Hole spin quantum beats in quantum-well structures

X. Marie, T. Amand, P. Le Jeune, M. Paillard, and P. Renucci
Laboratoire de Physique de la Matiere Condensee, CNRS-UMR 5830 INSA, Avenue de Rangueil, 31077 Toulouse Cedex, France

L. E. Golub, V. D. Dymnikov, and E. L. Ivchenko
A. F. Ioffe Physico-Technical Institute, Russian Academy of Sciences, Politechnicheskaya 26, 194021 St. Petersburg, Russia

(Received 5 April 1999)

We report experimental and theoretical investigations of the quantized hole states in a magnetic field. We observe spin quantum beats in the time-resolved photoluminescence of N-modulation-doped GaAs/$A_xGa_{1-x}As$ quantum wells in a magnetic field perpendicular to the growth direction. The measurement of these quantum beats, which originate from the Larmor precession of heavy-hole spins, yields the accurate determination of the transverse heavy-hole Landé g factor. We find $|g_{h,\perp}|=0.04\pm0.01$, in good agreement with the theoretical calculations based on the $\mathbf{k}\cdot\mathbf{p}$ theory in the five level model. [S0163-1829(99)10931-7]

I. INTRODUCTION

The effective Landé g factor of electrons, holes, and excitons in low-dimensional semiconductor systems has received considerable attention recently since it provides numerous informations on the subband structure. Most of the theoretical and experimental investigations in this field have been devoted to studies of the electron g factor.[1] It has been measured by electron spin resonance,[2] Hanle effect,[3] spin-flip Raman scattering[4] (SFRS) or, more recently, spin quantum beats (QB).[5–7] Thanks to the very high accuracy of this last technique, the anisotropy of the electron g factor in quantum wells (QW's) first predicted theoretically[8] has been quantitatively determined as a function of the well width.[9]

The effective g factor of size-quantized heavy holes (HH) in semiconductor heterostructures has received less attention. In D_{2d} symmetry, the HH g factor exhibits a strong anisotropic character with a great difference between $g_{h,\parallel}$ and $g_{h,\perp}$, where $g_{h,\parallel}$ and $g_{h,\perp}$ are the components of the effective g-factor tensor for the magnetic-field parallel and perpendicular to the QW growth axis (Oz), respectively.[10] Van Kesteren *et al.*, from optically detected magnetic resonance (ODMR) experiments carried out on type-II QW's, measured a longitudinal component $g_{h,\parallel}$ of about 2.5.[11] SFRS experiments from acceptor-bound holes in type-I QW's led to a $g_{h,\parallel}$ value of about 2.[12] The HH longitudinal g factor has also been determined as a function of the well width from the Zeeman splitting of the luminescence line by Snelling *et al.*[13] The longitudinal HH Zeeman splitting has been recently calculated for QW's in the multiband envelope function approximation, with a satisfactory agreement with experiment.[14]

Whereas the longitudinal HH g factor has been measured and calculated by different authors, the knowledge on the transverse component $g_{h,\perp}$ is still very poor. In type-II QW's, no signature of a transverse HH Zeeman splitting was found in ODMR experiments performed in a transverse magnetic field.[11] The authors deduced then that $g_{h,\perp}$ is smaller than 0.01. Mashkov *et al.* did not find evidence of any transverse HH Zeeman splitting in spin quantum beats experiments performed on intrinsic type-II QW's.[7] In type-I QW, the transverse HH g factor was reported to be zero within the accuracy of SFRS experiments.[12]

Most of the previously reported works mentioned above have been performed in unintentionally doped QW's. As a consequence, these experiments performed in transverse magnetic field generally involve the Zeeman splitting of the electron $\hbar\omega_e=g_{e,\perp}\mu_B B$ and also the exciton exchange energy δ due the spin-spin coupling of the electron and the hole forming the exciton. For typical transverse magnetic field, $\hbar\omega_e$ and δ are much larger than the expected hole Zeeman splitting $\hbar\omega_h$. This probably explains the absence of accurate measurements of $g_{h,\perp}$ up to now.

In order to overcome these difficulties, we have studied free HH states in type-I N-modulation-doped QW's. We present in this paper experimental and theoretical investigations of the quantized HH states in the transverse magnetic field. Experimentally, we find $g_{h,\perp}=0.04\pm0.01$ in reasonable agreement with the theoretical calculations.

The multiple quantum well (MQW) samples investigated were grown by molecular-beam epitaxy on (001)-oriented GaAs substrates. The results presented here concern a GaAs/$Al_{0.3}Ga_{0.7}As$ sample (sample I) which has 60 periods of $L_W=4.8$ nm GaAs wells separated by $L_B=15$ nm barriers with a central Si δ-doped layer. Three monolayers of AlAs were grown next to every GaAs/$Al_{0.3}Ga_{0.7}As$ interface. We have measured the electron density n_e transferred from the doping level by Hall experiments performed at 4.2 K and found $n_e\simeq6\times10^{11}\ \mathrm{cm}^{-2}$. Very similar results have been obtained on three other GaAs/$Al_{0.3}Ga_{0.7}As$ MQW with different parameters listed in Table I. The sample details can be found in Ref. 15.

