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

B. M. Ashkinadze,* E. Linder, and E. Cohen
Solid State Institute, Technion-Israel Institute of Technology, Haifa 32000, Israel

L. N. Pfeiffer
Bell Laboratories, Lucent Technologies, Murray Hill, New Jersey 07974, USA
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The photoluminescence (PL) spectrum of modulation-doped GaAs/AlGaAs quantum wells 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, 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 subbands that are shifted in k-space under $B_\parallel$, accounts qualitatively for the observed spectral modifications. In the HJs, the 2DEG-hole PL intensity is strongly enhanced relatively to the bulk exciton PL with increasing $B_\parallel$. This means that the distance between the photoholes and the 2DEG decreases with increasing $B_\parallel$, and thus free holes are responsible for the 2DEG-hole PL.

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I. INTRODUCTION

The low-temperature radiative recombination of the two-dimensional electron gas (2DEG) with photoexited 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 filling factors $\nu=2\pi n_{2D}L_B^2$ [n_{2D} is the 2DEG density, $L_B=(c\hbar/eB)^{1/2}$ is the magnetic length] were reported.[1–3] The most remarkable PL-modifications were observed in structures having a large 2D-electron-valence-hole (2De-h) separation, d_{eh}, since then the holes weakly affect the many-body interactions of the 2DEG. Examples are asymmetrically modulation-doped, GaAs/AlGaAs quantum wells (MDQW) (with a QW-width exceeding 20 nm)[1,4] and single GaAs/AlGaAs heterojunctions (HJ).[5–7]

In the latter case, the photoexcited electron-hole pairs are rapidly separated by the built-in HJ electric field (over distances of $d_{eh}>100$ nm within the entire undoped GaAs layer). Due to the small 2D electron-hole wave function overlap, their emission intensity is negligibly low, and the PL spectrum of high quality HJ's, in the absence or at low $B_\perp(\nu>2)$, is dominated by emission of excitons from the undoped (p-type) GaAs layer.[7,8] However for filling factors $\nu<2$, this excitonic PL transforms into a 2De-h PL involving transitions between the lowest e-h Landau levels. This PL changeover was considered to reflect an increased 2De-h wave function overlap with increasing $B_\perp$ (at $\nu<2$),[5,7,9,10] but its physical mechanism is not fully understood. Recently, we proposed that free holes are delivered to the 2DEG layer owing to the exciton drift in the gradient of the built-in HJ electric field and consequent $B_\perp$-induced (at $\nu<2$) dissociation of the excitons into 2D-electron and free hole.[11]

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,[12–15] but there are only a few reports on the $B_\parallel$-effects on the 2DEG PL in MDQWs.[16–18] A noticeable case is the effect of $B_\parallel$ on the spatially indirect exciton PL in biased double quantum wells.[19] We report on drastic $B_\parallel$-induced PL spectral changes in high quality 25 nm width MDQW's and HJ's as well as on the dependence of the PL line shape on the 2De-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 decreasing the hole-2DEG separation with $B_\parallel$ on the PL spectrum of HJ's, 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 z-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, ϵ_k.[20] In particular, the conduction subband minimum shifts to a higher wave vector, $k_y^B=d_{eh}/L_B^2$ and the in-plane electron effective mass (m_{ey}) increases along the y-direction.[20,21] Thus, an indirect band gap 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.[23] The PL intensity at a photon energy $\hbar\omega=E_g+\varepsilon_e+\varepsilon_h$ is

$$I(\hbar\omega) = \int\int dk_x dk_y f(\varepsilon_e) f(\varepsilon_h) \delta(\hbar\omega - E_g - \varepsilon_e - \varepsilon_h). \quad (1)$$

Here $E_g, \varepsilon_e, \varepsilon_h$ are the band gap, electron and hole in-plane energies, and $f(\varepsilon_e), f(\varepsilon_h)$ are the Fermi distribution function for 2D electrons and the Boltzmann distribution function for nondegenerate holes, respectively. In the direct band gap limit ($B_\parallel = 0$), all optical transitions with a given $\hbar\omega$ occur at $\hbar k_e = \hbar k_h = [2\mu(\hbar\omega - E_g)]^{1/2}$ (μ is the reduced electron-hole effective mass). Thus, the PL spectrum is described by $I(\hbar\omega) \propto f(\varepsilon_e) f(\varepsilon_h)$.

