Exciton dynamics in a single quantum well with self-assembled islands

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We present a study on the exciton dynamics in a thin quantum well grown with self-assembled islands with thicknesses ranging from 1 to 5 ML. The exciton dynamics is investigated by combining continuous-wave and time-resolved photoluminescence measurements as a function of temperature. We analyze the exciton dynamics through a system of rate equations and we are able to obtain quantitative information on the exciton localization at the interface roughness. [S0163-1829(96)06123-1]

I. INTRODUCTION

During the last decade, semiconductor heterostructures have been grown extensively to study fundamental properties and development of devices. At the actual stage of the growth techniques for III-V compounds, when most of the basic problems related to material quality are under control, interface morphology remains one of the intricate points to improve these structures. Several works have been devoted to study the correspondence between the interfaces on heterostructures and their optical and electronic properties.\(^1\)\(^-\)\(^8\)

Efforts to improve the interface quality on single quantum wells (QW’s) have led to structures presenting multiple emission lines. These results are interpreted as evidence of the formation of plateaus with different well thicknesses. In the case of thin QW’s the role of the interface is enhanced and the plateaus may either be connected to each other or be isolated. In both cases, the thin QW is effectively replaced by islands of one material embedded on the other material, or in an alternative description, by an alloy formed by both materials.

In order to have a clearer picture of the complex physics involved in these systems, it is usual to separate the interface roughness into macroroughness and microroughness. The characteristic length for this nomenclature is the exciton diameter since we are considering the interband transition as the probe of the crystalline structure. The interface macroroughness turns out to be plateaus with the same average thickness and with lateral dimensions larger than the exciton diameter. They are responsible for the multiple line emission. The microroughness are interface fluctuations with a characteristic length much smaller than the exciton diameter. They give origin to a myriad of localized states. The optically created excitons in the extended states quickly relax to the localized states. The latter are spread in a certain range of energies responsible for broadening of the luminescence lines.

In this work we investigate the exciton dynamics in a single narrow quantum well whose electronic properties are dominated by interface roughness. We have used both continuous-wave (PL) and time-resolved (TRPL) photoluminescence techniques. The dynamics in such structures is an especially involved problem because it depends on several processes: radiative and nonradiative recombination and interisland transference, and the relative weight of each contribution depends strongly on the samples’ peculiarities. Several works have been devoted to studying the carrier dynamics in quantum well systems presenting islands.\(^9\)\(^-\)\(^14\)

However, the analyses presented in these works are usually based on the excitonic lifetime, without resolving the various processes that contribute to it. One can expect to obtain enough information to identify the different contributions by measuring both the PL and the TRPL at different temperatures. Theoretical and experimental studies show that radiative and nonradiative decays have very different temperature dependences.\(^15\)\(^-\)\(^17\) It is also expected that extended and localized excitons undergo radiative recombination with different temperature dependences.\(^16\)\(^,\)\(^17\) In this work, we explore these facts to resolve the processes involved in the photoluminescence decay. We analyze the results with a model based on a system of rate equations representing the exciton density in each QW island. Our analysis delivers an estimate of the average exciton trapping energy to the interface microroughness as well as information on the transfer process between islands.

II. EXPERIMENT

The samples were grown by the chemical beam epitaxy technique using trimethylindium (TMIn), cracked arsine (As\(_2\)), and cracked phosphine (P\(_2\)) on (100) InP substrates. The structure consists of a 2000-Å InP buffer layer, a single InAs QW, and a 200-Å InP top layer. The nominal integrated InAs QW width based on thick layer growth rate is 1.5 ML. However, typical PL spectra show as many as five well-resolved photoluminescence bands, corresponding to relatively thick islands as compared to the expected nominal value. The origin of the islands is attributed to the high strain
in this system, which endeavors a quasi-three-dimensional growth. Details on the growth have been described in a previous publication.\textsuperscript{18} The multiple line spectra provide an especially useful system to investigate the exciton dynamics within interface islands.

