Optical properties of Self-assembled InAs Quantum Dots based P-I-N Structures Grown on GaAs and Si Substrates by Molecular Beam Epitaxy

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Abstract

Extensive work on InAs quantum dots grown on GaAs substrates has been reported in the literature. However, research in the use of different substrate materials such as silicon to achieve an ideal and full integration of photonic and electronic systems is still a challenge. In this work we have investigated the effect of the substrate material (Si and GaAs) and strain reducing layer on the optical properties of InAs quantum dots for possible applications in laser

devices grown by Molecular Beam Epitaxy. Two InAs quantum dots structures with similar active regions grown on GaAs and Si substrates using strain reducing layer consisting of InAs QDs/6nm $In_{0.15}Ga_{0.85}As$ have been investigated. Atomic Force Microscopy, Transmission Electron Microscopy, and photoluminescence have been used for the characterization of the samples. We have observed a red shift of the InAs QD photoluminescence peak energy for the sample grown on Si substrate as compared to the sample grown on GaAs substrate, which was associated with residual biaxial strain from the Si/GaAs heterointerface. This red-shift of the photoluminescence peak energy is accompanied by a broadening of the photoluminescence spectrum from ~31 meV to a value of ~46 meV. This broadening is attributed to the quantum dots size inhomogeneity increase for samples grown on Si substrate. This result open new insights for the controlling the emission of InAs quantum dots for photonic devices integration using Si substrates.

Introduction

Considerable efforts have been made to investigate the optical properties of self-assembled quantum dots (QDs) due to their wide range of applications in optoelectronics such as lasers, photodetectors, amplifiers, and solar cells [1-3]. Among the QDs systems, InAs QDs attracted an intensive research activity motivated by the possibility to achieve light emission covering the optical communication wavelength bands [4-6]. Many strategies have been used for the extension of the wavelength including growing larger QDs [7] and InGaAs metamorphic buffers (MB) which behave as virtual substrates where the lattice parameter can be controlled by an adroit design of the composition profile of the MB, keeping them separated from the active region of the device [8-12]. Another adopted strategy is the strain reducing layer (SRL) [6,13]. The SRL preserves the size of QDs during capping by reducing the indium dissolution [14]. In spite of photoluminescence (PL) emissions closer to 1.3 µm have been achieved [6,7-13], the larger lattice–mismatch strain between GaAs and InAs (~7%) had resulted in inhomogeneous dot size distribution and smaller dot density which limiting the device performance. It was found that the best way to preserve InAs QD size is the use of SRL [15-17]. Huang et al. [18] reported that $GaAs_{1-x}Sb_x$ SRL improved the performance of InAs/GaAs quantum-dot infrared photodetectors. Recently, Salhi et al. [6,15] have shown that the emission wavelength reached 1.32 µm when the InAs QDs are either covered by InGaAs or GaAsSb, while the incorporation of 1% of Sb in the InGaAs SRL extends further the wavelength to 1.37 µm. Extensive work on InAs QDs grown on GaAs substrates has been reported in the literature, however, research in the use of different substrate materials such as silicon to achieve an ideal and full integration of photonic and electronic systems [19, 20-23] is still under development. Therefore, studies to find suitable capping layer (CL) or SRL materials for covering InAs QDs grown on both GaAs and Si substrates are highly motivated by an enhancement of their morphology quality and optical properties, as well as exploring possibilities for monolithic photonic integration on silicon platform. On the other hand, it is well known that there are many challenges to achieve high-quality epitaxial growth of III-V materials on Si substrates. The lattice and thermal expansion mismatches between silicon and most III-V materials are the most important of these challenges. The 4% lattice constant mismatch between GaAs and Si introduces a build-up of strain energy on the epitaxial layer during growth. It leads to highly defective heteroepitaxial films, such as antiphase boundaries and threading dislocations [24], since the nucleation of a large number of interfacial dislocations is needed to relax the misfit strain between the two semiconductors. However, to alleviate the problems associated with the lattice mismatch, InGaAs/GaAs multilayers or superlattice defect filters are used [6, 24].

In this work, we report on the effect of the substrate material on the optical properties of InAs QDs based laser structures. Two InAs QD laser structures with similar active regions grown on GaAs and Si substrates using strain reducing layer (SRL) consisting of GaAs/InGaAs have been investigated. We have observed that the type of substrate has important influence on the strain lattice and structural associated defects, and consequently on the PL properties of self-assembled InAs QDs.

Experimental

The two InAs QD lasers studied in this work were grown on 2” (100) GaAs (Sample A: control sample) and 2” (100) Si (Sample B) substrates using a Veeco Gen20A Molecular Beam Epitaxy system (MBE) system equipped with a valved cracker to generate As_2. The layer sequence of Sample A, grown on n-type GaAs substrate, is depicted in Figure 1(a) and consists of the following layers: a 50 nm n-type GaAs buffer layer, a 1500 nm n-type $Al_{0.42}Ga_{0.58}As$ cladding layer, a 108 nm undoped GaAs spacer layer, 5× [2.5 monolayers (MLs) InAs QDs/10nm $In_{0.15}Ga_{0.85}As$ (SRL)/ 40 nm GaAs], a 64 nm undoped GaAs spacer layer, a 1500 nm p-type $Al_{0.42}Ga_{0.58}As$ cladding layer, and a 300 nm p-type GaAs layer.

