Extraction of Recombination Coefficients for Electrically Injected InGaAs/GaAs Monolithic Nano-ridge Laser Diodes Integrated on Silicon

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***Abstract*—We present the extraction of recombination coefficients for electrically injected monolithic nano-ridge laser diodes by first determining the effective carrier capture time from the small signal modulation response. The effect of the nano-ridge box size on the recombination coefficients is investigated.**

***Index Terms*—monolithic laser, epitaxial growth, nano-ridge engineering, recombination**

I. Introduction

Electrical pumping of monolithic $In_{0.2}Ga_{0.8}As$/GaAs multi-quantum well lasers, fabricated using nano-ridge engineering, has been challenging due to significant losses caused by absorption in the metal contacts. However, the introduction of a mode-beating effect has effectively mitigated these losses, enabling lasing under electrical injection [1]. Continuous-wave lasing at room temperature has been demonstrated for nano-ridge laser arrays monolithically grown on 300 mm silicon substrates, with an emission wavelength around 1020 nm. Fig. 1 shows the nano-ridge laser stack, with the p-type contact formed by a tungsten grating. Nano-ridges with wider trench width (a in Fig. 1) feature larger box height (b) and width (c). The sparse tungsten plugs, spaced 4.8 μm apart, result in significant carrier transport times, which in turn affect the electrical impedance and the modulation response.

In this work, we extract the effective carrier capture time and recombination coefficients of these lasers, and further explore how the nano-ridge size influences the recombination coefficients.

II. Characterization

A. Effective Carrier Capture Time

The effective carrier capture time that includes the carrier capture time and the carrier transport time can be extracted from the small signal modulation response [2].

$$H(\omega) = \frac{{\omega_R}^2}{({\omega_R}^2 - \omega^2 + j\omega\gamma)(1 + j\omega\tau_s)} \tag{1}$$

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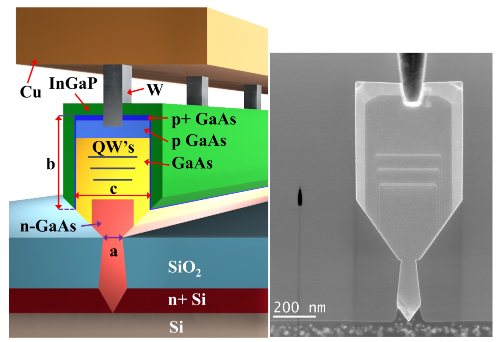

Fig. 1: Schematic of a nano-ridge laser stack and TEM picture of an 80 nm trench nano-ridge cross-section.

where ω_R is the resonance frequency, γ is the damping factor and τ_s is the effective carrier capture time.

To measure the small-signal modulation response, a DC bias and small-signal modulation are injected into the laser diodes via a high-speed microwave picoprobe. Emission is collected from a cleaved facet using a lensed fiber connected to a 1.6 GHz photodetector, with the electrical output sent to a network analyzer. Fig. 2 shows the measured modulation response of a device at a bias current of 8.6 mA, above threshold, along with the curve fit based on (1) and the extracted effective carrier capture time of 114 ps which is slightly higher than reported values for typical quantum well lasers of 20 - 100 ps.

B. Recombination Coefficients

A subthreshold reflection coefficient (S11) measurement was performed using a network analyzer to evaluate the input impedance. Taking the extracted effective carrier capture time from the modulation response, the differential carrier lifetime can be extracted from the real part of the input impedance at each bias current as shown in Fig. 3(a) by using [2]:

$$Z(\omega) = R_s + \frac{R_d}{(1 + j\omega\tau_d)(1 + j\omega\tau_s)} \tag{2}$$

where Z is the input impedance, R_s is frequency and bias independent series resistance, R_d is frequency and bias depen-

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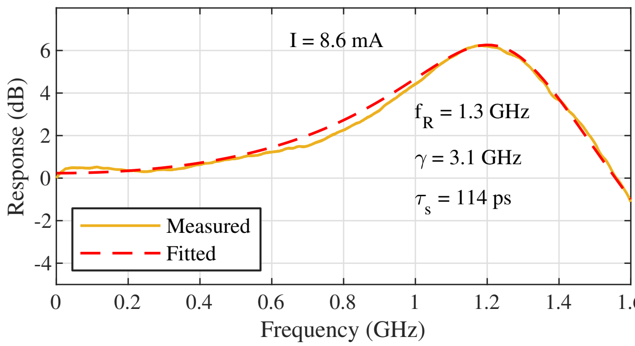

