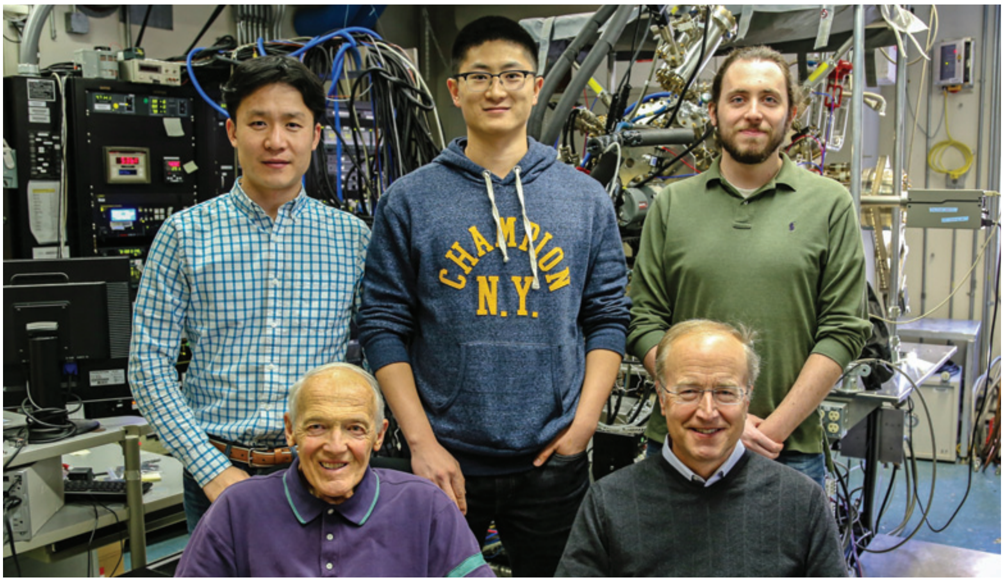
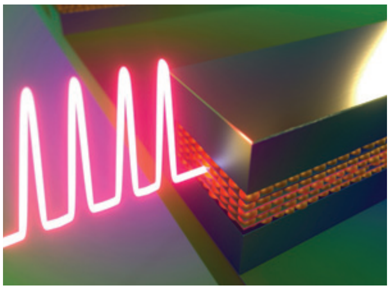
FURTHER READING

'490 fs pulse generation from a passively mode-locked single section quantum dot laser directly grown on on-axis GaP/Si', Songtao Liu, Daehwan Jung, Justin C. Norman, MJ Kennedy, Arthur C. Gossard and John E. Bowers, page 432.

US researchers demonstrate first single-section QDML laser directly grown on CMOS compatible on-axis GaP/Si substrate

a first for single-section QDML lasers on Si





TOP: The research team standing in front of molecular beam epitaxy equipment at University of California, Santa Barbara (Front from the left: Arthur C. Gossard and John E. Bowers, back from the left: Daehwan Jung, Songtao Liu and Justin C. Norman)
BOTTOM: 3D schematic diagram of silicon-based single section quantum dot mode locked lasers emitting high-repetition rate pulses

The first single-section quantum dot mode-locked laser directly grown on a CMOS-compatible silicon substrate has been produced by researchers in the US. Their achievement could open the door to much lower complexity, cheaper laser sources for future large-scale silicon photonic integrated circuits.

Incompatible for integration

Mode-locked (ML) lasers have unique properties that allow them to generate ultrashort pulse trains as well as coherent optical frequency combs. This makes them promising light sources for many applications including time and wavelength division multiplexing systems, photonic-assisted analogue-to-digital conversion, interchip/intrachip clock distribution, arbitrary waveform generation, millimetre-wave signal generation, sensing and spectroscopy.

Quantum dot (QD) mode-locked lasers are of particular interest compared with alternatives using bulk or quantum well materials, because they give stable, low-noise combs due to their inhomogeneously-broadened gain spectrum, ultrafast carrier dynamics, superior temperature stability, high saturation power, small linewidth enhancement factor and low level of amplified spontaneous emission.

