Well-width dependence of light-hole exciton dephasing in GaAs quantum wells

A. V. Gopal and A. S. Vengurlekar
Tata Institute of Fundamental Research, Mumbai 400005, India
(Received 12 January 2000; revised manuscript received 16 March 2000)

We investigate coherent emission from light-hole ground-state excitons (lh1 excitons) in 8 nm and 17.5 nm GaAs quantum wells (QWs) in transient degenerate four-wave mixing (DFWM) experiments. The lh1 excitons are resonantly excited using femtosecond laser pulses. The lh1-exciton energy in the 8 nm QW lies within the continuum of electron–heavy-hole pair states in the first subbands, but that in the 17.5 nm QW is discrete (nonresonant with the continuum). The DFWM signal decay and DFWM spectra show different behavior in the two cases. In particular, at vanishing excitation densities, the DFWM signal decay rate for lh1 excitons in the 8 nm QWs is found to be several times larger than the corresponding rate for the 17.5 nm QWs. The results suggest that the population lifetime of the resonant lh1 exciton may be very short (<0.4 ps).

I. INTRODUCTION

It is well known[1] that the degeneracy of the heavy-hole and light-hole valence band states at the valence band edge in bulk GaAs is lifted when the carriers are confined to GaAs quantum wells (QWs). The energy separation (Δ_{lh}) of ground-state light-hole (lh1) and heavy-hole (hh1) excitons in GaAs QWs is smaller than the exciton binding energy (E_B) for QW width $W>12$ nm.[2] In these QWs, both hh1 and lh1 excitons are discrete electron-hole bound states. However, as W decreases below 12 nm, Δ_{lh} exceeds E_B. The lh1 excitons then become energetically degenerate with the electron–heavy-hole subband continuum, as shown schematically in Fig. 1. In the past, several authors[3–6] have referred to the Fano interference-type effect expected when discrete exciton states are resonant with the e-hh continuum. Clear experimental evidence for the lh-exciton Fano resonance is not available yet, although resonance broadening of the lh1 excitons in narrow GaAs QWs was pointed out by Broido *et al.*[4] using photoluminescence (PL) and PL excitation (PLE) measurements on QWs with different well widths.

It should be interesting to investigate the QW width dependence of the dynamics of such lh-exciton states directly in the time domain. To our knowledge, this has not been reported so far using time-resolved measurements. In this paper, we investigate the coherent emission from lh1 excitons in GaAs QWs with well widths of 8 nm and 17.5 nm in femtosecond degenerate four-wave mixing (DFWM) experiments. The lh-hh exciton energy separation is 15.5 meV for the 8 nm QWs and 5.4 meV for the 17.5 nm QWs. These values may be compared with the corresponding binding energies of 10 meV and 7.5 meV for the hh1 excitons in the two QWs, respectively. Thus the lh1-exciton energy is resonant with the lowest-energy electron–heavy-hole ($e1$-hh1) subband continuum for the 8 nm QWs [Fig. 1(a)] but is nonresonant for the 17.5 nm QWs [Fig. 1(b)]. In our experiments, resonant excitation of the lh1 excitons in the 17.5 nm QWs represents a case of a discrete exciton coexcited with higher-energy $e1$-hh1 continuum states. This is to be compared with the 8 nm QWs case where coherent excitation of the lh1 exciton resonant with $e1$-hh1 continuum states occurs.

