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Invited Paper

Intensity noise and modulation dynamic of epitaxial quantum dot semiconductor lasers on silicon

F. Grillot*[a,b], J. Duan[a,c], S. Zhao[a], B. Dong[a], H. Huang[a], J. C. Norman[d], and J. E. Bowers[d]
[a]*LTCI, Télécom Paris, Institut Polytechnique de Paris, Palaiseau 91120, France;*
[b]*Center for high Technology Materials, 1313 Goddard SE, Albuquerque, New-Mexico M 87106-4343, USA;*
[c]*State Key Laboratory on Tunable Laser Technology, School of Electronic and Information Engineering, Harbin Institute of Technology, Shenzhen, 518055, China;*
[d]*Materials Department, University of California, Santa Barbara, California 93106, USA;*

grillot@telecom-paris.fr

ABSTRACT

Quantum dot lasers directly grown on silicon are excellent candidates to achieve energy and cost-efficient optical transceivers thanks to their outstanding properties such as high temperature stability, low threshold lasing operation, and high feedback tolerance. In order to reach even better performance, p-type doping is used to eliminate gain saturation, gain broadening due to hole thermalization and to further reduce the linewidth enhancement factor. Optical transceivers with low relative intensity noise are also highly desired to carry broadband data with low bit-error rate. Indeed, the intensity noise stemming from intrinsic optical phase and frequency fluctuations caused by spontaneous emission and carrier noise degrades the signal-to-noise ratio and the bit-error rate hence setting a limit of a high-speed communication system. This paper constitutes a comprehensive study of the intensity noise properties of epitaxial quantum dot lasers on silicon. Results show minimal values between - 140 dB/Hz and - 150 dB/Hz for doping level between 0 and 20 holes/dot in the active region. In particular, the intensity noise is insensitive to temperature for p-doped QD laser. Modulation properties such as damping, carrier lifetime, and K-factor are also extracted from the noise characteristics and analyzed with respect to the doping level. We also provide numerical insights based on an excitonic model illustrating the effects of the Shockley-Read-Hall recombination on the intensity noise features. These new findings are meaningful for designing high speed and low noise quantum dot devices to be integrated in future photonic integrated circuits.

INTRODUCTION

The relative intensity noise (RIN) of semiconductor lasers degrades the signal-to-noise ratio (SNR) and increases the bit-error rate of optical signals hence setting a limit of a high-speed communication system [1]. System limitations due to poor SNR can be compensated by increasing the bias current of the laser source but at the price of a larger energy consumption. Thus, optical sources with low RIN are highly desired to carry broadband data with low bit error rate [1]. The RIN mainly stems from intrinsic optical phase and frequency fluctuations caused by spontaneous emission as well as the carrier noise, describing the fluctuations in the optical power of a laser [2]. The RIN of a laser is defined as the ratio between the fluctuations of optical power and the average optical power. In radar related applications, it is requested the laser's intensity noise to be drastically limited by the shot noise

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over a bandwidth ranging up to 20 GHz [3]. Owing to the atom-like discrete energy levels, QD lasers exhibit outstanding properties such as high temperature stability, low threshold lasing operation, long device lifetime and low linewidth enhancement factor [4]. The RIN of QD lasers is usually lower by comparison with their bulk or quantum well counterparts ascribed to the unique QD carrier dynamics. In particular, the modulation properties and the noise spectra are driven by the same dynamical processes meaning that the highly damped limited response of QD lasers can offer unique low noise characteristics [5]. For example, a RIN level as low as -160 dB/Hz was experimentally measured with InAs/GaAs and InAs/InP QD lasers [5][6] whereas a QD comb laser with a RIN level ranging from -120 to -145 dB/Hz in the 0.1-10 GHz frequency band was also achieved for applications in wavelength-division multiplexing and passive optical networks [7]. QD lasers epitaxially grown on silicon are regarded as an excellent candidate to achieve energy and cost-efficient optical sources in order to enhance the performance of future photonics integrated circuits (PIC) [4]. Such epitaxial QD lasers have outstanding properties such as high temperature stability, low threshold lasing operation, and high feedback tolerance [8][9]. It was also shown that QD lasers epitaxially grown on silicon exhibits a RIN from -140 dB/Hz to -150 dB/Hz by comparison with that directly grown on germanium found much higher RIN at -120 dB/Hz [10, 11]. Finally, another work unveiled that the RIN of a QD laser emitting on the pure ES emission is more suppressed than that of the GS one [12]. This paper analyzes the intensity noise properties of epitaxial QD lasers on silicon with respect to the doping level. In particular, the intensity noise of p-doped QD laser is found relatively insensitive to the temperature. Modulation properties including damping, carrier lifetime, and K-factor are also extracted from the intensity noise characteristics and then analyzed with respect to the doping level. Finally, numerical results based on an excitonic model [2] is used with the view to analyze the effects of the Shockley-Read-Hall recombination on the intensity noise features. Overall, these results are of first importance for designing high speed and low noise QD devices to be integrated in future PICs.