The InAs QDs were grown at 500 °C and at a growth rate of 0.03 monolayer (ML)/s. This growth rate was chosen to obtain a uniform QD size distribution and reduce the PL linewidth [25]. A short growth interruption under As_2 flux was introduced before the growth of the 6 nm-thick $In_{0.15}Ga_{0.85}As$ Strain Reducing Layer followed by 10 nm-thick GaAs layer at the same temperature and using a growth rate of 0.5ML/s. The growth temperature was then ramped to 570 °C to grow the remaining GaAs cap layer. The spacers, claddings and contacts layers were grown at 570°C and using a growth rate of 1ML/s.

The laser structure grown on silicon substrate (Sample B), was grown by using the same process and growth conditions as the one used for Sample A grown on a GaAs substrate except for the buffer layer which is designed and used to reduce the defects resulting from lattice mismatch between Si and GaAs substrates. The defect filter undoped buffer layer consisted of 5 nm AlAs, 1000 nm GaAs, 4 periods of [6× InGaAs (10nm)/GaAs (20nm)]/ 280nm GaAs], 5 periods of AlAs (10nm)/GaAs (10nm), 50 nm GaAs and 200nm $Al_{0.5}Ga_{0.5}As$ (Fig.1b). More details regarding the growth of the dislocation filter can be found in reference [6]. The purpose of this specific buffer layer was to reduce dislocations between silicon substrate and the active layers due to the large lattice mismatch between Si and GaAs. The rest of the structure is similar to Sample A. It is important to highlight that the formation of InAs QDs was verified by means of Reflection High Energy Electron Diffraction (RHEED) where a chevron patterns in the RHEED screen was clearly observed.

For atomic force microscopy (AFM) analysis, uncapped QDs grown on GaAs and Si (with dislocation filter) substrates were also grown. AFM was used to characterize the morphology of the uncapped QDs and the optical properties of the samples were characterized using temperature and power-dependent photoluminescence (PL). Transmission Electron Microscopy (TEM) was used for the structural analysis of InAs/InGaAs QDs grown on GaAs and Si substrates.

The PL signal of both samples were investigated as a function of laser power and temperature using a Janis closed-loop helium cryostat. The samples were excited with a 532 nm solid state green laser. The PL spectra was collected in an Andor Shamrock 500i spectrometer coupled with a high sensitivity Andor iDus InGaAs CCD camera. The PL experimental conditions were the same for both samples in order to compare their PL spectra shape and intensities.

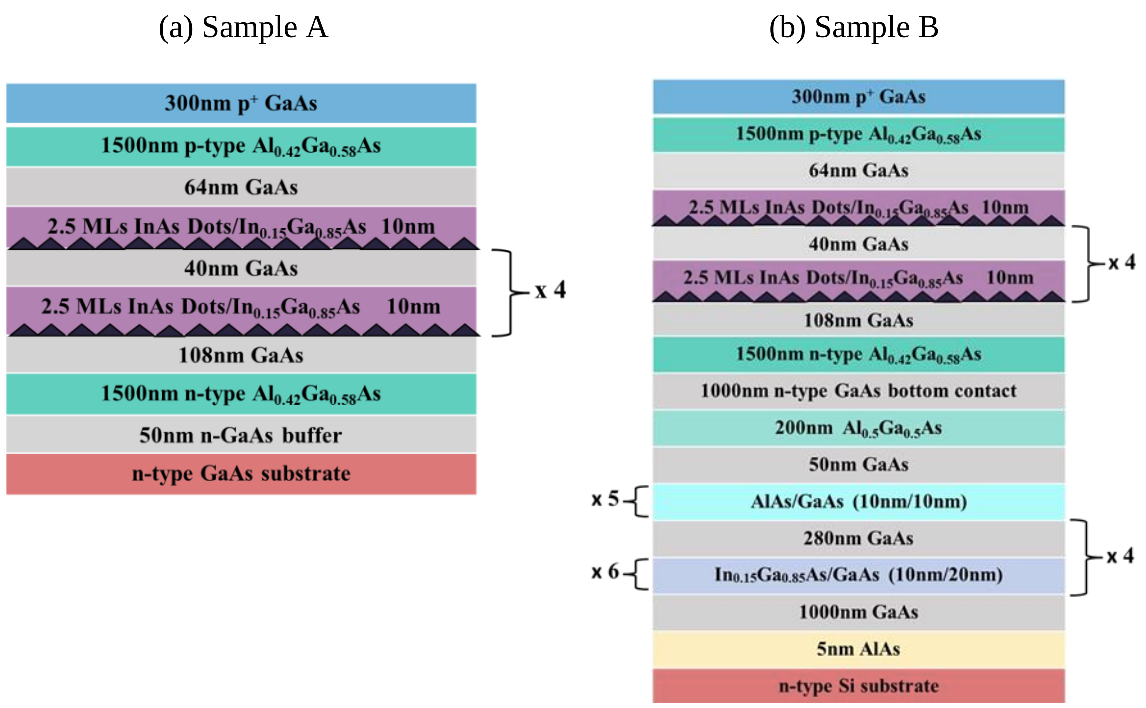


Figure 1. Schematic structure of QDs laser samples grown on (a) GaAs substrate (Sample A) and (b) on Si substrate (Sample B).

