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LETTER TO THE EDITOR

The field-induced phase transition of an electron–hole system in weakly coupled double quantum wells

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Abstract. The sudden reduction of the photoluminescence linewidth observed at low temperature in coupled quantum wells is analysed in view of possible 2D phase transitions occurring at different density limits. The linewidth calculated within a BCS-like transition is found to be proportional to the gap below T_c. This can be regarded as a 'fingerprint' for identifying the nature of the condensed phase.

Recently, Fukuzawa, Mendez and Hong [1] reported that below a certain critical temperature ($T < 10$ K) the photoluminescence linewidth measured in coupled quantum wells made from $GaAs/Ga_{0.7}Al_{0.3}As/GaAs$ compounds suddenly reduced. They found that a single, broad photoluminescence peak split into two peaks under an electric field $\mathscr{E}$ ($\perp$ *xy*—epitaxial plane); the low-energy peak became sharper and more intense with the increasing electric field at low temperature. The reduction of linewidth was observed only under an electric field for certain excitation power densities in the region of 0.6 W cm^{-2}, and for certain barrier thickness ($\simeq$40 Å) allowing only weak coupling between adjacent quantum wells. These observed changes were attributed to the transition of excitons in the quantum wells to an ordered phase with a long coherence length, so their energy is prevented from broadening due to the structural imperfections. For almost two decades the possibility of such a phase transition leading to a liquid state or droplets has been of continuing interest in condensed matter physics [2, 3]. Earlier, Lozovik and Yudson [4] and Shevchenko [5] pointed out a fundamentally different pairing mechanism and, hence, formation of a superconductive phase. This was the Coulomb attraction between quasi-2D electrons and holes, separated by dielectric media, which may lead to a finite gap of single-particle excitations. Inspired by the work of those authors, Fuzukawa *et al* [6] predicted earlier a phase transition that was similar to one observed experimentally [1]. They also argued that excitons created in coupled double quantum wells can undergo a Bose–Einstein condensation.

In an electric field the electrons and holes can, in fact, be confined in spatially adjacent wells to form excitons. A simple argument based on the minimization of electrostatic energy due to oppositely charged sheets suggests that the density of excitons of this kind is proportional to the electric field (i.e. $\sim \varepsilon\mathscr{E}/e$). Accordingly, the intensity of the e_1b_1 transition [1] increases linearly with $\mathscr{E}$, while that of e_2h_1 decreases. This is qualitatively the situation observed in experiment [1]. Because of this effect of $\mathscr{E}$, the

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time for recombination increases with the decrease of overlap between the electron and hole wave functions, and a situation identical to that described by the above-mentioned theories [4, 5] will be created.

If what was observed by Fukuzawa *et al* [1] is a phase transition, it might be of one of the following three types: Wigner crystal, Bose–Einstein condensation, and BCS-like. By examining the limits of these types we argue that the model described by Fuzukawa *et al* [6] may lead to a BCS-type phase transition, but neither to a Bose–Einstein condensation [3] nor to a Wigner crystal. In these phase transitions two parameters are of prime importance: the spatial extent of the exciton in the xy plane (λ), and the exciton–exciton separation (l). If $\lambda \ll l$ one can consider the Wigner crystal or Bose–Einstein condensation. In this low-density limit, electrons and holes can be viewed as individual quasiparticles, which can form excitons, but not other condensed forms (droplets or molecules), because the parallel dipoles repel in the xy plane. The other limit, $\lambda \gg l$, is appropriate for the BCS transition. By consideration of the expected exciton density [1] ρ_e ($\sim 10^{10}$ cm^{-2}) one can obtain the very crude estimates $l \simeq 1000$ Å and $\lambda \simeq 200$ Å for the given separation of quantum wells of 40 Å.