INTENSITY NOISE PROPERTIES

The QD laser was epitaxially grown on a silicon template and the active region consists of five periods of QD layers. Each dot layer was separated by a 37.5 nm GaAs spacer, which included 10 nm of p-type material for the p-doped device. As for the undoped one, the p-type layer is absent. The p-doping is used to improve the thermal stability. Indeed, QD lasers suffer from thermal broadening of carriers, especially holes due to their heavier effective mass and consequent tightly spaced energy levels [9]. The thermal broadening decreases the QD ground state gain and increases temperature sensitivity. In this work, three batches of QD lasers with unintentionally doped (undoped), 0.5×10^{18} cm^{-3}, and 1×10^{18} cm^{-3} p-type dopant concentration in the active region are compared. These doping concentrations correspond to 0, 10, and 20 extra holes per QD. It is noted that these three lasers have the same ridge waveguide width of 4 µm, while the undoped QD laser is 1.1 mm long and the p-doped is 1.35 mm long. Figure 1 depicts the light current characteristics of the undoped and p-doped QD (10 holes/dot) lasers for various temperatures ranging from 288 K to 308 K. The threshold current I_{th} is 11 mA at 288 K for the undoped laser while that of the p-doped laser is found at 23 mA. By varying the temperature from 288 K to 308 K, I_{th} varies from 11 mA to 22 mA (100 % increase) for the undoped laser, while it is only from 23 mA to 25 mA (9% increase) for the p-doped one. Compared with the undoped material, the larger threshold current of p-doped QD lasers results from the increase of the optical loss due to high free carrier absorption from the large number of holes in the dots. Let us stress that, when p-doping increases from 10 to 20 holes/dot, the I_{th} further increases from 23 mA to 39 mA (not shown). However, the inclusion of the p-type doping mitigates the thermal spread of holes which leads to a rather temperature insensitive threshold current [4][13].

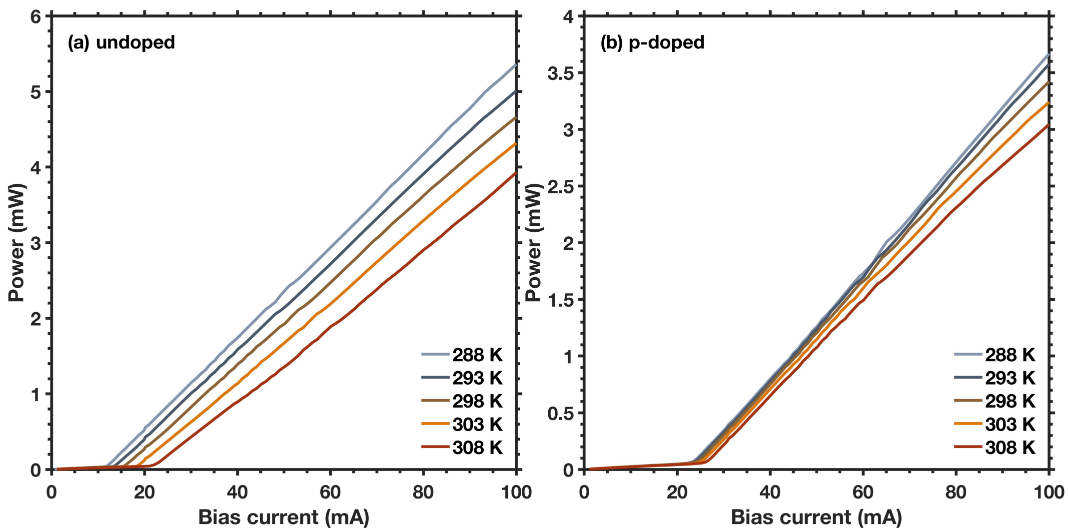

Figure 1. Temperature dependence of the light-current characteristics for the (a) undoped and (b) p-doped QD lasers with doping level of 10 holes/dot. The temperature is varied from 288 K to 308 K.

