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InAs/GaAs Quantum Dots Grown By Metal Organic Chemical Vapor Deposition at Different Temperatures

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Abstract

InAs/GaAs quantum dots (QDs) were grown by low pressure Metal Organic Chemical Vapor Deposition in Stranski-Krastanov growth mode. The influence of growth temperature on the QD density was investigated. Atomic Force Microscopy (AFM) was used to study the growth behaviour of the QD structure. It was identified that the growth temperature plays major role in determining the growth and distribution of InAs QDs due to the temperature-dependent dislocation propagation from the GaAs substrate. A high InAs on GaAs QD density 6.4 x 1010 cm-2 was obtained and this proposes a potential superiority of nanodevice operation.

Keywords: MOCVD, Structural, InAs, Quantum Dot, Atomic force microscopy

1. Introduction

Low dimensional semiconductor structures have reached great interest due to their modified electronic and optical properties. Quantum dot structures, which provide electron confinement in three dimensions, can be grown in-situ, without using lithography, by the so-called “self-assembly” effect or Stranski-Krastanov (S-K) growth mode. In this growth mode at a certain critical thickness, an initially two-dimensional (2D) epitaxial layer under compressive strain relaxes into self organized three-dimensional (3D) coherent islands (dots), and a remaining thinner 2D wetting layer [1]. By forming 3D islands the strain can relax in three dimensions and the total energy of the system is reduced.

Self-assembled growth of InAs/GaAs QDs using S-K growth mode has advanced rapidly by MBE, exhibiting low threshold current densities, reasonable differential efficiencies and output powers for telecommunications [2-4]. However, growth by Metal Organic Chemical Vapor Deposition (MOCVD) has proved more challenging with relatively few reports of MOCVD grown InAs/GaAs QD [5-8]. This is due to an increase role of growth kinetics which can lead to island coalescence and defect formation. This is especially true for the InAs/GaAs system where the lattice mismatch is high and the nucleation process is rapid. In this paper, we will discuss the influence of the growth temperature ranging from 500 to 600 ^{o}C for the InAs/GaAs system fabricated on *n*-type GaAs wafer. The critical issue is to avoid formation of larger islands which are particularly susceptible to dislocation formation in MOCVD growth, yet still achieve the high QD densities necessary for device applications.

2. Experiment

All samples in this work were grown in a vertical low pressure NanoEpi MOCVD reactor with trimethylindium (TMIn), trimethylgallium (TMGa) and Arsine (AsH_3) as precursors and H_2 as carrier gas. The reactor pressure for all the growth was set at 76 Torr. The V/III ratio of the source flow flux was set at 14 and 5 for the GaAs and InAs layers respectively [9]. GaAs wafer used for all growth were epi-ready semi-insulating and oriented in the (001) ± 0.1^{o} direction with 0.4mm thick.

The GaAs wafer were cut to quarter sizes and placed in the vertical reactor. After initial process for soft and hard baking of susceptor, a GaAs buffer layer were grown at 750 ^{o}C to remove any dust or particles. This is then followed by another GaAs buffer layer grown at 550 ^{o}C to stabilize active region between layers and dots. The growth was then interrupted for 2 sec before series of InAs QDs grown at temperatures between 500 to 600 °C. The sample was then allowed to cool to room temperature. Figure 1 shows the typical MOCVD flow process for the InAs/GaAs QD structures with 2 sec interrupt.

3. Results and discussions

AFM was used to investigate the QD morphology and to correlate formation trends with changes in growth conditions. InAs/GaAs structures were grown at different temperatures, ranging from 500 to 600 °C. Increase in temperature provides increase in surface adatom energy. Therefore QD nucleation and formation begins and surface materials migrate towards the existing sites. The extent of adatom surface diffusion during and just after nucleation determines the QD density and uniformity [10]. The kinetics that determine the density and QD size are not fully understood, but the two features are interrelated and strongly temperature dependent.

