Effect of in-plane magnetic field on the photoluminescence spectrum of modulation-doped quantum wells and heterojunctions

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The photoluminescence (PL) spectrum of modulation-doped GaAs/AlGaAs quantum wells (MDQW) and heterojunctions (HJ) is studied under a magnetic field ($B_\parallel$) applied parallel to the two-dimensional electron gas (2DEG) layer. The effect of $B_\parallel$ strongly depends on the electron-hole separation ($d_{eh}$), and we revealed remarkable $B_\parallel$-induced modifications of the PL spectra in both types of heterostructures. A model considering the direct optical transitions between the conduction and valence subband that are shifted in k-space under $B_\parallel$, accounts qualitatively for the observed spectral modifications. In the HJs, the PL intensity of the bulk excitons is strongly reduced relatively to that of the 2DEG with increasing $B_\parallel$. This means that the distance between the photoholes and the 2DEG decreases with increased $B_\parallel$, and that free holes are responsible for the hole-2DEG PL.

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I. INTRODUCTION

The low-temperature radiative recombination of the two-dimensional electron gas (2DEG) with photoexcited holes is an effective optical probe of the many-body interactions and their modification under a magnetic field that is applied perpendicularly ($B_\perp$) to the 2D-electron layer. Kinks in the $B_\perp$-dependence of the photoluminescence (PL) peak energy, the PL line broadening and the intensity changes for integral and fractional 2D-electron Landau levels. This changeover in HJs was considered to reflect an increased 2D e-h wavefunction overlap with increasing $B_\perp$ ($\nu < 2$), but its physical mechanism is not fully understood. Recently, we proposed that the interaction of free excitons in the GaAs buffer layer and the magnetized 2DEG forming on the GaAs/AlGaAs interface, leads to an exciton dissociation into 2D-electron and free hole at $\nu < 2$. The excitons drift to the 2DEG in the gradient of the built-in HJ electric field. Thus, the exciton drift and its dissociation deliver free holes to the 2D-e.

In order to elucidate the effect of the 2D-electron-hole separation on the PL spectrum, we studied the PL of GaAs/AlGaAs HJ’s and MDQW’s under a magnetic field that was applied parallel to the 2DEG plane, $B_\parallel$. Extensive transport and magnetoabsorption studies of the 2DEG under $B_\parallel$ were reported, but there are only a few reports on the $B_\parallel$-effects on the 2DEG PL in MDQWs. A noticeable case is the effect of $B_\parallel$ on the spatially indirect exciton PL in biased double quantum wells. We report on drastic $B_\parallel$-induced PL spectral changes in high quality 25nm-width MDQW’s and in HJ’s as well as on their dependence on the 2D e-h separation. We present a model that is based on the conduction and valence subband realignment under $B_\parallel$ that accounts qualitatively for the observed spectral modifications. The effect of a $d_{eh}$ decrease with $B_\parallel$ on the PL spectrum of HJs, is also considered.

II. MODEL. PL SPECTRAL MODIFICATIONS INDUCED BY $B_\parallel$

An in-plane $B_\parallel$ that is applied along the x-axis, creates a crossed fields configuration with the perpendicular, built-in electric field $E_\perp$ (directed along the y-axis) that exists in the asymmetrically modulation-doped structures containing a 2DEG. This causes an in-plane electron (hole) drift (in the y-direction, perpendicular to $B_\parallel$),
resulting in a deformation of the subband energy surfaces, $\epsilon_{k B}$. In particular, the conduction subband minimum shifts to a higher wave vector, $k_y^B = d_{eh}/L_y^2$ (where $L_y$ is the magnetic length) and the in-plane electron effective mass ($m_{e_y}$) increases along the y-direction.

Thus, an indirect bandgap appears, and the 2DEG-free hole PL spectrum that originates in the direct optical transitions, is strongly modified.

