Collective Excitations in Reduced Dimensionality Nanostructures

NSF ECCS 1306871 – Prof. Igor Bondarev, PI – North Carolina Central University, Durham, NC 27707

I. Recent Outcomes & Accomplishments:

- ❑ Effects of spatial confinement in the optical response of ultrathin plasmonic films of finite thickness have been studied theoretically. The plasma frequency is predicted to acquire spatial dispersion typical of 2D materials, gradually shifting to the red with film thickness reduction. This explains recent experiments and offers ways to tune spatial dispersion and associated magneto-optical properties of plasmonic films and metasurfaces. (*see top right figure panel*)
- ❑ Bose-Einstein condensation (BEC) of excitons in double walled carbon nanotube (CNT) structures has been demonstrated theoretically. The BEC mechanism is enabled by the coupling of excitons residing on one tubule to the near field generated by the plasmon modes of the other coaxial tubule. The effect opens up new avenues for fundamental science and nanophotonics applications with double walled CNTs.
- ❑ Monopolar charge fluctuation effects are formulated and studied between planar graphitic nanostructures (e.g., graphene nanoribbons) and metals (*see bottom right*). A theoretical model is developed to describe the electron transport through the hybrid system of a semi-conducting CNT that encapsulates a one-atom-thick metallic wire. The theory can be used to optimize charge transfer in hybrid nanodevices built on metal-semiconductor CNT systems.
- ❑ Quantum Electrodynamics (QED) theory of resonance Raman scattering is developed between an atom and a CNT. The near-field coupling between CNT plasmons and the atom allows for significant surface Raman scattering enhancement. (*see bottom right figure panel*)
- ❑ The many-particle Hamiltonian and exciton-plasmon energy dispersion have been elaborated to describe exciton-plasmon (photonic) band formation in a periodic densely packed CNT array.

1) I.V.Bondarev & V.M.Shalaev, Optical Materials Express **7**, 3731 (2017)
2) I.V.Bondarev & A.Popescu, MRS Advances, DOI: 10.1557/adv.2017.435
3) D.Drosdoff, I.V.Bondarev, A.Widom, R.Podgornik, & L.M.Woods, Phys. Rev. X **6**, 011004 (2016)
4) M.F.Gelin & I.V.Bondarev, Phys. Rev. B **93**, 115422 (2016)
5) I.V.Bondarev & A.V.Gulyuk, Superlattices and Microstructures **87**, 103 (2015)

II. Basic Principles:

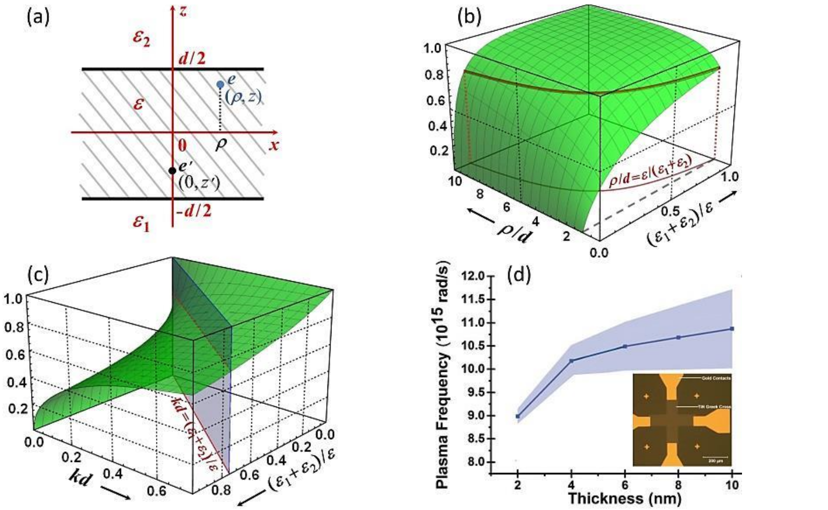
Technical *(for the engineering professional or researcher):*
Quite generally, far-field electromagnetic interaction with reduced dimensionality nanostructures are due to the excitation of excitons, while the near-field electric interaction is due to the plasmon excitation. The latter is within the field of nanoplasmonics, and the former is related to the field of nanophotonics. As an example, CNTs carry both excitons and plasmons in the same frequency range, controlled by their diameter-chirality, to allow for new unique optoplasmonic applications.

