Overview and Key Goals

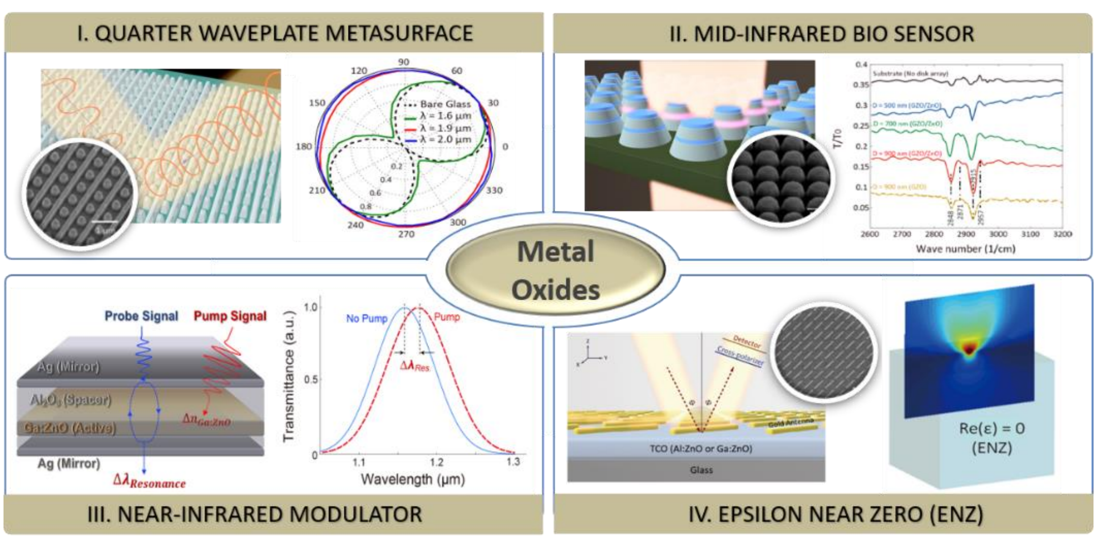
With a strong demand for compactable optical devices, significant advances have been made in the field of plasmonic and nanophotonics, including a development of metamaterials, metasurface, nanoscale laser and on-chip photonic devices. Especially, the recent growth of material platforms has accelerated the progress of nanophotonic devices, allowing us to extend the spectral range and the application domain. In my research career, I have worked on the establishment of metal oxides as key components for the development of unique nanophotonic and optoelectronic devices in the infrared (IR) range. To enable this, my research has extended from exploring the fundamental optical properties of materials to developing original concepts and approaches to designing novel optical devices for various applications. Behind my distinct career choice is a strong desire to advance many novel physical phenomena in plasmonics and nanophotonics into real and practical technologies. I intend to pursue this goal with a three-pronged approach:

- ***Study on the fundamental characteristic of the intriguing optical phenomena*** *such as epsilon near zero (ENZ), nonlinear dynamics, hot carrier effects and Casimir forces in solid-state materials to achieve insight into this physics for the development of light-controlled and tunable devices.*
- ***Explore potential material platforms in nanophotonics*** *by engineering the intrinsic properties of materials for the extension of spectral regimes and the improvement of device performance.*
- ***Develop building blocks for the construction of high density photonic circuits*** *based on the research of both novel mechanisms and materials.*

The successful development of those research plans will bring new fundamental understanding of the evolved physics and a solution to bridge the gap between new findings and future technologies for a new era in nanophotonic.

Previous and Current Research

My PhD work on metal oxides are motivated by searching for low optical-loss metallic components for IR plasmonics. I developed systematic approaches to study metal oxides and their devices applications. These approaches include film growth, ellipsometry analysis, nano-patterning, and device characterization[1-3]. Based on these approaches, my work led to 1) multilayered plasmonic resonator for surface-enhanced infrared absorption spectroscopy (SEIRAS) applications[4] and 2) dual-band quarter waveplate metasurface for the near-IR[5]. Those works successfully demonstrate that metal oxides are a very promising material platform for sensing and light control applications in terms of tunability, compatibility with other materials, and simplicity of geometry to create resonance in the IR range.



