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P-doping effect on external optical feedback dynamics in 1.3-μm InAs/GaAs quantum dot laser epitaxially grown on silicon

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ABSTRACT

This work reports on the optical feedback dynamics of InAs/GaAs QD lasers epitaxially grown on silicon operating in both the short and long delay regimes. Both undoped and p-doped QD lasers are considered. Whatever the external cavity length, no chaotic oscillations are observed on both samples as a result of the small α-factor observed in the silicon QD lasers. Despite that, experiments conducted in the short-cavity region raise period-one oscillation for the undoped QD laser. In addition, the transition from the short to long delay regimes can be finely covered by varying the external cavity length from 5 cm to 50 cm, and the boundaries associated to the appearance of the periodic oscillation are identified. In the short-cavity region, boundaries show some residual undulations resulting from interferences between internal and external cavity modes; whereas in the long-delay regime, the feedback ratio delimiting the boundaries keeps decreasing, until it progressively becomes rather independent of the external cavity length. Overall, our results showed that the p-doped device clearly exhibits a much higher tolerance to the different external feedback conditions than the undoped one, seeing that its periodic oscillation boundaries are barely impossible to retrieve at the maximum feedback strength of -7 dB. These results show for the first time the p-modulation doping effect on the enhancement of feedback insensitivity in both short- and long-delay configurations, which is of paramount importance for the development of ultra-stable silicon transmitters for photonic technologies.

Keywords: quantum dot, silicon, integrated photonics, optical feedback, short delay, α-factor, p-doping

1. INTRODUCTION

Monolithic photonic integration is a solution of importance to meet the requirement of developing compact, robust and energy-efficient transmitters, which are needed in upcoming applications, including high-speed telecommunication industry,[1,2] next generation datacom transceivers[3] and advanced LIDAR systems applied to self-driving automobiles.[4] In particular, the optical light source is a key component of the photonic integration circuits (PICs) and quantum dots (QDs) have shown numerous advantages as a gain medium over widely utilized quantum wells (QWs). For instance, lasers grown from QDs are found to have low threshold,[5] narrow spectral linewidth,[6,7] improved temperature stability,[8] low relative intensity noise (RIN),[8,9] bit error free,[10,11] ultrafast gain dynamics

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applicable to mode-locked lasers (MLLs)[12–14] and optical frequency combs (OFCs)[15,16] and higher resistance against optical feedback.[17] Note that the latter is advantage of interest to develop the isolator-free PICs applications while guaranteeing an error-free transmission,[17] which is therefore beneficial to reduce the device footprint. In addition, the reduced sensitivity to crystalline defects[18,19] makes QD lasers an ideal solution for epitaxial integration on silicon, which is in favor of the development of future large-scale, small-footprint, low-cost and energy-efficient silicon photonic integrated circuits.[20]

In this paper, we characterize two chaos-free InAs/GaAs QD lasers epitaxially grown on silicon and investigate the p-modulation doping effect on the external feedback dynamics. To this end, one device is p-modulation doped in the active region whereas the other is undoped for comparison. The p-type doping is beneficial for the improvement of material gain, which is attributed to the enhanced population inversion introduced by the extra holes;[21] such effect can eventually lead to an ultra-low α-factor.[22] The α-factor (also named the linewidth enhancement factor) is known as an important parameter in influencing the nonlinear dynamics of semiconductor lasers including the feedback sensitivity;[23–25] Prior work has demonstrated that p-doped silicon QD lasers with ultra-low α-factor have high tolerance for external feedback.[8] In this work, we go a step beyond by investigating the device feedback dynamics from the long- to short-delay region by varying the external cavity length L_{ext} from 50 to 5 cm. Our initial results show that both the p-doped and undoped QD lasers are free of chaos as the feedback ratio is increased up to $\sim$ 20%. Despite that, experiments conducted in the short-cavity region raise period-one oscillation for the undoped QD laser. In this study, the boundaries associated to the appearance of the periodic oscillation are well identified and are shown to depend on the external cavity length. As counterpart, the p-doped QD laser is always free of any dynamics up to the maximum feedback strength in the short delay region. Last but not the least, whatever the external cavity length, the p-doped QD laser always exhibits a higher tolerance for the external feedback over the undoped one owning to the lower α-factor. Overall, these results show for the first time the p-modulation doping effect on the enhancement of feedback insensitivity in both short- and long-delay configurations, which is of paramount importance for the development of ultra-stable silicon transmitters for photonic technologies.