In order to measure the RIN, the QD laser is pumped by a DC current source, while the device temperature is kept constant at 293 K using a thermo-electric cooler. The laser emission is coupled into a lensed fiber and then the optical signal is converted into the electrical domain through a low-noise photodiode with a bandwidth of 10 GHz. The DC voltage is measured by a voltage meter through the DC monitor port of the photodiode, while the AC signal is amplified by a broadband amplifier with a typical small-signal gain of 30 dB. In the end, the amplified noise spectrum is measured on an electrical spectrum analyzer (ESA). It is noted that the RIN can also be limited by the shot noise resulting from the random occurrence of the photons. However, the RIN of the laser is usually much above that of the shot noise level, meaning that the measured noise spectrum from the detector reflects the contribution of carriers. The intrinsic laser noise S_{Laser} can be expressed as:

$$S_{Laser} = S_{Total} - S_{Thermal} - S_{Shot} \tag{1}$$

where S_{Total} the total noise measured by the ESA, $S_{Thermal} = 4k_BT/R_L$ is the thermal noise, which is independent on the optical power and is determined when the laser is turned off. k_B the Boltzmann constant, T the temperature and R_L the load resistance of the ESA with a value of 50 Ω. S_{Shot} is white noise determined by $S_{Shot} = 2qI_{DC}R_L$ with q the elementary charge, I_{DC} the DC current. Overall, the RIN of the lasers can be recasted as follows:

$$RIN = 10log_{10}\left[\frac{(S_{Total}-S_{Thermal})/(RBW\times G)-S_{Shot}}{P_{DC}}\right] \tag{2}$$

with P_{DC} is the electrical DC power, RBW is the resolution bandwidth of the ESA with a value of 200 kHz and G is the gain of the experimental setup including the amplifier, which is measured by the vector network analyzer (VNA).

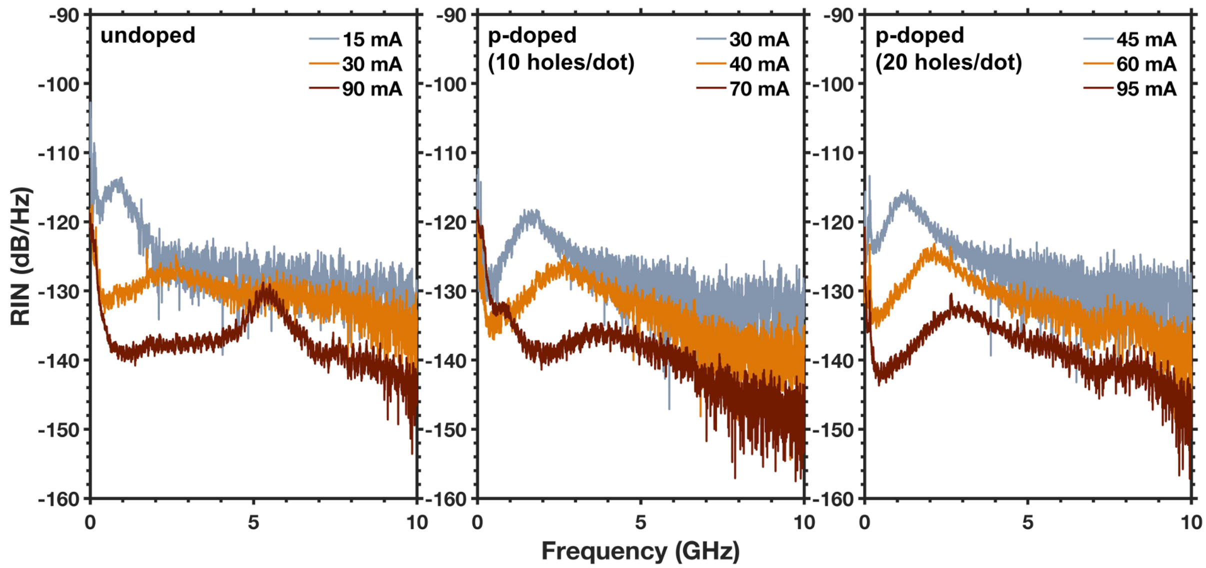

Figure 2. Measured RIN spectra at different bias conditions at 293 K for undoped laser, p-doped laser with doping level of 10 holes/dot, and p-doped laser with doping level of 20 holes/dot, respectively.

