Time-resolved photoluminescence spectroscopy of resonant tunneling in a GaAs-AlAs triple-barrier structure

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(Received 1 June 1994)

Transport of electrons and holes through an asymmetric GaAs-AlAs triple-barrier structure is investigated using time-resolved photoluminescence spectroscopy. Carriers are excited in the GaAs contact regions of the diode only, by choosing the excitation energy below the absorption edge of the quantum-well states. The intensity, half width, and temporal development of the photoluminescence signal of the quantum-well ground-state transitions are investigated by sweeping the applied bias through the tunneling resonances. Resonant tunneling of photocreated electrons is found to occur on a time scale shorter than about 50 ps, whereas resonant transfer of holes takes about 200 ps. Nonresonant tunneling times of both types of carriers, however, are on the order of 1 ns.

I. INTRODUCTION

Transport through resonant tunneling structures in the GaAs-Al_xi Ga_{1-x}As material system has become a field of great interest during the last few years. This system allows the investigation of fundamental physical principles of resonant tunneling, but also shows a potential for a variety of applications.¹ So far, most work has been performed on resonant tunneling diodes (RTD) made out of double-barrier structures (DBS),²⁻⁵ or on coupled quantum-well (QW) systems such as, e.g., the asymmetric double quantum well (ADQW).⁶⁻⁸ In the first case tunneling occurs from the unconfined emitter states into the quantum-well states and subsequently out of the structure, whereas in the latter one only the resonances of the bound states of the QW's are important. A detailed qualitative analysis of the transient- and cw-luminescence behavior of a double-barrier structure has been presented in Ref. 9. Recently, a similar type of sample, the triple-barrier structure (TBS), which is a combination of a DBS and an ADQW,¹⁰ has been shown to have a great potential for optoelectronic applications. It has been demonstrated that in this device an optical emission ratio between the resonant and the nonresonant case of 10⁴:1 is possible.¹¹ The QW states are occupied via tunneling from the unconfined emitter states, but also via a resonant charge transfer between the discrete states of the quantum wells, since the structure consists of two quantum wells separated from each other as well as from the contact layers by thin barriers. Detailed knowledge

of the transport properties of both carriers, i.e., electrons as well as holes, within the TBS is necessary for further applications of such structures. Especially the transport times into and the escape times out of the QW states are of major interest, regarding the performance of fast devices.

We investigate a TBS using time-resolved photoluminescence spectroscopy (PL) in the picosecond time regime to gain further insight into these processes. The samples are excited with a short laser pulse at an energy slightly above the band gap of the GaAs contact layers, but below the absorption edge of the two quantum wells in order to prevent creation of photoexcited carriers inside the QW's. Keeping the excitation density below 10¹¹ cm⁻², the density of electrons and holes excited outside the QW structure does not disturb the externally applied electric field across the system, leaving the *I-V* characteristics unchanged. In this sense, the excitation density is moderate and we are able to measure hole as well as electron transport times through the TBS. The photocreated carriers enter the QW states only via tunneling from the contact layers. The discrete states of the QW's are aligned to resonance by means of an externally applied electric field. The field strength can be calculated assuming a linear voltage drop across the intrinsic region of the TBS. In the experiment we simultaneously monitor the temporal development of the PL signal of the fundamental transitions of the two QW's as a function of the applied electric field. The rise time as well as the intensity of the PL strongly depends on the resonant coupling of the QW's, as the PL signal arises only from

carriers tunneling into the QW system from the emitter states of the diode. Therefore, these experiments are interpreted as an optically detected transport experiment with picosecond time resolution.

The paper is organized in the following way. In Sec. II the sample and the experimental technique are described. Section III contains the electrical characterization followed by Sec. IV, in which the photoluminescence spectra in forward and reverse bias and the analysis of the time-resolved PL spectra are presented. The paper closes with a summary.

II. EXPERIMENT

The investigated sample consists of an asymmetric triple-barrier structure grown by molecular-beam epitaxy (MBE) on a (100) n^+ -GaAs substrate with two GaAs quantum wells of different widths. The layer sequence starts on the substrate side with a 413 nm GaAs:Si spacer layer ($n = 2 \times 10^{18} \text{ cm}^{-3}$), followed by a 50 nm GaAs:Si contact ($n = 2 \times 10^{16} \text{ cm}^{-3}$), the undoped triple-barrier system, and another 50 nm GaAs:Si ($n = 2 \times 10^{16} \text{ cm}^{-3}$) layer, and ends with a 300 nm GaAs:Si ($n = 2 \times 10^{18} \text{ cm}^{-3}$) top contact. The triple-barrier structure contains three 4 nm AlAs barriers and two GaAs quantum-wells of 8 nm and 5 nm widths. The structure is processed into circular mesas of 60 μm diameter using optical lithography and wet chemical etching. The back and front sides of the sample are contacted in a metallization step leaving a 40 μm diameter hole in the top contact to provide optical access to the TBS.

