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Microwave frequency characterization of undoped and *p*-doped quantum dot lasers

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The maximum relaxation frequency of directly modulated *p*-type doped quantum dot (QD) lasers decreases monotonically from 4.6 to 3.6 GHz with *p*-doping levels in the range of 20–40 holes/dot. Modulation efficiencies decrease as well with these *p*-type concentrations. These results are shown to originate from significantly larger internal losses in the *p*-doped QD devices that, despite an increased maximum ground state modal gain, causes increased gain compression and decreased differential gain for constant cavity length lasers. © *2007 American Institute of Physics*.
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Due to their three-dimensional quantization, quantum dot (QD) based lasers are expected to demonstrate an improved performance compared to their quantum well (QW)-based counterparts in terms of modulation characteristics due to a theoretically high differential gain.[1] More widely, unique properties such as an extremely high characteristic temperature,[2,3] low Henry factor,[4] and tolerance to optical feedback[5] have been demonstrated. However, the results published so far indicate no significant improvement in the speed of the lasers; enhanced nonlinear gain, population of carriers in excited states, and inhomogeneous broadening are apparently the limiting factors. A solution to overcome these problems has been proposed by Shchekin and Deppe using *p*-type doping to avoid gain saturation due to inadequate hole thermalization. This technique leads to a theoretical dynamic response as high as 30 GHz.[6] However, on the experimental level, this prediction has not yet been proven as pointed out by Deppe and Huang[6] who also showed that the bandwidth could be lowered by a slowed electron capture from the wetting layer or gain compression.[7]

So far, Fathpour *et al.* compared the small-signal characteristics of undoped and *p*-doped QD lasers emitting at 1.1 μm while they reported a 3 dB bandwidth of 8 GHz for a *p*-doped device at 1.3 μm at 15 °C (Ref. 8) for a *p*-type doping level optimized through photoluminescence measurements. Ishida *et al.* demonstrated temperature independent 10 Gbytes/s operation within 20–90 °C.[9] In Ref. 9 the direct modulation bandwidth amounts to 8 GHz at room temperature for a *p*-type concentration of ten acceptors per QD. All these results evidenced that the *p*-type doping technique has not yet been proven successful in greatly increasing the modulation bandwidth as it was demonstrated in QW-based lasers.[10] However, the literature lacks studies comparing the modulation bandwidth of undoped 1.3 μm QD lasers, with *p*-doped devices, with relatively large doping level greater than 10 holes/dot.

In this work, we report the measurement of the small-signal modulation characteristics in continuous wave (cw) operation of QD GaAs-based lasers emitting at 1.24 μm fabricated from four wafers, corresponding to an undoped one and three different *p*-type concentrations. Our results show that the modulation efficiency and the maximum relaxation frequency decrease when the *p*-doping concentrations range from 20 to 40 holes/dot.

The molecular beam epitaxy growth method used for the laser active region which contains six "dots-in-a-well" layers has been previously described.[7,11] To study the impact of the *p*-doping level on the modulation response, four wafers were grown with different doping densities corresponding, respectively, to an undoped wafer (wafer 632), 30 holes/QD (618), 20 holes/QD (619), and 40 holes/QD (620). 50-μm-wide broad area lasers were fabricated from these structures. The injection efficiency η_i and the internal loss α are listed in Table I for these devices. These latter values are extracted from the evolution of the external differential quantum efficiency (deduced from the slope efficiency) of broad area lasers versus the cavity length (from 0.5 to 2 mm). The extracted values are determined within 10% of accuracy. Although the internal losses increase with the *p*-doping level, the values here are comparable to the previous published results, where it amounts to 6.6 cm^{-1} depending on the *p*-type doping level.[8]

The laser structures were further processed into 3.5-μm-wide single-mode ridge waveguides (RWGs). Benzocyclobutene planarization ensured a low parasitic capacitance, compatible for high-speed direct modulation. 1.2 mm-long lasers had cleaved mirrors and were soldered on submounts to avoid deleterious heating. The slope efficiency (SE), the threshold modal gain g_{th}, the threshold currents at 20 °C, and the characteristic temperatures T_0 (from 20 to 80 °C) obtained in cw operation are also summarized in Table I. The threshold modal gain is calculated as the sum of the internal loss and the mirror loss for a 1.2-mm-long cavity. The modal gain is estimated with 10% accuracy. Similar slope efficiencies were measured in pulsed regime and the absence of roll off in the light-current curves until 140 mA proved that there were no significant heating effects. The SE of 0.36 W/A at the lowest hole concentration is similar to the reported results[8] indicating that our *p*-doped QD material is of high quality. An increase in the maximum

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TABLE I. Static performance of the undoped and p-doped lasers.