Time-resolved photoluminescence experiments were performed using the up-conversion technique.\textsuperscript{19} We have used two synchronously pumped mode-locked dye lasers operating at 920 and 620 nm. The 920-nm laser was used to excite the sample. The resulting luminescence was then mixed in a nonlinear crystal with the 620-nm laser. We have chosen the excitation energy below the InP barrier band gap in order to generate carriers only in the InAs well. The pulse width for both lasers was 5 ps. The cross-correlation trace between the scattered laser light from the surface of the sample and the delayed laser beam at the nonlinear crystal provides the time resolution of the system [\(\approx 60\) ps full width at half maximum (FWHM)]. The up-converted signal was analyzed by a 0.5-m spectrometer and a cooled charge-coupled device array. The sample was held on a variable-temperature continuous-flow He cryostat.

Continuous-wave photoluminescence measurements have been performed using a Ti:sapphire laser tuned to the same excitation energy of the TRPL measurements (920 nm). The luminescence signal was analyzed by a 1-m spectrometer and a cooled Ge detector. The temperature was varied from 2 to 300 K.

**III. EXPERIMENTAL RESULTS**

Figure 1 shows the PL spectrum of an InAs/InP quantum well. The PL bands are labeled \(a\) to \(e\) in creasing order of energy. The inset shows the temperature dependence of the integrated PL intensity for the four main emission bands \((a-d)\). The bands are attributed to recombination at the different QW islands. The estimated thicknesses range from approximately 1 to 5 ML.\textsuperscript{18} The excitonic states are distributed among the localized states. They correspond to an average layer thickness and therefore no integer number of monolayers can be exactly associated to each line. The existence of multiple lines, however, shows that islands with similar average layer width are present and that the description of the interface roughness by macroroughness and microroughness has physical grounds.

Some insight into the dynamics can be obtained by inspecting the qualitative behavior of the PL results. For instance, we observe a decrease of PL intensity with temperature for all emission lines, indicating that nonradiative processes dominate at high temperatures. The temperature at which the PL intensity starts to decrease depends, however, on the effective island thickness. The thicker the island, the higher the boundary temperature. It is also possible to observe a slight increase in the PL intensity at lower temperatures for the lower-energy bands. Since we expect that the radiative efficiency always decreases with temperature, the increase of PL intensity within a certain range should be associated with a corresponding increase of the excitonic population. If we consider that the photogeneration rate is roughly temperature independent, the increase in population can only be explained by excitonic migration among islands. The overall picture then indicates some transference of excitons from thinner to thicker islands.

We measured the time evolution for the main PL bands at different temperatures within a time window of approximately 600 ps. Figure 2 shows the luminescence time evolution for bands \(d, c,\) and \(b,\) as labeled in Fig. 1. As a first approximation, the experimental data can be reasonably well described by monoexponential decays. We therefore obtained the time constants presented in Fig. 3. The time constants for band \(a\) at all temperatures and for band \(b\) at temperatures higher than 150 K are not presented because the poor signal-to-noise ratio prevented us from obtaining reliable values from these measurements. The temperature dependence of the PL decays is clearly different for the various PL bands suggesting distinct dynamics for excitons at different islands. In the next section we analyze the results from each emission band separately.

**IV. DISCUSSION**

**A. Rate equations**

We consider the contribution of the following relaxation processes for the PL decay: radiative recombination, nonradiative recombination, and exciton transference between islands. Our model is based on the following hypotheses: (i) Instantaneous exciton thermalization with the lattice. Since the thermalization time is small compared to our measured PL decays,\textsuperscript{9} it is reasonable to neglect it in our analysis. (ii) Negligible exciton transference from thicker to thinner islands. We argue that due to the energy separation between two adjacent emission lines of around 70 meV, the thermal occupation process of the high-energy bands is relatively small and this process is therefore neglected in our model. (iii) Exciton photogeneration is independent of well width and temperature. The excitation energy (1.35 eV) is below the InP band gap. Electron-hole pairs are then created only in the InAs well. Therefore, the absorption should not depend significantly either on well width or on temperature. (iv) A
whole PL band can be described by a single set of parameters. An emission band comprises then the recombination from free excitons, localized excitons, and free carriers. Moreover, these contributions should depend on energy. These effects should result in an energy-dependent decay time within each emission band. Since it is not possible to resolve these processes, each decay is described by parameters representing the average of all frequency components for a given band. Figure 4 shows a scheme of the relaxation processes as assumed here and considering our four islands.

