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Letter to the Editors

Time resolved photoluminescence study of strained-layer InGaAsP/InP heterostructures

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Abstract

A time-resolved photoluminescence study of strained and unstrained InGaAsP/InP double heterostructures has been performed at low photogenerated carrier densities (i.e. $\leqslant 10^{16}$ cm^{-3}) using a novel high-efficiency germanium photon-counting detector. The photoluminescence decay times are observed to decrease with increasing strain. Samples grown on substrates with lattice orientation (3 1 1)B are shown to have shorter excess carrier lifetimes than those grown on lattices orientated (0 0 1) or (3 1 1)A.

The use of semiconductor lasers in telecommunications is now widespread and continuing interest is being shown in laser structures incorporating the quaternary alloy InGaAsP. It has been found that the threshold current performance of multiple quantum-well (MQW) InGaAsP laser diodes can be improved by the introduction of strain into the lattice [1]. The mechanisms whereby strain decreases the threshold current density are thought to include the reduction of the hole effective mass and density of states near the band edge. The effect of lattice strain on semiconductor laser performance is reviewed by O'Reilly and Adams [2] amongst others. In this paper we report an initial time-resolved photoluminescence (TRPL) study of the effect of strain and substrate lattice orientation on the excited-state lifetime of carriers in double-heterostructure (DH) InGaAsP/InP structures. Photoluminescence (PL) decays from such samples have been measured using a novel high-efficiency photon-counting system which has permitted analysis, for the first time, of PL decays at low photogenerated carrier densities.

Seven double-heterostructure samples were grown on InP substrates with three differently orientated crystal lattices and a range of values of strain. The samples were grown by atmospheric

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Table 1
Details of the seven strained-layer InGaAsP samples

Sample number	Substrate orientation	Strain (ppm)/ Strain (approx. %)	InGaAsP thickness (nm)	InGaAsP composition	PL wavelength (μm)
1	(0 1 1)	– 890/0 Matched	550	$In_{0.73}Ga_{0.27}As_{0.54}P_{0.46}$	1.294
2	(0 1 1)	– 5400/½ Tensile	30	$In_{0.66}Ga_{0.34}As_{0.57}P_{0.43}$	1.298
3	(0 1 1)	+ 9200/1 Compressive	30	$In_{0.90}Ga_{0.10}As_{0.49}P_{0.51}$	1.351
4	(3 1 1)A	+ 150/0 Matched	550	$In_{0.74}Ga_{0.26}As_{0.57}P_{0.43}$	1.303
5	(3 1 1)A	– 5100/½ Tensile	30	$In_{0.72}Ga_{0.28}As_{0.42}P_{0.58}$	1.290
6	(3 1 1)B	– 400/0 Matched	520	$In_{0.75}Ga_{0.25}As_{0.52}P_{0.48}$	1.276
7	(3 1 1)B	– 5600/½ Tensile	32	$In_{0.65}Ga_{0.35}As_{0.58}P_{0.42}$	1.296

pressure MOVPE at temperatures of 650°C for (0 0 1) substrates and 600°C for (3 1 1)A and B substrates. A 500 nm thick InP buffer layer was grown on top of the substrate followed by the InGaAsP layer and an InP capping layer of 2–100 nm thickness. All layers were grown nominally undoped, with the background doping level estimated to be $\sim 1.5 \times 10^{15}$ cm^{-3} (n-type). The InGaAsP layer was 30 nm thick in the strained samples and ~500 nm thick in the unstrained samples. The range of InGaAsP compositions was employed in order to preserve a ~1.3 μm emission wavelength in all cases. The detailed layer dimensions for the individual samples are given in Table 1 together with their strain, substrate orientation and active-layer composition.

TRPL measurements were made using a unique microscope-based instrument, described in detail elsewhere [3]. The excitation source used in these measurements was a passively Q-switched GaAs/GaAlAs laser diode [4] which emitted 10 ps duration pulses of energy ~8 pJ at a wavelength of 860 nm. This laser excited an area of approximately 60 μm diameter in each of the samples, giving rise to an estimated peak excess carrier density of $\sim 3 \times 10^{16}$ cm^{-3}. The PL was collected by the same microscope objective used for focussing the excitation beam and directed to the detector by a polarising beam-splitter. TRPL measurements were made in the spectral region 1.29–1.35 μm (individual PL emission wavelengths are detailed in Table 1), with wavelength discrimination provided by optical bandpass filters. A schematic representation of the TRPL instrument is shown in Fig. 1.