In order to describe the spectral modifications, we use the general expression for the spectrum of the 2De-h radiative recombination. The PL intensity at a photon energy $\hbar \omega = E_h + \epsilon_m + \epsilon_e$ is

$$I(\hbar \omega) = \int \int dk_x dk_y \delta(\hbar \omega - E_h - \epsilon_m - \epsilon_e) f(\epsilon_m) f(\epsilon_e) \delta(\hbar \omega - E_h - \epsilon_m - \epsilon_e)$$

(1)

Here $E_h$, $\epsilon_m$, $\epsilon_e$ are the band gap, electron and hole in-plane energies, and $f(\epsilon_m)$, $f(\epsilon_e)$ are the Fermi distribution function for 2D-electrons and the Boltzmann distribution function for nondegenerate holes, respectively. In the direct band gap limit ($B_y = 0$), all optical transitions with a given $\hbar \omega$ occur at $h \omega = h \omega_{c} = (2\mu(h \omega - E_h))^{1/2}$ ($\mu$ is the reduced electron-hole mass). Thus, the PL spectrum is described by $I(\hbar \omega)f(\epsilon_m)f(\epsilon_e)$.

In the presence of $B_y$, direct optical transitions occur between the valence and conduction subbands that are displaced in k-space away from each other by $k_y^B = d_{eh}B_y/\hbar$. Thus, the momentum and energy conservation laws require that for given $h \omega$ and $k_y$:

$$k_x = \frac{2\mu}{h^2}(h \omega - E_h - \frac{h^2 k_y^2}{2m_{h}} - \frac{2(k_y - k_y^B)^2}{2m_{e_y}})^{1/2}$$

(2)

and conduction (and valence) band states of different energies participate in the optical transitions at the same photon energy. The optical transitions at $\hbar \omega$ involve states with $k_y$ varying between $k_{y1}$ and $k_{y2}$ that are the roots of the Eq.2 (at $k_x = 0$). Then, integrating Eq.1 once, we obtain

$$I(\hbar \omega) = \int_{k_{y1}}^{k_{y2}} dk_y \frac{f(\epsilon_m)f(\epsilon_e)}{k_x(k_y)} \delta(\hbar \omega - E_h - \epsilon_m - \epsilon_e)$$

(3)

where $f(\epsilon_b) = \exp(-\epsilon_b/k_BT)$, $f(\epsilon_e) = (1 + \exp((\epsilon_e - E_F)/k_BT))^{-1}$. $T$ and $k_BT$ are the effective electron and hole temperatures, and $E_F = E_F'(m_{ex}/m_{ex}m_{ey})^{1/2}$ is the Fermi energy in the presence of $B_y$. We note that $E_F < E_F'$ since $m_{ey}$ increases with $B_y$ [14,15,17].

In Fig.1, numerically calculated PL spectra are presented for several $k_y$ values that correspond to increasing $B_y$ values. The PL peak intensities are obtained from the condition of B-independent spectrally-integrated PL. In the presence of $B_y$, the lowest PL energy shifts by

$$\epsilon_B = \frac{(h k_y^B)^2}{2(m_{ex} + m_h)} = \frac{\epsilon^2 B_y^2}{2c^2(m_{ex} + m_h)}$$

(4)

and the PL spectrum is strongly deformed, particularly at large $k_y^B$. This results from a change of number of the occupied free-hole states participating in the recombination process. For example, as $k_y^B$ increases, the direct optical transitions between the 2D-electrons at $E_F$ and the lowest energy, highly populated valence hole states, have become available. This leads to a pronounced PL intensity enhancement at $E_F$, as can be seen in Fig. 1. The PL spectral evolution with increasing $k_y^B$ is shown in Figs. 1a, b for two values of the 2DEG density. These spectra demonstrate that the main effect of $B_y$ is not an enhanced diamagnetic shift (see Eq.3) as was considered before [20], but the drastic modification of the entire 2De-h PL spectrum. For example, the lowest optical transition shifts by $\epsilon_B \approx 2$ meV at $k_y^B \approx 1.8 \cdot 10^6$ cm$^{-1}$ ($B_y = 7$ T and $d_{eh} = 18$ nm), while the PL peak-energy shift depends on the 2DEG density and reaches 7 meV at $n_{2D} = 2 \cdot 10^{11}$ cm$^{-2}$ (see Figs. 1a, b).