A schematic band diagram of the structure with the relevant QW subbands indicated is shown in Fig. 1. The resonance voltages of the conduction and valence band

states of the two quantum wells are calculated using an envelope function approximation and assuming a linear electric field across the structure. The resulting values are listed in Table I. The sample is mounted into a chip carrier which is placed on the cold finger of a continuous helium flow cryostat in order to maintain a temperature of about 15 K during the measurements. The sample is excited with 2 ps laser pulses of a tunable Ti:sapphire laser, which is pumped by a cw Ar^+ -ion laser. The excitation energy of the Ti:sapphire-laser was chosen to be $E_{\text{ex}} = 1.53 \text{ eV}$ in order to excite carriers only in the quasi-three-dimensional contact regions. The photoluminescence signal is dispersed in a 0.32 m monochromator and the resulting spectrum is focused on the entrance slit of a Hamamatsu streak camera, with a two-dimensional readout. The PL spectra are taken in the time range of 1.7 ns with an overall time resolution of about 7 ps. The applied voltage is varied from $V_{\text{ap}} = -1.5$ to 1.5 V. All spectra are taken with a moderate excitation density leaving the I - V characteristics unchanged under illumination. The PL signals arising from the recombination of carriers between the lowest conduction subband ($C1_n$ and $C1_w$, n and w denoting the narrow and wide well, respectively) and the lowest valence subband (heavy hole $H1_n$ and $H1_w$ respectively, cf. Fig. 1) of both QW's are detected simultaneously while the applied electric field is changed by sweeping through the different conduction band as well as the valence band resonances.

III. ELECTRICAL CHARACTERIZATION

The I - V characteristic recorded at 15 K without illumination between -2 and 2 V is plotted in Fig. 2. We can clearly identify three resonances in this bias region. Without illumination only electrons are injected into the quantum wells from the contact regions and the I - V curve is dominated by the conduction band resonances of the quantum wells. We approximate the electric field according to $F_{\text{ap}} = V_{\text{tot}}/d$, where $d = 3d_b + d_w + d_n$ is the width of the effective intrinsic region (d_b, d_w, d_n denoting the barrier, the wide well, and the narrow well, respectively). The total voltage across the intrinsic re-

FIG. 1. Schematic diagram of the TBS under (a) forward bias and (b) reverse bias. The relevant QW states and the respective optical transitions are also shown.

TABLE I. Calculated resonance voltages for the relevant conduction and valence band resonances in forward and reverse bias direction.

Forward		Reverse	
Resonance	$V_{\text{ap}} \text{ (V)}$	Resonance	$V_{\text{ap}} \text{ (V)}$
$H1_n \rightarrow L1_w$	0.04	$E_{F,\text{emitt}} \rightarrow H1_w$	-0.07
$E_{F,\text{emitt}} \rightarrow C1_w$	0.105	$H1_w \rightarrow H1_n$	-0.13
$H1_n \rightarrow H2_w$	0.11	$H1_w \rightarrow L1_n$	-0.26
$C1_w \rightarrow C1_n$	0.25	$E_{F,\text{emitt}} \rightarrow C1_n$	-0.275
$H1_n \rightarrow H3_w$	0.37	$E_{F,\text{emitt}} \rightarrow H2_w$	-0.28
$H1_n \rightarrow L2_w$	0.56	$H1_w \rightarrow H2_n$	-0.93
$E_{F,\text{emitt}} \rightarrow C2_w$	1.07	$C1_n \rightarrow C2_w$	-0.98
$H1_n \rightarrow H4_w$	0.76	$H1_w \rightarrow L2_n$	-1.34
$H1_n \rightarrow H5_w$	1.25	$H1_w \rightarrow H3_n$	-2.02
$H1_n \rightarrow L3_w$	1.42	$H1_w \rightarrow H4_n$	-3.1
$C2_w \rightarrow C2_n$	1.7	$C1_n \rightarrow C3_w$	-3.61

FIG. 2. I - V characteristics at 5.6 K. The traces have been measured without illumination. The current of the first resonance in forward bias is enlarged for clarity by a factor of 50.

gion, V_{tot} , is calculated from the applied voltage V_{ap} using $V_{\text{tot}} = V_{\text{ap}} - V_{\text{dp}} - V_{\text{acc}}$ with V_{dp} and V_{acc} denoting the voltage drop across the depletion and accumulation region, respectively.

