1.3 µm Photoluminescence from InAs/GaAs Quantum Dots on CMOS-compatible (001) Silicon by Metal-organic Chemical Vapor Deposition

Yating Wan, Qiang Li, Yu Geng, and Kei May Lau*

Photonics Technology Center, Department of Electronic and Computer Engineering,
Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong.
Phone: (852) 2358-7049, E-mail: eekmlau@ust.hk

Abstract

We report the growth and characterization of self-assembled InAs/GaAs quantum dots (QDs) on nano-patterned on-axis (001) silicon by metal-organic chemical vapor deposition. High quality QDs with densities above 10^{10} cm^{-2} and ground state emission at 1.3 µm in room temperature have been obtained. This result demonstrates promising potential to integrate III-V based light emitting devices on CMOS-compatible Si (001) substrate by direct epitaxial growth.

1. Introduction

Monolithic integration of III-V optoelectronic devices on Si substrates has key merits for optical networks-on-chip, a promising solution to address the bandwidth limitation and power consumption issues in conventional on-chip electrical interconnects [1]. Defect management to meet the requirement for reliable device operation has always been a prime challenge in heteroepitaxy. Various methodologies such as metamorphic buffer layers, thermal cycle annealing, insertion of interlayers and the use of misorientated Si wafers have been studied extensively in traditional blanket heteroepitaxy [2]. Nevertheless, an electrically pumped laser on Si by direct epitaxy using metal-organic chemical vapor deposition (MOCVD) has yet to be realized. The superior capability of quantum dots (QDs) to withstand non-radiative defects as compared to their quantum well counterparts may be the ultimate solution [3]. Recently, we have developed compliant substrates of GaAs on on-axis (001) silicon. Extremely high crystalline quality and anti-phase-domain-free GaAs thin films were grown out of highly ordered in-plane nanowires on V-grooved Si [4]. In this work, we investigated self-assembled InAs/GaAs QDs grown via the Stranski–Krastanow (SK) mode on the high quality GaAs-on-Silicon (GoS) templates. Atomic force microscopy (AFM) was used to characterize the morphology of the QDs. High optical quality and good interface were verified by photoluminescence (PL) and transmission electron microscopy (TEM).

2. Experiments

The growth was conducted in an Aixtron AIX-200/4 MOCVD system with a Laytec EpiRAS spectrometer for the in-situ growth reflectance measurement. Trimethylindium (TMIn) and triethylgallium (TEGa) were used as the group III precursors, and tertiarybutylarsenic (TBA) was used as the group V precursor. The reactor pressure was maintained at 100 mbar during the growth. A GoS template and a GaAs substrate were placed in the reactor side by side during the QD structure growth for comparison. A thin GaAs buffer of 100 nm was first grown at 630℃. The temperature was then cooled down to 500℃ for the growth of a 2 nm $In_{0.12}Ga_{0.88}As$ wetting layer, followed by a 2.6 monolayer (ML) InAs deposition with a growth rate of 0.63 ML/min and a V/III mole ratio of 0.375. A growth interruption of 20 s was introduced subsequently without TBA flux to facilitate the formation of dots. An additional 100 nm GaAs capping layer was formed on top for PL evaluation. The schematic of the as-grown structure is shown in Fig. 1.

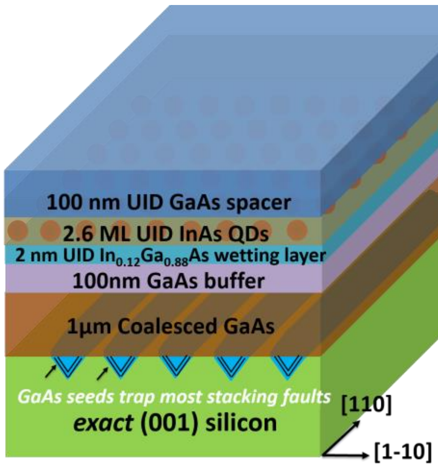

Fig. 1 Schematic of InAs/GaAs quantum dots on the GoS template.

Fig. 2 shows the AFM image of the uncapped InAs dots. Highly uniform QDs have been achieved with densities of 6.2×10^{10} cm^{-2} and 5.6×10^{10} cm^{-2} on the GaAs substrate and the GoS template, respectively. Density of coalesced dots on the GoS template is slightly higher (1.6×10^{9} cm^{-2}) compared to that on GaAs substrate (1.1×10^{9} cm^{-2}), negatively impacting the optical proficiency of the QDs. This is also reflected in the PL data. The typical dot sizes were measured to be about 21 and 19 nm in diameter for samples on the GaAs substrate and the GoS template, respectively. The smaller dot size on the GoS template is partially attributed to the residual compressive stress from the interface between GaAs and silicon, which also brings about a slight blue shift in the PL spectrum.

