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CONFERENCES AND SYMPOSIA

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Mesoscopic and strongly correlated electron systems “Chernogolovka 97”

1. Quantum dots and wells

The first conference session included the following presentations:

(1) **Timofeev V B, Larionov A V** (Institute of Solid State Physics, RAS, Chernogolovka, Russia), **Zeman J, Martinez G** (High Field Magnetic Laboratory MPI/CNRS, Grenoble, France), **Hvam J, Birkedal D, Soerensen K** (Microelectronic Centre, Lyngby, Denmark) “Interwell radiative recombination of a 2D electron gas in electrically biased double quantum wells”;

(2) **Sivan U et al.** (Technion, Haifa, Israel) “Exchange and correlation energy of 2D fermions at high r_s numbers”;

(3) **Al’tshuler B L** (Princeton, USA), **Kamenev A** (Weizmann Institute, Israel), **Levitov L S** (Massachusetts Institute of Technology, Cambridge, USA), **Gefen Y** (Weizmann Institute, Israel) “Inelastic quasi-particle time in a quantum dot”;

(4) **Forchel A** (Universität Würzburg, Germany) “Far and near field luminescence studies of III – V semiconductor quantum dots”;

(5) **Finkelstein G, Shtrikman H, Bar-Joseph I** (Department of Condensed Matter Physics, The Weizmann Institute of Science, Rehovot, Israel) “Shakeup processes of a two-dimensional electron gas in GaAs/AlGaAs quantum wells at high magnetic fields”;

(6) **Kulakovskiĭ V D** (Institute of Solid State Physics, RAS, Chernogolovka, Russia), **Bayer M, Michel M, Forchel A, Gutbrod T, Faller F** (Technische Physik, Universität Würzburg, Germany) “Excitonic molecules in InGaAs/GaAs quantum dots”;

(7) **Marcus C** (Stanford University, USA) “Experiments on phase-coherent transport through ballistic quantum dots”;

(8) **Bimberg D** (Technische Universität Berlin, Germany) “InAs quantum dots: from growth to lasers”;

(9) **Butov L V** (Institute of Solid State Physics, RAS, Chernogolovka, Russia) “Anomalous transport and luminescence of indirect excitons in coupled quantum wells”;

(10) **Ihn T** (Department of Physics, University of Nottingham, UK; Solid State Physics Laboratory, Zürich, Switzerland), **Thornton A, Itskevich I E, Beton P H, Martin P, Moriarty P, Nogaret A, Main P C, Eaves L, Henini M** (Department of Physics, University of Nottingham, UK), **Müller E** (Solid State Physics Laboratory, Zürich, Switzerland) “A self-assembled InAs quantum dot used as a quantum microscope looking into a two-dimensional electron gas”.

Papers 1, 5, 6, 9, and 10 are published below. Paper 3 was published in *Phys. Rev. Lett.* **78** 2803 (1997); for paper 7 see cond-mat/9708090, cond-mat/9708170, cond-mat/9709126.

Interwell radiative recombination of a 2D electron gas in electrically biased double quantum wells

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G Martinez, J Hvam, D Birkedal, K Soerensen

Coupled quantum well systems — double quantum wells (DQW) and superlattices (SL) have attracted considerable interests during the past decade [1 – 5]. In part, this interest is motivated by the expectation that these systems can be utilized for optoelectronic applications. On the other hand, some properties of these coupled quantum well systems are very attractive on pure fundamental grounds. Particularly, in the case of a DQW subjected to an applied electric field perpendicular to the layers, the interest lies in the possibility of photoexcitation of the interwell excitons with bound particles spatially separated by a barrier. Such interwell excitons, in contrast to intrawell ones (with electrons and holes located in the same well), should have long radiative decay times. Therefore these excitons can, in principle, easily be accumulated in high densities with the possibility of cooling them down to very low temperatures. In these conditions theory predicts very interesting collective properties for the interacting interwell excitons [6 – 9]. There are a few publications where some unexpected collective phenomena in a gas of interacting interwell excitons in an electrically biased DQW were claimed to have been observed [4, 5].The main goal of our report is to demonstrate that in the case of GaAs/AlGaAs p – i – n-DQW with a symmetric quantum structure the interwell radiative processes develop within a different, unexpected scenario.

