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# Effects of accumulated strain on the surface and optical properties of stacked 1.3 μm InAs/GaAs quantum dot structures

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**Abstract**

We report the effects of accumulated strain by stacking on the surface and optical properties of stacked 1.3 μm InAs/GaAs quantum dot (QD) structures grown by MOCVD. It is found that the surface of the stacked QD structures becomes more and more undulated with stacking, due to the increased strain in the stacked QD structures with stacking. The photoluminescence intensity from the QD structures first increases as the stacking number increases from 1 to 3 and then dramatically decreases as it further increases, implying a significant increase in the density of crystal defects in the stacked QD structures due to the accumulated strain. Furthermore, we demonstrate that the strain can be reduced by simply introducing annealing steps just after growing the GaAs spacers during the deposition of the stacked QD structures, leading to significant improvement in the surface and optical properties of the structures.
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## 1. Introduction

Self-assembled InAs/GaAs quantum dot (QD) lasers operating at 1.3 μm have attracted considerable attention because of their potential to provide low-cost and efficient light sources for next-generation high-speed communication systems. Furthermore, stacked QD structures have been widely employed to increase the density of the QDs and then to increase the modal gain of the QD lasers. However, the accumulation of strain by stacking the QDs can cause misfit dislocations and undulated interfaces (e.g. the interface between the upper GaAs separate confining heterostructure layer and p-doped AlGaAs cladding layer) that greatly debase the performance of the lasers [1–4]. Therefore, it is necessary to reduce the strain in the stacked QD structures by optimizing the growth of the stacked QD structures in order to improve the performance of the lasers.

In this paper, we investigate in detail the effects of accumulated strain by stacking on the surface and optical properties of stacked 1.3 μm InAs/GaAs QD structures grown by MOCVD. We find that the surface of the stacked QD structures becomes more and more undulated with stacking and the photoluminescence (PL) intensity from the QD structures first increases with stacking and then dramatically decreases as the stacked QD layers exceed 3, due to the accumulated strain. We demonstrate that the strain can be reduced by simply introducing annealing processes (IAPs) just after growing the GaAs spacers during the deposition of the stacked QD structures, leading to significant improvement in the surface and optical properties of the structures [4].

## 2. Experiments

Two series of samples having different layers of InAs QDs, with and without IAPs, were grown on GaAs (0 0 1) substrates by low-pressure MOCVD, using trimethylindium, trimethylgallium, and tertiarybutylarsine (TBA) as source materials. Fig. 1 schematically illustrates the

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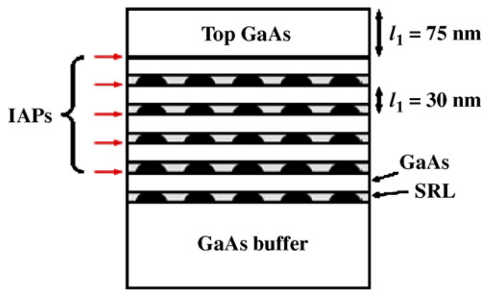


Fig. 1. Schematic cross-sectional structure of samples of five-layer InAs QDs. The horizontal arrows indicate where annealing processes are introduced just after growing the GaAs spacers.

cross-sectional structure of samples of five-layer InAs QDs, in which the GaAs buffer layer (200 nm) was grown at 700 °C, InAs QD layers (2.6 MLs) and 5 nm-thick $In_{0.1}Ga_{0.9}As$ strain-reducing layers (SRLs) capping on the QDs were deposited at 500 °C, and GaAs spacer layers (25 nm) and the top GaAs layer (100 nm) were grown at 560 °C. The only difference between the two series of samples with and without IAPs is if they have the IAPs just after growing the GaAs spacers of the samples, as indicated by arrows in Fig. 1. Moreover, the IAPs were carried out at the same temperature as the growth of the GaAs spacers to avoid the postgrowth annealing effect [3,4], but under half of the TBA flow during the growth of the spacers. The annealing time was 300 s for the IAPs. The surface morphologies of the samples were characterized by an atomic force microscope (AFM), while the optical properties of the samples were evaluated by PL.