Our time-integrated DFWM measurements show interesting differences in the DFWM signal decay behavior and the DFWM spectra for the two QWs. We also measure the excitation intensity dependence of the DFWM signal decay rates. We find that the lh1-exciton DFWM signal decay rate

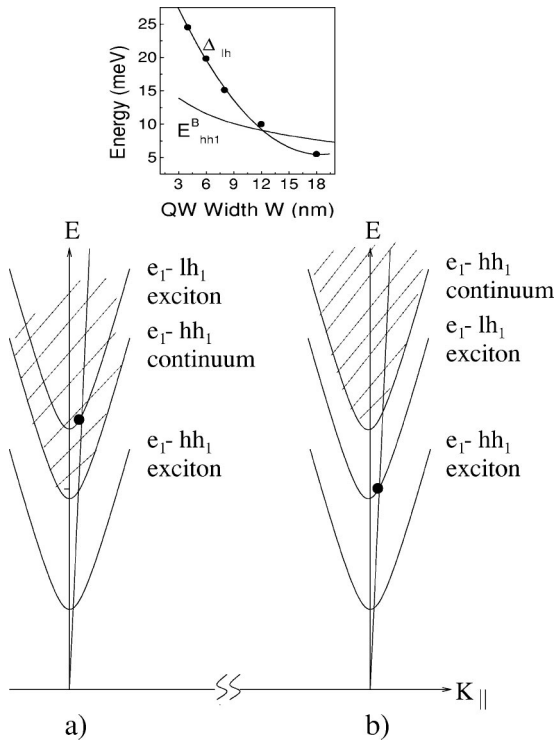

FIG. 1. The energy-center-of-mass wave vector (in the QW plane) relation for the electron-hole pair states in the first subbands of the QWs is shown schematically for the cases when the lh1 exciton is (a) and is not (b) resonant with $e1$-hh1 continuum (region marked with lines). Also shown is the photon dispersion (straight lines). Filled circles indicate excitation of lh1 excitons. The inset shows light–heavy-hole exciton energy separation (Δ_{lh}) and exciton binding energy E_B for different QW widths (W) using results from Ref. 2.

for the 8 nm QWs at zero exciton density is several times larger than the corresponding zero density rate for lh1 excitons in the 17.5 nm QWs. While a complete many-body exciton-continuum theory will be required to understand the excitation intensity dependence of coherent emission from the exciton-continuum resonances, we assume that the relaxation time approximation is adequate to describe the zero-density results. This leads to the conclusion that the observed fast decay of the DFWM signal at zero density for the resonant lh1 excitons in the 8 nm QWs is due to a very short population lifetime (<0.4 ps).

In the following, we first present the results of our CW PL, PLE, and DFWM measurements performed on the QWs. These are then discussed in the light of available understanding of DFWM coherent emission from exciton-continuum resonances in literature.[7–9]

II. EXPERIMENT

The GaAs QWs (20 in number) used in our experiments are grown using molecular beam epitaxy. The QWs are separated by 15 nm thick $Al_{0.33}Ga_{0.67}As$ barriers. The samples are maintained at 8 K in a cryostat. cw PL and PLE measurements are performed using a cw He–Ne and a tunable cw Ti-sapphire laser source. The DFWM measurements are performed using $\approx$180 fsec wide pulses from a Ti-sapphire laser. The laser pulses have a spectral width of about 9 to 10 meV. The time-integrated (TI) DFWM measurements are made in a two-beam arrangement. The two exciting beams are colinearly polarized. The DFWM signal is spectrally resolved using a 0.35 m monochromator. The signal is detected in the backward reflection geometry. This avoids any strain that may result when the substrate is etched out, as in transmission measurements.[10] Also, we may mention that unlike in some of the previous measurements,[7] no magnetic field is necessary to obtain an exciton-continuum resonance.

III. RESULTS

A. cw PL and PLE spectra

The 8 K cw PL spectrum (Fig. 2) has a full width at half maximum (FWHM) of 1.8 meV and 0.85 meV for the hh1 excitons in the 8 nm and 17.5 nm QWs, respectively. The upper panel in Fig. 2 shows the PLE spectra for the QWs, with a very small (<0.5 meV) Stokes shift. It is interesting to note that the lh1-exciton line in the PLE spectrum for the 8 nm QW is much broader (FWHM of 3.3 meV) than that for the 17.5 nm QW (FWHM of 0.75 meV). The ratio of the PLE linewidths for the lh1 excitons and the hh1 excitons is $\approx$1.8 for the 8 nm QWs and $\approx$1 for the 17.5 nm QWs. The larger PLE width for resonant lh1 excitons seen in Fig. 1 is in agreement with previous such observations.[4,11]

