# Dynamics of Quantum Dot Lasers on Silicon

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***Abstract*—InAs/GaAs quantum dot lasers epitaxially grown on Si substrates are promising candidates as light sources for Si photonic integrated circuits. We discuss their dynamic properties via small-signal and pulsed simulation and experiment, with a special focus on their potential for data transmission applications.**

***Keywords*—Modulation, optical pulses, quantum dot lasers, semiconductor device modeling, silicon photonics**

## I. INTRODUCTION

Silicon photonics is predicted potentially to be one of the key technologies to transform the future data communication landscape by providing high bandwidth and integration density at low power consumption and manufacturing cost. A monolithic light source is imperative to truly benefit from these advantages, making III-V lasers monolithically grown on Si substrates long sought-after optical components. Within the past decade, researchers have succeeded in growing high quality 1.3 $\mu$m InAs/GaAs quantum dot (QD) lasers on Si with excellent static performance characteristics, indicating their great potential as externally modulated on-chip light source. However, to use direct modulation, a response much faster than 25 Gb/s is required. Whereas 25 Gb/s PAM-4 modulation of a QD laser on Si has been realised [1], the so far fastest reported small-signal bandwidth is only 6.5 GHz [2]. Yet as the 10 Gb/s Ethernet Passive Optical Network becomes the leading technology for fiber-to-the-home access, there is a large market emerging for inexpensive lower modulation bandwidth lasers. Since laser growth on low-cost Si wafers offers a great cost advantage compared with the use of native III-V substrates, it is crucial to understand the physics behind the dynamic properties of QD lasers on Si, especially with respect to the impact of the high dislocation density, in order to assess their potential for ≥10 Gb/s applications. We present, therefore, results of gain-switching and small-signal modulation experiments using III-V QD lasers on Si, supported by numerical simulations with a special focus on the impact of dislocations.

## II. EPITAXIAL STRUCTURE AND DEVICE LAYOUT

The experiments are performed using MBE-grown laser structures. First, an AlAs nucleation layer, a GaAs buffer layer, and InGaAs/GaAs strained-layer superlattices acting as dislocation filters are grown on an offcut Si substrate. The dislocation density in the resulting GaAs-on-Si virtual substrate is <$10^6$ cm$^{-2}$. The active region consists of a five-stacked InAs/ InGaAs/GaAs dot-in-a-well (DWELL) structure sandwiched in a GaAs/AlGaAs graded-index separate confinement heterostructure. The InAs QDs are embedded in 8 nm $In_{0.15}Ga_{0.85}As$ quantum wells (QWs) and show a dot density of $3 \times 10^{10}$ cm$^{-2}$. More information on the growth can be found in [3]. The finished wafers are fabricated into 2.5 mm × 2.2 $\mu$m narrow ridge-waveguide lasers and the thinned laser bars are mounted on a copper heatsink. Finally, a 95 % high-reflection coating is applied to the rear facet.

## III. GAIN SWITCHING EXPERIMENTS AND SIMULATIONS

Gain-switched optical pulses are generated using a circuit producing a nanosecond-long electrical pulse of variable amplitude and duration. The shortest obtained pulse is displayed in Fig. 1. A three-level rate equation traveling-wave model is used to simulate the dynamics of the QD laser on Si, showing that limited gain and high gain saturation restrict the pulse dynamics. Compared with gain-switching experiments performed with a QD broad-area laser grown on Si [4], the narrow ridge-waveguide laser used here tends to show slightly shorter pulse durations and fall times, which is reflected in a lower gain compression factor ($1\times10^{16}$ cm$^3$ versus $5\times10^{16}$ cm$^3$). Physically, this is expected since the single-transverse mode narrow ridge-waveguide provides better optical confinement, whereas in the 50 $\mu$m broad-area waveguide, contributions from individual transverse modes are unlikely to build up simultaneously, leading to a pulse broadening and a lengthening of the trailing edge. Further simulations on ways to improve the observed performance will be presented at the conference.

## IV. SMALL-SIGNAL EXPERIMENTS AND SIMULATIONS

The Si-based lasers' data transmission potential is investigated through small-signal modulation. As shown in Fig. 2a, the 3dB bandwidth of the QD laser is ~2.3 GHz. Fitting the respective small-signal response curves (Fig. 2a inset) using a standard three-pole transfer function reveals that a parasitic

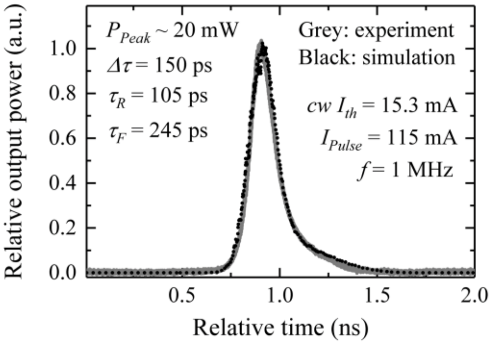

Fig. 1. Normalised gain-switched pulse from a QD laser on Si. $\Delta\tau$, $\tau_R$, and $\tau_F$ denote the optical pulse width at half height and the rise and fall time.

