Low linewidth enhancement factor and high optical feedback resistance of p-doped silicon based quantum dot lasers

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Abstract: This work shows that p-doped quantum dot lasers grown on silicon exhibit a low linewidth enhancement factor and hence a high resistance against optical feedback which are promising for isolator-free transmissions in photonic integrated circuits.

1. Introduction

The integration of optical functions on a microelectronic chip brings many innovative perspectives, along with the possibility to enhance the performances of photonic integrated circuits (PIC) [1]. Owing to the delta-like density of states, quantum dot (QD) lasers epitaxially grown onto silicon are very promising for achieving low-cost transmitters with high thermal stability and large insensitivity to optical reflections [1]. In this work, we investigate the linewidth enhancement factor (LEF) of a p-doped QD laser as well as its sensitivity to optical feedback. The p-doping is used to improve the thermal stability which occurs in QD lasers due to thermal broadening of carriers. Our results unveil that the p-doped QD laser exhibits a very low LEF which transforms into a high degree of resistance against optical feedback without exhibiting a route to coherence collapse as opposed to what is observed in heterogeneously integrated quantum well (QW) lasers [2]. As no on-chip optical isolators with sufficient isolation ratio and low loss have been reported so far, these results are decisive for the realization of chirp-free and Peltier-free silicon-based transmission systems without optical isolation.

2. Laser structure and experimental results

QD lasers consist of deeply etched ridge waveguide lasers epitaxially grown onto on-axis (001) GaP/Si substrates enabled by improved GaAs templates with a threading dislocation density (TDD) of 7.3×10^6 cm^{-2} [3]. The first 10 nm GaAs layer was undoped, followed by a 10 nm p-GaAs layer at a target hole concentration of 5×10^{17} cm^{-3} using Be. A photoluminescence spectra of the full laser sample revealed a very narrow full-width at half-maximum (FWHM) of about 30 meV from the ground state (GS) peak as shown in Fig. 1(a), indicating a highly homogeneous InAs QD size throughout the five QD stacks. The inset depicts an atomic force microscope image of an uncapped InAs QDs with an area density of 4.9×10^{10} cm^{-2}. The Fabry-Perot (FP) cavity is 1.35 mm long in length and 3.5 μm in width with ~60% reflectivity on the front facet and ~99% reflection on the rear. Fig. 1(b) depicts the LI curve measure at room temperature

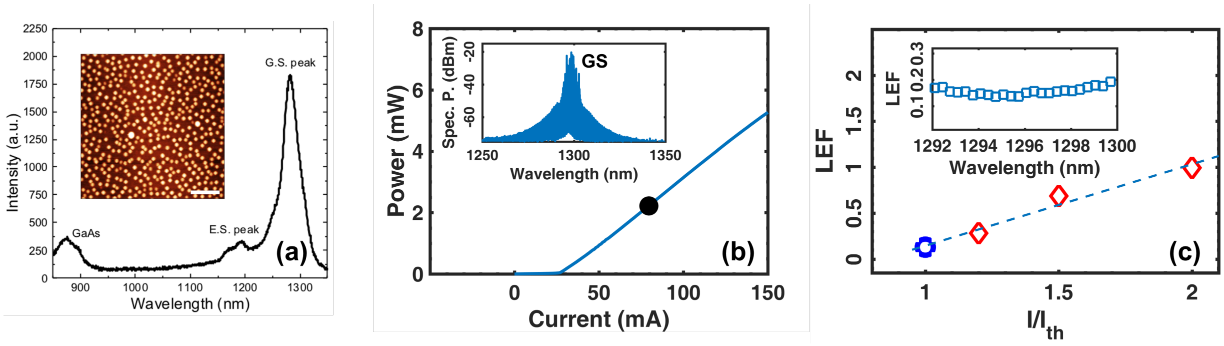

Figure 1: (a) Photoluminescence spectrum of the full laser sample. The inset shows atomic force microscope image of InAs quantum dots grown on a GaAs/Si template. Scale bar is 200 nm. (b) Light-current characteristics at 293 K. The inset shows corresponding optical spectra measured at $3 \times I_{th}$ (black marker). (c) The LEF measured above threshold. The inset shows the LEF measured below threshold.

