Optical and electrical properties of stacked binary InAs-GaAs quantum dot structures prepared under Surfactant-mediated growth conditions

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Abstract. The structural, optical and electrical properties of a 10-layer InAs/GaAs quantum dots (QDs) system having InAs layers (2.9ML) grown under surfactant growth conditions, using only an impinging In beam, were investigated. This growth mode still resulted in the formation of quantum dots, but with dot sizes smaller and sample quality better than those for normal growth (NG) of ~3ML InAs-GaAs QD structures. Room temperature photoluminescence measurements showed PL emission from this sample at 1200-1300 nm, i.e. reaching the telecom O-band. At low substrate growth temperatures (LT), 250°C, and under the same “Arsenic free” growth condition an InAs/GaAs superlattice structure without the formation of QD was successfully grown with up to 2.9MLs of InAs, which was not achievable under NG conditions. Both samples showed a noticeable photocurrent when illuminated with 1.2 - 1.3 μm lasers. Thus they can be used as photoconductive materials that can be excited with wavelength longer than that used for the well-known LT-GaAs ultrafast material and close to the telecom wavelengths of 1.3 μm for Terahertz imaging or other optoelectronic applications.

1. Introduction

Semiconductor quantum dots (QDs) have been extensively investigated in recent years due to their unique optical properties arising from their discrete energy levels, i.e., delta function-like density of states, which make them useful for optoelectronic applications. InAs QDs have attracted much attention due to the effective bandgap energy which allows emission and absorption at one of the telecom wavelengths (~1.3 μm), where silica fibers have one of their minimum losses windows and minimum dispersion. For the Stranski-Krastanow growth mode the density of the dots is between $10^9$ - $10^{11}$ cm$^2$ depending on the growth parameters, and this density corresponds to a small fractional area occupancy ~ 10% [1]. This low surface coverage of QDs reduces some of the physical values that are important in optoelectronic applications, such as the low normal incident absorption and low model gain for a single dot plane lasers [2]. Therefore, multiple QD layers, stacked QD structures, are normally grown in order to enhance the performance of QD-based devices. [3-5]

It has been found that reducing the thickness allows the strain fields to act as nucleation centres for the self-assembled QDs in the subsequent grown layer. Such strain leads to a correlation between QDs
to form stacks of vertically aligned QDs [1, 6] which alter the optical and electrical properties of the multilayered QD materials [1]. Moreover, Ng et al. [7] studied the effect of increasing the InAs’ nominal thickness on the properties of the same QDs system, i.e. InAs/GaAs multiple QD. The study showed that, in addition to the formation of InAs QDs, there was a formation of volcano-like defects after increasing the thickness to 2.73 MLs. These defects, extending from the initial InAs layers to the surface of the sample, degraded the structural and optical quality of the structure. Although such extended defects can be reduced by increasing the thickness of the spacer layer [8], this study will show another method by which these defects can be eliminated without changing the thickness of the spacer layers.

In this work, two stacked binary InAs/GaAs QD structures were grown under surfactant-mediated growth conditions at two different temperatures. The growth technique will be illustrated in the following section followed by a discussion of some of the structural, optical and electrical properties of these samples and some applications they can be used to.

2. Growth technique

The two samples analysed in this study were grown using a RIBER VG V90H MBE system. Both samples consist of a 170 nm buffer layer grown at 580°C, followed by ten periods of 25 nm thickness GaAs spacers and InAs with a nominal thickness of 2.9 monolayers (MLs). The growth rate of GaAs and InAs was 1 ML/sec⁻¹ and 0.033 ML/sec⁻¹ respectively. The only difference between the samples was the growth temperature of the InAs/GaAs layers which was 450°C for sample no. 1949 and low temperature LT, i.e. 250°C, for sample no. 1753. The InAs layers of both samples were grown using only the In beam while the As source was closed. The group V elements were obtained under such a “surfactant growth technique” from the residual As in the growth chamber.