2. DESCRIPTION OF DEVICES

2.1 Device structure

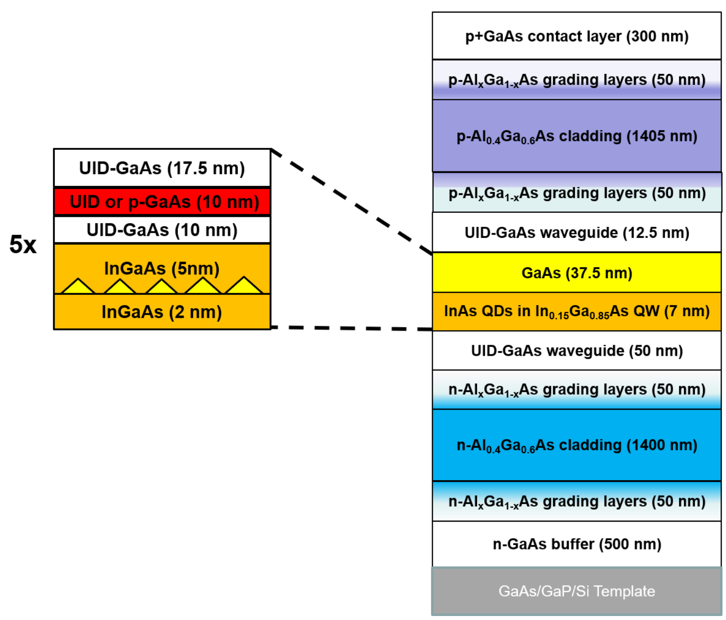

Figure 1. Schematic drawings of the QD laser epilayer structure (p-doped and undoped).

The QD devices presented in the following experiments are designed for emission around 1300 nm and their epitaxial structure based on the typical design is depicted in Figure 1. The active region consists of five periods of InAs QDs with 2 nm $In_{0.15}Ga_{0.85}As$ QWs below and 5 nm at the top of the dots. Each dot layer was separated by a 37.5 nm GaAs spacer, where a 10 nm unoped or 5×10^{17} cm^{-3} p-type material layer is added in, for the case of undoped and p-doped device, respectively. The 2.55 ML thick InAs is deposited at 500°C and 0.113 ML/s with a V/III ratio of 35. The whole active region is then sandwiched by a 1.4 μm $Al_{0.4}Ga_{0.6}As$ GRINSCH with p-cladding material on top and another 1.4 μm n-cladding on the bottom. The bottom cladding is grown at 580°C while the top cladding is grown at 550°C to minimize interdiffusion in the active region. All the growth conditions mentioned above ensure the minimization of the inhomogeneous broadening within the gain section, which results from the dot size fluctuations. The QD density is 6.5×10^{10} cm^{-2} with photoluminescence (PL) full-width at half maximum (FWHM) below 30 meV. Further details of the epitaxial growth are available elsewhere.[21]

We studied Fabry-Perot (FP) cavities that were fabricated with standard dry etch and electron beam metal deposition techniques. Note that the cavity of these two lasers are designed at similar length, which is 1.1 mm for the undoped one and 1.35 mm for the other. Both the devices are deeply etched with 3.5 μm wide ridges and the facets formed by cleaving were then applied using ion beam deposition of repeated periods of SiO_2/Ta_2O_5 to give reflectivities of 60% (front) and 99% (rear) to the undoped laser, and 32% on both facets to the p-doped one. It is worth noting that the first hopf bifurcation associated to the coherence collapse regime is influenced by the power facet reflectivity R. When R is low, the laser is more open to the external world. A simulation result demonstrated that a low R contributes to degrade the feedback tolerance in QD laser.[26] Nevertheless, our results presented hereinafter indicate that the p-doped QD laser with low R is still more resistant to external reflection than the undoped one, which gives another insight into the benefit of p-modulation doping in improving the feedback insensitivity of QD lasers.

