P-type δ-doping of highly-strained VCSELs for 25 Gbps operation

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***Abstract*—We present the utilization of δ-doping to mitigate the rise in nonlinear gain compression in highly-strained InGaAs VCSELs and compare it with unstrained and undoped active region designs. High speed 25 Gbps operation is also demonstrated.**

Keywords- VCSELs, optical interconnect, highly-strained, δ-doping

I. INTRODUCTION

The rapidly expanding web of servers and racks are increasingly being connected optically. These optical interconnects can carry more data, are faster and do not heat up. However with the growing number of connections, they also need to be energy efficient. Vertical cavity surface emitting lasers (VCSELs) have long been recognized as a key component for optical interconnects because of their small size, speed and low power consumption.

Recent progress has shown that by moving to highly-strained quantum wells with wavelengths around 1060 nm highly-energy-efficient VCSELs [1] can be achieved. This is because increased strain enhances differential gain and reduces the gain transparency condition [2]. However, strain has been linked to an increase in nonlinear gain compression, mainly through carrier heating [3], which can reduce the modulation bandwidth. One method to address this issue is to increase intraband scattering events by adding modulation doping to the active region [4].

In this report we compare two sets of highly-strained 1060 nm VCESLs and demonstrate that nonlinear gain compression can be suppressed with δ-doping. The doped VCSEL also shows superior intrinsic characteristics compared to commercial 850 nm VCSELs. A maximum f_{3dB} bandwidth of 18.5 GHz and large signal operation of 25 Gbps is achieved.

II. DEVICE DESIGN

We grew the VCSELs on (100) semi-insulating GaAs substrates using molecular beam epitaxy (MBE) system. The bottom mirror consisted of unintentionally doped (UID) GaAs/AlAs followed by a 1 ¾ λ thick layer of Si doped GaAs to form an intracavity n-contact layer. The tapered oxide aperture layer is ½ λ thick and is placed so that the tip of the taper occurs at the standing wave null. Four periods of deep oxidation layers are grown after that to reduce capacitance. The top mirror consists of GaAs/AlGaAs mirrors that are bandgap-engineered for low resistance and low optical loss. Details of this design can be found in [5].

The active region is surrounded by an asymmetric $Al_{0.3}Ga_{0.7}As$ separate confinement heterostructure (SCH) that is parabolically graded down to GaAs spacers. Three 8 nm thick highly-strained $In_{0.3}G_{0.7}As$ quantum wells (QWs) are separated by 8 nm GaAs barriers. Growth is stopped halfway into the barrier and the surface is δ-doped with carbon using a carbon tetrabromide (CBr_4) precursor. We found that by pausing growth after each doped layer residual dopants in the chamber could be pumped out more thoroughly thereby reducing the probability of incorporating nonradiative recombination centers into the QWs. Once inside the barrier, carbon will move very little compared to beryllium because of its low diffusion coefficient [6]. The finished device is shown in Fig. 1.

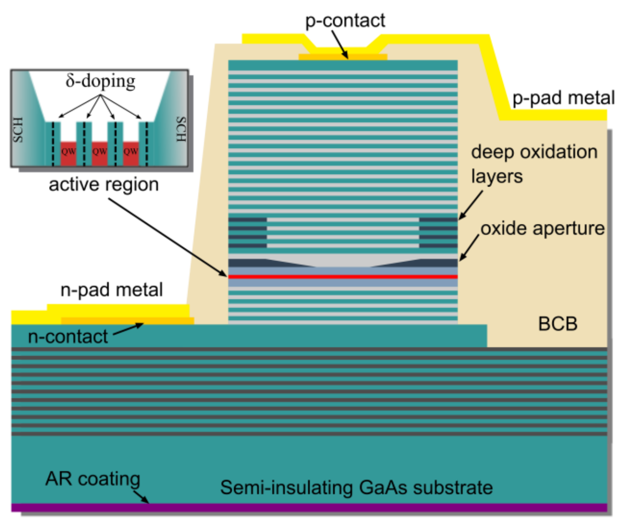

Fig. 1 Schematic showing notable components of the VCSEL. The inset is an expanded view of the active region with the δ-doping regions labeled.

