Relative intensity noise of injection-locked epitaxial quantum dot laser on silicon

Qi Chu*, Shiyuan Zhao†, Frédéric Grillot†‡, Jiawei Wang*, Feng He*, Mingyu Zhang*, Xiaochuan Xu*, Yong Yao* and Jianan Duan*§

*State Key Laboratory on Tunable Laser Technology, School of Electronic and Information Engineering, Harbin Institute of Technology, Shenzhen 518055, China

†LTCI, Telecom Paris, Institut Polytechnique de Paris, 91120 Palaiseau, France

‡Center for High Technology Materials, The University of New-Mexico, Albuquerque, NM 87106, USA

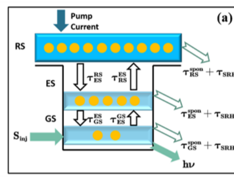
§duanjianan@hit.edu.cn

***Abstract*—This work investigates the relative intensity noise (RIN) characteristics of quantum dot (QD) lasers epitaxially grown on silicon subject to the optical injection. The effect of threading dislocation (TD), which acts as nonradiative recombination centers in the Shockley-Read-Hall (SRH) process, is considered in the rate equation model. The results reveal that the RIN is enhanced by decreasing the nonradiative recombination lifetime. It is shown that this high RIN characteristics is suppressed by the optical injection. In the stable injection-locked area, the RIN is reduced down to - 168 dB/Hz by adjusting the injection ratio and frequency detuning. This work provides an effective method for designing low RIN lasers for photonics integrated circuits (PICs) on silicon.**

***Index Terms*—Quantum dot laser, Optical injection, Relative intensity noise.**

I. INTRODUCTION

QD lasers epitaxial grown on silicon have been regarded as the most potential on-chip laser source to achieve energy and cost-efficient optical transmission for PICs on silicon [1]. With the rapidly progressing silicon photonics integration technologies, epitaxial QD lasers on silicon have recently achieved record performance with long lasing device lifetime, near-zero linewidth enhancement factor (α_H) and high feedback resistance. However, due to lattice mismatch, the epitaxial growth of III-V materials on silicon produces a large number of TD defects, which acts as nonradiative recombination centers in the SRH process, thereby affecting the performance of QD lasers [2]. In particular, on-chip laser source with low RIN is required to increase the signal-to-noise ratio and carry broadband data with low bit error rate. Compared with QD lasers on native substrate, the silicon-based QD lasers have shown a bit higher RIN values of - 150 dB/Hz due to the higher TD density [3]. It has been shown that the optical injection can considerably improve dynamical performances of semiconductor lasers including modulation bandwidth, frequency chirp and noise properties [4]. This work theoretically investigates the RIN characteristics of injection-locked area of epitaxial QD lasers on silicon. The results reveal that the RIN of laser is enhanced at shorter nonradiative recombination lifetime whereas high RIN characteristics is suppressed by the optical injection. In the stable locking area, the RIN is reduced down to - 168 dB/Hz by adjusting the injection ratio and frequency detuning. This work provides an effective method for designing low RIN lasers for PICs on silicon.



(b)

$$\frac{dN_{RS}}{dt} = \frac{I}{q} + \frac{N_{ES}}{\tau_{RS}^{ES}} - \frac{N_{RS}}{\tau_{ES}^{RS}}(1-\rho_{ES}) - \frac{N_{RS}}{\tau_{RS}^{spon}} - \frac{N_{RS}}{\tau_{SRH}} + F_{RS}$$

$$\frac{dN_{ES}}{dt} = \left(\frac{N_{RS}}{\tau_{ES}^{RS}} + \frac{N_{GS}}{\tau_{ES}^{GS}}\right)(1-\rho_{ES}) - \frac{N_{ES}}{\tau_{GS}^{ES}}(1-\rho_{GS}) - \frac{N_{ES}}{\tau_{RS}^{ES}} - \frac{N_{ES}}{\tau_{ES}^{spon}} - \frac{N_{ES}}{\tau_{SRH}} + F_{ES}$$

$$\frac{dN_{GS}}{dt} = \frac{N_{ES}}{\tau_{GS}^{ES}}(1-\rho_{GS}) - \frac{N_{GS}}{\tau_{ES}^{GS}}(1-\rho_{ES}) - \Gamma_p v_g g_{GS} S_{GS} - \frac{N_{GS}}{\tau_{GS}^{spon}} - \frac{N_{GS}}{\tau_{SRH}} + F_{GS}$$

$$\frac{dS_{GS}}{dt} = (\Gamma_p v_g g_{GS} - \frac{1}{\tau_p})S_{GS} + \beta_{sp}\frac{N_{GS}}{\tau_{GS}^{spon}} + 2k_c\sqrt{S_{inj}S_{GS}}\cos\phi + F_S$$

$$\frac{d\phi}{dt} = \frac{1}{2}\Gamma_p v_g(g_{GS}\alpha_H^{GS} + g_{ES}\alpha_H^{ES} + g_{RS}\alpha_H^{RS}) + \beta_{sp}\frac{N_{GS}}{\tau_{GS}^{spon}} - \Delta\omega_{inj} - k_c\sqrt{S_{inj}/S_{GS}}\sin\phi + F_S$$

