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Piezoelectric effects in sidewall quantum wires grown on patterned (311)A GaAs substrate

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Time-resolved photoluminescence measurements have been performed on sidewall InGaAs/AlGaAs quantum wires and quantum wells. Experimental data show a band filling of quantum wells and quantum wires that is dominant in the first 400 ps after the excitation pulse, then a dynamical screening of the built-in piezoelectric field (F_p) by means of fast injection of photo-generated charges is observed allowing an efficient radiative recombination. At longer time delay, during the regime when the F_p unscreened value is recovered, a strong quantum confined Stark effect is observed. A good agreement is obtained for the energy shift and the overlap integrals of electrons and heavy holes by means of discrete element calculations.

1 Introduction Semiconductor quantum wires (QWRs) have been widely studied because of their peculiar optical properties that turn out to be very interesting for both fundamental physics and devices applications [1, 2]. Studies on QWR cover a wide range of physical processes as, for example, lasing action [2], transport processes [3], strain effects in mismatched structures on the excitons and carriers dynamics [1, 4], kinetics of carrier recombination [4, 5] and dot-wires coupling for spintronics [6]. The role of strain in QWR is also of great interest for device applications, not only for the control of of materials quality but also because the strain related properties can be exploited in devices as modulators [1].

In this paper we address the study of piezoelectric effects on the electrons and holes recombination kinetics in a sidewall single-layer QWR and QW structure grown on (311)A GaAs substrates. The sidewall growth technique provides QWRs connected by lateral almost flat and well geometrically defined QWs that results in a less complex structure compared with the one obtained by V-groove technique in which is present also a vertical QW. Furthermore in these QWRs, due to the choice of an high Miller indexes plane for the growth, a strong piezoelectric polarization $\boldsymbol{P}_p$ is achieved. The piezoelectric charges generated at the interfaces induce in the QW a homogeneous piezoelectric field $\boldsymbol{F}_p$ in the growth direction, while in the QWR a more complex $\boldsymbol{F}_p$ pattern is obtained due to the shape of the QWR itself. As a result, we observe a large quantum confined Stark effect (QCSE) of the QWR

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emission. In addition, strong optical non-linearities are induced by the dynamical screening of the built-in $\boldsymbol{F}_p$ by means of carrier photo-injection by laser pulse excitation. The strain pattern, piezoelectric polarization and charge density have been calculated by means of a continuum mechanical model finding a good agreement with the experimental results.

2 Sample and experimental The investigated sample has been grown by molecular beam epitaxy on patterned GaAs (311)A substrate made up by shallow mesa stripes 10 µm wide and 20 nm deep obtained along [01-1] by optical lithography and wet chemical etching. The sample has been grown on this substrate starting with 50 nm of GaAs buffer layer followed by a 50 nm thick barrier $Al_{0.5}Ga_{0.5}As$ layer. After the deposition of the 3 nm thick active $In_{0.2}Ga_{0.8}As$ layer again a 50 nm thick $Al_{0.5}Ga_{0.5}As$ barrier and a 10 nm cap layer of GaAs have been grown. The QWRs are formed spontaneously during the growth at the sidewall by migration of InGaAs from the flat adjacent quantum wells (QW) regions. As a result of this migration the cross sectional shape of the QWR is similar to an irregular triangle. Piezoelectric polarization P_p is expected along the [133] direction that is not parallel to the [311] growth direction. Therefore a capacitor-like charge distribution is present in the QW, with $\boldsymbol{F}_p$ directed in the growth direction, while a more complex pattern and a non-zero $\boldsymbol{F}_p$ in the in-plane direction appear in the QWR. In the following we will present a series of time resolved photoluminescence (TR–PL) measurements after non resonant excitation ($\hbar\omega = 3.5$ eV) in the barrier continuum of states by using the second harmonic of a ps Ti : sapphire laser with a repetition rate of 81 MHz. The PL signal has been analyzed with a spectral resolution of ~ 1 nm and detected by means of a Streak Camera apparatus that provides an overall time resolution of 10 ps.