A typical QDML semiconductor laser structure has two sections – a gain section and a saturable absorber (SA) section to realise passive mode locking or, combined with an electrical modulation imposed on the SA section, to realise hybrid mode-locking operation. More recent designs of Fabry-Perot (FP) structures have eliminated the need for the SA section – single section designs – but all of these have been grown on GaAs or InP, rather than on a CMOS compatible silicon substrate, which would be more suitable for industrial-scale fabrication.

Growing together

The QDML laser presented in this Issue by a team from University of California, Santa Barbara, is the first to combine the advantages of a single section design with a CMOS compatible silicon substrate.

"In this work, we demonstrate ML lasers with femtosecond pulse generation monolithically integrated onto a CMOS compatible silicon substrate. It's a single section design without SA section, where only forward bias on the gain section is needed. This is a very simple structure that could result in low-cost sources of very short optical pulses and enable integration with other optical and electrical devices on silicon," Dr Songtao Liu, a member of the University of California team, explains. "For example, when integrated in future large scale silicon photonic integrated circuits, the wide coherent optical spectrum generated by the mode locked laser could replace hundreds of single mode lasers, and that greatly simplifies the system and lowers the cost as well as the power consumption. Corresponding femtosecond pulses also can be used in time division multiplexing schemes to further increase the transmission capacity."

According to the team, the major challenge was epitaxially growing high quality III/V materials on (001) on-axis silicon substrates. The large lattice mismatch and polar/non-polar interface between materials like GaAs and Si introduces a high density of threading dislocations and antiphase domains; both of which harm performance in optoelectronic devices. They addressed these through optimisation of the materials' growth conditions and structures.

Bright futures

In terms of the impact of the work, the team believe this demonstration that femtosecond pulse sources can be realised on CMOS compatible silicon substrate, combined with previous results on FP lasers with record long lifetimes, shows the maturity of the material system. "This represents a huge step toward industrial scale fabrication of high quality III/V QD lasers on silicon, which can be further integrated with large scale silicon photonic circuits leveraging advanced CMOS techniques," Liu commented. "In the near future, we hope to demonstrate high capacity transmission using the QD MLSLs with its wide coherent optical spectrum as well as novel device design. From a long-term perspective, integration with other active and passive components all monolithically integrated on a silicon substrate is a first priority."

The Santa Barbara team are now investigating the mechanism behind the self-mode-locking behaviour of their QD MLSL, which is not yet fully understood. Their aim is to further improve aspects of the laser performance such as widening the mode locking regime and narrowing the pulse-width. They are also working to improve the material quality by lowering the threading dislocation densities and intra-cavity loss; as a means to better laser performance in terms of threshold, slope efficiency and lifetime.

Beyond these current efforts the team have several areas in mind for future work; this includes long-term reliability of the QD lasers at elevated temperatures, coupling the light from the QD laser to the low-loss silicon waveguide and study of the mechanism of QD self-mode locking to effectively control the system. "This is an exciting field that is moving quickly, and various novel designs and theories will emerge," said Liu. "This will lead to a fully integrated silicon photonic integrated circuits era that changes the world of photonics."

doi: 10.1049/el.2018.0834

490 fs pulse generation from passively mode-locked single section quantum dot laser directly grown on on-axis GaP/Si

S. Liu✉, D. Jung, J. C. Norman, M. J. Kennedy, A. C. Gossard and J. E. Bowers

We demonstrate, for the first time, a single section passively mode-locked InAs/InGaAs quantum dot laser directly grown on on-axis (001) GaP/Si substrate. The laser has a continuous-wave threshold current of 34 mA at 20°C. By forward biasing the laser gain section current at 470 mA, 490 fs pulse generation with 31 GHz repetition rate can be obtained. This simple femtosecond pulse generation structure with CMOS fabrication compatibility makes the laser a promising light source candidate in future large-scale silicon photonic applications.

