On vortex phase of systems with pairing of spatially separated electrons and holes

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The possibility of the emergence of a macroscopic amount of planar vortices with identical circulation in systems with pairing of spatially separated electrons and holes was predicted by us recently [S. I. Shevchenko, Phys. Rev. B56, 10355 (1997); ibid. B57, 14809 (1998)]. In the present work, we consider a structure formed by planar vortices in a disk-shaped sample in a magnetic field whose two-dimensional divergence differs from zero. The total number of vortices and the energy of a system of vortices are determined as functions of the external magnetic field and the sample size. It is found that the energy of the vortex structure is proportional to the volume of the system, and hence a vortex state is a new thermodynamic phase of the investigated system (analogous to the Shubnikov phase in conventional superconductors).

1. INTRODUCTION

In recent years, several publications have appeared which contain the results of experimental investigations of double-layered 2D-electron-hole and electron-electron systems and report on the observation of several effects probably associated with the emergence of spontaneous interlayer coherence (“condenser” superconductivity) in these systems. Thus, Cooper et al. have attributed the increase in the longitudinal resistance of three-layered InAs/GaSb/AlSb heterostructures for identical densities of electrons in the InAs layer and holes in the AlSb layer to the formation of bound electron-hole pairs. Lilly et al. have studied the drag of electrons in one layer by the current of electrons in the other layer in the system GaAs/AlxGa1–xAs in a strong magnetic field for a half-filled lower Landau level in each layer. They observed a number of anomalies in the drag current and attributed them to a strong correlation between electrons in adjacent layers. Butov et al. studied the time evolution of luminescence of indirect excitons in double quantum wells AlAs/GaAs after pulse laser excitation in strong magnetic fields (B ≤ 12 T) at low temperatures (T ≤ 1.3 K). Butov et al. observed an anomalous increase in the diffusion coefficient with increasing field and decreasing temperature, and interpreted it as the onset of superfluidity of excitons as a result of their condensation. The anomalously rapid transport of indirect excitons detected by Butov and Filin was also attributed by them to the emergence of superfluidity of excitons.

Many authors have reported the results of theoretical investigations of systems with spontaneous interlayer correlations. The possibility of superfluidity of electron-hole pairs in systems with pairing of spatially separated electrons and holes (PSSEH) was predicted about two decades ago (see also Ref. 8). A large number of theoretical works have been published in recent years describing the effect of a strong uniform magnetic field on pairing of spatially separated electrons and holes, as well as the peculiarities of superfluidity in such fields. However, the fact that a nonuniform magnetic field can produce qualitatively new effects remained unnoticed.

One of the authors of the present work studied the behavior of systems with PSSEH in a magnetic field below the point of transition of electron-hole pairs into superfluid state and showed that a nonuniform magnetic field with a nonzero two-dimensional divergence (div y H) may produce in the system a macroscopic amount of planar vortices with identical circulation. The term planar vortex stands for a vortex in which electron-hole pairs rotate as a single entity in the plane of the structure. Although planar vortices are in many respects similar to the well-known Onsager-Feynman vortices or Abrikosov vortices, they do not form a lattice unlike these vortices. It was shown in Refs. 31 and 32 that in the limit when planar vortices can be treated as continuously distributed, their density is proportional to div y H. It follows hence that the total number of planar vortices is proportional to the magnetic flux across the sample boundary. The latter quantity is proportional to the perimeter of the system and not its area, and hence one can ask whether the predicted effect of emergence of planar vortices in superconducting systems with PSSEH is two- or three-dimensional. It will be shown in the present work that this effect is three-dimensional, and hence the vortex state is a new thermodynamic phase analogous to the Shubnikov Phase in conventional superconductors.

Returning to the problem of experimental confirmation of the transition of indirect excitons to the superfluid state, it must be remarked that certain difficulties are encountered in the direct measurement of conductivity of each layer. In this