## 3. Results and discussion

Fig. 2 summarizes the surface roughness for the two series of samples with and without IAPs as a function of stacking number, obtained in the measured area of $5 \times 5\,\mu m^2$. From the figure, an increase in surface roughness with stacking can be first observed for both the series of samples, indicating that the surface for both the series of samples becomes more and more undulated with stacking. The increase in surface roughness with stacking may arise from the increased strain in the samples with stacking, which results from the lattice mismatch between the InAs and GaAs, and propagates in the growth direction with stacking. The local strains above the QDs can cause different growth rates between the areas with and without the strains during capping, and lead to undulated growth surfaces as measured in Fig. 2. Furthermore, it can be observed from the figure that the surface roughness for the series of samples with IAPs is reduced in comparison to the corresponding ones without IAPs, implying that the strain in the samples can be reduced by IAPs. In particular, this reduction in surface roughness is more marked for the samples with the stacking numbers smaller than 6 as shown in Fig. 2, and it is attributable to the IAPs that can greatly enhance the surface migration of Ga during annealing and

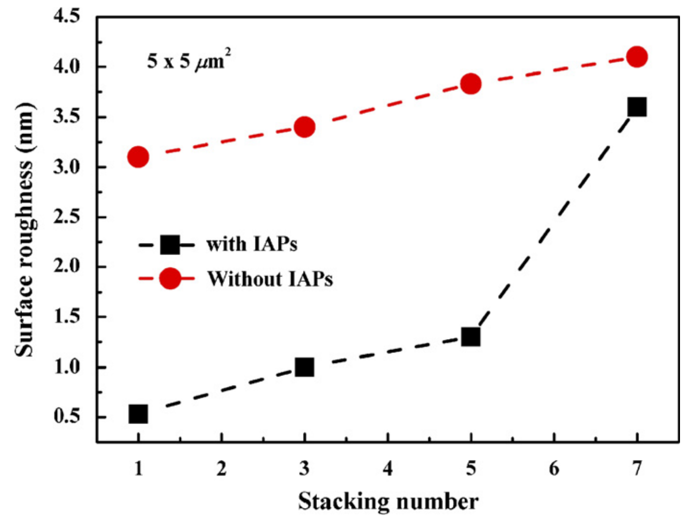


Fig. 2. Surface roughness of samples with and without IAPs as a function of the stacking number, measured in $5 \times 5\,\mu m^2$ areas.