For such (001)-grown QW's, the relevant symmetry is D_{2d} and the growth direction (Oz) is taken as the quantization axis for the angular momentum. The conduction band is s like, with two spin states, $s_{e,z}=\pm\frac{1}{2}$. At the center of the Brillouin zone, the upper valence band is split into the HH band with the total angular momentum projection $j_{h,z}=\pm\frac{3}{2}$ and a light-hole (LH) band with $j_{h,z}=\pm\frac{1}{2}$. As the energy separation between the HH and LH bands is much larger than any Zeeman splitting, we are only concerned with the heavy-hole band and it is convenient to use an effective HH

TABLE I. Parameters of the GaAs/A_xA_{1-x}As MQW samples and the measured transverse Lande factor $g_{h,\perp}$ of heavy holes.

Sample	Lw (nm)	AlAs layers	L_B (nm)	e^- density ($\times 10^{11}$ cm^{-2})	$g_{h,\perp}$
I	4.8	Yes	15	6	0.05
II	4.2	Yes	15	6	0.03
III	4.8	No	15	3	0.03
IV	6	Yes	15	6	0.035

spin or pseudospin $\tilde{s}=\frac{1}{2}$ to describe its sublevels: as in Ref. 11 we identify $j_{h,z}=-\frac{3}{2}$ with $\tilde{s}_{h,z}=-\frac{1}{2}$ and $j_{h,z}=+\frac{3}{2}$ with $\tilde{s}_{h,z}=+\frac{1}{2}$. In terms of the pseudospin $\tilde{s}=\frac{1}{2}$, the Zeeman Hamiltonian is written as

$$\mathcal{H}_B=\mu_B(g_{h,\perp}\tilde{\mathbf{s}}_{h,\perp}\cdot\mathbf{B}_\perp+g_{h,\parallel}\tilde{s}_{h,z}B_z). \quad (1)$$

The sample, at 1.7 K, is excited by 1.2-ps pulses generated by a tunable Ti-doped sapphire laser at a repetition rate of 80 MHz. The photocreated carrier density is about 10^8 cm^{-2}. The photoluminescence (PL) signal is detected by the up-conversion technique using a $LiIO_3$ nonlinear crystal; the overall time resolution is thus limited by the laser temporal width. The excitation light is right circularly polarized using a Soleil-Babinet compensator. To measure the luminescence components of the same (I^+) and opposite (I^-) helicity as the excitation light, a rotating λ/4 plate is placed before the nonlinear crystal, which acts as an analyzer.

II. EXPERIMENTS

A. Measurement of the Zeeman splitting by the spin quantum beats technique

Because the transverse HH Zeeman splitting is in the sub-meV range, it cannot be resolved in the optical spectra. The measurement can, however, be performed in the time domain. The time-resolved experimental method used here to determine the HH transverse g factor is based on tracing the spin quantum beats (QB) and finding the beat frequency, in a similar way as previously used for electrons or excitons in MQW.[5,6] These QB have their origin in the Larmor precession of spins in an external magnetic field. The technique has been applied with success to the very accurate determination of the transverse electron $g_{e,\perp}$ factor in QW's (Ref. 5) and measurement of the temperature dependence of g_e in bulk GaAs.[16] It also allowed to study the well-size dependence of the electron g-factor anisotropy in QW's in oblique magnetic fields.[9] In addition, the observation of exciton spin QB yields values of the exciton exchange energy in type-I QW's.[6]

The limitation of the spin QB technique is that the carrier spin-relaxation time has to be longer than the beat period since the QB manifest as oscillations in the intensity of the polarized luminescence components. The application of the spin QB technique to the determination of the transverse HH g-factor value requires thus a very stable HH spin.

In a bulk III-V semiconductor, the hole spin relaxation is very fast, i.e., of the order of the momentum relaxation time.[17] In QW's however, due to the lifting of degeneracy in the center of the Brillouin zone between the HH and LH bands, different theoretical approaches have predicted much slower hole spin relaxation.[18,19] The clearest measurements have been performed in N-modulation-doped GaAs/Al_xGa_{1-x}As QW's.[15,20,21] Hole spin relaxation times τ_h up to 1 ns have been reported.[15,21] We have shown in a previous work that τ_h is a rapidly decreasing function of the HH population temperature.[15] This is why the experiments presented below are performed with an excitation energy close to the threshold fixed by the conduction electron Fermi energy and under very low-excitation intensity in order to limit the heating of the photoexcited holes.

B. Results

The inset in Fig. 1 displays the cw PL and cw photoluminescence excitation (PLE) spectra. We have checked that the shift between the PL line and the first peak in the PLE spectrum is in good agreement with the Fermi-level position determined from the measured electron density. Figure 1 shows the time evolution of I^+, I^-, and the corresponding polarization

$$P_L=\frac{I^+-I^-}{I^++I^-}$$

at the peak of the PL spectrum for an excitation energy ℏω lying near the Moss-Burstein edge (see the inset). We observe a very slow depolarization. Since the density of photoexcited holes considered here is about three orders of magnitude lower than the doping level, the PL signal corresponds to band-to-band recombination of polarized photoexcited heavy holes with unpolarized majority electrons. The spin relaxation of electrons is thus irrelevant and the measured