We point out that the islands are randomly distributed in the QW. Consequently, a given island shall have neighboring islands with any thickness, with equal probability. We estimated the area densities of the islands, i.e., the percentage of the total probed area that corresponds to a given island, from TRPL measurements. The integrated emission over a PL band immediately after the excitation pulse is given by the integrated carrier density generated by the pulse within the corresponding island, over the radiative recombination time. The photocarrier density generated by the pulse at each island is proportional to its area density. It is also reasonable to assume that the radiative decay time at low temperature has approximately the same value for all islands. With these considerations, we can directly estimate the area densities of the islands from the integrated emission over a PL band immediately after the excitation pulse. We obtained the following proportionality ratios: \( d : c : b : a = 10 : 7 : 3 : 1 \). We neglected the area density of island \( e \) because it is more than one order of magnitude smaller than the others. Therefore, we will neglect the contribution of island \( e \).

With the above hypothesis, the rate equation for the exciton density on island \( d \) is given by

\[
\frac{dN_d}{dt} = r_d G(t) - N_d \left( \frac{1}{\tau_{rd}} + \frac{1}{\tau_{nrd}} + \frac{1}{\tau_{td}} \right),
\]

where \( G(t) \) is the generation rate of excitons by photoexcitation and \( r_d \) is the relative area density of island \( d \). \( \tau_{rd} \) and \( \tau_{nrd} \) correspond, respectively, to radiative and nonradiative recombination times at island \( d \). Excitons generated in island \( d \) can be transferred to all possible neighbor islands with a characteristic transfer time, \( \tau_{td} \). On the other hand, no neighbor island can transfer excitons to island \( d \).

For a constant exciton generation rate, which is the case of continuous-wave measurements, the stationary solution of \( N_d \) is given by

![FIG. 2. Time evolution of the PL intensity for bands \( d, c, \) and \( b \) following short pulse excitation at different temperatures. The zero time corresponds to the situation of zero delay between the luminescence and the reference pulse in the crystal.](image1)

![FIG. 3. PL decay time constants as a function of temperature for bands \( d, c, \) and \( b \). The values were obtained assuming monoexponential decays for the PL bands.](image2)

![FIG. 4. Exciton relaxation processes in the InAs islands. Vertical arrows represent the radiative (wavy arrows) and non-radiative (straight arrows) recombination processes.](image3)
\[ N_d = r_d G \tau_d, \]  

where \( 1/\tau_d \) corresponds to the total loss rate from island \( d \), which includes radiative and nonradiative losses, i.e.,

\[ \frac{1}{\tau_d} = \frac{1}{\tau_{rd}} + \frac{1}{\tau_{nd}} + \frac{1}{\tau_d}. \]

For time-resolved measurements, the exciton generation rate \( G(t) \) can be approximated by a \( \delta \) function, since the excitation pulse (5 ps FWHM) is much shorter than the measured PL decay times (Fig. 3). The transient solution of Eq. (1) is then given by

\[ N_d(t) = N_d(0) \exp(-t/\tau_d). \]

The rate equation for island \( c \) is similar to island \( d \):

\[ \frac{dN_c}{dt} = r_c G(t) - N_c \left( \frac{1}{\tau_{rc}} + \frac{1}{\tau_{nc}} + \frac{(r_{blda} + r_{aldb})}{\tau_{nc}} \right) + \frac{N_d}{\tau_d} r_{clica}, \]

except that we now have to consider that island \( c \) can receive excitons from island \( d \), resulting in the additional last term for exciton generation, and that excitons from island \( c \) can only migrate to islands \( b \) and \( a \), resulting in a factor smaller than 1 in the term proportional to \( 1/\tau_{rc} \). The weighting factor \( r_{iijh} \) is the area density of island \( i \) relative to the integrated density of islands \( i, j, k \) \( \{r_{ijhijh} = r_i/(r_j + r_j + r_k)\} \). The stationary solution for island \( c \) is thus

\[ N_c = r_c G(1 + g_{d--c}) \tau_c, \]

where the total loss rate from island \( c \) is given by

\[ \frac{1}{\tau_c} = \frac{1}{\tau_{rc}} + \frac{1}{\tau_{nc}} + \frac{(r_{blda} + r_{aldb})}{\tau_{nc}} \]

and

\[ g_{d--c} = \frac{r_{dica}}{1 + \tau_d/\tau_{rd} + \tau_d/\tau_{nd}}. \]

