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Effect of the growth parameters on the structure and morphology of InAs/InGaAs/GaAs DWELL quantum dot structures

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Abstract

The paper reports a systematic analysis by cross-sectional transmission electron microscopy of the structural parameters of molecular beam epitaxy grown multilayer InAs/InGaAs/GaAs dot-in well quantum dot (QD) lasers with a view to improve aspects such as uniformity of QD size, high spatial density, improved confinement and to reduce or eliminate defects. Based on our standard structure, previously optimised by considering only PL efficiency, we have modified parameters such as well composition and thickness and shown that the previously observed photoluminescence degradation as these parameters are increased, is due to threading dislocations. The use of the modified high-temperature growth for the barrier is shown to be effective in suppressing this dislocation mechanism. Processed laser devices with these samples exhibit room temperature threshold currents ~30 A cm^{-1}, amongst the best reported in the literature. Finally, the use of reduced (35 nm) barrier thickness produces both vertically correlated QDs and quantum wells, with the resulting structure resembling a 'dot within a dot' structure.

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Keywords: A1. Defect; A1. TEM; A3. DWELL; A3. MBE; A3. Quantum dots; B1. GaAs

1. Introduction

Self-organised semiconductor structures with reduced dimensionality are currently attracting strong interest due to the potential device advantages resulting from the highest level of confinement [1]. One major area of research has been the growth of In(Ga)As islands for ultra-low threshold quantum dot (QD) lasers in which interest for telecommunication applications around 1.3 μm has focused on structures based on the so-called

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dot in well (DWELL) approach, where the QD is embedded in a matrix of low indium composition InGaAs in the form of a quantum well (QW). Using multilayer DWELL structures, excellent laser device characteristics have been reported [1–4]. As an example, we have recently reported 300 K CW operation for such a structure with current threshold, lasing wavelength and characteristic temperature values of 39 A cm^{-2}, 1.307 μm and 111 K, respectively [4].

To further improve the device properties, aspects such as an improved uniformity in QD size, a high spatial density of dots without relaxation and improved confinement are needed, as well as an overall improvement in the reliability of the MBE growth process. To address these issues a systematic study of the structural parameters of multilayer InAs/InGaAs/GaAs DWELL QD lasers grown by MBE has been undertaken using cross-sectional transmission electron microscopy (xTEM) and the results have been compared to the photoluminescence data and laser device properties.

Multilayer DWELL samples, containing 3 ML of InAs embedded in an InGaAs QW have been grown by molecular beam epitaxy (MBE) using a VG Semicon V90+ system. The growth of both the QD layers and the In$_x$Ga$_{1-x}$As well layers took place at 510 °C using growth rates ~0.1 ML/s for the QDs and ~0.3 ML/s for the InGaAs QW. In all cases, 2 nm of InGaAs was placed below the QD. Both test structures and full laser device structures are considered here. The generic structure of the DWELL samples is shown in Fig. 1. The structural parameters that have been varied are the thickness (t) and composition (x) of the well, the barrier thickness (d) between the DWELL layers in the stack and the growth temperature (T_s) during the barrier deposition. For the transmission electron microscopy (TEM) analysis, cross-sectional specimens (xTEM) were prepared by mechanical polishing followed by ion milling in a Gatan PIPS instrument at low incidence angle and examined in a Philips 420 Transmission Electron Microscope.

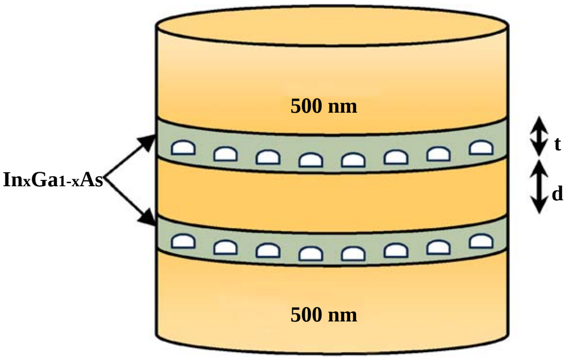

Fig. 1. Schematic of the DWELL structure.