B. DFWM signal decay

The DFWM signal is detected at the lh1-exciton energy, following resonant excitation of the lh1 excitons in the 8 nm and 17.5 nm QWs. Figure 2 shows the various states coexcited during resonant excitation of the lh1 excitons in the two QWs. We estimate that for an average laser intensity of 0.1 mW, the density of free carriers excited is about 5

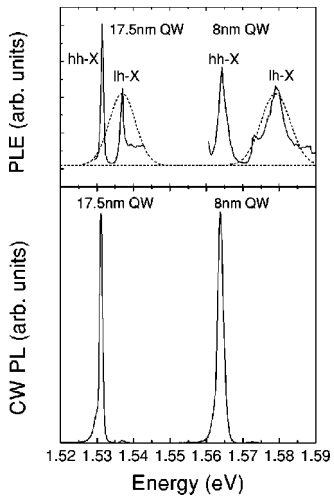

FIG. 2. The cw PL spectra at 8 K shows hh1 excitons. Also, the PLE spectra show hh1 and lh1 excitons for the two QWs. The energy spectrum and the peak energy of the laser pulse used to resonantly excite the excitons in DFWM measurements are also shown (dotted curves).

$\times 10^8$ cm^{-2} for the 8 nm QWs and 2.5×10^8 cm^{-2} for the 17.5 nm QWs for an absorption coefficient of 10^4/cm in the continuum.

Figure 3 shows the DFWM signal decay for the lh1 excitons in 8 nm QWs at different excitation intensities. In comparison, TI DFWM measurements performed on the lh1 excitons in the 17.5 nm QWs show a strikingly different behavior (Fig. 4). We first focus attention on the DFWM signal near zero delay and then describe its decay for positive delays.

1. DFWM signal near zero delay

The DFWM signal in Fig. 4 for lh1 excitons in 17.5 nm QWs shows a peaked behavior near zero delay, with a ''quasi-instantaneous'' decay. This peak is well fitted with a symmetric Gaussian, as shown in the examples of Fig. 5. We

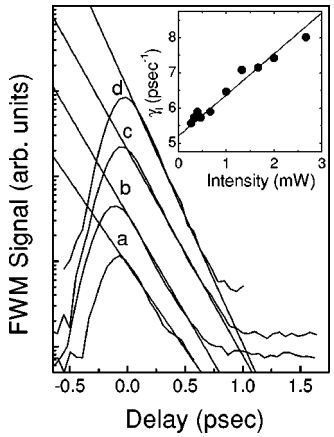

FIG. 3. The DFWM signal decay is shown for the lh1 excitons in 8 nm GaAs QWs at an average excitation intensity of 0.27 mW (a), 0.33 mW (b), 0.67 mW (c), and 1.33 mW (d), along with exponential fits (curves at different intensities are displaced vertically to avoid crowding). The inset shows the exponential decay rate plotted as a function of excitation intensity.

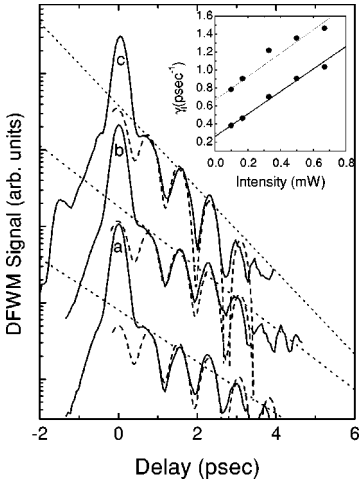

FIG. 4. The DFWM signal decay is shown for the lh1 excitons in 17.5 nm GaAs QWs at an average excitation intensity of 0.1 mW (a), 0.17 mW (b), and 0.33 mW (c). (The curves at different intensities are displaced vertically to avoid crowding.) Dashed curves show fits based on Eq. (15) of Ref. 15. Also shown are simple exponential fits (dotted lines) at large delays. The inset shows the decay rates deduced from the two fits as a function of excitation intensity.

find that the FWHM of the Gaussian fit changes very little as the excitation intensity changes by one order. The signal for lh1 excitons in the 17.5 nm QWs drops by a factor of about 20 during the initial decay.

