Heavily doped semiconductors: a platform for integrated nonlinear plasmonics

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The control and the concentration of light at subwavelength scales are of extreme importance for the realization of integrated optical technologies, especially to reach operational efficiencies in devices based on nonlinear optical effects. In this context, the study of light interaction with free electrons (FEs), i.e. plasmonics, in materials characterized by a high carriers density has a central role. Notoriously, noble metals have been the main material choice for plasmonic devices in the visible spectrum for many years. Heavily doped semiconductors (i.e. with charge densities $\mathrm{n_0} \sim 10^{19}$ - $10^{20}\ \mathrm{cm^{-3}}$), on the other hand, have recently emerged as alternative materials for plasmonics in the near-infrared (NIR), i.e. $0.8 < \lambda < 2$ μm, and in the mid-infrared (MIR), i.e. $2 < \lambda < 20$ μm [1]. Being low-loss high-quality materials that can be compatible with standard microelectronics fabrication processes, and being their optical response tunable through electrical or optical doping, heavily doped semiconductors offer a unique perspective for integrated optical devices in the NIR and in the MIR. [2].

In this talk we show that FE nonlinearities could be up to two orders of magnitude larger than conventional semiconductor lattice nonlinearities [3,4]. We use a hydrodynamic description that includes terms up to the third order, usually negligible for noble metals. Within the hydrodynamic formalism, the third-order response, expressed through the third-order polarization vector is inversely proportional to the squared equilibrium charge density, i.e. $\mathbf{P}_{\mathrm{NL}}^{(3)} \propto \frac{1}{n_0^2}$. Indeed, doped semiconductors with a plasma wavelength in the MIR have a charge density ($\mathrm{n_0} \sim 10^{19}\ \mathrm{cm^{-3}}$) much lower than noble metals, such as gold ($\mathrm{n_0} \sim 10^{22}\ \mathrm{cm^{-3}}$). Hence, FE nonlinearites may grow as much as six orders of magnitude, overcoming by far the contributions originating in the crystal lattice nonlinear susceptibility $\chi^{(3)}$, which instead represents the dominant third-order nonlinear source in gold due to the high concentration of charge carriers. Moreover, the nonlinear active volumes are expected to increase in semiconductors due to their smaller effective masses [3].

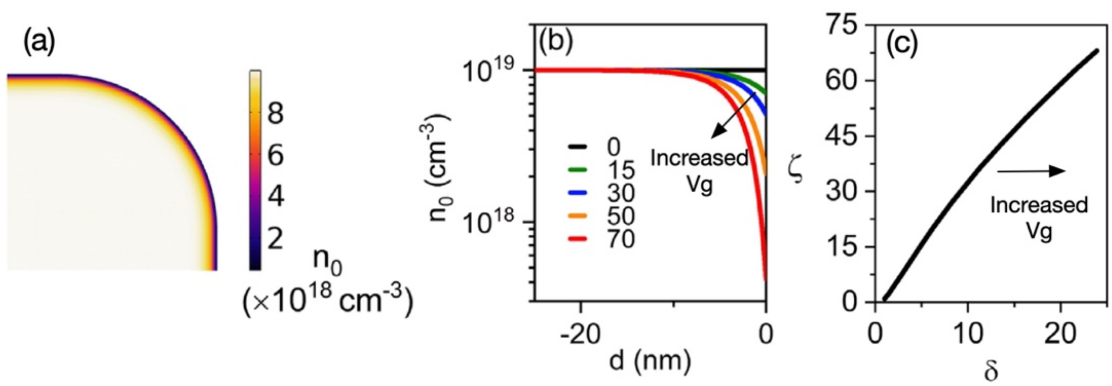

Fig. 1 Effects of surface charge depletion on the FE THG efficiency η of a doped InP semi-infinite grating: (a) charge density distribution along the contour of the grooves. (b) equilibrium charge density as a function of the distance *d* from the surface of the slab for different levels of modulation (in V/μm); (c) enhancement factors ζ as a function of the depletion factor δ in correspondence of the peak efficiencies $\lambda_{\mathrm{FF}} = 12.2$ μm.

Finally, we consider modifications of the charge density at the semiconductor surface obtained through the application of an external bias, i.e. by means of field-effect modulation (Fig. 1). We present a model for describing the influence of surface charge depletion on FE nonlinearities and make quantitative predictions about the role of field-effect modulation for the control of the optical nonlinear response of heavily doped semiconductors [5]. This technique may provide the unique ability to externally and dynamically modulate the nonlinear coefficients of heavily doped semiconductors by a simple setting of DC electric potential levels.

References

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