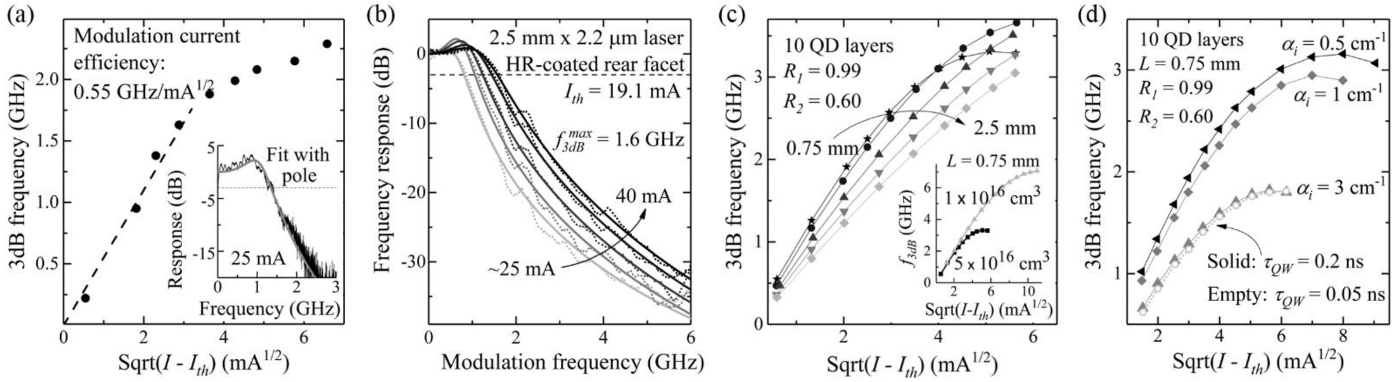

Fig. 2. (a) 3dB bandwidth versus the square root of current above threshold with the inset showing the respective modulation response curve at 25 mA. (b) Small-signal curves of another QD laser on Si. (c) Modelled 3dB bandwidth versus the square root of current above threshold based on a laser parameter set that fits the curves shown in Fig. 2b. The inset shows the impact of the gain compression factor on the 3dB frequency. (d) Simulations on the impact of optical loss and non-radiative recombination in the QWs embedding the QDs on the modulation response of a QD laser on Si.

pole at about 1 GHz limits the modulation response. In a high-frequency-optimised design, the maximum modulation bandwidth should be about 3.5 GHz. Another tested QD laser on Si with the same dimensions shows a smaller 3dB bandwidth limited to 1.6 GHz (Fig. 2b). Numerical simulations indicate that gain saturation is the origin of this reduced bandwidth, analogously to what is found in modelling the gain-switched pulses. Additional simulations, shown in Fig. 2c, suggest that a higher 3dB bandwidth of up to 7 GHz, depending on the level of gain compression, could be reached by using more active layers and by enhancing the optical feedback with two HR-coatings, thus indicating potential for 10 Gb/s applications. A very high gain of almost 60 cm$^{-1}$ has been reported in [5], proving that growing high-gain QD active regions on Si substrate is not an insurmountable hurdle. Indeed, faster modulation bandwidths of 4.0 GHz and 6.5 GHz have been reported using similar 580 $\mu$m long devices with unintentionally doped and $p$-doped active regions, respectively, although the 9.5 GHz predicted by the extracted $K$-factor of 0.92 ns were not reached due to the laser electrodes not being optimised for high-speed operation [2].

While QD lasers in general are known to have a limited modulation response compared with QW lasers, due to their lower modal gain and cascaded carrier transport, the small-signal bandwidths measured so far raise the question whether the monolithic growth on Si impairs the dynamic properties of Si-based QD lasers fundamentally, or if the smaller bandwidths can be attributed to the QD properties. The two main points of concern are optical loss through scattering at dislocation cores and enhanced non-radiative carrier recombination. The latter takes place as carriers from the barrier layers and the QWs in the DWELL structure migrate into defect states formed by threading dislocations, whereas carriers captured into QD states are believed to be mainly unaffected by this process. To assess the impact of these mechanisms on the lasers' dynamic behaviour, additional simulations are performed using a longer and a strongly reduced QW lifetime, representing the cases of low and high dislocation densities, and different levels of optical loss. The results, displayed in Fig. 2d, indicate that the QD laser's modulation response is almost independent of the QW lifetime. Although high QW carrier loss increases eventually the QD laser's threshold and reduces its slope efficiency, carrier loss at dislocations does not appear to be a major issue with respect to the dynamics as long as sufficient carriers are supplied to the QDs. Dislocation-induced optical loss, however, affects the small-signal performance, since it reduces the available gain, which plays a key role for the laser's modulation speed. A more detailed discussion will be given at the conference.

## V. CONCLUSIONS

Gain-switching and small-signal modulation experiments were performed using InAs/GaAs quantum dot lasers grown on Si. Numerical simulations were used to understand the observed dynamics, confirming that high gain is a key quantity for fast QD lasers. Additional theoretical investigations on the impact of dislocations on the modulation speed reveal that dislocation-induced optical loss affects the dynamic performance negatively, whereas non-radiative recombination at dislocations does not appear to limit the lasers' dynamics.

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