Nanoscale Science and Technology
Room 206 A W - Session NS-MoA

Light-Matter Interactions at the Nanoscale

Moderators: Nikolai Klimov, National Institute of Standards and Technology, **Sesha Challa**, NIST-Gaithersburg

1:30pm **NS-MoA-1 Ultrafast and Ultrasmall Characterization of Excitations in Two-Dimensional Heterostructures***, **Archana Raja,*** Lawrence Berkeley National Laboratory (LBNL) **INVITED**

Atomically thin van der Waals crystals allow for the creation of arbitrary, atomically precise interfaces simply by stacking disparate monolayers without the constraints of covalent bonding or epitaxy. By leveraging the environmental sensitivity of interactions at the ultra-thin, two-dimensional (2D) limit, we can "paint" potential energy landscapes to create and control the electronic structure and excitations in these systems. We have characterized and discovered phenomena in such 2D potential landscapes from the atom scale to the application scale using multimodal photon and electron-based spectroscopies.

I will provide an overview of our joint experimental and theoretical work on the prototypical 2D semiconductor interface of monolayer WS_2 and monolayer WSe_2. In part one, we use ultrafast electron diffraction to reveal the role of layer-hybridized electronic states for controlling energy and charge transport across atomically sharp junctions [1]. In part two, we align the registry of the two layers to create a moiré superlattice ~9 nm in size and use electron energy loss spectroscopy to directly visualize the real space localization of excitonic states within a single moiré unit cell [2]. This suggests the possibility of engineering excitonic superlattices with nanometer precision. In the third and final part, I will discuss the transport of energy across the plane of such a superlattice potential using interlayer excitons [3]. We uncover unexpected trends in the temperature dependent exciton diffusivity, which suggests that the moiré potential landscape is dynamic down to very low temperatures

[1] A. Sood*, J. Haber*, A. Rajaet al. "Bidirectional phonon emission in two-dimensional heterostructures triggered by ultrafast charge transfer," *Nature Nanotechnology* 18 (1), 29-35 (2023)

[2] S. Susarla*, M. H. Naik*, A. Rajaet al. "Hyperspectral imaging of excitons within a moiré unit-cell with a sub-nanometer electron probe," *Science* 378 (6625), 1235-1239 (2022)

[3] A. Rossi*, J. Zipfel*, I.Maity*, A. Raja et al. "Anomalous interlayer exciton diffusion in WS_2/WSe_2 moiré heterostructure," *ACS Nano* 18 (28), 18202-18210 (2024)

2:00pm **NS-MoA-3 Towards the Development of Robust Chip-Scale Photonic Thermometers*, Sesha Challa,*** *Michal Chojnacky, Kevin Douglass, Thinh Bui, Daniel Barker, Nikolai Klimov,* NIST-Gaithersburg

Accurate, high-precision temperature metrology is critical for industries, defense, and healthcare. Temperature also is ranked as the second most measured physical property, following time and frequency, underscoring its role in both applied and fundamental sciences. Resistance-based temperature sensors such as standard platinum resistance thermometers (SPRTs), are the benchmark for conventional temperature metrology due to their high accuracy and widespread acceptance. However, their performance is hindered by sensitivity to environmental conditions and mechanical stress. These inherent limitations, coupled with the critical need to reduce dependence on the calibration chain, have spurred significant interest in developing alternative technologies such as photonic thermometry.

At the National Institute of Standards and Technology (NIST), we are developing an integrated photonic-based temperature sensing platform that can bypass the limitations of SPRTs and transform the way temperature is realized and disseminated. Photonic-based sensors also offer the potential to eliminate costly and disruptive recalibration processes. At the core of this sensing platform is an ultra-sensitive photonic thermometer (SPoT). It consists of an on-chip integrated silicon nanophotonic resonator. The device's optical resonance frequency shifts with temperature, enabled by the high thermo-optic coefficient of single-crystal silicon. This allows precise tracking of temperature variations with exceptional sensitivity. The performance of the SPoT device is critically influenced not only by the sensor design but also by key factors in photonic packaging, which together determine its overall sensitivity, stability, and reliability. Reproducibility in sensor performance is often compromised by fabrication variability, especially in shared nanofabrication facilities.

In this work, we address fabrication-induced variability by investigating sensor designs that are inherently tolerant to process deviations. Our study focuses on photonic crystal cavities, ring resonators, and tapered-width resonators, all fabricated under identical conditions. These structures are implemented on a commercially available 220 nm silicon-on-insulator platform to evaluate their robustness and suitability for reliable, reproducible photonic thermometry.