The above features may be compared with the DFWM signal decay for lh1 excitons in the 8 nm QWs (Fig. 3). The DFWM signals for the lh1 excitons in the 8 nm QWs decay rapidly with delay by about two orders of magnitude. A major difference from the 17.5 nm QW case is that the DFWM signal decay for the 8 nm QWs is not symmetric near zero delay. This is highlighted by the examples shown in Fig. 5. Although the negative delay part of the peak at zero delay for the 8 nm QWs also fits a Gaussian, it shows a different behavior on the positive delay side. The Gaussians in Fig. 5 have identical FWHM's for both 8 nm and 17.5 nm QWs.

We find that the lh1-exciton DFWM signals for the 8 nm QWs at zero delay are smaller than those for the 17.5 nm QWs by about an order of magnitude at similar excitation intensities. We may mention that, previously, Kim *et al.*[12] found in 10 nm GaAs QWs that the DFWM signal for $e2$-hh2 excitons (which are energetically resonant with $e1$-hh1 continuum) was smaller than the hh1-exciton signal by over an order of magnitude. This was attributed to hybridization of the $n=2$ exciton states with the $n=1$ continuum.

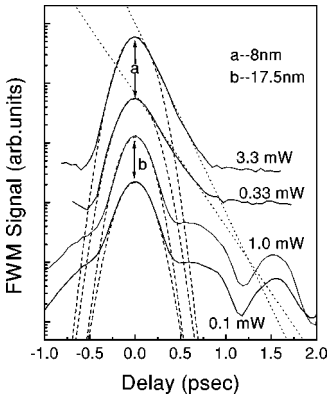

FIG. 5. Near-zero delay DFWM signal for lh1 excitons in the 8 nm QWs is shown for two intensities of 0.33 and 3.3 mW (a), and in the 17.5 nm QWs for 0.1 mW and 1 mW (b). Dashed and dotted curves are Gaussian and exponential fits, respectively.

2. DFWM decay for positive delay

The DFWM signal for lh1 excitons in the 8 nm QWs decays rapidly with increasing delay (Fig. 3). No DFWM signal could be detected beyond a delay of about 1.5 psec. In contrast, after the ''quasi-instantaneous'' decay near zero delay, the DFWM signal decay for lh1 excitons in the 17.5 nm QWs is much slower. Unlike the lh1 excitons in the 8 nm QWs, the DFWM signal decay for the 17.5 nm QWs persists for several picoseconds after the initial rapid decay.

As shown in Fig. 3, the signal decay for lh1 excitons in the 8 nm QWs at positive delays is well fitted by an exponential $[\exp(-\gamma_l t)]$. The exponential decay rates (γ_l) obtained at different densities are plotted in the inset of Fig. 3. Very fast dephasing of lh1 excitons in the 8 nm QWs even at the smallest excitation intensity used is evident in Fig. 3. The zero density decay rate is $\gamma_l = 5.2$ psec (Fig. 3, inset). The corresponding time constant (γ_l^{-1}) for exponential decay of the DFWM signal is about 0.2 psec. We find that this is nearly 12 times smaller than the zero density value of 2.3 psec obtained for hh1 excitons in the 8 nm QWs (data not shown here).

Since the laser pulse spectral width is larger than the hh-lh exciton energy separation for the 17.5 nm QWs, quantum beats are seen for the DFWM signal decay for positive delays in Fig. 4. In principle, the lh1-exciton dephasing for the 17.5 nm QWs could have been directly measured by using a diffraction grating to make the spectral width of the exciting femtosecond laser pulse narrow enough to avoid coexcitation of hh1 excitons and the hh-lh exciton quantum beats, as in the case of 8 nm QWs. However, an estimate of the lh1-exciton DFWM signal decay can also be obtained by fitting the data of Fig. 4 to an expression based on a theory of the quantum beats[13] for inhomogeneously broadened hh1 and lh1 excitons.