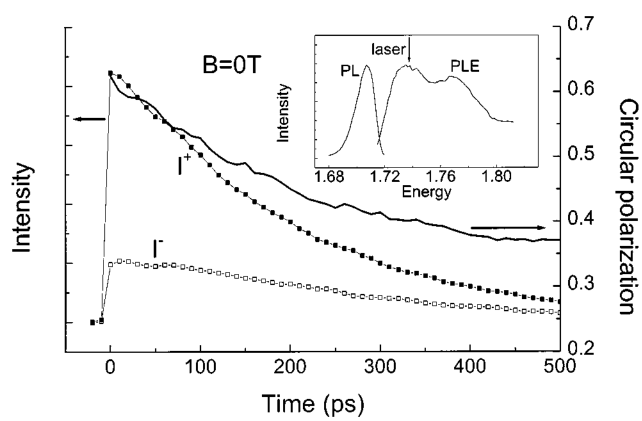

FIG. 1. Time evolution of the circular luminescence components I^+ and I^- after a σ^+-polarized excitation pulse ($B=0$ T); the full line displays the corresponding circular polarization P_L. The inset presents the cw PL and PLE spectra at $T_L=1.7$ K.

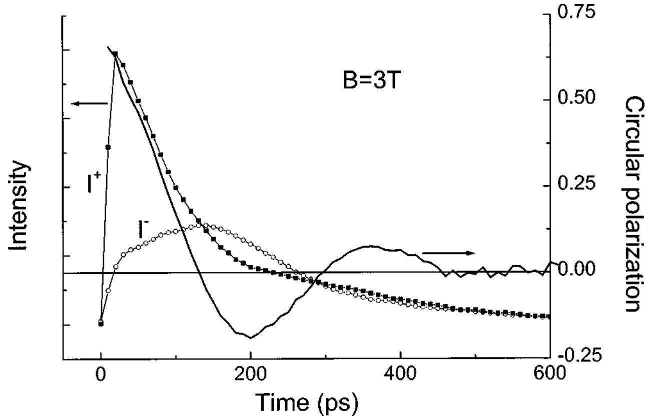

FIG. 2. Time evolution of I^+, I^-, and P_L for $B=3$ T.

decay time of the PL polarization is the spin-relaxation time τ_h of thermalized holes. We find $\tau_h \simeq 700$ ps.

A magnetic field of $B=3$ T applied perpendicularly to the growth axis strongly modifies the decay of the polarized luminescence components, as shown in Fig. 2. We observe: (i) oscillations of the luminescence polarization P_L that arise from the oscillations of the luminescence components I^+ and I^- with a relative phase shift of π.

(ii) a faster depolarization than in Fig. 1 ($B=0$ T).

The QB presented in Fig. 2 are interpreted as the result of the Larmor precession of the HH spin in the transverse magnetic field with a pulsation ω_h given by the HH spin splitting expression $\hbar\omega_h = g_{h,\perp}\mu_B B$. We emphasize that the beats do not correspond to the well-known Larmor precession of electron spin since the measured beat pulsation is much smaller than the pulsation $\omega_e = |g_{e,\perp}|\mu_B B/\hbar$ for this QW size.[5,9] The above interpretation is in agreement with the assumption that the recorded luminescence arises from the recombination of unpolarized majority electrons with polarized photoexcited heavy holes. To reduce the uncertainties on the determination of $g_{h,\perp}$, we have recorded the time evolution of the luminescence polarization P_L at different magnetic field strengths from 1 to 3 T. The results are displayed in Fig. 3. We note that the beat pulsation depends linearly on the magnetic-field strength. An accurate determination of $g_{h,\perp}$ requires a fitting procedure, which is presented below.

C. Analysis

It is important to investigate the impact of a misalignment of the magnetic-field direction with respect to the QW plane. First, we emphasize that no oscillations of the circularly polarized luminescence would be observed if $g_{h,\perp}$ were strictly equal to zero. But if $g_{h,\perp} \neq 0$, a very small angle of the magnetic field with respect to the QW plane can have an impact on the pulsation of the QB, i.e., on the measurement of $g_{h,\perp}$. We recall that the longitudinal HH Landé factor $g_{h,\parallel}$ for this well width is ≈ 2,[12] i.e., about two orders of magnitude larger than $g_{h,\perp}$ as estimated directly from the pulsation of oscillations in Fig. 2.

The experimental and theoretical study of the electron QB in a tilted magnetic field has been performed in Ref. 9. In the framework of an effective HH spin $\tilde{s}_{h,z} = \pm\frac{1}{2}$, a similar approach applies here. It can be deduced from Ref. 9 that the

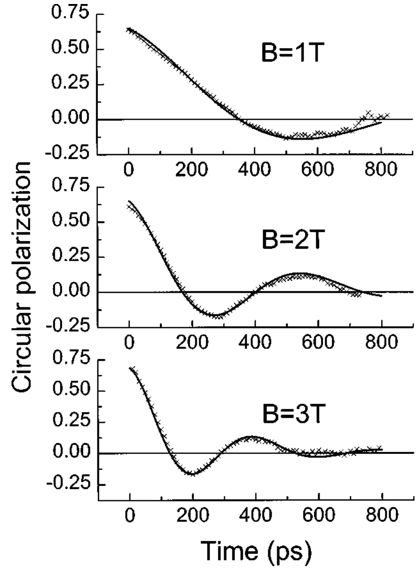

FIG. 3. Experimental time evolution of the luminescence circular polarization P_L for different magnetic-field values. The full lines correspond to the fit with the model presented in the text.