Figure 2 shows the measured RIN of the tested three QD lasers, which are extracted using equation (2). The RIN spectra are measured at various bias currents depending on their threshold currents. However, for a better comparison, the last spectrum for each laser is measured for the same coupling power corresponding to the maximal limit of the photodiode (0.72 mW). The RIN at low frequencies is relatively high resulting from the bias current noise, thermal noise as well as mode partition, and it reduces with the increasing frequency and saturates at higher bias currents. At 293 K, a low RIN level of -140 dB/Hz (at 90 mA) at 10 GHz is demonstrated for the undoped laser, while the laser is overdamped due to the absence of the relaxation oscillation frequency (ROF) peak whatever the bias current. It is worth nothing that the resonance peak at 6 GHz is not the ROF of the laser and rather results from the QD size dispersion induced impurity of longitudinal modes since it appears only at high bias current. In contrast, the p-doped QD laser with doping level of 10 holes/dot exhibits a strong ROF peak at around 3.6 GHz at 70 mA due to a smaller damping factor with a reduced RIN level of -150 dB/Hz at 10 GHz. Overall, the minimal RIN level is achieved between -140 dB/Hz and -150 dB/Hz in both undoped and p-doped lasers, which is also in agreement with results in [10,14].

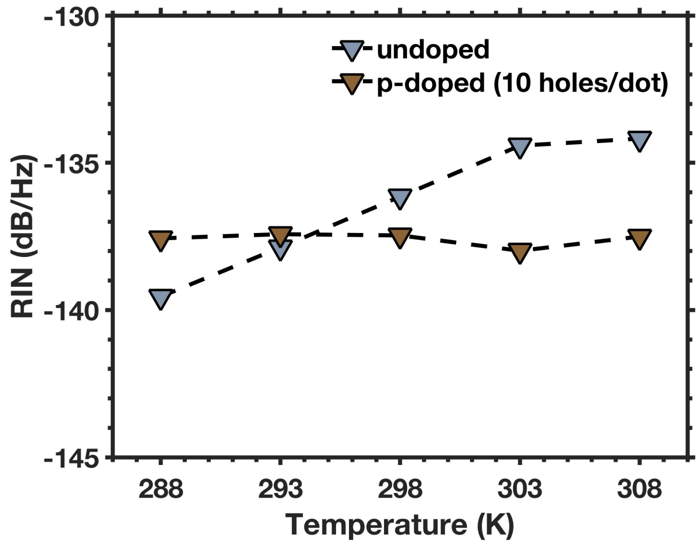

Figure 3. Comparison of averaged RIN values between 1 GHz and 4 GHz as a function of temperature ranging from 288 K to 308 K for undoped laser and p-doped laser with doping level of 10 holes/dot.

Figure 3 illustrates the averaged RIN values between 1 GHz and 4 GHz as a function of temperature ranging from 288 K to 308 K for undoped laser and for p-doped laser (10 holes/dot). For each temperature, the RIN values correspond to those taken at the same bias current, hence 90 mA for the undoped QD laser against 70 mA for the p-doped one. As shown, the RIN values maintain the same level within the temperature range for the p-doped laser because the threshold current is rather constant with temperature. On the contrary, the RIN of the undoped laser increases from -140 dB/Hz at 288 K to -134 dB/Hz at 308 K. These results indicate that the p-doping does contribute to improve the thermal stability.

MODULATION DYNAMICS

In what follows, both the ROF and damping factor are extracted from the curve-fitting of the RIN spectrum according to the equation [1]:

$$RIN(\omega) = \frac{a+b\omega^2}{(\omega^2-\omega_{RO}^2)^2+\gamma^2\omega^2} \tag{3}$$

where ω_{RO} the angular ROF, γ the damping factor, ω the angular frequency, *a* and *b* coefficients used for the curve-fitting. Figure 4(a) shows the damping factor as a function of the squared ROF for the three QD lasers, respectively. The evolution is linear following the relationship:

$$\gamma = Kf_{RO}^2 + \gamma_0 \tag{4}$$

with K-factor the slope and γ_0 the inverse of the differential carrier lifetime. Figure 4(b) depicts the evolution of the K-factor and γ_0 extracted from the curve-fitting as a function of the doping level. As QD lasers behave as quasi-class-A oscillators, the damping factor is rising quickly, hence the value is found as large as 33 GHz at $3\times I_{th}$ with a K-factor of 4.7 ns. When the doping level increases from 0 to 20 holes/dot, the K-factor decreases from 4.7 ns to 1.5 ns whereas γ_0 increases from 1.5 GHz to 5.2 GHz. The damping factor offset γ_0 is quite important at low powers where the ROF is small, while for larger resonance frequencies, the K-factor usually describes the damping of the response which can be used to evaluate the maximum 3-dB bandwidth ($f_{3dB,max}$) from the following equation:

$$f_{3dB,max} = \frac{2\sqrt{2}\pi}{K} \tag{5}$$

As expected, the calculated $f_{3dB,max}$ is 1.9 GHz for the undoped laser, which can be further increased to 5.9 GHz for the optimum p-doping level of 20 holes/dot. These results are consistent with the previous works which showed that the p-doping improves the maximum modulation bandwidth [13]. Compared with the record modulation bandwidths of 17.5 GHz in InAs/InP QD laser [15], this modulation bandwidth is not good enough for high-speed modulation. We believe that this doping level is not the optimum solution and further work will concentrate on optimizing the doping level [16]. It is worth noting that the damping factor is relatively high in QD lasers which can be useful for isolator-free applications. Although isolator-free applications remain an important objective, an overdamped laser would of course be somewhat detrimental for direct modulation since the modulation bandwidth would be too much limited.

The temperature dependence of the damping factor and ROF is also investigated, Figure 5 shows the damping factor as a function of the squared ROF for the undoped and p-doped (10 holes/dot) lasers at 293 K and 303 K, respectively. For the undoped laser, the K-factor is reduced from 4.6 ns at 293 K to 3 ns at 303 K leading to a smaller damping factor of 23 GHz at $3\times I_{th}$. By comparison, the damping factor of the p-doped laser maintains the same level within the temperature variation. Once again, those results prove that the QD laser with p-doping is more stable with temperature not only in terms of the RIN but also for the damping factor.

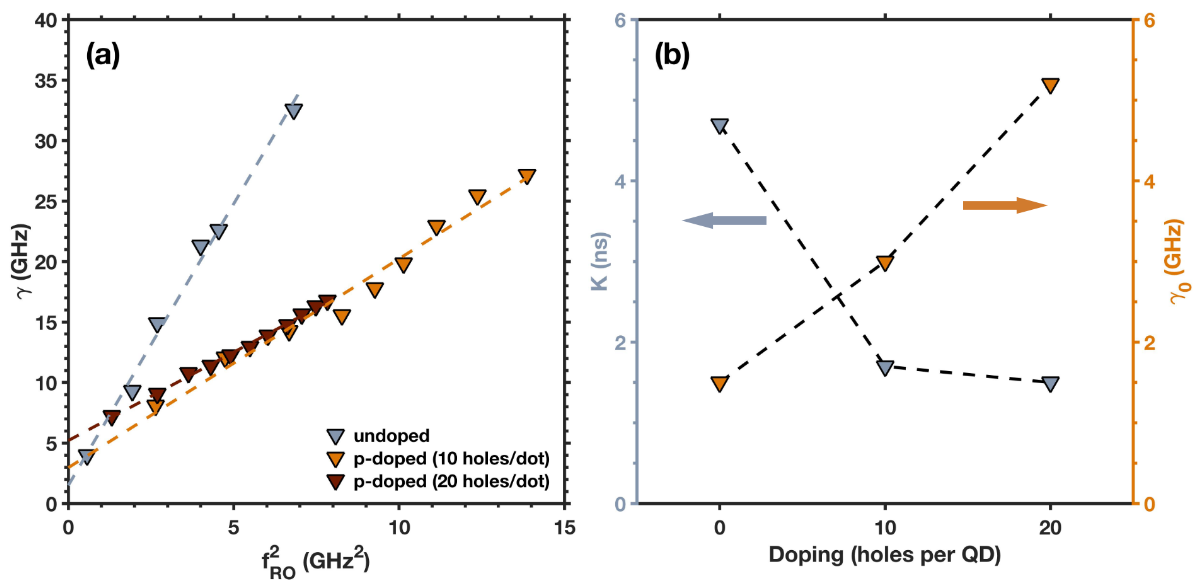

Figure 4. (a) Measured damping factor (γ) as a function of the squared relaxation oscillation frequency (f_{RO}^2) for undoped laser, p-doped laser with doping level of 10 holes/dot and p-doped laser with doping level of 20 holes/dot, respectively. (b) K-factor and inverse differential carrier lifetime (γ_0) versus the doping level between 0 and 20 holes/dot.