2.2 Characterization of device

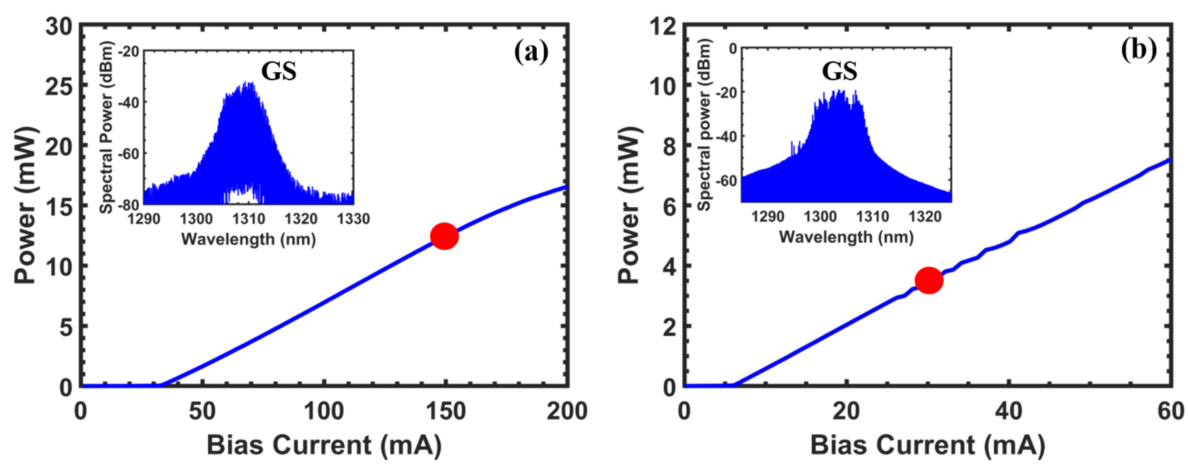

Figure 2. Light-current characteristics of the (a) p-doped and (b) undoped QD lasers at 293 K. The insets show show the corresponding optical spectra measured at $5\times I_{th}$, which are remarked by red bullets.

Figure 2 depicts the light current characteristics of the p-doped (a) and undoped (b) devices, and the insets show the corresponding optical spectra measured at $5\times I_{th}$, which are remarked by red bullets. Both the devices emit on the sole GS transition close to 1300 nm and the operation temperature is fixed to 293 K throughout the measurements. The threshold current I_{th} of the undoped and the p-doped QD laser is measured at 6 mA and 32 mA, respectively. The higher threshold of the former is attributed to the increased optical loss introduced by a higher free carrier absorption resulting from the large number of holes in the dots. Nevertheless, let us stress that the p-doped QD laser exhibits a better lasing performance over the undoped one through showing an increased lasing power and an enhanced temperature stability;[8] the former is attributed to the higher material gain.[21]