3. Results

In comparison to the normal growth condition (NGC) technique, the surfactant growth condition (SGC) mode resulted in an improvement in the quality of the sample structure. This can be seen from the double crystal x-ray diffraction (DCXRD) curves presented in Figure 1. Such quality improvement is apparent from the sharpness of the satellite peaks with FWHM of 69.5 arcsec for the zeroth order peak as can be seen from the rocking curve of the VMBE#1949 sample in comparison with the broader peaks with FWHM of around 105 arcsec for the zeroth order DCXRD peak of the structure grown under NGC [7]. In addition, there was no presence of peaks associated with the satellite peaks in the DCXRD spectrum of the SGC sample unlike the very weak second periodic peaks in the spectrum of the NGC sample which is largely correlated with the formation of volcano-like defects in such NGC structures, as reported previously [7].

![Figure 1](image1.png)

**Figure 1.** DCXRD rocking curves of the samples grown at: (a) 450°C and (b) 250°C.

![Figure 2](image2.png)

**Figure 2.** TEM Images of the samples grown at: (a) 450°C and (b) 250°C.
In addition to the sharp satellite peaks, the excellent quality of the samples can be seen from the bright field TEM images which show the formation of InAs QDs in sample no. 1949. Figure 2a. As can be noticed from the strained regions around the InAs QDs, the average width of the QDs is less than 20nm which is smaller than that of the 2.73MLs-InAs/GaAs QDs grown under NGC by Ng et al. where the width of QDs appeared to be above 50nm. This result shows the strong effect of the As pressure reduction during the growth of the QDs and such size reduction can be the reason for the absence of the volcano-like defects in the SGC sample as this reduces the extended strain between the adjacent InAs layers which are thought to be the reason for the defect formation.

As shown in Figure 2b, there was no formation of QDs in the LT grown sample, no. 1753, which can be due to the lower migration length of the adatoms at LT which leads to the formation of a superlattice structure instead of QDs. Thus, by controlling the amount of arsenic at low temperatures as occurs in the SGC mode, the critical thickness of InAs can be extended well beyond the 1.7 ML limit seen at higher growth temperatures. It should be mentioned here that attempts to achieve such a thickness of InAs layers, 2.9 MLs, under normal growth conditions were not successful as the InAs layers turned into a halo-like structure within ~1.5 ML at low substrate growth temperature.

Room temperature photoluminescence (PL) measurements carried out using 532 nm excitation wavelength showed clear PL emission from the QD sample, no. 1949, at around 1246 nm, i.e. close to the 1.3 um telecom O-band, with FWHM of around 50 nm, indicating a reasonable uniformity in the size of the QDs (see Figure 3). In addition, there was another peak at about 1180 nm having an intensity almost 10 times less than the intensity of the main PL peak and with about 90 nm FWHM. This peak can be related to a transition between exited states, whereas the main peak is a result of ground state e-h recombination in the QDs. On the other hand and as expected, there was no noticeable emission from the LT grown sample, no. 1753, which can be due to the point defects created during LT growth acting as nonradiative recombination centres.

Post-growth annealing on the LT grown sample showed no improvement in its optical quality. In addition the sample maintained its superlattice structure after annealing with no changes towards the QD morphology. However, the excess arsenic incorporated in the material due to the LT growth started to interact with the InAs layers at annealing temperature above 400°C as such a process enhances the point defects to form As nanoparticles very close to the InAs layers which consequently alter the morphology of these layers as shown in Figure 4. The size of these As clusters increased from an average diameter of 3 nm after 450°C to 13 nm after 550°C annealing temperatures; such interaction between the As clusters and the InAs layers were studied in more details elsewhere. [9].
Due to the presence of the QDs in the higher temperature grown sample and the As defects in the LT sample which can reduce the carrier lifetime, these samples can be used as ultrafast photoconductive PC materials for generating and detecting terahertz radiation using photomixing or broadband pulsed techniques. Both techniques required PC materials with an ultrashort carrier lifetime for fast response and a very high resistance to minimize the dark current in the THz emitters and detectors. LT GaAs is one of the well known materials that are used for this purpose; however, its band gap prevents the use of telecom lasers for excitation. The two samples studied in this work can be used as alternatives due to the narrower bandgap material imbedded in the structure, i.e. InAs. In order to measure the resistance and the responsivity of the samples to the 1.3µm excitation, PC devices have been fabricated by depositing bow-tie shape metal contacts with a gap length of 5 µm. Figure 5 shows the dark resistance of the sample as a function of the annealing temperature. Sample no 1949 shows the high resistance caused by the QDs acting as traps for the carriers, but annealing showed no significant effect which was expected as the sample was grown at a relatively high temperature. In contrast, the resistance of sample no 1753 was very low for an unannealed sample due to the hopping conduction between midgap states created by As point defects. The reduction in the point defects’ density after annealing, in addition to the formation of As clusters which form depletion regions around themselves acting as buried Schottky barriers that lead to a dramatic increase in the resistance. Both samples showed a resistance as high as that reported for LT-GaAs material, that is, the well-known material used for THz devices [10].