We use a AlGaAs/GaAs ($x = 0.35$) DQW-structure grown using the MBE-technique on the (001) surface of n-doped GaAs substrate (Si doping: 2×10^{18} cm^{-3}). The structure has the following sequence of layers: a 0.5 μm n-doped GaAs buffer layer (Si doped to 10^{17} cm^{-3}); a 0.5 μm AlGaAs barrier (Si doping: 10^{17} cm^{-3}); a 0.3 μm AlGaAs insulating barrier; an 8 nm GaAs well; a 5 nm AlGaAs barrier; an 8 nm GaAs well; a 0.3 μm insulating AlGaAs barrier; a 0.3 μm top contact AlGaAs layer (Be doping: 10^{18} cm^{-3}) and finally a 4 nm GaAs cap layer. We used a 1×1 mm^2 lithographically etched mesa made in the above structure with ohmic contacts to the p- and n-regions. All

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optical measurements were performed with optical fibers in a temperature range down to 100 mK using the standard optical set-up. In darkness at low laser photoexcitation powers ($\leqslant 1$ mW cm^{-2}) and energies lower than the AlGaAs barrier gap the DQW-structure showed an $I-V$ characteristic typical for p–i–n-diodes and at maximum reverse bias (−3.5 V) the total current was less than 10 μA.

We first discuss the interwell luminescence corresponding to the regime of strong localization of photoexcited electrons and holes in adjacent wells. Under an applied electric bias non-equilibrium electrons and holes are trapped at first in spatially separated neighboring quantum wells. In addition, these carriers at low enough temperatures are localized in each well due to random potential fluctuations, enhanced by the electric field. Such a strong localization of carriers should occur if $kT \leqslant \Delta$, where Δ is the characteristic amplitude of potential fluctuations, and if the concentration of carriers, n_e or n_h , is less than a critical value n_c. This value is determined by the mobility edge and corresponds to the metal–insulator transition in each well. In the present case the main origin of these potential fluctuations is related to the ionized residual impurities in the insulating part of the structure depleted by the electric field. In such a case, the shape of the luminescence spectrum is expected to be a convolution of distribution functions representing fluctuations which localize electrons and holes. Therefore the corresponding luminescence should appear as a broad luminescence line, reflecting the amplitudes and size distribution of the random potential fluctuations. Localized nonequilibrium electrons and holes are weakly bound in the corresponding wells in such a way that their radiative recombination is analogous to the donor–acceptor pair recombination or electron–acceptor recombination. As an example, interwell and intrawell luminescence features observed in the PL spectra of p–i–n-DQW and measured at different bias voltages for $T = 7$ K are shown in Fig. 1. We indeed observe a broad interwell luminescence line (I-band) in this regime which shifts linearly with the applied voltage as theoretically expected. Besides this band, a narrow line, corresponding to the direct intrawell heavy hole excitons (1sHH), appears at a spectral position E_{exc} which is much less sensitive to the bias. When the excitation power increases, the interwell line energy moves towards E_{exc} which reflects the screening of the local electric field by nonequilibrium carriers confined in quantum wells. For this reason all the data presented here were obtained at a low photoexcitation power ($\leqslant 1$ mW cm^{-2}) for which the external electric field was practically unscreened. Time-resolved experiments under pulsed photoexcitation and the evolution of spectra with applied magnetic fields, perpendicular to the layers, confirm that the observed interwell luminescence corresponds to the radiative recombination of spatially separated and localized e–h pairs [10].