At low temperatures (T < 550°C), high-density QDs are formed due to shorter diffusion wavelengths. The existing surface material distributes over a large number of QDs forming smaller QDs. At higher temperatures, a greater migration distance leads to a lower QD density of large QDs. Figures 2(a) – (e) show the AFM images of InAs QD ensembles grown on a GaAs buffer layer at 500 to 600 °C. Figures 2(a), 2(b), 2(c), 2(d) and 2(e) correspond to growth temperatures of 500, 525, 550, 575 and 600 °C respectively. We see that InAs QDs on GaAs form only for the temperature 525, 550 and 575 °C. Outside of this range, QD formation does not occur due to lack of surface mobility at $T \leq 500$ °C and indium evaporation at $T \geq 600$ °C [5]. At temperatures below 500 °C the InAs QDs still does not occur and we assume that this is due to epilayer material under compression. As for the sample at 600 °C, the cracking efficiencies begin to drop off significantly and incompletely dissociated metal-organic molecules [11].

In ordinary S-K self-assembled InAs/GaAs QD growth, a few monolayers (ML) of InAs thin layer with a large lattice mismatch is grown on a GaAs buffer. It is reported that the lattice constants of InAs (0.605 nm) and GaAs (0.565 nm) can result in 7% lattice mismatch [12]. This 7% lattice mismatch is good enough to induce S-K growth mode of QDs with a maximum height up to 120 nm, if the mismatched strain is properly relaxed. Growth of QDs can be stopped by stopping the flow of TMIn source while keeping the substrate temperature constant and AsH_3 flowing for post-growth interruption. During the post-growth interruption, coherent three-dimensional islands or QDs are formed by self-assembly, accompanied by a thin wetting layer, to release the strain energy accumulated by the large lattice mismatch between the InAs and GaAs buffer layer. In our case, the interruption for forming InAs QDs was set at 2 sec.

From AFM images, we can see the QD density of InAs QDs decreased from 6.4×10^{10} cm^{-2} at 525 °C to $0.5 \times 10^{10} cm^{-2}$ at 575 °C. The QDs start to form uniformly when the temperature reach 550 °C. The diameter of the QD increases with increasing temperature from 80.6nm at 500 °C to 129.8 nm at 525 °C and 149.7 nm at 550 °C. For the temperatures greater than 550 °C the size of InAs QDs decreases and this phenomena occurred because the layer of the samples start cracking with In evaporated at T > 550°C. The energy of the epilayer system also exceed the ripening process and towards equilibrium, and these phenomena agreed with Ostwald ripening and stable dot-arrays [13,14]. The resulting QD diameter and InAs QD densities data are plotted as a function of growth temperature in Figure 3 and 4.

4. Conclusion

In summary, we have investigated the structural properties of InAs quantum dots grown on GaAs buffer layer at varying temperatures ranging from 500 – 600 °C using a vertical MOCVD reactor. We find that the QD formation is affected by changes in surface atom mobility relative to the temperature dependence. In this work, we achieve InAs QD densities of $6.4 \times 10^{10} cm^{-2}$ and average dot diameter 149.7nm at optimum temperatures 550 °C. In future, the fluctuations in size and shape of nanometer scale islands formed in the S-K growth mode have to be further reduced in order to produce QDs with superior electronic performance at room temperature.