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

$$k_x = \left[\frac{2\mu}{\hbar^2} \left(\hbar\omega - E_g - \frac{\hbar^2 k_y^2}{2m_h} - \frac{\hbar^2 (k_y - k_y^B)^2}{2m_{ey}} \right) \right]^{1/2}, \quad (2)$$

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 Eq. (2) (at $k_x = 0$). Then, integrating Eq. (1) once, we obtain

$$I(\hbar\omega) = \int_{k_{y1}}^{k_{y2}} dk_y \frac{f(\varepsilon_h) f(\varepsilon_e) \delta(\hbar\omega - E_g - \varepsilon_e - \varepsilon_h)}{k_x(k_y)}, \quad (3)$$

where $f(\varepsilon_h) = \exp(-\varepsilon_h / k_B T_h)$, $f(\varepsilon_e) = \{1 + \exp[(\varepsilon_e - E_F)/k_B T_e]\}^{-1}$. T_e and T_h are the effective electron and hole temperatures. In the presence of $B_\parallel$, the Fermi energy (E_F^0 at $B = 0$) is $E_F = E_F^0 m_{ex} / (m_{ex} m_{ey})^{1/2}$.

With increasing $B_\parallel$, the lowest PL energy shifts by

$$\epsilon_B = \frac{(\hbar k_y^B)^2}{2(m_{ey} + m_h)} = \frac{e^2 d_{eh}^2 B_\parallel^2}{2c^2 (m_{ey} + m_h)} \quad (4)$$

and the 2DEG-hole spectrum narrows since $E_F < E_F^0$ due to the increased m_{ey}.[14,15,17]

In Fig. 1, numerically calculated PL spectra are presented for several k_y^B values that correspond to increasing $B_\parallel$ values. The PL peak intensities are obtained from the condition of B-independent spectrally integrated PL. Applying $B_\parallel$ leads a strong deformation of the 2DEG-hole PL spectra, 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 $k_y^B \propto B_\parallel$ is shown in Figs. 1(a) and 1(b) for two values of the 2DEG density. These spectra demonstrate that the main effect of $B_\parallel$ is not an enhanced diamagnetic shift [see Eq. (4)] as was considered before,[16] but the drastic modification of the entire 2D*e*-*h* PL spectrum. For example, the lowest optical transition shifts by $\epsilon_B \simeq 2$ meV at $k_y^B \simeq 1.8 \times 10^6$ cm^{-1} (at chosen values of $B_\parallel = 7$ T and $d_{eh} = 18$ nm), while the PL peak-energy shift depends on the

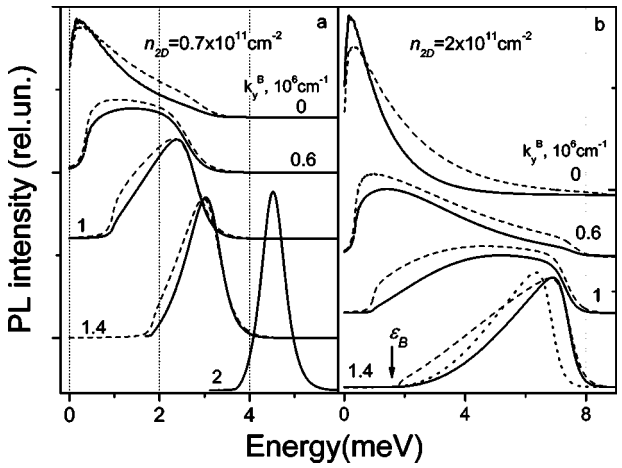

FIG. 1. The calculated PL spectra for two n_{2D} values at increasing $k_y^B = d_{eh} e B_\parallel / \hbar c$ (k_y^B values are shown near the curves). $m_{ex} = 0.067 m_0$, $m_h = 0.35 m_0$, $T_L = T_e = 1.9$ K. Solid (dashed) lines are for $T_h = 1.9$ K ($T_h = 4$ K), respectively. The dotted curve in (b) shows the effect of increased $m_{ey} = [0.067(1 + 10^{-7} k_y^B)] m_0$. All the spectra are normalized to the same integrated intensity and are vertically offset. The diamagnetic shift ε_B for $k_y^B = 1.4 \times 10^6$ cm^{-1} is shown by the arrow.

2DEG density and reaches 7 meV at $n_{2D} = 2.10^{11}$ cm^{-2} [see Figs. 1(a) and 1(b)].