<Figure 1. Nanophotonics devices based on metal oxides. I) Metasurface for controlling the polarization state of reflected light resulting in quarter waveplate operation. II) Surface enhanced IR absorption spectroscopy with layered metal oxides for sensing. III) Metal oxide embedded nanocavity for high speed optical modulation in the near-IR range. IV) ENZ substrate for controlling nano-antenna's resonance and radiation.>

In parallel, I have performed research on extraordinary physics including epsilon near zero (ENZ) properties[6] and ultrafast nonlinear response[7, 8] in metal oxides. ENZ properties in metal oxides allow us to develop a new approach to control the resonance and radiation of nanoscale antenna[6], and the nonlinear response in metal oxides enable us to achieve ultrafast (>400fs) spectral tuning of the near-IR resonance of metal oxide embedded Fabry-Pérot nanocavities[9]. Additionally, the original approach to embed the functional system into a nanocavity enables us to develop multi-band optical color filters in the visible range by the introduction of metasurface into the metal-insulator-metal (MIM) optical nanocavity[10].

My primary postdoctoral work at the University of Maryland has been in the improvement of hot carrier generation in noble metals and the development of photodetection techniques applicable to Si-photonic devices. My colleagues and I have recently demonstrated the enhancement of hot carrier generation in thin metal films on ENZ substrate from near-perfect absorption in metal film. In addition, I proposed an original approach to achieve the high-efficient photodetection in Si/metal oxide thin film Schottky junctions with controlling the interface defect state as the source of carrier emission under below Si-bandgap illumination. Recently, my research field has expanded to Casimir force measurement (a nanoscale force that originates from quantum fluctuations of electromagnetic fields) to determine the geometrical effect on this force by measuring the force between a sphere and nanoscale metallic structure with diverse sizes and shapes, and these are currently underway.

Future Research

I. Study the Fundamental Physics of Emerging Optical Phenomena

Deep understanding of newly emerging optical phenomena is an essential step toward the development of novel nanophotonic devices. Firstly, I am highly interested in fundamental research on the impact of ENZ properties in nanophotonic systems for controlling light propagation. ENZ is an interesting concept to enable a wide variety of exciting phenomenon at optical frequencies, such as tunneling of EM (electromagnetic) field through subwavelength channels, small phase variation of EM field within an ENZ medium, and high optical impedance to the incident field. Metal oxides are one of the most suitable material platforms for ENZ experiments in the near-IR range because the dispersive permittivity of them crosses zero at the near-IR frequency with particularly low value of the imaginary part of the permittivity, allowing it to behave as a low index of refraction medium. For example, I would like to research the intriguing ENZ phenomena such as tunneling and squeezing of electromagnetic energy through subwavelength narrow ENZ channel for the development of a new class of optical filter and wavefront control device.

Secondly, I plan to research on controlling the capability of nonlinear carrier dynamics in metallic solid-state materials by engineering the material properties such as crystallinity, stoichiometry, and optical and electrical properties. The research on nonlinearity in metal oxides highly intersects the field's recent interest in the active control of nanophotonic devices. One of my Ph.D projects demonstrated the distinct independence of nonlinear responses under interband and intraband excitation[8]. As well as carrier dynamics via interband and intraband transition, I am interested in the ultrafast carrier dynamics of the defect states in a band-gap, which can be an additional channel to create nonlinear response. This research can provide another degree of freedom to control the modulation bandwidth and optical spectral tuning of an optical pulse. Furthermore, the experiment setup for this research can be utilized to extend the scope of my research to hot carrier effects and plasmoelectric effects in solid-state materials, which are associated with the free-carrier dynamics analogous to intraband excitation. These effects are interesting topics in nanophotonics and will aid in the development of new schemes for sensing, optical detection, and energy conversion.

