Semiconductor quantum dot lasers epitaxially grown on silicon with low linewidth enhancement factor

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This work reports on the ultra-low linewidth enhancement factor (H-factor) of semiconductor quantum dot lasers epitaxially grown on silicon. Owing to the low density of threading dislocations and resultant high gain, an H value of 0.13 that is rather independent of the temperature range (288 K–308 K) is measured. Above the laser threshold, the linewidth enhancement factor does not increase extensively with the bias current which is very promising for the realization of future integrated circuits including high performance laser sources. Published by AIP Publishing. 
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Silicon photonics is of interest for optical communications, optical signal processing and sensing, and integration of optical functions on a microelectronic chip to bring novel functionalities to future integrated circuits such as optical interconnects, which are an outstanding solution to the interconnect bottleneck posed by the conventional metal line.1 Engineering light emission out of the silicon has been of growing interest in the past few decades.2 Significant breakthroughs have been achieved by integrating direct bandgap III–V compound semiconductors with silicon using flip-chip throughs have been achieved by integrating direct bandgap III–V compound semiconductors with silicon using flip-chip or wafer bonding.3,4 Nevertheless, while good performance and complex integration have been reported, inexpensive and monolithically grown silicon light emitters with high-yield and thermal stability are desired. Direct epitaxial growth of GaAs layers onto silicon with InAs quantum dot (QD) nanostructures as gain media is very promising. Owing to the atom-like discrete energy levels, QD lasers on a GaAs substrate display a higher stability against temperature and a lower-threshold lasing operation, which is of first importance for reducing the energy per bit consumption.5 It has been shown that Ge- and Si-based InAs QD lasers have superior static characteristics over QW lasers.6–8 Unlike their QW counterparts, previous works have shown that carrier localization into QDs makes the lasers on Si less sensitive to the threading dislocation density (TDD) originating from the lattice and thermal mismatch.9 A recent work has reported on highly efficient 1.31 μm InAs QD based light sources directly grown on silicon with a reduced TDD of 7.3 × 10^6 cm^-2. At room temperature, ground state (GS) lasing takes place with a threshold current as low as 9.5 mA, an output power of 175 mW, and a wall-plug-efficiency of 38.4%. Further improvements were obtained by using a high-reflectivity on the rear facet, hence leading to a reduction of the threshold current down to 6.7 mA.9 In this paper, we go a step beyond by investigating the behavior of the linewidth enhancement factor (H-factor) of silicon based QD lasers. The H-factor is known as one of the most important parameters of semiconductor lasers, hence driving, for instance, the spectral linewidth and the sensitivity to optical injection or optical feedback.10 At the system level, a large H also results in a frequency chirping under direct modulation, hence limiting the maximum data rate and transmission distance over a dispersive fiber.11 The H-factor typically describes the coupling between the carrier-induced variation of real and imaginary parts of susceptibility and is defined as

\[ H = \frac{-4\pi dn/dN}{\lambda dg/dN}, \]  

where \( dn \) and \( dg \) are the small index and optical gain variations that occur for a carrier density variation \( dN \). Although many studies have suggested near-zero \( H \) values in QD lasers, most of the experimental observations have actually shown the opposite. Indeed, the strong vertical coupling between the GS level and the higher energy levels contributes to drastically increase the H-factor.12 In this work, we report the experiment on the H-factor of QD lasers directly grown on silicon substrates. Owing to the low TDD, an H value of 0.13 rather independent of the temperature range (288 K–308 K) is measured. Above the laser threshold, we show that the H-factor does not increase extensively with the bias current.

QD laser samples studied in this paper were grown in a Veeco Gen-II molecular beam epitaxy chamber. The full laser epitaxial structure and QD growth conditions can be found elsewhere.9 The laser consists of five QD layers spaced by 37.5 nm thick GaAs barrier layers. For p-modulation doped QD lasers, the first 10 nm GaAs layer was undoped, followed by a 10 nm p-GaAs layer at a target hole concentration of