The energy distribution of the photoexcited free holes participating in the 2De-h PL, strongly affects the PL spectrum under $B_y$. The energy distribution of the holes can be different from that corresponding to the lattice temperature ($T_L$) because the radiative recombination rate is higher than the energy relaxation rate in the MDQW at low temperatures. In order to demonstrate the effect of the nonthermalized holes on the PL, we display the PL spectra calculated for the effective hole temperature $T_h$ = 4 K (dashed lines in Fig. 1). $T_c$ is taken to be equal to $T_L$ = 1.9 K, since the photoelectron rapidly loses its energy by the electron-electron scattering process occurring in the dense 2DEG. Due to the heavier hole mass and the spatial separation of the holes and 2DEG, the efficiency of the hole-2DEG energy relaxation is lower, and $T_h$ is taken to be different from $T_c$. One can see in Fig. 1 that the high-energy valence states occupied by nonthermalized holes, result in a pronounce PL spectral modification under increased $B_y$.

The PL spectra shown in Fig. 1 were calculated with $m_{ey} = m_{ex}$. The dotted curve in Fig. 1b shows the calculated PL spectrum for $m_{ey} = m_{ex} + 4h \cdot k_y^B$-dependence with $k_y^B = 1.4 \cdot 10^6$ cm$^{-1}$ ($b = 10^{-2}$ is a numerical coefficient). The larger $m_{ey}$ leads to a PL band narrowing and a low-energy shift of the PL peak due to Fermi energy decrease. Thus, the strong $B_y$ effect on the 2De-h PL spectrum is predicted by this simple model. For a MDQW in which $n_{2D}$ can be varied, larger spectral modifications are expected at higher $n_{2D}$ since $d_{eh}$ increases with $n_{2D}$ due to the increased built-in electric field. Our analysis does not include the “usual” diamagnetic shift. The value of this small shift (< 1 meV at 7T) is close to the exciton diamagnetic shift under $B_y$ as measured for undoped 20nm wide QW (see below, Fig. 3).

The effect of $B_y$ is expected to be different in wide HJ’s, since $d_{eh}$ is large, and it varies with increasing $B_y$. The simplest estimate of $d_{eh}$ in a HJ at $B_y$ = 0, can be obtained by $d_{eh} \approx V_{eh} \tau = \mu_{h}E_{\perp} \tau$ where $V_{eh}$ is the valence hole drift velocity in the HJ electric field $E_{\perp}$ ($\mu_{h}$ is the hole mobility) and $\tau$ is the characteristic recombination time of the hole (due to capture by charged acceptors in the buffer p-type GaAs layer). Taking $\mu_{h} = 10^4$
cm$^2$/Vsec and a minimal value of $E_L = 10^3$ V/cm and $\tau = 10^{-10}$s, we obtain $d_{eh} > 10^{-4}$ cm. The photexcited holes are thus accumulating at a large distance where $E_L$ diminishes. Therefore, $d_{eh}$ is of the order of the GaAs buffer layer width (1µ), and it is much larger than that in the MDQWs.

In the presence of $B_\parallel$, the hole drift from the interface is slowed down, since it exhibits a helical motion along the y-direction (in $E_{L, \perp} B_\parallel$ crossed fields configuration). The hole drift velocity can be written in a classical approach as: \( v_B = \mu_B E_L / [1 + (\mu_B B_\parallel/c^2)] \), \( c \) is the light velocity. Then, for $B_\parallel > 2T$ \( (\mu_B B_\parallel/c \approx 1) \), $d_{eh}$ strongly decreases, reaching values $< 10^{-5}$ cm at $B_\parallel > 2T$. Thus, the spatial distribution of photexcited holes (in the buffer GaAs layer) is mainly determined by the incident light penetration depth. The hole density near the 2DEG layer increases while the density of holes situated away from the heterointerface decreases. Fewer holes are available to form excitons in the buffer GaAs layer, and the exciton PL intensity decreases while that of the 2De-h PL is enhanced with increasing $B_\parallel$. It is important to underline that the discussed PL modifications in $B_\parallel$ are only relevant for free holes that recombine with momentum conservation. In the case of recombination of localized holes with 2DEG, the spectral PL modifications are expected to be small since indirect optical transitions without $k$-conservation are allowed.