component of the average value of the effective HH spin in a tilted magnetic field $\mathbf{B} = (B_\perp, 0, B_z)$ is given by the following equation:

$$\langle \tilde{s}_{h,z} \rangle = \frac{1}{2}\left[1 - \left(\frac{\omega_\perp}{\omega}\right)^2 (1 - \cos\omega t)\right] e^{-t/T}, \tag{2}$$

where $\hbar\omega_\perp = g_{h,\perp}\mu_B B_\perp$, $\hbar\omega_\parallel = g_{h,\parallel}\mu_B B_z$ and $\omega = \sqrt{\omega_\perp^2 + \omega_\parallel^2}$ is the observed QB pulsation. For the sake of simplicity, we consider here equal transverse and longitudinal hole spin-relaxation times $T_\perp = T_\parallel \equiv T$. In our experimental conditions, where the spin polarization of the electron gas is zero, the PL circular polarization is simply given by

$$P_L = 2\langle \tilde{s}_{h,z} \rangle = \left[1 - \left(\frac{\omega_\perp}{\omega}\right)^2 (1 - \cos\omega t)\right] e^{-t/T}. \tag{3}$$

It follows then that a longitudinal magnetic-field component not only affects the QB pulsation but also leads to a reduction of the amplitude modulation, by a factor of $(\omega_\perp/\omega)^2$. This reduced amplitude modulation will allow a precise evaluation of the small longitudinal Zeeman splitting, $\hbar\omega_\parallel$, and thus a more accurate determination of the transverse component $\hbar\omega_\perp$. For the small misalignment angle α between the magnetic field and the QW plane, we can use the approximation: $B_\perp \simeq B$ and $B_z \simeq \alpha B$. The reduction factor, independent on the magnetic-field strength, is written then as

$$\left(\frac{\omega_\perp}{\omega}\right)^2 = \frac{(g_{h,\perp})^2}{(g_{h,\perp})^2 + (\alpha g_{h,\parallel})^2}. \tag{4}$$

The fit of the polarization oscillations is very sensitive to each one of the three parameters T, $(\omega_\perp/\omega)^2$, and ω, which act independently on the damping, the amplitude, and the period of the oscillations, respectively. For this reason the fit of the experimentally recorded polarization dynamics leads to a precise determination of the three parameters. We have checked that the description of the damping by two relax-

TABLE II. Fit parameters used in Fig. 3.

$B(T)$	T(ps)	$\omega(\mathrm{ps}^{-1})$	$(\omega_\perp/\omega)^2$
0	700		
1	600	0.0054	0.78
1.5	400	0.0081	0.78
2	350	0.011	0.78
2.5	260	0.0135	0.78
3	240	0.0158	0.78

ation times $T_\perp$ and $T_\parallel$ does not affect the determination of $(\omega_\perp/\omega)^2$ and ω. The fitting procedure is then the following.

The damping parameter T for each magnetic-field value is first adjusted on the polarization envelope decay. Then the modulation amplitude fixes the factor $(\omega_\perp/\omega)^2$ and the beat pulsation yields ω. Figure 3 displays very good fits of all the polarization data according to Eq. (3). These fits are performed with the data listed in Table II. Clear deteriorations of the fit quality are observed if anyone of the two parameters ω or $(\omega_\perp/\omega)^2$ are changed within $\pm 10\%$. The observed proportionality between the pulsation ω and the magnetic field, as displayed in Fig. 4, is the proof that the damping does not affect the QB pulsation. This linear dependence together with the $(\omega_\perp/\omega)^2$ fit parameter value yields the corrected HH transverse g factor. We find $|g_{h,\perp}|=0.05 \pm 0.005$.

The value 0.78 for $(\omega_\perp/\omega)^2$ corresponds to an angle α of only 0.8° if we take the HH longitudinal g factor $g_{h,\parallel}=2$ measured by Sapega *et al.* for the same well size.[12]

We have checked the extreme sensitivity of the QB amplitude modulation to a small longitudinal magnetic-field component by performing the following complementary experiment: we have recorded the time evolution of the polarization with a controlled angle α of about 5° (which is the smallest angle we can measure on our setup). We did not observe any QB, regardless of the magnetic-field strength between 0 and 3.5 T. This is because the QB amplitude modulation is too small: taking $|g_{h,\perp}|=0.05$ and $g_{h,\parallel}=2$ results in an amplitude modulation of only 7/100 [Eq. (4)]. We emphasize that the $g_{h,\perp}$ determined with the fitting procedure taking into account the small longitudinal magnetic-field component is only reduced by a factor of about 20% compared to the one crudely estimated from the QB pulsations in Fig. 3.

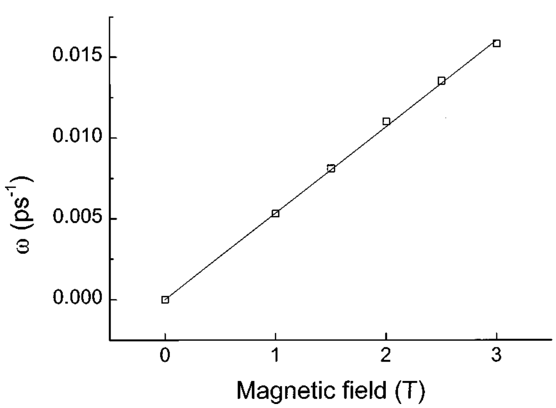

FIG. 4. Dependence of the heavy-hole spin Larmor pulsation ω on the magnetic-field strength.

