Exciton to two-dimensional electron-hole photoluminescence transitions driven by the quantum Hall effect in photoexcited heterojunctions

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A comprehensive experimental study of the photoluminescence (PL) spectral evolution under a magnetic field ($B \leqslant 25$ T) applied perpendicularly to a high-mobility two-dimensional electron gas (2DEG), is performed on modulation-doped GaAs/AlGaAs heterojunctions at $T_L = 0.3$ K. The abrupt transfer of the free exciton to hole-2DEG PL occurring at integer and fractional filling factors is analyzed in a phenomenological model, wherein free excitons photogenerated in the GaAs layer dissociate into a 2D electron and 3D hole near the 2D-electron channel. Such magnetic field induced exciton-(2De-h) transitions are able to explain the remarkable strong PL anomalies in single hetrojunctions as compared to those observed in modulation-doped quantum wells.

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I. INTRODUCTION

A two-dimensional electron gas (2DEG) in a modulation-doped GaAs/AlGaAs single heterojunction (HJ) occupies a very narrow (10 nm) region of the wide (1 μm) GaAs layer. Under photoexcitation by interband light, photoexcited holes are swept away from the 2DEG channel by the electric field E_{HJ} built in the HJ, and excitons are formed in the GaAs layer. Thus, coexistence of free excitons and the 2DEG is a distinct feature of photoexcited HJs.[1,2] Indeed, the photoluminescence (PL) from a high quality GaAs/AlGaAs HJ in the absence of a magnetic field B, shows narrow (bulk) exciton lines originating in the GaAs layer.[1–3] However, this exciton PL reveals a remarkable spectral evolution into 2DEG-free hole (2De-h) PL with increasing magnetic field applied either perpendicular or parallel to the 2DEG channel.[2–6]

Under a perpendicularly applied B, the PL intensity and peak energy exhibit abrupt and strong discontinuities at integer and fractional $2d$-electron filling factors, ν (see Fig. 1). This unique phenomenon is most clearly observed in high quality HJs where the 2D electrons recombine with itinerant holes that are photoexcited far away from the 2DEG. The 2De-h PL does not reveal similar sudden transitions neither in HJs where the 2D electron recombines with holes bound to acceptors, nor in GaAs/AlGaAs modulation-doped quantum wells (MQDWs), although various PL spectral anomalies were observed near integer and fractional ν values.[7–11]

The PL anomalies were interpreted as an indication of the appearance of an incompressible electron liquid at integer and fractional filling factors while the screening efficiency of the electron-hole interaction and the fluctuating potential due to remote impurities, is reduced.[4,8,11] This is suggested to lead to an increased 2D-electron-hole separation[9] or to localization of the holes.[8] Then, the radiative recombination rate decreases, and the observed PL quenching is due to the presence of competing nonradiative recombination channels.

The main objective of previous PL studies was to obtain spectroscopic evidence for the quantum Hall effects,[4,7–9] and the detailed mechanisms leading to the remarkable PL behavior with increasing B remain obscure. Suggestions about the underlying physics of the PL behavior in HJs have been made from the first report[4] and are still proposed now.[5] The absence of the 2De-h PL in HJs for $\nu > 2$ was explained by filled Landau levels being "inert for recombination," while its appearance for $\nu < 2$ is considered to be due to "an efficient coupling mechanism between the 2DEG and free holes."[5] This explanation, however, is inconsistent with the observation of 2De-h PL at $B = 0$ in MDQWs of various thicknesses, and with the fact that the integrated PL intensity barely varies at $\nu \simeq 2$.[8,9] On the other hand, the attraction of the free valence holes (that are far away from the 2DEG due to the presence of E_{HJ}) to the 2DEG-channel for $\nu < 2$ by some "coupling mechanism," does not clarify the underlying physics.

We have carried out a comprehensive experimental study of the PL in high-mobility HJs in order to provide a reliable experimental basis for developing the theory of the remarkable PL spectral evolution in a magnetic field. We propose a phenomenological model wherein free bulk excitons (FE) dissociate into a 2D electron and 3D hole near the HJ interface containing the magnetized 2DEG.[2] The dissociation rate ("exciton interface recombination") is determined by exciton dynamics in a total two-well-potential that is formed by the free exciton near the HJ interface and the 3D hole interacting with the 2DEG. The shape of this potential varies with in-