2:15pm **NS-MoA-4 SpoT On: Precision Photonic Thermometry System with Packaged Sensor and Modular Readout Architecture*, Michal Chojnacky,*** National Institute of Standards and Technology (NIST)/ University of Maryland, College Park*; CH. S. S. Pavan Kumar, Kevin Douglass, Thinh Bui, Nikolai Klimov,* National Institute of Standards and Technology (NIST)

Photonic temperature sensors have attracted significant interest as alternatives to resistance thermometers due to their high-temperature sensitivity, robustness to electrical interference and mechanical shock, small form factor, manufacturing scalability, and compatibility with CMOS fabrication processes. Different types of sensing elements, including photonic crystal cavities, fiber Bragg gratings, and microresonators have been demonstrated, along with strategies for device packaging and characterization. Each of these photonic temperature sensors relies on a temperature-dependent shift in the device's optical resonance frequency due to a combination of thermo-optic and thermal expansion effects, which can deliver sensitivities of 10s of pm/K and resolve sub-mK level temperature changes. However, implementing these technologies in a practical thermometry platform capable of providing stable, reliable, and repeatable temperature measurements remains a challenge. In this work, we describe the development of a chip-scale, silicon microresonator-based photonic thermometer, with the goal of delivering a packaged, functional, field-deployable thermometer and the supporting photonic readout to enable its use in both calibration laboratories and demanding field environments.

The Sensitive Photonic Thermometer (SPoT) described in this presentation is based on a silicon microring resonator integrated in a photonic chip. The device is fiber-bonded and packaged in a capsule format suitable for performance testing in International Temperature Scale of 1990-defining fixed point cells and thermometric baths. We present the metrological characterization of SPoT and benchmark its performance against the state-of-the-art Standard Platinum Resistance Thermometer (SPRT). We provide an overview of different device interrogation architectures that can be used for deployable and cost-effective photonic readout of SPoT. We also outline further steps for achieving a metrology-grade SPoT platform with an absolute frequency axis suitable for replacing SPRTs in calibration laboratories.

2:30pm **NS-MoA-5 Development of New Chip-Scale Photonic AC-DC Thermal Transfer Standard***, Sesha Challa, Michal Chojnacky, Kevin O. Douglass, Daniel S. Barker,* NIST*; Stefan Cular,* Howard Community College, Columbia, MD*; **Nikolai Klimov,*** NIST

One of the state-of-the-art ac-dc thermal transfer standards, such as Multijunction Thermal Converter (MJTC), relies on comparing the Joule resistive heating of an unknown ac signal to a known dc signal. The resistive temperature sensor, a thermocouple array, detects the heat generated by an electrical signal applied to the heater. Despite being accurate, MJTC reached its fundamental limitations. MJTC suffers from frequency-dependent heater impedance due to capacitive coupling between the ac current flowing through the resistive heater and the thermocouple array. Furthermore, the precision of ac-dc difference cannot be increased much further by increasing the size of the thermocouple array. To address these limitations and to reduce the ad-dc difference calibration chain, we are developing an alternative, photonics-based technology to perform ac-dc difference measurements. Our new chip-scale Photonic Thermal Transfer Standard (PTTS) device is designed to match or exceed the metrological performance of conventional thermal transfer standards, overcome the current technological barriers, and reduce the ac-dc difference calibration chain. The PTTS device, similar to the MJTC standard, detects local temperature changes from Joule heating induced by ac/dc electrical currents. However, in contrast to MJTC, the temperature sensing element in PTTS is photonics-based. Waveguide-integrated microscale photonic thermometer not only has ultra-high resolution and precision but is also immune to RF interference and does not have a capacitive coupling with the resistive heater. In this work, we demonstrate the first prototype chip-scale photonic device to perform ac-dc difference. The device exhibits a larch ac response above 100 kHz, typical of conventional MJTCs due to fixture constraints (cables, wire bonding, leads). The following generation of PTTS chips will address these limitations. At the end of the presentation, we will outline the future directions toward the development of the new photonics-based thermal transfer standard.