3 Results The PL spectra do not show any emission from $Al_{0.5}Ga_{0.5}As$ barriers, moreover the PL risetime of both QW and QWR is very fast, comparable to our time resolution ~ 10 ps, denoting an efficient transfer and relaxation of the carriers into the QW and QWR region. Figure 1a the time–energy PL pattern acquired at low temperature ($T = 10$ K) and b) three TR spectra extracted at different time delays Δt. Two PL bands are present corresponding to the QW (higher energy) and the QWR (lower energy) emissions. Both emissions show a red shift when increasing the time delay Δt with respect to the pulse excitation. For delays ≤ 400 ps the QW and QWR bands are broad and merged together, denoting a large band filling occurring at high densities of injected charges that rapidly relax in the active layer. As a consequence, at early times, the maximum of the PL emission obtained by a simple two Gaussians fit cannot directly be attributed to the energy of the fundamental transitions. The relevant excited state filling and the large inhomogeneous broadening of both the QW and the QWR emission bands does not allow a straightforward separation of the two contributions.

After ~ 400 ps a clear separation in the PL spectrum appears between the QW and QWR bands, denoting that the state filling does not dominate anymore the recombination kinetics. Therefore we can assume that, for time delays longer than ~ 400 ps, the PL peak position can be associated to the

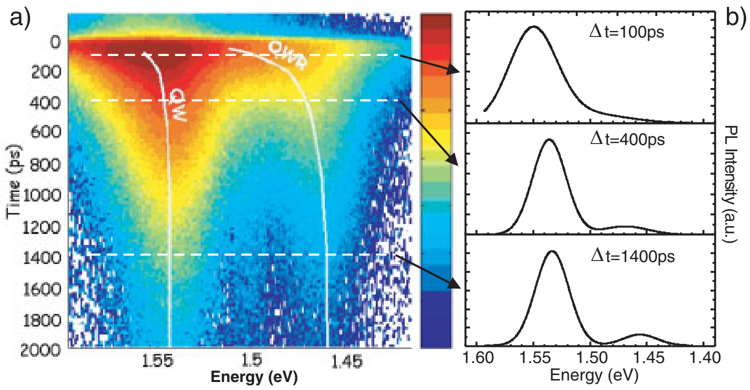

Fig. 1 (online colour at: www.interscience.wiley.com) a) Time–energy pattern of PL emission: solid white lines show the peak position of the QW and QWR emission bands as resulting from a two Gaussians fit. b) Time-resolved spectra at a time delay corresponding to the dashed lines in a)

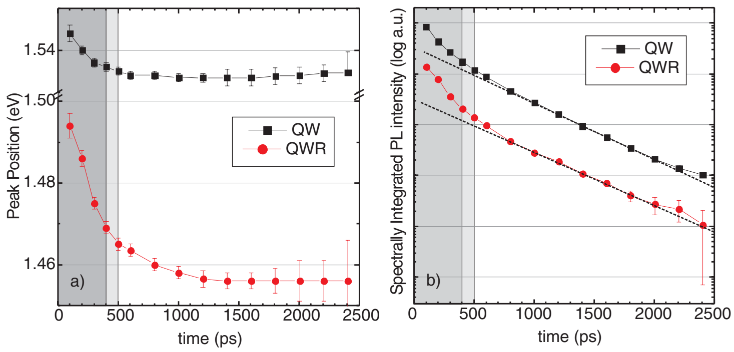

Fig. 2 (online colour at: www.interscience.wiley.com) a) Extracted peak positions and b) integrated PL intensities of the QW and QWR emissions as a function of time after the excitation pulse. The dark gray area marks the band filling regime. The light gray area marks the time interval from which the QCSE can be considered the main cause of the energy shift.

fundamental transition energy. Nevertheless a further red shift of the peak position of the PL bands ($\sim 12 \div 14$ meV for the QWR and $\sim 1 \div 3$ meV for the QW) is observed up to the final band positions. We attribute this shift to the dynamical QCSE due to the piezoelectric field $\boldsymbol{F}_p$ screened by the high density of injected carriers. At early times the piezoelectric field $\boldsymbol{F}_p$ is screened and there is not QCSE. Increasing the time delay the carrier population (and therefore the screening) decays and for long delays the $\boldsymbol{F}_p$ and the QCSE are fully restored making the QW and QWR emissions red shifted. The TR–PL spectra can be nicely fitted by two Gaussian profiles peaked at the energies reported in Fig. 2a; the dark gray areas in Fig. 2 refer to the regime dominated by state filling effects. In Fig. 2b the spectrally integrated PL intensity is reported for both the QW and QWR emissions. Non-exponential PL decays with an increasing lifetime are observed at early times while for longer delays the PL decays are almost exponential and very similar for the two emissions. As already mentioned, outside the state filling regime a red shift of the PL bands is observed being the shift larger in the QWR ($12 \div 14$ meV) with respect to the QW ($1 \div 3$ meV).