Results and discussion

AFM was used to characterize the morphology of the uncapped QDs and the results are shown in Figure 2 (a-d). The obtained values of the QDs' density is ~1.8 x 10^{10} cm^{-2} for both samples grown on GaAs and Si substrates. However, we noticed a reduction of the QDs aspect ratio for the sample grown on Si. The average diameter and height of the QDs grown on GaAs and Si substrates were 30.8±2.1 nm and 13.3±0.9 nm, and 30.7±4.2 nm and 11.8±1.9 nm, respectively. During the capping process, the QDs size was reduced in both samples as shown in the bright field transmission electron microscopy (TEM) images (Figure 2 (c,d)). In particular, the diameter of the QDs in both samples ranges between 20 and 25nm and the height is reduced to 10nm which is the same as the width of the $In_{0.15}Ga_{0.85}As$ QWs (Figure 2c and Figure 2d). We note that it is not easy to do a direct comparison of TEM and AFM data as the number of QDs measured with TEM (10 QDs) is far below the number of QDs measured by AFM (~200 QDs).

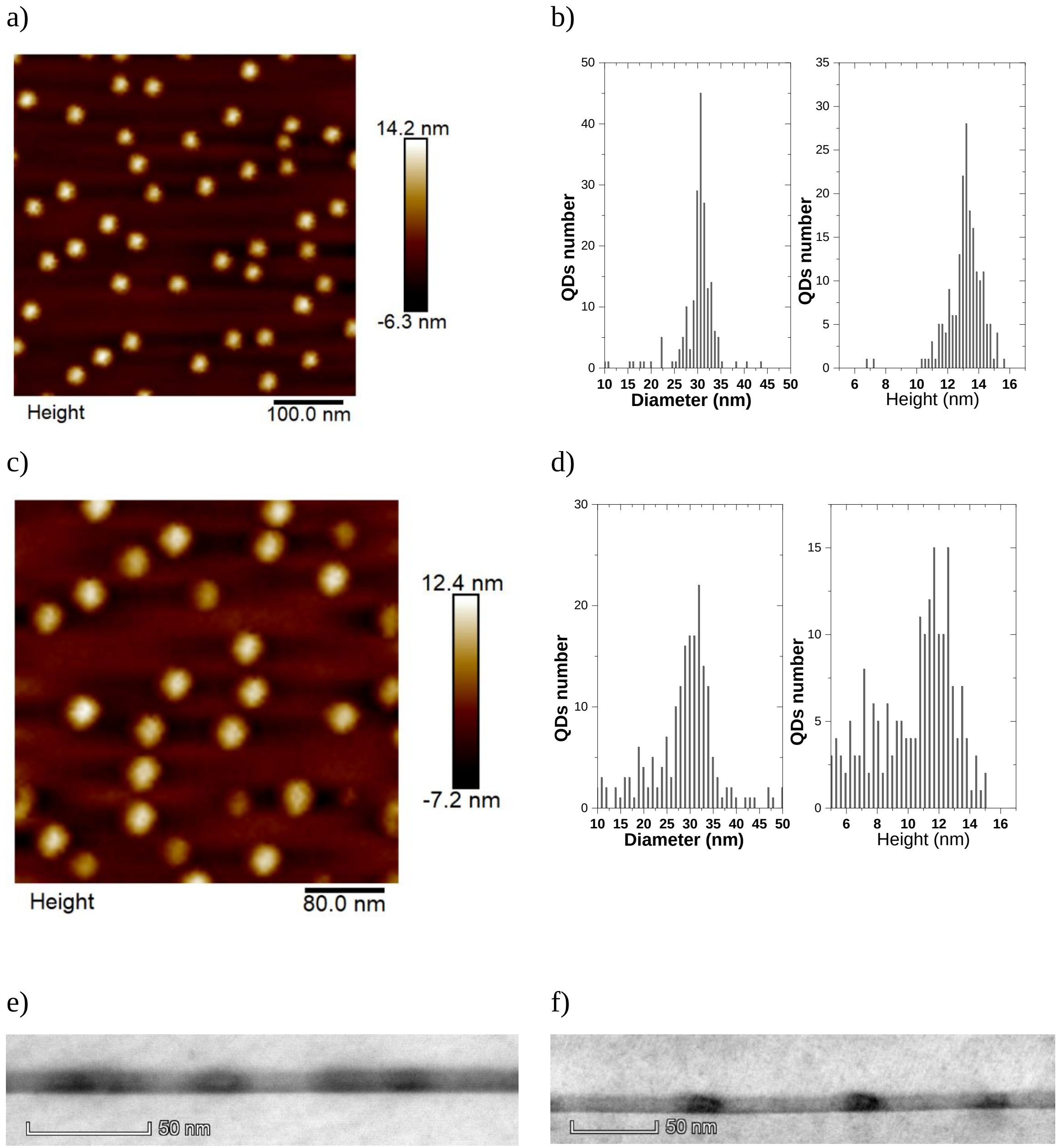


Figure 2. AFM images (0.4µm×0.4µm) and histograms distribution of 2.5 MLs uncapped InAs QDs grown on (a-b) GaAs substrate and (c-d) Si substrate. Bright field TEM images of InAs/InGaAs QDs grown on GaAs substrate (e) and Si substrate (f).

