A-6-08 Extended Abstracts of the 2022 International Conference on Solid State Devices and Materials, Makuhari, 2022, pp45-46

Development of Epitaxial Regrowth for GaAs-Based Quantum Dot PCSELs

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Abstract

We present the development of epitaxial regrowth processes to allow the realization of a PCSEL utilizing a quantum dot active region. An electron microscope-based study investigates the effect of group-III surface mobility on grating infill. An optimal process utilizing AlGaAs infill is used to fabricate QD devices that display room temperature ground state lasing at 1230 nm.

1. Introduction

Photonic crystal surface emitting lasers (PCSELs) offer high-power, single mode emission [1], however the emission wavelength range of GaAs-based devices is currently limited by the near-universal use of quantum wells as the active element. The integration of quantum dot (QD) active regions, on the other hand, would greatly extend the wavelength range of devices towards 1.3 μm, allow for improved the temperature sensitivity of the devices [2], and allow a route to multiple wavelength lasers on one monolithic device. Previous reports of QD PCSELs have utilized deeply etched photonic crystal (PC) gratings and ITO contact layers [3,4], however, to the best of our knowledge, there have been no examples of devices realized through epitaxial regrowth, a key requirement for high slope efficiencies [1].

A key aspect of the epitaxial regrowth process is control over the formation of voids that define the photonic crystal (PC) layer, and optimization of their geometry. In this regard, it is crucial to balance the effects of self-shadowing of the growth front and the mobility of the group-III species involved. Whilst the effects of growth conditions and grating geometry have been investigated previously [5,6], the effects of inherent group-III mobility are yet to be reported.

In this paper we present the first instance of an epitaxially regrown QD PCSEL on GaAs. Initially, a regrowth study is presented which explores the effect of infill layer composition on void formation, and is used to inform the fabrication of devices. QD PCSELs display room-temperature ground state lasing at 1230 nm under quasi-CW conditions.

2. Epitaxial Regrowth

PC test structures consisting of a square array of circular pits were defined on bare GaAs substrates by e-beam lithography and reactive ion etching. Three samples were regrown using metalorganic vapour-phase epitaxy (MOVPE) at 650 °C and a growth rate of 6 nm/min. The infill layer com-

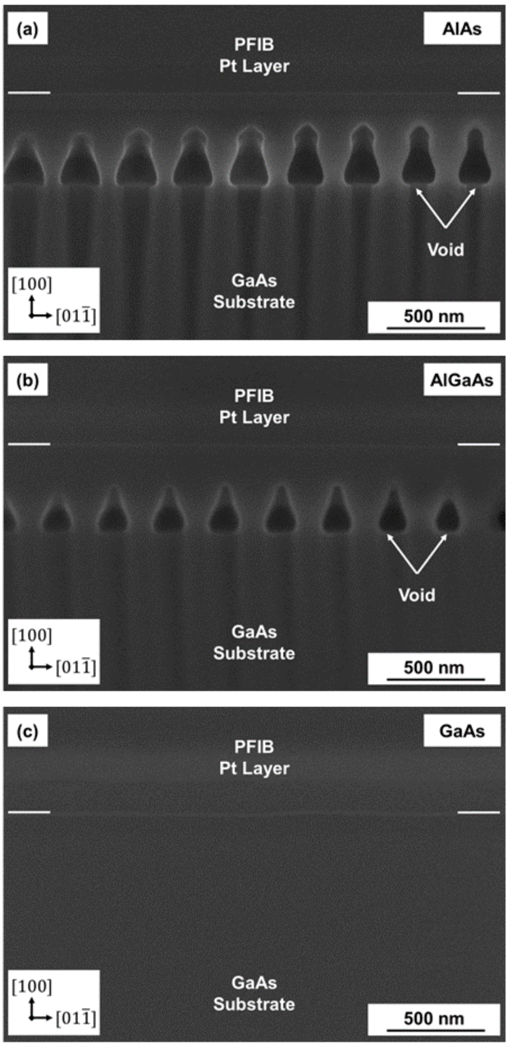

Fig. 1. Cross-sectional SEM images of PC structures following regrowth with (a) AlAs, (b) AlGaAs, and (c) GaAs, as viewed along the [011] direction. Void dimensions decrease from (a) to (b) in line with increasing adatom mobility, with void formation being eliminated in the case of GaAs

position was varied in each case, with either AlAs, $Al_{0.35}GaAs$, or GaAs being used. In order to aid with structural analysis, a superlattice structure was employed in the infill layer, allowing the evolution of the growth front to be visualized.