Fig. 1. (a) Schematic representation of the electronic structure and carrier dynamics into the quantum dot. (b) Rate equation model.

II. RATE EQUATION MODEL

Fig. 1(a) illustrates the schematic of the carrier dynamics of the QD laser. The exciton model consists of a two-dimensional carrier reservoir (RS) as well as excited state (ES) and ground state (GS) of QD. The dynamics among the three level is characterized by capture time τ_{ES}^{RS}, relaxation time τ_{GS}^{ES} and escape time τ_{ES}^{GS} and τ_{RS}^{ES}. In addition, carriers in RS, ES, GS are also recombined spontaneously within spontaneous emission time $\tau_{RS,ES,GS}^{spon}$ and only the stimulated emission from the GS is considered in this work. The corpuscular rate equations describing the dynamics of carrier number $N_{RS,ES,GS}$, photon number S_{GS} , and the phase ϕ are shown in Fig. 1(b). I is the pump bias current, q is the electron charge, $\rho_{GS,ES,RS}$ are the carrier occupation probabilities in GS, ES and RS, Γ_p is the optical confinement factor, v_g is the group velocity, $g_{RS,ES,GS}$ are the material gain of each state, τ_p is the photon lifetime, β_{sp} is the spontaneous emission factor. $F_{RS,ES,GS}$, F_S, F_ϕ are the Langevin noise for the carrier, photon, and phase noise sources, respectively. τ_{SRH} is the nonradiative recombination lifetime in each level. The master-slave optical injection mechanism is taken into account with S_{inj} is the injected photon number from master laser. The injection ratio defined as $R_{inj} = S_{inj}/S_0$, where S_0 is the photon number of the free-running laser. $\Delta\omega_{inj}$ is the frequency detuning defined as the frequency difference between the master laser and the slave laser. k_c is the coupling coefficient of the two lasers.

978-1-6654-7899-1/22/$31.00 ©2022 IEEE

III. Results and discussion

The epitaxial defect density in QD lasers on GaAs substrate is typically in the range of 10^5-10^6 cm^{-2} corresponding to τ_{SRH} on the order of 10 ns. In contrast, the defect density is at least one orders of magnitude higher (10^6-10^8 cm^{-2}) in silicon-based QD lasers hence the τ_{SRH} is on the order of 0.5-1 ns. Fig. 2(a) depicts the photon number as a function of the bias current for different τ_{SRH} ranging from 0.5 ns to 10 ns. The threshold current increases from 52 mA at $\tau_{SRH} = 10$ ns to 125 mA at $\tau_{SRH} = 0.5$ ns due to the high defect density. The RIN is defined as the ratio of the square of photon number variation to the square of average photon number. Fig. 2(b) depicts the RIN spectra of free-running laser for different τ_{SRH}. It demonstrates that a short τ_{SRH} raises the RIN level at low frequencies below the relaxation oscillation frequency (ROF). The low-frequency RIN value at 0.01 GHz increases from -161 dB/Hz at $\tau_{SRH} = 10$ ns to -157 dB/Hz at $\tau_{SRH} = 0.5$ ns, while the high-frequency RIN remains constant.

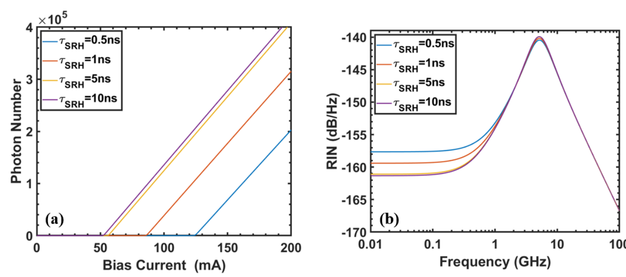


Fig. 2. (a) Photon numbers emitted from the GS as a function of the bias current. (b) Nonradiative recombination effects on the RIN spectra.

