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Effect of tunneling transfer on thermal redistribution of carriers in hybrid dot-well nanostructures


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The thermally induced redistribution of carriers between quantum well (QW) and quantum dot (QD) layers in a hybrid dot-well system composed of InAs QDs and an InGaAs QW is studied by means of photoluminescence (PL) spectroscopy. This redistribution significantly affects the QD and QW PL intensities depending both on the dot-well barrier thickness and height. For comparatively thin barriers, the interplay between tunnel and thermal carrier fluxes becomes crucial, governing the exciton dynamics in a tunnel injection dot-well structure at elevated temperatures. For a sufficiently thick spacer, it is shown that exciton localization within the QW, apparently induced by QD strain fields, has a profound influence on the transfer dynamics at low temperatures. © 2013 American Institute of Physics. [http://dx.doi.org/10.1063/1.4779686]

I. INTRODUCTION

Recently semiconductor quantum dots (QDs) have been shown to offer a wide spectrum of applications, from QD lasers and amplifiers, ultrafast optical switches, and quantum information processors, to solar cells and quantum cryptography. In order to extend the QD functionality, they should be connected with other nanoscale objects, creating hybrid nanosystems such as, for example, tunnel injection nanostructures. In a tunnel injection heterostructure, an additional quantum well (QW) is connected with a QD layer through a thin barrier and serves as a carrier reservoir/injector for the QDs. Cold carriers (electrons) from the QW tunnel into the QD lasing states without heating other carriers or phonons. This reduces carrier leakage from the active region, and hence, increases the differential gain in high-speed tunnel injection QD lasers. The carrier transfer mechanisms in hybrid QW/QD structures have been widely discussed including both resonant and non-resonant tunneling processes that depend on the barrier thickness between the QD layer and the QW, carrier density, and temperature. Recent low-temperature experiments on the InAs/GaAs-InGaAs/GaAs dot-well structures have demonstrated effective exciton tunneling with a characteristic time spanning from a few picoseconds to nanoseconds depending on the GaAs barrier thickness and the relative energy levels within each system. Furthermore, it has been shown for coupled 0D-2D nanostructures that the coupling strength has a direct influence on the QD–QW system ground-state radiative lifetime; that a refilling time, \( \tau \), from the well to the dots varies from a few microseconds for the thinnest barriers to hundreds of microseconds for the thickest barriers; and that exciton interactions in a QW-QD structure lead to the fast decay rates attributed to exciton-bound hole spin flips between optically active and inactive states. Various other hybrid structures have also been considered recently including: InAs/InGaAs/InGaAlAs/InP material systems where a QW is separated by a few nanometer thick barrier from quantum dashes; InGaAs/GaAs and Ge/Si light-emitting heterostructures with active regions consisting of a system of different size nanostructures; a double tunneling-injection QD laser structure where both electrons and holes are injected into QDs by tunneling from two separate quantum wells; a novel hybrid material/structure consisting of a GaInNAs QW and stacked InAs/InGaAs QD layers on GaAs substrate, where the strong quantum confined Stark effect within the QW effectively controls well-dot detuning when a reverse bias voltage is applied. Finally, several specific effects caused by coupling in 0D-2D structures have been recently described: ultrafast gain and refractive index dynamics of tunnel injected QD-based semiconductor optical amplifiers in the 1300 nm range, many-body effects in the optical spectra of a semiconductor QD interacting with a degenerate electron gas; and the resonant coupling of wetting layer and QW states in hybrid dot-well structures.

The general microscopic mechanisms of carrier and energy transfer in hybrid dot-well structures are, however, far from being well understood. There are several competitive mechanisms that make the real physical scenario of carrier transfer complicated, especially concerning the exciton dynamics at higher temperatures. In this case, numerous channels of non-radiative escape of carriers both from the QW and the QDs are thermally activated. As a result, a strong temperature dependence of the transfer rate is expected and observed experimentally. In fact, the interplay between carrier relaxation and transfer dictates the
primary features of the carrier dynamics in hybrid QW/QD structures.