The use of the dislocation filter and the GaAs buffer layer for the growth on silicon substrate is equivalent to a virtual GaAs substrate and allowed to achieve the same QD density and nearly the same dimensions compared to the ones grown on GaAs substrate as confirmed by AFM measurement. The growth of InAs QDs grown directly on silicon substrate would have a significantly different QD distribution and density because of the large lattice mismatch.

Photoluminescence

Figure 3 shows typical PL spectra of (InGaAs/GaAs) QDs for Sample A (GaAs substrate) and Sample B (Si substrate), at 10 K and laser excitation power P_{EXC}=40mW corresponding to a laser power density of 2.0 W/cm^2 (laser spot diameter ~ 0.8 mm). The dominant peak at 1.02 eV in Sample A is ascribed to interband transition occurring from the electron ground state E_0 to the heavy hole ground state HH_0 of the InAs dot (E_0-HH_0). This PL band also exhibits some asymmetry in the high-energy side that could be ascribed to reduced filling of QDs excited states, not well distinguishable and resolved in PL spectra. In addition, a small peak at 1.477 eV is attributed to the GaAs capping layer. For Sample B, the observed E_0 (1.00 eV), E_1 (1.11 eV) and E_2 (1.07eV) PL peaks are well resolved and correspond to ground state transition, first and second excited states, respectively. It is plausible to suggest the presence of these same excited states peaks on the high energy shoulder of the PL spectra of Sample A, although they are not well pronounced and well resolved as in Sample B.

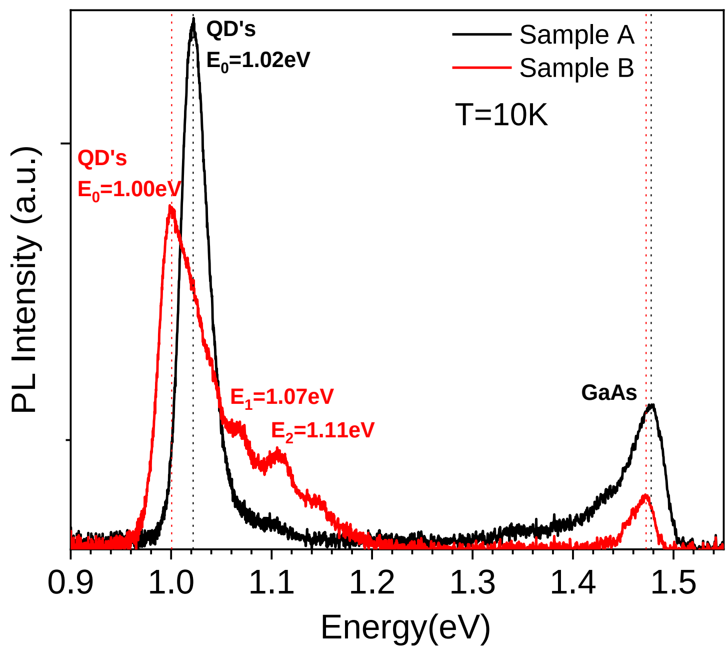


Figure 3: PL spectra of InGaAs/GaAs QDs grown on GaAs (Sample A) and silicon (Sample B) substrates at laser power P_{EXC}=40mW and 10K. The PL bands attributed to InAs QDs and GaAs capping layer are indicated.

Figure 4 (a) presents the PL spectra for Sample A measured under different excitation power intensities at 10 K. At low excitation power (3 mW) only one symmetric peak is present at 1.02 eV (ground state transition E_0 to HH_0) and it remains nearly symmetric and unchanged up to an excitation power < 10 mW. With increasing excitation power, one additional peak is evidenced on the high-energy side of the PL spectra (1.1 eV, see inset), which corresponds to the filling of the first excited state E_1.

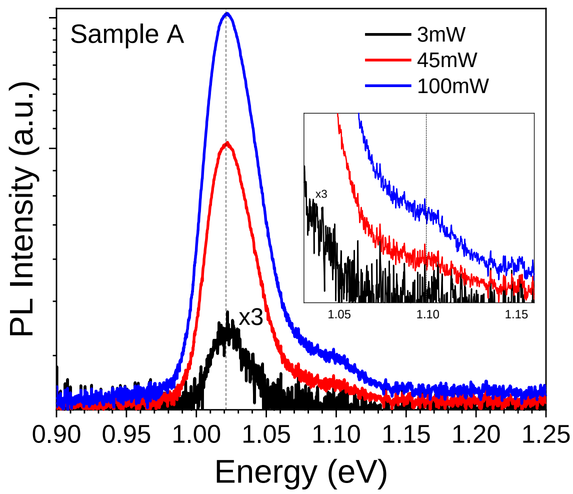
Figure 4(c) shows the E_0 PL peak (1.00 eV) observed in Sample B, and it is clearly asymmetric and broader than the one detected in Sample A. The peak energy also remains nearly unchanged with increasing excitation power. Therefore, the broad and asymmetric PL peak at 1.00 eV may reflect an inhomogeneous size distribution of the QDs, associated with E_0 transition induced from the finite-size distribution of the QDs as a consequence of carrier's random distribution at low temperatures. As the laser power increases, additional peaks are revealed. These peaks are probably due to excited states of the self-assembly QDs as discussed before. Figure 4 (b,d) shows that the QD PL intensity decreases for Sample A in the temperature range of 30-120 K, and quenches completely at temperatures above ~180 K, while for Sample B although the PL intensity at 10K is smaller than Sample A, it decreases and quenches completely at a higher temperature of ~220 K than Sample A. This decrease of the PL intensity as function of temperature is usually attributed to thermal escape of carriers from the QD ground states into the continuum followed by nonradiative recombination in the InGaAs and GaAs barriers (SRL and capping layer) at higher temperatures, when the thermal escape becomes dominant [25-27]. As will be discussed below, the difference in the PL intensity between the two samples shown in Fig. 3 is attributed to the different surface growth condition that could change the QD emission efficiency.