The transient solution for island \( c \) is given by

\[ N_c(t) = [N_c(0) + N_d(0)A] \exp\left(-\frac{t}{\tau_c}\right) - N_d(0)A \exp\left(-\frac{t}{\tau_d}\right), \]

where \( N_c(0) \) is the exciton density created in the \( i \)th island by the exciting pulse and \( A \) is a constant given by

\[ A = \frac{r_{clica}}{\tau_d(1/\tau_d - 1/\tau_c)}. \]

The same reasoning can be applied successively to islands \( b \) and \( a \). However, the complexity of the equations, and consequently their analyses, increases progressively for the lower-energy islands, so that we will limit our quantitative analysis for islands \( d \) and \( c \).

![FIG. 5. Radiative recombination time obtained from band \( d \) considering different values for the radiative efficiency at 4 K. The small variation observed for the time constant at low temperatures indicates that localized excitons dominate at this range.](image)

**B. Island \( d \)**

The PL integrated intensity of band \( d \), \( I_{PL,d}(T) \), is proportional to \( N_d/\tau_d \). Since we considered \( G \) temperature independent, it follows from Eq. (2) that the temperature dependence of \( I_{PL,d}(T) \) can be written as

\[ I_{PL,d}(T) = I_{0d} \frac{\tau_d(T)}{\tau_d(T_0)}, \]

where \( I_{0d} \) is a constant proportional to the exciton generation rate at island \( d \) (\( I_{0d} \approx r_d G \)). We can express \( I_{0d} \) as a function of the radiative efficiency, \( \eta_d(T) = \tau_d(T)/\tau_d(T_0) \), at a given temperature. We use the liquid-helium temperature as a reference and express \( I_{0d} \) as

\[ I_{0d} = \frac{I_{PL,d}(T=4 K)}{\eta_d(T=4 K)}, \]

where \( \eta_d(T=4 K) \) remains an adjustable parameter.

From Eq. (11), we obtain

\[ \tau_d(T) = I_{0d} \frac{\tau_d(T)}{I_{PL,d}(T)}. \]

We can therefore directly determine the radiative recombination time combining two experimental results, \( \tau_d(T) \) and \( I_{PL,d}(T) \). This procedure has been used before as a method to investigate the radiative and nonradiative recombination rates in QW’s without islands.

The time constants presented in Fig. 3 for band \( d \) can be directly interpreted as \( \tau_d(T) \), since in our model the decay of band \( d \) is actually expressed as a single exponential [Eq. (4)]. Figure 5 shows the results obtained for \( \tau_d(T) \) considering different values for \( \eta_d(T=4 K) \), namely, 0.1, 0.5, and 0.9. The curves differ only by a scale factor, being shifted to larger values as the radiative efficiency decreases, as expected. The radiative recombination time for island \( d \) is nearly constant up to 50 K, increasing with temperature for higher temperatures.
It is well accepted that localized excitons present a nearly temperature independent radiative recombination time. On the other hand, we expect the radiative recombination time for free excitons to increase with temperature in a not very well established function.\textsuperscript{15–17,25–27} The temperature dependence presented in Fig. 5 indicates that the behavior of the radiative recombination time is dominated by localized excitons at low temperatures. It also suggests an increase in the proportion of free excitons with an increase in temperature, resulting in the change of slope around 50 K.

We can define a total effective nonradiative loss rate as

\[
\frac{1}{\tau_{\text{effd}}} = \frac{1}{\tau_{\text{rd}}} + \frac{1}{\tau_{\text{nr}}},
\]

which can also be obtained from our experimental results by subtracting the radiative rate \(\tau_{\text{rd}}(T)\), obtained above, from the total decay rate \(\tau_d(T)\). This effective rate comprehends the nonradiative and the transference rates. Figure 6 shows the results obtained for \(\tau_{\text{effd}}(T)\) considering different values for \(\eta_d(T=4\,\text{K})\). Note that \(\tau_{\text{effd}}\) is very sensitive to \(\eta_d(T=4\,\text{K})\) for temperatures up to 50 K, but is almost independent of it for higher temperatures.