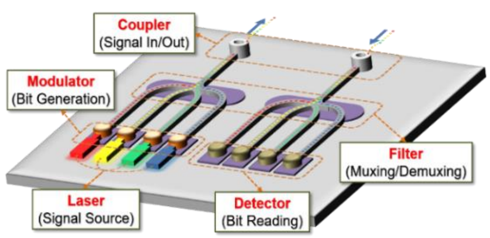
II. Extension of Potential Material Platforms

With the rapid development of nanophotonics, it is clear that no single material can be suitable for all applications at all frequencies. An extension of material platforms is an inevitable research direction for further progress in nanophotonics. The research in this direction is fairly opened and provides an excellent opportunity to explore and develop new dimensions. Similar to the way silicon revolutionized the microelectronics industry, the development of better materials will usher in the next-generation of nanophotonic technologies.

From my interdisciplinary research experience on fundamental properties of various materials such as metal oxides, vanadium oxides [11], metal nitrides [12], and silicon carbide [6], I will explore potential materials as constituent material platforms in nanophotonic systems to make an enormous impact on optics resulting in a new generation of unparalleled device applications. For instance, perovskites lead the fastest-advancing solar technology to date due to low cost manufacture and high efficiency, hence perovskite-based nanostructures boost the performance of solar cells by the induced strong-light absorption and extra-carrier generation with hot carrier effects in these confined volumes. Another example is to develop ENZ materials by engineering the optical properties of transition metal nitride to achieve the cross-over frequency at the desired frequency, especially in the visible range where no natural, low-loss ENZ material has been reported yet. Without the existence of these ENZ materials, it is fundamentally difficult to study those effects at the desired spectral regime. Therefore, further development of ENZ materials will have a profound impact on research in nanophotonics through the realization of practical ENZ devices operating at these unexplored spectral ranges.

III. Compact Optical Component for High Density Si Photonic Circuits

Silicon photonics is a novel technology aimed at achieving large-scale integrated circuits through well-established CMOS manufacturing systems. However, the typical sizes of device components for on-chip photonics are about tens or hundreds of micrometers, and further scaling down is hampered by, among other difficulties, the optical diffraction limit. Here I plan to work on scaling down these photonic devices using ENZ properties. As demonstrated in my previous work[6], ENZ materials have the exciting potential as optical insulators, which help to decouple the individual components by blocking the leakage of light, allowing us to scale down the device dimension.



<Figure 2. Silicon photonic circuit consisting of optical components that can be replaced with nanophotonic devices for further scaling down beyond diffraction limits>

Furthermore, I would like to investigate an alternative approach to develop ultra-compact devices, which can be integrated into Si photonic circuits. For a miniaturization of optical devices, plasmonics has been highlighted because of the ability to confine light down to the subwavelength scale; however, plasmonics typically suffers from high optical losses. The approach to solve this drawback is to balance the advantages of both plasmonics and photonics. My recent work demonstrated that photonic nano-cavities can be converted into an optically controllable modulator[9] or a multi-bandpass filter[10] by inserting an ultrathin metal oxide layer or a designed metasurface, respectively. This approach poses abundant research opportunities to develop the key components in Si photonic circuits as depicted in Fig. 2. As examples, gain media or an emitter can be embedded in nanocavity to develop a compact laser with high efficiency, and hot-carrier effect and interface defect in metallic components can enable a subwavelength-scale photo detector.

Research Strategy and Funding

For the preliminary research, I will actively look for internal collaborators and internal facilities such as pulse laser deposition, sputtering, atomic layer deposition and chemical vapor deposition. For the case that the internal facilities are not enough to realize the devices, I can utilize an external vendor or collaborators under the consideration on cost effectiveness and time efficiency. For the advanced optical characterizations such as pump-probe measurement and broadband photocurrent measurement, I will utilize my current research network at Purdue University and University of Maryland before I establish my own measurement set-up in the lab.

I will also immediately begin discussions with program managers at funding institutions to further aid my research endeavors. Previous projects on the metal oxides IR devices was supported by Office of Naval Research (ONR) and Air Force Office of Scientific Research (AFOSR), which are the largest federal research funders in the United States. National Science Foundation (NSF) is another potential funding agency, where I have extensive experiences on writing the proposals by assisting the professors. I plan to write the proposals to NSF programs of Electronics, Photonics and Magnetic Devices (EPMD) where supports innovative research on novel devices based on the principles of optics and photonics, optoelectronics, opto- and electromechanics, electromagnetics, and related physical phenomena.

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