Fig. 2: Small signal modulation response at I = 8.6 mA with curve fitting and extracted parameters

dent resistance associated with the differential laser impedance and τ_d is the differential carrier lifetime. After determining the differential carrier lifetimes at various bias points, the carrier density can be calculated by [3]:

$$N(I) = \frac{\eta_i \int_0^I \tau_d(I)\, dI}{qV} \tag{3}$$

where N is the carrier density, I is the bias current, η_i is the injection efficiency, q is the elementary charge and V is the volume of the quantum wells. With an injection efficiency of 80% obtained from electrical simulations and the active region volume calculated by taking dimensions from TEM cross-sections of samples, the carrier density is determined at each bias current. Finally, the recombination coefficients are extracted from the differential carrier lifetime versus carrier density curve using the standard recombination formula [3].

$$\tau_d(N) = \frac{1}{A + 2BN + 3CN^2} \tag{4}$$

where A, B and C are recombination coefficients associated with defects, radiative recombination and Auger recombination respectively. Fig. 3(b) illustrates the extraction of the recombination coefficients by employing (4) for one device.

To investigate the impact of the trench width on the recombination coefficients, three groups of devices with trench widths of 60 nm, 80 nm, and 100 nm were characterized, each consisting of three devices. Fig. 3(c) illustrates the dependence of the A, B, and C coefficients on the trench width. Notably, the A coefficient appears to increase with trench width, possibly due to the presence of confined threading dislocation defects being trapped closer to the trench opening (or the nano-ridge volume) or unconfined defects in the nano-ridge device stack as the trenches widen. Additionally, nano-ridges with 100 nm trenches exhibit lower C and higher B values. This may be attributed to device heating from hot spots near the sparse metal plugs, which likely decreases as the device volume increases.

III. Conclusion

We extracted the effective carrier capture time and recombination coefficients of electrically injected monolithic nano-ridge lasers with varying trench widths. Sparse contacts have

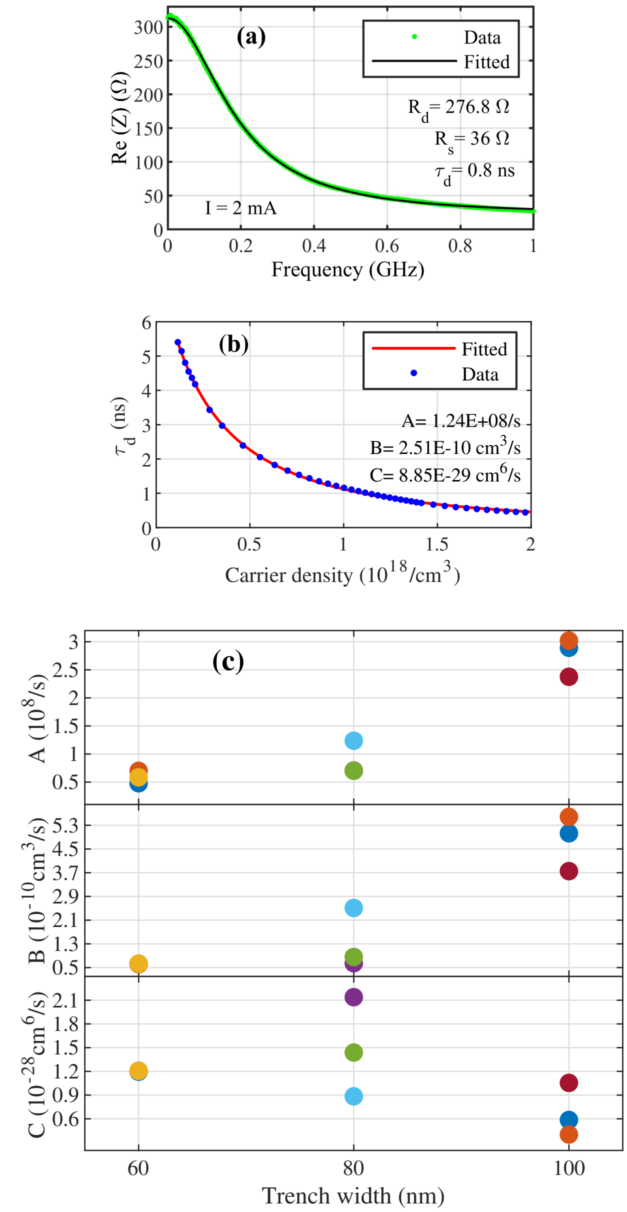

Fig. 3: (a) Extraction of R_s, R_d and τ_d at I = 2 mA (b) Extraction of A, B and C (c) A,B and C vs trench width.

led to a large carrier transport time. Nano-ridges with larger GaAs box sizes exhibited higher defect-related recombination. Additionally, nano-ridges with a 100 nm trench width showed higher B and lower C coefficients.

References

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