In this paper, we study the temperature dependent nature of the carrier transfer in a series of InAs/GaAs-InGaAs/GaAs dot-well samples with variable Ga(Al)As barrier thicknesses by means of femtosecond pump-probe reflection spectroscopy, continuous wave (cw) photoluminescence (PL), and PL excitation (PLE) spectroscopy. An unusual, strongly non-monotonic temperature dependence of the carrier transfer rate between QW and QD layers is discovered, which is interpreted in terms of exciton localization at the interface, resonant and phonon-assisted tunneling, and non-radiative energy transfer mechanisms.

II. EXPERIMENT

InAs QD/InGaAs QW samples with varying GaAs barrier thickness were grown on semi-insulating GaAs (001) substrates by molecular beam epitaxy (MBE). Growth of a 0.3-μm-thick GaAs buffer layer was carried out at an increased temperature of 580 °C in order to smoothen the surface. Then the temperature was lowered to 350 °C for the growth of a 14-nm-thick In0.15Ga0.85As QW. After the QW growth and a subsequent 30 s growth interruption, a GaAs barrier was deposited, varying in thickness from 8 to 20 nm. The effective barrier height was also varied using a 1–4 nm thick AlAs layer which was incorporated in the GaAs spacer symmetrically. Then, self-assembled QDs were formed by the deposition of 2-monolayers (ML) of InAs on top of the GaAs spacer. Finally, the structures were covered with a 50 nm GaAs cap layer. Reference samples containing either the self-assembled InAs/GaAs QDs or In0.15Ga0.85As/GaAs QW were grown under the same growth conditions as the QD/QW nanostructures.

Structural analysis of the samples was carried out using transmission electron microscopy (TEM). The InAs QDs appeared as platelets with a height of ~5 nm and a base diameter of ~20 nm on average with an areal density of ~10^10 cm^-2. For these densities and below, we expect the carrier transfer between the QD and QW layers to be independent of density. For higher densities (~10^12 cm^-2), the lateral interdot coupling can significantly complicate the description of carrier transfer dynamics. The measured thickness of the In0.15Ga0.85As QW is found to be 14 ± 0.5 nm. The TEM study reveals a high degree of QD (QW) similarity between samples, which is also verified by the PL measurements.

The cw PL measurements were performed in a variable temperature, 10–300 K, closed-cycle helium cryostat with excitation from the 532 nm line from a frequency doubled neodymium doped yttrium aluminum garnet (Nd:YAG) laser. The PL signal from the sample was dispersed by a monochromator and detected by a liquid nitrogen-cooled InGaAs photodiode detector array. Time-resolved studies of the exciton dynamics in the QW were performed using a non-collinear pump-probe setup with 220 fs, 920 nm laser pulses generated in a tunable Ti:sapphire laser operating at a repetition rate of 76 MHz. A tunable Ti:sapphire laser was used also in the PLE measurements.

III. RESULTS AND DISCUSSION

The samples for investigation were engineered in such a way that the energy of the exciton ground state in the QW coincides with the energy of the third QD excited state in order to provide resonant tunnel coupling between two-dimensional (2D) excitons in the QW and zero-dimensional (0D) quantum-confined QD excitons. Coupling to the QD excited states allows carrier transfer from the QW to the QDs with subsequent inter-sublevel relaxation and emission from the QD ground exciton state. The efficient, incoherent carrier relaxation within the QDs results in spectrally well separated QW and QD emission bands. The coupling strength between QW and QD excitons is controlled by the geometrical thickness of the GaAs barrier, d_sp, or by the effective barrier thickness d_B defined as

\[ d_B = \int_0^{d_p} \left( \frac{E(z)}{1000} \right)^{1/2} dz, \]

where \( E \) is the energy of the starting level, \( V(z) \) is the barrier height in case of the insertion of an AlAs layer in the GaAs spacer.