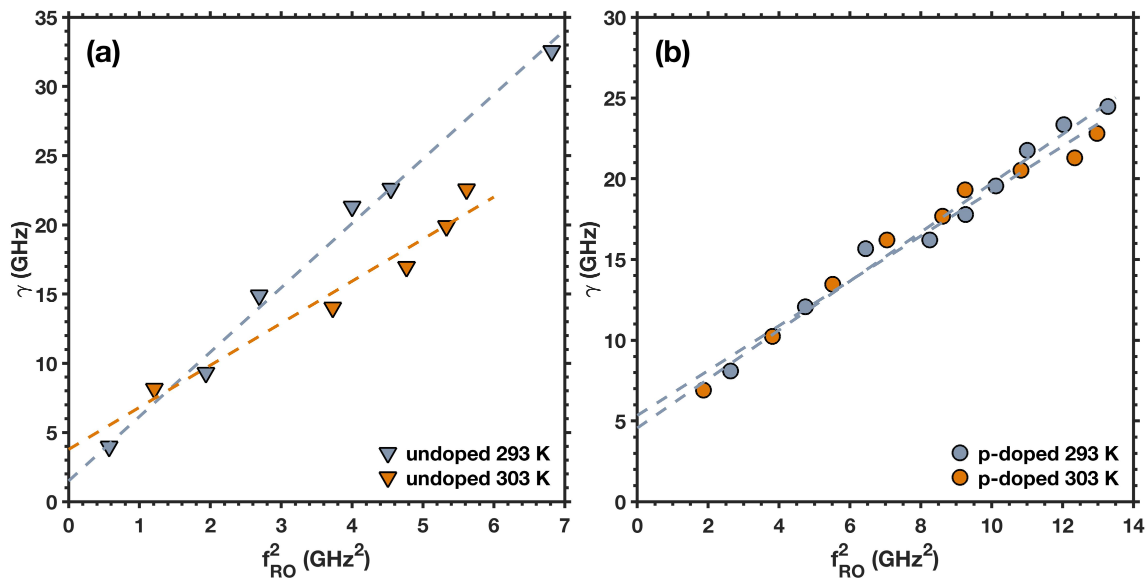

Figure 5. Temperature dependence of the damping factor (γ) as a function of the squared relaxation oscillation frequency (f_{RO}^2) for (a) undoped and (b) p-doped laser with doping level of 10 holes/dot.

Gain compression in semiconductor lasers refers to the decrease of the gain coefficient with optical intensity [1]. It limits the modulation dynamics of directly modulated transmitters through adiabatic chirp and is also responsible for the bending of the light-current characteristic curves. Now, we discuss the impact of the doping level on the gain compression effect. Figure 6(a) plots the square of ROF versus the output power for QD lasers under study. The ROF is proportional to the square root of the optical output power, hence the curve-fitting to be used is based on the following expression [17]:

$$f_{RO}^2 = \frac{AP}{1+\varepsilon_P P} \tag{6}$$

where ε_P denotes the gain compression coefficient related to the output power P indicating that for this pumping level, nonlinear effects start to be significant. A is the modulation efficiency and can be approximated by the initial slope of the curves. The gain compression factor linked to photon density (S) can then be expressed through the relationship: $\varepsilon_S = \varepsilon_P P/S$. Figure 6(b) displays the calculated ε_S as a function of the doping level indicating values in the range from 5.7×10^{-16} cm^3 to 1.5×10^{-15} cm^3 which are in agreement with prior studies [17]. Compared with quantum well lasers, these large gain compression factors in epitaxial QD lasers on silicon lead to an over-damped modulation response with limited modulation bandwidth of ~ 6 GHz and also the flat RIN spectra as low as -150 dB/Hz at 10 GHz. To sum, the results show that the maximum modulation bandwidth can certainly be improved for doping levels between 0 and 20 holes/dot beyond which no real improvements take place due to the joint effects of higher induced internal loss and gain nonlinearities.

