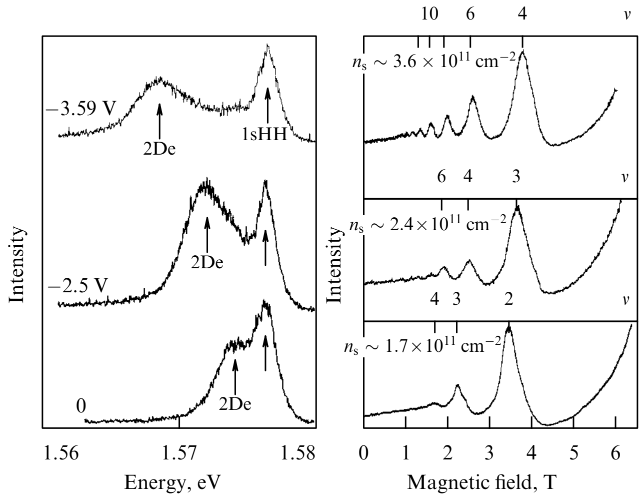

Figure 5. Oscillations of the luminescence intensity measured at E_{exc} as a function of the magnetic field for differing electric bias shown on the right. The corresponding luminescence spectra measured in the same bias conditions and $B = 0$ T are shown on the left.

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

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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):

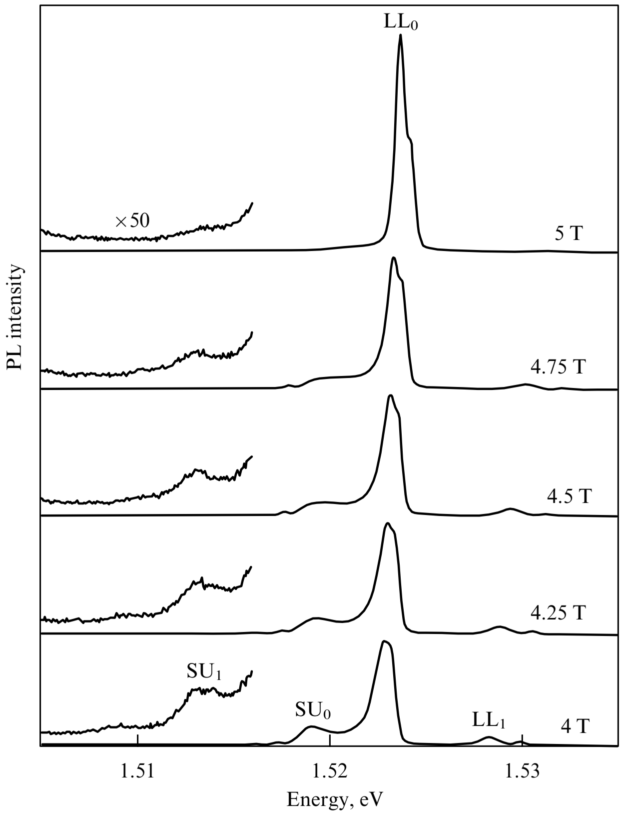

Figure 1. Photoluminescence spectra of the $n \approx 2 \times 10^{11}$ cm^{-2} sample at several magnetic fields around the filling factor $\nu = 2$ ($B = 4.75$ T) and $T = 1.5$ K.

(a) The valence band hole is virtually excited to some LL_m and shakes up an electron to a higher LL. Next the hole recombines with another electron with the same index m.

(b) The valence band hole recombines with an electron from LL_0. Next an electron from LL_m descends to the empty space at LL_0 shaking another electron to a higher LL.

In both cases an electron from LL_m is absent in the final state, and we therefore will write in the following that an electron from LL_m recombined with the valence band hole. (Due to selection rules the direct recombination of electrons from $LL_{m\neq 0}$ with holes from LL_0 is suppressed.) It turns out, that when the electron from the lowest LL recombines ($m = 0$) the two contributions to the transition amplitude (a) and (b) exactly cancel each other, and the SU intensity vanishes. This is the case at $\nu < 2$, when all the electrons are on the lowest LL. On the other hand, when $\nu > 2$ the electron may recombine from a higher LL and the SU intensity is finite. For example, the two processes schematically depicted in Fig. 2 have $m = 1$ and do not cancel each other. This gives rise to the SU_1 line.