2. Effect of thickness (t) and composition (x) of the QW

As previously reported [5], increasing the indium composition of the In$_x$Ga$_{1-x}$As QW results in a higher dot density, increasing from 1.3 to ~4 × 10^{10} as the composition, x, increases from 0 to 0.25. Over the same composition range, the emission wavelength of the QDs red-shifted by ~300 nm due to the reduction in indium out diffusion [6] and the reduction in hydrostatic strain [7]. Fig. 2 shows a cross-section image of a sample containing $x = 0.15, 0.2$ and 0.25 InGaAs wells, using the $\boldsymbol{g}_{200}$ dark field condition. The sample

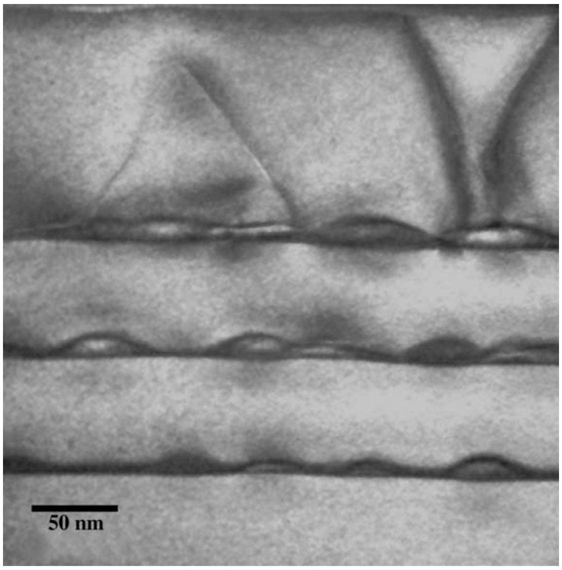

Fig. 2. DWELL structure with $x = 0.15$, 0.2 and 0.25.

shows a very high density of dots, even for $x = 0.15$. As the composition is increased, there is an increase in density and size and substantial overlap between QDs occurs for $x = 0.25$, enough to generate a high density of threading dislocations in this sample. These results should be compared to our previous studies [5], in which the PL intensity reaches a maximum at $x = 0.15$, remains reasonably high at 0.2 and decreases rapidly above this value. The figure shows that the reduction of PL intensity for larger compositions occurs as a result of threading dislocations being formed. The results confirm a limit for the well composition of $x = 0.15-0.2$.

Fig. 3 shows a cross-section of our standard DWELL structure with a $t = 8$ nm QW. Typical dot heights measured from TEM of samples with $x = 0.15$ are in the range 8–10 nm and the dot is not well confined by the upper QW interface, which may result in a loss of confinement in the QD as it penetrates into the barrier. We have therefore studied the use of thicker QWs to see if this confinement can be improved. PL studies show that the PL intensity and linewidth improve on increasing the well thickness from 8 to 10 nm, after which the intensity falls rapidly. Fig. 4 shows a cross-section of a sample with a $t = 12$ nm QW thickness. Although a detailed analysis of this structure shows that the confinement is indeed improved, with up to 5 nm of QW now above the dot, the increased well thickness has generated a high density of threading dislocations which spread from the lowest layer through the upper layers of the structure. These attempts to optimise the structure, based on small modifications to our standard $t = 8$ nm, $x = 0.15$ DWELL configuration, have in both cases resulted in serious degradation due to the formation of dislocations.

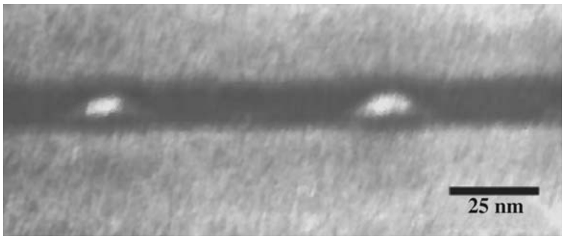

Fig. 3. DWELL structure with 8 nm QW thickness.