3. EXTERNAL OPTICAL FEEDBACK DYNAMICS

3.1 Experimental configuration

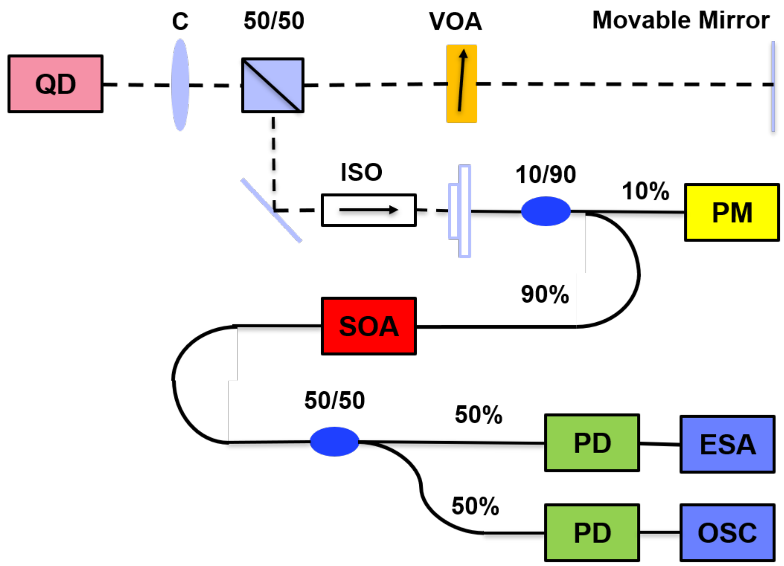

Figure 3. Schematic diagram of the experimental setup used for investigating optical feedback. QD, QD lasers under study; C, collimator; VOA, variable optical attenuator; ISO, isolator; PM, powermeter; SOA, semiconductor optical amplifier; PD, photodiode; ESA, electrical spectrum analyzer; OSC, oscilloscope.

The experimental setup used for investigating the optical feedback is shown in Figure 3. The free-space laser beam is firstly collimated and then it pass through a 50/50 beam-splitter thus divides into two paths: one feedback path and the other for analysis. The movable mirror in the feedback path is applied to reflect the light back to the laser cavity and adjust the length of the external cavity from 5 cm to 50 cm. In this configuration, a free-space variable optical attenuator (VOA) is inserted to give extra losses thus we can slightly change the feedback strength r_{ext}. With the view of accurately calculating r_{ext} and maximizing the effects of the optical feedback, all the losses from the collimator, the beam-splitter and in the free-space setup are well taken into account, we can therefore ensure a maximum r_{ext} at $\sim$ -7 dB (20%). In this work, r_{ext} is defined as the ratio between the power return to the laser cavity and the free-space emitting power of laser. The remaining 50% output light from the beam-splitter is then transferred to an isolator to eliminate any reflection in the experimental setup; next step, it is captured by a lens and then coupled into an optical fiber where the whole coupled light will be amplified by a semiconductor optical amplifier (SOA). In the end, the amplified light is transferred to the electrical spectra analyzer (ESA) and the oscilloscope (OSC) for further analysis.

3.2 Results and discussions

As aforementioned in this paper, it is known that the value of α-factor affects the reflection sensitivity of any semiconductor laser; note that a reduced α-factor was also observed on a p-doped QD laser in prior work, compared with an undoped one.[22] The study on the p-doping effect on laser feedback sensitivity is therefore of interest to be taken into account. In this study, the relaxation oscillation frequency f_{RO} of both the devices is 2.5 GHz, hence the short-cavity region is defined as the case when $f_{RO}/f_{ext}<1$ with f_{ext} the external cavity frequency ($f_{ext} = \mathrm{c}/2L_{ext}$); whereas the long-cavity region is the case when $f_{RO}/f_{ext}>1$.[27] Figure 4 depicts the feedback dynamics of the devices under study, when the L_{ext} is fixed to 5 cm (marked by yellow dashed line in Figure 5). Let us stress that the external cavity with $f_{ext} = 3$ GHz is well in the short-cavity region. When both

