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Superconductivity in semiconductor structures: The excitonic mechanism

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A B S T R A C T

We theoretically study the dependency of the superconductivity transition critical temperature (T_C) on the electron and exciton–polariton densities in layered systems, where superconductivity is mediated by a Bose-Einstein condensate of exciton–polaritons. The critical temperature increases with the polariton density, but decreases with the electron gas density, surprisingly. This makes doped semiconductor structures with shallow Fermi energies better adapted for observation of the exciton–polariton-induced superconductivity than metallic layers. For realistic GaAs-based microcavities containing doped and neutral quantum wells we estimate T_C as close to 50 K. Superconductivity is suppressed by magnetic fields of the order of 4 T due to the Fermi surface renormalization.

1. Introduction

High temperature superconductivity (HTSC) has been desperately searched for during decades since the appearance of the seminal work of Bardeen–Cooper–Schrieffer (BCS) [1] in early 50 s. Among many different paths physicist have tried to achieve it, the excitonic mechanism of superconductivity (SC) deserves particular attention [2–4]. According to Ginzburg [5,6], the excitons are expected to be suitable for realization of HTSC. The reason is that the characteristic energy, above which the electron attraction mediated by excitons vanishes, is several orders of magnitude higher than the Debye energy limiting the attraction mediated by phonons.

Despite optimistic expectations, to the best of our knowledge, the exciton mechanism of SC has never worked until now, most likely due to the reduced retardation effect [4,7]. Phonons in the BCS model are very slow compared to electrons on the Fermi surface. Hence there is a strong retardation effect in the phonon-mediated electron–electron attraction, so that the size of a Cooper pair is very large (of the order of 100 nm), and the Coulomb repulsion may be neglected at such distances. In contrast, excitons with wave-vectors comparable with the Fermi wave-vector in metals are very fast quasi-particles. Therefore the replacement of phonons with excitons leads to the loss of retardation and smaller sizes of Cooper pairs, that

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is why the Coulomb repulsion starts playing an important role. In realistic multilayer structures the Coulomb repulsion appears to be stronger than the exciton-mediated attraction so that Cooper pairs cannot be formed. In literature [8,9] one finds reports on layered metal-insulator structures where SC occurs at 50 K in the layered metal-insulator structures, nevertheless there is still no evidence that the excitonic mechanism is responsible for this effect. Recently, the novel mechanism to achieve superconductivity mediated by exciton–polaritons has been proposed in Refs. [10,11]. Exciton–polaritons are quasi-particles that arise due to the strong coupling of excitons with light. Particularly interesting phenomena related to exciton–polaritons have been observed in semiconductor quantum wells (QW) embedded in microcavity [12,13]. Bose–Einstein condensation of cavity polaritons at room temperature has been observed [14–19], making the exciton–polariton a promising boson to bind Cooper pairs at high temperatures. Moreover, it has been shown that the strength of electron–electron interactions mediated by a condensate of cavity polaritons can be controlled optically.

The systems considered previously in Refs. [10,11] consist of microcavities where free electrons in a thin layer interact with exciton–polaritons contained in the adjacent semiconductor layer. Both layers are brought sufficiently close to each other to assure the efficient coupling between the electrons and exciton–polaritons. In this way, phonons are replaced with the excitations of an exciton–polariton condensate providing the exciton-mediated attraction of free electrons. While the retardation effect characteristic of the weak-coupling BCS model is essentially suppressed in this regime, the exciton-mediated attraction appears to be strong enough to overcome the Coulomb repulsion for Cooper pairs of a characteristic size of 10 nm. In comparison to the mechanism considered by Bardeen [1] and Ginzburg [5,6], electron–electron attraction mediated by excitons is much stronger in the presence of the exciton–polariton bosonic condensate for two reasons: firstly, the exchange energy needed for creation of an excited state of the condensate is much smaller than the energy needed to create a virtual exciton. Secondly, the exciton–electron interaction strength increases proportionally to the occupation number of the condensate. This exciton–polariton mechanism of superconductivity was studied theoretically in a model structure where the electron–electron attraction potential was calculated and then substituted into the gap equation that yielded the critical temperature of the superconductivity phase transition. The proof of concept calculation showed a high potentiality of the excitonic mechanism of SC.

In order to proceed with the experimental verifications of this prediction, several issues still need to be clarified. Namely, it has been unclear how the electron density in the two-dimensional electron gas (2DEG) QW influences the critical temperature T_C and what structure is the most appropriate for experimental observation of the predicted effect: the one where the metallic layer is put in contact with the semiconductor, or an entirely semiconductor multilayer structure containing doped and undoped QWs.

2. Results

In this manuscript we analyze the behavior of superconducting gap and T_C as a function of exciton–polariton and electron densities and conclude on the most convenient structure design for observation of the exciton-mediated SC. The system we study is a microcavity where an electron gas confined to a quantum well (2DEG) interacts with a polariton condensate localized in an adjacent semiconductor QW, as shown in Fig.1. The microscopic Hamiltonian that describes this system is derived in Ref. [11]. Here we only need the expression for the reduced Hamiltonian that appears after the Bogoliubov transformation and describes the coupling of electrons via bogolons, excitations of a polariton condensate:

$$H = \sum_{\mathbf{k}} E_{el}(\mathbf{k})\sigma^{\dagger}_{\mathbf{k}}\sigma_{\mathbf{k}} + \sum_{\mathbf{k}} E_{bog}(\mathbf{k})b^{\dagger}_{\mathbf{k}}b_{\mathbf{k}} + H_c + \sum_{\mathbf{k},\mathbf{q}} M(\mathbf{q})\sigma^{\dagger}_{\mathbf{k}}\sigma_{\mathbf{k}+\mathbf{q}}\left(b^{\dagger}_{-\mathbf{q}} + b_{\mathbf{q}}\right). \quad (1)$$

Here E_{el} is the free electron energy, the bogolon dispersion is given by the formula:

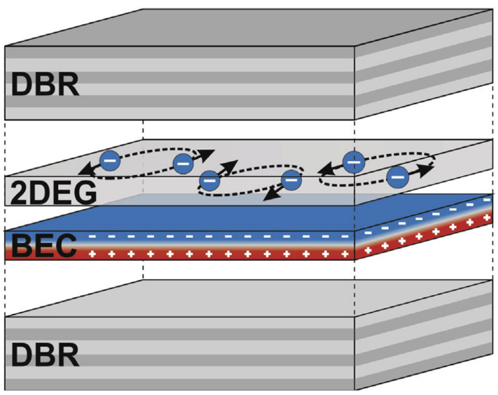

Fig. 1. The scheme of the model microcavity structure with an n-doped QW interacting with an exciton–polariton BEC localized in an adjacent QW.