III. EXPERIMENTAL RESULTS AND DISCUSSION

The PL spectroscopic study was performed on several GaAs/AlGaAs HJ and MDQW samples grown by molecular beam epitaxy. The HJ samples have a thick GaAs buffer layer (width of 1µ) and the MDQW samples have a single 25nm-wide QW. The 2DEG densities and dc mobilities at 4K vary in the ranges of $n_{2D} = (0.7 - 3) \cdot 10^{11} \text{cm}^{-2}$ and $\mu = (1 - 4) \cdot 10^6 \text{cm}^2/\text{Vsec}$, respectively. Photoexcitation was done by illumination with a Ti-sapphire laser light (photon energy of 1.56 eV) or by a He-Ne laser. The incident light intensity was kept below $10^{-2}$ W/cm$^2$. The He-Ne laser photon energy (1.96eV) is greater than the band gap of the AlGaAs barrier, thus, $n_{2D}$ can be reduced due to optical deple- tion by increasing the He-Ne laser intensity. The PL spectra were measured with a high resolution by using a double spectrometer equipped with a CCD camera. The samples were immersed in liquid He at temperature $T_L = 1.9K$, and photoexcitation and PL detection were performed perpendicularly to the 2DEG plane under an in-plane $B_\parallel$.

Figs. 2a-c display the PL spectral evolution with increasing $B_\parallel$ measured on two MDQW samples. At $B = 0$, the PL spectra can be well described by a simple product of the distribution functions for the 2D electrons of density $n_{2D}$ at the electron temperature $T_e = T_L$ and nondegenerate holes with effective $T_h$ (Eq.1). The 2DEG Fermi energy is then estimated from the 2De-h PL bandwidth.

Upon applying $B_\parallel$, the PL spectra show remarkable modifications: a high-energy shift, intensity redistribution, and band narrowing. Fig. 2a presents the PL spectra of the MDQW with $n_{2D}^0 = 3 \cdot 10^{11} \text{cm}^{-2}$ at $B_\parallel = 0$, 4.5 and 7T and the calculated spectra for $k_B = 0.1, 1.4$ and $1.6 \cdot 10^6 \text{cm}^{-1}$ for $T_e = 1.9K$, $T_h = 4K$. A $d_{eh}$ value of 15 nm can be estimated from the comparison of these spectra. Figs. 2b, c show the effect of varying $n_{2D}$ on the PL spectral evolution under $B_\parallel$. The PL spectra are measured on the same MDQW with $n_{2D}^0 = 1.8 \cdot 10^{11} \text{cm}^{-2}$ under two He-Ne laser intensities (under optical depletion). As $n_{2D}$ is reduced, less spectral modifications are observed since $d_{eh}$ decreases. The total width of the 2De-h PL spectra ($\propto E_F$), decreases with $B_\parallel$. At $B_\parallel = 7T$, $E_F$ decreases by 1.5-1.3 times as a result of an electron mass enhancement.

The observed PL spectra display the main features predicted by the simple model of Sec II. This model does not account for the $B_\parallel$-effect on the electron(hole) wavefunctions, but we assume that the discrepancy between the calculated and observed PL spectra may result from the nonthermalized hole distribution function, which is not described by the Boltzman distribution with the effective $T_h$.

