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Electrically-pumped continuous-wave O-band quantum-dot superluminescent diode on silicon

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Abstract: High-power, broadband quantum-dot (QD) superluminescent diodes (SLDs) are ideal light sources for optical coherence tomography (OCT) imaging systems but have previously mainly been fabricated on native GaAs- or InP-based substrates. Recently, significant progress has been made to emigrate QD SLDs from native substrates to silicon substrates. Here, we demonstrate electrically pumped continuous-wave (CW) InAs QD SLDs monolithically grown on silicon substrates with significantly improved performance thanks to the achievement of a low density of defects in the III-V epilayers. The fabricated narrow ridge-waveguide device exhibits a maximum 3-dB bandwidth of 103 nm emission spectrum centred at O-band together with a maximum single-facet output power of 3.8 mW at room temperature. The silicon based SLD has been assessed for application in an OCT system. Under optimised conditions, the predicted axial resolution of 3.5 µm is achieved with a corresponding output power of 0.66 mW/facet. The capability of high-performance III-V SLDs on silicon substrates will be the enabling technology for low-cost, large-scale deployment of fully integrated silicon photonic OCT systems. © 2019 Optical Society of America

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Silicon photonics has been under intensive development over the past decade and is reaching the tipping point. While such technology for data- and tele-communications applications is well known and attracting great interest [1], its potential for other applications, for example, medical diagnostics [2], chemical and biological sensing [3], and nonlinear optics [4], is now building on this progress by leveraging the greatest promise of silicon photonics: large-scale, streamlined manufacturing using commercial CMOS foundry infrastructure. Optical coherence tomography (OCT) has become a powerful medical diagnostic tool to monitor medical treatment and diagnose disease within the skin and other biological tissues non-invasively [5]. The technique currently relies on costly and bulky combinations of separate light source, optical and electronic components. As a result, there is a strong motivation to achieve a low-cost, compact, and maintenance-free bioluminescent imaging solution using CMOS-compatible photonic integrated circuits (PICs), which could potentially allow monolithic integration of low-cost silicon photonic waveguides, high-speed silicon photodiodes and electronics combined with the heterointegration of an efficient and reliable III-V-W, in a longer term simply silicon-based [6,7] light source. Various demonstrations have shown the potential of silicon photonic integrated chips for OCT [8-10] yet, all have required external III-V light sources. This limits the potential for ultra-compact and large-scale integration. The availability of integrated light sources, therefore, a key technology for a fully integrated silicon photonic OCT system. Self-assembled quantum dots (QDs) grown on silicon substrates are required. Superluminescent diodes (SLDs) operating both low-coherence and high output power, permit a low-cost and robust route to provide high axial resolution and deep penetration in such scenarios [11,12]. Self-assembled quantum dots (QDs) constructed by the Stranski-Krastanov growth method have been extensively studied for SLDs over the past two decades, with a view to achieving a broad bandwidth enabled by their naturally occurring large size inhomogeneity, which could also be extended by using of both the ground and excited states for even broader emission [13]. Recently, the self-assembled QD technique is gaining even more importance due to the emergence of promising monolithic III-V/silicon photonic integration applications. Their unique properties, in particular, the enhanced tolerance to defects [14] and reflections [15], as well as the ultralow linewidth enhancement factor [16], have witnessed rapid development in various types of O-band InAs/GaAs QD lasers grown directly on silicon substrates [17-25]. Despite significant progress being made in QD lasers grown...
to a minimum axial resolution of 5.3 µm, offering the possibility of successful demonstration of a CW silicon-based InAs QD SLDs structure grown on silicon to a reference sample grown on native GaAs under the same excitation conditions. The inset shows the representative AFM image of an uncapped QD sample grown on silicon.

on silicon substrates and QD SLDs on native GaAs substrates [26-30], respectively, a high power, broadband continuous wave (CW) InAs QD SLD monolithically grown on a silicon substrate has not yet been demonstrated as a result of the massive material dissimilarity between the two material systems [31].