In order to have a general trend, we performed a systematic study on a series of N-modulation-doped GaAs/Al_xGa_{1-x}AsQW with different well widths or/and barrier compositions. As mentioned before, the spin QB method requires a stable hole spin population. When the QW size increases, the mixing between the HH and LH states becomes stronger, which leads to much faster hole spin-relaxation times.[22] As a consequence, the study is restricted to rather thin QW that have a strong two-dimensional (2D) character. The results obtained on four samples are summarized in Table I. It is not possible to deduce a significant size-dependence law of the transverse HH g factors due to the small well-width range which could be explored. We find $0.03<|g_{h,t}|<0.05$.

III. THEORY AND DISCUSSION

In the following, we use the canonical basis $|m\rangle_e$ ($m=\pm\frac{3}{2},\pm\frac{1}{2}$) for the bulk states Γ_8 in the electron representation. The similar basis in the hole representation is obtained by applying the time inversion operator, namely, $|m\rangle_h=\mathcal{K}|-m\rangle_e$, where by definition $\mathcal{K}\hat{\psi}=\sigma_y\hat{\psi}^*$.[1] In particular,

$$|\tfrac{3}{2}\rangle_e=-\uparrow\frac{X+iY}{\sqrt{2}},\quad |-\tfrac{3}{2}\rangle_e=\downarrow\frac{X-iY}{\sqrt{2}}$$

and $|\frac{3}{2}\rangle_h=i|\frac{3}{2}\rangle_e$, $|-\frac{3}{2}\rangle_h=-i|-\frac{3}{2}\rangle_e$.

For the lowest heavy-hole subband $hh1$, the Zeeman effective Hamiltonian in a transverse magnetic field $\mathbf{B}\perp Oz$ can be obtained by calculating the off-diagonal matrix element $V(\frac{3}{2},-\frac{3}{2})=\langle hh1,\mathbf{k},\frac{3}{2}|\hat{V}|hh1,\mathbf{k},-\frac{3}{2}\rangle$, where $|hh1,\mathbf{k},\pm\frac{3}{2}\rangle$ are the heavy-hole quasi-two-dimensional states with the in-plane wave vector $\mathbf{k}$, and the perturbation $\hat{V}$ is given by

$$\hat{V}=-2q\mu_B(J_x^3B_x+J_y^3B_y)-\frac{e}{c}\{\mathbf{A}(z)\hat{\mathbf{v}}\},\quad \hat{v}=\frac{1}{\hbar}\frac{\partial}{\partial\mathbf{k}}\mathcal{H}. \tag{5}$$

Here, J_α and $\mathcal{H}$ are the angular momentum matrices and the Luttinger Hamiltonian in the Γ_8 basis, the vector-potential is taken in the form $\mathbf{A}(z)=(B_yz,-B_xz,0)$ where it depends only on the coordinate z, and $\{\mathbf{A}(z)\hat{v}\}=(\frac{1}{2})[\mathbf{A}(z)\hat{v}+\hat{v}\mathbf{A}(z)]$. Note that the sign of q in Eq. (5) is taken in accordance with Refs. 23 and 24.

For a free heavy hole in a QW at the point $k_x=k_y=0$, the transverse g factor, $g_{h,\perp}$, is defined as a coefficient in the Zeeman Hamiltonian

$$\mathcal{H}_\perp=\tfrac{1}{2}g_{h,\perp}\mu_B(\sigma_yB_y-\sigma_xB_x), \tag{6}$$

where σ_x and σ_y are the Pauli matrices corresponding to the basis $|\pm\frac{3}{2}\rangle_h$. In this basis the in-plane pseudospin components introduced in Eq. (1) are given as $\tilde{s}_{h,x}=-\sigma_x/2$, $\tilde{s}_{h,y}=\sigma_y/2$. The contribution to the $g_{h,\perp}$ comes from the first term in Eq. (5) and can be written as

$$g_{h,\perp}=-3\langle q\rangle, \tag{7}$$

where $\langle q\rangle=w_Aq_A+w_Bq_B$, the indices A and B refer to the quantum-well and barrier compositional materials, for example, to GaAs and $Al_xGa_{1-x}As$, respectively, $w_{A,B}$ is the probability to find a heavy hole in the quantum well or barrier. Note that $w_B = 1 - w_A$.

The second term in Eq. (5) leads to a k^2-dependent contribution to the Zeeman Hamiltonian. Taking into account k-induced admixture of the $|\pm 1/2\rangle_h$ Bloch functions to the heavy-hole states $|hh1,\mathbf{k},\pm 3/2\rangle$ and assuming the barriers to be infinitely high we come to the following k^2 correction to the matrix element $V(\frac{3}{2},-\frac{3}{2})$:

$$\delta V(\tfrac{3}{2},-\tfrac{3}{2}) = -\tfrac{1}{2}\mu_B G L_W^2[(\gamma_3-\gamma_2)(k_x^2+k_y^2)B_+ + (\gamma_2+\gamma_3)k_-^2 B_-], \tag{8}$$

where L_W is the QW thickness, γ_j ($j=1,2,3$) are the Luttinger positive band parameters, $k_\pm = k_x \pm ik_y$, $B_\pm = B_x \pm iB_y$,

$$G = \frac{1024}{\pi^4}\sum_{m=1}^{\infty}\frac{3n^2}{(4n^2-1)^3}\frac{\gamma_3}{4(\gamma_1+2\gamma_2)n^2-\gamma_1+2\gamma_2}. \tag{9}$$