The effect of the silicon substrate on the QDs' PL emission is clearly demonstrated by the following observations (from Sample A to Sample B): (i) the QD PL peak red-shifted from 1.02 eV to 1.00 eV; (ii) the PL intensity decreased by a factor of ~ 1.75; and (iii) the Full Width at Half Maximum (FWHM) increased from 31 meV to 46 meV (at a laser excitation power of 3mW). In our previous discussion we showed that the size of the QDs is similar for both samples, with a slight reduction of the aspect ratio from Sample A to Sample B, which is a negligible effect in terms of quantum confinement between the two samples. Although the redshift in the PL energy has been reported and explained by different mechanisms along with strain and carrier confinement, in this case it is probably due to dislocations coming from the

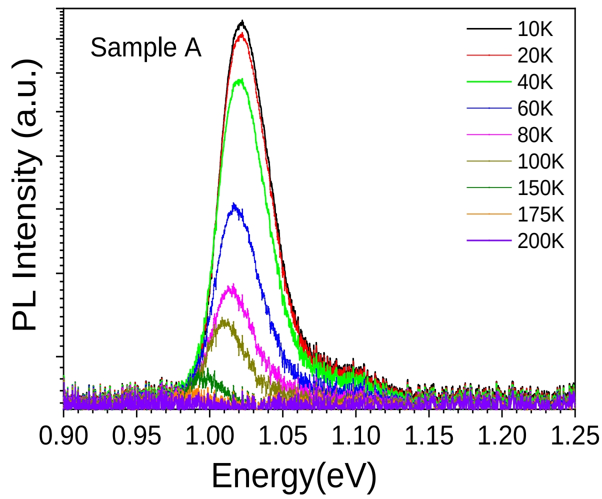
Si/GaAs interface and reaching the QD region that could affect the surface conditions for the growth of the QDs, and thus reducing their emission efficiency. The residual strain of the GaAs/Si heterointerface is not expected to have a very significant influence in these samples since there is a GaAs layer with a thickness of more than 3 microns before the QDs layer and, therefore, the strain should be fully relaxed [28-30]. Additionally, the decrease of the PL intensity of Sample B as compared to Sample A indicates that the growth condition of QDs was significantly changed in the InAs QDs active region when Si substrate is used, reducing the optical emission efficiency [31-34].

Furthermore, the QDs PL peak of Sample A (FWHM= 31 meV) at 10K and 3mW laser power excitation is narrower than that for Sample B (FWHM= 46 meV) by considering only the deconvoluted transition associated with E_0. As discussed before, the distribution of the InAs QD size in the samples grown on GaAs and Si substrates is possibly affecting the changes observed in the PL results. The observed narrower FWHM for samples grown on the GaAs substrate sample indicates that the QD size distribution is better in Sample A than in Sample B (as shown in Figure 2b and Figure 2d), meaning that the QDs distribution is more inhomogeneous for Sample B than in Sample A, since the FWHM is inversely correlated with QD size and shape uniformity. It is important to note that the emission efficiency can also be reduced due to the introduction of different surface growth conditions for the QDs, resulting in more inhomogeneous size and shape distributions. These aspects may have been caused by the relatively higher number of threading dislocations in the active region, while the increase of the FWHM confirms a less uniform QD size distribution for this sample. Therefore, the use of Si substrates can have a profound impact on the optical properties of InAs QDs.

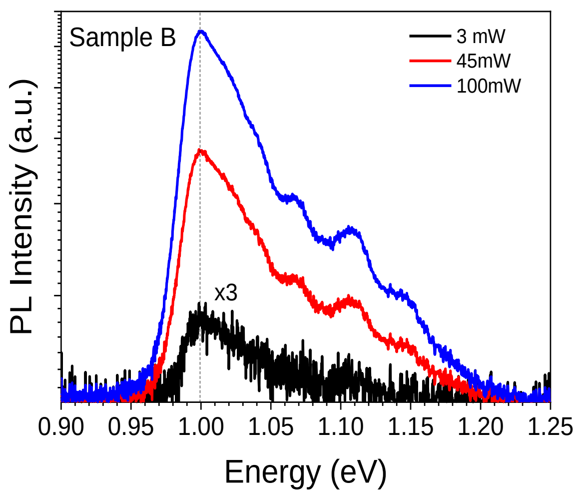
(a)