We have previously demonstrated the first electrically pumped monolithic SLD on silicon by using GaAs nucleation layer (NL) and InAlAs/GaAs strained layer superlattices (SLSs) combined with InAs QDs as the active region [32]. However, the devices are limited to pulsed operation. While the first successful demonstration of a CW silicon-based InAs QDs SLD followed soon after [33], these CW devices showed significantly diminished performance in terms of maximum achievable emission bandwidth (~50 nm) and output power (~0.55 mW) mainly because of material quality issues and limited device fabrication. Clear unstrained epitaxial InGaAs buffer layers, which acts as the lower cladding layer, a 60 nm GaAs lower waveguide layer, a five-layer of InAs/GaAs dot-in-a-well (DWELL) active region, a 60 nm GaAs upper waveguide layer, a 1.4 µm n-type AlGaAs upper cladding layer, and a 300 nm p-doped GaAs contact layer. Each DWELL structure consisted of a 3-monolayer layer of InAs QDs sandwiched by 2 nm InGaAs and 6 nm InAlAs and separated by 45 nm undoped GaAs barriers. The DWELLs were grown at 510 °C, and GaAs and AlGaAs layers were grown at 590 °C.

Figure 1(b) presents a bright-field scanning transmission electron microscopy (BF-STEM) image of the III-V buffer layer grown on a silicon substrate. As expected, a high density of dislocations is generated at the III-V/Silicon interface due to the large lattice mismatch between the two materials. Fortunately, it is clear to see that after the last set of InGaAs/GaAs SLSs, most of the defects have been filtered. Above all, a nearly defect-free DWELL active region is preserved as seen in Fig. 1(c), which also shows the photoluminescence (PL) emission of QDs grown on silicon and GaAs substrates, where a comparable PL intensity of QDs on silicon to that of on GaAs is obtained. The slight blueshift in the peak emission wavelength is mainly attributed to the residual strain between GaAs and silicon. These findings suggest that the III-V buffer layer plays a critical role in suppressing the formation of APBs and the propagation of threading dislocations, thanks to the adopted strategy of an InGaAs/GaAs SLS and in situ thermal annealing.

The inset of Fig. 1(c) shows the atomic-resolution BF-STEM image of a single dot, where the typical dot size is ~20 nm in diameter and ~7 nm in height. The inset of Fig. 1d shows an atomic force microscopy (AFM) image for uncapped InAs QDs grown on silicon. An average dot density of ~3×10^10 cm^-2 was derived from the image. A maximum net modal gain of ~13 cm^-1 at the ground state (GS) peak wavelength was obtained in this structure by a segmented-contact method.

Optical microscopy and scanning electron microscopy (SEM) images of the fabricated devices are shown in Fig. 2. The 2.2 µm width ridge waveguides were defined using electron beam lithography (EBL) and dry etching. To avoid oxidation of the Al-containing layers, a passivation layer of SiO2 was first deposited. Planarisation was then carried out by using hydrogen silsesquioxane (HSQ) thermally cured at 180 °C. For the ohmic contact metallisation, Ti/Pt/Au and Au/Ge/Au/Ni/Au were used for the P+ GaAs contacting layer and the exposed n+ GaAs layer,
respectively. The device cavity length for all devices described in this letter is 4 mm and is defined by cleaving. No facet coating is applied. To achieve only ASE, the device was protected against the laser effect by suppressing cavity reflections using an 8° off-angle tilted waveguide. The SLD bars were mounted epie-side up on a copper heat sink using indium silver low-melting-point solder and directly probed to enable testing. Unless stated otherwise, all SLD measurements were performed under CW operation at RT (20 °C) with no active cooling.

Figure 3 shows the light-current-voltage (LIV) measurement for a typical RT electrically pumped InAs/GaAs QD SLD grown on a silicon substrate. As seen, above a current of ~100 mA, an apparent superlinear behaviour is observed by the superlinear increase of output power with increasing current. A single facet output power of 38 mW was obtained at an injection current of 400 mA with only slight power roll over at this current due to the thermal effects. For application in OCT systems, higher power is desired for better depth penetration. As the output power spectrum depends linearly on spontaneous emission rate and exponentially on the optical gain, it follows that a high value of modal gain is critical for obtaining high output power.

