Investigation of $\text{In}_x\text{Ga}_{1-x}\text{As}$ strain reducing layers effects on InAs/GaAs quantum dots

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Abstract: Optical and morphological properties of self-assembled InAs quantum dots (QDs) covered by $\text{In}_x\text{Ga}_{1-x}\text{As}$ strain reducing layers (SRL) with different thicknesses (2, 4, 6 and 8 nm) and compositions ($x=0.13$, 0.18 and 0.30) were investigated. Photoluminescence from InAs QDs shows the dependence on indium mole fraction and thickness of the overgrown $\text{In}_x\text{Ga}_{1-x}\text{As}$ SRL. Improvement in PL intensity and narrowing of PL width up to 26 meV occurred together with a red shift of up to 138 nm when the QDs were covered with 6 nm of $\text{In}_{0.18}\text{Ga}_{0.82}\text{As}$. Also, we found that when the total amount of InAs deposited to form the QDs and the SRL was larger than a critical value of around 6 MLs, the surface roughness increased and the PL intensity decreased drastically.

Keywords: molecular beam epitaxy, photoluminescence, atomic force microscopy, quantum dots, strain reducing layer

Classification: Photonics devices, circuits, and systems

References

1 Introduction

Considerable efforts have been devoted to studying the growth and properties of InAs/GaAs quantum dots (QDs), with significant progress made in producing optoelectronics devices for applications at around 1.3 μm [1, 2, 3]. Theoretical investigations have predicted that the QD lasers should have higher gain, lower threshold currents and higher characteristics temperature as compared to quantum well lasers. However, up to now, their performance in actual devices is inferior to that of quantum wells because of the inhomogeneity of QD size (currently, around 10% of size variation) [4]. Shape and size distribution of QDs have to be improved to obtain a performance similar or better than quantum well devices.

Light emission with a wavelength of 1.3 μm has also been reported from QDs grown by using atomic layer epitaxy [5] or alternate beam molecular beam epitaxy [6]. Using the InxGa1−xAs strain reducing layer (SRL) instead of GaAs as the capping layer, band gap energy of InAs QDs is reduced due to the relaxation of compressive strain in InAs QDs and the reduction of quantum confinement effect. As a result, the photoluminescence (PL) peak of InAs QDs shifts towards a longer wavelength. Several groups have investigated the optical characteristics of InAs and InyGa1−yAs QDs capped with InxGa1−xAs SRL [7, 8, 9, 10].

2 Approach

The technologically important wavelength (1.3 μm) has to be achieved from QDs without reduction in the PL intensity and also the size uniformity has to be improved. To achieve this, systematic investigation is necessary. In this paper, the optical and morphological properties of InAs QDs covered by different thickness (2, 4, 6 and 8 nm) of InxGa1−xAs SRL with three different
compositions (x= 0.13, 0.18 and 0.30) have been investigated. We found that morphology and optical properties such as PL intensity, wavelength and width of InAs QDs depend strongly on the indium mole fraction and thickness of the overgrown SRL layer.

3 Experimental conditions

All samples were grown on GaAs (100) substrate using Varian Gen-II MBE. The growth rates were 0.54 mono layer (ML)/s and 0.11 ML/s for GaAs and InAs respectively. In order to obtain different compositions in the SRL, we used another Ga cell with different growth rates while keeping the InAs growth rate constant. A 300-nm GaAs buffer layer was first grown at 540°C after oxide desorption, followed by 300-nm Al_{0.28}Ga_{0.72}As and 110-nm GaAs. InAs QDs were formed at this stage at 520°C under Stranski-Krastanow (S-K) growth mode. It was followed by the growth of In_xGa_{1-x}As SRL at the same temperature. For PL measurements the structure was capped with 110-nm GaAs, followed by a 250-nm Al_{0.28}Ga_{0.72}As and 20-nm and a GaAs cap layer at 540°C.

4 Results and discussions

Figure 1 (a) shows an atomic force microscopy (AFM) image of QDs formed by 2.4 MLs of InAs deposited at 520°C on GaAs (100) substrate. The dot density and height were found to be about 2.3 × 10^{10} cm^{-2} and 4–6 nm. The dot diameter varied from 30 to 40 nm. Figure 1 (b), (c) and (d) show the AFM image of the QDs covered by 6 nm of In_xGa_{1-x}As with x=0.13, 0.18 and 0.30 of indium composition respectively. Figure 1 (c) and (d) show more...
roughness as compared to Fig. 1 (b).

The InAs QDs covered with In$_x$Ga$_{1-x}$As (x=0.30) SRL shows very large islands with diameter around 150 nm. The roughness of the surface with the In$_x$Ga$_{1-x}$As SRL has been measured by AFM. The root mean square (Rms) value increased as the indium composition in the SRL increased as shown in Table I. For 6 nm of In$_x$Ga$_{1-x}$As (x=0.13), the Rms value was 0.22 nm. The low Rms value indicates that the surface is very flat. As the indium composition in the SRL (6 nm) increased the Rms value increased to 1.23 nm and 2.21 nm for the indium composition of x=0.18 and x=0.30 respectively. The increase in Rms value might be due to In$_x$Ga$_{1-x}$As islands nucleating on top of the InAs QDs when the indium composition in SRL increased.