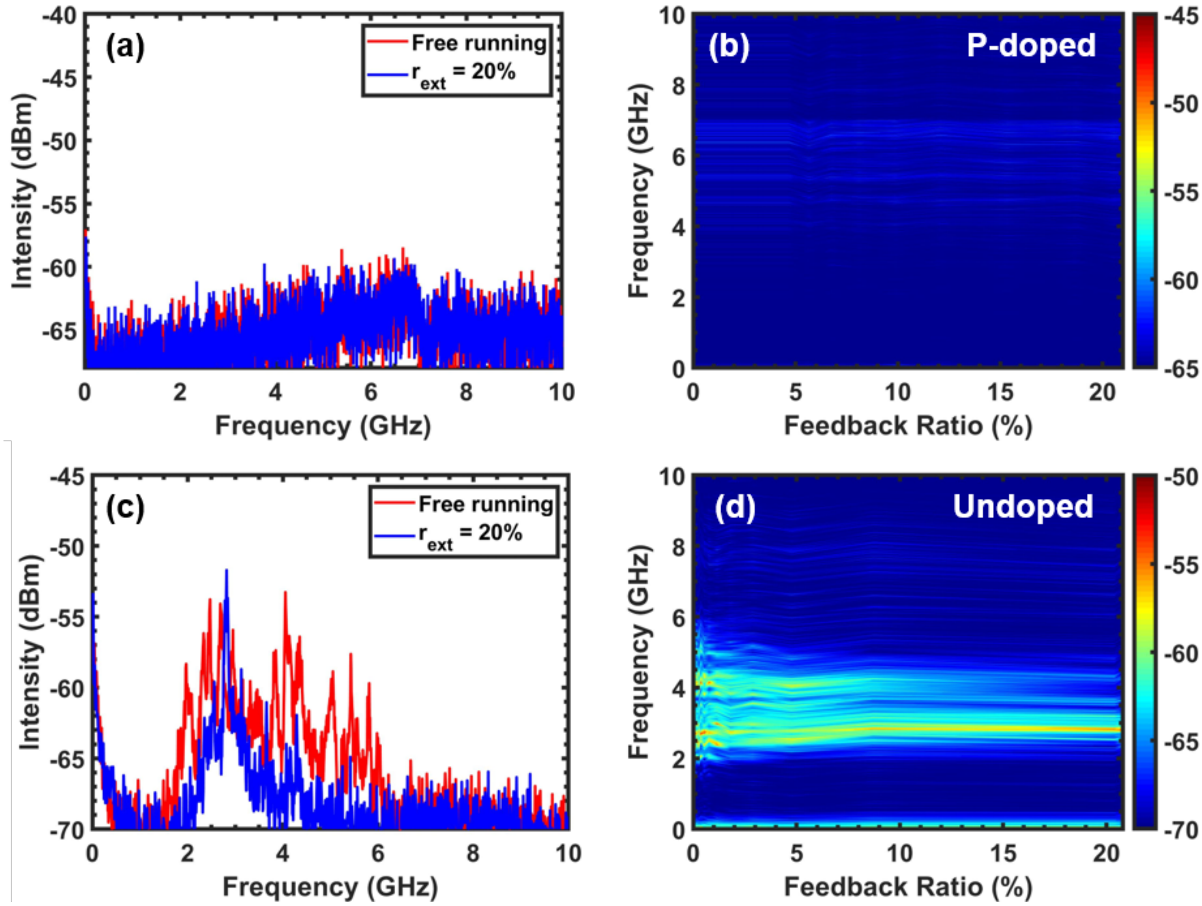

Figure 4. RF spectra measured with L_{ext}=5 cm (f_{ext} = 3 GHz): (a) p-doped QD laser under free-running operation (red) and maximal feedback strength of 20% (blue); (c) undoped QD laser under free-running operation (red) and maximal feedback strength of 20% (blue). (b) and (d) RF spectral mappings as a function of the feedback strength for the p-doped and undoped QD lasers. Both devices are biased at 5×I_{th}.