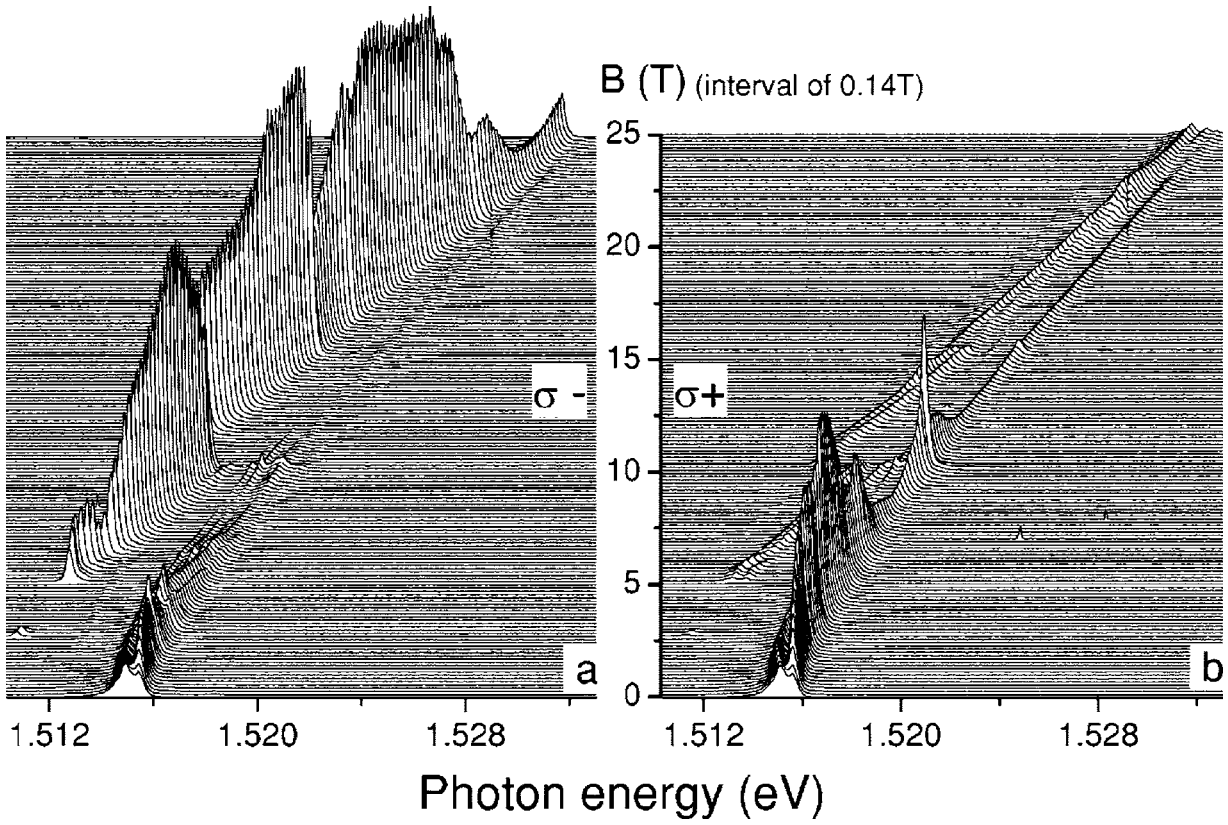

FIG. 1. Evolution of the σ^- and σ^+-PL spectra with increasing B for the HJ having $n_{2D}=2.5\times10^{11}$ cm^{-2} at $T_L=0.3$ K. A spike of the σ^+-exciton PL is seen at 10.25 T ($\nu=1$).

creasing B and reveals the singularities of the 2DEG energy. In addition, the potential variation changes the overlap between the 2D-electron and itinerant 3D-hole wave functions, affecting the 2De-h radiative recombination lifetime. Thus, the number of free holes and their separation from the 2DEG varies with increasing magnetic field. This causes the striking PL anomalies in the single HJs when compared to those observed in MDQWs.

II. EXPERIMENTAL PROCEDURE

We have studied the magneto-PL spectra in high quality, single-sided modulation-doped, GaAs/$Al_{0.33}Ga_{0.67}$As heterojunctions that have a nominally undoped 1μ-wide GaAs layer situated between GaAs/$Al_{0.33}Ga_{0.67}$As layers. The 2DEG density n_{2D} in the range $(1.2-2.5)\times10^{11}$ cm^{-2} was supplied by the δ-doped (Si) layer separated from the interface by a 80–100 μ-wide GaAs/$Al_{0.33}Ga_{0.67}$As spacer. The samples have a high dc mobility, $\mu>3\times10^6$ cm^2/V sec at $T_L=4$ K. All studied samples show similar behavior, and here we present the data obtained on the HJ with a 2DEG density $n_{2D}^0=2.5\times10^{11}$ cm^{-2} (in the dark).