The first peak in forward bias (at about $V_{\text{ap}} = 0.25$ V) can be assigned to the $C1_w \rightarrow C1_n$ resonance (cf. Table I), which can only be seen in this bias direction, since the ground state in the conduction band of the narrow well is higher in energy at zero bias than the corresponding one of the wide well (cf. Fig. 1). Therefore, positive bias refers to electrons entering the wide well first, followed by tunneling through the central barrier into the narrow well and finally out of the structure into the contact layer as sketched in Fig. 1(a). Another peak in the I - V characteristic is found at around $V_{\text{ap}} = 1.6$ V, which originates from the $C2_w \rightarrow C2_n$ resonance (cf. Table I). In this bias region the lowest conduction band state of the wide QW has already dropped below the band edge of the accumulation layer and no resonant tunneling via the ground state of QW_w is possible. No additional resonances are observed in forward bias with further increasing bias, since the narrow well contains only two bound states in the conduction band.

In reverse bias, electrons enter the narrow well first and a peak at around $V_{\text{ap}} = -1$ V is found, originating from the alignment of the first conduction band subband of the narrow well, $C1_n$, with the second conduction band subband of the wide well, $C2_w$. The resonance $C1_n \rightarrow C1_w$ could not be observed in this bias direction, since at zero field $C1_n$ is higher in energy than $C1_w$. This difference increases further with increasing field under reverse bias. The resonance $C1_n \rightarrow C3_w$ (cf. Table I) could not be investigated, since the current becomes too large in this field range.

IV. PHOTOLUMINESCENCE SPECTRA

The PL spectra of the two quantum wells and their variation with external bias are shown in Figs. 3(a) and 3(b). Figure 3(a) displays the low bias region on an en-

larged voltage scale, while Fig. 3(b) covers a larger voltage range of the I - V characteristics in Fig. 2. The PL signal of QW_w is observed at $E_w = 1.577$ eV, whereas the 5 nm QW emits at $E_n = 1.652$ eV under flatband conditions. The traces are taken at a time delay of 500 ps to remove the influence of the cooling process of the carriers. A strong variation of the intensity as well as the widths of the respective PL lines is observed. A small red shift of both transitions arising from an increasing Stark effect is also present. This shift is more pronounced for the wide well than for the narrow well, as follows from the theory of the quantum-confined Stark effect. In forward bias, the QW_n PL shows a sharp peak in intensity at low fields followed by a decrease. At high values of V_{ap} the spectrally integrated intensity increases. The wide well luminescence exhibits a sharp onset at low fields and a broad peak of the PL intensity at $V_{\text{ap}} = 0.7$ V. In reverse bias, an onset of the PL signal is observed for both wells at low bias. The QW_n transition shows only one small peak of the PL intensity around -0.4 V. The signal remains small with increasing field, whereas the QW_w PL is very intense with a main peak of the PL intensity around -0.8 V. At high fields the QW_w PL is substantially decreased as can be seen from the spectra.

FIG. 3. Photoluminescence spectra of the TBS at a time delay of 500 ps as a function of the applied bias for small (a) and large (b) voltages.

A. Intensities

1. Forward bias

The respective peak intensities of the two PL lines originating from the two quantum wells are plotted in Fig. 4. In the region without applied field, $V_{ap} = 0$ V, no PL signal from the QW's is observed, demonstrating the absence of directly photoexcited carriers in the wells. A sharp onset of the photoluminescence occurs with increasing bias, first for the wide quantum well at around $V_{ap} = 0.1$ V. This increase arises at a value of the electric field where the $C1_w$ state and the Fermi edge of the emitter layer are resonantly aligned (cf. Table I). Thus a large number of electrons enter QW_w , recombining there with holes which are tunneling through the narrow well into $H1_w$. At slightly higher fields the conduction band ground states of the two quantum wells become resonantly aligned (cf. Table I), and the PL signal of QW_n appears and increases rapidly, whereas the wide well PL is slightly decreased. This decrease is due to two facts: first, the number of electrons is slightly reduced because of the fast escape of carriers out of QW_w into QW_n . Second, the number of holes tunneling into the valence band states of QW_w is smaller because an intense recombination is taking place in QW_n leaving only a small amount of holes to be supplied through the central barrier.