The lh1-exciton DFWM signal decay rate (γ_l) thus deduced from Fig. 4 is plotted in the inset of Fig. 4 at different excitation intensities. Using this, γ_l at zero density is obtained to be about 0.26/psec. Note that this is nearly 20 times smaller than the value of 5.2/psec obtained for lh1 excitons in the 8 nm QWs (Fig. 3). If simple exponential fits such as those shown in Fig. 3 are used to obtain γ_l for the 17.5 nm QWs, this results in different values of γ_l and a larger value of $\gamma_l = 0.66$/psec at zero density (Fig. 4, inset). However, this is still several times smaller than $\gamma_l = 5.2$/psec obtained for lh1 excitons in the 8 nm QW at zero density (Fig. 3, inset).

C. DFWM spectra

We have also measured the DFWM spectra at zero delay at different resonant excitation intensities for lh1 excitons in the 8 nm and 17.5 nm QWs. These are shown in Fig. 6, with the corresponding FWHM's in the Inset.

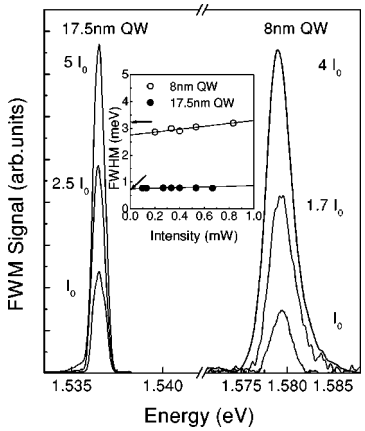

FIG. 6. DFWM spectra are shown at different intensities for lh1 excitons in the 8 nm ($I_0=0.2$ mW) and 17.5 nm QWs ($I_0=0.13$ mW). The inset shows the excitation intensity dependence of the DFWM spectral widths. Arrows show the PLE widths.

The zero-density widths obtained from an extrapolation to zero intensity are 2.8 meV and 0.8 meV for lh1 excitons in the 8 nm QWs and 17.5 nm QWs, respectively. Since the lh1-exciton lines are partly inhomogeneously broadened, the zero-density widths deduced may not be related to the transverse dephasing time in a simple way. However, it is interesting to note that the zero-density DFWM linewidth for lh1 excitons in the 8 nm QWs is much larger (nearly 3.5 times) than that for the 17.5 nm QW. (In comparison, the hh1-exciton DFWM spectral linewidth at zero density for the 8 nm QWs is less than 2 times that for the 17.5 nm QW.) These features are similar to the behavior seen in the PLE spectral widths (Fig. 2). Arrows in Fig. 6 show the PLE widths for comparison.

IV. DISCUSSION

The main purpose of the present paper has been to report the differences in the DFWM measurements on the coherent emission from lh1 excitons in the 8 nm QWs (resonant case) and the 17.5 nm QWs (nonresonant case). For the 8 nm QW, coexcitation of the resonant lh1-exciton and continuum states occurs. On the other hand, for the 17.5 nm QW case, coexcitation of the discrete lh1 exciton and higher-energy continuum states occurs. The results obtained in Sec. III may now be summarized as follows.

(i) Although the DFWM signal initially decays rapidly for lh1 excitons in both the QWs, the overall decay behavior is significantly different. For the 17.5 nm QWs, the signal decay is initially quasi-instantaneous (near-pulse-width-limited), with a pronounced, symmetric peak at zero delay. This is then followed by much slower decay for positive delays. For 8 nm QWs, the DFWM signal shows a rapid single exponential decay for positive delays.