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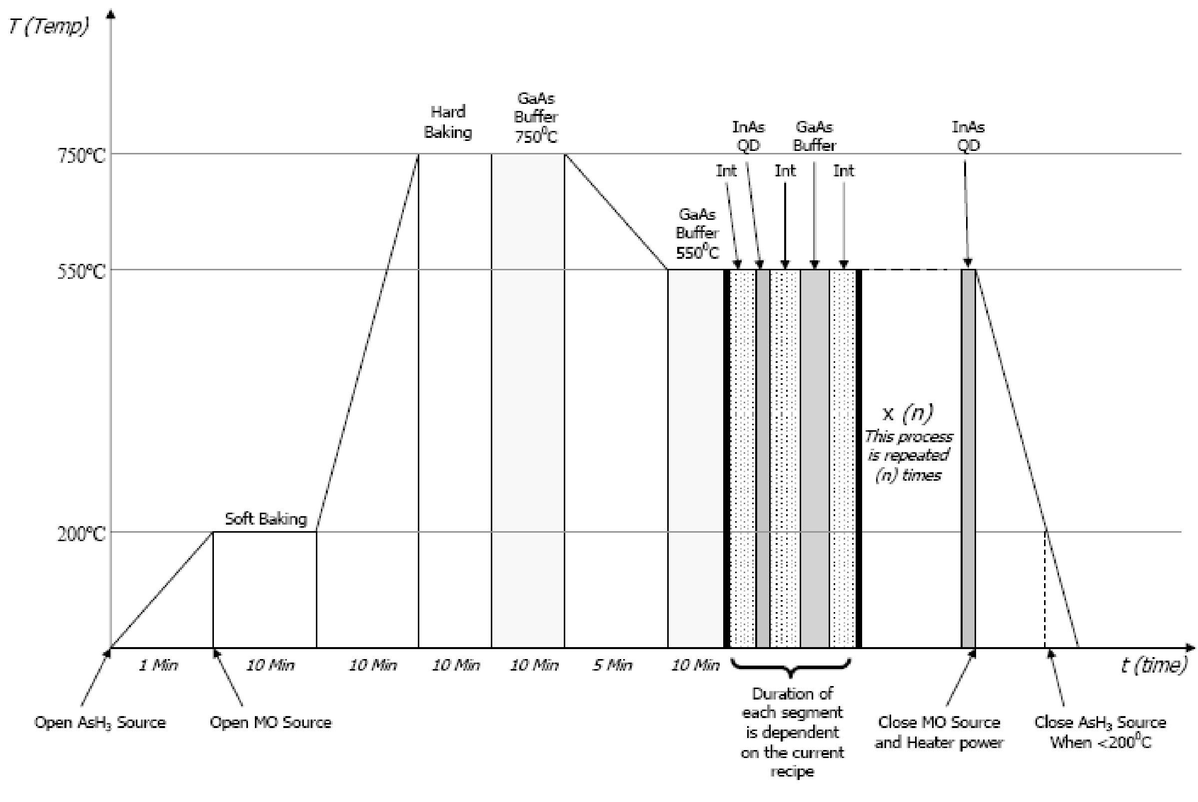

