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Enhanced Photoluminescence from InAs Quantum Dots Monolithically Grown on Si (100) using InGaAs/GaAs dislocation filter layers

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Abstract

The direct growth of III-V quantum dots on Si(100) is an unsolved problem for monolithically integrated photonic devices on the Si platform. Here, we report the growth of InAs/GaAs quantum dots on Si(100) substrates without patterns or offcut. InAs/GaAs quantum dot layers were grown on top of a dislocation filter layer of InGaAs/GaAs strained layer superlattice. Due to the dislocation filtering of the superlattice layer, together with quantum dots' unique insensitivity to non-radiative defects, the optical properties of InAs/GaAs quantum dots are enhanced: The photoluminescence intensity of InAs quantum dots on dislocation filter layer is 4 times higher than those of without dislocation filter layer samples. This result represents a key step towards the realization of monolithically integrated silicon photonics.

1. Introduction

III-V quantum dot (QD) lasers have been demonstrated with low threshold current, high operating temperature due to QD's discrete energy level [1]. In addition, QD device has insensitivity to crystal defects [2]. For these reasons, III-V QD growth on Si is a core technology for the monolithic integration of Si photonics light sources [3]. However, because of the differences in crystal structure between III-V semiconductors and Si, such as lattice mismatch, polar / non-polar nature, and difference of thermal expansion, high density threading dislocations and anti-phase domains (APDs) are generated at the III-V/Si interface [4]. Off-axis or patterned Si (100) substrates with dislocation filter layers have been adopted for decreasing the dislocation density in the QD layers in recent reports [3,5-10], but there are still several problems relating to CMOS-process compatibility and waveguide coupling. Previously, we grew the InAs QD layers on Si(100) just substrates without dislocation filter layer. However, the photoluminescence intensity of samples was only ~ 20% intensity of samples grown on GaAs [11].

In this study, we introduced InGaAs/GaAs strained layer superlattice (SLS) to GaAs buffer as dislocation filter on unpatterned Si(100). By using this method, high optical quality InAs QDs was grown on unpatterned on-axis Si (100) substrates.

2. Experimental method

All the samples were grown by conventional solid-source molecular beam epitaxy (MBE) system (VG semicon V80H). Arsenic tetramer (As_4) was supplied from valved cell. High resistance n-type Si (100) 'on-axis' substrates were used for this study. A native oxide layer (~2 nm) on the Si wafer was removed with diluted hydrogen fluoride acid (DHF). After loading to the growth chamber, the Si wafer was normally pre-heated at 950°C for 10 min. Figure 1 shows a schematic illustration of the structure grown on a Si(100) substrate. Firstly, 40 nm-thick $Al_{0.3}Ga_{0.7}As$ seed layer was grown at 500 °C. Next, an 800 nm-thick GaAs layer was grown at 560 °C, and then, 5 layers of $In_{0.18}Ga_{0.82}As$(10 nm) / GaAs(10 nm) SLS and 400 nm-thick GaAs layer were repeatedly grown by 3 times. Subsequently, InAs QDs were grown at 480 °C, and then, capped by thin InGaAs / GaAs layer. 8 layers of InAs / InGaAs / GaAs QD were grown between a 1400 nm (lower) and 100 nm (upper) $Al_{0.4}Ga_{0.6}As$ layer. Finally, the structure was capped with a 100 nm-thick GaAs layer. For comparison, the same structures without the SLS dislocation filter layers were grown on Si and GaAs(100).

