shelf (COTS) items. These components must then be integrated into the overall VAS system in a way that meets all seismic and safety requirements needed to maintain tritium confinement. In addition to developing safety-critical double-gasket vacuum flanges, the certification of standard CF flanges to B31.3 has been required.

The VAS system's interfaces and location through the tokamak building have created another set of challenges to the use of standard vacuum equipment. The tokamak building will be subjected to radiation and high magnetic fields during plasma operations. The proximity of vacuum systems to high power RF systems and tritium containment are all design inputs for VAS design. The SVS portion of VAS, in addition to its role of interfacing between clients and the roughing header, acts as an integral part of plant safety systems. The interspaces between the gaskets on safety related flanges are actively monitored by SVS to detect any change in pressure which could indicate a leak. As an example, the SVS is used to verify the integrity of diamond vacuum windows used in high-powered RF plasma heating systems.

The work detailed in this paper, shall illustrate the progress being made to reach the first plasma milestone.

4:20pm **VT-TuA7 Importance of Advanced Vacuum Technology to the Present Thin Film Photovoltaics Industry***, **Timothy Gessert**,* Gessert Consulting, LLC **INVITED**

World use of photovoltaic (PV) solar electricity has been increasing at an average annual exponential growth rate >35% since about 2000. Not surprisingly, during this same time, the percentage of US-consumed energy (~100 Quadrillion BTUs total) derived from PV has increased from ~0.003% in 2004, to >1% at the end of 2018. Indeed, if these trends continue, PV could produce >50% of all energy consumed in the US by as early as 2030. Combining this with the rapidly decreasing energy costs for large grid-tied PV systems (presently <2.5¢/kWh for long-term power purchase agreements) largely explains why PV-derived energy is – even now – a main source of *new* US and world energy. Although the majority of this PV-derived energy is presently generated by crystalline-based Si module technologies, because of combined efficiency, production, cost, and other advantages, an ever-increasing amount of PV energy is being produced from polycrystalline thin-film (TF) materials. These TF PV technologies owe much of their rapidly advancing success to improved understanding in related materials synthesis, while applying these advancements to industry, in turn, has relied on design innovations of related vacuum-process equipment. This talk will briefly overview the present state of TF PV technologies, taking into consideration both the present dominance of crystalline Si PV, and evolving trends in TF PV. Several examples where keen understanding of vacuum processes in laboratory-scale devices has fostered successful utilization of advanced vacuum technology in the commercial TF PV industry will be presented. The talk will also suggest some areas where further advancements in vacuum-process and equipment innovation could yield potentially even lower-cost TF PV technologies.

5:00pm **VT-TuA9 Enabling Hydrogen as an Energy Carrier through Analytical Electron Microscopy**, ***David Cullen***, *K. More,* Oak Ridge National Laboratory **INVITED**

Hydrogen is an important energy carrier which can be produced from renewable or intermittent energy sources for use in markets ranging from metal refining to transportation. Polymer electrolyte membrane fuel cells (PEMFCs) are a key technology for converting the chemical potential energy of hydrogen in electrical energy and driving down the cost of these systems is important towards enabling a hydrogen economy. At the heart of the matter is the membrane electron assembly (MEA), which consists of an anode and cathode separated by a proton-conducting membrane. Pt-based catalysts are typically used to drive the sluggish oxygen reduction reaction (ORR) at the cathode and are responsible for much of the cost of the MEA. Near term approaches to reduce Pt loading and hence cost involve the development of Pt-alloy catalysts which show exceptionally high mass activity but require improvements in durability. Long-term solutions will require the development of stable platinum group metal-free (PGM-free) catalysts, with current best-in-class candidates being derived from transition metal doped metal organic frameworks (MOFs). In both approaches, accelerated materials discovery and development is required to keep pace with increasing market and performance demands.

To this end, scanning transmission electron microscopy (STEM) has been employed to study MEAs from the atomic to micron scale. The application of atomic-resolution spectroscopic techniques to assess the quality and durability of Pt-alloy and PGM-free electrocatalysts will be presented. At a wider scale, the impact of particle dispersion, hierarchal porosity and proton-conducting ionomer distribution will be linked to electrochemical performance limitations through quantitative STEM imaging and energy dispersive X-ray spectroscopy (EDS). Finally, the movement of dissolved species across the membrane and gaseous diffusion layer will be explored to explain durability losses during fuel cell cycling. The synergy between electron microscopy and other characterization techniques such as X-ray photoelectron spectroscopy, X-ray absorption spectroscopy, and Mossbauer spectroscopy will also be discussed

Research sponsored by the Fuel Cell Technologies Office, Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy (DOE), as part of the FC-PAD and ElectroCat Consortia, which is part of the Energy Materials Network. Microscopy performed as part of a user project at ORNL's Center for Nanophase Materials Sciences (CNMS), which is a U.S. DOE Office of Science User Facility.

5:40pm **VT-TuA11 Defect Manipulation to Control Energy Processes in Electronic Materials**, ***Leonard Brillson,*** The Ohio State University **INVITED**

The control of native point defects in advanced electronic materials and device architectures is critical to a wide array of energy intensive processes including generation, transport, storage, switching, and display. AVS research in electronic materials surfaces and interfaces at the nanoscale has played an important role in this arena. Defect control of transparent conducting oxides such as ZnO for smart windows and heads-up displays have revealed how to create homojunctions with high electron mobility 2-dimensional interfaces.[1] Surface/interface techniques enable identification and control of native defects in Ga_2O_3,[2] outlooked for RF power amplification and power switching. Defect control has enabled creation of 2-dimensional hole gases at $LaAlO_3/SrTiO_3$ interfaces, opening an avenue to new architectures for complex oxide electronics. Depth-resolved defect measurements in V_2O_5 battery electrode films reveal how lithiation introduces degenerate doping and secondary phase formation, integral to ion and charge transport inside next-generation nanoscale battery architectures.[3] Direct, localized optical, and electrical measurements of ZnO nanowires – envisioned for wearable electronics and displays - show that native point defects inside the nanowire bulk and created at metal-semiconductor interfaces are electrically active[4,5] and play a dominant role electronically, altering the doping, carrier density along the wire length, and the injection of charge into the wire.[6] Defects in all these materials can now be manipulated by ion beams, electric fields, remote oxygen plasmas, and nanoscale design, opening new avenues to control charge injection, transport, and storage.

1. G. M. Foster et al., "Direct Measurement of Defect and Dopant Abruptness at High Electron Mobility ZnO Homojunctions," Appl. Phys. Lett. **109**, 143506 (2016).

2. H. Gao et al., " Optical Signatures of Deep Level Defects in Ga_2O_3," Appl. Phys. Lett. **112**, 242102 (2018).

3. H. Lee et al., "Direct observation of a two-dimensional hole gas at oxide interfaces," Nature Materials **17**, 231-236 (2018).

4. W.T. Ruane et al., "Defect Segregation and Optical Emission In ZnO Nanowiresand Microwires," Nanoscale **8**, 7631-7637 (2016).

5. A. Jarjour et al., Single Metal Ohmic and Rectifying Contacts to ZnO Nanowires: A Defect Based Approach," Ann. Phys. (Berlin), **530**, 1700335 (2018).

6. J.W. Cox et al., "Defect Manipulation to Control ZnO Micro-/Nanowire-Metal Contacts," Nano Letters **18**, 6974 (2018). **DOI:** 10.1021/acs.nanolett.8b02892

Author Index

Bold page numbers indicate presenter