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High-Power Quantum-Dot Superluminescent Diodes With p-Doped Active Region

Marco Rossetti, Lianhe Li, Andrea Fiore, Lorenzo Occhi, Christian Vélez, Sergey Mikhlin, and Alexey Kovsh

Abstract—We demonstrate the use of p-doping in the active region of quantum-dot superluminescent diodes. Modal gain measurements and light output–current characteristics prove that p-doping is beneficial for achieving higher gain, higher output power, and better temperature stability.

Index Terms—Gain, optical coherence tomography (OCT), p-doping, quantum dot (QD), superluminescent diode, temperature characteristics.

I. INTRODUCTION

SEMICONDUCTOR superluminescent diodes (SLDs) are ideal optical light sources for optical coherence tomography (OCT) [1] due to their compactness and lower cost as compared to solid-state laser sources. Broad output spectrum, high power, and ideally temperature-independent operation are the key requirements for these applications. SLDs not only find application in OCT but also in fiber-optic gyroscopes, sensors, and optical components testing. Several semiconductor structures have been proposed so far for SLDs, exploiting single quantum wells [2], chirped quantum wells [3], [4], or bulk materials [5] as active medium. Recently quantum-dot (QD) devices are attracting an increasing interest in this field [6]–[10]. QDs with the high radiative efficiency required for optoelectronic applications are commonly obtained by self-assembled growth, in the Stranski–Krastanow growth mode. Large size fluctuations are common for these systems and introduce spectral broadenings of several tens of millielectronvolts, making them an ideal system for applications where a broad spectrum is required. Furthermore, three-dimensional carrier confinement produced by these heterostructures gives rise to a series of fully quantized states with energies mainly determined by the dot dimensions. Provided that the spacing between the energy levels is much larger than $k_B T$ at room temperature, a temperature insensitive operation could be in principle achieved, providing a source for low-cost uncooled applications.

QD SLDs with broad output spectrum have been reported [8], [9]. In particular, in [9] we proposed and demonstrated the use of

chirped QD multilayers to achieve a spectral width > 100 nm. However, so far the output power of QD SLDs has remained limited, particularly in the 1300-nm wavelength region, due to the limited maximum gain in QD ensembles. In this letter, we demonstrate the use of p-doping in the active region of QD SLDs as a means to increase the optical gain and thus the output power. Output powers > 60 mW are achieved for the first time in QD SLEDs at 1300 nm.

II. RESULTS

Three samples with identical epitaxial structure, grown under the same conditions, but with different doping levels in the active region were processed into SLDs. All of them contained ten InAs QD layers in a GaAs active region embedded between 1.5- μm -thick $\text{Al}_{0.35}\text{GaAs}$ cladding layers. In Sample A, the dot layers are separated by undoped GaAs spacers, while in Samples B and C, carbon doping is introduced inside a thin region of each GaAs spacer. The doping level was estimated to correspond to the introduction of around 8 and 15 extra-holes per QD, for Samples B and C, respectively. The use of p-doping has been proposed to overcome the problem of carrier spreading among the closely spaced energy levels in the valence band [11]. The hole thermal dispersion can be detrimental for the device temperature characteristics and negatively affects the differential gain of the QD material. Introducing extra holes in the active region can be thus beneficial for the achievement of higher modal gain and better temperature stability. P-doping has been shown to increase the T_0 of QD lasers [12], [13] and, very recently, to increase the modal gain [14]. Here we present direct measurements of modal gain and we present the strong impact it has on the light output–current (L – I) characteristics of the QD SLDs. The devices are processed as follows: 7° tilted single-mode ridge-waveguides (3–4 μm width) are formed on the sample surface by dry etching, the exposed surface is passivated and planarized with a BCB (benzocyclobutene) polymer and Ti–Pt–Au p-contacts are deposited by metal evaporation and liftoff. The substrate is then thinned-down and Ni–Ge–Au–Ni–Au n-contacts are deposited. Finally, 4-mm-long chips are cleaved and positioned p-side up on a copper submount for characterization. Measurements were performed in pulsed regime with a 50-KHz repetition rate and 800-ns pulsewidth, to eliminate the influence of heating and clearly evidence the effect of p-doping.

The spectral characteristics show very similar behavior for the three samples, except for small variations in the spectral center wavelength (1267, 1270, and 1300 nm for Samples A, B, and C, respectively), demonstrating that for the considered doping levels the dispersion of the QD density of states is not

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Fig. 1. Spectral characteristics of the slightly doped SLD. In the inset the spectrum of an SLD for GS = ES emission is reported, showing a bandwidth of 105 nm.

substantially modified. In Fig. 1, we report the spectral characteristics of SLD B, which is also representative for Samples A and C. At low injection the emission relative to the recombination from the QD ground state (GS) is centered around 1270 nm with a broadening of few tenths of nanometers, which is typical in QDs optimized for lasing at 1.3 μm . When the injection is increased the emission from the GS saturates because of state filling and a second line related to the first excited state (ES) appears on the high energy side of the spectrum. A detailed analysis of this behavior can be found in [10]. When GS and ES contributions are comparable, provided that the bandwidth of each line is large enough to produce a smoothed superposition, a very large bandwidth (FWHM > 100 nm) can be achieved. The inset of Fig. 1 shows the spectrum of an SLD where such condition was fulfilled using seven chirped QD layers [15], so demonstrating that a QD SLED can be operated in the regime GS = ES to produce a spectrum suitable for applications in high-resolution OCT.