Figure 1 presents low temperature (T = 10 K) PL spectra for our dot-well samples with different d_sp measured at a moderate excitation intensity of \( I_{exc} = 4 \times 10^{-4} I_0 \), where \( I_0 = 1000 \text{ W/cm}^2 \). All spectra are normalized with respect to the maximum of the QD emission. A single Gaussian-shaped PL band at \( E_{max} = 1.145 \text{ eV} \) with full width at half maximum (FWHM) of ~38 meV corresponds to the exciton ground state emission from the QD ensemble, whereas the PL peak at \( E^x \sim 1.345 \text{ eV} \) (FWHM 8 meV) arises due to the excitonic emission from the In0.15Ga0.85As QW in the hybrid structure. In the case of thickest spacer (d_sp = 20 nm), the QD and QW layers in the hybrid structure are essentially uncoupled and

![FIG. 1. Low temperature (T = 10 K) cw PL spectra of hybrid InAs QDs/In0.15Ga0.85As QW structures with different GaAs spacer thicknesses d_sp measured at excitation intensity of \( I_{exc} = 4 \times 10^{-4} I_0, I_0 = 1000 \text{ W/cm}^2 \). All spectra are normalized to the QD PL maximum and vertically shifted for clarity. Inset: Schematic energy level alignment in hybrid InAs QDs/In0.15Ga0.85As QW structures.]
both PL bands are strongly pronounced. For thinner spacers, the dot-well coupling increases resulting in a significant tunnel flux from the QW states into the QD states suppressing the QW PL. For smaller $d_{sp}$, the QW PL progressively quenches so that for $d_{sp} = 8$ nm it is virtually undetectable on the same scale. Since these experiments have been performed with off-resonant excitation at 2.33 eV, well above the GaAs barrier, the strong quenching of the PL may reflect a rapid tunneling of carriers from the QW into excited QD states. However, we have to consider the possibility that the efficiency of trapping of electron-hole pairs into the QW may be reduced for samples with thinner barrier thickness. For a more quantitative analysis of the tunneling, we have therefore performed time-resolved experiments with resonant QW excitation, as will be discussed below.

Temperature induced changes in the PL spectrum of the dot-well sample with $d_{sp} = 8$ nm are shown in Figure 2. All spectra are normalized to the QD PL maximum. As the temperature increases from 10 K to 250 K, the QD PL band is characterized by a significant decrease of integrated intensity and a red shift of $\sim 70$ meV. As the temperature approaches 250 K, we see the appearance of the first excited exciton state from the QDs, 66 meV higher in energy from the QD exciton ground state emission. The behavior of the QW PL band through the same temperature range is shown in the inset of Fig. 2. Here, we see an unexpected behavior. In addition to the normal red shift, 67 meV here, we find a temperature-induced modulation of the relative QW PL intensity. For temperatures near $\sim 120$ K, the QW PL is vanishingly weak. This increase in temperature is unlikely to largely affect the probability to trap optically excited electron-hole pairs into the QW, therefore the decrease in QW PL intensity likely indicates an increase in the carrier transfer rate through this temperature interval. Further increase in temperature restores the QW PL indicating either a decrease in tunneling probability or a thermally induced filling of QW states.

In order to verify the QD-QW coupling, PLE spectra were measured on the $d_{sp} = 8$ nm sample with a detection wavelength corresponding to the QD PL maximum at various temperatures. Figure 3 shows a pronounced PLE resonance, which shifts with temperature, caused by the absorption transition of the bound heavy-hole exciton in the In$_{0.15}$Ga$_{0.85}$As QW. Thus, exciting resonantly in the QW effectively transfers energy to the QD exciton ground states. The effectiveness of this transfer depends on the strength of the dot-well coupling, and the PL results suggest that this strength becomes maximum at $\sim 115$ K when we assume a temperature-independent QD PL yield.

Figure 4 shows the temperature dependences of the QW PL intensity, $I_{W}(T)$, for different $d_{sp}$ in the hybrid QD-QW structures. In the high temperature regime, $T > \sim 200$ K, all samples have the same intensity variation with temperature.

**FIG. 2.** PL spectra of an InAs QDs/In$_{0.15}$Ga$_{0.85}$As nanostructure with $d_{sp} = 8$ nm at different temperatures. All spectra are normalized to the QD PL maximum. The inset shows zooms into the region of the QW emission at different temperatures.

**FIG. 3.** PLE spectra recorded by detecting emission at the QD PL maximum in an InAs QDs/In$_{0.15}$Ga$_{0.85}$As QW nanostructure with $d_{sp} = 8$ nm at different temperatures.