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5 × 10^{17} \text{ cm}^{-3} \text{ using } \text{Be}. \text{ The } p\text{-doping is used to improve the thermal stability. Indeed, } QD \text{ lasers suffer from thermal broadening of carriers, especially holes due to their heavier effective mass and consequent tightly spaced energy levels.}^{13} \text{ The thermal broadening decreases the } QD \text{ ground state gain and increases temperature sensitivity of the threshold current. The final 17.5 nm GaAs layer was undoped again to complete the } p\text{-MD GaAs barrier. Figure 1(a) shows an atomic force microscopy image of an uncapped InAs } QD \text{ grown on a GaAs/Si template. The } QD \text{ density is } 4.9 \times 10^{10} \text{ cm}^{-2}, \text{ and the corresponding acceptor/QD ratio is } \approx 10. \text{ A photoluminescence spectrum of the full laser sample revealed a very small full-width at half-maximum (FWHM) of 29.3 meV from the GS peak as shown in Fig. 1(b), indicating a highly homogeneous InAs } QD \text{ size throughout the five } QD \text{ stacks.}^{14} \text{ Note that the FWHM of room temperature PL from a single stack ranges from 2 to 10 m.} \text{ 1 pair of SiO}_2/\text{Ta}_2\text{O}_5 \text{ films was applied to the front and back facet of the laser to reduce reflection.} \text{ The laser ridge waveguide width was fabricated using photolithography and dry etching. Since the Si wafer is on-axis (001) orientation without offcuts, a Fabry-Perot (FP) cavity was formed by cleaving after thinning the wafer to } \approx 150 \mu m. \text{ Figure 1(c) shows a facet of a laser. A two-top contact scheme was employed to avoid the GaAs/Si heterointerface that can lead to a high series resistance. The laser ridge width ranges from 2 to 10 m. 1 pair of SiO}_2/\text{Ta}_2\text{O}_5 \text{ films was applied to achieve } \approx 60\% \text{ reflection on a facet, and 8 pairs were for } \approx 99\% \text{ reflection on the other facet. In what follows, both } p\text{-doped and undoped } QD \text{ lasers are compared. The undoped (p-doped, respectively) } QD \text{ laser is 1 mm (1.35 mm, respectively) long. Both devices have a ridge waveguide width of 3.5 } \mu m. \text{ Figure 2 depicts the light current characteristics of the undoped (a) and } p\text{-doped (b) } QD \text{ lasers, and the insets show the corresponding optical spectra measured at } 2 \times I_{th}. \text{ Devices emit on the sole GS transition close to 1300 nm. The threshold current } I_{th} \text{ at room temperature (293 K) for the undoped } QD \text{ laser is 6 mA, while that of the } p\text{-doped laser is found at 26.5 mA. By varying the temperature from 288 K to 308 K, } I_{th} \text{ varies from 5.3 mA to 8.3 mA (57% increase) for the undoped laser, while it is only from 26 mA to 28.5 mA (10% increase) for the } p\text{-doped one. Compared with the undoped material, the larger threshold current of } p\text{-doped } QD \text{ lasers results from the increase in the optical loss due to high free carrier absorption induced by the large number of holes in the dots. However, the inclusion of the } p\text{-type doping mitigates the thermal spread of holes, which leads to a rather temperature insensitive threshold current.}^{13} \text{ The } \zeta_H\text{-factor is at first extracted from a spectroscopic analysis using amplified spontaneous emission (ASE). The ASE method relies on direct measurements of the differential gain } dG \text{ and differential refractive index } dn \text{ as a function of slight changes in the semiconductor laser carrier density in sub-threshold operation. The differential index is measured by tracking the frequency shift of the longitudinal FP mode resonances, while the differential gain is obtained by measuring the net modal gain from the FP modulation depth (gain ripple) in the ASE spectra. The differential gain is equivalent to the variation of net modal gain } G_{net} \text{, which can be extracted as}^{15}

\[ G_{net} = \frac{1}{L} \ln \left( \frac{1}{\sqrt{R_1 R_2}} \frac{\sqrt{x - 1}}{\sqrt{x + 1}} \right) \] (2)

with } L \text{ the cavity length, } x \text{ the ratio of the peak-to-valley intensity levels, and } R_1 \text{ and } R_2 \text{ the front and back facet reflectivities (in intensity), respectively. The differential refractive index } dn \text{ within the active layer is then related to the modal wavelength } \lambda_m \text{ shift } d\lambda_m \text{ through } d\lambda_m = \Gamma dn/n \text{ which combined with Eqs. (1) and (2) implies that the } \zeta_H\text{-factor can be reexpressed as a function of measurable parameters such as}

\[ \zeta_H = \frac{4 \pi}{I_{th}} \frac{d\lambda_m}{dl} \frac{dG_{net}}{dl}. \] (3)