Sample A
3mW
45mW
100mW
x3
PL Intensity (a.u.)
0.90
0.95
1.00
1.05
1.10
1.15
1.20
1.25
Energy (eV)

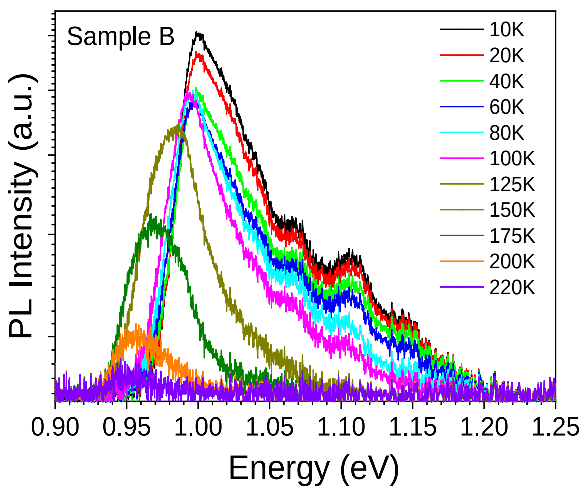
(b)


Sample A
10K
20K
40K
60K
80K
100K
150K
175K
200K
PL Intensity (a.u.)
0.90
0.95
1.00
1.05
1.10
1.15
1.20
1.25
Energy(eV)

(c)


Sample B
3 mW
45mW
100mW
x3
PL Intensity (a.u.)
0.90
0.95
1.00
1.05
1.10
1.15
1.20
1.25
Energy (eV)

(d)


Sample B
10K
20K
40K
60K
80K
100K
125K
150K
175K
200K
220K
PL Intensity (a.u.)
0.90
0.95
1.00
1.05
1.10
1.15
1.20
1.25
Energy (eV)

(e) (f)

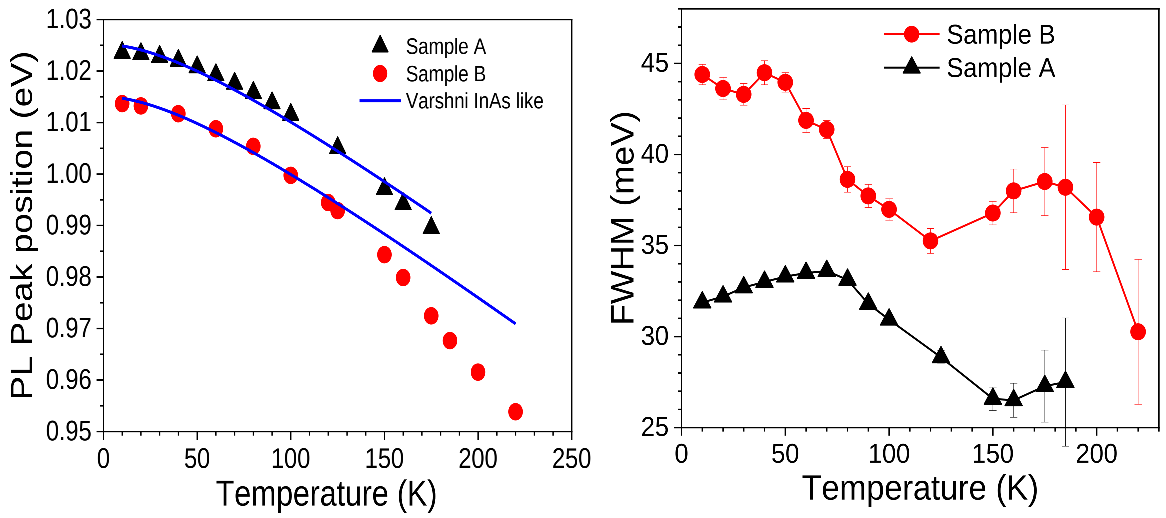


Figure 4: 10K PL spectra as function of laser power (a: Sample A, c: Sample B). PL spectra as function of temperature for a laser excitation power P_{EXC}=40mW (b: Sample A, d: Sample B). (e) PL peak energy and (f) PL FWHM of E_0 transition as a function of temperature for InAs/GaAs QDs grown on GaAs (Sample A) and Silicon (Sample B) substrates at a laser excitation power P_{EXC}=25mW and respective error bars. Solid lines in (e) are the InAs band gap shrinkage obtained from Varnish law. The results of E_0 transition from PL data was obtained from the deconvoluted PL spectra (excluding effects of QD excited states).

Figure 4 (e) shows the E_0 PL peak as function of temperature as well as the InAs-like band gap decrease by using the Varshni approximation fitting [35]. The PL peaks match well with the band gap variation up to 150 K. However, the QD PL peak redshifts faster when further increasing the temperature. The competing mechanisms of the carrier's thermal escape and recapture between the QDs, results in the redshift of the PL peak energy and the narrowing of the FWHM as the temperature increases [27]. This behaviour indicates that the carriers experience a transfer from the smaller QDs with deeper energy levels to the larger QDs with shallower energy confinement under thermal excitation, which results in a lower interband emission energy and a red-shift of the PL peak position [36]. This same carrier transfer process could also be evidenced by the temperature dependence of the PL FWHM for E_0 transition for both samples as shown in Fig. 4 (f), and will be discussed below.