The nth term in the sum describes the contribution to G due to k-dependent mixing between the heavy-hole $hh1$ and light-hole $lh2n$ subband states. The lifetime of photoholes is much longer than their momentum relaxation time and we can average $\delta V(3/2,-3/2)$ over the directions of $\mathbf{k}$ and obtain the k^2 correction to the transverse g factor

$$\delta g_{h,\perp} = -G(\gamma_3-\gamma_2)(k_x^2+k_y^2)L_W^2. \tag{10}$$

Note the similarity between this correction and the renormalization of the parameter q in the electron-hole Hamiltonian for a $\Gamma_6\times\Gamma_8$ exciton[26] or in the effective Hamiltonian for an acceptor-bound hole[27] in a bulk zinc-blende-lattice semiconductor. As well as the contribution proportional to $\tau-1 \equiv(\gamma_2-\gamma_3)/\gamma_3$ in Refs. 26 and 27, the additional contribution (10) arises from the mixing of heavy- and light-hole states, respectively due to the relative electron-hole motion in the bulk exciton, the hole motion around the acceptor and the in-plane motion of a free hole in the QW.

For the finite barriers, the linear-in-$\boldsymbol{k}$ light-hole envelope component, $\varphi_{3/2,1/2}$ or $\varphi_{-3/2,-1/2}$, in the state $|hh1,\mathbf{k},\pm\frac{3}{2}\rangle$ can be found by solving the second-order differential equation

$$\left[\frac{d^2}{dz^2}+\frac{2m_0}{\hbar^2}\frac{E_{hh1}-V_h(z)}{\gamma_1+2\gamma_2}\right]\varphi_{\pm 3/2,\pm 1/2}(z) = -i\frac{2\sqrt{3}\gamma_3}{\gamma_1+2\gamma_2}(k_x\pm ik_y)\frac{d}{dz}\varphi_{\pm 3/2,\pm 3/2}(z). \tag{11}$$

Here E_{hh1} and $\varphi_{\pm\frac{3}{2},\pm\frac{3}{2}}(z)$ are respectively the zero-order energy and envelopes calculated for $k=0$, $V_h(z)$ is equal to zero in the well and to the valence-band offset V_h in the barrier, and m_0 is the free-electron mass.

For the $GaAs/Al_{0.3}Ga_{0.7}As$ parameters with the valence-band offset $V_h = 143$ meV and $L_W = 48$ Å, the value of $\delta g_{h,\perp}$ increases as compared with Eq. (10) by a factor of 1.7 and one can take $G\approx 3.6\times 10^{-3}$. If photoholes are characterized by the effective temperature $T_{\rm eff}$, the factor k^2 in Eq. (10) can be changed by $2\mu_{hh}k_B T_{\rm eff}/\hbar^2$, where k_B is the Boltzmann constant and μ_{hh} is the heavy-hole in-plane effective mass. For $T_{\rm eff}=6$ K we finally obtain $\delta g_{h,\perp}\approx 6\times 10^{-3}$, which is essentially smaller than the observed value of $(3-5)10^{-2}$.

The third contribution to $g_{h,\perp}$, which has to be estimated arises in N-doped quantum wells due to an anisotropic term in the electron-hole exchange interaction (see, e.g., Ref. 26)

$$V_{\rm exch} = \left(\Delta_0\boldsymbol{\sigma}\mathbf{J}+\Delta_2\sum_\alpha \sigma_\alpha J_\alpha^3\right)a_0^3\delta(\mathbf{r}_e-\mathbf{r}_h). \tag{12}$$

Here, $\mathbf{r}_{e,h}$ is the electron or hole radius vector, $\sigma_\alpha(\alpha = x,y,z)$ are the conventional Pauli matrices, a_0 is the lattice constant (in GaAs $a_0\approx 5.6$ Å), the factor a_0^3 allows to introduce the exchange energy parameters Δ_0 and Δ_2. For the degenerate electron gas, the third contribution can be written as

$$\delta g'_{h,\perp} = \frac{3f}{4\pi}\frac{a_0}{L_W}\frac{\Delta_2 m_e}{(\hbar/a_0)^2}g_{e,\perp}, \tag{13}$$

where m_e and $g_{e,\perp}$ are the conduction-electron effective mass and transverse g factor,

$$f = L_W\int dz\,\varphi_{e1}^2(z)\varphi_{3/2,3/2}^2(z),$$

$\varphi_{e1}(z)$ is the electron envelope function in the lowest conduction subband $e1$. The estimation gives $\delta g'_{h,\perp} < 10^{-3}$, which allows to ignore this contribution. The k^2-dependent contribution exceeds $\delta g'_{h,\perp}$ but, on the other hand, is small as compared with the experimental value of $g_{h,\perp}$. Thus, we conclude that the measured transverse heavy-hole g factor is mainly determined by a value of $3\langle q\rangle$ and the modulus of $q_A\approx\langle q\rangle$ can be estimated as 10^{-2}.