In addition to output power, another critical factor for high-quality OCT images is the spectral bandwidth since the axial resolution is governed by the coherence length, which is inversely proportional to the spectral bandwidth of the light source deployed in the system. Figure 4 shows the ASE spectra and, correspondingly, the evolution of the 3-dB linewidth as well as the central wavelength as a function of injection current. At a low drive current of 40 mA, the emission is dominated by the GS and ES1. Figure 5(b) shows the dependence of predicted axial resolution and measured single facet output power on the injection current. As seen, while a minimum predicted axial resolution of 5.2 µm was achieved at 200 mA, the corresponding output power was less than 0.5 mW. With the increase of the current above 200 mA, there is a trade-off between the axial resolution and output power. As a result, at 400 mA, although a high single facet output power of 3.8 mW was obtained, the predicted axial resolution has been significantly reduced to 18.9 µm. Under the optimised condition of 220 mA, a good axial resolution of 5.3 µm was realised with a reasonable single facet output power of 1.56 mW.

Figure 5(a) depicts an example of self-coherence function derived from the ASE spectrum (shown in the inset of Fig. 5(a)) where the 3-dB bandwidth of 103 nm centred at 1276 nm. A minimum axial resolution of 5.3 µm is predicted. Undesirable sidelobes are observed due to the non-Gaussian ASE spectrum; this introduces a penalty to axial resolution and could be minimised by reducing the ASE spectrum dips between the GS and ES1. Figure 5(b) shows the dependence of predicted axial resolution and measured single facet output power on the injection current. As seen, while a minimum predicted axial resolution of 5.2 µm was achieved at 200 mA, the corresponding output power was less than 0.5 mW. With the increase of the current above 200 mA, there is a trade-off between the axial resolution and output power. As a result, at 400 mA, although a high single facet output power of 3.8 mW was obtained, the predicted axial resolution has been significantly reduced to 18.9 µm. Under the optimised condition of 220 mA, a good axial resolution of 5.3 µm was realised with a reasonable single facet output power of 1.56 mW.

In summary, we have demonstrated a RT electrically pumped CW InAs/GaAs QD SLD directly grown on a silicon substrate, with significant improved CW performance compared to previous works on monolithic III-V SLDs on silicon, their device performance is inferior when compared to native GaAs substrates previously reported in terms of output power and spectrum bandwidth. Output power can be increased in future devices by increasing the overall dot density through high-density QD growth combined with its multilayer growth [35] and the use of p-type modulation doping of the active region [36]. Strategies to further improve the spectral bandwidth are multifaceted: chirped QDs [37], QD intermixing [38], and hybrid quantum well / QD structures [39].

In summary, we have demonstrated a RT electrically pumped CW InAs/GaAs QD SLD directly grown on a silicon substrate with significantly improved CW performance compared to previous reports. The high-quality III-V epi-layers and the use of InAs QDs as the active region lead to a maximum 3-dB linewidth of 103 nm centred at 1275 nm together with a maximum single facet output power over 3.8 mW from a narrow-ridge tilted waveguide AR-coating free device. Assessment of this silicon
REFERENCES for exploiting low-cost, miniaturised OCT for medical diagnosis. High-performance QD SLDs on silicon substrates opens the way for exploiting low-cost, miniaturised OCT for medical diagnosis.

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Disclosures The authors declare no conflicts of interest.

Fig. 5. (a) Self-coherence function calculated from emission spectrum shown in the inset of Fig.5(a). (b) Dependence of predicted axial resolution and single facet output power on the injection current.

Based SLD for OCT application indicates that an axial resolution of 5.3 µm should be possible with a corresponding single facet output power of 0.66 mW. The successful demonstration of high-performance QD SLDs on silicon substrates opens the way for exploiting low-cost, miniaturised OCT for medical diagnosis.