Figure 1. Typical MOCVD Flow Process

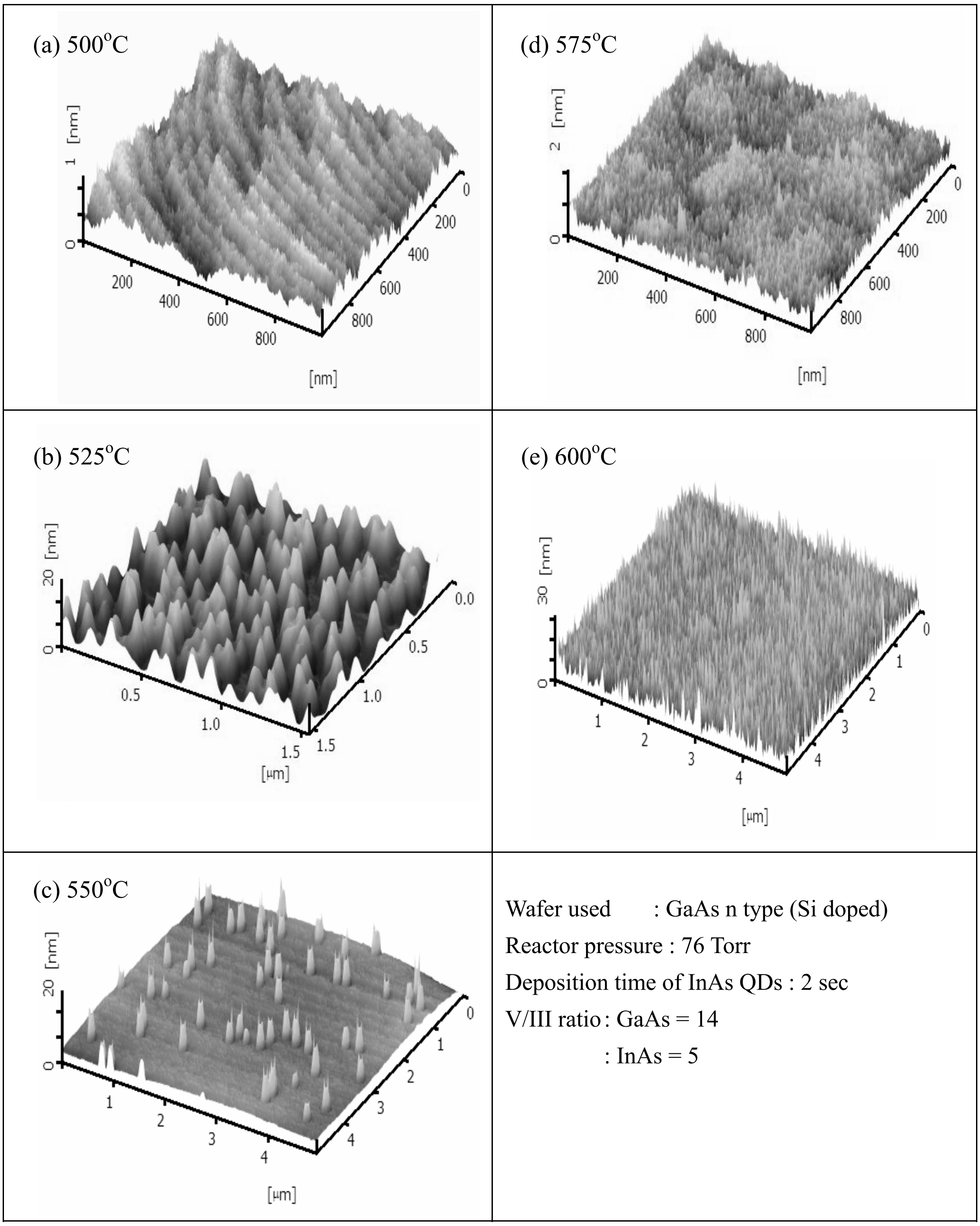

Figure 2. Atomic Force Microscopy 3D images of InAs QDs grown on GaAs buffer layer at (a) 500°C, (b) 525°C, (c) 550°C, (d) 575°C and (e) 600°C

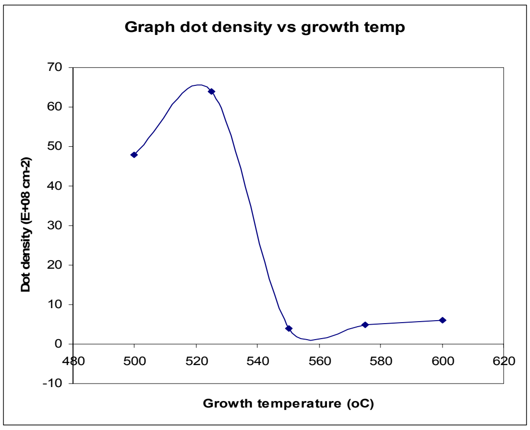

Figure 3. Data plots from AFM measurements of QD density as a function of temperature.

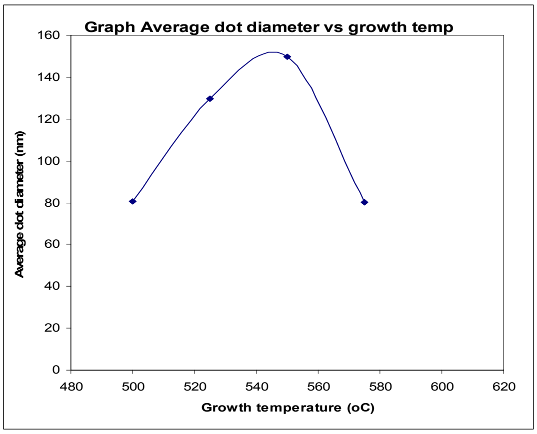

Figure 4. Graph average InAs QD diameter on GaAs buffer layer