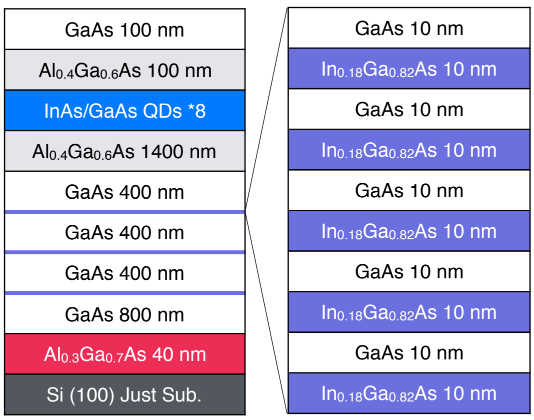

Fig. 1 Schematic illustration of the structure grown on a Si(100) substrate (left) and InGaAs/GaAs strained layer superlattice (SLS) dislocation filter (right).

3. Results and Discussion

Optical Properties

We performed macro-photoluminescence spectroscopy on the grown QDs at room temperatures. Conventional semiconductor laser light at 632 nm was employed for pumping the samples.

Figure 2 shows room temperature photoluminescence spectra of grown structures on Si with and without SLS dislocation filter. Photoluminescence intensity of QDs on the SLS dislocation filter is quadruple of that without SLS dislocation sample. It is believed that the QD layer grown on SLS filter layer on silicon only exhibits a limited degradation of optical properties. The emission wavelength of on Si with SLS filter sample (1290.1 nm) is slightly blueshifted with respect to the on Si without SLS filter sample (1310.9 nm).

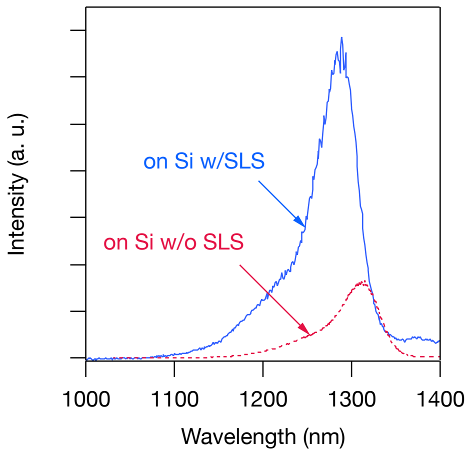

Fig. 2 Room temperature photoluminescence spectra of grown structures on Si with SLS dislocation filter (blue solid line), and on Si without SLS dislocation filter (red dotted line)

Surface Morphologies

The surface morphologies of the QD layers grown on the GaAs and Si substrates were measured using atomic force microscopy (AFM).

Figure 3 shows AFM image of the 8th InAs QD layer surface on Si(100) with SLS dislocation filter layer. The scan area was 1 μm square. The average diameter and height of uncapped QDs on Si were 28.5 nm and 9.5 nm, respectively. The height and lateral size of on the SLS filter sample's QDs are slightly bigger than that on the GaAs sample's QDs. Then, the QD density and giant QD density are a half of ($3.2\times10^{10}/cm^2$), and 6 times ($1.5\times10^{8}/cm^2$), those measured in the GaAs sample, respectively. The contour line shaped atomic steps, which indicate low surface roughness, underneath the QD structures is also observed. Although the dislocations are not perfectly eliminated in the Si substrate samples, degradation of crystal quality is limited.

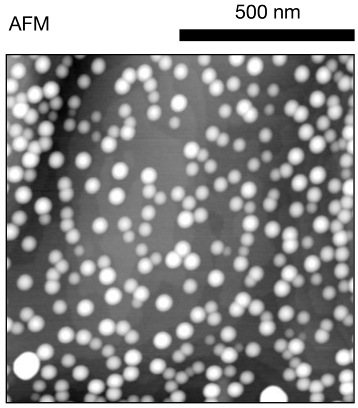

Fig. 3 AFM image of the 8th InAs QD layer surface on Si(100) with SLS dislocation filter layer.

4. Conclusion

We have successfully demonstrated the direct growth of InAs QDs on Si (100) just substrates. Thanks to the InGaAs / GaAs strained superlattice dislocation filter layers and GaAs / AlGaAs buffer layer, the emission from the samples maintain narrow linewidth with the high emission intensities. This monolithic approach will open the way toward facile integration of QD laser devices into Si-based platform.

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