Excitonic insulator in a magnetized quasi-2D plasma

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In a neutral low-temperature magnetoplasma, electrons and holes from upper occupied Landau levels in the conduction band and in the valence band bind to form magnetoexcitons. In other words, a state of an excitonic insulator is realized. The magnetoexcitons in a common Landau level ($j_e^N - j_k^N$) may be thought of as noninteracting. The interaction between magnetoexcitons of different levels leads to a lowering of the energy.

1. It has been shown in several theoretical papers[1] that the attractive interaction between electrons *e* and holes *h* in an *e–h* plasma in a semiconductor or semimetal may lead to the formation of bound *e–h* pairs (excitons) at the Fermi level. Such excitons are analogs of Cooper pairs in superconductors. Since excitons are neutral, their formation causes the originally metallic plasma to become an insulator. Such a state has been called an "excitonic insulator." We are unaware of any published experimental observation of an excitonic insulator in a semiconductor. A transition to a state of an excitonic insulator would be expected at low temperatures, with the electron and hole Fermi surfaces having the same shape or approximately the same shape. Systems with reduced dimensionality would be preferable, for two reasons. First, the exciton rydberg is larger in such systems; second, the screening of the Coulomb interaction is reduced.[2] In this letter we are reporting a study of a quasi-zero-dimensional (quasi-0D) system: a neutral photoexcited quasi-2D *e–h* plasma in a strong magnetic field.

A low temperature is a necessary condition for the realization of an excitonic insulator. In a dense, magnetized *e–h* plasma in $In_xGa_{1-x}As/GaAs(x = 0.28)$[3] and GaAs/AlGaAs quantum wells,[4] photoexcited at a bath temperature ~2 K, the electron temperature reaches 200 K or more. Such values are above the exciton binding energy. The situation is more favorable in an $In_{53}Ga_{47}As/InP$ quantum well, in which the electron temperature of an e–h plasma at a density $n_{eh} < 10^{12}$ cm^{-2} does not exceed 40 K (because of the lower recombination rate).[5] We reported some preliminary experimental results in Ref. 5.

2. Undoped InP/$\mathrm{In_{0.53}Ga_{0.47}As}$/InP heterostructures with single quantum wells ($L = 15$ nm) were grown by metal–organic chemical vapor deposition.[6] Nonequilibrium carriers were excited by a cw argon laser with $\lambda = 5145$ Å. The samples were immersed in superfluid helium in a cryostat with a superconducting solenoid ($H < 8.7$ T). Particular care was taken to ensure homogeneity of the e–h plasma. For this purpose, we blocked movement of the e–h plasma in the plane of the quantum well through the fabrication of 50×50 μm mesas, and we used a cw-laser beam of slightly larger diameter (100 μm).

3. Figure 1 shows emission spectra of magnetized plasmas with various values of n_{eh}, recorded in a magnetic field $H = 8.65$ T directed perpendicular to the plane of the quantum well, at $T_{\mathrm{bath}} = 2$ K. At a low density, we find a single line in the spectrum. This line corresponds to emission of a zero–zero magnetoexciton from the zeroth Landau level ($j_e = j_h = 0$). As the density n_{eh} is increased, the electron and hole Landau levels are progressively filled, and new lines appear in the spectrum. These new lines correspond to allowed ($j_e = j_h$) transitions between Landau levels in the conduction band (j_e) and in the valence band (jh). We see from Fig. 1 that the carriers appear at the first Landau level before the overall intensity of the 0–0 lines reaches saturation. The reason in the finite relaxation time of the photoexcited carriers. An effective electron temperature can be estimated from the intensity ratio of the emission lines. At $n_{eh} < 10^{12}$ cm^{-2} we find that this effective temperature is no higher than 40 K, well below the cyclotron energy and the direct Coulomb energy (> 10 meV) in the system.

