
Proceedings of the 12th International Symposium UFPS, Vilnius, Lithuania 2004

Photoelectrical Properties of 1.3 μm Emitting InAs Quantum Dots in InGaAs Matrix

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We present a study of photoelectrical properties of the Stranski–Krastanow InAs quantum dots embedded in an InGaAs matrix with low In content, emitting at about 1.3 μm . The ground-state electron–hole transition of the dots was investigated as a function of the temperature in presence of electric fields parallel and perpendicular to the plane of the dots by photocurrent spectroscopy. Microphotoluminescence measurements were also carried out, allowing us to evidence carrier capture from the GaAs matrix into the dots.

PACS numbers: 78.67.Hc, 73.63.Kv, 81.07.Ta

1. Introduction

In recent years self-assembled InAs quantum dots (QDs) embedded in an InGaAs matrix have been the subject of intense interest, because of the possibility to develop GaAs-based devices operating in the telecommunication wavelength range of 1.3–1.55 μm to replace the expensive InP based devices [1–7]. For the development of optoelectronic devices based on these structures, such as infrared detectors [6] and emitters [7], it is crucial to study the electronic properties in connection with the transport mechanisms in the QDs. To this scope, a number of techniques has been employed, such as photocurrent (PC) spectroscopy [8–11], capacitance–voltage (C – V) characterization [8], and deep-level transient spectroscopy (DLTS) [12]. In particular, PC spectroscopy is a direct, sensitive, and relatively simple technique, which combines the advantages of both electrical and

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optical methods of investigation. The PC signal reflects, in part, the optical absorption in the QD layer, but its intensity is governed by the interplay between the recombination and escape rates of photogenerated carriers [9].

In this work we use both PC and microphotoluminescence (μ -PL) spectroscopy in order to investigate absorption and carrier capture in the dots. In particular, we studied structures containing a single layer of the Stranski–Krastanow InAs QDs embedded in an InGaAs matrix with low In content, emitting at 1.24–1.26 μm , grown by molecular beam epitaxy (MBE) on both semi-insulating and doped GaAs substrates. PC measurements were performed by applying electric fields parallel and perpendicular to the plane of the dots. Carrier capture mechanisms from the GaAs matrix into the dots were investigated by μ -PL measurements.

2. Experimental

Two different structures based on InAs QDs embedded in an InGaAs matrix with low In content, were grown on semi-insulating (sample SK53) and doped (sample SK88) GaAs (100) substrates by MBE. In both cases, a 0.2 μm thick undoped GaAs buffer layer was grown at 580°C on the GaAs substrate. InAs QDs embedded in an InGaAs quantum well were then formed under the Stranski–Krastanow growth mode at 530°C by continuous deposition of InAs with a nominal thickness of 3.5 monolayers (ML) and 3.0 ML for the samples SK53 and SK88, respectively. A 0.2 μm thick undoped GaAs cap layer was finally grown at 580°C. In the sample SK88 the $\text{In}_x\text{Ga}_{1-x}\text{As}$ matrix has a higher indium content ($x = 0.15$) with respect to the sample SK53 in which $x = 0.12$. Tuning of the emission wavelength towards 1.3 μm was achieved by using a growth interruption time after the InAs deposition of 280 s and 10 s for the sample SK53 and SK88, respectively. Further details on the growth conditions are reported in Ref. [1].

Morphological characterization of the InAs dots was performed by atomic force microscopy (AFM) measurements on uncapped samples. The AFM images, recorded in air by contact mode, show that the QDs of the sample SK53 have both lower areal density and lower aspect ratio than those of the sample SK88, consistently with the different growth interruption times (see Table).

TABLE
Morphological characteristics of the InAs QD samples.

Sample	Areal QD density ρ [cm^{-2}]	Lateral QD diameter [nm]	Vertical QD size [nm]
SK53	$(1.01 \pm 0.01) \times 10^{10}$	61 ± 9	5 ± 2
SK88	$(3.35 \pm 0.05) \times 10^{10}$	35 ± 7	7 ± 2

Au/Ti squared pixels (200 $\mu\text{m} \times 200 \mu\text{m}$) 10 nm thick, were deposited on top of the structure by using e-beam evaporation and standard photolithography tech-

niques. Some of the pixels have a guard-ring contact 100 μm wide and 50 μm far from the pixel edge. Since Ti on GaAs works as the Schottky contact, the structure pixel/guard-ring can be seen as a back to back planar Schottky diode structure. This structure allows us to apply electric fields parallel (planar configuration) to the plane of the dots. The current is confined in this case in the epitaxial layers by the underlying semi-insulating GaAs substrate. In order to realize transverse Schottky diodes (transverse configuration), we have used n^+ -GaAs substrates, by defining the Schottky pixel contacts on the grown structure and the ohmic contact on the back of the substrate. A good ohmic contact on the back of n^+ -GaAs substrate was obtained by the indium layer needed to keep the sample during the epitaxial growth process. The two structures are sketched in Figs. 1 which show that in planar configuration (Fig. 1a) the excitation light impinges between two Schottky contacts, while in transverse configuration (Fig. 1b) the light impinges onto a Schottky contact which, being semitransparent, provides optical access to the sample.