The energy distribution of the photoexcited free holes participating in the 2D*e*-*h* PL, strongly affects the PL spectrum under $B_\parallel$. At low temperatures, the energy distribution of the holes can be different from that corresponding to the lattice temperature (T_L) because the radiative recombination rate in the MDQW is higher than the hole energy relaxation rate due to acoustic phonon emission.[2] 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_e 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. However, the efficiency of the photohole-2DEG energy relaxation is much less due to the heavier hole mass and the spatial separation of the holes and 2DEG. Therefore, T_h is taken to be different than T_e. One can see in Fig. 1 that the high-energy valence states occupied by nonthermalized holes, result in a pronounced PL spectral modification under increased $B_\parallel$.

The PL spectra shown in Fig. 1 were calculated with $m_{ey} = m_{ex}$. The dotted curve in Fig. 1(b) shows the calculated PL spectrum at $k_y^B = 1.4 \times 10^6$ cm^{-1} for $m_{ey} = m_{ex} + b k_y^B$ dependence (b is a numerical coefficient). An increasing m_{ey} with $B_\parallel$ leads to a PL band narrowing and a low-energy shift of the PL peak due to Fermi energy decrease.

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 7 T) is close to the exciton diamagnetic shift under $B_\parallel$ as measured for undoped 20 nm wide QW (see below, Fig. 3). Thus, the strong $B_\parallel$ effect on the 2D*e*-*h* PL spectrum is predicted by this simple model.

The effect of $B_\parallel$ is expected to be different in wide HJ's, since the distance between the photoexcited valence holes and the 2DEG is large, and it varies with increasing $B_\parallel$. In order to get the simplest estimate of d_{eh} in a HJ, we consider the usual case of photoexcitation above the GaAs band gap, when the created free *e*-*h* pairs rapidly lose their coherence and are moving as free particles. Then, the electron is attracted to the interface with the 2DEG, and hole moves in the opposite direction due to the HJ electric field $E_\perp$. At $B_\parallel=0$, the hole drifts over a distance, $d_{eh}\simeq V_h\tau=\mu_h E_\perp \tau$ where V_h is the valence hole drift velocity (μ_h is the hole mobility) and τ is the characteristic hole recombination time (due to capture by charged acceptors in the *p*-type GaAs buffer layer). Taking $\mu_h=10^4$ cm^2/V s (Ref. 22) and a minimal value of $E_\perp=10^3$ V/cm and $\tau=10^{-10}$ s, we obtain $d_{eh}>10^{-4}$ cm. The photoexcited holes are thus accumulating at a large distance where $E_\perp$ 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 $E_\perp$-$B_\parallel$ crossed fields configuration). The hole drift velocity can be written (in a classical approach) as $V^B=\mu_h E_\perp/[1+(\mu_h B_\parallel/c)^2]$ (c is the light velocity). Then, for $B_\parallel>1$ T ($\mu_h B_\parallel/c\simeq 1$), d_{eh} strongly decreases, reaching values $<10^{-5}$ cm at $B_\parallel>2$ T. Thus, the spatial distribution of photoexcited holes (in the GaAs buffer layer) is mainly determined by the incident light penetration depth. With increasing $B_\parallel$, the hole density near the 2DEG layer increases while the density of holes situated away from HJ decreases. Fewer holes are available to form excitons in the GaAs layer, and the exciton PL intensity decreases while that of the 2D*e*-*h* PL is enhanced with increasing $B_\parallel$. It is important to underline that the discussed PL modifications with $B_\parallel$ are only relevant for free holes that recombine with momentum conservation. In the case of recombination of localized holes with the 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/$Al_{0.3}Ga_{0.7}$As HJ and MDQW samples grown by molecular beam epitaxy. The HJ samples have a 1μ thick GaAs buffer layer, and the MDQW samples have a single 25 nm wide QW. The 2DEG densities and dc mobilities at 4 K vary in the ranges of $n_{2D}=(0.7-3)\times 10^{11}$ cm^{-2} and $\mu=(1-4)\times 10^6$ cm^2/V s, respectively. Photoexcitation was done by illumination with a Ti-sapphire laser light (photon energy of 1.54 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 (1.96 eV) is greater than the band gap of the $Al_{0.3}Ga_{0.7}$As barrier, thus, n_{2D} can be reduced due to optical depletion by increasing the He-Ne laser intensity.[24] 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 $T_L=1.9$ K, and photoexcitation and PL detection were performed perpendicularly to the 2DEG plane under an in-plane $B_\parallel$.