The $B_\parallel$ dependencies of the integrated PL intensity ($J$) and the energy $E_B$ that was obtained by extrapolating the PL intensity of low energy part of spectrum to zero, are shown in Fig. 3. We note that the integrated PL intensity varies only slightly with $B_\parallel$. $E_B$ is presented for a MDQW at two 2DEG densities, $n_{2D}^0 = 1.8 \cdot 10^{11}$ cm$^{-2}$ and $n_{2D} ≈ 1 \cdot 10^{11}$ cm$^{-2}$ (curves 1 and 2, respectively). These dependencies are comparable with the behavior of the exciton PL peak energy versus $B_\parallel$ that was measured in the 20nm-wide undoped QW (curve 3). $E_B ≈ \epsilon_B$ in the MDQW varies with $n_{2D}$, and it strongly depends on $B_\parallel$ when compared with the exciton diamagnetic shift in undoped QW.

Fig. 4 displays the PL spectra of the HJ sample upon applying a perpendicular magnetic field, $B_\perp$ (Fig. 4a) and a parallel field, $B_\parallel$ (Figs. 4b, c). Figs. 4b and c show the PL spectra for the same HJ ($n_{2D}^0 = 1.6 \cdot 10^{11}$ cm$^{-2}$) under photoexcitation with $E_L = 1.52$ eV and 1.96 eV (under optical depletion), respectively. At $B = 0$, the PL spectrum consists of two strong narrow lines originating in free and bound excitons of GaAs buffer layer. With decreasing $n_{2D}$ (Fig 4c), the built-in electric field decreases, holes are situated closer to the heterointerface, and the broad 2De-h PL band appears at $B = 0$. Under photoexcitation that does not vary $n_{2D}$ (Figs. 4a, b), the 2De-h PL can be detected as a low-energy low-intense background PL. These broad PL bands are due to a radiative recombination of the photoexcited holes and 2D-electrons whose wavefunctions weakly overlap at $B = 0$. At $B_\perp ≃ 3.2$ T ($\nu \sim 2$), the PL changeover occurs, and the 2De-h PL intensity sharply enhances while the exciton PL intensity decreases (Fig. 4a). Another drastic 2De-h PL modification is observed near $\nu \sim 1$ ($B_\perp \sim$...
The PL evolution with applying in-plane $B_∥$ is shown in Figs. 4b, c. Starting from low $B_∥$, an increase of the 2De-h PL (low-energy PL tail) intensity and an narrowing of the band with $B_∥$ are clearly observed. A redistribution between the 2De-h and exciton integrated PL intensities with increasing $B_∥$ is presented in inset of Fig. 5. A smooth changeover from the exciton to the 2De-h PL under $B_∥\simeq 1$T is revealed. This is in contrast to the case of the sharp, 2DEG density-dependent changeover observed under $B_∥$.

The 2De-h PL intensity enhancement seen in Figs. 4b, c, results from the $B_∥$-induced delivering of free holes to the heterointerface while the narrowing and spectral PL shift is caused by the effect of $B_∥$ on the PL spectral shape. Indeed, with increasing $B_∥$, the photoexcited holes are swept away for smaller distances, and increased number of the holes can recombine with 2D-electrons giving rise to the 2De-h PL. There is a set of the $d_{eh}$ values because the holes are spatially distributed in GaAs buffer layer. This leads to a specific PL spectrum having a long low-energy tail since the PL intensity strongly reduces with increasing $d_{eh}$. As $B_∥$ increases, $d_{eh}$ decreases, however $d_{eh}$ is large enough so that $k^B$ is high, and the PL line shape at $B_∥$=7T corresponds to the PL spectrum calculated for $k^B > 2.10^6$cm$^{-1}$ as one can see in Fig. 1.

In Fig. 5, we compare the HJ PL spectra under parallel (curves 1,4), normal (curve 2) and 45$^\circ$-tilted magnetic field (curve 3). The spectra presented by curves 1 and 2 are obtained at $B_∥$=5T and $B_∥$=7T, respectively. The high-energy, excitonic part of both spectra are at the same energies, and it is independent of the B-orientation. The excitonic part of the spectrum under tilted magnetic field ($B_∥$ = $B_⊥$=5T, curve 3) is similar to that measured at $B_∥$=7T (curve 4). Both these facts give evidence to the bulk nature of the high-energy part of the PL spectrum in the HJ. The 2De-h parts of the PL spectra obtained under $B_∥$ and $B_⊥$ (curves 1 and 2) are completely different, and these differ from that observed under tilted magnetic field. In the latter case, the 2De-h PL originates in the radiative recombination from the lowest e-h Landau levels (due to $B_⊥$-component) while an additional spectral shift $\varepsilon_B$ is caused by $B_∥$-component. The value of this shift is of 1.8meV, and the 2De-h separation of 25 nm can be estimated by using Eq. 3. Thus applying $B_∥$=5T, leads to a reduced hole drift that results in the strong 2De-h PL enhancement.