	Broad area lasers			1.2-mm-long RWGs		
Wafer	α_i (cm^{-1})	η_i (%)	g_{th} (cm^{-1})	i_{th} (mA)	SE (W/A)	T_0 (K)
Undoped	2	65	12	8	0.54	57
20 hole/dot	7.5	56	17.5	25	0.36	48
30 hole/dot	8.7	63	18.7	31	0.28	48
40 hole/dot	10	60	20	32	0.32	32

ground state net gain at threshold up to about 40% is also observed when comparing the p-doped devices to the undoped. These results are consistent with the previous work which showed that p-doping leads to an increase in the net gain at threshold at a fixed quasi-Fermi level separation.[12]The peak of the emission spectrum is at 1.24 μm for the four wafers.

Small signal microwave characterization was performed on the lasers in cw mode at 20 °C with a high-speed photodetector (45 GHz bandwidth) connected to an HP8722D network analyzer.[7] The measurements were performed on the four lasers by using the same calibration to ensure a good accuracy. We used a curve-fitting procedure[7] for each modulation response to extract the relaxation frequency f_r and the damping factor γ. The dynamic performance of the four lasers is summarized in Table II.

The relaxation frequency f_r versus the square-root of the normalized current $(i-i_{th})^{1/2}$ is plotted in Fig. 1 for the four different lasers. The maximum relaxation frequency obtained for a normalized bias current of ~10 decreases monotonically with the p-doping level from 5.3 (undoped) to 3.6 GHz (40 hole/dot). For each wafer, the data indicate a sublinear evolution of f_r versus the normalized current. It is not attributed to heating effects as was confirmed above.

Instead, the trend is claimed to arise from larger gain compression factors as previously reported in undoped QD lasers[7] and decreased differential gain. To substantiate this statement, it is noted that in the linear regime $[(i-i_{th})^{1/2}$ up to 6], the highest modulation efficiencies obtained among the lasers decrease monotonically with p-doping from 0.54 (undoped) to 0.46 GHz/mA$^{1/2}$ (40 holes/dot) which are higher than previous reported results.[8] Since this modulation efficiency is not photon lifetime dependent and the injection efficiencies are very similar, the differential gain must be decreasing with the p-doping level. It is conjectured that the increased internal loss with increased p doping more than offsets, the larger maximum ground state gain and, consequently, causes gain saturation. To confirm nonlinear gain compression, the evolution of the squared relaxation frequency versus the output power is plotted in Fig. 2. These results evidence a nonlinear regime which is more pronounced when the p-type doping level is high. Indeed, using a curve fitting procedure,[7] we extracted a gain compression coefficient P_{sat} which decreases from 90 mW for the undoped wafer to 18.4 mW for 40 holes/dot (Table II).

TABLE II. Dynamic performance of the undoped and p-doped lasers.

Wafer Unit	Maximum f_r (GHz)	modulation efficiencies (GHz/mA$^{1/2}$)	$f_{-3\text{ dB}}$ (GHz)	K factor (ns)	P_{sat} (mW)
undoped	5.3	0.54	5.2	1.42	90
20 hole/dot	4.6	0.51	4.6	1.14	62.7
30 hole/dot	3.8	0.48	4.2	1.04	53.2
40 hole/dot	3.6	0.46	4.4	1.01	18.4

An anomalous behavior is observed in the evolution of the K factor (extracted from the slope of the damping factor γ versus the relaxation frequency squared f_r^2), which decreases monotonically from 1.42 to 1.01 ns when the level of p doping increases. These results mean that the modulation bandwidths of the p-doped lasers are not described well by the traditional K-factor theory. The reason is that the K factor assumes a linear relationship between f_r and the square of the photon density, which is not valid when strong gain compression is present.

It is suspected that the optimum level for the p doping should be between 0 and 20 hole/dot. Our results are consistent with a previous group[7] which showed that the modulation bandwidth of p-doped QD lasers are not substantially larger than undoped QD lasers for p-doping level of 10 hole/dot, but no dynamic comparisons with an undoped wafer from the same growth campaign were reported. Further experiments are under way to investigate the optimum p-doping level which results in the highest modulation bandwidth of the QD lasers compared to an undoped wafer.