A single optical fiber was used for photoexcitation and PL collection from the sample mounted in a ^{3}He cryostat at temperature of 0.3 K$<T_L<$1.5 K. The cryostat was placed in an electromagnet producing a magnetic field (up to 33 T) that was applied perpendicularly to the 2DEG layer. Photoexcitation was done by a He-Ne laser with an intensity in the

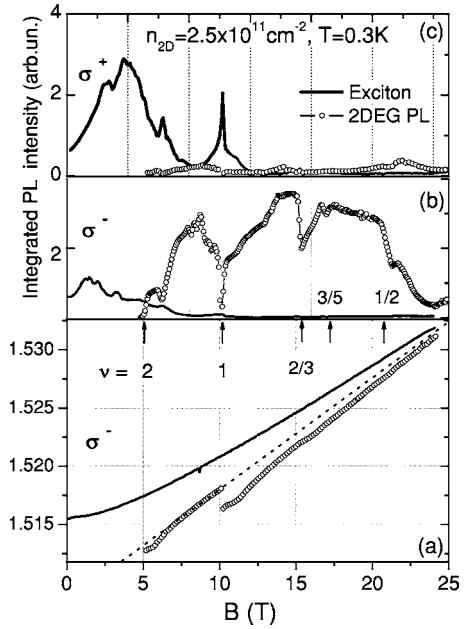

FIG. 2. Peak energy (a) and integrated exciton and 2De-h PL intensity for the σ^- (b) and σ^+ (c) circular polarizations as a function of B. Filling factor values are shown by arrows. Dashed straight line represents the emission energies due to the recombination of the 2D electron from the first Landau level of the lowest confined band with the 3D hole on the first Landau level of valence band: E_{2D} (eV)$=1.5084+0.00096\times B$.

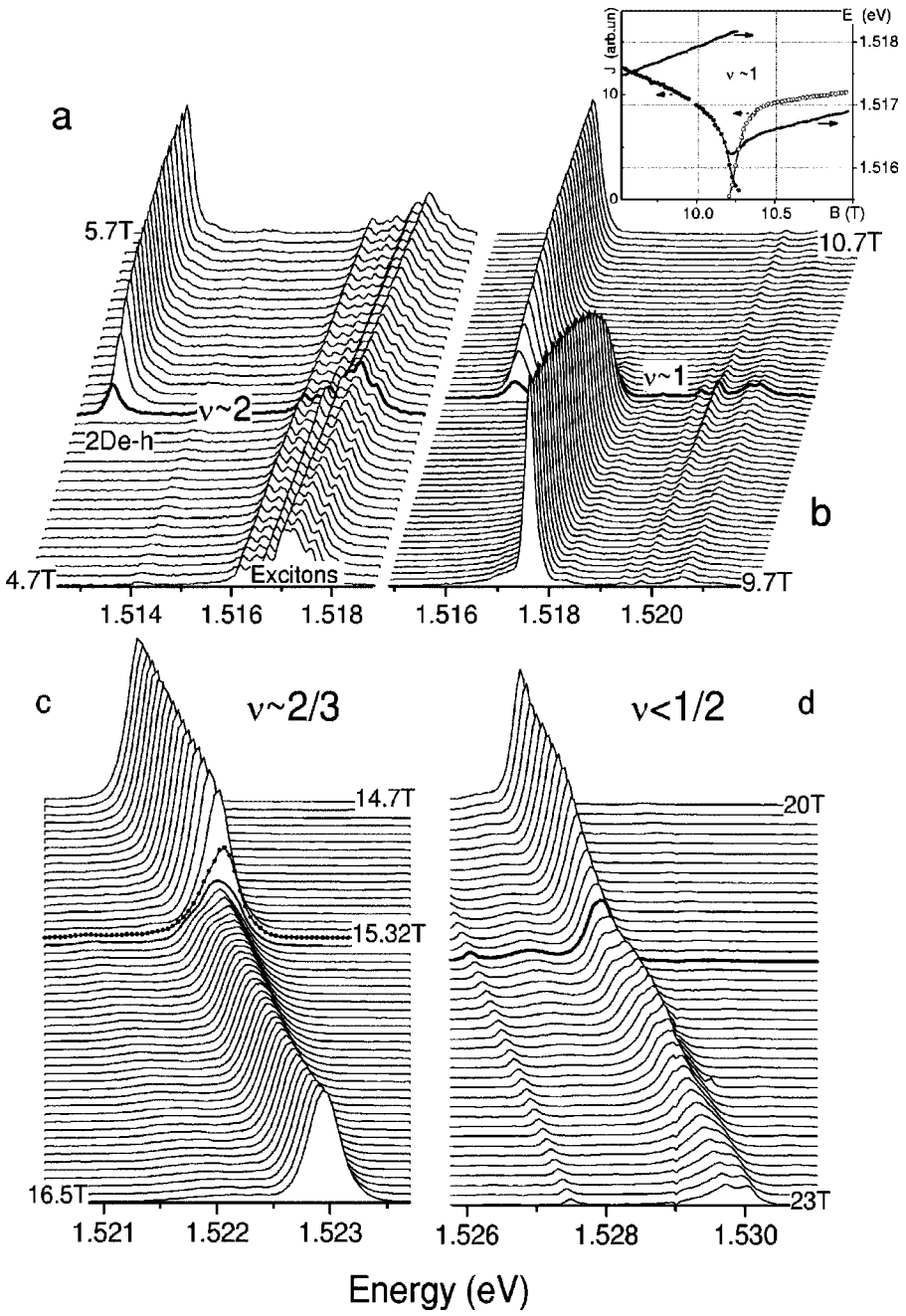

FIG. 3. PL spectral evolution near $\nu=2,1,2/3,1/2$. Inset shows a behavior of the energy (E_{2D}) and integrated intensity (J_{2D}) of the 2De-h PL near $\nu=1$.