We turn now to the low temperature regime where, in the same p–i–n-DQW structure, a 2D-electron gas (2DEG) appears in one of the quantum wells, due to the preferential accumulation of electrons with a concentration exceeding the critical value n_c in the corresponding QW. The appearance of the 2DEG, when lowering the temperature, is accompanied by abrupt and spectacular changes of the luminescence spectra over a short range of temperature. This is illustrated in Fig. 2 where spectra, measured in the temperature range 2–7 K at fixed forward bias (0.64 V) and low excitation power (1 mW cm^{-2}) are displayed. At $T > 6$ K the spectrum looks like that presented in Fig. 1. At $T < 5.9$ K the interwell luminescence of localized e–h pairs disappears and a low energy tail appears at the 1sHH-exciton line. This tail corresponds, as will be proved later, to the interwell luminescence related to the radiative recombination of a 2DEG, appearing in one of the wells, with photoexcited holes in the adjacent well. The appearance of a 2DEG is accompanied by a strong redistribution of the electrical field in the insulating region of the pin-structure due to the effect of screening. At some critical temperature (here at $T_c = 5.9$ K), when this transition occurs, large instabilities of the internal electrical field appear, leading to strong fluctuations (low frequency noise) of the interwell and intrawell luminescence intensities. In other words, at T_c, a fluctuating switching is observed between the regime of localized e–h pairs (weak screening) and the regime of charge accumulation (strong screening). Such noisy behavior occurs in a narrow temperature range of ±0.6 K around T_c. It is not clearly understood at the moment why such an accumulation of electrons occurs over such a narrow temperature range but the analysis of the spectra suggests that this instability is certainly related to the metal–insulator transition occurring in the hole gas. Independent measurements of the temperature variation of the vertical impedance (parallel to the structure growth axis) show a sharp drop in the reactive part and a related increase in the active part of the impedance in the region close to T_c. So below T_c nonequilibrium electrons, created by photoexcitation or the current through the p–i–n-structure, can be more easily accumulated in one of the wells. Such a transition from the regime of localized e–h pairs to the regime of 2DEG

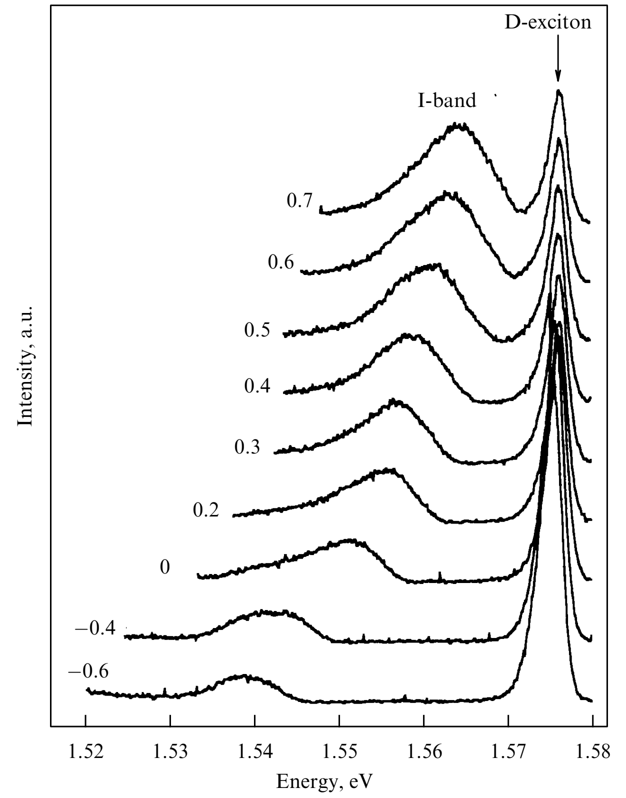

Figure 1. Intrawell (1sHH-exciton) and interwell (I-band) luminescence of the p–i–n-DQW structure for different electric bias conditions and $T = 7$ K. At zero applied voltage the luminescence corresponds to the built-in-field. The excitation power of the Ne–He laser on the mesa was around 0.1 mW cm^{-2}.

