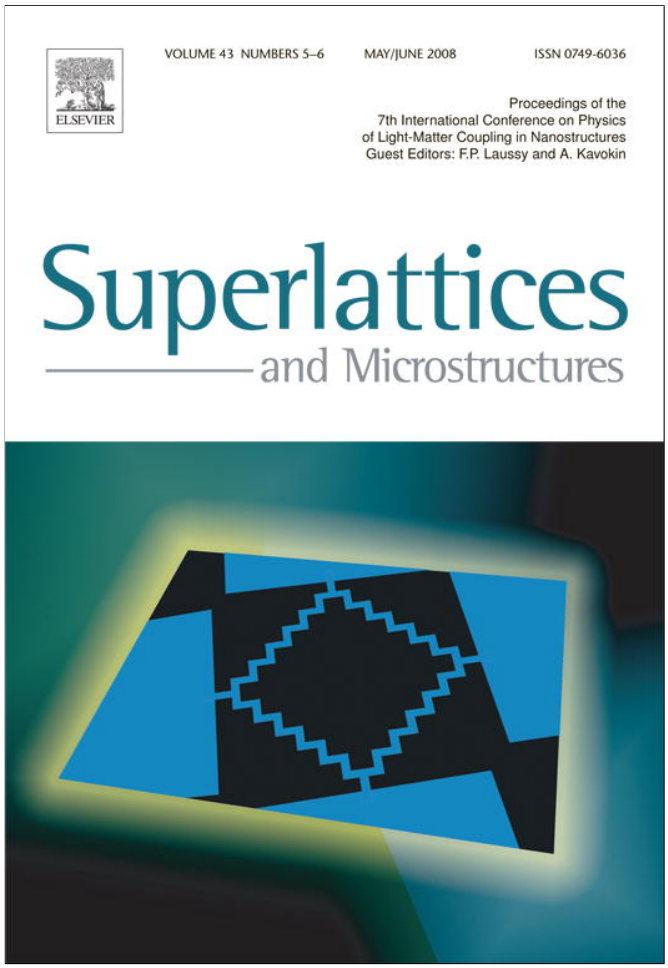

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Theory of the excitonic Mott transition in quasi-two-dimensional systems

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Abstract

The excitonic Mott transition in single and double quantum wells is studied using the Green's function technique. An abrupt jump in the value of the ionization degree, which happens with an increase of the carrier density or temperature, is found in a certain density–temperature region. The opposite effect – the collapse of the electron–hole plasma into an insulating exciton system – is predicted to occur at lower densities. The critical density of the Mott transition for spatially indirect excitons may be much smaller than that for direct excitons.

Keywords: Exciton; Electron–hole plasma; Quantum well; Phase transitions

The excitonic Mott transition is the avalanche ionization of excitons as a result of screening and momentum space filling effects [1]. Excitons, which dominate optical spectra of semiconductors at low temperatures and densities, are completely ionized at elevated temperatures and high densities and a free electron–hole plasma is formed. There is a long-standing question as to whether the transition between excitonic and plasma phases is smooth or abrupt, and despite significant effort there is still no firm theoretical understanding of this effect. Because of the inhomogeneous excitation generated by the finite absorption coefficient, an electron–hole pair density is not well defined in a bulk sample. Therefore, the search for the excitonic Mott transition has recently turned towards quasi-two-dimensional systems [2].

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In a single quantum well (SQW), recombination significantly erodes electron–hole pair density before the system reaches the thermal equilibrium. The recent SQW experiments [2] have shown a smooth transition from excitonic to electron–hole–plasma-type luminescence over the range of pair densities exceeding an order of magnitude. However, the studied SQW system could not be cooled below an estimated temperatures of about 30 K. A spatially separated quasi-two-dimensional electron–hole system, such as a double quantum well (DQW) subjected to an external electric field, should be more promising for experimental observation of the Mott transition, since the lifetime of excitons in it is relatively long and the intra-layer repulsion of like particles prevents the formation of electron–hole liquid droplets [3].