range of $I_L=(0.03-10)$ mW/cm^2, and this allows us to tune n_{2D} by optical depletion.[7,12,13] At the lowest I_L, the 2DEG density was not reduced with He-Ne illumination, and the PL spectra were the same as that observed under photoexcitation below the AlGaAs barrier (with a Ti:sapphire laser at a photon energy of 1.56 eV). The PL spectra were measured with a spectral resolution of 0.1 meV by using a spectrometer equipped with a cooled CCD. Circularly polarized (σ^- and σ^+) PL spectra were obtained by placing a linear polarizer and a quarter-wave retardation plate between the optical fiber and the sample, and by reversing the current in the electromagnet.

III. EXPERIMENTAL RESULTS

Figures 1(a) and 1(b) display the evolution of the σ^- and σ^+ polarized PL spectra with increasing B for the HJ structure having $n_{2D}^0=2.5\times10^{11}$ cm^{-2}. The spectra were measured under the lowest He-Ne laser intensity that does not reduce the n_{2D} value. For $B=0$, the PL originates in the recombination of free and localized (bulk) excitons in the GaAs layer.[1] With increasing B, the exciton energy, E_x exhibits a diamagnetic shift [Fig. 2(a)] with the $E_x(\sigma^-)$ values being slightly higher than $E_x(\sigma^+)$,[2] and the integrated intensity of the σ^--polarized exciton PL decreases, while the σ^+-polarized PL intensity increases [Figs. 2(b) and 2(c)]. We observed similar energy and intensity dependencies on B in a pure 10-μm-wide GaAs layer as well as in a HJ structure with $n_{2D}=1.7\times10^{10}$ cm^{-2}.

At increased magnetic field, the free-exciton GaAs PL exhibits several PL lines in both σ^- and σ^+ polarizations, and such a splitting is due to the mixing between exciton states with total spin $S=1$ and 2.[14] A similar splitting of the exciton

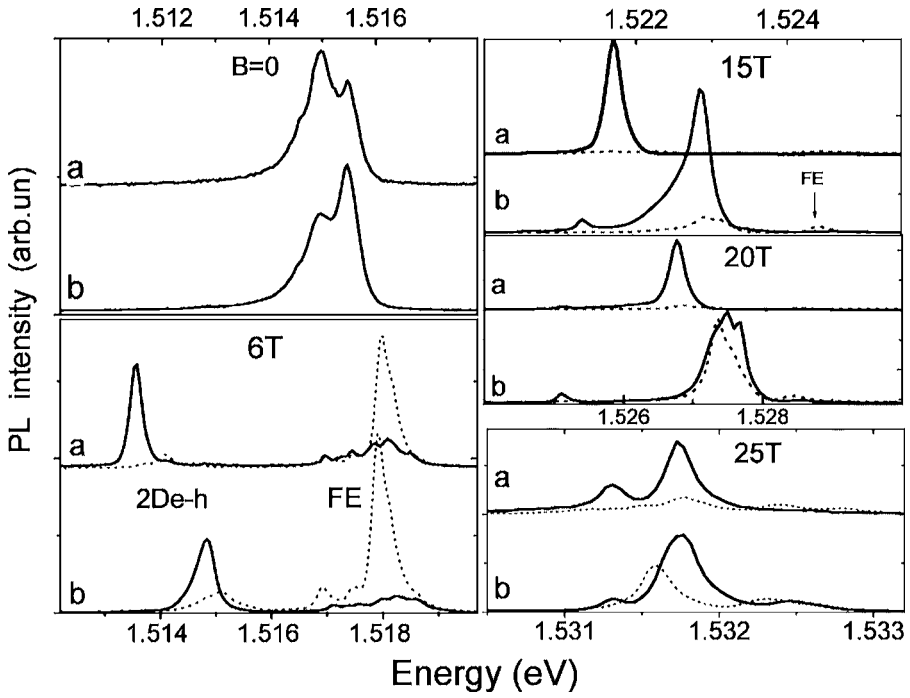

FIG. 4. PL spectra in σ^- and σ^+ circular polarization (solid and dashed lines, respectively) for $n_{2D}=2.5\times10^{11}$ cm^{-2} (*a* curves) and $n_{2D}\simeq2.1\times10^{11}$ cm^{-2} (*b* curves) for several B values.

