ECIO 2016
18TH EUROPEAN CONFERENCE ON INTEGRATED OPTICS 2016
18–20 MAY | WARSAW | POLAND

Direct Integration of Quantum Dot Lasers on Silicon

Alwyn SEEDS[1*], Siming CHEN[1], Jiang WU[1], Mingchu TANG[1], Huiyun LIU[1]
[1]Department of Electronic and Electrical Engineering, University College London,
Torrington Place, London, WC1E 7JE, England
* a.seeds@ucl.ac.uk

Complex photonic systems for optical communications can benefit from monolithic integration of the key photonic devices with their interconnecting waveguides. Advantages include improved stability and environmental ruggedness, reduced size and reduced cost.

Although silicon photonics technology has demonstrated high performance optical modulators and detectors [1,2], efficient electrically pumped optical sources are key to delivering the required range of system functions.

To date the most successful approach has been wafer bonding of compound semiconductor gain sections to silicon waveguides [3,4]. Direct epitaxial growth of compound semiconductor materials on silicon has been frustrated by material lattice mismatch and incompatible thermal expansion coefficients between III–V materials and silicon leading to high-density threading dislocations [5].

Quantum dot (QD) laser gain regions have proved to be less sensitive to defects than conventional bulk materials and quantum well structures, due to carrier localization and hence a reduced interaction with the defects [6,7]. In our work, we have combined QD gain regions with the use of superlattice defect filter layers to enable the direct epitaxial growth of telecommunications wavelength lasers on silicon substrates.

Figure 1 shows the laser structure [8, 9].

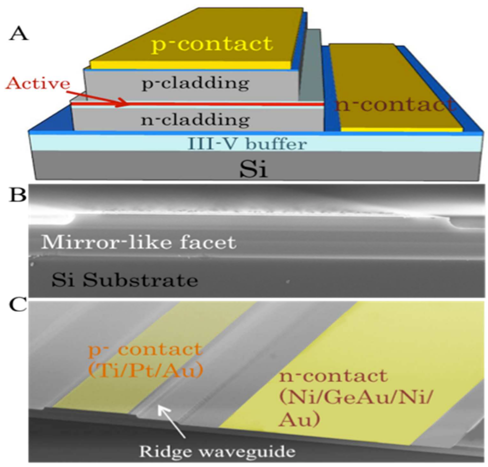

Fig. 1. III-V laser directly grown on Si substrates. (A) Schematic of the layer structure. (B) Cross-sectional SEM image, of the fabricated Si laser with as-cleaved facet, showing very good facet quality. (C) SEM overview of completed III-V laser on silicon.

A thin (5 nm) AlAs nucleation layer was first deposited by migration enhanced epitaxy using alternating Al and As4 flux at a low growth temperature of 350 °C. Following the

5 nm AlAs nucleation layer, a three-step growth technique of GaAs epitaxial growth was used with temperatures of 350 °C, 450 °C, and 590 °C for 30 nm, 170 nm, and 800 nm, respectively. Superlattices (SLSs) were then grown as dislocation filter layers on the top of the GaAs buffer layer. Each SLS is made of five periods of 10-nm In0.18Ga0.82As/10-nm GaAs and repeated for four times separated by 300 nm GaAs spacing layers. The strain relaxation of the SLSs applies an in-plane force to the threading dislocations, which enhance the lateral motion of threading dislocations considerably, increasing the probability for annihilation. Using this growth technique a dislocation density as low as 10^5 cm^{-2} was obtained. A typical QD laser structure was then grown, including five repeats of InAs/GaAs dot-in-a-well (DWELL) structures separated by 50 nm GaAs spacers in the middle of 140 nm undoped GaAs waveguide, 1.4 µm n-type lower and p-type upper $Al_{0.4}Ga_{0.6}As$ cladding layers. The laser structure was completed with a 300 nm p-type GaAs contact layer.

Broad area lasers were fabricated by optical lithography with as-cleaved facets. The measured room temperature threshold current density was 62.5 A cm^{-2}, very similar to the best values for lasers grown on native substrates. Optical output powers as high as 105 mW were measured for a current density of 650 A cm^{-2}. Lasing was obtained for substrate temperatures as high as 120 °C. An ageing test was carried out at 26 °C and 1.75 times threshold current for 3,100 hours, during which the output power reduced by 27.9% (26.4% in the first 500 hours). The extrapolated time to failure, defined as a doubling of threshold current, was 100,158 hours.

In conclusion, we have demonstrated the first telecommunications wavelength quantum dot laser directly grown on a silicon substrate having high performance and long lifetime.

References

[1] G. T. Reed, G. Mashanovich, F. Gardes, D. Thomson, *Silicon optical modulators*, Nature Photonics. 4, 518-526 (2010).
[2] L. Virot et al., *Germanium avalanche receiver for low power interconnects,* Nature Communications. 5(2014).
[3] A. W. Fang et al., *Electrically pumped hybrid AlGaInAs-silicon evanescent laser,* Optics Express. 14, 9203-9210 (2006).
[4] K. Tanabe, K. Watanabe, Y. Arakawa, *III-V/Si hybrid photonic devices by direct fusion bonding,* Scientific Reports. 2, 349 (2012).
[5] H. Park et al., *Device and integration technology for silicon photonic transmitters,* IEEE Jnl. Sel. Topics in Quantum Electron., 17, 671-688 (2011).
[6] C. Ribbat et al., *Enhanced radiation hardness of quantum dot lasers to high energy proton irradiation*, Electron. Lett. 37, 174-175 (2001).
[7] N. Ledentsov, *Quantum dot lasers: the birth and future trends,* Semiconductors. 33, 946-950 (1999).
[8] S. Chen et al., *1.3 µm InAs/GaAs quantum-dot laser monolithically grown on Si substrates operating over 100 C*, Electron. Lett. 50, 1467-1468 (2014).
[9] M. Tang et al., *1.3-µm InAs/GaAs quantum-dot lasers monolithically grown on Si substrates using InAlAs/GaAs dislocation filter layers,* Optics Express. 22, 11528-11535 (2014).
[10] S. Chen et al., *Electrically pumped continuous-wave III–V quantum dot lasers on silicon*, Nature Photonics doi:10.1038/nphoton.2016.21 (2016)