The main thrust of experimental work on DQWs has been directed towards the observation of exciton Bose–Einstein condensation [4], guided by earlier extensive theoretical studies [6]. However, the question of conditions for the existence of excitons at different temperatures and densities should be answered before interpreting results of BEC experiments. There is also some experimental indication of a Mott transition in DQWs [5], although a corresponding theory does not exist. A spectacular ring formation in DQWs [4], which was initially attributed to the manifestation of excitonic BEC, has found another (classical) explanation [7]. The ring fragmentation, which is still not clearly understood, might be related to the Mott transition. The main goals of the presented work is to provide a brief outline of the main results of our theory of the excitonic Mott transition in both SQWs and spatially separated electron–hole systems.

We believe that for an adequate description of the excitonic Mott transition in quasi-two-dimensional systems one must account for momentum space filling effects as well as the contribution of scattering states [8,9]. In addition, the specific geometry of the spatially separated electron–hole system requires the introduction of a new screening mechanism — screening by spatially indirect excitons [10–12]. We take all these issues into account in our theory.

Before studying the Mott transition, which is essentially a jump in the ionization degree of the electron–hole plasma, one should clarify the concept of ionization degree and exciton density at medium and high plasma densities. In the dilute case, excitons can be considered as well-defined boson particles, and the problem of finding the ionization degree can be solved simply by counting electrons and holes in bound states pairwise. This approach, however, runs into trouble when the density of carriers increases and the exciton wavefunctions start to overlap. Furthermore, the chemical picture is not applicable if the scattering states are occupied, since counting particles in scattering states pairwise leads to divergences.

Therefore, it appears more practical to formulate the theory in terms of primary quasi-particles, i.e. in terms of electrons and holes. Instead of considering excitons in the system we investigate the single-particle density at given temperature $T = 1/\beta$ and quasi-Fermi levels μ_e and μ_h. To this end we use many-body theory for a system of interacting quasi-particles within the ladder approximation [8]. Starting with the self-energy, which is based on the electron–electron and electron–hole pair-interaction series, and performing a derivation similar to that of Zimmermann and Stolz for the 3D case [13], we obtain an expression for the electron density in the following form:

$$n_e = n_e^0(\mu_e) + n^{ee}(\mu_e) + n^{eh}(\mu_e + \mu_h), \tag{1}$$

where $n_e^0 = m_e/(\beta\pi\hbar^2)\ln(1 + \exp(\beta\mu_e))$ is the density of free quasi-particles, and n^{ee} (n^{eh}) originates from the electron–electron (electron–hole) interaction

$$n^{ab} = \frac{2}{\beta\pi\hbar^2}\sum_{m=-\infty}^{+\infty}\left[(1-\delta_{ab})\sum_n M_{eh}L_{eh}(\epsilon_{mn}) + \frac{1}{\pi}M_{ab}\lambda_m^{ab}\int_0^\infty \mathrm{d}k L_{ab}\left(\frac{\hbar^2k^2}{2m_{ab}}\right)2\sin^2\delta_m^{ab}(k)\frac{\mathrm{d}\delta_m^{ab}}{\mathrm{d}k}\right], \quad (2)$$

$$L_{ab}(\epsilon) = -\ln[1-\exp(\beta(\mu_a+\mu_b-\epsilon))], \quad (3)$$

$$M_{ab} = m_a + m_b, \quad m_{ab} = \frac{m_a m_b}{m_a+m_b}, \quad \lambda_m^{ab} = 1-\delta_{ab}(-1)^m/2. \quad (4)$$

Here, m_e (m_h) is the electron (hole) effective mass, the quasi-Fermi levels are measured from the edges of the lowest quantized subbands, and ϵ_{mn} are the exciton levels. The quantities $\delta_m^{ab}(k)$ are the generalization of scattering phase shifts for the case of non-negligible k-space filling. Refs. [11,14] show the derivation of these expressions in more detail.

