Fermi edge singularity in ultracold neutral electron-hole plasma

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Abstract: We studied electron-hole plasma in separated electron and hole layers. We observed a strong enhancement of photoluminescence intensity at the Fermi energy of the ultracold plasma that evidences the emergence of excitonic Fermi edge singularity.

The theory of an ultracold neutral electron-hole (e-h) system considers two density regimes. At low e-h densities, $n \ll 1/a_B^D$ (a_B is the exciton Bohr radius, D the dimensionality), electrons and holes bind to hydrogen-like pairs – excitons, which form a Bose-Einstein condensate at low temperatures [1]. In dense electron-hole systems, $n > 1/a_B^D$, e-h plasma can be realized and, at low temperatures, the theory predicts Cooper-pair-like excitons at the Fermi energy and a BCS-like exciton condensation [2].

For a 2D e-h plasma above the condensation temperature, the photoluminescence (PL) spectrum is step-like corresponding to the step-like 2D density of states, and the plasma PL linewidth is approximately the sum of the electron and hole Fermi energies [3]. In contrast, exciton PL linewidth is determined by the homogeneous and inhomogeneous broadening, it is significantly smaller than the e-h plasma PL linewidth in high-quality heterostructures. The BCS-like condensation in the ultra-cold e-h plasma with Cooper-pair-like excitons at the Fermi energy should be accompanied by a PL intensity enhancement at the Fermi level of a step-like e-h plasma emission line, similar to the Fermi edge singularity in a Fermi-gas of electrons [4,5].

The e-h systems can be created by laser excitation, with the density controlled by the excitation power. However, due to e-h recombination, the temperature of e-h system (T_{eh}) exceeds the semiconductor lattice temperature and lowering T_{eh} below the condensation temperature is challenging. To create cold e-h systems, we work with heterostructures with separated electron and hole layers. In these heterostructures, spatially indirect excitons (IXs), also known as interlayer excitons, are formed by electrons and holes confined in spatially separated layers. IXs can cool below the temperature of quantum degeneracy due to their long lifetimes [6]. An overview of experimental studies of IX condensation in the low-density regime and phenomena in the IX condensate can be found in [7].

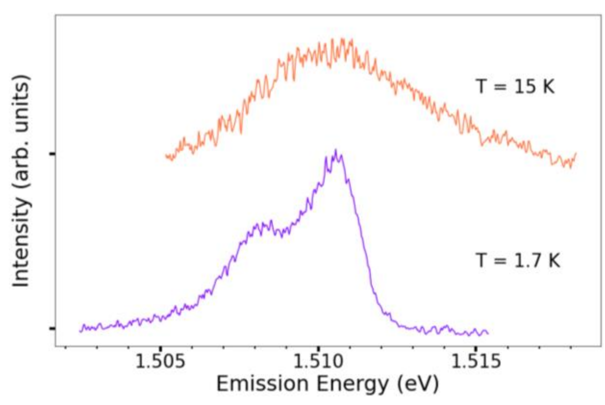

Figure 1: PL spectra of e-h plasma with separated electron and hole layers (I-EHP) at $T = 1.7$ and 15 K. The laser excitation power $P = 44$ mW. The spectrally integrated PL intensities are normalized.

In this work, we study ultracold neutral spatially indirect e-h plasma (I-EHP) in separated electron and hole layers in a GaAs/AlGaAs coupled quantum well heterostructure. The electrons and holes are confined in 15 nm GaAs QWs separated by 4 nm AlGaAs barrier. The long e-h recombination lifetimes ($\tau \sim \mu$s) due to the spatial separation between the electron and hole layers allows for cooling the plasma to low temperatures. The creation of cold I-EHP is facilitated by separating the e-h plasma from the laser excitation in space and time: (i) The measurements are performed $\delta t = 120$

ns after the laser excitation pulse within t_w = 10 ns window. This delay δt is sufficient for cooling the photoexcited e-h system to low temperatures [6]. At the same time, δt, $t_w \ll \tau$ so the density stay high and nearly constant during the measurements; (ii) The measurements are performed ~50 μm away from the edge of the mesa-shaped laser excitation spot. This separation further facilitates cooling of the photoexcited e-h system, however, the density does not drop substantially since the separation is much shorter than the IX and I-EHP propagation lengths in the heterostructure. The laser excitation is resonant to the direct exciton energy (λ = 810.25 nm) that increases absorption and further facilitates the realization of a cold and dense I-EHP. The laser pulses are 800 ns on, 150 ns off. The densities of photoexcited e-h system are controlled by the laser excitation power from the low-density IX regime to the high density I-EHP regime.

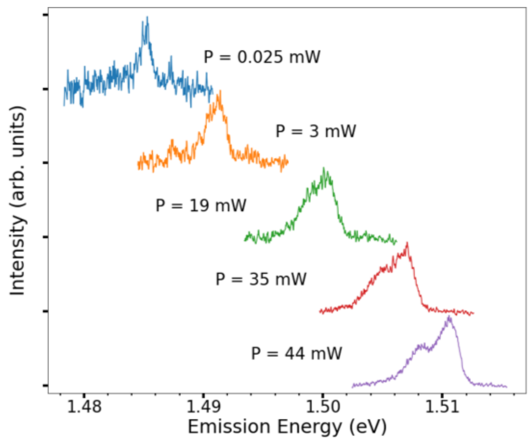

Figure 2: (b) PL spectra at different P = 0.025, 3, 19, 35, and 42 mW, from the low-density excitonic (IX) regime to the high-density plasma (I-EHP) regime. T = 1.7 K. The PL intensity maxima are normalized.

In the plasma regime, we observed a broad I-EHP line with a linewidth exceeding the IX binding energy and increasing with density (Figs. 1 and 2). At high temperatures, the I-EHP PL line is typical for plasmas above the condensation temperature (Fig. 1 top) [3]. At low temperatures, we observed a strong enhancement of the PL intensity at the Fermi energy of cold plasma (Fig. 1 bottom) that evidences the emergence of the excitonic Fermi edge singularity. The vanishing of this enhancement with increasing temperature supports its many-body origin (Fig. 1a).

We control the e-h density by the laser excitation power (Fig. 2). In contrast to the high density I-EHP regime, in the low-density excitonic regime, we observed a narrow IX line with the full-width-half-maximum down to < 1 meV. With increasing e-h density, we observe a transition from the ultracold gas of IXs, hydrogen-like bound pairs of separated electrons and holes, at low e-h densities to the ultracold I-EHP with the Fermi edge singularity at high e-h densities (Fig. 2). The realization of ultracold e-h plasma opens the opportunity to experimentally study phenomena in this quantum system.

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*equal contribution

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