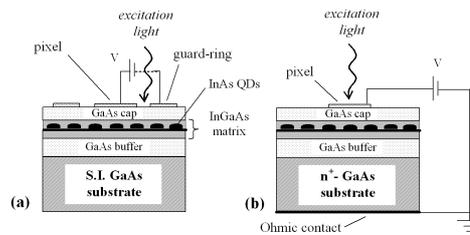


Fig. 1. Schematic diagram of the sample structure and the Schottky diode under illumination in planar (a) and transverse (b) configuration.

The excitation source for PC measurements was a tungsten–halogen lamp, dispersed by a 0.11 m monochromator, filtered through a high-pass filter with cut-off at 830 nm, and normally incident onto the sample surface. At room temperature, the PC signal was recorded using standard ac lock-in techniques, while at low temperature, it was measured using an HP 4140 B pA-meter/d.c.-voltage source. μ -PL measurements were performed with the optical excitation provided by the green line of an Ar^+ ion laser ($\lambda = 514.5$ nm), being the spatial resolution of 1 μm .

3. Results and discussion

Figures 2 show PC spectra recorded in planar and transverse configuration under different voltage at room temperature. Figure 2a refers to SK88 in transverse configuration. The spectra exhibit, even with no applied voltage, the ground-state electron–hole recombination (e_0 – h_0) QD-related peak at 1250 nm and two further features at 860 nm and 1000 nm arising from GaAs barrier and InGaAs matrix absorption, respectively. At all the voltages, a broad background PC signal is

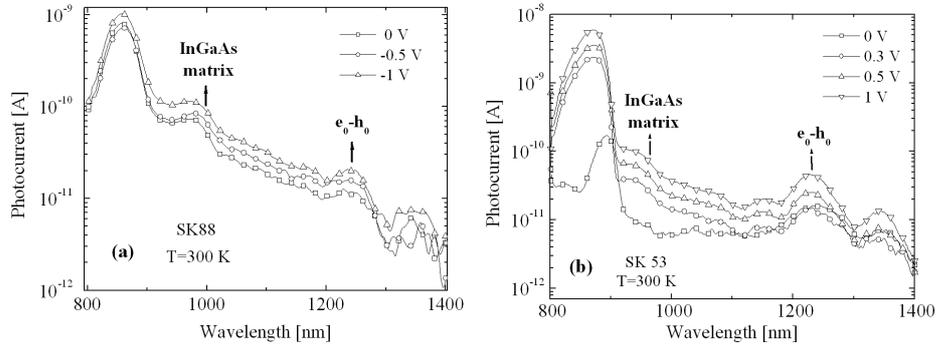


Fig. 2. Photocurrent spectra at room temperature as a function of the applied voltage for the sample SK88 in transverse configuration (a) and for the sample SK53 in planar configuration (b).

evident, whose intensity increases by increasing the photon energy. As pointed out in other theoretical [13] and experimental works [10], this PC signal could be attributed to the transitions between the discrete dot levels and the surrounding electronic continuum.

The PC spectra recorded for the sample SK53 in planar configuration, are shown in Fig. 2b as a function of the applied voltage. The PC peak due to QD (e_0-h_0) transitions is observed at 1230 nm, shifted to a wavelength shorter than that showed for the sample SK88 in agreement with the lower height of these dots (Table) which increases the ground-state transition energy due to the higher confinement along the growth direction. These PC results are in agreement with the photoluminescence (PL) measurements (not reported here). In fact, the (e_0-h_0) peak in the InAs QDs was observed by PL measurements to be at 1256 nm for the sample SK88 and 1237 nm for the SK53. Compared to the SK88, the sample SK53 also exhibits a blue shift of the PC signal due to the absorption edge of the InGaAs matrix to around 965 nm which is consistent with the In content dependence of InGaAs energy gap [14].