2:45pm **NS-MoA-6 Deterministic Design of Pseudo-Randomly Distributed Nanostructures for Antireflectivity in the MWIR.** *, **Samir Paudel**, Menelaos K. Poutous,* University of North Carolina at Charlotte

Binary-phase subwavelength gratings (SWG) can perform as antireflective structures. Fabricating SWG for applications in the mid-wave infrared (MWIR, 3-5 µm wavelength) can be challenging due to a substrate's optical index and hardness. For high index contrast, antireflective SWG are required to have a depth which can be of the order of a wavelength [1]. The SWG fill-factor can be numerically optimized to improve antireflective efficiency, without any conceptual insight into the SWG profile. Recent experimental results show that pseudo-randomly distributed nanostructures (PRnS) can enhance optical transmission through dielectric windows as well [2,3]. In contrast to optimization by numerical iteration techniques, we have utilized deterministic principles to design PRnS with a-priori minimum-feature dimensions, and specific selection rules for off-axis transmitted intensity scatter profiles. To enhance antireflectivity, we used more than one binary phase transition within the periodic basis cell, to control the effective index value and off -axis scatter profile. We selected linear, low and high scatter PRnS patterns, with a universal critical feature size of 400 nm, to achieve optical surface transmission enhancement above Fresnel limits within the MWIR bandwidth. To ease fabrication requirements, the designs were restricted to a binary phase-depth close to π/2, and unit cell periodic dimensions between 0.8 µm and 4 µm. The PRnS patterns were fabricated using direct two-photon laser-writing in a negative-tone polymer film on a sapphire substrate. To verify fabrication fidelity and tolerance, the PRnS patterns were characterized using a contactless UV-laser confocal microscope. Unpolarized spectral transmission was measured at normal angle of incident using a spectrophotometer in the 2 – 5 µm wavelength band. The measured unpolarized spectral transmission indicates that, with the same critical feature size, wide off axis scatter PRnS patterns exhibit superior antireflectivity performance compared to narrow off-axis scatter PRnS patterns. The experimental results were in good agreement with numerical rigorous coupled-wave analysis simulation predictions.

References:

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2)S. Paudel, P. Gadamsetti, and M. K. Poutous "Design and fabrication of deterministic, pseudo-randomly distributed, binary phase nanostructures for reflectivity suppression", Proc. SPIE 12898 (2024).

3)S. Paudel and M. K. Poutous "Wide angle-of-incidence reflectivity suppression in the NIR by pseudo-randomly distributed binary phase nanostructures", Proc. SPIE 13362 (2025).

3:00pm **NS-MoA-7 Plasmonic Behavior in Boron-Doped Diamond Arising from Low Energy, Intervalence Band Electronic Excitations***, **Souvik Bhattacharya**, R. Mohan Sankaran,* University of Illinois at Urbana Champaign

Diamond is well-known for its extraordinary mechanical, thermal, and optical properties. The introduction of impurity dopants can further tune and transform diamond. For example, boron, a p-type dopant, has been used to enhance electronic conductivity[1] and produce superconductivity[2]. In recent years, a whole host of other impurity atoms in combination with vacancies have been found to create color centers with unique spin properties that have potential for quantum technologies.[3]

In this talk, we will discuss our recent discovery of low energy (<0.5 eV) plasmonic excitations emerging from the valence subbands as a result of boron doping of diamond.[4] Our study was made possible by recent advancements in characterization techniques including scanning transmission electron microscopy-valence electron energy loss spectroscopy (STEM-VEELS) and near-field infrared (IR) spectroscopy. Applying these techniques to boron-doped diamond, we obtain complementary information about the material response in terms of the energy loss and absorption. A theoretical treatment based on first-principles calculations is then carried out to elucidate the fundamental band origin of the response. We show that boron doping leads to emptying of valence subbands, opening up intervalence band (IVB) transitions. Further analysis of the real dielectric component of the calculated response function reveals a resonance and zero-crossing that blue shifts with increasing carrier density, indicating the emergence of metallicity and plasmonic behavior. This mechanism is notably distinct from the collective Drude-like intraband excitations that are reported in traditional metals and other doped semiconductors. The possibility of plasmonic properties in diamond is yet another insight into this remarkable material that could be combined to for example, enhance the fluorescence of color centers for quantum sensing applications.

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3:15pm **NS-MoA-8 Two-Layer Dual-Mode Reflective-Transmissive Polarization Converter by Stereometamaterials***, **Sanchita Sarker**, Mohammad Parvinnezhad Hokmabadi,* University of North Carolina at Charlotte

The ability to control light polarization is vital for applications in imaging, communications, metrology, among others. and. This work reports a systematic approach using supercells of periodic metamaterials to achieve enhanced polarization control. The use of supercells, with identical resonators, provides enhanced parameter flexibility, enabling facile control over the phase and polarization of scattered beams through rotation, flipping, and shifting of the resonators. In particular, we show that by changing the symmetry of the structure from reflection to inversion in a subwavelength two-layer supercell, a transmissive polarization conversion device can be transformed into a reflective counterpart, both with near-unity polarization conversion ratios. This systematic use of supercells highlights their potential for advanced polarization manipulation in electromagnetic and optical devices.