PL lines was detected in highly-resolved spectra of the HJ (see Fig. 2 in Ref. 2), and such a splitting results in a broadening of the exciton PL spectra in the present experiments.

As Figs. 1 and 2 show, the 2De-h PL band abruptly appears at $\nu\leqslant2$.[2–5] Its energy is about 5 meV below that of the GaAs free exciton, and its intensity increases with increasing B [Figs. 2(b) and 2(c)]. The 2De-h PL is highly σ^--polarized while the exciton PL is mainly σ^+-polarized [Figs. 2(b) and 2(c)]. The intensity of the σ^--2De-h and the σ^+-exciton PL varies in opposite ways in the range $2>\nu>1$. At $\nu\simeq1.5-1.6$, a decrease of the 2De-h PL intensity is accompanied by an increased exciton PL intensity [Figs. 2(b) and 2(c)]. The variation of the total integrated $(\sigma^-+\sigma^+)$ PL intensity in the range $0<B<20$ T is small ($\sim20\%$) as one can conclude from Figs. 2(b) and 2(c).

The detailed evolution of the σ^--polarized PL near $\nu=2$, 1, 2/3, and 1/2 is presented in Figs. 3(a)–3(d). At $\nu=2$, the σ^--polarized 2De-h PL emerges at the expense of the σ^+-exciton PL component [see Fig. 1(b)]. At $\nu=1$ ($B=10.25$ T), sudden changes in the 2De-h PL intensity and energy occur (observed in the σ^- polarization). The peak energy, E_{2D} abruptly shifts down by ~2 meV [Figs. 2(a) and 3(b)]. A similar spectral discontinuity has been previously observed and explained by the asymmetry in the electron-hole interaction for $\nu>1$ and $\nu<1$.[3,15,16] The inset of Fig. 3(b) displays the dependencies of the integrated intensity and energy for the 2De-h PL band. In our high quality sample, the intensity transfer from the high-energy 2De-h PL ($\nu>1$) to the low-energy 2De-h PL ($\nu<1$) occurs very sharply, however, both (high- and low-energy) 2De-h PL bands coexist within ~0.05 T. A remarkable spike of the σ^+-exciton PL intensity occurs at $\nu=1$ as the 2De-h PL quenches [Figs. 1(b) and 2(c)], and this fact demonstrates that both recombination channels are competing with each other.

At $\nu\simeq2/3$ ($B=15.3$ T), a splitting of the 2De-h PL band [Fig. 3(c)], a decrease in the integrated PL intensity [Fig. 2(b)] and a kink in the E_{2D} vs B dependence [Fig. 2(a)] are clearly observed. These anomalies at $\nu=2/3$ evolve smoothly in comparison with those at $\nu=2$ and 1. The PL intensity variation with B is asymmetric near $\nu=2/3$ [Figs. 1(a) and 2(b)]. With further increasing B, a weak PL intensity anomaly is detected at 17 T ($\nu=3/5$). At $B>20$ T ($\nu<1/2$), the integrated PL intensity strongly decreases [Figs. 1(a) and 2(b)], the PL line broadens [Fig. 3(d)], and then, a low-energy PL line splits off (see Fig. 4 for 25 T).

Figure 4 shows the σ^- and σ^+ polarized PL spectra for two n_{2D}-values at $B=0$, 6, 15, 20, and 25 T. Curves *b* are measured at higher He-Ne laser light intensity for which a decreased value of $n_{2D}\simeq2.1\times10^{11}$ cm^{-2} was obtained due to optical depletion. At $B=0$, the PL spectrum does not show significant changes with varying n_{2D} (beside the PL redistribution between free and localized excitons, Fig. 4). Its energy dependence on B is the same for all n_{2D} values (He-Ne laser intensities) (see Fig. 4 for $B=0-15$ T). These factors confirm the excitonic nature of the high-energy PL bands originating in the GaAs layer (for which the PL should not shift with n_{2D}). In contrast, at reduced n_{2D}, the 2De-h PL band shifts to higher energy (Fig. 4), and the PL anomalies appear at lower B values (at corresponding ν).[2] The energy shift is mainly due to a reduced exchange energy that causes a conduction-valence band gap narrowing for the higher density 2DEG.

Up to 20 T, the 2De-h PL is completely σ^- polarized (Fig. 4). However, the σ^+-polarized PL intensity increases at higher B (as well as for lower n_{2D}), so that the polarization degree significantly decreases at $B>20$ T (Fig. 4). We suppose that a 2DEG localization in photoexcited HJ[17] may lead to such a PL behavior at $\nu<1/2$, and we will not discuss here the results obtained at $\nu<1/2$.