For the p-doped wafers, 800-μm-long cavities with one high reflection (HR)-coated (95%) facet, and thus lower cavity loss than the as-cleaved devices, were also characterized. The 20 °C cw threshold currents and slope efficiencies from the as-cleaved side were found to be 15 mA and 0.25 W/A for 20 holes/dot, 20 mA and 0.23 W/A for 30 holes/dot, and 24 mA and 0.21 W/A for 40 holes/dot. Compared to the 1.2 mm as-cleaved lasers, the response data in Fig. 3 show larger maximum relaxation frequencies equal to 5.0, 5.5, and 4.3 GHz for the p-doped device set, presumably due to reduced gain saturation. The lower relaxation frequency of the

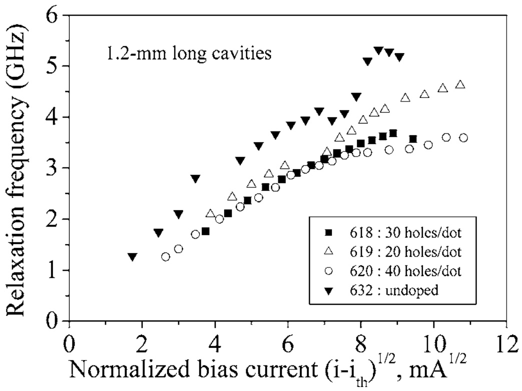

FIG. 1. Relaxation frequency vs the square root of the normalized bias current of the four lasers in cw mode at 20 °C.

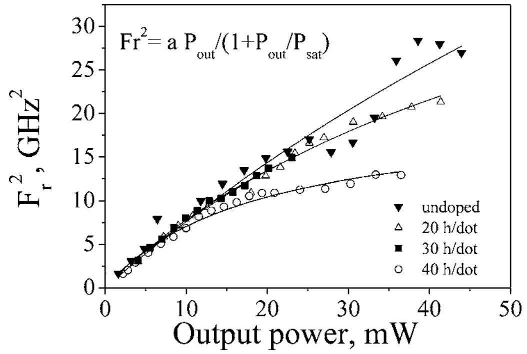

FIG. 2. Squared relaxation frequency vs output power. The curve fitting shows that the gain compression increases with *p*-type doping level.

wafer 619 lasers compared to 618 could be attributed to a less efficient HR coating. Moreover, experiments with wafer 619 above $(i-i_{\text{th}})^{1/2} \cong 8$ could not be performed. Indeed, the frequency response exhibited distortions which might be related to feedback from the coupled fiber. A comparison of the modulation efficiencies in the linear regime [up to a $(i-i_{\text{th}})^{1/2} \cong 7$] led to 0.60, 0.58, and 0.44 GHz/mA$^{1/2}$ for the three *p*-doped QD wafers. These values are higher on average than those of the 1.2 mm cleave/cleave lasers. Nonetheless, these results further confirm that the differential gain of *p*-doped QD lasers decreases with doping density in the range explored given a constant cavity length.

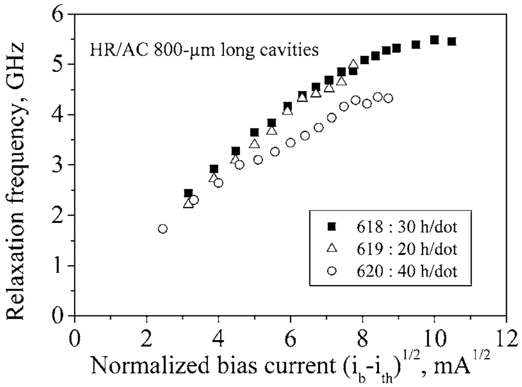

FIG. 3. Relaxation frequency vs the square root of the normalized bias current of the three doped lasers with one HR-coated facet.

Microwave frequency characterization was performed on GaAs-based QD lasers fabricated from an undoped wafer and wafers with three different levels of *p*-type doping. In terms of high-frequency performance, there is an obvious trade-off between the beneficial increase in maximum ground state gain with *p*-type doping of QDs and an undesirable increase in internal losses that induces gain saturation and gain compression. The modulation efficiency and the highest relaxation frequency of 1.2 mm cavity length lasers decrease monotonically with the *p*-doping level from 0.54 GHz/mA$^{1/2}$ and 5.3 GHz (undoped wafer), to 0.51 GHz/mA$^{1/2}$ and 4.6 GHz (20 holes/dot), 0.48 GHz/mA$^{1/2}$ and 3.8 GHz (30 holes/dot), and finally 0.46 GHz/mA$^{1/2}$ and 3.6 GHz (40 holes/dot). The net result is that a *p*-type concentration in the range of 20–40 holes/dot decreases the differential gain for lasers with constant cavity length. The gain compression factor is also found to increase with the *p*-type level, again because of the higher internal losses that induce gain saturation. HR coatings applied to shorter cavities with lower total cavity loss demonstrated higher relaxation frequencies.

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