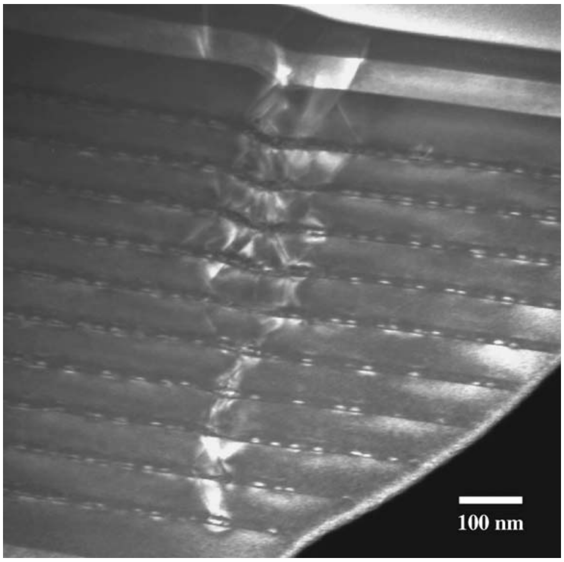

Fig. 4. DWELL structure with 12 nm well thickness.

3. Effect of growth temperature (T_s)

Until recently, we have employed low growth temperatures suitable for the growth of InGaAs for both the DWELL and the barrier in multilayer structures. This temperature is chosen to be at or within 10 °C higher than the GaAs (2×4) to $c(4 \times 4)$ transition temperature observed by RHEED, which we (somewhat arbitrarily) define to be 505 °C. In general, single layer DWELL structures, or multilayers with few repeats and thick barriers, grown using this low temperature show very few defects. Very occasional isolated threading dislocations, stacking faults and loop defects have been observed, but with a very low density (10^{-3}–$10^{-4}\,\mathrm{cm}^{-1}$). However, in multilayer structures with larger numbers of repeats we have observed a considerable amplification in the relaxation which comes from the interaction of dislocations with QD layers grown on top [8]. Here, an initial low level of relaxation, starting from QDs in a lower lying plane, proceeds to interact with the growth of upper lying dots, pulling more dots into the relaxed region and further creating dislocations. The large-area defected QD regions have a major detrimental effect on the laser properties.

To control the threading dislocations in these structures we have used a modified high-temperature process. A micrograph of a five-layer sample, which has the standard 8 nm DWELL structure and 70 nm barriers, but has a modified growth temperature profile is shown in Fig. 5. In this sample the first 15 nm of the GaAs barrier layers was grown at 510 °C, as before, and the second 35 nm at an elevated temperature of 585 °C. In contrast to the previous sample, the formation of dislocated QDs is completely suppressed by this modified growth method and the QD density is constant through the layers at a value of $1.9 \times 10^5\,\mathrm{cm}^{-1}$. The use of the modified temperature profile therefore effectively suppresses the formation of these defects.

To understand the formation of these defects we must consider the growth of the GaAs barrier above the QD. Under the influence of the high tensile strain above a dot, Ga adatom migration acts first to smooth the growth front and then produce a depression under the further influence of the strain field as the barrier growth proceeds. Some preliminary experiments suggest that this flattening takes place in the first 10 nm of the barrier growth, after which migration continues to form a depression which proceeds until the strain field becomes negligible (~30–50 nm). The presence of this depression has been confirmed by atomic force microscopy images of partially capped surfaces. It is partially a consequence of the low Ga adatom mobility at the lower growth temperature. If, however, the growth temperature is increased after the initial flattening process, the rate of planarisation increases and the growth interface below the next QD layer may be sufficiently flattened. We have chosen 15 nm for this transition point, at which the growth is interrupted and the GaAs growth temperature is increased to 580 °C. The resulting method appears highly effective, as seen from Fig. 5.