Cross-sectional scanning electron microscope (SEM) analysis (Fig. 1) reveal that, whilst complete grating infill is achieved for GaAs, void formation in promoted when AlGaAs and AlAs is used. This is attributed to the reduced surface mobility associated with Al which suppresses the diffusion of adatoms into the grating pit, with void dimensions increasing in line with Al mole fraction. In this case, AlGaAs infill results in voids with more optimal dimensions for device applications. Scanning transmission electron microscope (STEM) analysis of AlGaAs-regrown samples (Fig. 2) reveals a degree of asymmetry in the void shape in the plane of the PC layer, as viewed along orthogonal crystal plane directions. This asymmetry, which provides increase radiation constants for this PC geometry, is attributed to the differing polarities and incorporation rates of high-index {311} planes at the bottom of the PC pit.

3. QD PCSEL

A base epi structure containing an 8-layer InAs/GaAs QD stack was grown on 2°-offcut (100) *n*-GaAs substrate by molecular beam epitaxy (MBE). A 338 nm period square lattice PC, consisting of circular pits with r/a of 0.2, was defined in the top *p*-GaAs layer, after which the structure was regrown with *p*-AlGaAs and *p*-GaAs cladding layer. Devices were fabricated so as to provide emission through the *n*-type substrate, and tested under quasi-CW conditions. Ground state lasing corresponding to 1230 nm was demonstrated at room temperature (Fig. 3), with 12 mW of power recorded at 2 A (1.8 I_{th}) for an un-thinned substrate emitting device, where output power is underestimated by a factor of around 3.

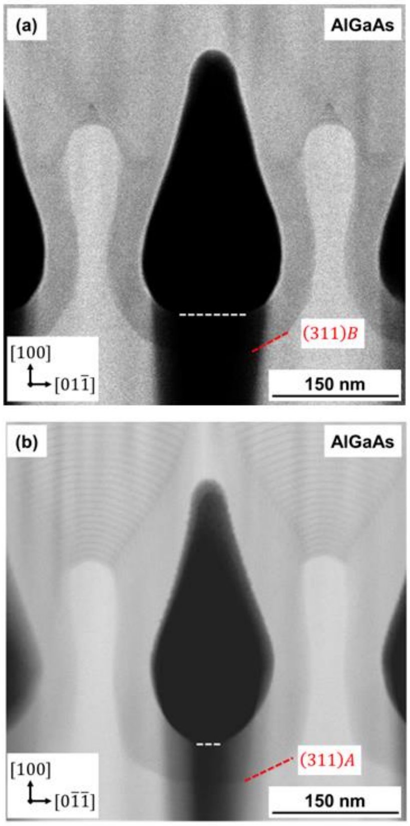

Fig. 2. Cross-sectional HAADF-STEM images of PC structures following regrowth with AlGaAs, as viewed along the (a) [011], and (b) [01$\bar{1}$] directions. Void shape displays an in-plane asymmetry due to growth rate anisotropies associated with the differing polarities of high-index {311} planes

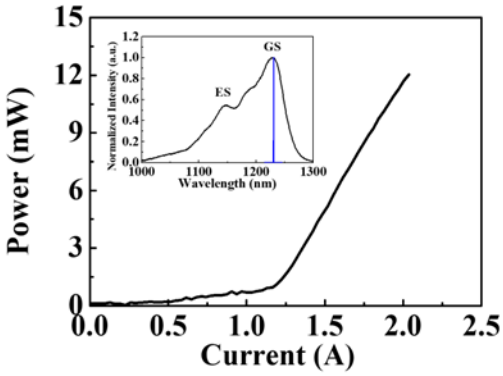

Fig. 3. Room temperature quasi--CW LI characteristics and ground state lasing spectrum (inset) of QD PCSEL. Pulse conditions: 10 µs pulse width, 1 % duty cycle. Device display a threshold current density of 0.685 kA/cm^2 and output power of 12 mW at 2 A current (1.8 I_{Th}).

4. Conclusions

We have reported the development of epitaxial regrowth process that allow an InAs/GaAs QD PCSEL to be realized. A SEM and STEM based study of regrown PC structures reveal that void formation can be tuned or eliminated through the choice of layer composition, with void dimensions increasing with Al mole fraction. In addition, void shapes are shown to be asymmetric in the plane of the PC due to the presence of high-Miller index crystal planes. Devices fabricated using AlGaAs regrowth display room temperature ground state lasing under quasi-CW operation.

Acknowledgements

A.F.M is supported by an Industrial Fellowship from the Royal Commission for the Exhibition of 1851.

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