**Table I.** Rms and total In (MLs) values for different In-GaAs SRL thickness.

<table>
<thead>
<tr>
<th>In composition</th>
<th>SRL thickness (nm)</th>
<th>Rms Value (nm)</th>
<th>Total In (MLs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>13%</td>
<td>2</td>
<td>0.65</td>
<td>3.26</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.33</td>
<td>4.12</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>0.22</td>
<td>4.98</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>0.17</td>
<td>5.84</td>
</tr>
<tr>
<td>18%</td>
<td>2</td>
<td>1.16</td>
<td>3.60</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.86</td>
<td>4.78</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>1.23</td>
<td>5.9</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>2.12</td>
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<td>30%</td>
<td>2</td>
<td>2.0</td>
<td>4.38</td>
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<tr>
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<td>4</td>
<td>1.97</td>
<td>6.37</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>2.21</td>
<td>8.38</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>2.83</td>
<td>10.34</td>
</tr>
</tbody>
</table>

Next, we studied the room temperature PL of InAs QDs covered with GaAs and different In$_x$Ga$_{1-x}$As SRL. Figure 2 shows the PL of InAs QDs covered with (a) 2 nm (b) 4 nm (c) 6 nm and (d) 8 nm of InGaAs SRL for three different In compositions. The peak wavelength for InAs QDs with GaAs cap was 1157 nm and full-width at half maxima (FWHM) was around 56 meV. When QDs were covered with 2 nm of In$_{0.18}$Ga$_{0.82}$As the PL peak shifted to a longer wavelength of 1226 nm and the FWHM became 40 meV. The intensity increased nearly two times than GaAs covered QDs. It is also noted that the energy state at the InAs QDs also excited, which corresponded to PL emission at the wavelength of around 1148 nm, which is nearly 68 meV towards the high energy side. Since the lattice constant of the SRL is larger than that of GaAs, the biaxial strain component in the plane of the QD layer is reduced, resulting in a shift of the PL peak toward longer wavelength. Also, as Nishi *et al.* [7] reported that size uniformity is improved by covering the QD layer with In$_x$Ga$_{1-x}$As. Thus, the PL emission peak shows a shift toward longer wavelength and the peak width becomes narrower. Further,
increase in the thickness of the SRL lead to more red shift up to 1295 nm for 6 nm of SRL. The FWHM became as narrow as 26 meV. The PL intensity increased around 2.2 fold when compared to GaAs covered structure. When the QDs were covered with 2 nm of In_{0.30}Ga_{0.70}As the PL peak shifted to 1270 nm. However, the PL intensity becomes weaker as the thickness of SRL increased to 4 nm (Fig. 2) even though the peak position was shifted up to 1331 nm.

Figure 3 shows the PL peak intensity, wavelength and FWHM for different thickness and composition of In_{x}Ga_{1−x}As SRL. In the case of In_{x}Ga_{1−x}As SRL with x=0.13 there is no much intensity dependence on SRL thickness. However, when the thickness of the SRL for x=0.18 and x=0.30 increased, the PL intensity varied as shown in Fig. 3. When the thickness of In_{0.18}Ga_{0.82}As and In_{0.30}Ga_{0.70}As increased to 8 nm and 4 nm (total amount of InAs deposited to form the QDs and the SRL is above 6 MLs) respectively the PL intensity drastically decreased. Also, when the In_{0.30}Ga_{0.70}As thickness increased further to 6 nm (Total InAs is 8.36 MLs) PL emission could not be detected at room temperature. As shown in Fig. 1 (d) the surface becomes rougher when 6 nm of In_{0.30}Ga_{0.70}As SRL was grown on InAs QDs. These
results suggest that when the total supply of InAs exceeds a critical value (around 6 MLs), In$_x$Ga$_{1-x}$As islands begin to nucleate on the top of the InAs QDs as a result misfit dislocations will appear and lead to degradation in the PL intensity. Therefore, the distribution of stress on the top of InAs islands covered by SRL with high indium composition becomes inhomogeneous, leading to the increment of FWHM as shown in Fig. 3.

On the other hand, when the indium composition is $x=0.13$ there is no much change in the FWHM. The low FWHM and high PL intensity from the QDs covered with 6 nm of In$_{0.18}$Ga$_{0.82}$As prove the improvement in size uniformity and less misfit dislocations.

5 Conclusion

In summary, we fabricated InAs QDs emitting luminescence around a wavelength of 1300 nm at room temperature. We have systematically studied the optical and morphological properties of InAs QDs covered with In$_x$Ga$_{1-x}$As SRLs. Improvement in PL intensity (around 2.2 fold) and reduction in PL peak width were observed for InAs QDs covered by 6 nm of In$_{0.18}$Ga$_{0.82}$As layer as compared to QDs covered with GaAs. Furthermore, we found that when the total amount of InAs deposited to form the QDs and the SRL was larger than a critical value (around 6 MLs), surface roughness increased and
the PL intensity decreased.

Acknowledgments

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