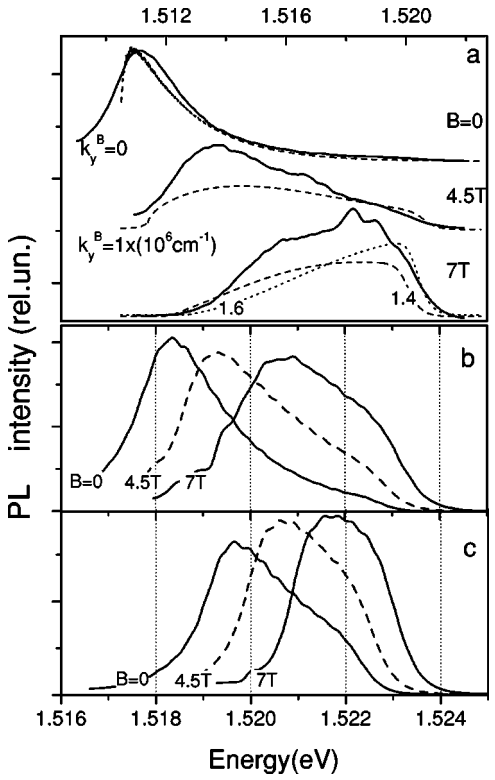

FIG. 2. PL spectral evolution under a parallel magnetic field, $B_\parallel=0$, 4.5, and 7 T. (a) 25 nm wide MDQW with $n_{2D}^0\simeq 3\times 10^{11}$ cm^{-2} (solid lines). The fitted spectra [using Eq. (3)] with corresponding k_y^B values are presented by dotted lines. The spectra are vertically offset. (b), (c) 25 nm wide MDQW with $n_{2D}^0\simeq 1.8\times 10^{11}$ cm^{-2} photoexcited with a He-Ne laser (under optical depletion). The laser intensity in (b) is less than in (c).

Figures 2(a)–2(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 an effective T_h [Eq. (1)].[25] The 2DEG Fermi energy is estimated from the 2D*e*-*h* PL bandwidth. Upon applying $B_\parallel$, the PL spectra show remarkable modifications, a high-energy shift, intensity redistribution, and band narrowing. Figure 2(a) presents the PL spectra of the MDQW with $n_{2D}^0=3\times 10^{11}$ cm^{-2} at $B_\parallel=0$, 4.5, and 7 T. The calculated spectra for $k_y^B=0$, 1, 1.4, 1.6×10^6 cm^{-1} ($T_e=1.9$ K, $T_h=4$ K) shown in Fig. 2(a), allow one to estimate a d_{eh} value of 15 nm. Figures 2(b) and 2(c) demonstrate the effect of varying n_{2D} on the PL spectral evolution under $B_\parallel$. The PL spectra are measured on the same MDQW with $n_{2D}^0=1.8\times 10^{11}$ cm^{-2} under two He-Ne laser intensities (that cause optical depletion). As n_{2D} is reduced, less spectral modifications are observed since d_{eh} decreases. The total width of the 2D*e*-*h* PL spectra ($\propto E_F$), decreases with $B_\parallel$. At $B_\parallel=7$ T, E_F decreases by 1.5–1.3 times as a result of an electron mass enhancement.[14,15]

The observed PL spectra display the main features predicted by the simple model of Sec. II. This model does not

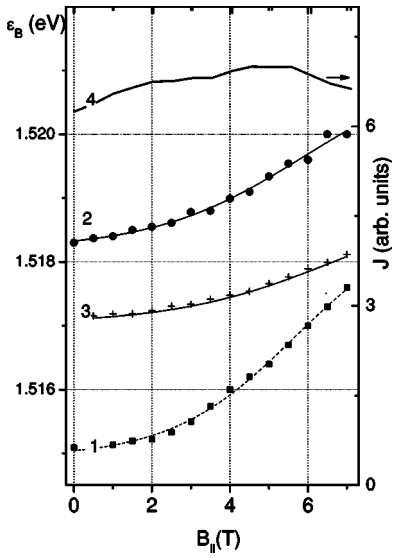

FIG. 3. $B_{\|}$-dependencies of the lowest PL energy shift, ε_B for a MDQW at two 2DEG densities, $n_{2D}(1) > n_{2D}(2)$. Curve 4, the integrated PL intensity dependence on $B_{\|}$. Curve 3, exciton PL peak energy shift with $B_{\|}$ for an undoped QW.

take into account the effect of $B_{\|}$ on the electron (hole) wave functions. 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 Boltzmann distribution with the effective T_h.