3:30pm **NS-MoA-9 Metamaterial Enabled Semiconductor Lasers***, Sanchita Sarker, **Mohammad Parvinnezhad Hokmabadi**,* University of North Carolina at Charlotte

Over the past two decades, metamaterials—judiciously designed subwavelength structures—have revolutionized optics, enabling breakthroughs in imaging and optical analog computation, among other areas. Recently, interest has expanded to include their use in on-chip beam manipulation and light outcoupling in passive systems. However, their potential within *active* photonic devices—particularly for controlling light inside laser cavities and shaping unconventional cavity geometries—remains largely unexplored. While techniques such as photonic crystals, topological photonics, and optical supersymmetry have been leveraged to enhance laser performance, metamaterials have yet to be fully utilized in this context.

Metamaterials offer distinct advantages that distinguishes them from other structures, particularly their ability to manipulate phase and amplitude at subwavelength scales that are not readily available in other platforms. In this work, we exploit these properties to engineer surface phase profiles that couple into the laser cavity, thereby enhancing the performance of semiconductor lasers. Our devices are based on InGaAsP quantum wells, emitting near 1550 nm. In a standard configuration, the laser cavity supports higher-order lateral modes, which degrade the spatial coherence and brightness of the emitted beam. To address this, we have integrated metamaterial nano-resonators into the cavity of this laser to manipulate light propagation in the lateral direction.

Through careful design of these subwavelength structures, we demonstrate suppression of higher-order lateral modes in favor of the fundamental mode. As a result, the laser emits predominantly in the fundamental lateral mode, significantly enhancing its brightness. To our knowledge, this is among the first demonstrations of incorporating metamaterials directly into the active region of a semiconductor laser cavity, paving the way for novel applications of metamaterials in active photonic devices.

4:00pm **NS-MoA-11 Direct-Write Ion Patterning of Aluminum Nitride Towards Tuning Integrated Photonics***, **Bogdan Dryzhakov**, Kyle Kelley,* Oak Ridge National Laboratory

Leveraging focused ion beams, this study spatially patterns point defects into wurtzite aluminum nitride (AlN), achieving defect-driven tunability of ferroelectric, optical, and thermal properties. The robust bonding and strong restoring forces of the AlN lattice help preserve long-range polar order even at ion irradiation doses up to 10^{18} ions/cm^2, enabling highly localized defects that act as domain nucleation sites for ferroelectric polarization reversal. Notably, ion irradiation induces stable ferroelectricity in nominally piezoelectric AlN and reduces the ferroelectric switching barrier in boron-substituted aluminum nitride ($Al_{0.94}B_{0.06}N$) by more than 40%. Advanced spectroscopic imaging, including photo- and cathodoluminescence, Raman spectroscopy, and thermal conductance mapping, spatially tracks evolving signatures of defect states and directly correlates them with the emergent ferroelectric functionality and significant (>10×) thermal tunability. Finally, integrating this localized defect engineering of AlN films into quantum photonic integrated circuits enables on-chip tuning of piezoelectric and nonlinear optical coefficients, demonstrating its promise as a practical method for advanced electro-optic and photonic device engineering.

4:15pm **NS-MoA-12 Actively Tunable in-Plane Hyperbolicity in Excitonic Single-Walled Carbon Nanotubes***, **Jason Lynch**, Deep Jariwala,* University of Pennsylvania

Hyperbolicity allows for the confinement of extremely large electric fields on the nanometer scale and the control of the propagation of electromagnetic energy within it. Hyperbolic metamaterials in the visible and near infrared rely on free-carrier effects since plasmonic media were the only ones with strong enough optical responses to host negative permittivities in this energy range. As a results of using plasmonic media, hyperbolic systems lack tunability and emissivity without the implementation of an adjacent active layer. However, narrow, inorganic excitons have recently been shown to exhibit negative permittivities in several different media just above their resonant energies. Therefore, excitons promise to enable hyperbolic media that is intrinsically emissive and highly tunable. Most of these systems require low temperatures (with the exception of chiral-pure single-walled carbon nanotubes (SWCNTs) and hBN-encapsulated, exfoliated WS_2), and they typically lack in-plane optical anisotropy. Here, we study the electro-optical properties of chiral-pure, aligned SWCNTs, and we observe that SWCNTs have a hyperbolic region that is actively tunable using electrostatic doping. We first use the Lorentz oscillator model to provide insights on the requirements for excitons to exhibit negative permittivity, and what would be needed for a true epsilon-near-zero excitons. Using these insights, we find that excitonic SWCNTs must be chiral-pure and high-density to exhibit negative permittivities. Next, micro-Mueller matrix ellipsometry is used to observe actively-tunable, in-plane hyperbolicity in aligned SWCNT films. The hyperbolic window is tuned by 50 meV by injecting $\approx 10^{13}$ carriers/cm^2. For comparison, the Drude model predicts that the plasmon resonance would be tuned by < 1 meV in ITO at the same transition energy. Therefore, SWCNTs have a 60x improvement in hyperbolic tunability than free-carrier systems when normalized for energy. Additionally, the loss in the SWCNTs at the hyperbolic transition is found to be comparable to TiN showing that it could be implemented in similar hyperbolic systems. When combined with the ability for SWCNTs to be globally-aligned on the wafer-scale, our work demonstrates that SWCNTs has great potential as a hyperbolic medium for both emissive and active photonics.