IV. CONCLUSIONS

In conclusion, our study shows that in-plane magnetic field leads to a remarkable spectral modification of the 2DEG-hole PL in MDQWs and SHJs. The smooth intensity redistribution between the PL of the bulk excitons and of the 2DEG is revealed in HJs. This is caused by the effect of $B_∥$ on the free hole distribution in the HJ. The 2De-h PL evolution studied upon applying $B_∥$, evidences that free holes are responsible for this emission in the high quality HJs. Thus, we can conclude that the sharp PL changeover observed at $\nu \simeq 2$ in HJs under perpendicularly applied $B_⊥$, is induced by a threshold spatial redistribution of the free holes whose possible physical mechanism was recently proposed.

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FIG. 1: The calculated PL spectra for two $n_{2D}$ values at increasing $k^B_y = \frac{d_e e B ||}{\hbar c}$. $m_{ex} = 0.067m_0$, $m_{ey} = 0.067(1 + 10^{-7}k^B_y)m_0$, $m_h = 0.35m_0$, $T_L = T_e = 1.9$ K. Solid (dashed) lines are for $T_h = 1.9$K ($T_h = 4$K), respectively. Dotted curve in Fig.1b shows the effect of increased $m_{ey}$. $k^B_y$-values are shown near the curves.

FIG. 2: 2DEG PL spectral evolution under a parallel magnetic field, $B|| = 0, 4.5, 7$T. a). 25-nm wide MDQW with $n^0_{2D} \simeq 3 \cdot 10^{11}$cm$^{-2}$ (solid lines). The fitted spectra with corresponding $k^B_y$-values are presented by dotted lines. b, c) 25-nm wide MDQW with $n^0_{2D} \simeq 1.8 \cdot 10^{11}$cm$^{-2}$ at two He-Ne laser light intensities, $I_L$: $I_{L1}$ (b) is less than $I_{L2}$ (c).

FIG. 3: $B||$-dependencies of the $E_B$-shift for the MDQW at two $n_{2D}$: curve 1 is obtained at higher $n_{2D}$ than curve 2. Curve 3 - exciton PL peak energy shift for an undoped QW. Curve 4 - integrated PL intensity versus $B||$ for the MDQW.
FIG. 4: The PL spectral evolution in the HJ upon applying $B_{\perp}$ (a) and $B_{\parallel}$ (b, c). a and b are measured under photoexcitation at $E_L=1.52$ eV, (c) - at 1.96 eV.

FIG. 5: PL spectra of HJ. 1 and 4 - under $B_{\parallel}=5$ and 7T, respectively; 2 - under $B_{\perp}=5$T and 3 - under a 45°-tilted magnetic field ($B=7$T, $B_{\parallel}=B_{\perp}=5$T). Inset: Integrated intensity of the exciton and 2De-h PL versus $B_{\parallel}$. 
\[ k_y^B = 1 \times 10^6 \text{cm}^{-1} \]

Energy, eV

PL intensity

Energy, eV
The image shows a graph with PL intensity on the y-axis and Energy, eV on the x-axis. The graph is divided into three panels (a, b, c). Each panel contains multiple curves labeled with energy values: 0, 3.2, 5.2, and 7. The curves are shaded to indicate different energy values. Arrows point to features labeled as FE, B\textsubscript{normal}, and 2De-h. The graph is labeled with HJ, 1.9K and B\textsubscript{||}, T.
Energy, eV

PL intensity

2DEG

Exciton

B, T

1.512

1.516

1.520

Energy, eV