III. RELATIVE INTENSITY NOISE

Although increasing stain is known to enhance differential gain, it is suspected that nonlinear gain compression, ε, is also simultaneously enhanced. We investigated this by simulating fits to relative intensity noise (RIN) measurements to extract the damping rate, γ, which is an indicator of the laser's intrinsic modulation bandwidth. Because the *K*-factor in the damping rate relation (1) is a function of both differential gain, ∂g/∂N and ε, it is useful to

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solve for the individual contribution to γ from these terms using (2) and (3).

$$\gamma = K f_r^2 + \frac{1}{\tau_c} \quad (1)$$

$$f_r = \frac{1}{2\pi}\sqrt{\frac{\Gamma v_g \eta_i \partial g/\partial n (I - I_{th})}{qV}} \quad (2)$$

$$K = \frac{(2\pi)^2}{v_g}\left(\frac{\varepsilon}{\partial g/\partial n} + \frac{1}{\alpha_i + \alpha_m}\right) \quad (3)$$

The light output was coupled into a multimode fiber using a collimating aspheric lens and a fiber port. The threshold current for ~8 µm diameter doped and undoped VCSEL was around 300 µA. From broad area laser measurements, the internal loss, α_i was determined to be 5.5 cm^{-1} and 11.5 cm^{-1} for the undoped and δ-doped material respectively.

Calculated and measured values for our highly-strained VCSELs are compared against a 850 nm GaAs MQW VCSEL [7] shown in Table I. There is a very noticeable enhancement in ∂g/∂N going from an unstrained GaAs to a highly-strained $In_{0.3}Ga_{0.7}As$ QW design accompanied by a large increase in ε. However, the addition of δ-doping mitigates the rise in ε and cuts the *K*-factor by over 50%.

TABLE I.
EFFECT OF δ-DOPING ON HIGHLY-STRAINED VCSELS

	∂g/∂N (cm^2)	*ε (cm^3)*	*K-factor (ns)*
Undoped 850 nm GaAs VCSEL [7]	7.19 e-16	2.5 e-17	0.393
Undoped 1060 nm $In_{0.3}Ga_{0.7}As$ VCSEL	2.35 e-15	1.2 e-16	0.442
δ-doped 1060 nm $In_{0.3}Ga_{0.7}As$ VCSEL	2.54 e-15	3.0 e-17	0.202

IV. MODULATION RESPONSE

High speed modulation testing revealed a f_{3dB} bandwidth of 18.5 GHz and 16.5 GHz for the δ-doped and undoped VCSELs respectively. The parasitic free f_{3dB} bandwidth calculated from the relation $f_{3dB}|_{max} = 2\pi\sqrt{2}/K$ indicates that the δ-doped VCSEL has a max bandwidth of 44 GHz while the undoped VCSEL has only a 20 GHz max bandwidth. The large difference is a result of the reduced damping in doped VCSELs. Both devices however, are limited by electrical parasitic and thermal limits. Error-free operation at 25 Gbps was achieved using a δ-doped 8 µm aperture device. The data-rate to power dissipation ratio is 2.5 Gbps/mW which is 400 fJ/bit.

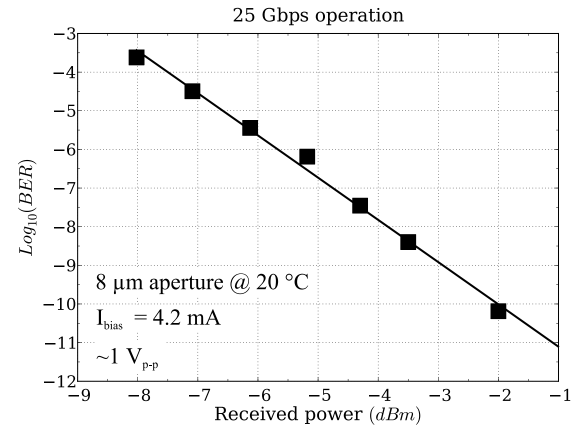

Fig. 2 Bit error rate for a δ-doped 8 µm device.

V. CONCLUSION

We have shown that despite the increase in differential gain, highly-strained active regions also have a much higher nonlinear gain compression coefficient. For efficient operation, doping in the active region is essential to mitigating this effect by enhancing the intraband scattering rate and reducing damping.

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