In the experiments, light from the QD lasers is coupled into a 20 pm high resolution optical spectrum analyzer via an anti-reflection coated lensed fiber. To eliminate any source of optical feedback from the setup, an isolator is also inserted after the laser. In order to only account the net carrier-induced frequency shift, thermal effects must be eliminated. To do so, } QD \text{ devices are biased using the minimal pulse width of 100 ns,}^{16} \text{ while the device temperature is carefully monitored and kept constant throughout the measurement. The peak wavelength is then recorded for each duty cycle from 0.1% to 10% in 2% increment. For each sub-threshold bias current, the peak wavelength values are plotted as a function of duty cycle, and the extrapolation at 0% duty
cycle allows extracting the corresponding values without thermal effects. Finally, a data processing involving a Lorentzian curve-fitting of each FP mode is applied in order to retrieve the peak information in terms of modal wavelength and intensity. Overall, taking into account all the aforementioned elements, the uncertainty of the $\zeta_H$-factor measurement is of order 0.5%. Figure 3 displays the spectral dependence of the $\zeta_H$-factor for the p-doped QD laser. The figure in the inset shows the net modal gain for different subthreshold bias currents ranging from $0.88 \times I_{th}$ to $I_{th}$. The black arrow indicates that the gain is blue-shifted as the bias level increases. At threshold, the net modal gain is about 2.4 cm$^{-1}$ per QD layer. As for the $\zeta_H$-factor, a variation from 0.13 to 0.29 at 293 K is unveiled over a span of 20 nm. At the gain peak ($\approx$1295 nm), the $\zeta_H$ value is of 0.13 which is the lowest value ever reported for any semiconductor laser on silicon. Such a value which is actually even lower than those recently reported on InAs/GaAs QD lasers $^{17}$ can be explained by the high quality of the material and the reduced TDD which reduces the inhomogeneous gain broadening and concentrates the oscillator strength at the resonant wavelength. Then, the temperature dependence of the $\zeta_H$-factor is investigated for both p-doped and undoped QD lasers. Figure 4 presents the comparison assuming a temperature range from 288 K to 308 K with a step of 5 K. For each temperature, the $\zeta_H$ values correspond to those taken at the gain peak. Note that the linear curve-fittings (dashed lines) are the guide for the eye. As expected, the $\zeta_H$-factor of the undoped slightly increases from 0.29 at 288 K to 0.36 at 308 K, while that of the p-doped device remains constant with a value of 0.13 over the same temperature range. For undoped QD lasers, the increase in the $\zeta_H$-factor with temperature is due to the increased occupancy in the non-resonant states which reduce the GS differential gain and increases the refraction index variations. $^{18}$ On the contrary, for p-doped QD lasers, the refraction index variation is rather constant with temperature because the Auger recombinations decrease, whereas those in the barrier and wetting layer increase. Besides, the $\zeta_H$-factor of the p-doped QD laser is smaller than that of the undoped QD laser which is due to the reduced transparency carrier density. $^{19}$ Lastly, the impact of the ridge waveguide width is also studied. Figure 5 depicts the room temperature evolution of the $\zeta_H$-factor as a function of the ridge width for both p-doped and undoped lasers. As shown, in both situations, the $\zeta_H$-factor clearly increases with the ridge waveguide. While a very narrow ridge is usually required to lase in a single spatial mode, any increase in the ridge width affects the injected current density and the device properties such as the modal gain and the $\zeta_H$-factor. $^{20}$ Finally, the effective $\zeta_H$-factor is analyzed above the threshold. Although, previous studies have shown $\zeta_H$-factors below the unity in InAs/GaAs QD lasers emitting on the GS transition, $^{17}$ it is important to remember that this statement remains mostly true at threshold beyond which as the injection current increases, the lower energy states are saturated and the carrier filling into the higher energy levels balloons the $\zeta_H$-factor to larger values. $^{21}$

In this work, the above-threshold GS $\zeta_H$-factor is measured using the injection-locking (IL) technique, which is based on the asymmetry of the stable locking region over a range of detuning on both positive and negative sides of the locked mode. $^{22}$ By exploiting both negative and positive detuning locking boundaries $\Delta \omega_{min}$ and $\Delta \omega_{max}$ at a fixed bias current, the $\zeta_H$-factor is retrieved from

$$\zeta_H = \sqrt{\frac{\Delta \omega_{min}^2}{\Delta \omega_{max}^2}} - 1. \quad (4)$$

FIG. 4. The $\zeta_H$-factor as a function of temperature for p-doped (red) and undoped (blue) QD lasers. The linear curve-fittings (dashed lines) are the guide to the eye only.

FIG. 5. The $\zeta_H$-factor as a function of the ridge waveguide width for p-doped (red) and undoped (blue) QD lasers (293 K).
Further works will also concentrate on the time-delay dynamics for the conception of isolator-free on-chip light sources.

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