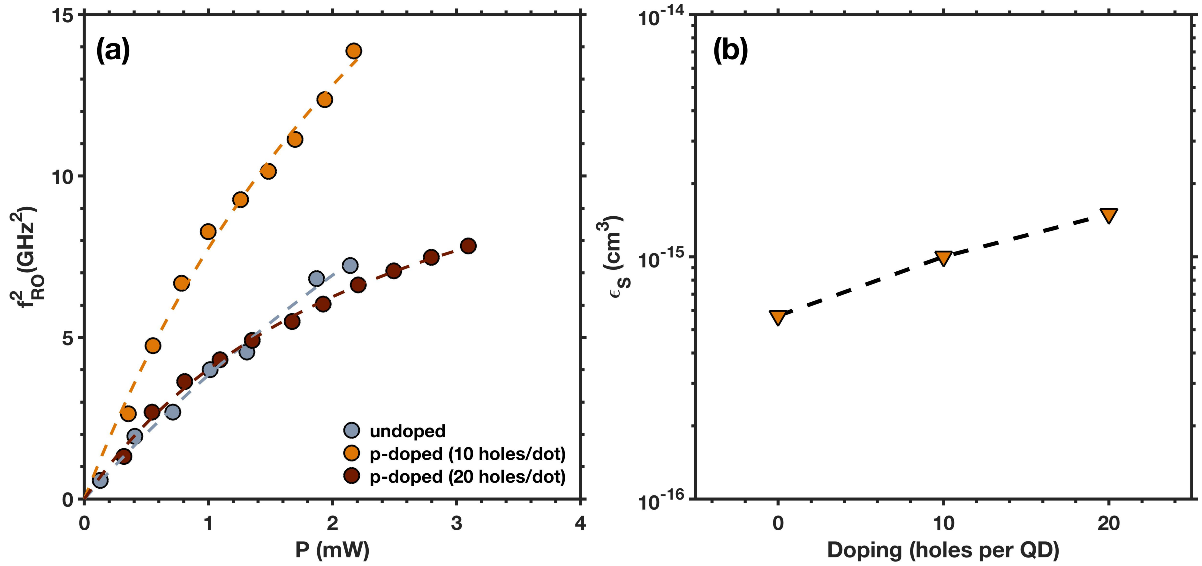

Figure 6. (a) Squared relaxation oscillation frequency (f_{RO}^2) versus the output power (P) for undoped laser, p-doped laser with doping level of 10 holes/dot and p-doped laser with doping level of 20 holes/dot, respectively. (b) Gain compression factor (ε_S) versus the doping level.

EFFECT OF THE SHOCKLEY-READ-HALL RECOMBINATION

The effect of the Shockley-Read-Hall recombination on the RIN is now investigated based on QD rate equations model using the excitonic approach [2]:

$$\frac{dN_{RS}}{dt} = \frac{I}{q} + \frac{N_{ES}}{\tau_{RS}^{ES}} - \frac{N_{RS}}{\tau_{ES}^{RS}}(1-\rho_{ES}) - \frac{N_{RS}}{\tau_{RS}^{spon}} - \frac{N_{RS}}{\tau_{nr}} + F_{RS}(t) \tag{7}$$

$$\frac{dN_{ES}}{dt} = \left(\frac{N_{RS}}{\tau_{ES}^{RS}} + \frac{N_{GS}}{\tau_{ES}^{GS}}\right)(1-\rho_{ES}) - \frac{N_{ES}}{\tau_{GS}^{ES}}(1-\rho_{GS}) - \frac{N_{ES}}{\tau_{RS}^{ES}} - \frac{N_{ES}}{\tau_{ES}^{spon}} - \frac{N_{ES}}{\tau_{nr}} + F_{ES}(t) \tag{8}$$

$$\frac{dN_{GS}}{dt} = \frac{N_{ES}}{\tau_{GS}^{ES}}(1-\rho_{GS}) - \frac{N_{GS}}{\tau_{ES}^{GS}}(1-\rho_{ES}) - \Gamma_p v_g g_{GS} S - \frac{N_{GS}}{\tau_{GS}^{spon}} - \frac{N_{GS}}{\tau_{nr}} + F_{GS}(t) \tag{9}$$

$$\frac{dS}{dt} = \left(\Gamma_p v_g g_{GS} - \frac{1}{\tau_p}\right) S + \beta_{sp}\frac{N_{GS}}{\tau_{GS}^{spon}} + F_S(t) \tag{10}$$