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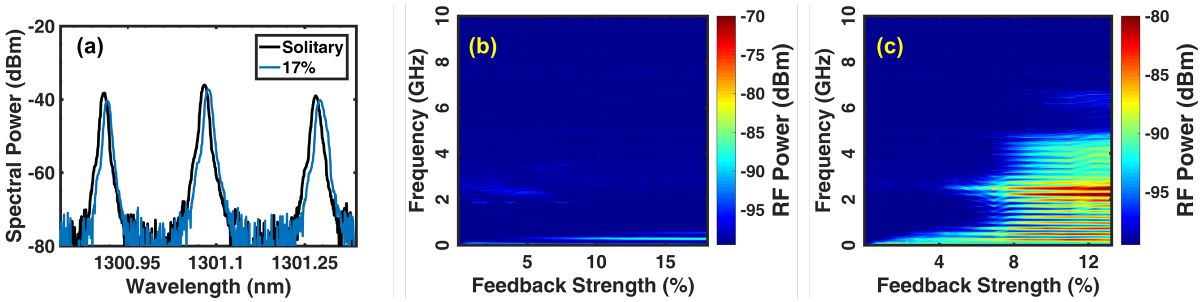

Figure 2: (a) Optical spectra at 3×I_{th} for the solitary ($r_{ext} = 0$) and at the maximum feedback ($r_{ext} = 17\%$). (b) RF mapping as a function of the feedback strength for (b) a p-doped silicon QD laser and (c) a heterogeneously integrated QW laser on silicon.

(293 K), with a threshold current I_{th} of 26.5 mA. By varying the temperature from 288 K to 308 K, I_{th} varies from 26 mA to 28.5 mA (not shown) which shows that the inclusion of the p-type doping leads to a rather temperature insensitive threshold current. The inset also shows the FP laser emits exclusively on the sole GS transition close to 1300 nm. The LEF of the laser is first extracted from amplified spontaneous emission in sub-threshold operation. After a proper elimination of the thermal effects, the LEF is found as low as ≈ 0.1 at threshold which is displayed in the inset of Fig. 1(c). This very low value results from the low TDD and fewer defects in the active region as well as the large QD size uniformity. The above-threshold LEF is then measured using optical injection assuming an injection ratio of -2 dB. Fig. 1(c) reveals that the LEF slightly increases from 0.1 at threshold to about 1 at 2 ×I_{th}. Such a relatively low LEF variation with the bias current is an excellent prerequisite to make highly feedback resistant QD lasers.

In order to analyze the laser's response to optical feedback, a long external fibered loop is considered. In the feedback path, light is reinjected into the laser through a back-reflector integrating a variable attenuator [4]. Measurements are performed at 3×I_{th} and 293 K. The feedback strength r_{ext} defined as the ratio of the returning power to that of the laser output power ranges from 0 to 17% which allows to analyze the laser dynamics on a very wide range of optical feedback values. Fig. 2(a) shows the evolution of the FP modes for the solitary case ($r_{ext} = 0$) and at the maximum feedback ($r_{ext} = 17\%$). In the latter case, only a small red-shift is observed which means that for $r_{ext} = 17\%$ the laser remains perfectly stable without showing spectral instabilities and broadening. Fig. 2(b) depicts the feedback dynamics in the radio-frequency (RF) domain. As it can be seen, no complex dynamics is observed whatever the feedback strength. Only a small increase of the RF power at low frequencies is detected due to mode competition within the FP cavity. This effect is slightly excited at higher feedback strength but overall the laser holds a high degree of stability. This feedback insensitivity that remains valid at higher temperatures (not shown) is a direct consequence of the low LEF. On the contrary, Fig. 3(c) illustrates the feedback dynamics of a heterogeneously integrated QW laser on silicon [5]. The result exhibits a typical destabilization route with birth of coherence collapse taking place at 6% optical feedback. This result agrees with prior works [2] which have shown that hybrid silicon lasers exhibit a higher feedback sensitivity due to additional reflections originating from the different interfaces between the active/passive transitions and which becomes highly problematic for PIC integration.

3. Conclusions

To summarize, this work demonstrates the high potential of p-doped QD lasers epitaxially grown onto silicon. The high resistance to optical feedback results from the very low LEF originating from the low TDD and fewer defects in the active region. These initial results demonstrate the ability of such lasers to operate without an isolator in future silicon photonics systems.

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