COLORED GRAPHICAL ABSTRACT:

**Comparative study on InAs/InGaAs dots-in-a-well structure grown on GaAs (311) B and (100) substrates**

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Comparative study on InAs/InGaAs dots-in-a-well structure grown on GaAs (311) B and (100) substrates

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Abstract
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Key words: InAs; quantum dots; high miller index; uniformity; photoluminescence.

1. Introduction

Self-assembled InAs quantum dots (QDs) have been intensively studied over the past decades because of their atomic-like properties and potential device applications.1 However, the homogenous broaden of QD ensemble hampered the QD based device from achieving better performance. For example, it is believed that the broad emission linewidth is at least one reason for the lower detectivity of quantum dot infrared photodetector2 and the low gain saturation of GaAs based InAs QD laser.3

There are two common methods to narrow the emission linewidth of QDs. One is embedding the InAs QDs in an In0.53Ga0.47As quantum well (QW) fabricating a so called dots-in-a-well (DWELL) structure.4 Another approach to optimize the uniformity problem is growing InAs QDs on high miller index GaAs substrates.5 For example, QDs grown on GaAs (311) B surface with higher uniformity than GaAs (100) substrates grown ones have been observed in many experiments. However, to our knowledge, there is no report of the combining to these two methods: fabricating DWELL on GaAs (311) B despite of the possibility of achieving narrower QD emission linewidth. In addition, the QD growth dynamics on high miller index surface is still unclear.6 So we believe a comparative study on the structural and optical properties of DWELL structures grown on GaAs (311) B (DWELL_{311}) and (100) substrates (DWELL_{100}) contain both applied and fundamental
This article presents our recent study on structural characteristics and optical properties of DWELL$_{311}$ and DWELL$_{100}$. Distinguished structural characteristics and optical properties of these two DWELL structures were observed and discussed.

2. Experimental details

The samples we studied were grown in a conventional Molecular Beam Epitaxy (MBE). Two GaAs (311) B and (100) substrates were held side by side with indium on same molybdenum holder in order to keep identical growth environment. 500nm GaAs buffer layer was grown at rate of 0.5μm/h, 590°C, then 2nm In$_{0.15}$Ga$_{0.85}$As layer, 2.3 monolayer (ML) InAs QDs layer, 6nm In$_{0.15}$Ga$_{0.85}$As capping layer were grown at 530°C with the rate of 0.022ML/s for InAs. Then after 20s’ growth interruption, a 100nm GaAs spacer layer was grown at 590°C. Finally, the 2nm In$_{0.15}$Ga$_{0.85}$As layer and InAs QDs layer were grown again for the morphology tests.

The atomic force microscopy (AFM) test was conducted in the tapping mode. The photoluminescence (PL) measurements were performed with the sample mounted in a variable temperature He gas cryostat using the 632.8 nm line with the excite intensity less than 5W/cm$^2$. The resulting luminescence signal was analyzed with a grating monochromator.

3. Results and discussion

The surface morphology of the InAs/InGaAs QDs varied a lot according to the different substrate orientations, as can be seen in Fig.1. Despite of the mature QDs grown on GaAs (311) B substrates, only a few large QDs formed on GaAs (100) substrate. This phenomenon can be explained by the transition thickness difference of InAs/InGaAs QDs grown on GaAs (311) B and (100) substrates.$^6$ Numerous small QDs were also formed on GaAs (100) substrate. This bimodal size distribution of QDs grown on GaAs (100) substrates was commonly found in self-assembled QDs if growth interruption was performed after the QDs’ formation.$^7$ On the contrary, QDs grown on GaAs (311) B substrate were quite uniform. It is interesting to note that, as can be seen in the inset picture of Fig.1 (a), we observed a fluctuated morphology on the DWELL$_{311}$ origin from strain driven growth instability.$^8$ The ranges of the lateral and vertical fluctuations were several micron meters and tens of nanometer respectively. But we did not found similar morphology in DWELL$_{100}$.