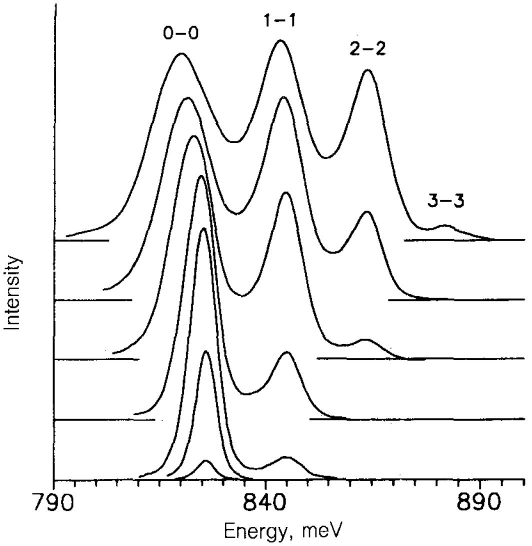

FIG. 1. Emission spectra of a magnetized electron–hole plasma in a 15-nm $\mathrm{In_{0.53}Ga_{0.47}As}$/InP quantum well for various values of n_{eh} ($H = 8.65$ T, $T_{\mathrm{bath}} = 2$ K).

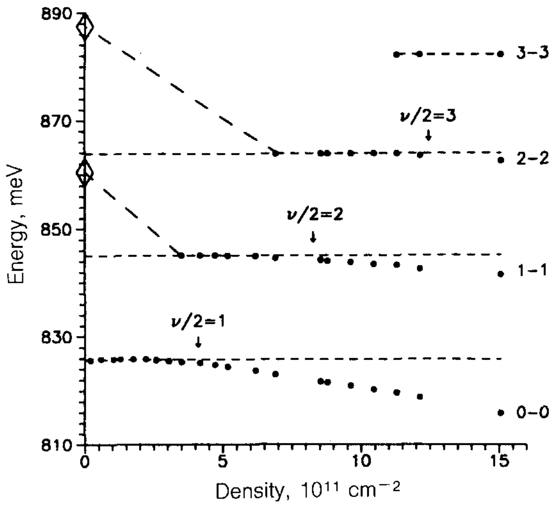

FIG. 2. Transition energies versus n_{eh} ($H = 8.65$ T).

Figure 2 shows the changes in the energies of the allowed transitions between Landau levels with increasing n_{eh}. The values of the energy for $n_{eh} = 0$ were found from the photoexcitation spectra of the 0–0 magnetoexciton; the other energy values were found from the emission spectra. It can be seen from Figs. 1 and 2 that an increase in the number of carriers in the upper filled Landau level ($j_e = j_h = j^u$) results in a lowering of the energies of all the transitions, except $j^u - j^u$.

4. At small values of n_{eh} the position of the emission line corresponds to the energy of the 0–0 magnetoexciton, which is $E_{0-0} = E_g + 1/2\hbar\omega_c - E_0$, where E_g is the gap width, $\hbar\omega_c$ is the cyclotron energy, and E_0 is the binding energy of the 0–0 magnetoexciton. In the limit of a strong magnetic field we have $E_0 = (\pi/2)^{1/2}e^2/kl_H$, where k is the dielectric constant, and l_H is the magnetic length, which determines the size of the magnetoexciton. As the exciton density increases, we would expect corrections for an exciton–exciton interaction.[7] Excitons repel each other at distances $r < l_H$ by virtue of the Pauli principle, while an exchange attraction is dominant at large distances. In the strong-field limit these two contributions to the scattering amplitude cancel out, and the energy of the excitons should remain unchanged up to the point at which Landau level 0 is completely filled.[7] This conclusion agrees with the experimental observation that the energy of the 0–0 transition remains constant at $\tilde{\nu} = \nu/2 < 1$ (Figs. 1 and 2).