the devices are biased at 5×I_{th}, the RF spectrum at the free running state (without feedback, red) and that under maximum feedback strength (blue) of the p-doped device and those of the undoped one are shown in Figure 4(a) and (c), respectively. It should be noticed that even the r_{ext} is increased up to $\sim$ 20%, the p-doped QD laser is still free of any dynamics, whereas the Hopf bifurcation through period-one oscillation arise above 20% for the undoped one. Accompanied with that, the undoped device is stabilized through the suppression of all the other frequencies except for the f_{ext}. Nevertheless, let us stress that the unstable RF spectrum of the undoped laser at free running should not result from chaotic oscillation but might be attributed to the degradation of device. In order to get a more complete overview of the dynamics, Figure 4(b) and (d) also depict the RF spectral mapping as a function of r_{ext} of the p-doped QD laser and that of the undoped one, respectively, where the color bar represents the RF power measured by the photo-detector. With the increase of r_{ext} to about 20%, the dynamics of the undoped QD laser evolves from an unstable solution to periodic oscillations without any chaotic pulsations, and the boundary $r_{ext,p}$ associated to the periodic oscillation need to be well identified. To do so, the threshold of the periodic oscillation is defined as the excited peak of f_{ext} being 5 dB above the free-running noise level. With the RF spectral mappings measured at different L_{ext}, we can therefore extract the boundaries associated with the periodic states both in short- and long-delay regions.

In what follows, the $r_{ext,p}$ extracted from short- to long-cavity region of the undoped QD laser is shown in Figure 5. Extending the L_{ext} from 5 cm to 50 cm, which corresponds to a ratio f_{RO}/f_{ext} ranging from 0.83

to 8.3, the boundaries of the periodic oscillation of the undoped laser show some residual undulations in the short-cavity region, which results from the interferences between the internal and external cavity modes;[28,29] whereas in the long-cavity region, the $r_{ext,p}$ keeps decreasing until it progressively becomes rather independent of L_{ext}. Let us stress that whatever the L_{ext} is, both the p-doped and undoped devices exhibit high tolerance for external reflection without showing any chaotic pulsations up to $\sim 20\%$. In particular, the p-doped device clearly exhibits a much higher resistance against feedback than the undoped one as its $r_{ext,p}$ are barely impossible to retrieve. Last but not the least, such a discrepancy in the feedback sensitivity of the two devices, which is in line with a recent study,[8] indicates that the p-type doping indeed contributes to enhancing the laser performance in reflection insensitivity through reducing the α factor.

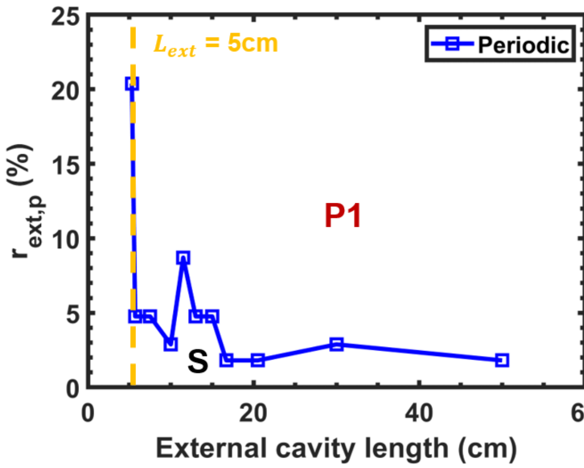

Figure 5. Extracted boundaries of periodic oscillations $r_{ext,p}$ with respect to the external cavity length L_{ext} measured at $5\times I_{th}$ for undoped QD lasers. S, solitary region without dynamics; P1, period one oscillation region.

4. CONCLUSIONS

In this work, we have investigated the p-type doping effect on the external feedback dynamics of QD lasers epitaxially grown on silicon. Results show that both the p-doped and undoped QD lasers are highly resistant against optical perturbations without raising any chaotic pulsations whatever the external cavity length and feedback strength. In addition, the evolution of the extracted boundaries associated to periodic oscillations of the undoped QD laser unveils a clear dependence on the external cavity length of oscillations in the short-delay region, while in the long-delay regime the system becomes rather independent of the feedback phase. Nevertheless, the p-doped QD laser clearly exhibits a much higher insensitivity for the feedback than the undoped one as its periodic oscillation boundaries are barely impossible to retrieve at the maximum feedback strength of -7 dB. As a conclusion, these results show for the first time the p-modulation doping effect on the enhancement of feedback insensitivity in both short- and long-delay configurations, which is of paramount importance for the development of ultra-stable silicon transmitters for photonic technologies.

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