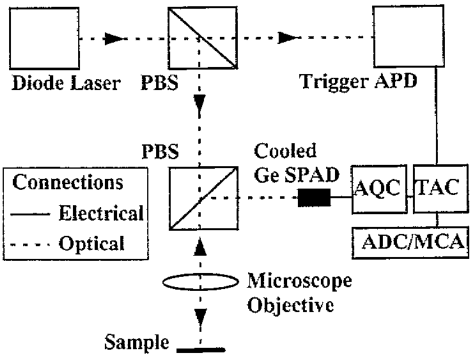

Fig. 1. A schematic representation of the TRPL set-up showing the optical routing of the laser excitation and PL by polarising beam splitters (PBSs). The components of the TCSPC electronics are indicated – Trigger avalanche diode (Trigger APD), active quenching circuit (AQC), time-to-amplitude converter (TAC), analogue-to-digital converter (ADC) and multi-channel analyser (MCA). The Ge-SPAD is biased above breakdown for ~200 ns per 1 ms laser cycle by a square-wave voltage input to the AQC (not shown).

The TRPL measurement system uses the time-correlated single-photon counting technique (TCSPC) [5]. As shown in Fig. 1, a fraction of the laser output is detected by an analogue silicon APD which provides an electrical signal at every laser pulse. This electrical signal acts as an initiation signal for the timing process by 'starting' the time-to-amplitude converter (TAC). The timing process is 'stopped' when the TAC receives an output from the single-photon counting detector. The TAC then produces an output pulse with an amplitude proportional to the time interval between the start and stop inputs. This is then digitised by an analogue-to-digital converter (ADC) and stored in a multichannel analyser (MCA).

The photon-counting detector was a commercially available small-area (~30 μm diameter) germanium avalanche photodiode, cooled to 77 K and biased 0.6 V above breakdown to enable a single photon to generate a large avalanche response. These Ge detectors have only recently been exploited for TRPL measurements [6, 7] – utilising their high quantum efficiency at these wavelengths in the photon-counting mode, when compared to alternative photon-counting detectors. With this instrument, PL emission at wavelengths ~1.3 μm from InGaAs/InP quantum wells has been measured at photogenerated carrier densities lower than ~10^{15} cm^{-3}, exhibiting excellent sensitivity when compared to alternative carrier lifetime measurement techniques such as nonlinear pump–probe [8] or up-conversion luminescence [9] measurements. The Ge single-photon avalanche diode (SPAD) is operated in a gated active quenching circuit (AQC) [10]. TRPL measurements at wavelengths up to ~1.50 μm are achievable with this system [6], with an instrumental temporal half-width of ~300 ps.

The TRPL data from the seven samples described above are shown in Figs. 2–4. The data has been corrected for the distortion caused by counting photons at a high proportion of the laser repetition rate ('pulse pile-up'), a process described in Ref. [6] and references therein. Fig. 2 shows the PL decays from the three unstrained samples (Samples 1, 4 and 6 in Table 1) on substrates orientated (0 1 1), (3 1 1)A and (3 1 1)B, respectively. Fig. 3 shows the equivalent PL decays from three strained samples (2, 5 and 7) all having the same strain (−0.5% tensile) but with differently orientated substrates. Fig. 4 shows a direct comparison of differently strained samples on (0 0 1) substrates. The best-fit exponential decay times τ_{PL}, fitted to the PL data using reconvolution analysis are shown in Table 2 which summarises the TRPL results.

Direct comparison of strained and unstrained samples in the set shown here is inhibited by the variation in InGaAsP and InP capping layer thicknesses. Therefore, comparisons are made between samples with essentially identical layer thickness but with variations in *either* strain *or* substrate orientation. From the examination of Figs. 2 and 3 (and the associated time-constant data in Table 2) it may be seen that, in both unstrained and strained samples, the PL decay from samples grown on substrates orientated (3 1 1)B is significantly faster than that from samples grown on substrates

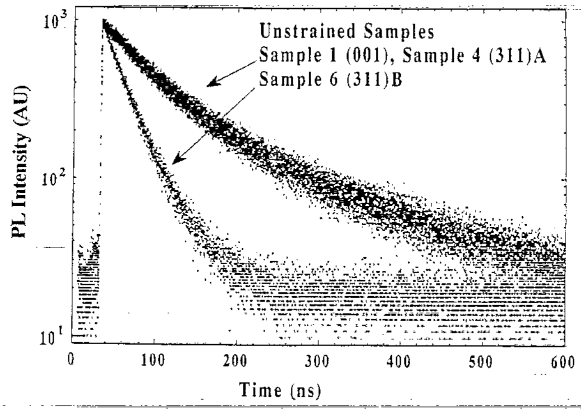

Fig. 2. TRPL decays at 1.29–1.35 μm wavelength from three unstrained structures grown on (0 0 1), (3 1 1)A and (3 1 1)B orientated substrates. Note that the decays from samples grown on (0 0 1) and (3 1 1)A are superimposed.