Photocurrent measurements were performed with a tunable laser (spot radius 6 µm) and fairly high photocurrent peaks around the ground state transition peak were observed. Figure 6 shows the current responsivity as a function of the excitation wavelength at 20 V bias. The photocurrent measured from the unannealed LT grown sample was smaller than the one from unannealed QDs sample which is likely due to the shorter carrier lifetime in the LT material. The photocurrent peaks were more pronounced at high bias voltages.

Figure 5. Dark resistance as a function of the annealing temperature. The gap length of the metal contacts was 5 µm.

Figure 6. Current responsivity as a function of the excitation wavelength, both samples are unannealed, gap length 5 µm, bias 20 V.

4. Conclusion
Structural, optical and electrical properties of novel normal and LT 10-layer InAs/GaAs surfactant grown materials were investigated. The results presented here showed that the use of SGC technique to grow stacked 2.9ML InAs-GaAs quantum dot structures at normal growth temperature eliminated the formation of extended (volcano-like) defects that were present in NGC samples while using the same technique for LT growth resulted in the formation of up to 2.9ML-thick InAs layers without quantum dot formation thus extending greatly the critical thickness of InAs at these very low growth temperatures.
The dependences on exciting wavelength, power and bias voltage were studied and the data obtained suggests that they can be used as photoconductive materials for Terahertz imaging or other optoelectronic applications. Unlike LT-GaAs, these samples can be excited at wavelength above 870nm and close to the telecom wavelengths of 1.3 μm and compared to other lower bandgap materials used for THz applications, e.g. LT InGaAs [11,12], the InAs/GaAs superlattice and QDs structures have the additional advantage of a high resistivity of the material. Further investigations of these samples such as lifetime measurements are on-going.

The authors from The University of Strathclyde acknowledge the financial support from EPSRC, Project No. EP/E025021.

References

[1] Migliorato M, Wilson L, Mowbray D, Skolnick M, Al-Khafaji M, Cullis A and Hopkinson M 2001 J. Appl. Phys. 90 6374-8
[2] Fry P W, Harris L, Parnell S R, Finley J, Ashmore A D, Mowbray D J, Skolnick M S, Hopkinson M, Hill G, and Clark J C 2000 J. Appl. Phys. 87 615-7
[3] Schmidt O G, Kirstaedter N, Ledentsov N N, Mao M H, Bimberg D, Ustinov V M, Egorov A Y, Zhukov A E, Maximov M V, Kopev P S, and Alferov Z I 1996 Electron Lett. 32 1302-4
[4] Heinrichsdorff F, Mao M, Kirstaedter N, Krost A, Bimberg D, Kosogov AO and Werner P 1997 Appl. Phys. Lett. 71 22-4
[5] Tatebayashi J, Hatori N, Ishida M, Ebe H, Sugawara M, Arakawa Y, Sudo H and Kuramata A 2005 Appl. Phys. Lett. 86 053107-9
[6] Henini M Microelectr. J. 2003 34 333-6
[7] Ng J, Bangert U and Missous M Semicond. Sci. Tech. 2007 22 80-5
[8] Ng J and Missous M Microelecetr. J. 2006 37 1446-50
[9] Alduraibi M, Mitchell C, Chakraborty S and Missous M Microelecetr. J. 2009 40 550-3
[10] Gregory I S, Baker C, Tribe W R, Evans M J, H. Beere E, Linfield E H, Davies A G and Missous M 2003 App. Phys. Lett. 83 4199-201
[11] Baker C, Gregory I, Evans M, Tribe R, Linfield EH and Missous M Opt. Express 2005 13 9639-44
[12] Takazato A, Kamakura M, Matsu T, Kitagawa J and Kadoya Y Appl. Phys. Lett. 2007 91 011102