4:30pm **NS-MoA-13 Imaging Photonic Resonances within an All-Dielectric Metasurface via Photoelectron Emission Microscopy***, **Andrew Kim**,* Sandia National Laboratories*; Chloe Doiron,* Sandia National Laboratories, USA*; Fernando Vega,* Purdue University, USA*; Jaeyeon Yu, Alex Boehm, Joseph Klesko, Igal Brener, Raktim Sarma, Alexander Cerjan, Taisuke Ohta,* Sandia National Laboratories, USA

Dielectric nanophotonics aims to achieve precise control of light-matter interactions by confining light within subwavelength structures and manipulating the electromagnetic fields therein. Such precise control is utilized towards technological applications that include imaging, holography, and sensing, among others. Here, we use photoelectron emission microscopy (PEEM) to demonstrate near-field imaging of optical resonances within a dielectric metasurface in the ultraviolet to visible wavelength range. This approach involves far-field photonic excitation akin to the illumination conditions of photonic devices and allows for near-field imaging at a sub-optical wavelength spatial resolution. We analyze the local volumetric field variations within the meta-atoms as a function of excitation wavelength and polarization by comparing photoelectron images to finite-difference time-domain simulations. The metasurface supports two distinct resonances that occupy regions of different material thickness within the metasurface, resulting in a contrast in photoemission intensity due to the inelastic mean free path (IMFP) of the photoelectrons. The simulations replicate the intensity distribution in PEEM images by accounting for this IMFP as the two resonances shift their intensity as wavelength is varied. Through our analysis, we determine the IMFP of very low kinetic energy (<1 eV) photoelectrons to be ~35 nm, which is comparable to the meta-atom height and thus highlights the PEEM sensitivity to resonances within the volume. Overall, these results demonstrate that photoelectron imaging with sub-wavelength resolution is suitable for examining light-matter interactions in volume-type (as opposed to surface) photonic modes within dielectric nanophotonic structures.

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4:45pm **NS-MoA-14 Investigation the Photocatalytic effect of RuO_2 loading on TiO_2 towards Hydrogen Evolution in Visible Light***, **Moses Ashie**, Bishnu Bastakoti,* North Carolina A&T State University

The significant role that fossil fuels have played in energy utilization cannot be underestimated. However, owing to the non-renewable and CO_2 emission associated to its usage has paved a way for a search for a more renewable and environmentally unfriendly energy sources of which hydrogen energy identified as a potential target. A highly porous TiO_2-RuO_2 heterogenous solvothermally engineered photocatalyst revealed how varying synthesis conditions can contribute to the modification of TiO_2 towards effective photocatalytic water splitting in the visible region of the electromagnetic spectrum. Characterization techniques such as XRD, SEM, TEM, UV-Vis DRS, and electrochemical analysis revealed that TiO_2-RuO_2-20 exhibited reduced band gap, improved light absorption capability, lower electron-hole recombination rate, lower solution resistance which collectively contributed to effective photocatalytic activity. In addition, a high surface area and mesoporous nature contributed to 1794.8 mmolg^{-1}h^{-1} of hydrogen gas. Compared to the pristine RuO_2 (21.9 mmolg^{-1}h^{-1}) and the commercially available TiO_2 (246.4 mmolg^{-1}h^{-1}), the TiO_2-RuO_2-20 sample produced a yield that is almost 81 times and 7 times respectively. This therefore proves the effectiveness of the solvothermal method and the ruthenium dioxide in modulating the photocatalytic properties of TiO_2 photocatalyst for photocatalytic water splitting in visible light.

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