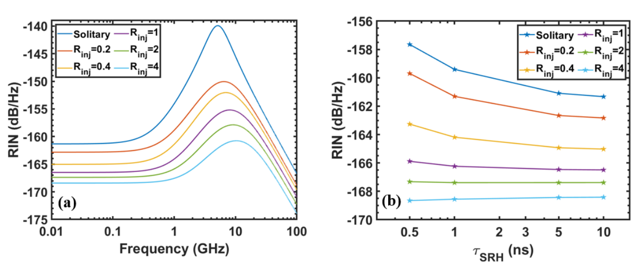


Fig. 3. (a) Injection ratio dependence of the RIN spectra with $\tau_{SRH} = 10$ ns. (b) Low-frequency RIN at 0.01 GHz versus τ_{SRH} for different injection ratio.

The effect of injection locking on the RIN performance of QD laser is now investigated. Fig. 3(a) shows the RIN spectra of the injection-locked QD laser at different injection ratios with $\tau_{SRH} = 10$ ns and a zero frequency detuning. With the increase of injection ratio, the RIN decreases in the whole spectral range and the ROF shifts towards a higher frequency along with a reduced peak amplitude. The injection ratio dependence of low frequency RIN at 0.01 GHz versus τ_{SRH} is shown in Fig. 3(b). Compared with the free-running QD laser, the RIN in the injection-locked area is reduced by about 7 dB at $\tau_{SRH} = 10$ ns, and 11 dB at $\tau_{SRH} = 0.5$ ns with the injection ratio of 4. In addition, it is noted that the RIN is almost constant when further increasing the injection ratio hence the effect of defects on the RIN can be completely offset in silicon-based QD laser. Fig. 4 displays the map of the RIN with the variation of both injection ratio and frequency detuning at $\tau_{SRH} = 0.5$ ns. The RIN in the stable injection-locked area is reduced down to -168 dB/Hz with the increase of the injection ratio. However, this stable area is asymmetric with respect to zero frequency detuning and shifts to positive frequency detuning. The asymmetry of boundary for stable area results from the asymmetry in the gain profile leading to a non-zero α_H factor [4].

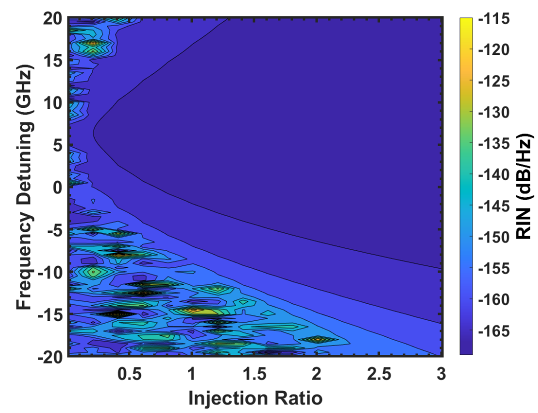


Fig. 4. The map of RIN in the stable injection-locked area with the variation of injection ratio and frequency detuning for $\tau_{SRH} = 0.5$ ns

IV. Conclusion

In summary, we theoretically demonstrate that the large RIN in silicon-based QD lasers induced by high defect density resulting in short nonradiative recombination lifetime can be compensated by the injection locking. Compared with the free-running laser, the injection-locked laser can achieve RIN as low as -168 dB/Hz which is reduced by about 7dB at $\tau_{SRH} = 10$ ns, and 11 dB at $\tau_{SRH} = 0.5$ ns. Overall, this work brings new insights for designing integrated injection-locked QD lasers on a silicon chip for low noise applications.
Funding: Guangdong Basic and Applied Basic Research Foundation (2021A1515110076), Shenzhen Science and Technology Program (RCBS20210609103824050) and Research Startup Fund of HITSZ.

References

1 Norman, J. C., Jung, D., Wan, Y., and Bowers, J. E., "Perspective: The future of quantum dot photonic integrated circuits," *APL photonics*, vol. 3, no. 3, p. 030901, 2018.

2 Zhao, S. and Grillot, F., "Effect of shockley-read-hall recombination on the static and dynamical characteristics of epitaxial quantum-dot lasers on silicon," *Physical Review A*, vol. 103, no. 6, p. 063521, 2021.

3 Duan, J., Zhou, Y., Dong, B., Huang, H., Norman, J. C., Jung, D., Zhang, Z., Wang, C., Bowers, J. E., and Grillot, F., "Effect of p-doping on the intensity noise of epitaxial quantum dot lasers on silicon," *Optics Letters*, vol. 45, no. 17, pp. 4887–4890, 2020.

4 Wang, X.-G., Zhao, B.-B., Grillot, F., and Wang, C., "Frequency noise suppression of optical injection-locked quantum cascade lasers," *Optics Express*, vol. 26, no. 12, pp. 15 167–15 176, 2018.