(ii) The DFWM signal decay rates have a linear relationship with excitation intensity. The extrapolated zero-density decay rate for lh1 excitons in the 8 nm QWs is several times larger than that for the 17.5 nm QWs.

(iii) The ratios of the widths for lh1 and hh1 excitons in the PLE and DFWM spectra for the 8 nm QWs are larger than the corresponding ratios for the 17.5 nm QWs, implying additional broadening in the resonant lh1-exciton case.

Previously, several authors have studied the linear and nonlinear optical properties of certain selected exciton-continuum resonances at low densities.[5,6] For example, Oberli *et al.*[5] used PLE spectra to identify a Fano resonance line shape for the $e1$-hh3 transition in a 16.5 nm–4.8 nm double GaAs QW with a 1.4 nm AlAs barrier in between. Glutsch *et al.*[6] found that coupling of higher-order ($n>1$) magnetoexcitons to energetically degenerate continuum of lower Landau levels in bulk GaAs under magnetic field of 10 T showed Fano resonance line shapes in absorption spectra.

Coherent emission from such a magnetoexciton resonance was seen in bulk GaAs by Siegner *et al.*,[7] who showed that the decay of the TI DFWM emitted from the resonant magnetoexciton was quasi-instantaneous, mainly limited by the 100 fsec pulse width. This was attributed to destructive quantum interference of the magnetoexciton and continuum transitions when the exciting pulses did not overlap in time. This rapid decay was found to be unrelated to exciton transverse dephasing. The DFWM spectral linewidths for the resonant magnetoexcitons were small and consistent with slow dephasing seen for the real time-resolved (TR) DFWM signal. The rapid decay of the TI DFWM signal and the slower decay of the TR DFWM signal was also noted by Arlt *et al.*[9] in a 50 nm GaAs QW for coherent excitation of the Fano continuum resonance at $e3$-hh3, coexcited with several other resonant and nonresonant states, including the subband edge discrete $e1$-hh1 ''Lorentzian'' exciton, by 100 fsec laser pulses.

A pulse-width-limited decay of the TI DFWM signal was also found in 13 nm and 16 nm GaAs QWs in which a discrete Lorentzian exciton was coherently coexcited with a ''flat'' continuum at higher energies.[8] It was shown[8] that excitation-induced dephasing (EID) is the most likely reason for the quasi-instantaneous decay of the DFWM signal at zero delay in these cases.

These DFWM studies point out a discrepancy between the rapid TI DFWM decay rate and small DFWM spectral widths (which are related to the TR DFWM dephasing) when a resonant exciton is coexcited with continuum states. If the exciton is a discrete state, the TI DFWM signal shows a slow decay after the initial EID-induced rapid decay near zero delay.[8] For an exciton energetically resonant with the continuum, the slow component is not seen.[7]

In light of the above, we find that the case of resonant excitation of lh1 excitons in the 17.5 nm QW, where a discrete exciton and a ''flat'' continuum are coexcited by femtosecond pulses, is similar to that studied by Birkedal *et al.*[8] Indeed, as in Ref. 8, the DFWM data of Fig. 4 show the behavior expected when EID is effective.

In contrast, the lh1 exciton in the 8 nm QWs is not a discrete state but is Coulomb coupled with the hh1 continuum. Together, they form a new eigenstate of the QW above the band edge, giving a structured continuum state.[9] Figure 5 shows that although the DFWM signal decay in this case also decays rapidly, the overall behavior is different from that shown by the lh1 excitons in the 17.5 nm QW.

It is not clear why the DFWM decay behavior seen in Fig. 3 for the resonant lh1 excitons in the 8 nm GaAs QWs is different from that seen in Ref. 7 for the resonance of hh2 magnetoexciton with the hh1 continuum in bulk GaAs at 10 T. We may mention that our PLE measurements have not

established the lh1 excitons in the 8 nm GaAs QWs to be a clear case of Fano resonance type coupling unlike in Ref. 7.