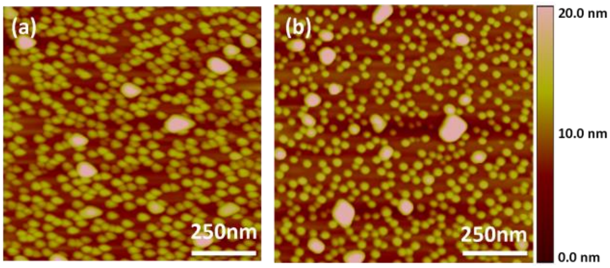

Fig. 2 AFM image of (a) 1×1 μm² area uncapped InAs QDs grown on the GaAs substrate; (b) 1×1 μm² area uncapped InAs QDs grown on the GoS template.

Room temperature emission at 1.3 μm was measured. As seen from Fig. 3, QDs on the GoS template achieved a narrow full-width-at-half-maximum (FWHM) of 29 meV, close to the state-of-the-art value for similar density of QDs grown on the GaAs substrates [5]. It is noted that PL peak intensity for the sample on the GoS template is about 54% of that on the GaAs substrate in room temperature and 58% of that on the GaAs substrate in low temperature (40 K). This is attributed to the formation of non-radiative centers in the active region during heteroepitaxy. Defect density could be further reduced by thermal annealing or insertion of superlattices in the GaAs buffer [6].

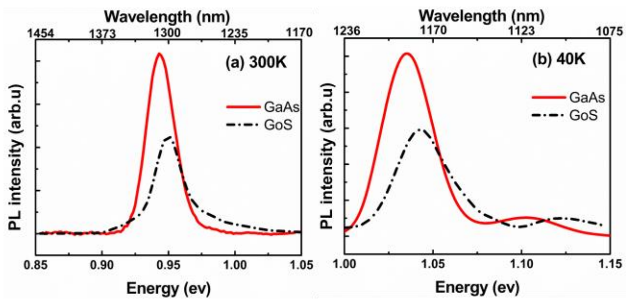

Fig. 3 (a) Room Temperature (300 K) and (b) low temperature (40 K) PL spectra of the capped InAs QDs grown on the GoS template and the GaAs substrate.

Fig. 4(a) presents a cross-sectional TEM image of the InAs/GaAs QDs grown on the GoS template. A zoomed-in view of the hetero-interface is shown in Fig. 4(b). Most of the defects are (111) plane stacking faults (SFs), aligned in parallel with the growth surface and confined by the V-grooves. Low defect density was achieved in the upper active region to facilitate the formation of uniform dot arrays, which is visualized in Fig. 4(c). A high resolution TEM image in Fig. 4(d) reveals the typical size and shape of the dots.

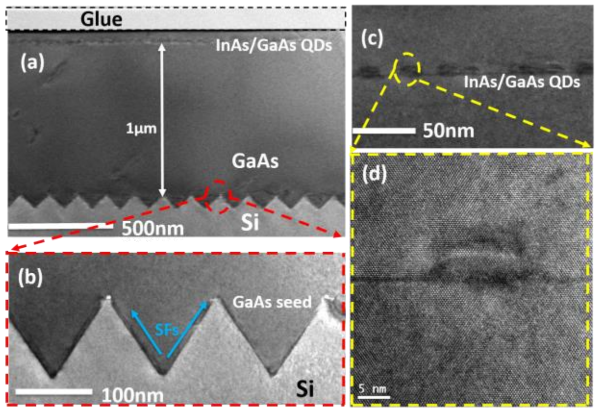

Fig. 4 (a) cross-sectional bright-field low-resolution TEM image of the whole structure with a total buffer thickness around 1 μm; (b) high-resolution TEM of the interface between Si substrate and GaAs seed, showing the defect trapping by a “tiara”-like structure formed by Si; (c) TEM image of the InAs/GaAs QDs; (d) high-resolution TEM image revealing the typical size and shape of the dots.

3. Conclusions

In conclusion, utilizing a novel engineered GaAs-on-Si template, we have demonstrated the growth of high density InAs/GaAs QDs on CMOS-compatible Si (001) substrates with emission in 1.3 μm. Structural and optical properties have been investigated, revealing promising potential to realize monolithically integrated QD laser for silicon photonics applications.

Acknowledgements

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