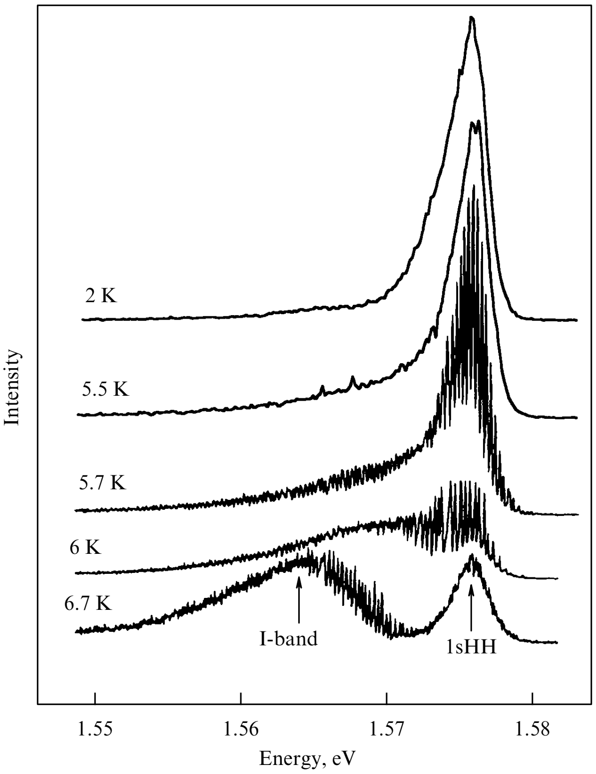

Figure 2. Luminescence spectra measured at different temperatures $T = 6.7$, 6, 5.7, 5.5, 2 K and fixed forward bias $U = 0.64$ V. The excitation power of the Ne–He laser is 0.1 mW cm^{-2}.

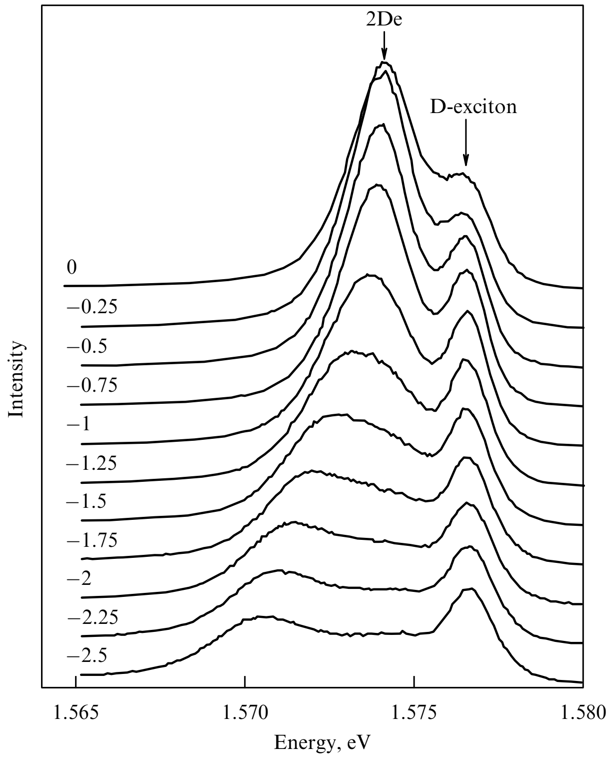

Figure 3. Interwell and intrawell luminescence spectra for different electric bias and $T = 0.18$ K. Photoexcitation was performed with an Ar^{+3}-laser, of excitation power 0.1 mW cm^{-2}.

accumulation was observed for different applied biases at temperatures close to 6 K.