The $B_{\|}$ dependencies of the integrated PL intensity (J) and the energy ε_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 $B_{\|}$. ε_B is presented for a MDQW at two 2DEG densities, $n_{2D}^0 = 1.8 \times 10^{11}$ cm^{-2} and $n_{2D} \approx 1 \times 10^{11}$ cm^{-2} (curves 1 and 2, respectively). These dependencies are compared with the dependence of the exciton PL peak energy on $B_{\|}$ that was measured in the 20 nm wide, undoped QW (curve 3). The ε_B shift for the MDQW varies with n_{2D}, and it strongly depends on $B_{\|}$ when compared with the exciton diamagnetic shift in undoped QW.

Figure 4 displays the PL spectra of the HJ sample upon applying a *perpendicular* magnetic field, $B_{\perp}$ [Fig. 4(a)] and a parallel field, $B_{\|}$ [Figs. 4(b) and 4(c)]. Figures 4(b) and 4(c) show the PL spectra of the same HJ sample ($n_{2D}^0 = 1.6 \times 10^{11}$ cm^{-2}) under photoexcitation with $E_L = 1.54$ 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 the GaAs buffer layer.[8] With decreasing n_{2D} [Fig. 4(c)], the built-in electric field decreases, holes are situated closer to the heterointerface, and the broad 2De-h PL band appears. Under photoexcitation that does not vary n_{2D} [Figs. 4(a) and 4(b)], the 2De-h PL can be detected as a low-energy, low-intensity background. This broad PL band is due to a radiative recombination of the photoexcited holes and 2D electrons whose wave functions weakly overlap at $B = 0$. At $B_{\perp} \simeq 3.2$ T ($\nu \sim 2$), a PL changeover occurs, and the 2De-h PL intensity sharply enhances while the free exciton (FE) PL intensity decreases [Fig. 4(a)].[11] Another 2De-h PL modification is observed near $\nu \sim 1$ ($B_{\perp} \sim 6.5$–7 T).[4,11]

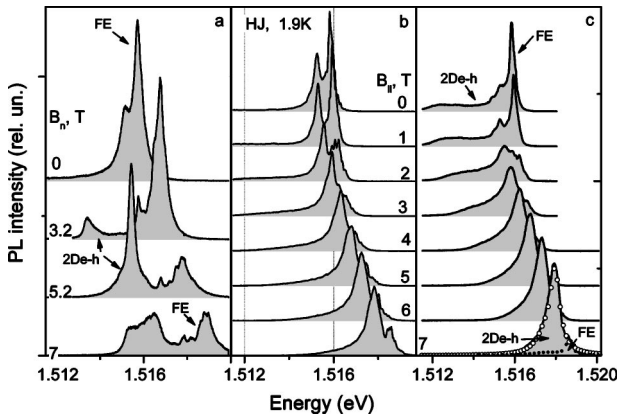

FIG. 4. The PL spectral evolution of the modulation-doped HJ upon applying $B_{\perp}$ (a) and $B_{\|}$ (b), (c). The spectra in (a), (b) are measured under photoexcitation at $E_L = 1.54$ eV and in (c) at $E_L = 1.96$ eV. The PL spectrum at 7 T (c) is fitted by two PL bands that are due to free excitons (FE) and to the 2DEG-h recombination (shown by dotted curves).

The PL evolution with applying in-plane $B_{\|}$ is shown in Figs. 4(b) and 4(c). With increasing $B_{\|}$, an increase of the 2De-h PL (low-energy tail) intensity and a narrowing of its bandwidth are clearly observed. In Fig. 4(c), the PL spectrum at 7 T is approximated by two bands, 2De-h and FE PL. The intensity redistribution between these PL bands with increasing $B_{\|}$ is presented in the inset of Fig. 5 where the 2De-h and exciton integrated PL intensities are plotted vs B. A *smooth* changeover from the exciton to the 2De-h PL under $B_{\|} \simeq 1T$ is revealed. This is in contrast to the case of the sharp, 2DEG density-dependent changeover observed under $B_{\perp}$.[11]

The enhancement of the 2De-h PL seen in Figs. 4(b), 4(c), and 5, results from the $B_{\|}$-induced delivering of free holes to the heterointerface. Indeed, with increasing $B_{\|}$, d_{eh} decreases since the photoexcited holes are swept away