The PL FWHM presents a similar trend for both samples, with a decrease of the FWHM as the sample's temperature increases. The PL FWHM variation with temperature is generally attributed to the carrier thermal redistribution amongst QDs with different sizes. A decrease of the FWHM together with a red shift of the PL emission, when the temperature rises up to 150 K, are usually observed in the mid temperature range and explained by thermal escape of carriers occurring at lower temperatures for high-energy dots and carriers being recaptured by dots emitting on the low-energy side of the distribution [37]. Sample B also shows the largest FWHM variation and has the highest FWHM for all temperature ranges. With a further increase of the temperature above 150 K, the broadening of PL FWHM is likely attributed to the electron-phonon scatter over QDs with different sizes [36,38].

In general, our results indicate that the use of Si substrate combined with a SRL to grow InAs QDs is a promising approach to integrate them with Si technology what is demonstrated by QD morphology data and a significant efficiency of the optical emission. However, there are still some important issues for obtaining the appropriate design and materials for the dislocation filter at the Si/GaAs heterointerface in order to reduce the dislocations coming from the Si/GaAs interface that reach the QD region, consequently improving the optical properties of the QDs.

Conclusion

In summary, the structural, morphological and optical properties of two InAs QD laser structures with similar active regions grown on GaAs and Si substrates using strain reducing layer (SRL) have been investigated using AFM, TEM and PL techniques. Our results evidenced the formation of quite similar QDs in both structures, with higher strain for QDs in sample grown on Si substrate. It was observed that the PL intensity from QDs grown on Si substrate decreased by a factor of ~ 1.7 when compared with those grown on GaAs substrate control sample. However, despite this reduction, our results demonstrate the possibility of growing InAs QDs on Si substrates with good emission efficiency for laser applications. In addition, was also observed in the InAs QDs grown on Si substrate a broadening of the PL spectrum from ~30 meV to a value of ~52meV for an excitation power of 3 mW. This broadening is attributed to the QD size inhomogeneity increase during the growth on Si substrate. This opens up new possibilities for controlling the density and size of QDs when using specific type of SRL/substrate.

Acknowledgments

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References

[1] Z. M. Wang, New York: Springer-Verlag (2008).

[2] D. Bimberg, Quantum dots for lasers, amplifiers and computing, J. Phys. D Appl. Phys. 38, 2055 (2005).

[3] D.L. Huffaker, G. Park, Z. Zou, O.B. Shchekin, D.G. Deppe, 1.3 mm room temperature GaAs-based quantum-dot laser, Appl. Phys. Lett. 73, 2564 (1998).

[4] A. Creti, V. Tasco, A. Cola, G. Montagna, I. Tarantini, A. Salhi, A. Al-Muhanna, A. Passaseo, M. Lomascolo, Role of charge separation on two-step two photon absorption in InAs/GaAs quantum dot intermediate band solar cells, Appl. Phys. Lett. 108, 063901 (2016).

[5] M. V. Maksimov, Yu. M. Shernyakov, N. V. Kryzhanovskaya, A. G. Gladyshev, Yu. G. Musikhin, N. N. Ledentsov, A. E. Zhukov, A. P. Vasil'ev, A. R. Kovsh, S. S. Mikhrin, E. S. Semenova, N. A. Maleev, E. V. Nikitina, V. M. Ustinov, and Zh. I. Alferov , High-Power 1.5 mm InAs–InGaAs Quantum Dot Lasers on GaAs Substrates Semiconductors, Vol. 38, No. 6, 732–735 (2004).

[6] A. Salhi, S. Alshaibani, Y. Alaskar, A. Albadri, A. Alyamani, Achieving wavelength emission beyond the C-band from Type-II InAs-GaAsSb quantum dots grown monolithically on silicon substrate, Journal of Alloys and Compounds 771, 382e386 (2019).

[7] M.J. da Silva, A.A. Quivy, S. Martini, T.E. Lamas, E.C.F. da Silva, J.R. Leite, InAs/GaAs quantum dots optically active at 1.5 mm, Appl. Phys. Lett. 82, 2646 (2003).

[8] Ledentsov, N.N.; Shchukin, V.A.; Kettler, T.; Posilovic, K.; Bimberg, D.; Karachinskii, L.Y.; Gladyschev, A.Y.; Maksimov, M. V; Novikov, S. V; Shernyakov, Y.M.; et al. J. Cryst. Growth, 301, 914-922 (2007).

[9] Mi, Z.; Bhattacharya, P.; Yang, J. Appl. Phys. Lett., 89, 153109 (2006).

[10] Semenova, E.S.; Hostein, R.; Patriarche, G.; Mauguin, O.; Largeau, L.; Robert-Philip, I.; Beveratos, A.; Lemaitre, A. J. Appl. Phys., 103, 103533 (2008).

[11] Seravalli, L.; Trevisi, G.; Frigeri, P. J. Appl. Phys., 114, 184309 (2013)

[12] Golovynskyi, S.L.; et al. J. Appl. Phys., 117, 214312 (2015).

[13] J. Tatebayashi, M. Nishioka, Y. Arakawa, Over 1.5 mm light emission from InAs quantum dots embedded in InGaAs strain-reducing layer grown by metalorganic chemical vapor deposition, Appl. Phys. Lett. 78, 3469 (2001).