For unbound e and h, an increase in n_{eh} should lead to a lowering of the energy of the 0–0 transition, while the exchange energy of the electrons and holes does not depend on their pairing. The Pauli repulsion drops out of the picture in this case because of the degeneracy of the Landau level. In the complete absence of e–h pairing, the energy of the 0–0 transition would decrease by $2E_0$ as the filling factor increased from 0 to 1; this change would amount to 30 meV in a field of 8.7 T. The plateau on the plot of the energy of the 0–0 transition versus n_{eh} indicates that all the e's and h's in Landau level 0 are bound into excitons, up to the point that the level is completely filled. Since the system is a quasi-0D system in a magnetic field, the screening of the Coulomb interaction in it is greatly suppressed, and the binding energy of the magnetoexciton remains essentially constant up to the point at which the level is completely filled.[7,8]

The 1–1 transition with $n_{eh} = 0$ corresponds to the emission of a 1–1 magnetoexciton. Its energy is $E_{1-1} = E_g + 3/2\hbar\omega_c - E_1$, where $E_1 = (3/4)E_0$ is the binding energy of a 1–1 magnetoexciton. To explain the change in the energy of the 1–1 transition with increasing n_{eh}, we note that the Pauli repulsion drops out of the picture in the case of an interaction between particles from different Landau levels, whose wave functions are constructed from different quasimomenta. The exchange attraction, on the other hand, remains in force. The energy of the 1–1 magnetoexciton thus decreases as Landau level 0 becomes filled ($\tilde{\nu} < 1$), and the energy of the 0–0 transition decreases during filling of Landau level 1 ($1 < \tilde{\nu} < 2$). At $\tilde{\nu} = 1$, the lowering of the energy of the 1–1 transition is equal to the exchange interaction energy of the *e–h* pair in level 1 with all pairs of filled level 0.[7,8] In the strong-field limit, this energy is E_0 (16 meV at $H = 8.65$ T). The experimental value of 15 ± 3 meV agrees with this figure.

The energy of the 1–1 transition in the region in which the first Landau level is filled ($1 < \tilde{\nu} < 2$) does not depend on n_{eh}. This means that all the *e*'s and *h* 's in Landau level 1 are bound into excitons over the entire range $1 < \tilde{\nu} < 2$. For these excitons, the Pauli and exchange contributions cancel out. The behavior of the 2–2 magnetoexciton (Figs. 1 and 2) is similar to that of the 1–1 magnetoexciton. Its energy decreases 23 ± 3 meV during the filling of Landau levels 0 and 1, while it remains constant during the filling of level 2. The magnetoexcitons of a common Landau level ($j_e^N - j_h^N$) thus do not interact, but the interaction of magnetoexcitons of different levels leads to a lowering of the energy, i.e., is attractive. Recent studies[9] of the spectra of a 2D *e–h* plasma during selective excitation of a small number of magnetoexcitons in Landau levels 0 and 1 revealed that the magnetoexcitons of different levels attract each other in a strong magnetic field, while the interaction of a small number of magnetoexcitons in a single level does not lead to a change in their energy (within the errors involved).

The fact that the energy of the *j–j* magnetoexcitons remains constant over the entire region of densities with $j \leqslant \tilde{\nu} \leqslant j + 1$ indicates that all the *e*'s and *h* 's in the upper Landau level are bound into excitons, so a state of an excitonic insulator prevails in the system. We wish to stress that a pairing of the *e*'s and the *h* 's also occurs at $\tilde{\nu} > 1$, where the interparticle distance is smaller than the size of the magnetoexcitons. In this case the magnetoexcitons are also analogs of Cooper pairs.

In a zero magnetic field, the excitons at the Fermi surface are dynamic pairs, while pairing below the Fermi level is weakened because of the reduction of the number of sites for scattering in *k* space. In a strong magnetic field, magnetoexcitons are static pairs,and in a first approximation the pairing energy at the Landau level does not depend on whether there are carriers in higher-lying levels. When Auger processes are taken into account, a magnetoexciton below the Fermi level can no longer be regarded as a stable bound state. This circumstance is reflected, in particular, in an increase in the width of the emission line for transitions between Landau levels below the Fermi level (Fig. 1). In addition, the shift of the 1–1 line upon a change in $\tilde{\nu}$ from 0 to 1 is substantially greater than the shift of the 0–0 line as $\tilde{\nu}$ changes from 1 to 2, although in the absence of Auger transitions these shifts should be identical according to the model under consideration here.[10]