The suppression of the SU intensity at $\nu < 2$ has, in fact, much deeper roots, and is a manifestation of a hidden symmetry of the electron – hole system on the lowest LL [6]. It was shown that the optical spectrum of this system is not affected by the many-body interactions and consists of only one line at exactly the exciton recombination energy. When the hidden symmetry is broken the many-body effects, such as SU, are revealed. In particular, a strong breaking of this symmetry occurs when higher electron LL are occupied ($\nu > 2$).

3. The SU_0 line

Let us now discuss the nature of the SU_0 line and the reason for its giant intensity. For simplicity we shall discuss the case of $2 < \nu < 4$. The resonant process relevant in this case is schematically depicted in Fig. 3. Namely, the valence band hole recombines with an electron from LL_0. Next an electron from LL_1 descends to the empty space at LL_0 shaking another electron to the next LL. Due to Coulomb interaction the energy of the electron excitation to the next LL is larger than $\hbar\omega_c$ by a certain ΔE [7]. As a result of energy conservation SU_0 is shifted by ΔE to lower energy relative to LL_0. It can be shown that the same energy ΔE enters the SU_0 quantum mechanical transition amplitude as a denominator. The probability of the SU_0 process is therefore proportional to ΔE^{-2}. Similarly, the probability of SU_1, which is shifted from LL_0 by $\sim \hbar\omega_c$, is proportional to $(\hbar\omega_c)^{-2}$. Thus, the SU_0 line is enhanced with respect to the non-resonant SU_1 line by a factor $\sim (\hbar\omega_c/\Delta E)^2$. Extracting $\hbar\omega_c$ and ΔE from the energy splittings in the photoluminescence we obtain an order of magnitude enhancement of SU_0 with respect to SU_1. The measured ratio of SU_0 and SU_1 intensities is in reasonable agreement with this estimation.

Following the evolution of the SU_0 line in the vicinity of $\nu = 2$ (see Fig. 1) we note, that as it decreases in intensity the lower spin component of LL_0 increases, while the upper spin component of LL_0 stays unaffected. This behavior confirms our identification of SU_0 as related to electron recombination from LL_1. Indeed, at filling factors slightly above $\nu = 2$ the electrons on LL_1 occupy only the lowest spin sublevel and compete with the electrons from the lower spin sublevel of LL_0 on the same holes for recombination. On the other hand, the electrons from the upper spin sublevel of LL_0 recombine with the holes of the opposite spin polarization. The fact that the intensity of the upper spin component of LL_0 is unaffected

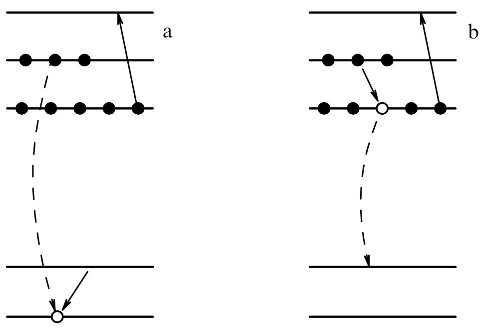

Figure 2. Schematic description of the two processes contributing to the SU_1 line.

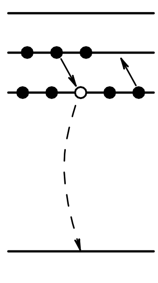

Figure 3. Schematic description of the resonant process contributing to the SU_0 line.

indicates that the equilibration of the holes population between the two spin components is suppressed, probably by the magnetic field.

Next, we wish to discuss the peculiar dependence of the SU_0 lineshape on the filling factor and temperature (Fig. 4). One may see, that the shape of SU_0 at $T = 1.5$ K is very sensitive to the filling factor. Following the evolution of the lineshape with the filling factor we notice a certain pattern of behavior: it is a broad shoulder at $\nu > 5$, becomes a peak at $4 < \nu < 5$, again evolves into a broad shoulder at $3 < \nu < 4$, and then turns into a sharp peak at $2 < \nu < 3$ (Fig. 4a). The remarkable fact is that the change in the lineshape is rather abrupt and occurs in a narrow magnetic field range around odd filling factors $\nu = 3, 5\ldots$ Examining the lineshape evolution at 4.2 K we observe a significantly different behavior. Namely, the lineshape stays as a broad shoulder throughout the magnetic field range (Fig. 4b). In fact, there is a strong similarity between the SU_0 lineshape at $T = 1.5$ K and $3 < \nu < 4$ and the lineshape which is observed at $T = 4.2$ K. Compare for example the spectrum at $T = 4.2$ K and $\nu = 2.43$ with the spectra at $T = 1.5$ K and $\nu = 3.90$.

