Bogolon-mediated electron capture by impurities in hybrid Bose-Fermi systems

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We investigate the processes of electron capture by a Coulomb impurity center residing in a hybrid system consisting of spatially separated two-dimensional layers of electron and Bose-condensed dipolar exciton gases coupled via the Coulomb forces. We calculate the probability of the electron capture accompanied by the emission of a single Bogoliubov excitation (bogolon), similar to regular phonon-mediated scattering in solids. Furthermore, we study the electron capture mediated by the emission of a pair of bogolons in a single capture event and show that these processes not only should be treated in the same order of the perturbation theory, but also they give a more important contribution than single-bogolon-mediated capture, in contrast with regular phonon scattering.

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I. INTRODUCTION

The presence of impurities in semiconductor nanostructures strongly modifies their physical properties [1,2]. At low temperature, the electron-impurity scattering is predominant and it determines the electric properties of the heterostructure, in particular, its conductivity [3]. Depending on the sign of the electron-impurity interaction, electrons can be either scattered by the impurities or captured by them [4–7]. In terms of the classical Drude theory, the former processes modify the effective scattering time of the electrons, whereas the latter processes literally result in the decrease of the number of free carriers of charge. As a result, nonradiative capture of electrons by charged attractive centers plays a crucial role in the transport of photoexcited carriers [8], drastically modifying the conductivity via electron lifetime. In particular, this lifetime is a crucial parameter for impurity photodetectors [9,10], which are commonly used in far-infrared range to monitor the emission from modern resonant tunneling diodes and quantum cascade lasers.

In the majority of cases, an electron capture is accompanied by the emission of crystal lattice excitation quanta referred to as acoustic and optical phonons [11–13]. Meanwhile the electron loses its energy and becomes localized. Phonon-mediated electron scattering has been so far considered to be the dominant capture mechanism. However, lattice vibrations are not the only phonons available, especially at low temperatures. For instance, in view of a recent discovery of exciton superfluidity and Bose-Einstein condensation (BEC) [14,15], one can consider the excitations of the BEC as an alternative type of phonons, commonly referred to as Bogoliubov quanta or bogolons and having linear dispersion law at small momenta. Such exciton BEC can be realized experimentally by external laser beams which produce photoexcited electrons and holes, relaxing their energy to form bound electron-hole pairs. We will show that in the presence of exciton gas, the interaction of the carriers of charge with impurities can be strongly modified, if the exciton gas is in the BEC phase.

In order to better understand fundamental properties of this phenomenon, it is important to separate the BEC from the conduction electrons and study the influence of different interactions separately. One of the recent active areas of research is hybrid Bose-Fermi systems which consist of two-dimensional (2D) spatially separated electron and exciton gases, interacting with each other via the Coulomb forces [16–20]. These systems can be a testbed for various physical phenomena, some of which occur when the exciton or exciton-polariton gas is in the BEC regime [21–23], which has been reported in various solid state systems [14,24,25]. In particular, the possibility of inelastic processes of electron capture has been so far disregarded, to the best of our knowledge.

In this article we will demonstrate that in the presence of exciton BEC, an additional mechanism of electron capture to attractive centers appears. This mechanism is the consequence of interlayer electron-exciton interaction. Being in the BEC regime, exciton gas can be described in terms of bogolons (with a soundlike dispersion in the long-wavelength limit). Naively, one can expect that the processes of electron capture due to interaction with the BEC of excitons are similar to the case of lattice phonon emission, in particular, due to the similarity of the dispersion laws. Indeed, it is partly true. However, we will show that in the presence of the BEC, an additional channel of nonradiative relaxation of electrons opens. It can be referred to as electron capture accompanied by the radiation of a pair of bogolons. Counterintuitively, such electron capture events should be treated within the same order of perturbation theory as the single-bogolon emission, moreover, as it will be demonstrated, they give more important contributions.

II. SYSTEM SCHEMATIC

We consider a hybrid nanostructure consisting of a 2D electron layer separated by a distance l from a double quantum well, containing the dipolar exciton gas, see Fig. 1.