**FIG. 4.** Temperature dependent QW integrated PL intensities $I_{W}(T)$ measured at $I_{ex} = 0.4$ W/cm$^2$ in hybrid InAs QDs/In$_{0.15}$Ga$_{0.85}$As QW structures with different $d_{sp}$. The $I_{W}(T)$ dependence of the reference In$_{0.15}$Ga$_{0.85}$As QW is shown with empty circles.
However, for low temperatures, the thinner spacers cause a dramatic drop in intensity of the QW emission. This surprisingly strong drop may again arise from either an increase in tunneling rate or a change in trapping efficiency when decreasing $d_{sp}$. Comparing the $I_{QD}^b(T)$ dependence for the reference QW, Fig. 4, with that for the QW in hybrid structures we find that for $d_{sp} = 20$ nm, where the two subsystems are effectively uncoupled, there is no apparent influence of the QD subsystem on the temperature dependence of the QW PL intensity.

The same conclusion can be derived from the analysis of the temperature dependence of the integrated PL intensity from the QDs, $I_{QD}^b(T)$, in the hybrid structures under investigation. Figure 5 summarizes these effects for our samples as compared to the reference QD sample. Again, we have a high temperature regime, $T > \sim 200$ K, where there is no difference in intensity between the samples. For low temperatures, however, we have a wide variation of the intensity on the spacer thickness. Thin spacers result in the highest $I_{QD}^b(T)$, while the sample with a thicker spacer, $d_{sp} = 20$ nm, show weaker QD PL, approaching the reference QD signal strength. In this case, we have a noticeable maximum in the reference QD dependence on temperature. In general, the temperature dependencies of $I_{QD}^b(T)$ (Fig. 4) and $I_{QD}^b(T)$ (Fig. 5) are well correlated.

In order to prove that the carrier transfer in our hybrid structures is controlled predominantly by the strength of the dot-well coupling, we investigated the temperature dependencies of the PL spectra for the samples with different effective barrier thickness $d_B$ defined by Eq. (1). This was achieved by introducing a symmetric AlAs layer in a GaAs barrier keeping the actual total thickness of the barrier to 8 nm. Figure 6 demonstrates the dependence of the QW PL intensities, $I_W^b(T)$, on temperature. These are found to have a striking similarity to the temperature dependence of the QW PL intensity as a function of barrier thickness alone (Fig. 4).

This supports that the carrier dynamics is greatly affected by carrier tunneling through the hybridized dot-well states.

For a better understanding of the physical mechanisms responsible for the temperature dependence of the carrier transfer in semiconductor hybrid nanostructures, we model our hybrid structures to consist of various subsystems as shown schematically in Figure 7. Let us introduce the following occupation numbers: $n_W$, for the QW, $n_D = \sum n_i$, for a QD, where the sum is taken over all excited QD states, $i$; $n_{WL}$, for the wetting layer (WL); and $n_{tr}$ for any traps in the QD layer. The rate of carrier capture, $\tau^{-1}$, from the upper
state $\alpha$ (GaAs barrier (B), wetting layer (WL), quantum well (W), traps (tr)) into the lower lying state $\beta$ (WL, W, tr, quantum dots (D)) is denoted by downward arrows, whereas the thermally activated transitions from the $\beta$ state into the upper state, $\alpha$, is distinguished by upward arrows, whereas the energy $E_{r}$. In this way, the rates of radiative recombination and non-radiative recombinations are $R_{r}$ and $R_{nr}$, respectively.

The numerical analysis of this set of equations is rather complicated with all of the relaxation channels defined in this way. Therefore, in order to use this set for the description of our PL experiments, we make the following parameterizations. Let us designate as reference samples. A number of useful relations and formulas are derived from the solution of Eqs. (2). Using the explicit form of the solution of Eqs. (5), we get the integrated PL intensities for the QW in both the hybrid and reference samples

