Free-electron optical nonlinearities in heavily doped semiconductors: from fundamentals to integrated photonics

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Abstract. Heavily doped semiconductors have emerged as an enabling platform for mid-infrared photonics, leveraging free electrons to achieve strong and tunable nonlocal-nonlinear light-matter interactions. In this talk, we will discuss recent theoretical and experimental studies on third harmonic generation and Kerr nonlinearity in heavily doped semiconductors, in which hydrodynamic contributions dominate.

Heavily doped semiconductors represent a highly promising platform for mid-infrared photonics, combining tunable optical properties with low losses. With free-electron densities of $10^{18}10^{19}$ cm^{-3}, these materials enable precise plasma frequency tuning through doping. Their free electrons exhibit quantum hydrodynamic behavior and low effective mass, facilitating strong nonlocal and nonlinear light-matter interactions. Crucially, their compatibility with mature semiconductor fabrication techniques makes them a compelling alternative to conventional noble-metal plasmonics.

The optical response of these materials can be accurately modeled using hydrodynamic theory (HT), which incorporates quantum pressure, convective effects, and electron density variations. Heavily doped semiconductors exhibit strong third-order free-electron nonlinearities due to their low carrier density, surpassing both free-electron nonlinearities in metals and traditional dielectric nonlinearities [1]. Experiments on third-harmonic generation (THG) in InGaAs nanoantennas have demonstrated that hydrodynamic effects dominate over lattice contributions [2], significantly enhancing THG efficiency and offering a reconfigurable nonlinear platform.

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Moreover, these semiconductors support longitudinal bulk plasmons (LBPs)—nonlocal charge density waves that propagate through the bulk and exhibit strong nonlinear behavior. By coupling LBPs with metallic gap plasmons in hybrid nanopatch antennas, we have achieved optical bistability at ultralow thresholds (1 mW/μm), as confirmed by solving coupled hydrodynamic-Maxwell equations in the time domain [3]. This bistability arises from Kerr-induced resonance shifts and a 60% increase in reflectance hysteresis, where LBPs provide a large nonlinear interaction volume while gap plasmons enable subwavelength light confinement. Such effects hold promises for optical memory and logic applications. Further integration with MOS structures—featuring gold electrodes and ultrathin hafnium layers—enables electrostatic control of the free-electron density, toggling between depletion and accumulation regimes [4]. This allows tuning of the plasma wavelength with a sensitivity of 0.89 μm/V. Our combined electrostatic-hydrodynamic model reveals that this approach reduces the optical bistability threshold to just 10 μW, making it ideal for low-power, reconfigurable photonic systems. Additionally, LBP-based free-electron Kerr nonlinearities can also be exploited in photonic circuits, such as hybrid waveguides with an undoped InGaAs/InP dielectric core/cladding and a heavily doped InGaAs plasmonic layer. This design supports long-range propagating modes and ultrahigh Kerr nonlinearities, enabling efficient nonlinear signal processing. For example, a Mach-Zehnder interferometer based on this configuration achieves 60% transmission modulation with input power, highlighting the potential of free-electron nonlinearity for nonlinear optical modulation.

In sum, heavily doped semiconductors combine strong nonlocal and nonlinear responses with dynamic electrostatic control and scalable fabrication. They offer a powerful pathway toward ultrafast (<1 ps), low-power mid-infrared photonic devices, opening new possibilities for reconfigurable optics and integrated photonic circuits.

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