with I is the bias current, q is the elementary charge, and $N_{RS,ES,GS}$ are the carrier populations in the RS, ES, and GS, respectively. Only stimulated emission originating from the ground state (GS) level is considered hence S accounts for the photon number in the GS level. In Equation 7-10, the carriers are first captured from the RS into the ES with capture time τ_{ES}^{RS}, then relax from the ES down to the GS with a relaxation time τ_{GS}^{ES}. Owing to the thermalization, carriers are reemitted from the GS to ES with an escape time τ_{ES}^{GS}, and from the ES to the RS with an escape time τ_{RS}^{ES}. In addition, carriers also recombine spontaneously with spontaneous emission times $\tau_{RS,ES,GS}^{spon}$. Lastly, let us stress that Γ_p is the optical confinement factor, τ_p the photon lifetime, v_g the group velocity and β_{sp} the spontaneous emission factor. $F_{RS,ES,GS}$, and F_S are the RS, ES, GS carrier noise and photon noise sources respectively. Epitaxial defect in silicon-based QD lasers induces nonradiative recombination through the Shockley-Read-Hall process, and the nonradiative recombination lifetime τ_{nr} is inversely proportional to the defect density. The effect of Shockley-Read-Hall process is included in the model through τ_{nr}, which is assumed to be the same for all the three carrier states. The RIN of the QD laser emitting on the GS transition is then expressed as follows:

$$RIN(\omega) = \left|\frac{\delta S(\omega)}{S}\right|^2 \tag{11}$$

with δS being the photon number variation in the frequency domain and S being the average photon number. Figure 7 demonstrates the simulated RIN spectra for different τ_{nr} ranging from 0.05 ns to 10 ns. As shown, the high epitaxial defects induced short nonradiative recombination lifetime raises the RIN level at low frequencies. However, the RIN at 10 GHz remains stable with the variation of the recombination lifetime, which is beneficial for low-noise applications. It is noted the simulated low-frequency RIN is found a bit lower than the measured RIN because the bias current noise, thermal noise as well as mode partition are not included in the model. Moreover, the simulated RIN at 10 GHz is found in a good agreement with the measured values.

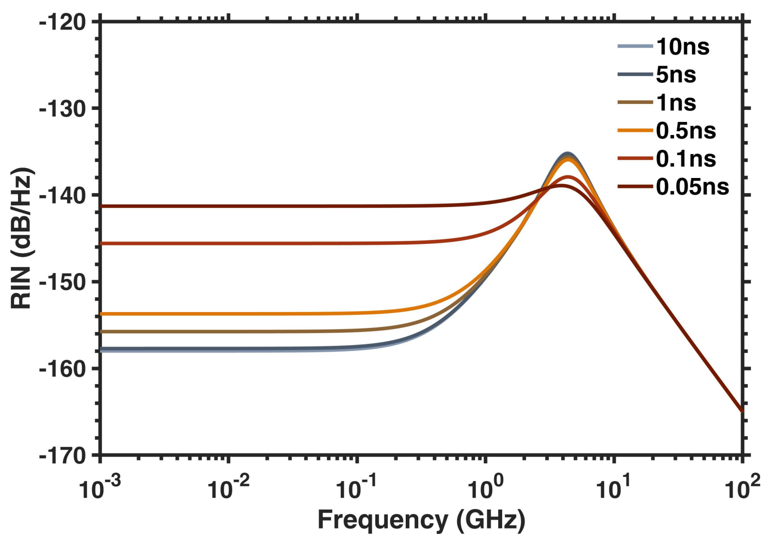

Figure 7. Shockley-Read-Hall effects on the RIN spectrum.

CONCLUSIONS

This paper studied the intensity noise properties of epitaxial quantum dot lasers on silicon. Results show minimal values between - 140 dB/Hz and - 150 dB/Hz for doping level between 0 and 20 holes/dot in the active region. In particular, we found that the intensity noise is relatively insensitive to temperature for p-doped QD laser. Modulation properties such as damping, carrier lifetime, and K-factor are also extracted from the noise characteristics and analyzed with respect to the doping level. We also numerically showed that the Shockley-Read-Hall recombination influences the intensity noise features. These new findings are meaningful for designing high speed and low noise quantum dot devices to be integrated in future photonic integrated circuits.

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