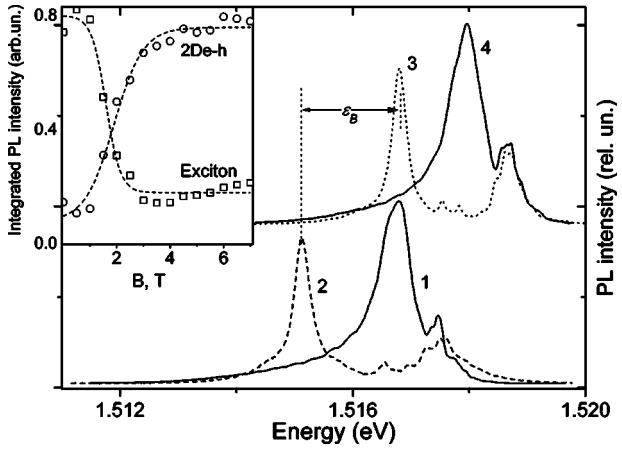

FIG. 5. PL spectra of the modulation-doped HJ. Spectra 1 and 4, under $B_{\|} = 5$ and 7 T, respectively; spectrum 2, under $B_{\perp} = 5$ T and spectrum 3, under a 45°-tilted magnetic field ($B_{\|} = B_{\perp} = 5$ T). The spectra are vertically offset for clarity. Inset, the integrated intensity of the exciton and 2De-h PL versus $B_{\|}$.

from the 2DEG for smaller distances. Therefore, a larger number of the holes can recombine with 2D electrons giving rise to the 2D*e*-*h* PL. There is a distribution of d_{eh}-values because the holes are spatially distributed in GaAs buffer layer. This leads to the observed PL spectral shape having a long low-energy tail, since the PL intensity strongly reduces with increasing d_{eh}. The narrowing and energy shift of the PL is caused by the effect of $B_{\|}$ on the 2D*e*-*h* PL spectral shape (as discussed above, see Fig. 1). In particular, the 2D*e*-*h* PL line shape at $B_{\|}=7$ T [Fig. 4(c)] corresponds to the PL spectrum calculated for $k_y^B > 2.10^6$ cm^{-1} as one can see in Fig. 1(a).

In Fig. 5, we compare the HJ PL spectra under parallel (curves 1,4), perpendicular (curve 2) and 45°-tilted magnetic field (curve 3). The spectra presented by curves 1 and 2 are obtained at $B_{\|}=5$ T and $B_{\perp}=5$ T, 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 a tilted magnetic field ($B_{\|}=B_{\perp}=5$ T, curve 3) is similar to that measured at $B_{\|}=7$ T (curve 4). Both these facts give an additional evidence of the bulk excitonic nature of the high-energy PL band in the HJ. The 2D*e*-*h* parts of the PL spectra measured under $B_{\|}$ and $B_{\perp}$ (curves 1 and 2) are completely different from that observed under tilted magnetic field. In the latter case, the 2D*e*-*h* PL originates in the radiative recombination from the lowest *e*-*h* Landau levels (due to $B_{\perp}$-component) while an additional spectral shift ε_B is caused by $B_{\|}$-component. The value of this shift at $B_{\|}=5$ T is of 1.8 meV, and using Eq. (4), we estimated the 2D*e*-*h* separation to be 25 nm. Thus applying $B_{\|}$ reduces d_{eh}, and this gives rise to the PL intensity transfer from the FE to 2D*e*-*h* PL.

IV. CONCLUSIONS

In conclusion, our study shows that an in-plane magnetic field leads to a remarkable spectral modification of the 2DEG-hole PL in MDQW's and HJ's. A model considering the direct optical transitions between the conduction and valence subbands that are shifted in k-space under $B_{\|}$, accounts qualitatively for the observed spectral modifications in the MDQW's. In HJ's, applying $B_{\|}$ leads to a smooth transfer of the bulk exciton PL intensity to the 2DEG-hole PL. This is caused by the effect of $B_{\|}$ on the free hole distribution in the HJ. The 2D*e*-*h* PL evolution studied upon applying $B_{\|}$, shows that free holes are responsible for this emission in high quality HJ's. Thus, we can conclude that the sharp PL changeover observed under a perpendicularly applied $B_{\perp}$ in HJ's, is induced by a threshold spatial redistribution of free holes at $\nu \simeq 2$, and a physical mechanism for this was recently proposed.[11]

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*Electronic address: borisa@tx.technion.ac.il

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