The Luttinger valence-band parameter q in a bulk zinc-blende-lattice semiconductor can be estimated by using the $\mathbf{kp}$ theory in the five-level model including the two valence bands, $\Gamma_8^v+\Gamma_7^v=\Gamma_{15}^v\times\mathcal{D}_{1/2}$, the lower conduction band, $\Gamma_6^c = \Gamma_1^c\times\mathcal{D}_{1/2}$, and the higher conduction bands $\Gamma_8^c+\Gamma_7^c=\Gamma_{15}^c \times\mathcal{D}_{1/2}$. The spin-orbit splitting, Δ'_0, of the Γ_{15}^c states yields in the first order of the perturbation theory[24,25]

$$q = \frac{2}{9}\frac{E_Q\Delta'_0}{(E'_0)^2}, \tag{14}$$

where

$$E_Q = \frac{2}{m_0}Q^2,\quad Q = i\langle X_c|\hat{p}_y|Z_v\rangle, \tag{15}$$

X_c, Y_c, Z_c and X_v, Y_v, Z_v are the Bloch functions representing the Γ_{15}^c and Γ_{15}^v, respectively, and E'_0 is the $\Gamma_{15}^c - \Gamma_{15}^v$ gap.

Lawaetz[25] used the set $E'_0 = 4.81$ eV, $\Delta'_0 = 0.64\Delta_0$, $\Delta_0 = 0.34$ eV, $E_Q = 1.19E_Q$(Si), E_Q(Si) $= 14.4$ eV and obtained $q\approx 0.04$. We have generalized the above Eq. (14) taking into account higher corrections in Δ'_0 and spin-orbit mixing between the Γ_{15}^c and Γ_{15}^v bands. The result reads

$$q = \frac{2}{9}\frac{E_Q}{E'_0(E'_0+\Delta'_0)}\left[\Delta'_0 - \frac{(\Delta^-)^2}{\Delta_0}\right]. \tag{16}$$

Here, $E_0'=E(\Gamma_7^c)-E(\Gamma_8^v)$, $\Delta_0'=E(\Gamma_8^c)-E(\Gamma_7^c)$, the spin-orbit-coupling parameter Δ^- is defined as[28]

$$\Delta^-=3\langle\Gamma_8^v,\tfrac{3}{2}|\hat{V}_{so}|\Gamma_8^c,\tfrac{3}{2}\rangle, \tag{17}$$

and $\hat{V}_{so}$ is the operator of spin-orbit interaction.

Taking $\Delta_0=0.34\,\mathrm{eV}$, $E_0'=4.488\,\mathrm{eV}$, $\Delta_0'=0.171\,\mathrm{eV}$, $\Delta^-=-0.085\,\mathrm{eV}$, $Q=0.47$ (in atomic units), we obtain $q=0.019$. Changing $\Delta^-=-0.085\,\mathrm{eV}$ into $\Delta^-=-0.11\,\mathrm{eV}$ (see Table VI in Ref. 28) we come to $q=0.017$ in a reasonable agreement with the values of $|g_\perp|/3=0.01$, 0.01, 0.012, and 0.017 for the four studied samples. Note that the further variation of Δ_0', Δ^- and allowance for the spin-orbit coupling with bands of the Γ_{12} and Γ_{25} symmetry can slightly modify the value of q.

Up to now we analyzed the Zeeman effect on free holes in an ideal QW. Interface micro-roughness and alloy disorder can substantially modify free hole states near the Γ point and form localized states. Localization effects may be taken into consideration and estimated assuming the averages $\langle k_\alpha k_\beta\rangle$ for a particular hole state to be finite. According to Eqs. (6) and (8) the off-diagonal Zeeman matrix element for this particular doubly degenerate state can be expanded as

$$V(\tfrac{3}{2},-\tfrac{3}{2})=-\tfrac{1}{2}\mu_B\{g_{h,\perp}^0B_+ + \langle k^2\rangle[aB_+ + (b(\eta_{xx}-\eta_{yy}) - 2ic\,\eta_{xy})B_-]\}, \tag{18}$$

where $g_{h,\perp}^0$ is the transverse g factor in an ideal QW at $\mathbf{k}=0$, $\langle k^2\rangle=\langle k_x^2\rangle+\langle k_y^2\rangle$, $\eta_{\alpha\beta}=\langle k_\alpha k_\beta\rangle/\langle k^2\rangle$, the coefficients b and c are close to each other and exceed a. The components $\eta_{xx}-\eta_{yy}$ and η_{xy} are nonzero if the lateral localizing potential is anisotropic. The absolute values of $\langle k_\alpha k_\beta\rangle$ and the principal axes of the 2D tensor $\eta_{\alpha\beta}$ evidently vary from one localized hole state to another. This results in an inhomogeneous broadening of the spin beat frequency and can explain the faster depolarization of the PL in the presence of the transverse magnetic field.

IV. CONCLUSION

In conclusion, we have performed time-resolved optical pumping experiments of N-modulation-doped GaAs/$Al_xGa_{1-x}As$ quantum wells in a transverse magnetic field. In contrast to previous studies, the observation of spin quantum beats in the time-resolved photoluminescence is a clear evidence of a nonzero transverse heavy-hole g factor. The various contributions to $g_{h,\perp}$ has been investigated theoretically, yielding calculated values in agreement with the measured ones. Finally, we attribute the increase of the spin-depolarization rate under magnetic field to the hole localization in a disorder-induced potential.

