Electron Optics of Self-Assembled Plasmonic Nanocomposite Metamaterials

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Plasmonic nano-antennas, which couple optics and electronics, are of increasing interest as waveguides, emitters, and interconnects in semiconductor devices, particularly in the near infrared region [1,2]. Dynamic enhancement of opto-electronic coupling could fundamentally impact performance of plasmonic nanoantenna semiconductor devices integrated into applications as diverse as biomedical theranostics, synthetic biology, and sustainable energy [3]. Fundamentally, quantized photon-exciton coupling is the source of electron-hole pairs in semiconductor photovoltaics, induced charge transfer in ordered DNA chains, and distance-dependent Forster resonance energy transfer in spectroscopic molecular rulers [4].

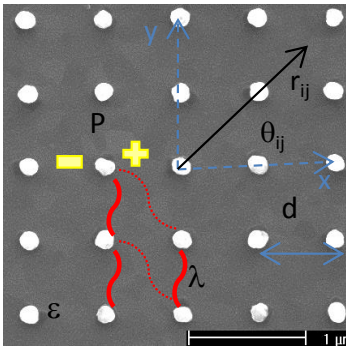

Fig 1. Describing self-assembled gold nanoparticle plasmonic metamaterial.

Our lab has recently distinguished relative contributions of quantized plasmon polarizabilities and photon diffraction to extraordinary opto-electronic coupling in ordered metal-ceramic and metal-polymeric nanocomposite metamaterials (see Fig 1) [5,6]. Metamaterials exhibit tunable electromagnetic functionality -- from simple iridescence in butterfly wings to radiofrequency cloaking -- due to coherent interference from multidimensional structuring of suitable condensed-matter composites. We showed that surface energy driven self-assembly of plasmonic metamaterials can occur by electroless nanosphere synthesis on nanolithographed anti-gecko lattices [7]. This novel result has been extended to modulate nanoscale photodynamic, hydraulic, and redox potentials to allow ionic precursors to nucleate into various nanostructured isoforms including spheres, island films, and clusters with various substrates (see Fig. 4) [8-10]. Recent progress has been made in distinguishing coherent and incoherent optical re-radiation and thermal dissipation from plasmonic nano-antennas in devices by correlating experimental and theoretical results [11].

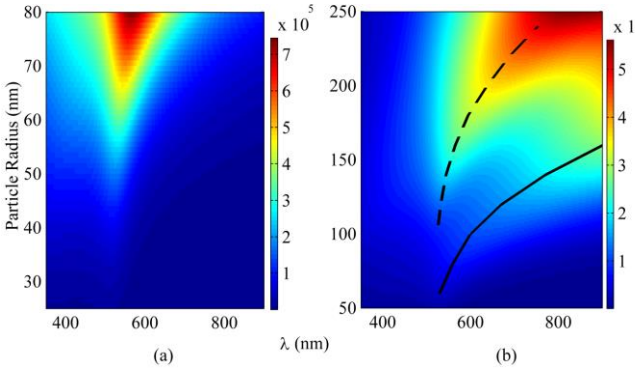

Fig 2. Frequency-dependent dipole and quadrupole polarizabilites for various gold nanoparticles [6].

Description and design of dynamical electron optics in systems and devices has been obstructed to date by expense and complexity of available numerical computations and effective media approximations [12,13]. Our group has developed and validated a suite of rapid approximate methods which synthesize tractable descriptions of near-field polarizability and far-field modal interference to efficiently describe energetics of electron optic coupling in plasmonic metamaterials (See Fig 2) [5,6,14]. In particular, this approach supports quantitative attribution of effects of physicochemical and geometrical features of nanocomposite metamaterials on quantum and continuum interactions that exhibit predictable Fano resonances and thermal dissipation in near infrared regions (see Fig 3) [15]. A recent extension of this approach to geometric optics supported accurate prediction and characterization of linear and non-linear influences, respectively, of plasmonic nanocomposites in microscale systems [13].

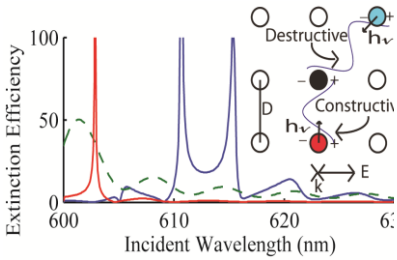

Fig 3. Phase interference modulates Fano resonant energy.

Characterization of fabricated metamaterials and validation of their fundamental descriptions has been facilitated in our lab by microspectroscopies (x-ray photoelectron; transmission UV; and Raman) and transmission/scanning electron and optical microscopies. Advances in these physicochemical characterization methods have supported measurable improvements in opto-electronic interactions in nano-scale metallic particles and films (see Fig. 4) [8,9,13,16]. These advances in modeling, fabrication, characterization, and systems integration are important milestones toward integrating electromagnetically active nanocomposite metamaterials into next-generation semiconductor devices that support micro-to-nano-scale electronics, tele-communications, with extensions to molecular engineering, disease diagnosis, personalized therapies, and energy harvesting [17].

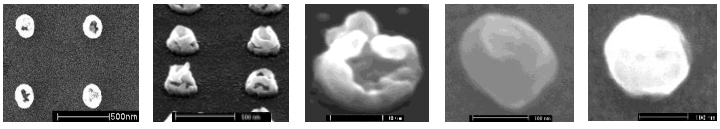

Fig 4. Thermally tunable metalloceramic nanomorphs.

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