In addition to the shape of the DFWM signal decay behavior (Fig. 5), we also need to understand differences in the excitation intensity dependence of the rate of decay of the DFWM signal with delay for the lh1 excitons in the 8 nm and the 17.5 nm QWs (displayed in the insets of Figs. 3 and 4, respectively). For this, we require a theory of many-body exciton-continuum coupling. Such a theory is not available at present. We therefore now focus attention only on the *DFWM signal decay rates at zero density*. These are obtained in Sec. III B from the intercepts at $I_x=0$ in the insets of Figs. 3 and 4.

A. Zero-density case

Since the excitation density-dependent effects are absent at zero density, we analyze the zero-density DFWM data by assuming the validity of the effective relaxation time approximation theory.[14] The exciton polarization relaxation time (T_2) can be expressed as

$$1/T_2 = 1/2T_1 + 1/T_2' . \tag{1}$$

At zero excitation density, T_2' (transverse relaxation) is governed by exciton scattering with phonons, impurities, interface roughness, alloy disorder, etc., whereas T_1 (longitudinal relaxation) accounts for dephasing due to population decay (including autoionization).

In the case of the discrete lh1 excitons in the 17.5 nm QWs at zero excitation density, T_2' at low temperature and at small exciton density is expected to be typically of the order of a few picoseconds, as for hh1 excitons in the QWs.[15] On the other hand, the exciton population decay time (T_1) for discrete excitons is several tens of picoseconds. Therefore, T_2 in Eq. (1) is determined primarily by T_2'. From Fig. 4, we have found γ_l^{-1} at zero density for the lh1 excitons in the 17.5 nm QWs to be ≈ 4 ps (if quantum beat theory[13] is used) and 1.5 ps if simple exponential fits are used (see Fig. 4, inset). These values, respectively, correspond to a dephasing time $T_2 \approx T_2'$ ($=4/\gamma_l$) of about 16 psec or 6 psec for an inhomogeneously broadened line. The associated homogeneous linewidth ($\Gamma_L = 2\hbar/T_2$) is 0.09 meV or 0.22 meV, respectively. These are smaller than the zero delay DFWM spectral width of 0.8 meV at zero density (Fig. 4), as expected for inhomogeneous broadening. Thus, there is no inconsistency between the TI DFWM decay and DFWM spectral measurements.

In comparison, we have $\gamma_l^{-1} = 0.2$ psec for lh1 excitons in the 8 nm QWs at zero density. If this is to be related to lh1-exciton dephasing, it corresponds to a zero-density homogeneous linewidth [$\Gamma_L(0)$] of $\hbar\gamma_l/2$ ($=1.7$ meV), assuming a predominantly inhomogeneously broadened lh1 exciton line, and to $\hbar\gamma_l$ ($=3.4$ meV) for a purely homogeneously broadened line. The lh1 exciton in the 8 nm QWs is most probably only partly inhomogeneously broadened. Assuming this, the ''true'' $\Gamma_L(0)$ can be determined only to be within the bounds:[14] 1.7 meV$<\Gamma_L(0)<$3.4 meV. This may be compared with the zero delay DFWM spectral width of 2.8 meV at zero density (Fig. 6) and the PLE width of 3.3 meV (Fig. 2). Once again, within the limits permitted by these bounds, there seems to be no obvious inconsistency in the DFWM spectral widths and those implied by the TI DFWM signal decay (both obtained at zero density) for a partly inhomogeneously broadened lh1 exciton in the 8 nm QWs.[16]

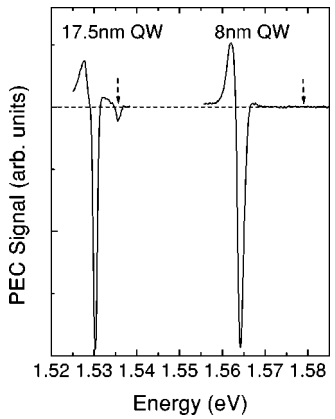

FIG. 7. PEC spectra at zero delay show signal for the discrete hh1 and lh1 excitons in the 17.5 nm QW and the hh1 exciton in the 8 nm QW, but there is no signal for the resonant lh1 exciton in the 8 nm QW. The arrows indicate lh1-exciton energies.