Increasing the applied electric field, the QW_n PL signal is decreased in intensity since the $C1_w \rightarrow C1_n$ states are tuned out of resonance. Therefore, the amount of electrons entering the narrow QW becomes smaller and the recombination of electrons and holes in this quantum well is reduced. At higher fields as the resonance $C2_w \rightarrow C2_n$ is reached, the PL intensity of the QW_n rises again in agreement with the discussion in Sec. III.

In contrast to this behavior the QW_w PL signal shows at low voltages ($V_{ap} = 0.33$ V) a small peak when the $H1_n$ and $H3_w$ states are resonantly aligned. This peak, however, is not very pronounced, since the $C1_w$ - $C1_n$ conduction band resonance also occurs in this bias region and most of the holes recombine in QW_n . With increasing bias an intense PL signal of the wide well is observed at around $V_{ap} = 0.8$ V. This is attributed to an alignment

of the $H1_n$ - $H4_w$ states, which leads to an efficient supply of holes into QW_w . No resonant electron escape of QW_w is possible in this voltage range. At high voltages (above 1 V) the wide well exhibits only a small PL signal for two reasons; no resonant hole transport is possible and the electrons begin to escape resonantly from QW_w , since the $C2_w \rightarrow C2_n$ conduction band resonance is approached.

We conclude that in the forward bias direction the PL signal of the narrow quantum well is governed by the dynamics of electron transport through the TBS, whereas the wide well PL reflects mainly the tunneling of holes.

2. Reverse bias

In the reverse bias direction, the situation is not simply inverted, although in this case the electrons enter the narrow well first and the holes the wide well. An onset of the narrow well PL signal is observed when the Fermi edge of the emitter is in resonance with the $C1_n$ state (cf. Table I), which can be seen from Fig. 4. This resonance condition is reached at a larger applied voltage than in the forward bias direction, since the quantization energy of the conduction band states of the narrow well is larger than that of the wide well. Increasing the applied bias, the QW_w PL signal also rises and shows an intense and broad PL line with a maximum intensity around -0.8 V (cf. Fig. 4). At this electric field the $C1_n$ state is resonantly coupled to the $C2_w$ state and electrons tunnel efficiently into QW_w . At even larger values of the electric field, the PL signal of the wide well decreases drastically, which is probably due to the fact that the $C1_n$ state falls below the Fermi edge of the emitter in this field range.

Except for a small peak at low fields, the photoluminescence of the narrow well shows no additional resonances and a low intensity throughout the whole bias range. According to the above given explanations, one would expect the narrow well signal to reflect the resonances of the valence band states of the two wells. Obviously this is not the case, since the signal of the wide well is very intense, and therefore recombination takes place almost exclusively in QW_w . As a consequence the number of holes is too small to give clear evidence of resonant hole tunneling in the reverse bias PL spectra of the narrow well QW_n .

We conclude that in reverse bias an intense PL signal of the QW_w due to electron accumulation in $C1_w$ is observed. Only a small PL signal of the QW_n exists, since most of the photoexcited holes recombine in the wide well.

B. Line width

This conclusion is confirmed by analyzing the full width at half maximum (FWHM) of the two PL lines in the different bias directions. The values of the FWHM as measured from the spectra are plotted versus the applied voltage for the two quantum wells in Fig. 5. Because of the moderate excitation density that was used in these experiments, the number of photocreated carriers is small compared to the electrically injected charge. Therefore

FIG. 4. Photoluminescence peak intensity of both quantum-well lines vs applied voltage at a time delay of 500 ps.

FIG. 5. Full width at half maximum (FWHM) of the two photoluminescence lines vs applied voltage at a time delay of 500 ps.

the minority carriers, i.e., the holes, act as a probe for the electron occupation of the conduction band states of the TBS. Taking this into account and assuming a fast relaxation of holes after tunneling through the barriers, the width of the PL lines is a direct measure for the number of free carriers in the conduction band states. Therefore the change of the linewidth directly reflects the carrier accumulation in the QW's. A detailed explanation of the underlying methods is given in Refs. 12 and 13.