Introduction: Compact, power-efficient, mass-producible mode-locked semiconductor lasers (MLSLs) are widely pursued in diverse applications, such as next generation time and wavelength division multiplexing systems, ADC, high speed optical sampling, and interchip/intrachip clock distribution [1–7]. This is due to their special characteristics of ultrashort pulse and wide optical spectrum generation. Quantum dot (QD) MLSLs are, in particular, of interest compared with their quantum well counterparts when considering their inhomogeneously broadened gain spectrum, ultrafast carrier dynamics, superior temperature stability, low chirp and low level of amplified spontaneous emission noise, which are quite beneficial for low noise and femtosecond pulse generation [3]. QD-MLSLs were first demonstrated in conventional two-section gain and saturable absorber (SA) configurations [1–4]. Recently, reports of a single section Fabry-Perot structure can eliminate the need of the SA section compared with two-section designs, which simplifies the laser operation with only direct current (DC) forward bias as well as the low cavity loss, leading to high optical output power [5–7]. However, these QD-MLSLs are all either grown on GaAs or InP substrates or wafer-bonded on a silicon substrate. It is desirable to realise directly grown CMOS compatible silicon substrate based QD-MLSLs for future industrial scale photonic applications.

In this letter, we present, to our best knowledge, the first experimental demonstration of a 31 GHz single section QD-MLSL directly grown on on-axis (001) GaP/Si substrate using molecular beam epitaxy. The QD laser shows a threshold current of 34 mA with a cavity length of 1330 μm at 20°C. 490 fs pulse generation with a narrow 3 dB RF linewidth of 100 kHz is obtained when the laser is forward biased around 470 mA.

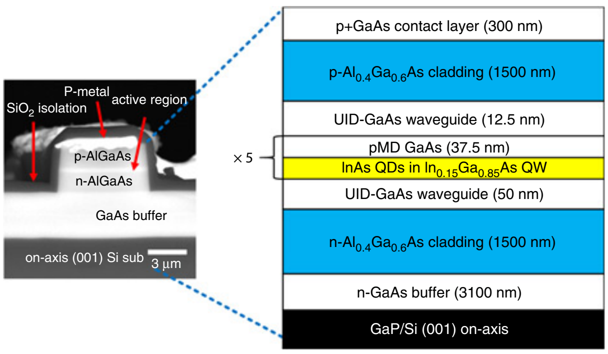


Fig. 1 *SEM image of epitaxially grown silicon QD laser with indicatrix showing various component layers of device (not to scale)*

Device design and fabrication: Fig. 1 shows the SEM image and schematic component layer (not to scale) of the silicon-based QD laser epitaxial structure. It is grown on an optimised GaAs buffer layer by molecular beam epitaxy with threading dislocation density of 6.9×10^6 cm^{-2}. The active region (shown in yellow) consists of five layers of QDs, of which the dots density is 5×10^{10} cm^{-2} per layer. 1×10^{18} cm^{-3} p-modulation doped GaAs barriers are used to improve the high temperature performance. The detailed laser and buffer growth conditions can be found elsewhere [8, 9]. The QD laser is fabricated into a deep-etched ridge waveguide structure to facilitate *n*-metal deposition by standard photolithography employing inductively coupled plasma dry etch. The ridge width is ∼ 6 μm. The laser is then cleaved to have a length of 1330 μm with both facets coated of high-reflectivity (HR) dielectric layers (SiO_2 and Ta_2O_5) to achieve 99% reflection on one facet and 60% on the other facet.

Experimental results and discussion: Fig. 2*a* presents the optical output power and voltage curve as a function of forward biased gain section current of the silicon QD-MLSL under a stage temperature of 20°C controlled by a thermoelectric cooler. Optical output power from the facet with 60% HR coating is collected by an integrating sphere. The threshold current of 34 mA with output power over 40 mW of the laser can be clearly observed. The dynamic differential series resistance is about 2 Ω. Under the investigated current range, excited state modes are 45 dB below the ground state modes.