As discussed, most of the excitons at low temperatures should be localized by fluctuations of the potential generated by interface roughness. Increase of the thermal energy increases the probability for a localized exciton to overcome this potential barrier and become mobile. As a free exciton propagates, it can find either a recombination center or an interface with another island, and eventually be transferred. Therefore, both the nonradiative and the transfer processes should depend on the fraction of free to localized excitons. We thus fitted the experimental data presented in Fig. 6 using the general expression

\[
\frac{1}{\tau_{\text{effd}}(T)} = R_1 + R_2\exp(-E_a/kT),
\]

where \(E_a\) corresponds to an activation energy of the process. We associate this activation energy to the detrapping from localized excitons to extended states.

The resulting parameters are presented in Table I for the three assumed values of \(\eta_d(T=4\,\text{K})\). Note that the obtained activation energy is nearly independent of \(\eta_d(T=4\,\text{K})\) and is about 17 meV. This value is in agreement with the observed Stokes shift for our samples, which is of the order of 20 meV.

Information on the relative contribution of the nonradiative and the transfer processes and the fraction of the thermally activated free excitons that actually undergoes transference can only be obtained by analyzing the data for the island \(c\), as we will discuss in the next subsection.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|}
\hline
\(\eta_d(T=4\,\text{K})\) & \(R_1\) (ns\(^{-1}\)) & \(R_2\) (ns\(^{-1}\)) & \(E_a\) (meV) \\
\hline
0.1 & 1.24 & 17.3 & 15.7 \\
0.5 & 0.69 & 22.4 & 16.8 \\
0.9 & 0.14 & 28.6 & 17.8 \\
\hline
\end{tabular}
\caption{Best parameters obtained by fitting Eq. (15) to the total effective nonradiative loss rate for island \(d\) (Fig. 6) assuming different values for the radiative efficiency at 4 K.}
\end{table}
The dynamics of carriers in island $c$ is coupled to that in island $d$ through the transfer process. To analyze the results for island $c$ it is therefore necessary to resolve the relative contribution of the nonradiative and the transfer processes in island $d$. This is accomplished by introducing a parameter $F$ that represents the fraction of the thermally activated free excitons in island $d$ that are transferred to the other islands. The analysis of island $c$ data is more involved than island $d$’s not only because it involves the extra parameter $F$ but because it is affected by the uncertainty of the data analysis for band $d$.

We fitted the transient solution for band $c$ [Eq. (9)] to the PL decays measured at different temperatures (Fig. 2) using two adjustable parameters, $\tau_c$ and $F$. The $F$ dependence of the transient solution comes from $\tau_{rd}$, which can be expressed as a function of $F$ and $E_a$. The fittings were performed assuming a given value for $F$ and allowing $\tau_c$ to vary. Based on a mean-square-root-error criterion, we established a range of values for $F$ within which it is possible to obtain a reasonable fit for the measured decays. This criterion sets a range of $F$ from 0 to an upper limit of the order of 30% of exciton transfer.

Once $\tau_c(T)$ is known, one can employ the same procedure used for island $d$ to obtain the radiative and nonradiative decay constants, $\tau_{rc}(T)$ and $\tau_{effc}(T)$. From Eq. (6), we obtain

$$\tau_{rc}(T) = I_{0c}[1 + g_{rad}(T)] \frac{\tau_c(T)}{I_{PL}(T)},$$

where $I_{0c} \propto r_c G$ can be expressed as a function of the radiative efficiency at the liquid-helium temperature [$\eta_c(T=4\,K)$ = $\tau_c(T=4\,K)/\tau_{rc}(T=4\,K)$] as

$$I_{0c} = \frac{I_{PL}(T=4\,K)}{\eta_c(T=4\,K)[1 + g_{rad}(T=4\,K)]},$$

where $\eta_c(T=4\,K)$ is again an adjustable parameter. The additional term related to transferance of excitons from island $d$ implies, however, a temperature dependence for the generation rate.

The total effective nonradiative loss rate is now given by

$$\frac{1}{\tau_{effc}} = \frac{1}{\tau_{rc}} \frac{1}{r_{bliba} + r_{aldb}} + \frac{1}{\tau_{nrc}}.$$  

It includes the sum of nonradiative recombination rate and exciton transfer rates from island $c$ to lower-energy ones and it can be obtained from our data by subtracting the radiative rate $\tau_{rc}(T)$ from the total decay rate $\tau_c(T)$.