The particle density expression, Eq. (1), can be divided into two parts according to the Fermi-level dependence. Indeed, the first two terms in Eq. (1) contain only the electron quasi-Fermi level, whereas the last, n^{eh}, depends on the sum $\mu = \mu_e + \mu_h$. We shall argue that the quantity n^{eh} can play the role of the excitonic density for the whole range of total concentrations. Firstly, the term n^{eh} becomes equal to the density of idealized bosons (excitons) in the limit of low densities. Secondly, a quantity, which contains the quasi-Fermi levels in the form of a sum has "insulating" properties. This can be illustrated by the following consideration. Suppose there is an electric field inside the structure, which generates a perturbation to the local potential, δV. Then, the first two terms in the density expression, Eq. (1), "feel" the disturbance, and the local values of the density given by the sum of these two terms will be either increased or decreased, according to the sign of the perturbation potential and the type of particles considered. This represents metallic behavior. At the same time, the last term, n^{eh}, is not influenced by the local-potential perturbation, since $\delta\mu_e$ and $\delta\mu_h$ cancel each other. Thus, this part of the density is not disturbed by the external electric field and can be considered as insulating. Therefore, it is reasonable to introduce the ionization degree of the electron–hole plasma as

$$\alpha = 1 - \frac{n^{eh}}{n_e} = 1 - \frac{n^{eh}}{n_h}. \quad (5)$$

A self-consistent procedure is used to calculate the parameters of the quasi-2D electron–hole plasma at a given temperature and chemical potential [14], then the results can be presented in terms of the total (pair) density. In Fig. 1(a) the ionization degree, α, is plotted as a function of density for three different temperatures. The low-temperature curves are truncated for numerical reasons. If the procedure had not been halted, these curves would have approached unity asymptotically. One can see that for low enough temperatures there is a density region where α is a three-valued function. Physically, this situation means the following. Changing the density of the carriers, one reaches a critical value, at which a slight increase of the carrier concentration results in a large jump in the ionization degree. Effectively, this means a transition from a system consisting mainly of excitons to an almost completely ionized state. Clearly, this is what the Mott transition is meant to be. If we start from the high-density limit, in which there is no excitons, and reduce the total carrier density, then (due to more efficient screening by free carriers) the collapse into the insulating excitonic state occurs at a lower carrier density. This hysteretic behavior only takes place below a certain temperature, which can be associated with the Mott transition temperature.