Let us now discuss the theoretical model. The elastic deformation of the structure is calculated by means of a continuum mechanical model [7, 8], taking into account boundary conditions for high Miller index crystal planes [9]. Then the piezoelectric polarization $\boldsymbol{P}_p$ is determined as a linear function of strain tensor: $P_i = e_{ijk}\varepsilon_{jk}$. Due to the lattice mismatch and to the high Miller indexes choice, the active InGaAs layer is compressed in the [-233] x-direction and stretched in the [311] y-direction. Figure 3a shows the ε_{xx} strain tensor component that turns out to be negative in the InGaAs layer. Near the material steps, where we have lattice mismatch in all three directions, large gradients of the strain tensor components are present. The cross sectional pattern of the piezoelectric charge density $\rho(\boldsymbol{r}) = -\mathrm{div}\,\boldsymbol{P}_p(\boldsymbol{r})$ is plotted in Fig. 3b. Two different kinds of charge contributions can be recognized: the surface charge at the interfaces due to the discontinuity of the polarization vector and the volume charge induced by non-homogeneous strain near the steps. The first contribution is a peculiarity of structures grown on [N11] oriented substrates. The surface charge is positive at the lower interface (A-termination) and negative at the upper interface (B-termination), leading to a uniform piezoelectric field in the QW region, while a more complex pattern is obtained in the QWR region. The calculated

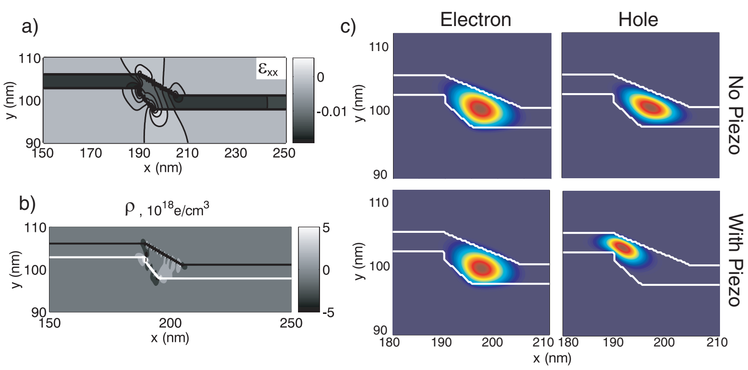

Fig. 3 (online colour at: www.interscience.wiley.com) a) Cross-sectional view of the ε_{xx} strain tensor component. b) Calculated piezoelectric charge density ρ. c) Calculated electron and hole wavefunctions with and without the piezoelectric field.

electron and hole wavefunctions, with and without the piezoelectric field are shown in Fig. 3c. The experimental energy positions of QW and QWR are well reproduced: the calculated transition energy for the QWR is reduced from 1.467 eV, in absence of piezoelectric field, to 1.454 eV corresponding to the long delay situation, in agreement with the experimental findings. It should be mentioned that geometrical variations of the wire shape slightly modify the calculated QCSE induced by the piezoelectric fields. The calculated piezoelectric shifts for the optical transition in the QW is instead of the order of 1 meV. The large differences in the piezoelectric induced QCSE in QW and QWR structure is related to the different extension of the carrier wavefunctions. The strong confinement provided by the 3 nm thick QW frustrates the electron and hole wavefunctions separation and leads to a small Stark shift. The lateral size of the QWR is instead pretty large and the piezoelectric field, which has a non-zero component in the in-plane direction, produces (as shown in Fig. 3c) a large separation of the electron and hole wavefunctions. The spatial separation of the carriers also reduces the overlap integral $|\langle \psi_e \mid \psi_h \rangle|^2$. For the QWR a relevant reduction of the overlap integral has been found: from 0.94 to 0.33, while for the QW a change of few percent is found. The reduction of the overlap integral, that is proportional to the radiative recombination rate, is expected to induce a non exponential decay of the emission as a consequence of a dynamical screening effect [10]. This prediction is also in qualitative agreement with the experimental data, even if the presence of large band filling makes the analysis more complicated and a direct comparison cannot be done. Finally the QW and QWR asymptotically show a pretty similar decay time. This can be due either to the presence of similar non radiative channels in the QW and QWR or to a transfer of carrier population from the QW to the QWR during the recombination. Experiments are in progress to further clarify these observations.

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