Further cooling down to 0.1 K does not influence the interwell luminescence spectra for given bias and photoexcitation power. Figure 3 illustrates the evolution of the 2DEG luminescence spectra as a function of the applied electrical field. These spectra are located on the low energy side of the 1sHH direct exciton and therefore correspond to interwell recombination (see the scheme of inter- and intrawell recombination processes in Fig. 4). The low energy edge of the 2DEG luminescence spectrum in Fig. 3 corresponds to the bottom of the 2DEG band at a given bias and the full width of the spectrum (FWHM) is a measure of the Fermi energy E_F for this 2DEG. When the reverse bias is grown the FWHM increases which reflects the accumulation of a higher density of electrons n_e in the corresponding well. One can estimate $n_e = E_F m^*/(\pi\hbar^2)$ knowing the effective mass m^*, and n_e is found to vary linearly with the applied bias. One can see in Fig. 3 that E_F is pinned to the energy position of the 1sHH intrawell exciton E_{exc} due to the resonant tunneling coupling between quantum wells. Therefore it is possible to increase the n_e only by applying a reverse bias. Under high photoexcitation powers, around or more than 100 mW cm^{-2}, the only observed luminescence is that of the intrawell 1sHH-excitons, because nonequilibrium carriers with high density screen the electric field and transform the system to the flat band conditions.

The accumulation of 2D-electrons above the critical concentration n_c is proved by the observation of an optical analogue of Shubnikov oscillations of the luminescence intensity of the 1sHH exciton when varying the magnetic field (Fig. 5). Because E_F is pinned to E_{exc} the intensity of the intrawell exciton line I_{exc} should oscillate with the magnetic field reflecting the oscillations of the 2DEG density of states at E_F. In order to observe this behavior, I_{exc} was recorded as a function of the magnetic field. This was done by adjusting the spectral position of the spectrometer in such a way that it coincided with the magnetic field dependent intrawell exciton energy (corrections taking into account a diamagnetic shift). Very clear oscillations of I_{exc} have been observed in a series of such measurements performed for different applied biases (see Fig. 5). These

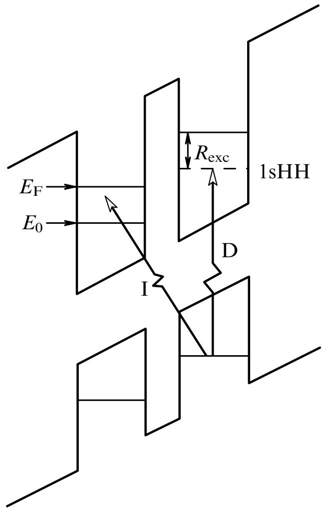

Figure 4. Scheme of interwell and intrawell recombination processes in electrically biased p–i–n-DQW.

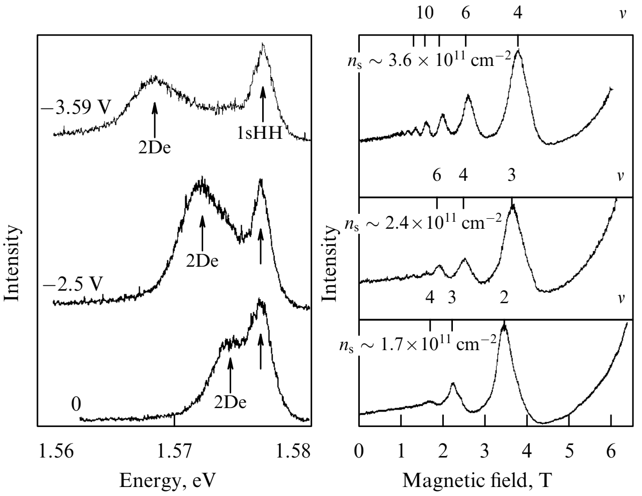

Figure 5. Oscillations of the luminescence intensity measured at E_{exc} as a function of the magnetic field for differing electric bias shown on the right. The corresponding luminescence spectra measured in the same bias conditions and $B = 0$ T are shown on the left.