Figure 7 shows the $\tau_{rc}(T)$ curves for the two limiting cases of exciton transferred fraction, $F=0\%$ and $30\%$. In both cases, the behavior of $\tau_{rc}(T)$ is very similar to that obtained for $\tau_{rd}(T)$. However, the range of temperature in which $\tau_{rc}(T)$ is roughly temperature independent is relatively large (up to $\sim 150\,K$).

The results for $\tau_{effc}$ are presented in Fig. 8. Fitting Eq. (15) to these results, we obtained an activation energy $E_a$, which is very sensitive to $F$. As one can see in Tables II and III, values range from $\sim 50\,meV$ ($F=0\%$) to $\sim 23\,meV$ ($F=30\%$).

As far as the fitting constraint is concerned, the entire range of $E_a$, from 23 to 50 meV, is allowed. However, one can argue that the reality of these values based on physical grounds. In Sec. III, we argued that with increasing the cw PL intensities of the lower-energy emission bands is experimental evidence that exciton transfer between islands does occur. Based on this result, the value $F=0\%$ is physically unlikely. We can also argue that the linewidths of both emission bands are roughly the same ($\sim 30\,meV$). This indicates that the interface roughness has similar effects in both islands, so that there is no reason to expect that the activation energy for exciton detrapping in island $c$ is much different from that found for island $d$ ($\sim 17\,meV$). This argument thus reinforces the likelihood of the higher limit for the exciton transfer parameter $F$.

### C. Island $c$

The analysis of island $c$ is more involved than island $d$’s. The reason is that island $c$ is affected by the uncertainty of the data analysis for island $d$.

#### Table III. Best parameters obtained by fitting Eq. (15) to the total effective nonradiative loss rate for island $c$ [Fig. 8(b)] assuming different values for the radiative efficiency at 4 K and $F=30\%$.

<table>
<thead>
<tr>
<th>$F_t$ (T=4 K)</th>
<th>$R_1$ (ns$^{-1}$)</th>
<th>$R_2$ (ns$^{-1}$)</th>
<th>$E_a$ (meV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>0.9</td>
<td>16</td>
<td>29</td>
</tr>
<tr>
<td>0.5</td>
<td>0.5</td>
<td>11</td>
<td>24</td>
</tr>
<tr>
<td>0.9</td>
<td>0.1</td>
<td>5.5</td>
<td>18</td>
</tr>
</tbody>
</table>

#### Table II. Best parameters obtained by fitting Eq. (15) to the total effective nonradiative loss rate for island $c$ [Fig. 8(a)] assuming different values for the radiative efficiency at 4 K and $F=0\%$.

<table>
<thead>
<tr>
<th>$F_t$ (T=4 K)</th>
<th>$R_1$ (ns$^{-1}$)</th>
<th>$R_2$ (ns$^{-1}$)</th>
<th>$E_a$ (meV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>0.8</td>
<td>28</td>
<td>47</td>
</tr>
<tr>
<td>0.5</td>
<td>0.5</td>
<td>67</td>
<td>56</td>
</tr>
<tr>
<td>0.9</td>
<td>0.1</td>
<td>77</td>
<td>55</td>
</tr>
</tbody>
</table>

### V. CONCLUSION

We studied the exciton recombination processes in a thin single InAs QW. The presence of self-assembled islands generated by interface macroroughness provided an interesting system to study the carrier dynamics. We investigated the various processes involved in these dynamics, radiative and nonradiative recombination and interisland transference, combining the results of temperature-dependent PL and TRPL.

Our results indicate that localized excitons dominate the dynamics at low temperatures. As the temperature increases, thermal activation of free excitons takes place. We estimated an activation energy of the order of 20 meV for the detrapping of excitons from the localization at interface macroroughnesses. The results indicate that exciton transference between neighboring islands does occur. Our analysis gives, however, an upper limit of the order of 30% for the efficiency of this transfer process. This result implies that most of the delocalized excitons able to propagate to an interface with another island encounter nonradiative recombination centers before being transferred.

### ACKNOWLEDGMENTS

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20 As discussed in Sec. IV, the radiative decay time is dominated by localized exciton at low temperatures. Former studies have shown that this decay time is not significantly dependent on the QW width (see Ref. 17).
24 Numerical deconvolution of the raw data was found to be unnecessary because the decay times are much larger than the time resolution of our experimental setup (60 ps).