$$I_{W}^{h} = \frac{\tau_{W}^{A}}{\tau_{W} + \tau_{run}}$$

and

$$I_{W}^{ref} = \frac{\tau_{W}^{ref}}{\tau_{W}^{ref} + \tau_{W}}.$$  

Then, a simple ratio

$$\Lambda_{W} = \frac{I_{W}^{ref} - I_{W}^{h}}{I_{W}^{ref}}$$

is derived, which is easily experimentally accessible. If the optical pumping rates in the reference and hybrid samples are identical, $A_{W}^{ref} = A_{W}^{h}$, it takes the simple form $\Lambda_{W} = \tau_{run}/(\tau_{W} + \tau_{run})$ and gives the probability that a single electron-hole pair in the QW tunnels into QD states and gives rise to QD emission. For the case of a thick barrier, $\tau_{run} \to \infty$ and $\Lambda_{W} \to \tau_{run}/\tau_{run} \to 0$. If the barrier thickness $d_{B}$ tends zero, the time of resonance tunneling $\tau_{run} \to 0$ and $\Lambda_{W} \to 1$.

Experimentally determined values for the ratio, $\Lambda_{W}$, for our hybrid samples, determined using the integrated QW PL intensities given in Fig. 4, are shown in Fig. 8. At low temperatures, this reproduces the behavior described above quite well, i.e., in the absence of tunneling or for $d_{B} = 20$ nm we find $\Lambda_{W} \to 0$, and for the case when the barrier is approaching zero or $d_{B} = 4$ nm, we find $\Lambda_{W} \to 1$. Indeed, it has been shown in Ref. 15 by means of time-resolved PL that for...
InGaAs QW in the hybrid InAs QDs/In0.15Ga0.85As QW structure the PL decay time $\tau_W$ is of the order of 550 ps at low temperature ($T = 10$ K). The tunneling time $\tau_{\text{tun}}$ at low temperatures can be estimated by using the experimentally derived equation $\tau_{\text{tun}} = \tau_0 \exp(\alpha d_{\text{sp}})$ with $\tau_0 = 0.3$ ps and $\alpha = 0.8$ nm. Thus, $\tau_{\text{tun}} = 185$ ps for $d_{\text{sp}} = 8$ nm, and $\tau_{\text{tun}} = 10$ ns for $d_{\text{sp}} = 20$ nm. Using these values, we find that $\Lambda_W$ has to be constant and should be $\approx 1$ for $d_{\text{sp}} = 8$ nm, and it reflects the temperature dependence of the $\tau_{\text{tun}}$ ratio in case of $d_{\text{sp}} = 20$ nm. For such a thick barrier, $\Lambda_W$ shows an interesting behavior. While the probability for tunneling is apparently very low at low temperatures, it can be greatly enhanced by raising the temperature above 50 K. It may be taken as a signature for a thermally activated tunneling out of the QW region. Different physical mechanisms may account for this increase in $\Lambda_W$. It could be an indication that the low temperature measurements probe the tunneling dynamics of excitons localized in local minima of the QW potential. Exciton localization in the 15 nm QW is likely to be enhanced by the spatially fluctuating strain field created by QD layer which enhances exciton localization and thus affects the tunneling dynamics. With increasing temperature, the probability to populate mobile exciton states increases and this may result in the observed increase in $\Lambda_W$. Also, at higher temperatures, the description of the carrier dynamics in terms of excitonic dynamics fails: due to exciton dissociation carriers are promoted into higher subbands of the QW system, potentially increasing the tunneling efficiency and thus $\Lambda_W$. For even higher temperatures, $T > 150$ K, $\Lambda_W$ drops again, even resulting in negative values.

Relations similar to Eq. (7) can be derived also for the QD emission in these hybrid structures. Similar to the QW, the integrated PL for the QDs in the reference and hybrid samples is given by

$$I_{\text{ref}}^h = \frac{\gamma_0}{\tau_D}$$

and

$$I_D^h = \gamma_0 \left( B + A \frac{\tau_D}{\tau_W + \tau_{\text{tun}}} \right) \frac{\tau_D}{\tau_D},$$

respectively. Similar to Eq. (7), we find the ratio for QDs to be

$$\Lambda_D = \frac{I_D^h - I_{\text{ref}}^h}{I_{\text{ref}}^h} = A B \Lambda_W.$$  