Non-Technical *(for the general public's understanding):*

- The rich ensemble of physical properties of metal and semiconductor nanostructures of reduced dimensionality, coupled with relative simplicity in their modelling, yields a great amount of new applications and deeper understanding of the physical principles underlying new phenomena.
- For example, the application of CNTs can be extended to the field of photonic metamaterials by generating a periodic lattice (array) of CNTs, whereby photonic bands are created which can be used for electromagnetic sensing.
- Graphitic nanostructures allow for the observation of new monopolar charge fluctuation effects that control the adhesion at nanoscale, which are usually hidden in solid state devices.

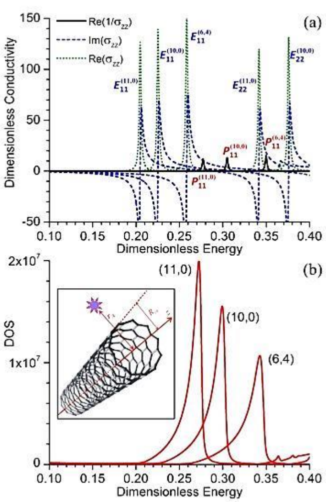
III. Broader Impact:

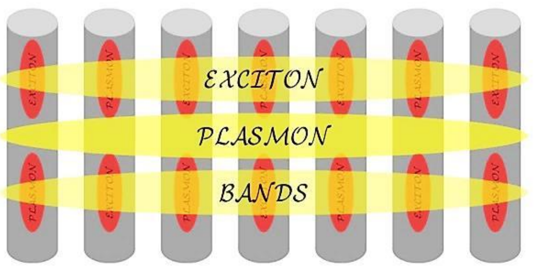
This project involves one graduate student and one postdoc. A fundamental understanding of low energy collective excitations in hybrid metal-semiconductor nanostructures of reduced dimension is able to guide the practical realization of new technological applications, ranging from enhanced electromagnetic absorption, conversion and rectification of electromagnetic fields to biosensorics and new materials development.

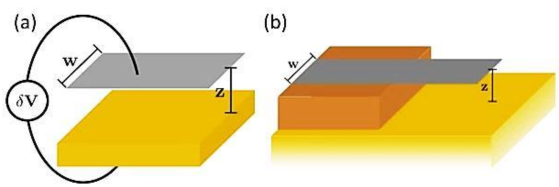


(a,b) Schematic of the confined thin film geometry (a) and the normalized Coulomb interaction potential (b) for ultrathin finite thickness plasmonic films. **(c)** Thin film plasma frequency normalized by the bulk plasma frequency derived theoretically in Ref.[1]. **(d)** Plasma frequency extracted from the ellipsometry measurements done on ultrathin TiN films (inset, see Ref.[2]) of controlled variable thicknesses fabricated at Purdue University.

[1] I.V.Bondarev and V.M.Shalaev, Opt. Mater. Expr. 7, 3731 (2017); [2] D.Shah, *et al.*, Adv. Opt. Mater. 1700065 (2017)







Left: (a) Individual CNT conductivity as a function of energy; (b) photonic density of states for an atom coupled to the plasmon generated near field of a carbon nanotube (see Ref.[1]). **Top right:** Closely packed, periodically aligned array of semiconducting carbon nanotubes carries coupled exciton-plasmon excitations, which form exciton-plasmon bands due to the array periodicity. **Bottom right:** Metal sheet and carbon nanoribbon system that exhibits monopolar charge fluctuation forces [2].

[1] I.V.Bondarev and A.V.Gulyuk, Superlatt. & Microstr. 87, 103 (2015); [2] D.Drosdoff, *et al.*, Phys. Rev. X 6, 011004 (2016)