The possible lattice structure of the Wigner crystal was studied earlier [7] for a similar system under a dipole–dipole interaction. This 2D Wigner crystal is assumed to melt via a Kosterlitz–Thouless transition, with the melting temperature given by $T_c = mb^2 v_t^2 v_l^2/[8\pi k_B a(v_t^2 + v_l^2)]$. Here, v_t, v_l, b, and a are respectively, longitudinal and transverse sound velocities, the Burgers vector and the area of the unit cell. With appropriate parameters and $m = m_h + m_e$ we found that T_c is negligibly small. Very low T_c as well as a significant value of λ/l rules out the Wigner crystal. As for the second possibility within the low-density limit, we assume that the system is an ideal 2D Bose gas, since excitons can be treated as bosons at this limit. Then the total number of bosons, N, can be calculated from the following expression:

$$N = z(\partial/\partial z) \ln Z(z, V, T) \tag{1}$$

with Z the grand partition function, z the fugacity and T the temperature. For free bosons confined in a 2D box of area S with infinite walls, we find that

$$N/S = (2\pi m_b k_B T/h^2) \ln(N_0 + 1) + N_0/S \tag{2}$$

where N_0 is the number of bosons in the zeroth energy level, m_b ($= m_e + m_h$) is the mass of the boson. We note that $N_0 = N$ for $T = 0$ K. Since the first term on the right-hand side changes slowly in comparison with the second one, near $T = 0$ K N_0 decreases from N (i.e. from the maximum value it attains at $T = 0$ K) linearly with temperature. The slope of this linear dependence is approximately $2\pi m_b k_B \ln N/h^2$, which is in the region of $10^{14} \ln N$ m^{-2} K^{-1}. With the values reported from the experiment for N/S this slope is $\sim 10^{15}$ m^{-2} K^{-1}. This means that even for $T \simeq 0.05$ K, N_0/S drops to half of its initial value. Furthermore, full solution of (2) shows that there is no critical temperature T_c at which N_0/S suddenly becomes non-zero. Instead, it changes from zero gradually as the temperature is decreased. In view of the fact that the ordered phases in 2D can occur through the Kosterlitz–Thouless transition, the relation $k_B T_c = \pi\hbar^2\rho_e/2m$ yields $T_c \simeq 0.3$ K. This simple analysis also shows that if the observed reduction of the linewidth is due to a phase transition of the electron–hole system in the weakly coupled quantum wells, this phase transition cannot be a Bose–Einstein condensation.

If the density of excitons is not very low, the interactions between electron gas in one well and hole gas in the other well are enhanced with the diminishing of excitons. In this case an electron–hole pair is treated like a Cooper pair, but neither as a boson nor as a free exciton. The Hamiltonian of this system can be written [4] by analogy with the standard BCS theory. To this end, one assigns creation and annihilation operators for electron states of energy $\varepsilon_e(\boldsymbol{k})$, as well as hole states $\varepsilon_h(\boldsymbol{k})$. The coupling constant is a screened, attractive Coulomb potential, through which an electron–hole pair of wave vectors $\boldsymbol{k}'$ and $-\boldsymbol{k}'$, respectively, is annihilated while another pair of wave vectors $\boldsymbol{k}$ and $-\boldsymbol{k}$ is created. Then, in the mean-field approximation, the energy spectrum of the quasi-particles that describes the excited states of the ordered phase is given by $E(\boldsymbol{k}) = [(\varepsilon_e(\boldsymbol{k} + \varepsilon_h(\boldsymbol{k}))^2/4 + \Delta_k^2]^{1/2}$. In the weak-coupling limit, we estimate that $\Delta_0 \simeq 1.3$ eV for $T_c \simeq 8.5$ K.

The peak observed in the photoluminescence experiment is simply due to the annihilation of an electron–hole pair to create a photon (i.e. recombination) as a result of the single-particle excitation across this gap. The spectrum $I(\omega)$ is calculated by assuming that $\mathscr{E}$ is strong enough that electrons and holes have already formed the BCS phase [4, 5] before they are recombined; furthermore, the effects of imperfections are neglected. It is expressed in atomic units as

$$I(\omega) = 2\pi \sum_{q} |\langle \Psi_q | V | \Psi_0 \rangle|^2 \, \delta(E(\boldsymbol{q}) - E_0 + \omega). \tag{3}$$

