Journal of Crystal Growth 465 (2017) 48–54

Contents lists available at ScienceDirect

Journal of Crystal Growth

journal homepage: www.elsevier.com/locate/crys

Selective growth of strained (In)GaAs quantum dots on GaAs substrates employing diblock copolymer lithography nanopatterning

Honghyuk Kim [a,*], Jonathan Choi [b], Zachary Lingley [c], Miles Brodie [c], Yongkun Sin [c], Thomas F. Kuech [d], Padma Gopalan [b], Luke J. Mawst [a]

[a] Department of Electrical and Computer Engineering, University of Wisconsin-Madison, USA
[b] Department of Material Science and Engineering, University of Wisconsin-Madison, USA
[c] Electronics and Photonics Laboratory, The Aerospace Corporation, USA
[d] Department of Chemical and Biological Engineering, University of Wisconsin-Madison, USA

ARTICLE INFO

Article history:
Received 21 November 2016
Received in revised form 20 February 2017
Accepted 27 February 2017
Available online 28 February 2017
Communicated by R. Fornari

Keywords:
A3. Metalorganic vapor phase epitaxy
A1. Nanostructures
A3. Selective epitaxy
A1. Etching
B3. Laser diodes

ABSTRACT

Semiconductor laser diodes (LD) were demonstrated employing a strained (In)GaAs quantum dot (QD) active region grown by metalorganic vapor phase epitaxy (MOVPE) on nominally exact (100) GaAs substrates using selective area epitaxy (SAE). The SAE QD growth employed a SiN_x nano-patterned mask defined by diblock copolymer (BCP) lithography. *In-situ* etching using carbon tetrabromide (CBr_4), prior to the SAE of the QDs, was shown to be effective to remove the processing-related damage introduced during the nanopattern transfer process, resulting in a significant reduction in the threshold current density of the LD under the optimal *in-situ* etching condition. Furthermore, the modal optical gain parameter and the transparency current density were extracted by the conventional cavity length analysis (CLA) on LD devices where the QD was grown with the optimal *in-situ* etching condition.

© 2017 Elsevier B.V. All rights reserved.

1. Introduction

Semiconductor laser diodes (LD) employing quantum dot (QD) active regions have attracted attention due to the theoretical predictions: ultra-low threshold current density and low device temperature sensitivity originated from the delta-function-like density of states and small active volume [1,2]. However, while high performance devices have been realized employing QD active regions formed by self-assembly under the Stranski-Krastanov (SK) growth mode, the realization of all the predicted advantages of ideal QDs has remained challenging. Key successes of SK QD lasers include ultra-low threshold current density diode lasers extending the emission into the 1.3 μm wavelength region [3–8] on GaAs substrates or 1.55 μm wavelength region [9–14] on InP substrates. The self-assembly growth mode requires a highly compressively strained material and careful optimization of growth interruptions to minimize the randomness of the QD size and distribution. For many commonly used material systems, such as compressively strained InGaAs QDs on GaAs or InP, SK QD formation leads to an inherent wetting layer formation [15], which has been identified as an underlying cause for the low optical gain and high temperature sensitivity in the LD as a result of the thermally activated carrier leakage out of the QDs into the wetting layers [16–18]. Also, the large and typically bi-modal distribution in the QD sizes leads to a large inhomogeneous broadening in the optical gain spectrum [19]. By contrast, nanopatterning and selective area epitaxy (SAE) offer a more controllable pathway for QD formation, allowing the QD size to be decoupled from the strain state of the material, leading to the formation of wetting layer-free QDs (i.e. full three-dimensional nano-confinement). To date, various methods have been successfully employed to fabricate such wetting layer-free semiconductor based nanostructures, including interferometric optical lithography [20], X-ray lithography [21], atomic force microscopy based lithography [22], electron beam lithography [23–26], scanning tunnelling microscopy (STM) [27] and self-organized anodic aluminium oxide membranes [28]. Among these techniques, the LDs employing the QDs formed by e-beam lithography have successfully demonstrated low threshold current density lasing at room temperature although the QD sizes were relatively large (~100 nm) [23]. Also, while electron beam lithography allows for precise control over the location and geometry of the nano-patterns, the lengthy fabrication time makes it less desirable for high-volume, large-scale device application. Challenges also remain for the other nanopatterning techniques such as

* Corresponding author.
E-mail address: hkim527@wisc.edu (H. Kim).

http://dx.doi.org/10.1016/j.jcrysgro.2017.02.046
0022-0248/© 2017 Elsevier B.V. All rights reserved.