

Purdue Materials Engineering

“Engineering Low-Dimensional Materials for Quantum Photonic and Plasmonic Applications”

By
Xiaohui Xu

Purdue MSE PhD Dissertation

Advisor: Professor Alexandra Boltasseva and Professor Haiyan Wang

ABSTRACT

Low-dimensional materials (LDMs) are substances that have at least one dimension with thicknesses in the nanometer (nm) scale. They have attracted tremendous research interests in many fields due to their unique properties that are absent in bulk materials. In this thesis, several types of LDMs are studied and engineered with the goal to improve their impact in plasmonic and quantum photonic applications. Two-dimensional hexagonal boron nitride (hBN) is receiving increasing attention in quantum optics/photronics as it hosts various types of quantum emitters that are promising for quantum computing, quantum sensing, etc. In the first study, we explore and demonstrate a radiation- and lithography-free route to deterministically create single-photon emitters (SPEs) in hBN with an atomic force microscope. The method applies to hBN on flat, chip-compatible silicon-based substrates, and an SPE yield of up to 36% is achieved. The negatively charged boron vacancy (VB⁻) defect is a recently discovered spin defect with spin properties suitable for sensing at extreme scales. In the second study, we resolve the low brightness issue of VB⁻ defects by coupling them with an optimized nano-patch antenna structure and observe emission intensity enhancement that is nearly an order of magnitude higher than previous reports. Zero-dimensional nanodiamond is another important host material for solid-state SPEs. Specifically, the negatively charged silicon vacancy (SiV) center in nanodiamonds exhibits optical properties that are suitable for quantum information technologies. In the third study, we, for the first time, demonstrate the creation of single SiV centers in nanodiamonds with an average size of ~20 nm using ion implantation. This confirms the feasibility of single-photon emitter creation in nanodiamonds with ion implantation, and offers new opportunities to integrate diamond color centers for hybrid quantum photonic systems. Finally, we have also explored using metal-semiconductor hybrid nanoparticles for plasmon-enhanced photocatalysis. A core-shell nanoparticle structure is synthesized, with titanium nitride (TiN) and titanium dioxide (TiO₂) being the core and shell material respectively. Such core-shell nanoparticles effectively catalyze the generation of single oxygen molecules under 700-nm laser excitation due to hot electron transfer. Considering the chemical inertness and low cost of TiN, TiN@TiO₂ NPs hold great potential as plasmonic photosensitizers for photodynamic therapy and other photocatalytic applications at red-to-near-infrared (NIR) wavelengths.

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