[14] Wang, P., Chen, Q., Wu, X. et al. Detailed Study of the Influence of InGaAs Matrix on the Strain Reduction in the InAs Dot-In-Well Structure. Nanoscale Res Lett 11, 119 (2016).

[15]A. Salhi, S. Alshaibania, M. Alhamdana, H. Albrithen, A. Alyamani, M. El-Desouki,Effects of Sb incorporation in GaAsSb-capping layer on the optical properties of InAs/GaAs QDs grown by molecular beam epitaxy, Superlatice Microstruct. Volume 101, 138-143 (2017).

[16] A. Hospodkov_a, J. Pangr_ac, J. Vysko_cil, M. Zíkov_a, J. Oswald, P. Komninou, E. Hulicius, Growth of InAs/GaAs quantum dots covered by GaAsSb in multiple structures studied by reflectance anisotropy spectroscopy, J. Cryst. Growth 414, 156e160 (2015).

[17] W.-S. Liu, T.-F. Chu, T.-H. Huang, Energy band structure tailoring of vertically aligned InAs/GaAsSb quantum dot structure for intermediate-band solar cell application by thermal annealing process, Opt. Express 22, 30963 (2014).

[18] C.T. Huang, Y.C. Chen, S.C. Lee, Improved photoresponse of InAs/GaAs quantum dot infrared photodetectors by using GaAsSb strain reducing layer, Appl. Phys. Lett. 100, 043512 (2012).

[19] D. Thomson, et al., J. Optic. 18, 073003 (2016).

[20] M. Buffolo et al., "Origin of the Diffusion-Related Optical Degradation of 1.3 μm Inas QD-LDs Epitaxially Grown on Silicon Substrate," in IEEE Journal of Selected Topics in Quantum Electronics, vol. 28, no. 1, 1900109 (2022).

[21] K. Li et al. O-band InAs/GaAs quantum dot laser monolithically integrated on exact (0 0 1) Si substrate, Journal of Crystal Growth, Volume 511, 56-60 (2019).

[22] Alan Y. Liu, Sudharsanan Srinivasan, Justin Norman, Arthur C. Gossard, and John E. Bowers, "Quantum dot lasers for silicon photonics [Invited]," Photon. Res. 3, B1-B9 (2015).

[23] J. C. Norman et al. A Review of High-Performance Quantum Dot Lasers on Silicon. IEEE Journal of Quantum Electronics, vol. 55, no. 2, pp. 1-11, 2000511 (2019).

[24] Park J-S, Tang M, Chen S, Liu H. Heteroepitaxial Growth of III-V Semiconductors on Silicon. Crystals. 10(12). 1163 (2020).

[25] P.B. Joyce, T.J. Krzyzewski, G.R. Bell, T.S. Jones, S. Malik, D. Childs, R. Murray, Journal of Crystal Growth 227–228, 1000-1004 (2001).

[25] E. C. Le Ru, J. Fack, and R. Murray. Temperature and excitation density dependence of the photoluminescence from annealed InAs/GaAs quantum dots. Physical Review B 67, 245318 (2003)

[26] J. Yang, P. Bhattacharya, and Z. Mi, "High-performance In 0.5 Ga 0.5 As/GaAs quantum-dot lasers on silicon with multiple-layer quantum-dot dislocation filters," IEEE Trans. Electron. Dev. 54(11), 2849–2855 (2007).

[27] R. Chen, H. Liu, and H. Sun, "Electronic energy levels and carrier dynamics in InAs/InGaAs dots-in-a-well structure investigated by optical spectroscopy," J. Appl. Phys. 107(1), 013513 (2010).

[28] Andrews, A. M., et al. Journal of Applied Physics 95.11: 6032-6047 (2004).

[29] Takano, Y., et al. Applied Physics Letters 73.20: 2917-2919 (1998).

[30] Samonji, K., et al. Journal of applied physics 86.3: 1331-1339 (1999).

[31] Wohlert, D. E., et al. Journal of Vacuum Science & Technology B: Microelectronics and Nanometer Structures Processing, Measurement, and Phenomena 17.3: 1120-1123 (1999).

[32] Hiwatashi, Fumito, and Koichi Yamaguchi. Applied surface science 130: 737-741 (1998).

[33] Himwas, Chalermchai, Somsak Panyakeow, and Songphol Kanjanachuchai. Nanoscale research letters 6.1: 1-7 (2011).

[34] Seravalli, Luca, Giovanna Trevisi, and Paola Frigeri. CrystEngComm 14.3: 1155-1160 (2012).

[35] K. P. O'Donnell and X. Chen, Temperature dependence of semiconductor band gaps Appl. Phys. Lett. 58, 2924 (1991).

[36] J. Wu et al. Monolithically integrated InAs/GaAs quantum dot midinfrared photodetectors on silicon substrates. ACS Photon., vol. 3, pp. 749–753, 18 (2016).

[37] E. C. Le Ru, J. Fack, and R. Murray, Temperature and excitation density dependence of the photoluminescence from annealed InAs/GaAs quantum dots. Phys. Rev. B 67, 245318 (2003).

[38] R. Heitz et al. Energy relaxation by multiphonon processes in InAs/GaAs quantum dots. Phys. Rev. B, vol. 56, pp. 10435–10445, 15 (1997).