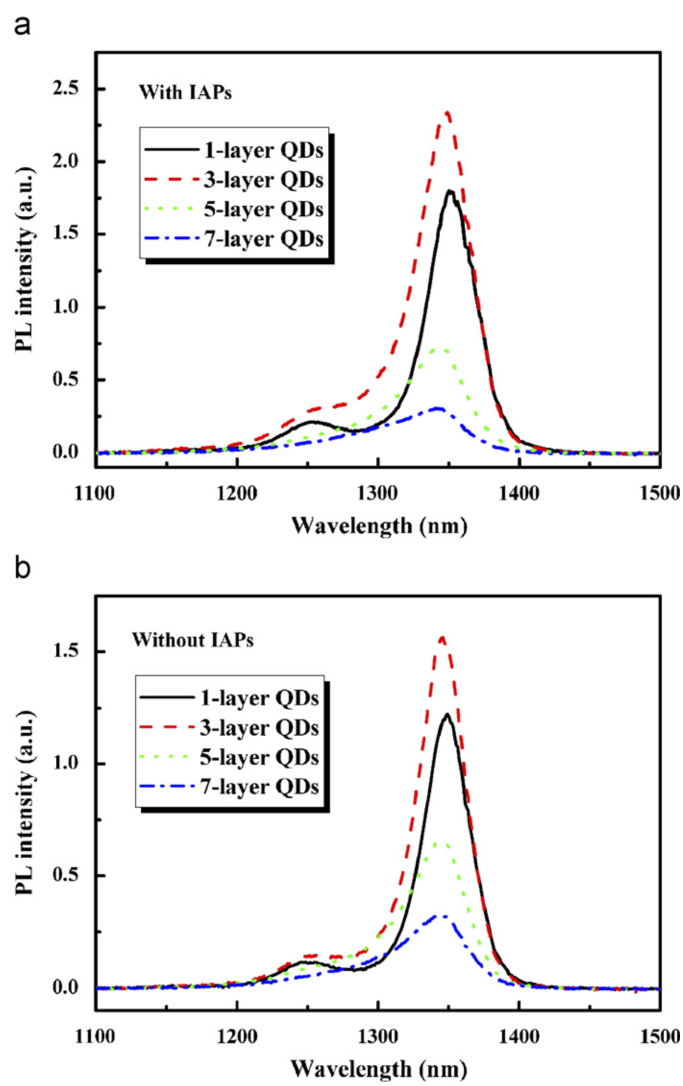


Fig. 3. RT-PL spectra from the two series of samples of different QD layers: (a) with IAPs and (b) without IAPs.

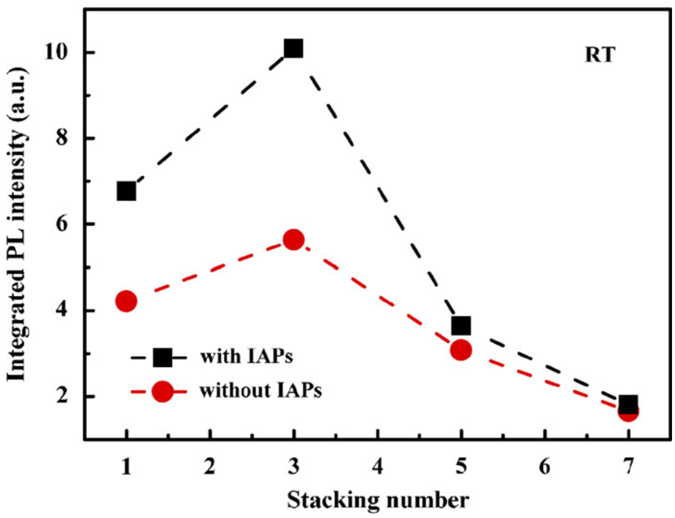


Fig. 4. Integrated PL intensity of the spectra in Figs. 3(a, b) as a function of the stacking number.

make the surface of the GaAs spacers much flatter [4], resulting in reducing the accumulated strain in the samples with IAPs and thereby decreasing the surface roughness of the samples.

Figs. 3(a, b), respectively, show PL spectra from the two series of samples with and without IAPs, measured at room temperature (RT). From the figures, it can be seen that the peak wavelength for the two series of samples having the identical stacking numbers is almost the same, indicating that inserting the annealing steps does not induce any shifts in emission wavelength of the QDs. Fig. 4 plots the integrated PL intensity of the spectra in Figs. 3(a, b) as a function of the stacking number. From the figure, a similar variation in intensity with stacking can be first seen for the two series of samples with and without IAPs, where the intensity first increases as the stacking number increases from 1 to 3 and then dramatically decreases as it further increases. The increase in intensity with stacking from 1 to 3 can be ascribed to the increase in the density of QDs with stacking, while the dramatic decrease in the intensity with further stacking is attributable to the significant increase of crystal defects in the samples resulting from the accumulation of strain. Moreover, by comparing the intensity between the two series of samples with identical stacking numbers, it can be seen that the greater improvement in intensity is only for the samples with the QD layers less than 4 due to the IAPs.

## 4. Conclusions

We have investigated the effects of accumulated strain by stacking on the surface and optical properties of stacked 1.3 μm InAs/GaAs QD structures grown by MOCVD. It is found that the surface of the stacked QD structures becomes more and more undulated with stacking and the PL intensity from the stacked QD structures significantly decreases when the stacked QD layers exceed 3, due to the accumulated strain. We demonstrate that the strain can be reduced by introducing annealing steps just after growing the GaAs spacers during the deposition of the stacked QD structures, leading to significant improvement in the surface and optical properties of the structures.

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