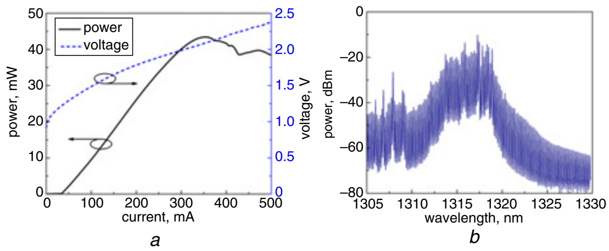


Fig. 2 *LIV curve and passive mode locking spectrum*

a Single section QD-MLSL's LIV curve
b Passive mode-locking optical spectrum of chip under 470 mA DC forward bias

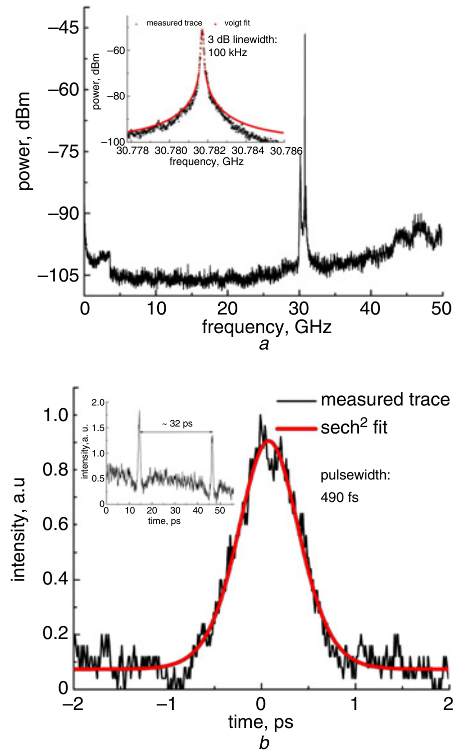


Fig. 3 *Passive mode locking performance in frequency domain and time domain*

a RF spectrum in 50 GHz span view (inset: zoomed-in view of RF peak with Voigt fit, 3 dB RF linewidth: 100 kHz, RBW: 50 kHz)
b Second harmonic generation autocorrelation trace with sech^2 fit (inset: pulse train in 55 ps span) of QD-MLSL (I_{gain} = 470 mA, T_{stage} = 20°C)

Due to the phase-locked property of the mode locking behaviour, passive mode locking operation of the single section silicon QD laser is first identified via routing the collected optical output signal directly into a fast u^2t 50 GHz photodiode connecting to an electrical spectrum analyser (Rohde&Schwarz FSU). By gradually increasing the forward bias current of the QD laser up to 470 mA, a sharp RF peak can be observed in the 50 GHz span view around 30.78 GHz in Fig. 3*a*, corresponding to the cleaved length of the tested QD-MLSL chip, which has a signal to noise ratio that is larger than 30 dB. The side peak beside the main signal is caused by a weak higher-order mode that co-existed in the cavity, as shown in the spectrum in Fig. 2*b*, which can be eliminated by narrowing the waveguide ridge width. The obtained RF 3 dB linewidth is determined to be 100 kHz [resolution bandwidth (RBW): 50 kHz] assuming a Voigt line shape, as shown in the inset of Fig. 3*a*, indicating the multiple oscillating longitudinal modes in the cavity are well phase-locked with each other when considering the linewidth of a single longitudinal mode of the QD-MLSL laser is around 30 MHz measured by self-heterodyne technique. The high four-wave-mixing efficiency that is exhibited in zero-dimensional QD material due to the fast intraband oscillations in the carrier occupation level is hypothesised to be the main mechanism behind this enhanced phase correlation [10]. This mode-locking behaviour can be further confirmed by time domain measurement utilising second harmonic generation autocorrelator (Femtochrome, FR-103MN). Fig. 3*b* shows the measured autocorrelation trace of a single isolated pulse. The pulse width is determined to be 490 fs when fitting to a $sech^2$ pulse profile. This is the first femtosecond pulse generation, to our best knowledge, from a QD laser directly grown on GaP/Si substrate. The inset of Fig. 3*b* shows a wider span view of the optical pulse train, with a pulse period of ~32 ps matching the 31 GHz repetition rate.