IV. DISCUSSION

Although some of the HJ's PL singularities described above have been previously observed for several

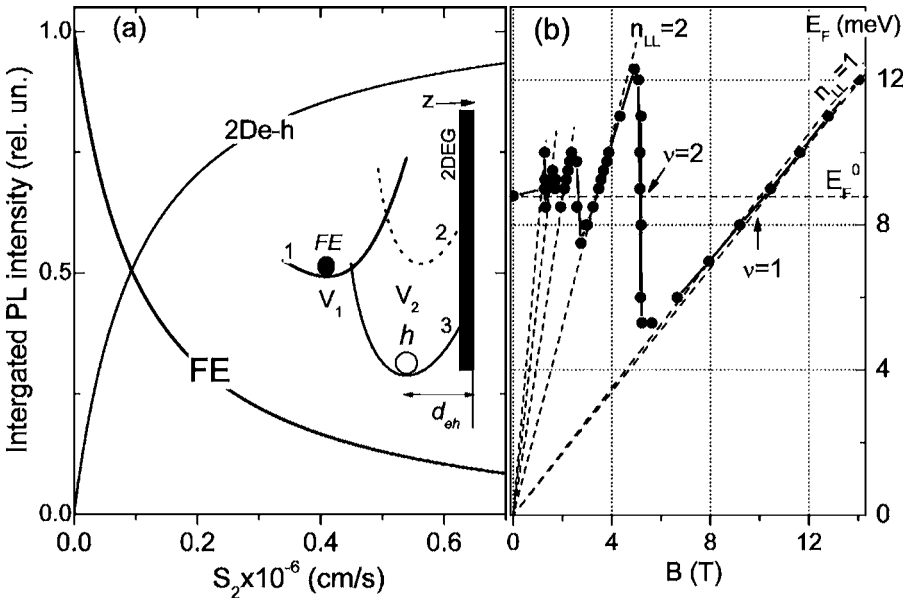

FIG. 5. (a) Calculated redistribution between the exciton and 2De-h PL intensities as a function of the exciton dissociation rate, S_2, near the 2DEG layer. In inset, schematically depicted potential wells for the exciton (V_1) and for the interacting valence hole and 2D electron (V_2) at low (curve 2) and high (curve 3) B. (b) Landau level positions (dashed lines) and the 2DEG Fermi energy, E_F (circles) calculated for $n_{2D}=2.5\times10^{11}$ cm^{-2} and 0.3 K, as a function of magnetic field.

years,[3–5,10,15] there is still no clear identification of the processes underlying these PL transformations. For example, the high-energy PL bands have been assigned to the recombination of valence holes with electrons in the second confined band (h-2cb PL),[4,5] and the intensity transfer from the h-2cb to 2De-h PL with increasing B, was considered as a consequence of the competition between the hole recombination with the 2D electron of the second or first confined states.[5] Below, we propose that this "thermodynamic equilibrium" model that assumes a B-independent valence hole density, should be replaced by a dynamical model that considers exciton dissociation near the magnetized 2DEG.[2]

Our study clearly shows that the high-energy PL bands originate in the bulk undoped GaAs layer, and the 2De-h PL does not appear for $\nu>2$ since *there are no valence holes* situated near the 2DEG in high-quality HJs. This claim was verified in our recent PL experiments with a magnetic field applied parallel to the 2DEG plane.[6] In this case, a smooth transformation of the exciton to 2De-h PL has been observed as a result of the increased hole density near the 2DEG when the *parallel B* hinders the hole drift away from the 2D-electron channel.

Once we established the different nature of the observed PL bands, we are going to discuss the physical mechanism for the transformation of the bulk exciton PL into the interface 2De-h PL.

The photoexcited hole drifts away from the interface over a distance $d\sim10^{-4}$ cm in a very short time $t_d\sim d/\mu_h E_{HJ}\sim10^{-10}$ sec. Therefore, the 2D-electron-free hole wave function overlap becomes negligible until the recombination between the free hole and the 2DEG might occur. We assume a hole mobility, $\mu_h=10^4$ cm^2/V sec[18] and low HJ electric field, $E_{HJ}=10^2$ V/cm. Thus the appearance of holes giving rise to the 2De-h PL with increased magnetic field, should be explained.

