Energy losses and transition radiation produced by the interaction of fast charged particles with two-dimensional materials

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Interactions of graphene and other two-dimensional (2D) materials with externally moving charged particles have been studied in recent years in the context of Electron Energy Loss Spectroscopy in Scanning Transmission Electron Microscope, which has become a very popular experimental technique for exploring the excitation of plasmons in graphene over a broad range of frequencies. On the other hand, the technological need for a stable and tunable source of terahertz (THz) radiation has prompted several recent studies of the electromagnetic radiation from graphene, induced by its interaction with fast electron beams.

We have recently developed a fully relativistic theory of energy losses for a fast charged particle traversing single-layer graphene [1,2] and multi-layer graphene (MLG) [3–5]. It was shown that the total energy loss of the external particle consists of two components: the energy absorbed by graphene layers in the form of electronic excitations (Ohmic losses), which include the excitation of Dirac plasmon polaritons (DPP), and the energy that is emitted in the far field as transition radiation (TR). The dynamic response of graphene was described by means of a 2D conductivity function, which was modeled using *ab initio* calculations [6] or empirical models [7].

We have studied the effects of varying the charged particle energy and angle of incidence [1,2], as well as the effects of hybridization between the DPPs in different graphene layers within MLG structures [3]-[5], in both the Ohmic energy loss distributions and in the angular spectra of TR. In the THz range of energy losses, we have observed intriguing asymmetry with respect to the direction of the incident particle in both the Ohmic losses and the TR spectra from MLG.

In recent work, we have applied our methodology to phosphorene, a single layer of black phosphorus, which exhibits strongly anisotropic optical properties. Describing this anisotropy by a 2D conductivity tensor, we have explored the possibility of directional excitation of the hyperbolic plasmon polaritons in phosphorene, which may arise in the infrared frequency range, by using incident charged particles under oblique angles of incidence upon phosphorene.

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