In forward bias the FWHM of the narrow well shows a small maximum at the $C1_w \rightarrow C1_n$ resonance and an increase from about 4 meV out of resonance to 8 meV as the $C2_w \rightarrow C2_n$ resonance is approached, indicating the charging of QW_n . The FWHM of the QW_w PL, however, increases for applied voltages, where no resonant escape out of the conduction band states of the wide well is possible and the charges reside in QW_w . Beyond the resonances the wells are depleted, resulting in a decrease of the PL linewidth (cf. Fig. 5). In reverse bias the width of the luminescence line reflects the conduction band resonances of the two wells, since the PL of the wide well is determined mainly by resonant tunneling of electrons. An increase from 4 meV out of resonance to 15 meV at the $C1_n \rightarrow C2_w$ resonance is observed indicating a charge accumulation in the conduction band ground state of the wide well. The same is true for the narrow well PL; however, the signal remains small, due to the absence of a reasonable amount of holes. Increasing the bias in the reverse direction leads to a depletion of the conduction band states of the quantum wells and therefore to a decrease of the FWHM of the PL lines. In both bias directions the increase of the FWHM of the quantum-well PL lines at the conduction band resonances reflects the charging of the electronic subbands of the wells. This effect is more pronounced for the wide well than for the narrow well. The field dependence of the FWHM of the respective interband transitions supports the interpretation of the PL intensity variation.

V. TEMPORAL DEVELOPMENT OF THE PHOTOLUMINESCENCE

We measured the rise time of the PL signals, to achieve a more detailed understanding of the dynamics of the

tunneling process. The luminescence signal rises slowly and lasts very long, since the carriers occupy the wells only via tunneling from the contacts. The change of the PL rise time is related to an effective tunneling time τ_{eff} , which incorporates the tunneling of photoexcited carriers into and subsequently out of the quantum wells (τ_{in} and τ_{out} , respectively) as well as the relaxation time τ_{rel} of these carriers when higher subbands are involved in the tunneling process. The relaxation time τ_{rel} , however, can be neglected since it is known that for subband spacings larger than the optical phonon energy in GaAs this relaxation occurs on a time scale below 1 ps.¹⁴⁻¹⁶ Furthermore, the lifetimes of the ground-state excitons in the two wells τ_w and τ_n , respectively, have to be taken into account. We determined τ_w and τ_n experimentally choosing an excitation energy above the ground state transitions of the two quantum wells and applying no bias. The $C1_w-H1_w$ exciton has a lifetime $\tau_w = 38$ ps, while for the $C1_n-H1_n$ exciton we determine $\tau_n = 182$ ps. Both time constants do not vary significantly with applied bias. In forward bias, according to the conclusions of the sections above, the wide well luminescence reflects tunneling of electrons through a single 4 nm AlAs barrier and transport of holes through the narrow well first. The QW_n PL instead shows the behavior of electrons which have to pass the wide well and holes which are injected through a single barrier. The rise time of the PL signal is therefore determined by the slower one of the corresponding time constants. The traces of a typical measurement are shown in Fig. 6 for the two QW's. A clear rise of the PL signal is observed. The trace of the wide well PL signal, however, shows a sharp peak at $t = 0$ ps, which is caused by the exciting laser pulse. At this bias value the rise time of the narrow well signal is shorter than the rise time of the wide well signal.

The rise time of the luminescence, which is obtained by fitting a single exponential on to the leading edge of the PL signal, is plotted in Fig. 7. A large variation of τ_{eff} is observed, which depends on the resonant coupling of the quantum-well states. In forward bias, where electrons enter the wide well first and holes the narrow well, the rise time of the QW_w PL signal reflects resonant hole

FIG. 6. Typical streaks of the two photoluminescence lines at an applied bias of 1.5 V. The sharp peak at $t = 0$ ps is caused by the exciting laser pulse

FIG. 7. Effective rise time τ_{eff} of the photoluminescence signal vs applied voltage. No data points are shown when the rise time exceeds the time range of the setup.

tunneling. For the $H1_n \rightarrow H3_w$ resonance at 0.3 V (cf. Table I) τ_{eff} is of the order of 200 ps. Increasing the electric field, the hole transport is no longer resonant and τ_{eff} increases to values above 1.5 ns. At $V_{\text{ap}} = 0.8$ V, as the $H1_n \rightarrow H4_w$ states are resonantly aligned (cf. Table I), τ_{eff} decreases again to the 200 ps regime but, as the bias is further increased, τ_{eff} also increases since holes are tunneling non-resonantly again in this bias regime.