The right side equality, here is valid when assuming that the optical pumping rates in the reference and hybrid systems are identical. The temperature behavior of $\Lambda_D$ is then determined by two factors: $\Lambda_W(T)$ shown in Fig. 8 and the ratio $\gamma(T) = \frac{\gamma(T)}{\gamma(T)}$. The factor, $\gamma(T)$, defines the redistribution of the thermally activated carriers through the WL, QW, and traps. Experimentally derived values of $\Lambda_D(T)$ are shown in Figure 9. It is interesting that for thick barriers ($d_{\text{sp}} = 20$ nm), the temperature dependence reproduces that of the $\Lambda_W(T)$ dependence being magnified by a factor $\gamma(T)$ in case of $d_{\text{sp}} = 20$ nm. At low temperatures, $\Lambda_W(T)$ is much less than unity, and the QD PL intensity is thus similar to that in the reference sample. However, it increases strongly when raising the temperature above 50 K. For smaller $d_{\text{sp}}$ values, $\Lambda_W(T)$ is constant, and the $\Lambda_D(T)$ behavior is ruled by the value of $\gamma(T)$, which essentially depends on the carrier distribution between the QD and QW systems.

The similarity between $\Lambda_D(T)$ and $\Lambda_W(T)$ for the case of thick GaAs barriers points to the following physical interpretation. $\Lambda_D(T)$ and $\Lambda_W(T)$ are related to the fractions of carriers appearing in the QD system which have directly escaped from the QW due to carrier or energy transfer through barrier. For a thick (high) barrier, the probability of the tunnel transfer exponentially decreases and becomes negligibly small at $d_{\text{sp}} = 20$ nm. Nevertheless, we observe substantial carrier or energy transfer even in this extreme case when increasing the temperature above 10 K. The rate of this transfer increases greatly with temperature, reflecting the temperature-induced change of the exciton dynamics within the QW and the resulting change of carrier transfer to the QDs. This change is likely to reflect the competition between carrier capture and the thermal emission in the QW heterostructure.  

$$\Lambda_D = \frac{I_D^h - I_{\text{ref}}^h}{I_{\text{ref}}^h} = A B \Lambda_W.$$  

FIG. 8. Temperature dependence of the ratio $\Lambda_W = \frac{I_D^h - I_{\text{ref}}^h}{I_{\text{ref}}^h}$ in hybrid InAs QDs/In0.15Ga0.85As QW samples with $d_{\text{sp}} = 8, 11, 15,$ and 20 nm.

FIG. 9. Temperature dependence of the ratio $\Lambda_D = \frac{I_D^h - I_{\text{ref}}^h}{I_{\text{ref}}^h}$ in hybrid InAs QDs/In0.15Ga0.85As QW samples with $d_{\text{sp}} = 8, 11, 15,$ and 20 nm.
localized and mobile exciton emission. In fact, exciton transport in the barrier, capture, and emission via LO-phonon scattering as well as non-radiative recombination at the hetero-interfaces influence $\tau_W (T)$. As the temperature increases, the PL decay time also increases, indicating the presence of free excitons.26,31–35

In order to investigate the exciton dynamics directly in our hybrid dot-well structures we performed femtosecond pump-probe experiments. For this purpose, orthogonally polarized pump and probe pulses with a duration of 200 fs and spectral bandwidth of 10 nm were centered at 920 nm, i.e., around the QW exciton resonance, $E_X$. The time dynamics of the differential reflectivity $\Delta R(\lambda = h\nu/E_X, \Delta t)$ is probed at the QW exciton resonance and this allows us to deduce the QW exciton lifetime directly. Figure 10 shows decay times, $\tau_d$, derived from these pump-probe measurements at low temperature ($T = 10$ K) for the hybrid samples with different effective thicknesses, $d_p$, with $d_{sp} = 8$ nm. All $\tau_d$ dependences are non-monotonic, increasing with temperature at low $T$. Two distinctly different regimes are observed. At lower temperatures, up to between 60 and 100 K, an increase in sample temperature increases the exciton lifetime in the quantum well, evidently suppressing tunnel coupling to the QDs. This mechanism is effective for all chosen parameters of the inserted AlAs barrier layer. For higher temperatures, the reverse effect is observed and the exciton lifetime decreases quickly with increasing temperature. It is known that at low temperature, the thermally induced coupling between optically active localized excitons and mobile exciton states is enhanced with increasing temperature.31–35