4. Effect of barrier thickness (*b*)

One of the major problems affecting QD lasers is gain saturation. It is therefore highly desirable to pack QD layers close together within the active region of the laser device. Our previous experience has been with 50–70 nm barrier thickness, for which the strain interaction between dots is relatively small. Fig. 6 shows a cross-section of a DWELL structure with the barrier thickness reduced to 35 nm. The picture shows that at

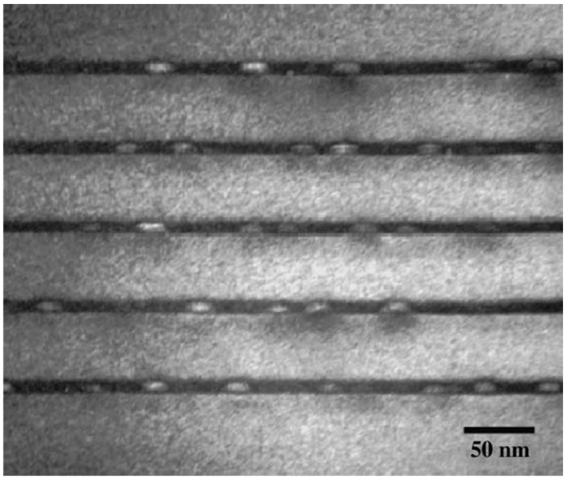

Fig. 5. Five-layer DWELL structure grown using the modified growth temperature method.

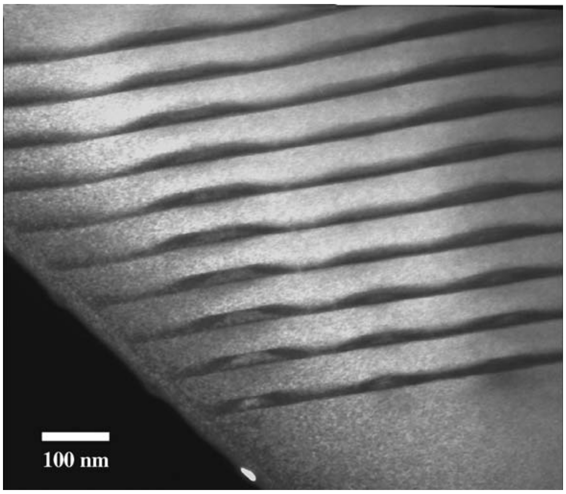

Fig. 6. DWELL structure with 35 nm barrier thickness.

35 nm spacing, a strong and remarkable vertical correlation is induced between the dots. The vertical correlation effect, which originates from the growth of subsequent QDs in the strain field of underlying dots, is very similar to that seen, and frequently reported in non-DWELL QDs (see Ref. [9], for example). However, what is also unusually seen in this sample is a strong distortion of the InGaAs well. In this structure, the InGaAs QW is also seeing the influence of the strain field of the underlying dot and its lateral growth rate is also being modified. The resulting structure appears as an InAs dot of dimensions: 30 nm base, 8 nm height, within a larger InGaAs dot which has the giant dimensions: 265 nm base, 21 nm height and a 15° apex. This effect is remarkable given that no 2D growth mode is normally present for single layers of $In_xGa_{1-x}As$ layer of composition $x = 0.15$ and illustrates a potential method for producing very dilute QDs in which underlying QDs are acting as stressors. The PL emission wavelength is blue-shifted by ~120 nm away from 1.3 μm in this structure. We are currently studying the properties of these layers and evaluating this structure for lasers.

5. Conclusions

Modifications to a standard multilayer DWELL structure, originally optimised by considering only PL efficiency, have been studied by cross-sectional TEM analysis. Changes to the well composition above $x = 0.15$ have shown that the previously observed reduction in PL efficiency is due to threading dislocations formed from interactions between larger dots with a higher density. Changes to the well thickness, although desirable due to the limited confinement of the current 8 nm well, also show that threading dislocation generation is the well thickness is increased. Investigations of the growth temperature profile of the GaAs barrier of multilayer DWELL structures have shown that this is an effective method to reduced interactions between dislocations and the gross propagation of defects. The use of the modified high-temperature growth method improves the planarity of the GaAs buffer and effectively prevents the propagation of this disturbance to the subsequent dot planes. As a result, improved PL and electrical characteristics are observed. Processed laser devices with these samples exhibit room temperature threshold currents $\sim 30\,\mathrm{A\,cm^{-1}}$, amongst the best reported in the literature.

Finally, we have considered the growth of DWELL multilayers with reduced (35 nm) barrier thickness. In these samples vertical correlation is seen both of the QDs and of the InGaAs QW. The resulting structure resembles a 'dot within a dot' structure and has important consequences for the growth of these technologically important multilayers.

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