The rise time of the QW_n PL shows a clear correlation with the resonant electron transport through the central barrier. This is due to the fact that in this bias direction QW_n is entered first by holes, whereas electrons have to tunnel through the wide well. Due to the moderate excitation density, which, however, is not negligible on the time scale of the photoluminescence experiment, the amount of electrons entering and radiatively recombining in QW_n is enhanced at the conduction band resonance. With respect to this, the present work differs significantly from the investigations on symmetrical DBS's, e.g., by Lovering *et al.*,⁹ where both types of carriers have to tunnel through identical barriers. Therefore, we expect a faster rise of the PL signal at the conduction band resonance. We find $\tau_{\text{eff}} \approx 50$ ps for the $C1_w \rightarrow C1_n$ resonance at 0.25 V (cf. Table I), whereas at higher bias values τ_{eff} increases to about 700 ps reflecting nonresonant tunneling of electrons. The PL risetime of QW_n starts to decrease again as the second conduction band resonance $C2_w \rightarrow C2_n$ is approached at higher voltages.

In reverse bias the directions of carrier transport are inverted. Now electrons enter the narrow well from the emitter and holes the wide well. The rise time of the QW_w PL signal should therefore reflect an upper limit for electron tunneling and τ_{eff} of the narrow well PL hole tunneling through QW_w . The effective time constant τ_{eff} of QW_w exhibits a slow rise at low bias voltages, as is shown in Fig. 7, since the conduction band states are out of resonance, in agreement with the behavior of τ_{eff} for the QW_n PL in forward bias. The PL rise time of the QW_w signal becomes shorter (≈ 250 ps), increasing the voltage in the reverse direction, since we approach the $C1_n \rightarrow C2_w$ conduction band resonance. This rise time is, however, rather long compared to the values of τ_{eff} for

the narrow well PL under forward bias. The mechanism which is responsible for this difference is not yet fully understood. It might be due to a charge accumulation in QW_w . Beyond this resonance, τ_{eff} of the wide well PL again increases due to nonresonant transport of electrons.

The rise time of the photoluminescence signal of the narrow well in reverse bias should reflect resonant hole transport. As was mentioned above, the intensity of the QW_n PL line exhibits only one small peak at low bias values, but no higher resonances of hole states. This behavior is also found in the rise time variation with increasing reverse bias. At low voltages τ_{eff} decreases from about 700 ps to 200 ps showing the $H1_w \rightarrow L1_n$ resonance. Beyond that no further resonances are observed, resulting in a long rise time of the QW_n PL throughout the whole bias region.

VI. SUMMARY

To conclude, we have investigated the resonant and nonresonant electron and hole transport in a triple-barrier structure (TBS) with time-resolved photoluminescence. Using an excitation energy well below the absorption edge of the QW's, carriers are only excited in the contact regions of the diode and enter the wells via tunneling from the emitter states. The intensity variation of the ground-state transitions of the two different quantum wells reflects thereby resonances in electron and hole transport through the TBS as the applied electric field is varied. We find in forward bias an increase of the narrow well PL for a resonant alignment of conduction band states, while the wide well PL intensity exhibits maxima when valence band states of the two QW's are in resonance. In reverse bias, the situation is in principle inverted. However, since the wells are of different widths, only one conduction band resonance is achievable.

The luminescence of the ground-state transitions of the quantum wells reveals a clear rise time, changing drastically as the QW states are tuned through the resonances by the externally applied electric field due to the absence of directly photoexcited carriers in the wells. In forward bias the rise time of the PL of the narrow well reveals the dynamics of electrons tunneling through the wide well, while the QW_w PL rise time reflects tunneling of holes through the narrow well. We find for resonant hole transport an effective transfer time of 200 ps, while resonant electron transport results in a PL rise time of 50 ps. In the nonresonant regime, the rise time of the PL increases to values above 600 ps for electrons and larger than 1 ns for holes.

ACKNOWLEDGMENTS

We wish to thank H. Lage and W. Müller for expert technical support and valuable discussions and P. Michler for a critical reading of the manuscript. This work was supported in part by the European Community ESPRIT Project No. 7193 PARTNERS and by the Bundesminister für Forschung und Technologie of the Federal Republic of Germany.

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