Here Ψ_0 is the BCS wave function with the eigenvalue E_0, and Ψ_q is the wave function obtained from the former by eliminating one electron–hole pair of $(\boldsymbol{q}; -\boldsymbol{q})$. Note that $E(\boldsymbol{q}) = E_q - (E_g + q^2/2m)$ in terms of the energy gap E_g and the reduced mass of the electron–hole pair. The interaction V producing the recombination is expressed as

$$V = -\frac{e_e}{2m_e c} \sum_{k,q} (2\boldsymbol{k} + \boldsymbol{q}) \cdot \boldsymbol{A}_q^e e_{k+q}^{\dagger} e_k - \frac{e_h}{2m_h c} \sum_{k,q} (2\boldsymbol{k} + \boldsymbol{q}) \cdot \boldsymbol{A}_q^h h_{k+q}^{\dagger} h_k \tag{4}$$

in terms of the Fourier transforms of the vector potentials $\boldsymbol{A}_q^e$ and $\boldsymbol{A}_q^h$ at the electron and hole planes, respectively. In order to produce (3) the following assumptions are made: (i) all the electrons and holes are separated in different wells; there is no exciton confined in a single well; (ii) the system at hand is in its ground state (i.e. all the electrons and holes are paired). Since the excited states are separated by a gap from the ground state, the second approximation is valid as long as T is not close to T_c. Substituting in the expression for V we obtain

$$I(\omega) = CA^2(4m\xi + q_F^2)\, u^2 v^6/(1 + v^2)|_{\xi=\bar{\xi}} \tag{5}$$

where $\bar{\xi} = (2\,\delta\omega - \sqrt{\delta\omega^2 + 3\Delta^2})/3$ with $\delta\omega = \omega - (E_g + q_F^2/2m)$; q_F is the Fermi momentum; $A = A_0^e = A_0^h$; u and v are usual coherence factors expressed in terms of the energy spectrum of normal and superconductive states; and C is a constant. In figure 1(*a*) we show $I(\omega)$ for various values of the superconductive gap, $\Delta(T)$. Note that the larger the value of Δ, the larger the full width at half maximum (FWHM). Since Δ is a function of temperature, so is $I(\omega)$. In figure 1(*b*) we plot the FWHM as a function of T/T_c. On the same plot we show the temperature dependence of the BCS gap. The FWHM is proportional to Δ. This is the expected result, since an electron and a hole can be recombined only if they are first excited from the ground state by $\sim\Delta$. Accordingly, the FWHM is expected to show the behaviour depicted in figure 1(*b*) in the interval $0 < T/T_c \leq 1$, if the observed transition is the BCS-like transition [4, 5]. The experimental variation of the FWHM also indicates the contribution of a different type of broadening mechanism, which is insensitive to the variation of temperature, but increases with decreasing $\mathscr{E}$. Therefore, the FWHM can never become zero as $T/T_c \rightarrow 1$. In conclusion,

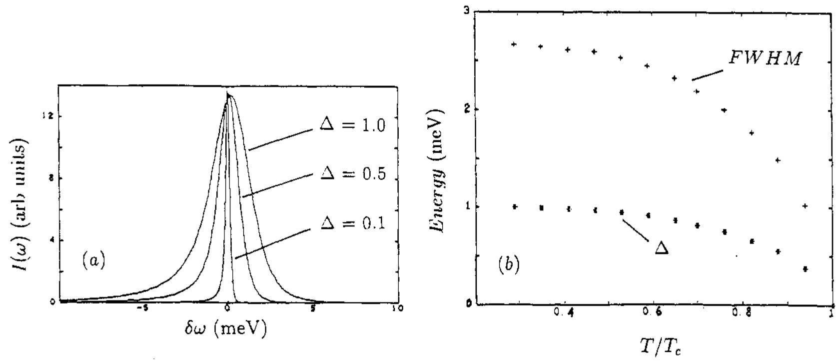

Figure 1. (*a*) Photoluminescence intensity versus ω (defined in the text) calculated for various values of Δ. (*b*) The variation of the FWHM and Δ with T/T_c. The calculations were carried out with $q_F^2/4m = 20$ meV.

the behaviour of the photoluminescence linewidth below T_c can be considered as a 'fingerprint' for deciding whether or not the observed event originates from a BCS-like phase transition of electron and holes. Further experimental investigation in the range below T_c is expected to shed light on the nature of the observed 'transition'.

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