The maximum net modal gain (modal gain minus optical losses: $\Gamma g - \alpha_i$) is a crucial element in determining the maximum SLD output power. This was measured observing the amplification of a tunable laser injected into one of the waveguide facets and collected from the opposite through single-mode, antireflection (AR)-coated, lensed fibers. The inset of Fig. 2(b) reports the maximum output power versus the maximum net modal gain for SLDs operating in the regime GS = ES at 20 $^{\circ}\text{C}$, measured over a series of QD samples with different epitaxial structures (varying number of dot layers, inhomogeneous broadening, doping level of the active region) together with an exponential fit. Output powers exceeding 20 mW can be achieved only with a net gain of 20 cm^{-1} or higher. In Fig. 2(a), the modal gain curves at the GS peak position versus current density are reported for Samples A, B and C. Each line interpolates a series of 80 data points measured tuning the injected laser at the GS peak wavelength and which were verified to be reproducible over several identical devices.

Fig. 2. (a) Modal gain curves for the undoped (dotted line), slightly doped (dashed line), and heavily doped (continuous line) sample. (b) $L-I$ characteristics: the square markers identify the regime GS = ES. In the inset the measured exponential increase of output power at GS = ES versus maximum modal gain is reported.

The plot shows an increasing maximum modal gain with increasing doping level. The maximum value of Γg_{GS} for Samples A, B, and C was measured to be 18, 22, and 25 cm^{-1} , respectively. The increase can be attributed to the modified carrier distribution in the valence band due to the introduction of several acceptors per QD, which has the effect of pushing the quasi-Fermi level deeply inside the band, increasing the hole population contributing to the gain. We note that an increased injection current is needed in p-doped devices to achieve the same gain level. P-doping is expected to increase monomolecular (through dopant-related defects), radiative, and Auger (through increased hole population) recombination rates. In particular, Auger has been demonstrated [16] to be the main nonradiative mechanism in these QDs. A combination of these effects is likely to produce the shift of the gain curves towards higher current. P-doping has an impact on the optical losses as well, through increased free carrier absorption. From the measured Fabry-Pérot fringe visibility and laser thresholds in untitled devices, we estimate the optical losses as $\alpha_i = 1.8, 3.5, 5 \text{ cm}^{-1}$ for Samples A, B, and C, respectively. The increase in modal gain in p-doped structures B and C exceeds the increase in optical losses, resulting

Fig. 3. Temperature characteristics of the undoped (triangles), slightly doped (squares), and heavily doped (circles) sample.

in a larger net gain. This is confirmed by the L - I characteristics shown in Fig. 2(b), where the saturated output power increases with increasing doping level. The output power at the injection level when GS and ES emissions are comparable (indicated by the square markers) increases from 9 mW in the undoped sample to 25 and 70 mW in Samples B and C. Here the effect of p-doping on the recombination rates is also visible, pushing the GS = ES regime towards higher current levels for Samples B and C. As the devices were uncoated, the residual facet reflectivities induced some spectral ripple on Sample C. This could be easily eliminated by the application of AR coatings. The power levels obtained in the p-doped devices are very attractive for OCT applications. Although broadening the gain spectrum, as needed to achieve a smooth >100-nm bandwidth, will reduce the peak gain, this can be easily compensated by stacking more QD layers.

In Fig. 3, the temperature characteristics of the SLDs in the range 20 °C–100 °C are presented. The output power values are measured at a fixed current chosen for each device so that GS = ES at 20 °C. For Samples A and B the variation is exponential over the full range of temperatures, while a better stability is achieved from 20 °C to 60 °C for Sample C. Over the full range all the three samples present a similar decrease of 16–18 dB. We have found a similar behavior in edge-emitting lasers fabricated from the same wafers, as also reported by other authors [12], with a temperature-independent threshold current in the 20 °C–80 °C region in p-doped devices. Thermally activated nonradiative recombination channels (as observed in time resolved photoluminescence experiments) play an important role in the temperature dependence of the L - I characteristics of undoped SLDs. The better temperature stability of p-doped QDs may be related to a different temperature dependence of nonradiative recombination, to a thermal redistribution of carriers in

the QD ensemble [17] and to lower thermal spreading in the valence band [10].

III. CONCLUSION

We demonstrate that introducing p-doping in the active region strongly improves the net modal gain, the output power, and the temperature dependence of QD SLDs. Using a doping level corresponding to the addition of 15 holes per QD results in output powers up to 70 mW out of single-mode ridge waveguides, opening the way to applications in OCT.

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