oscillations of the luminescence intensity are periodic in the inverse magnetic field. From the measured period of oscillations and using the effective electron mass $m_e = 0.69m_0$ one can deduce n_e for each bias condition. The values for n_e obtained from this analysis are in good agreement with those deduced from the full width of the interwell luminescence spectra at any fixed bias voltage. These oscillations are reduced in amplitude when the forward bias is increased and completely disappear at a voltage of 0.75 V. At this forward bias the 2DEG concentration, found from a simple linear extrapolation is $n_0 = (6 \pm 1.5) \times 10^{10}$ cm^{-2}. We think that this value of n_0 corresponds to the critical concentration n_c related to the mobility edge or the metal–insulator transition for the 2D-electrons in this system.

A very similar transition of the interwell luminescence from the regime of localized e–h pairs to the regime of 2D-electron accumulation in one of the wells has recently been observed in n–i–n-DQW [11]. So we think that the observed phenomena are quite general and of common interest for biased coupled QW systems. In that respect this work demonstrates that, in order to find excitonic collective phenomena in this kind of structure such as Bose condensation, special care must be taken when designing and growing the structure. Besides, we would like to mention that the discovered 2D-electron accumulation regime in p–i–n-DQW structures could be used for studies of 2DEG behavior in the ultra quantum regime.

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Shakeup processes of a two-dimensional electron gas in GaAs/AlGaAs quantum wells at high magnetic fields

G Finkelstein, H Shtrikman, I Bar-Joseph

1. Introduction

Shakeup (SU) is a fundamental many-body process that occurs in optical transitions in the presence of an electron gas. In this process, a recombining electron–hole pair excites the surrounding electrons via the Coulomb interaction. This results in a decrease of the emitted photon energy by the amount left to the electron gas. In particular, when an electron from a two dimensional electron gas (2DEG) at high magnetic fields recombines with a photoexcited hole, another electron may be excited from a certain Landau level (LL) to a higher LL, so that the emitted phonon looses an energy of $\sim \hbar\omega_c$. Indeed, a series of SU peaks with $n = 1, 2, 3$ was observed below the main photoluminescence (PL) line of a 2DEG in InGaAs quantum wells [1–3] and recently in GaAs quantum wells [4].

In this work we present our results on the SU processes in a PL of a high mobility 2DEG in GaAs quantum wells at high magnetic fields. We discuss the filling factor and temperature dependence of the SU lines. The low background impurity concentration of this material system, which is manifested in the high mobility of the 2DEG, enables us to investigate the shakeup process for delocalized electrons and holes. We measured a two single-sided modulation-doped quantum well 20 nm wide [4]. The only parameter which is different in the two samples is the spacer width: it is nominally 50 nm in the first sample and 15 nm in the second. The electron densities after illumination are $\sim 2 \times 10^{11}$ cm^{-2} and $\sim 5 \times 10^{11}$ cm^{-2}, respectively, and the sample mobility is in excess of 10^6 cm^2 (V · s)$^{-1}$. The measurements were performed at $T = 1.5$ K and 4.2 K.

2. The SU$_1$ line

Figure 1 displays several photoluminescence spectra of the lower density sample at $T = 1.5$ K and several magnetic fields around $\nu = 2$ (4.75 T). The spectral features marked LL$_0$ and LL$_1$ are due to a recombination of electrons from the two lowest LL with the photoexcited holes. In the low energy part of the emission spectrum we observe two shakeup lines, SU$_1$ and SU$_0$ [2, 4]. SU$_0$ is a strong emission line, which is sometimes comparable in intensity with the main PL line (Fig. 4) [4, 5].

An important observation in Fig. 1 is the strong reduction in the intensity of both the SU$_1$ and SU$_0$ lines in a narrow magnetic field range around $\nu = 2$. To explain this behavior we have considered the lowest order quantum mechanical transition amplitude between the initial and final states of the electron system in a SU$_n$ recombination process [4]. There are two contributions to this amplitude (Fig. 2):