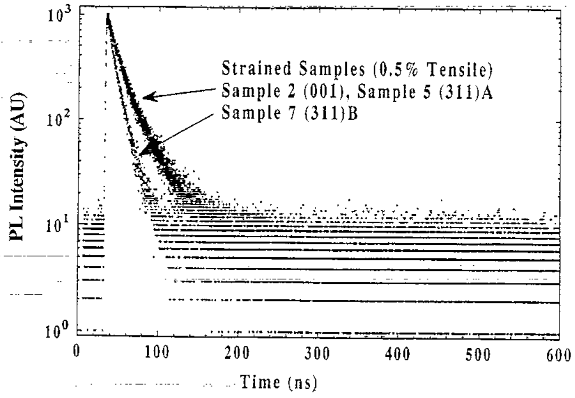

Fig. 3. TRPL decays at 1.29–1.35 μm wavelength from three strained-layer structures grown on (0 0 1), (3 1 1)A and (3 1 1)B orientated substrates. Strain is indicated in approximate percentage. Note that the decays from samples grown on (0 0 1) and (3 1 1)A are superimposed.

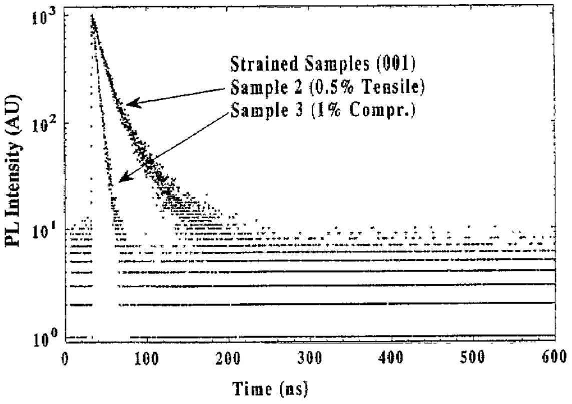

Fig. 4. TRPL decays at 1.29–1.35 μm wavelength from two strained-layer structures grown on (0 0 1) orientated substrates. Strain is indicated in approximate percentage.

Table 2
Exponential fits to the photoluminescence decay data

Sample number	Substrate orientation	Strain (ppm)/ Strain (approx. %)	Fitted τ_{PL} (ns)
1	(0 0 1)	− 890/0 Matched	150
2	(0 0 1)	− 5400/ $-\frac{1}{2}$ Tensile	30
3	(0 0 1)	+ 9200/ + 1 Compressive	6
4	(3 1 1)A	+ 150/0 Matched	190
5	(3 1 1)A	− 5100/ $-\frac{1}{2}$ Tensile	23
6	(3 1 1)B	− 400/0 Matched	35
7	(3 1 1)B	− 5600/ $-\frac{1}{2}$ Tensile	12

oriented (0 0 1) or (3 1 1)A. Fig. 4 shows a comparison between two samples grown on the same substrate (0 0 1) but with different strain. The effect of increased strain can be seen to be a marked increase in photoluminescence decay rate.

The PL decays from the strained samples with 30 nm thick InGaAsP layers are approximately single exponential in character (Figs. 3 and 4). From consideration of typical Auger and radiative decay coefficients for InGaAs (see Ref. [11] for example) and by analogy with theory developed for GaAs/AlGaAs quantum wells [12] it is likely at such carrier densities that the predominant decay mechanism is nonradiative recombination associated with defects at the heterostructure interfaces.

The PL decays from the unstrained samples (Fig. 2) are considerably slower than in the strained cases on equivalent substrates. As stated above, comparison with the strained samples is difficult since the greater InGaAsP layer thickness of the unstrained samples will tend to increase the carrier lifetime associated with interface recombination [12]. The decays may be seen to be multi-exponential in form – possibly indicating the influence of additional recombination processes which appear to be absent in the thinner, quantum-well-like strained heterostructures.

Only minimal changes in PL decay rate are seen on changing the substrate lattice orientation of either strained or unstrained samples from (0 0 1) to (3 1 1)A. However, the substrates orientated (3 1 1)B correspond to significantly shorter carrier decay times. It is possible that the effect of dopant incorporation may be greater in samples grown on (3 1 1)B than (3 1 1)A orientated substrates, as previously suggested by some authors [13, 14]. Interface recombination velocities in the unstrained case increase from 150–190 cm s^{-1} ((0 0 1) or (3 1 1)A) to 790 cm s^{-1} (3 1 1)B).

The increase in non-radiative recombination rate with increased strain may be explained by a degradation of interface morphology resulting from the lattice constant mismatch. As mentioned above, the evidence from other workers [1] indicates that the effect of moderate increased strain is to lower the laser threshold current density, implying, therefore, that the increased nonradiative recombination rates found in these TRPL measurements are compensated by significant changes in the hole density of states and sample symmetry.

In summary, quantitative measurements have been made of the excess carrier lifetime (at low photogenerated carrier densities) of strained and unstrained InGaAsP/InP heterostructures grown on a variety of substrate orientations. It has been shown that there is a significant increase in PL decay rate in samples whose substrate is orientated (3 1 1)B. In addition, it has been found that the effect of increasing strain in InGaAsP/InP laser heterostructures is to shorten their excess carrier lifetime at low photogenerated carrier densities, an effect ascribed to increased nonradiative recombination rates at the heterointerfaces.

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