PL tests were conducted at various temperatures to study the differences in the optical properties of these two samples. The results were shown in Fig.2. The peak positions for the PL of the DWELL$_{311}$ and DWELL$_{100}$ surfaces located at 1.20-1.22eV and 1.03-1.07eV respectively. We found that the PL peak of DWELL$_{100}$ substrate was consisted of two peaks. Since the emission of the QW and the WL in the InAs/ In$_{0.15}$Ga$_{0.85}$As DWELL structures located at around 1.3-1.4eV at 77K which is much larger than the energy of these two peaks (1.0-1.1eV), the origin of QW or WL was excluded.$^9$,$^{10}$ Considering the bimodal size distribution of QDs, we attributed these two peaks to the ground state exciton emission of small and large QDs respectively. The PL line width of the DWELL$_{311}$ is much narrower than the DWELL$_{100}$’s linewidth. At 53K, the full width of half maximum was 35meV for the DWELL$_{311}$ but about 72meV for the DWELL$_{100}$.

The intensity of both samples quenched quickly with the increasing of temperature. The PL intensities of the as mentioned three peaks acquired by Gausses fitting were shown in Fig.3. It can be found that the PL intensity of DWELL$_{311}$ quenched much quicker than DWELL$_{100}$’s. At 103K, the PL intensity of DWELL$_{311}$ can barely be observed. However, at the same temperature, the PL
intensity of DWELL\textsubscript{100} substrate was nearly constant for both large and small QDs. This fact suggested temperature had stronger impact on the optical properties of DWELL\textsubscript{311} than DWELL\textsubscript{100}.

We believe there should be several reasons for the higher quenching speed for the DWELL structure grown on GaAs (311) B. (i). The temperature dependence on the lineshape of QD PL was commonly explained based on the thermal escape of carriers and following the redistribution between QDs and surrounding matrix, then undergo a nonradioactive recombination there. So one possible reason for the higher quenching speed for the DWELL\textsubscript{311} is the lower thermal active energy resulting from a lower In composition in QDs. The evidence is the higher emission energy of DWELL\textsubscript{311}. (ii). The point defects in the QDs and surrounding matrix were found also have a strong influence on the temperature dependence of QD optical properties by acting as non recombination centre. In our case, we believe that the concentration of point defects should be higher at interface of the DWELL\textsubscript{311}. Because the fluctuated surface morphology was only observed on the DWELL\textsubscript{311}, the interface size would certainly larger of DWELL\textsubscript{311} than DWELL\textsubscript{100}. Since the defects are very likely to nucleate at the interface, this difference in morphology would certainly increase the concentration of point defects in DWELL\textsubscript{311}. In addition, high density of atom steps were often observed on GaAs (311) B substrates. These steps may also provide high density of point defects.

4. Conclusion

The DWELL structures were grown on GaAs (311) B and (100) by MBE. QDs grown on GaAs (311) B substrate are of higher density and more uniform size distribution yet QDs grown on GaAs (100) substrate demonstrate a bimodal size distribution. Low temperature PL tests showed that the linewidth of DWELL\textsubscript{311} was only half of the DWELL\textsubscript{100}. We also found a stronger temperature dependence of DWELL\textsubscript{311} PL intensity than DWELL\textsubscript{100}, which was explained by the lower thermal active energy and higher density of point defects in DWELL\textsubscript{311}.

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References and Notes

Fig. 1. AFM images for our samples. (a) DWELL structure grown on GaAs (311) B, 2×2 μm²; the inset picture shows a 10×10μm² image; (b) DWELL structure grown on (100), 2×2 μm².
Fig. 2 Temperature dependence on the PL lineshape of the DWELL structures grown on GaAs (311) B (a) and GaAs (100) (b).
Fig. 3. Temperature dependence on the PL intensity of the large QDs (a) and small QDs (b) grown on GaAs (100) substrates and QDs grown on GaAs (311) B substrates (c).
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