From the above, we deduce that T_2 for the lh1-exciton-continuum resonance in the 8 nm QWs at zero density satisfies the bound $T_2 = 2\hbar/\Gamma_L(0) < 0.8$ psec. Since T_2' at zero density is not expected to be so small, it appears from Eq. (1) that the small T_2 must be caused by a small population lifetime T_1. There is no obvious reason to expect that the *radiative and nonradiative recombination* lifetime of lh1 excitons is substantially smaller than that of hh1 excitons (usually several tens of picoseconds). We therefore have to conclude that the small T_1 ($\approx T_2/2 < 0.4$ psec) for the resonant lh1 excitons in 8 nm QWs at zero density is a result of their autoionization, presumably into $e1$-hh1 continuum states. This means that the TI DFWM signal vanishes rapidly with delay because the lh1 excitons themselves have a short lifetime, although the transverse relaxation time of the resonant lh1 excitons in the 8 nm GaAs QWs at vanishing density may not be so small.

On the other hand, if the rapid decay of the TI DFWM signal lh1 exciton in the 8 nm QWs were not related to the short population lifetime deduced above, one should see a clear signature of PL due to these resonant lh1 excitons in GaAs QWs in time-resolved up-conversion (UC) PL measurements. However, the contribution of lh1 excitons is usually not evident in picosecond UC PL spectral measurements on narrow QWs even at short delays.[17] The TR PL spectra in GaAs QWs at low densities are usually dominated by hh1 excitons.[18] Emission due to electron-hole pair recombination in the e-hh continuum, although weak, can also be seen in TR PL spectra at early times. However, the lh1-exciton TR PL is not identified in spite of the fact that the PLE spectra in QWs usually show that the oscillator strength of lh1 excitons is similar to that of hh1 excitons. A very short lifetime for the resonant lh1 excitons is therefore often assumed.[19] However, this was not demonstrated before.

That the lh1-exciton population lifetime is short in 8 nm QWs is further supported by photoexcitation-correlation (PEC) PL spectral measurements[20] performed on the two QWs. For this, two femtosecond pulses are cofocused on the

QWs, as in the DFWM case. The resultant intensity correlated nonlinear PL spectra at near-zero delay shows (Fig. 7) that while the signature of the lh1 excitons is clearly seen for the 17.5 nm QWs, there is no PEC signal for the lh1 excitons in the 8 nm QWs. This is consistent with a very short lifetime for the resonant lh1 excitons.

V. CONCLUSIONS

In summary, we resonantly excite lh1 excitons with femtosecond pulses to determine the lh1-exciton dephasing rates in 8 nm and 17.5 nm GaAs QWs. The lh1 excitons in the 8 nm QWs are energetically resonant with the $e1$-hh1 continuum, but those in the 17.5 nm QWs are discrete (nonresonant with the continuum). We find that the lh1-exciton DFWM signal for the 8 nm QWs decays relatively much faster with increasing positive delay. We analyze the DFWM signal decay rates and the DFWM spectra at vanishing excitation intensity. The results suggest that the fast decay of the DFWM signal for resonant lh1 excitons in 8 nm QWs at zero density is due to their short lifetime (<0.4 ps), possibly as a result of autoionization. The details of the mechanism by which this occurs remains to be investigated.

ACKNOWLEDGMENTS

We are grateful to J. Shah and L. N. Pfeiffer (Lucent Technologies, USA) for the QW samples. We thank F. Laruelle (L2M, France) for pointing out Ref. 4 to us. We acknowledge support from IFCPAR under Grant No. 1514-1 and from NSF under Grant No. INT-9714915.

[1] See, e.g., G. Bastard, *Wave Mechanics Applied to Semiconductors* (Halted Press, New York, 1988).

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