In high-quality and sufficiently thick InGaAs QW layers, such as the ones used in the present samples, this effect is generally not particularly pronounced since the energy differences between localized and mobile exciton states are small. The introduction of a nearby strained QD layer, however, will definitely enhance the localization energies and the corresponding localization phenomena. Evidently, the data in Fig. 10 reveal that tunneling out of localized exciton states is much more efficient than for higher energy mobile exciton states. This reflects the enhanced overlap of the localized exciton and QD wavefunction.32 At higher temperatures, thermal activation induces rapid carrier redistribution for interface-localized and mobile excitons, free carriers and higher energy states in the wetting layer and barrier.31–35

The rapid high-temperature decrease of the exciton lifetime together with the concomitant decrease in QW and QD PL clearly suggests that the rapid carrier escape into the barrier becomes the dominant mechanism at high temperatures. Other nonradiative transfer mechanisms such as, e.g., Förster coupling between QW and QD excitons may also contribute to the carrier exchange processes but are apparently not effective enough to be clearly resolved in our studies.

Finally, Fig. 11 analyzes the effect of temperature on the QD spectral linewidth. It shows the FWHM of the QD PL band in our dot-well samples with different $d_{sp}$ as a function of temperature. The QD PL band is inhomogeneously broadened and its shape thus directly maps the QD size distribution. The increase of the FWHM value for a modest change of the temperature ($T < 50$ K) gives direct evidence for the thermally-induced population of a wider QD ensemble. The contribution of this enlarged ensemble leads to an increase of the integrated PL intensity in Fig. 5. The QW excitonic system reacts synchronously. In Fig. 10, the decay time increases in the same temperature range indicating the appearance of free excitons and their contribution to the excitonic dynamics.

In fact, even the low temperature, PL spectra of the reference QD layer are heavily affected by thermal activation phenomena. The increase in the integrated QD PL in the range from 10 K to 120 K seen in Fig. 5 points to a mechanism which suppresses carrier capture at low
temperatures. This suggests that the strain field around the InAs QDs creates a potential barrier at the interface that decreases the carrier capture efficiency of dots at low temperature. From the fitting of the data to an Arrhenius plot, we estimate an activation energy of $E_a = 8$ meV for our reference QD sample. At higher temperatures, the carriers gain sufficient energy to overcome this potential barrier and become efficiently trapped by QDs, thus, increasing the QD integrated PL intensity. At higher temperatures, the carriers gain sufficient energy to overcome this potential barrier and become efficiently trapped by QDs, thus, increasing the QD integrated PL intensity. It can also be seen in Fig. 4 that this reduction becomes more pronounced after about 200 K. This suggests the onset of a different escape into the QW and WL.

IV. CONCLUSION

The thermally induced energy transfer and carrier redistribution between quantum dot and quantum well layers in a hybrid dot-well system composed of InAs QDs and an InGaAs QW has been studied by means of CW PL and PLE spectroscopy and time-resolved pump-probe spectroscopy. Bandgap engineering of InAs/GaAs QDs and InGaAs QW states allows us to bring into resonance the QW excitonic state and the third excited state of the QDs, thus, inducing efficient resonant tunneling between the systems. It is found that the thermal redistribution of carriers significantly affects QD and QW PL yields depending sensitively both on the dot-well barrier thickness and height. Direct time-resolved measurements of the exciton dynamics show that the interplay of tunnel and thermal carrier fluxes becomes crucial for the exciton dynamics in a tunnel injection dot-well structures at elevated temperatures. The data reveal the competition between two different microscopic processes. At lower temperatures, the thermal activation of excitons localized in strain-induced minima of the QW potential into mobile exciton states reduced the tunneling probability into excited QD states. At higher temperatures, the thermally induced redistribution among localized and mobile QW and QD exciton states, free carriers and states in the wetting layer and barrier significantly affects the carrier dynamics and PL yields in hybrid dot-well structures. Finally, thermal energy allows for the release of carriers trapped by the strain-induced localized states in the QD wetting layer at lower temperatures thus enhancing the QD PL yield at higher temperatures.

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