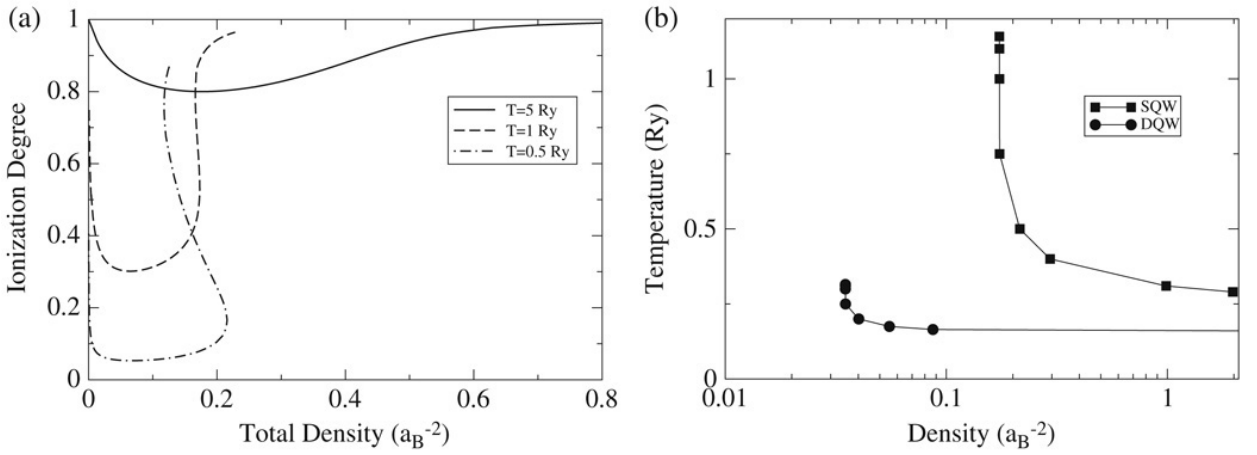

Fig. 1. (a) Ionization degree for an electron–hole plasma in an single quantum well as a function of total carrier density at different temperatures. (b) Mott transition temperature as a function of density for single and double quantum wells. In the DQW structure the inter-well distance is $0.2a_B$.

In Fig. 1(b), the Mott transition critical points for the SQW and DQW structures are shown. There are two characteristic temperatures for each curve. One is the maximum temperature at which the Mott transition disappears, and the other is the temperature at which the critical density increases drastically so that our medium-density two-body correlations approach fails. Both temperatures are smaller for the DQW structure, which indicates their relation to the exciton binding energy.

The most striking feature here is the much lower transition density for the DQW structure. This can be explained qualitatively by the larger Bohr radius of indirect excitons. This fact may facilitate the observation of the Mott transition in DQW structures, since the transition density at low temperature can be lowered (by increasing the quantum well separation) to experimentally accessible values.

We hope to encourage more experimental research, which would lead to irrefutable observation of such a fundamental effect as the excitonic Mott transition. Our theoretical results suggest the following method. The temperature should be set as low as possible and the pumping slowly increased to a high value, but so that the temperature kept constant. Then, as the system is placed in the stable insulating state below the Mott transition curve, one should slowly increase the temperature. The ionization degree will jump and an increased concentration of e–h pairs will appear.

References

[1] N.F. Mott, Philos. Mag. 6 (1961) 287.
[2] L. Kappei, J. Szczytko, F. Morier-Genoud, B. Deveaud, Phys. Rev. Lett. 94 (2005) 147403.
[3] T.M. Rice, in: H. Enrenreich, F. Seitz, D. Turnbull (Eds.), Solid State Physics, vol. 32, Academic Press, New York, 1977, p. 1.
[4] L.V. Butov, A.C. Gossard, D.S. Chemla, Nature 418 (2002) 751;
D. Snoke, S. Denev, Y. Liu, L. Pfeiffer, K. West, Nature 418 (2002) 754, and references therein.
[5] V.B. Timofeev, A.V. Larionov, M. Grassi-Alessi, M. Capizzi, J.M. Hvam, Phys. Rev. B 61 (2000) 8420.
[6] See e.g. X. Zhu, P.B. Littlewood, M. Hybertsen, T. Rice, Phys. Rev. Lett. 74 (1995) 1633, and references therein.
[7] L.V. Butov, et al., Phys. Rev. Lett. 92 (2004) 117404;
R. Rapaport, et al., Phys. Rev. Lett. 92 (2004) 117405.
[8] R. Zimmermann, Many-Particle Theory of Highly Excited Semiconductors, BSB Tuebner, Leipzig, 1987.
[9] M.E. Portnoi, I. Galbraith, Phys. Rev. B 58 (1998) 3963;
M.E. Portnoi, I. Galbraith, Phys. Rev. B 60 (1999) 5570.

[10] V.V. Nikolaev, M.E. Portnoi, Phys. Status Solidi a 190 (2002) 655.
[11] V.V. Nikolaev, Many-particle correlations in quasi-two-dimensional electron–hole systems, Ph.D. thesis, University of Exeter (2002).
[12] V.V. Nikolaev, M.E. Portnoi, Phys. Status Solidi a 190 (2002) 113.
[13] R. Zimmermann, H. Stolz, Phys. Status Solidi b 131 (1985) 151.
[14] V.V. Nikolaev, M.E. Portnoi, Phys. Status Solidi c 1 (2003) 1357.