ACKNOWLEDGMENTS

We are grateful to Max Brousseau and A.A. Kiselev for useful discussions. It is a pleasure to acknowledge R. Planel and V. T. Mieg for the growth and electrical characterization of the samples. L.E.G. and E.L.I. would like to thank the program ''Nanostructures'' (Russian Ministry of Science) and Volkswagen Foundation for financial support.

[1] E. L. Ivchenko and G. E. Pikus, *Superlattices and Other Heterostructures. Symmetry and Optical Phenomena*, Springer Series in Solid State Sciences Vol. 110 (Springer-Verlag, Heidelberg, 1995).

[2] G. R. Johnson, A. Kana-ah, B. C. Cavenett, M. S. Skolnick, and S. J. Baas, Semicond. Sci. Technol. **2**, 182 (1987); M. Dobers, K. von Klitzing, and G. Weimann, Phys. Rev. B **38**, 5453 (1988).

[3] M. J. Snelling, G. P. Flinn, A. S. Plaut, R. T. Harley, A. C. Tropper, R. Eccleston, and C. C. Philips, Phys. Rev. B **44**, 11 345 (1991).

[4] V. F. Sapega, T. Ruf, M. Cardona, K. Ploog, E. L. Ivchenko, and D. N. Mirlin, Phys. Rev. B **50**, 2510 (1994).

[5] A. P. Heberle, W. W. Rühle, and K. Ploog, Phys. Rev. Lett. **72**, 3887 (1994); R. M. Hannak, M. Oestreich, A. P. Heberle, W. W. Rühle, and K. Köhler, Solid State Commun. **93**, 313 (1995).

[6] T. Amand, X. Marie, P. Le Jeune, M. Brousseau, D. Robart, J. Barrau, and R. Planel, Phys. Rev. Lett. **78**, 1355 (1997).

[7] I. V. Mashkov, C. Gourdon, P. Lavallard, and D. Yu. Rodichev, Phys. Rev. B **55**, 13 761 (1997).

[8] E. L. Ivchenko and A. A. Kiselev, Fiz. Tekh. Poluprovodn. **26**, 1471 (1992) [Sov. Phys. Semicond. **26**, 827 (1992)].

[9] P. Le Jeune, D. Robart, X. Marie, T. Amand, M. Brousseau, J. Barrau, V. Kalevich, and D. Rodichev, Semicond. Sci. Technol. **12**, 380 (1997).

[10] G. L. Bir and G. E. Pikus, *Symmetry and Strain Induced Effects in Semiconductors* (Wiley, New York, 1974).

[11] H. W. van Kesteren, E. C. Cosman, and W. A. van de Poel, Phys. Rev. B **41**, 5283 (1990).

[12] V. F. Sapega, M. Cardona, K. Ploog, E. L. Ivchenko, and D. N. Mirlin, Phys. Rev. B **45**, 4320 (1992).

[13] M. J. Snelling, E. Blackwood, C. J. McDonagh, R. T. Harley, and C. T. Foxon, Phys. Rev. B **45**, 3922 (1992).

[14] A. A. Kiselev, and L. V. Moiseev, Phys. Solid State **38**, 866 (1996).

[15] B. Baylac, T. Amand, X. Marie, B. Dareys, M. Brousseau, G. Bacquet, and V. Thierry-Mieg, Solid State Commun. **93**, 57 (1995).

[16] M. Oestreich and W. W. Rühle, Phys. Rev. Lett. **74**, 2315 (1995).

[17] *Optical Orientation*, edited by F. Meier and B. P. Zakharchenya (North-Holland, Amsterdam, 1984).

[18] T. Uenoyama and L. J. Sham, Phys. Rev. B **42**, 7114 (1990); R. Ferreira and G. Bastard, *ibid.* **43**, 9687 (1991).

[19] N. S. Averkiev, L. E. Golub, and G. E. Pikus, Solid State Commun. **107**, 757 (1998).

[20] T. C. Damen, L. Viña, J. E. Cunningham, J. Shah, and L. J. Sham, Phys. Rev. Lett. **67**, 3432 (1991).

[21] Ph. Roussignol, R. Ferreira, C. Delalande, G. Bastard, A. Vinattieri, J. Martinez-Pastor, L. Carraresi, M. Colocci, J. F. Palmier, and B. Etienne, Surf. Sci. **305**, 263 (1994).

[22] T. Amand, B. Dareys, B. Baylac, X. Marie, J. Barrau, M. Brous-

seau, and D. J. Dunstan, Phys. Rev. B **50**, 11 624 (1994).
[23] J. M. Luttinger, Phys. Rev. **102**, 1030 (1956).
[24] J. C. Hensel and K. Suzuki, Phys. Rev. Lett. **22**, 838 (1969).
[25] P. Lawaetz, Phys. Rev. B **4**, 3460 (1971).
[26] K. Cho, S. Suga, W. Dreybrodt, and F. Willmann, Phys. Rev. B **11**, 1512 (1975).
[27] D. Bimberg, K. Cho, and W. Kottler, *Colloques Internationaux CNRS No. 242—Physique Sous Champs Magnétiques Intenses*, Grenoble, 1974 (Editions du Centre National de la Recherche Scientifique, Paris, 1975), p. 211.
[28] M. Cardona, N. E. Christensen, and G. Fasol, Phys. Rev. B **38**, 1806 (1988).