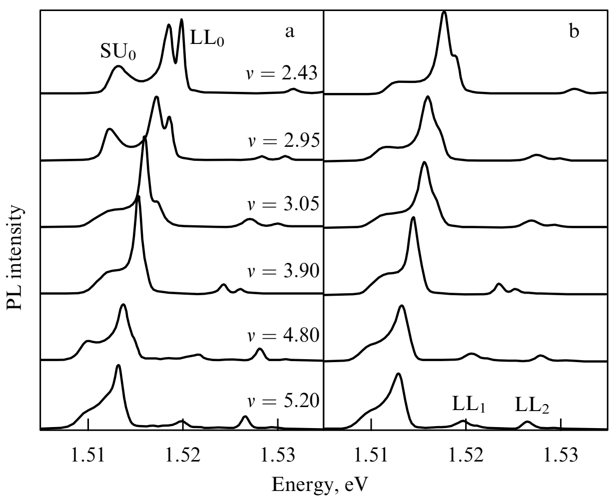

Figure 4. Photoluminescence spectra of the $n \approx 5 \times 10^{11}$ cm^{-2} sample at several filling factors: (a) $T = 1.5$ K and (b) $T = 4.2$ K.

The dependence of the SU_0 lineshape on T and ν points to the importance of the spin state of the electrons on the highest partially filled LL. At 4.2 K the temperature is larger than the spin gap, and the electrons on this LL are expected to occupy almost equally both spin states. At $T = 1.5$ K the two spin states are occupied at $3 < \nu < 4$ and $5 < \nu < 6$. Surprisingly, a slight change of the filling factor above $\nu = 3$ (and $\nu = 5$) brings a drastic change in the lineshape (compare the spectra at $\nu = 2.95$ and $\nu = 3.05$).

4. The many-body nature of SU excitations

Let us now discuss the nature of the excitations of the 2DEG, involved in the shakeup processes. To prove the many-body nature of the SU processes we experimentally realized a situation where the many-body interactions are absent. This is done by applying a gate voltage, causing the electrons in the 2DEG to become localized. In the insulating state the photoluminescence is excitonic, consisting of a neutral (X) and a negatively charged (X^-) exciton lines (Fig. 5, two lower curves). In a magnetic field one observes narrow shakeup lines, associated with X^-: when one electron in this complex recombines with the hole, the remaining electron is excited to a higher LL. This excitation is of a single particle, and therefore the shakeup lines are sharp and appear at an energy $\hbar\omega_c$ below the charged exciton line [8]. On the other hand, the SU_1 line in a more metallic state (two upper curves) is much broader and moves to lower energies, implying that the SU excitation acquires dispersion. We therefore conclude that the many-body nature of the shakeup excitation is indeed manifested in the shape and energy of the shakeup lines. Note that at these gate voltages the main PL line is still narrow and is practically indistinguishable from X^-. However, the observation of the dispersion of SU excitation allows us to conclude that this line is not a proper X^-, but rather contains more than two electrons interacting with the hole. After the recombination of one of these electrons with the hole the other electrons may be left in a spectrum of excited states with an energy close but not equal to $\hbar\omega_c$.

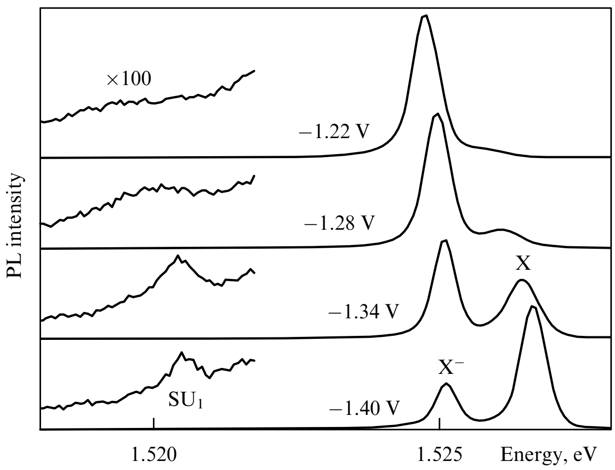

Figure 5. Photoluminescence spectra of the lower density sample at $B = 3$ T for several gate voltages; $T = 1.5$ K.

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