Figure 3 shows PC spectra recorded in the temperature range 320–160 K at the applied voltage of 0.1 V on the sample SK53 in planar configuration. The QD transition and the InGaAs matrix absorption are well identified at low temperature up to 260 K; for $T > 260$ K, the background signal tends to be predominant. The QD signal was found to be thermally activated with energy of (137 ± 7) meV. This behaviour indicates that in our structures, the main contribution to the QD-related signal is due to thermally activated emission out of the dots because the electric field values are not high enough for the tunneling process to be competitive with the thermionic emission. We also verified that the temperature dependence of the QD ground-state transition energies as measured by PC and PL, and the InAs bulk energy gap calculated by the Varshni empirical equation [15], are very similar. Furthermore, Figs. 2 and 3 reveal another PC peak at 1345 nm which

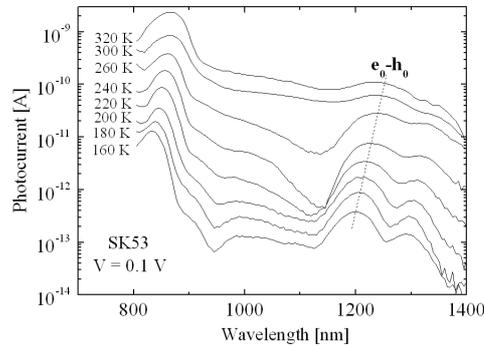


Fig. 3. Photocurrent spectra as a function of temperature for the sample SK53 in planar configuration with an applied voltage of 0.1 V.

shows a voltage and temperature dependence similar to that of the QD-related peak. Such signal might be attributed to a second family of lower density and larger relaxed dots, not revealed in the PL measurements.

The μ -PL measurements were carried out at 100 K on the sample SK53 with the laser spot impinging the region between the pixel and the guard-ring, under two different conditions: (i) varying the negative voltage applied to guard-ring with the laser spot impinging at 4 μm from it (Fig. 4a) and (ii) varying the distance between the laser spot and the guard-ring, which is biased at -20 V (Fig. 4b). In both cases the electric field is mainly localized near the guard-ring, which is the reverse-biased junction. Therefore, in the experiment (i) we observe μ -PL signal from a region where electric field is increased by the voltage. In the experiment (ii) the μ -PL signal comes from regions of higher electric fields as the spot is moved towards the guard-ring. As seen in Figs. 4a and b, μ -PL intensity diminishes with increasing the electric field. According with the results presented in Ref. [11], μ -PL

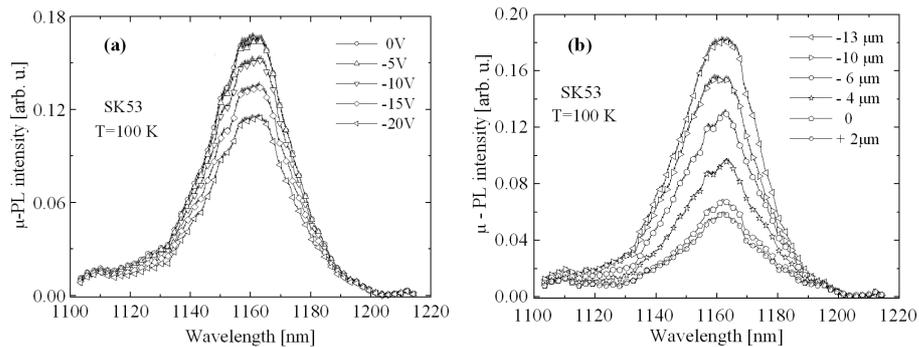


Fig. 4. Microphotoluminescence spectra at 100 K for the sample SK53 in planar configuration as a function of the applied voltage with the laser spot at 4 μm from the guard-ring (a) and as a function of the distance between the laser spot and the guard-ring contact, biased at -20 V (b).

measurements show that for an above-gap excitation the electric field reduces the capture of photogenerated carriers from the GaAs matrix into the dots. The above interpretation is in agreement with the fact that no change is observed when the laser spot is in regions characterized by a low electric field, at a distance greater than $25\ \mu\text{m}$ from the guard-ring. Moreover, as it is expected, in Figs. 4 $\mu\text{-PL}$ peak energy shows no change with increasing the electric field. In fact, the applied planar field is too low to induce a Stark shift of ground-state transition in a single layer of self-assembled QDs [16].

4. Conclusions

In summary, in this work we studied the photoelectrical properties of InAs QDs emitting at about $1.3\ \mu\text{m}$ by using PC and $\mu\text{-PL}$ spectroscopies. PC spectra provide a representation of the absorption arising from InAs QDs, InGaAs matrix, and GaAs barrier, in agreement with the dot size and the In content of the matrix. A broad background signal due to mixing between dot levels and continuum states of the surrounding GaAs, is also seen in the PC spectra. Finally, $\mu\text{-PL}$ spectroscopy is shown to provide an important method to study the electric field dependence of the carrier capture from GaAs matrix into the dots.

Acknowledgments

We wish to thank F. Quaranta for the realization of the Schottky diodes and M. Lomascolo for fruitful discussions. We also acknowledge G. Montagna and E. Melissano for technical support.

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