Conclusion: Femtosecond pulse generation from a single section QD laser directly grown on on-axis (001) GaP/Si substrate is first demonstrated. The QD-MLSL operates at 31 GHz repetition frequency, delivering 490 fs pulsewidth with a narrow 3 dB RF linewidth of 100 kHz. Higher rate pulse trains can be anticipated with shorter cavity length. The exhibited performance with CMOS compatibility of the laser makes it a promising light source candidate in future large-scale silicon photonic integrated circuits.

Acknowledgments: This research work was funded by U.S. Department of Energy under a contract of Advanced Research Projects Agency-Energy (ARPA-E) DE-AR000067. Songtao Liu and Daehwan Jung contributed equally to this work.

Submitted: *15 December 2017* E-first: *21 February 2018*
doi: 10.1049/el.2017.4639
One or more of the Figures in this Letter are available in colour online.

S. Liu, M. J. Kennedy, A. C. Gossard and J. E. Bowers (*Department of Electrical and Computer Engineering, University of California, Santa Barbara, California 93106, USA*)

✉ E-mail: songtao_liu@ucsb.edu

D. Jung (*Institute for Energy Efficiency, University of California, Santa Barbara, California 93106, USA*)

J. C. Norman (*Materials Department, University of California, Santa Barbara, California 93106, USA*)

References

1 Huang, X., Stintz, A., Li, H., *et al.*: 'Passive mode-locking in 1.3 µm two-section InAs quantum dot lasers', *Appl. Phys. Lett.*, 2001, **78**, (19), pp. 2825–2827, doi: 10.1063/1.1371244
2 Rafailov, E.U., Cataluna, M.A., Sibbett, W., *et al.*: 'High-power picosecond and femtosecond pulse generation from a two-section mode-locked quantum-dot laser', *Appl. Phys. Lett.*, 2005, **87**, (8), p. 081107, doi: 10.1063/1.2032608
3 Thompson, M.G., Rae, A.R., Xia, M., *et al.*: 'InGaAs quantum-dot mode-locked laser diodes', *J. Sel. Top. Quantum Electron.*, 2009, **15**, (3), pp. 661–672, doi: 10.1109/JSTQE.2008.2012265
4 Wang, Z., Fanto, M.L., Steidle, J.A., *et al.*: 'Passively mode-locked InAs quantum dot lasers on a silicon substrate by Pd-GaAs wafer bonding', *Appl. Phys. Lett.*, 2017, **110**, (14), p. 141110, doi: 10.1063/1.4979534
5 Lu, Z., Liu, J., Raymond, S., *et al.*: '312-fs pulse generation from a passive C-band InAs/InP quantum dot mode-locked laser', *Opt. Express*, 2008, **16**, (14), pp. 10835–10840, doi: 10.1364/OE.16.010835
6 Gao, F., Luo, S., Ji, H., *et al.*: 'Ultrashort pulse and high power mode-locked laser with chirped InAs/InP quantum Dot active layers', *Photonics Technol. Lett.*, 2016, **28**, (13), pp. 1481–1484, doi: 10.1109/LPT.2016.2561302
7 Renaudier, J., Brenot, R., Dagens, B., *et al.*: '45 GHz self-pulsation with narrow linewidth in quantum dot Fabry-Perot semiconductor lasers at 1.5 µm', *Electron. Lett.*, 2005, **41**, (18), p. 1007, doi: 10.1049/el:20052173
8 Jung, D., Norman, J., Kennedy, M., *et al.*: 'High efficiency low threshold current 1.3 µm InAs quantum dot lasers on on-axis (001) GaP/Si', *Appl. Phys. Lett.*, 2017, **111**, (12), p. 122107, doi: 10.1063/1.4993226
9 Jung, D., Callahan, P.G., Shin, B., *et al.*: 'Low threading dislocation density GaAs growth on on-axis GaP/Si (001)', *J. Appl. Phys.*, 2017, **122**, (22)
10 Dong, M., Cundiff, S.T., and Winful, H.G.: 'Physics of frequency modulated comb generation in semiconductor diode lasers'. Nonlinear Optics, Waikoloa, United States, 17–21 July 2017, p. M2A.4, doi: 10.1364/NLO.2017.NM2A.4