This can be done by considering nonequilibrium, dynamical processes occurring in the HJ. Under illumination of the sample (in the HJ growth direction, z), free electron-hole (e-h) pairs are generated practically uniformly throughout the GaAs layer since the light penetration length (at the photon energy close to GaAs bandgap), $\alpha^{-1}\sim10^{-4}$ cm.[18] The photoexcited e-h pairs are rapidly separated by the built-in HJ electric field, E_{HJ} which pushes away the holes from the 2DEG and attracts the electrons to the 2DEG layer. In the flat band region of the GaAs (buffer) layer (far from the interface containing the 2DEG), nonequilibrium electrons and holes are bound into free excitons (FE) that diffuse and drift to the higher field region. The FE diffusion length in GaAs samples having a high electron mobility, $L_{ex}=(D\tau_{ex})^{1/2}\simeq3\times10^{-4}$ cm. Therefore, L_{ex} exceeds the GaAs layer width, and the FE density is controlled by the processes occurring on both GaAs/AlGaAs interfaces. Here we use an exciton diffusion coefficient $D\approx100$ cm^2/sec and an exciton lifetime $\tau_{ex}\simeq10^{-9}$ sec, respectively.[18]

Let us consider a phenomenological model in which free excitons are photogenerated at a rate of $G(z)$ in the GaAs layer of width d. Then, the exciton density $n_{ex}(z)$, is obtained by solving the steady-state continuity equation:

$$G_0\exp(-\alpha(d-z))+D\frac{d^2n_{ex}(z)}{dz^2}-\frac{n_{ex}(z)}{\tau_{ex}}=0 \qquad (1)$$

with the boundary conditions[19]

$$\left[D\frac{dn_{ex}}{dz}-S_{1,2}\cdot n_{ex}\right]_{z=0,d}=0. \qquad (2)$$

Here, $S_{1,2}$ are the rates of the exciton surface recombination at the AlGaAs/GaAs ($z=0$) and GaAs/AlGaAs ($z=d$) interfaces, respectively. Exciton drift in the E_{HJ} gradient is not included in Eq. (1).

Let us suppose that excitons dissociate into a 3D hole and a 2D electron at a rate of S_2 near the HJ interface containing the 2DEG (at $z=d$). Such an exciton dissociation generates free holes near the 2DEG, and then, the 2De-h PL intensity is $I_{2De\text{-}h}=S_2\cdot n_{ex}(d)$. (We assume 100% quantum efficiency for the FE and 2De-h PL.) The solution of Eq. (1) in the limit of $\alpha d<1$, is

$$n_{ex} = G_0 \tau_{ex}[1 - A \exp(-z/L_{ex}) - B \exp(z/L_{ex})], \qquad (3)$$

where A and B are obtained from Eq. (2). The FE PL intensity, $I_{ex}=N_{ex}/\tau_{ex}$ where $N_{ex}=\int n_{ex}dz$ is the total number of excitons in the GaAs layer. The calculated I_{ex} and $I_{2De\text{-}h}$ dependencies on S_2 are presented in Fig. 5(a) for $S_1 = 10^3$ cm/sec and for the above given D, τ_{ex} and d-values. These simple numerical calculations that are performed for reasonable GaAs parameters, quantitatively demonstrate the feasibility of the free exciton to 2De-h PL transition with increasing S_2.

In order to explain the PL changeover observed in the HJ under magnetic field, we now propose that the exciton decay rate, S_2, is controlled by the magnetic field strength. At $B=0$, the excitons near the interface with the 2DEG, experience a high repulsive barrier.[20] Taking into account the built-in E_{HJ}, a potential well for the excitons, $V_1(z)$ [shown schematically by curve 1 in the inset of Fig. 5(a)], appears at a distance of (3–5) Bohr radii from the HJ's interface.[20] Thus, at low B, the exciton PL intensity is high since S_2 is low. On the other hand, another potential well—$V_2(z)$ can be formed by the interacting 2D electron and 3D hole [curves 2, 3 in Fig. 5(a)]. A bound state of these particles is predicted to appear for a high B.[21,22] It should be noted that this state can be realized only for holes generated very close to the 2DEG.

The decay of the 3D exciton into a 2D electron and hole at $z \simeq d$, can be considered as a transition of the e-h pair (exciton) from the $V_1(z)$ well into the $V_2(z)$ well, and in this way, holes are delivered to the 2DEG. The rate of such a transition is determined by the total potential shape, $V(z) = V_1(z) + V_2(z)$. This is a typical situation for a phase transition between two thermodynamic energy states.[23] Such a transition from an exciton (curve 1) to a 2De-h state (curve 3) is demonstrated in the inset of Fig. 5(a). As the energy barrier between the two wells approaches $\sim kT$ (or disappears), the excitons will be driven into the $V_2(z)$ well. The driving force is a very sensitive function of $V(z)$.

The shape of the $V_2(z)$ potential is determined by the kinetic and potential energies of the 2D electron and 3D hole. The kinetic energy that is needed to transfer the electron to the 2DEG channel, is the 2DEG Fermi energy, E_F while the potential (Coulomb) energy of the 2D-electron and 3D-hole pair depends on the screening properties of the 2DEG.[22] At integer ν, E_F singularities occur,[24] with the largest E_F fall at $\nu=2$ [see Fig. 5(b)]. Thus, $V_2(z)$ abruptly reduces [curve 2 goes down to curve 3 in Fig. 5(a)], the excitons spill over into the V_2 well, and dissociate into the 2D electron and 3D hole. Thus the 2De-h PL appears at $\nu=2$. At $\nu=1$, the 2DEG becomes incompressible, and the interaction energy between the 2DEG and 3D hole decreases leading to the increased V_2 [curve 3 in Fig. 5(a) goes up]. Then, S_2 is reduced, the excitons cannot dissociate, and the 3D-hole density near the 2DEG decreases.