In the particular case of integer values of $\tilde{\nu}$, we can find the transition energy for the completely filled Landau level closest to the Fermi level by introducing a new quasiparticle: a deexciton.[10] The energy of the deexciton consists exclusively of the exchange interaction of the *e*'s (*h*'s) with all the other *e*'s (*h*'s) in the band and the binding energy of the magnetoexciton.[10] Because of the electron-hole symmetry of the Landau level (the renormalization of E_g is taken into account), we can apparently also calculate the energies of transitions for arbitrary ν in terms of deexcitons, taking Pauli repulsion into account.

5. Figure 3 shows the transition energies versus H at fixed values of n_{eh}. At the various values of n_{eh}, the energies of the transitions between the filled upper Landau levels conform to a single Landau fan, shown by the solid lines in Fig. 3. This result reflects the circumstance that at a fixed value of H the energy of the magnetoexcitons in the upper level does not depend on the density up to the point at which the level becomes completely filled, and carriers appear in the next level (Figs. 1 and 2).

A decrease in H leads to a decrease in the degeneracy of the Landau levels. At

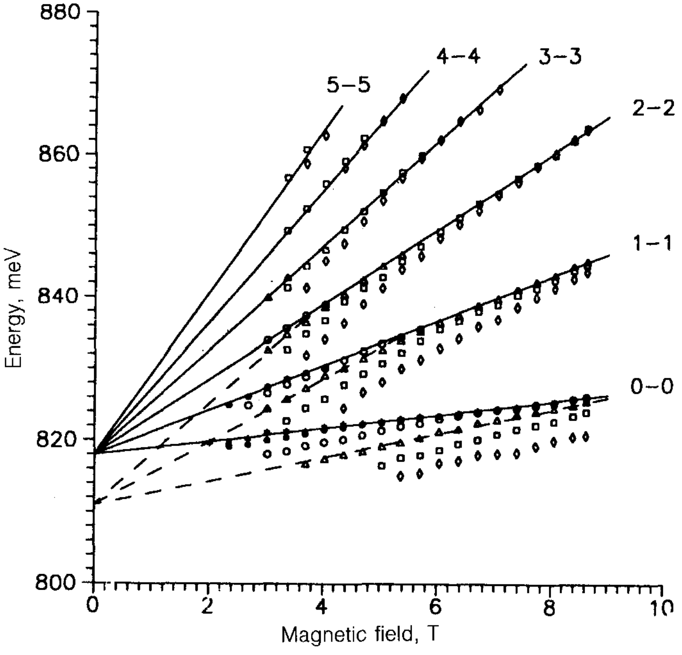

FIG. 3. Transition energies versus H for various values of n_{eh}. *—4×10^{10} cm^{-2}; ●—2.1×10^{11}; ○—2.9×10^{11}; ▲—4.8×10^{11}; □—6.8×10^{11}; ◇—10^{12} cm^{-2}.

$H_c(N) = 2\pi\hbar c n_{eh}/(N+1)e$ level N is filled completely, and level $N+1$ starts filling up. As was shown in §3, the magnetoexcitons in a common Landau level do not interact with each other, while the interaction of magnetoexcitons in different levels results in a lowering of the energy. At $H < H_c(N)$, a decrease in H leads to an increase in the number of magnetoexcitons in other levels ($j \neq N$), while at $H > H_c(N)$ it leads to a decrease in this number (the number remains constant in the case $N = 0$). At $H = H_c(N)$, there is thus a change in the slope of the plot of the energy of the N–N transition versus H (the plot is steeper in the case $H < H_c$). The energies of transitions between Landau levels below the Fermi level confirm to Landau fans (different fans for different values of n_{eh}), which converge at $H = 0$ on points corresponding to the renormalized gap width. One such fan (for $n_{eh} = 4.8 \times 10^{11}$ cm^{-2}) is shown by the dashed lines in Fig. 3.

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