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S. Chen, W. Li, J. Wu, Q. Jiang, M. Tang, S. Shutts, S. N. Elliott, A. Sobiesierski, A. J. Seeds, I. Ross, P. M. Smowton, and H. Liu, Nat. Photon. 10, 307 (2016).

M. Liao, S. Chen, Z. Liu, Y. Wang, L. Ponnampalam, Z. Zhou, J. Wu, M. Tang, S. Shutts, Z. Liu, P. M. Smowton, S. Yu, A. Seeds, and H. Liu, Photonics Res. 6, 1062 (2018).

Y. Wang, S. Chen, Y. Yu, L. Zhou, L. Liu, C. Yang, M. Liao, M. Tang, Z. Liu, J. Wu, W. Li, I. Ross, A. Seeds, H. Liu, S. Yu, Optica 5, 528 (2018).

W. W. Qi, J. H. Wang, B. Zhang, Y. J. Zhang, H. L. Wang, G. Feng, H. X. Xu, T. Wang, and J. J. Zhang, Appl. Phys. Lett. 113, 053107 (2018).

B. Chen, Y. Wu, D. Jung, J. C. Normann, J. K. Kennedy, H. K. Tsang, D. Dumonteil, A. Malik, H. K. Tsang, A. C. Gossard, J. E. Bowers, Laser Photonics Rev. 10, 2000037 (2020).

S. Chen, W. Liu, Z. Zhang, D. Childs, K. Zhou, J. Wang, J. Kennedy, M. Hughes, E. Clarke, I. Ross, L. Vida, and R. Hogg, Nanoscale Res. Lett. 10, 340 (2015).

C. Hou, H. Chen, J. Zhang, N. Zhou, Y. Huang, R. Hogg, D. Childs, J. Ning, Y. Zhang, F. Lu and J. Zhang, Light Sci. Appl. 7, 17170 (2018).

N. Qazi, D. T. D. Choi, J. Karma, T. S. Roberts, T. Yasuda, H. Sabate, H. Chiato, E. Watanabe, N. Ikeda, Y. Sugimoto, and R. A. Hogg, J. Appl. Phys. 119, 083107 (2016).

A. F. Forrest, M. Krakowski, P. Bardella, and M. A. Cataluna, Opt. Express 27, 1505 (2019).

N. Qazi, S. C. Takushi, Y. Hayashi, E. Watanabe, H. Ohsato, N. Ikeda, Y. Sugimoto, K. P. Fung, D. T. D. Choi, J. Karma, T. S. Roberts, and R. A. Hogg, Appl. Phys. Lett. 110, 191102 (2017).

M. Liao, S. Chen, J-S. Park, A. Seeds, H. Liu, Semicond. Sci. Technol. 33, 123002 (2018).

S. Chen, M. Tang, Q. Jiang, J. Wu, V. Dorogan, M. Benamara, Y. Mazur, G. Salamo, P. Smowton, A. Seeds, and H. Liu, ACS Photon. 1, 638 (2014).

S. Chen, M. Tang, S. Huo, S. Chen, J. Wu, M. Tang, K. Kennedy, W. Li, S. Kumar, M. Martin, T. Baron, C. Jin, I. Ross, A. Seeds and H. Liu, IEEE J. Sel. Top. Quantum Electron. 23, 1900910 (2017).

C. Akaev, P. Parrein, and J. Rolland, Appl. Opt. 41, 5256 (2002).

K. Nishi, K. Takemasa, and M. Sugawara, IEEE J. Sel. Top. Quantum Electron. 23, 1901007 (2017).

M. Sugawara and M. Usami, Nat. Photon. 3, 30 (2009).

L. Li, M. Rossetti, A. Fiore, L. Occhi, and C. Velez, Electron. Lett. 41, 41 (2005).

K. Zhou, Q. Jiang, Z. Zhang, S. Chen, H. Liu, Z. Lu, K. Kennedy, S. Matcher, R. Hogg, Opt. Express, 20, 26950 (2012).

S. Chen, K. Zhou, Z. Zhang, D. T. D. Childs, M. Hugues, A. J. Ramsay, and R. A. Hogg, Appl. Phys. Lett. 100, 041118 (2012).