Thus, the B-induced singularities of the total potential $V(z)$, control the 3D-hole density near the 2DEG and also affect the hole-2DEG distance, d_{eh} as it is illustrated in the inset of Fig. 5(a). It should be noted that less pronounced PL intensity transfers are also observed at other integer (fractional) ν (Fig. 1). In the proposed model, these anomalies result from slight variations of the $V_2(z)$ potential that lead to the changes in S_2.

The increased (at $\nu=2$) or decreased (at $\nu=1$) hole density near the 2DEG is likely to be a main cause for the abrupt exciton–(2De-h)PL intensity redistribution in the HJs [Figs. 2(b) and 2(c)] when compared with those observed in MDQWs. A remarkable spike of the free exciton PL intensity at $\nu=1$ [Fig. 1(a)] confirms this conclusion.

So far we have discussed only the intensity changeover between two PL bands. Let us now analyze the corresponding E_{2D} vs B dependence shown in Fig. 2(a). The straight (dashed) line presents the $E_{2D}(B)$ dependence ascribed to the interband recombination between the lowest Landau levels for free electron and valence hole:

$$E_{2D} = E_e^0 + E_h^0 + \frac{1}{2}(\hbar\omega_{ce} + \hbar\omega_{ch}). \qquad (4)$$

Here, E_e^0 and E_h^0 are the energy of the lowest 2D-electron subband and the hole energy near the top of the bended valence band at $B=0$, respectively. ω_{ce} (ω_{ch}) is the electron (hole) cyclotron frequency corresponding to the GaAs-electron (valence hole) mass $0.067m_0$ ($0.45m_0$). The straight line fits well the $E_{2D}(B)$ dependence in the range of $1.8 > \nu > 1$ [Fig. 2(a)]. However, the $E_{2D}(B)$ dependence reveals a sharp discontinuity at $\nu=1$ and significant deviations from the straight line near $\nu=2$ and 1. The slope of the $E_{2D}(B)$ curve varies with B for $\nu<1$, and, moreover, it decreases as n_{2D} reduces.

The spectral discontinuity at $\nu=1$ has been previously observed and explained by the asymmetry in the electron-hole interaction for $\nu>1$ and $\nu<1$ at a large spatial separation between the 2DEG and hole.[3,11,15,16] It should be noted that the abrupt E_{2D} change is specific to the recombination of the 2D electron with an itinerant hole, and it is more pronounced in the 2De-h PL of the HJs when compared to the 2De-bound hole recombination[7] or to the 2De-h PL in the MDQW's.[16,17]

Several effects might enhance the anomalies of the $E_{2D}(B)$ behavior observed in HJs. (a) As mentioned above, the hole distance from the interface d_{eh} varies with B. It leads to a change of the 2De-h interaction energy [magnetoexciton energy[22] which is not taken into account in Eq. (4)] with increasing B. (b) The hole energy E_h^0 also depends on d_{eh} since the 2De-h recombination is indirect in the z direction [see inset of Fig. 5(a)], and thus E_h^0 in Eq. (4) varies with B. (c) The confined self-consistent electron energy E_e^0 in Eq. (4) can also change as B increases. This can result from an electron redistribution between the 2D-electron channel and the adjacent, Si-doped AlGaAs layer.[25] Indeed, as E_F varies with B [Fig. 5(b)], the chemical potential of the 2DEG ($E_e^0 + E_F$) tends to be in equilibrium with that of the adjacent layers—otherwise, the 2DEG is in a nonequilibrium state. Under illumination of the sample, the equilibrium can be established faster than it usually occurs in the dark and then, E_e^0 changes with B.[25] Thus the 2DEG density variation affects the $E_{2D}(B)$ dependence in contrast to electrical measurements where the 2DEG transport properties near E_F are studied.

V. CONCLUSIONS

The evolution of the circularly polarized (σ^- and σ^+) PL spectra under a perpendicularly applied magnetic field and at

0.3 K, is studied on several GaAs/AlGaAs heterojuctions containing a high-mobility 2DEG. A phenomenological model wherein free excitons (photoexcited in the wide GaAs buffer layer) dissociate into a 2D electron and 3D hole near the magnetized 2DEG, is developed in order to explain an abrupt transfer of the exciton to hole-2DEG PL occurring at the electron filling factors $\nu=2$ and 1. Such magnetic field induced exciton-(2De-3Dh) transitions are able to explain the remarkable strong PL anomalies in the single HJs when compared to those observed in the modulation-doped quantum wells.

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