

Postgrowth Nondestructive Characterization of Dilute-Nitride VCSELs Using Electroreflectance Spectroscopy

S. A. Choulis, T. J. C. Hosea, S. Ghosh, P. J. Klar, and M. Hofmann

Abstract—We report electroreflectance (ER) measurements on a dilute-N GaInNAs vertical-cavity surface-emitting laser structure, as a function of temperature T , which probe the coupling between the cavity mode (CM) and a broad quantum-well (QW) ground state exciton. The latter is not separately observable in the ER, but, by monitoring the coupled CM-QW lineshape, we show it has maximum amplitude and is anti-symmetric when the CM and QW energies coincide at a certain T_{opt} . This predicted T_{opt} is confirmed by optically pumped lasing measurements on the same sample.

Index Terms—Cavity resonators, GaInNAs, material testing, optical spectroscopy, quantum-well devices, reflection, resonance, surface-emitting lasers, transitions.

I. INTRODUCTION

DILUTE-N GaInNAs is a promising active region material for vertical-cavity surface-emitting lasers (VCSELs) [1], [2]. Incorporating only a few percent of N into GaInAs reduces the band gap by ~ 150 meV per percent of N, allowing emission in the telecoms range 1.3 to 1.55 μm , using well-known GaAs technology. To obtain low threshold current and high output power, a close match between the energy of the cavity mode (CM) in the reflectance (R) spectrum and that of the quantum well (QW) ground state exciton transition, is required at the VCSEL operating temperature (i.e., $E_{\text{CM}} = E_{\text{QW}}$) [3], and references therein. For postgrowth characterization, simple R measurements give E_{CM} from the central dip in the high- R stopband, but E_{QW} is difficult to determine nondestructively by front surface techniques due to the presence of the top distributed Bragg reflector (DBR). However, photomodulated reflectance (PR) sometimes shows a clear QW feature, giving E_{QW} directly [4]. In other cases, we showed that E_{QW} can be inferred by monitoring either the amplitude [4]–[6] or phase [7] of the coupled CM-QW feature in PR. Nondestructive electro-modulated reflectance (ER) can also be used, and here, we show how it can predict the optimal working temperature T_{opt} of a representative GaInNAs VCSEL device, i.e., the temperature at which $E_{\text{CM}} = E_{\text{QW}}$. We use both the amplitude [4]–[6]

and phase [7] methods to locate T_{opt} . Optical-pumping measurements on the same piece of VCSEL wafer confirm that the lowest lasing-threshold power is achieved at this same T_{opt} .

II. EXPERIMENTAL DETAILS

The VCSEL structure, designed for optically pumped lasing at $\lambda \approx 1.3 \mu\text{m}$ [1], has stacks of three 7-nm $\text{Ga}_{0.7}\text{In}_{0.3}\text{N}_{0.025}\text{As}_{0.975}$ -GaAs QWs at each of the four optical antinodes of a GaAs cavity of optical thickness 2.5λ . The DBRs have 16 top, and 20.5 bottom, pairs of undoped GaAs-AlAs. For the ER, a piece of as-grown wafer was held in a capacitor-like arrangement, between two electrodes, one being a transparent indium-tin-oxide (ITO)-coated glass slide [8]. As the sample is not coated with contacts, this technique is essentially nondestructive. The structure is undoped and has no p-n junction, so techniques like PR, which modulate any built-in electric field, do not work. Thus, it was necessary to apply a fairly high ac voltage (~ 1 kV root mean square) to modulate the QW and obtain an appreciable modulated reflectance signal ΔR . Conventional R and ΔR spectra were measured in a cryostat from ~ 0.96 to ~ 1.01 eV with a resolution of ~ 2.0 meV. For the lasing studies, the sample was optically pumped with a mode-locked (80 MHz, 100-fs pulsewidth) Ti : sapphire laser at 1.348 eV [1].

III. SPECTROSCOPIC ASSESSMENT OF THE AS-GROWN WAFERS

With cooling, E_{QW} blue shifts more rapidly than E_{CM} , changing their relative energy, $E_{\text{CM}} - E_{\text{QW}}$ [4]. Fig. 1(a) shows representative R spectra, giving E_{CM} from the dip, and Fig. 1(b) the corresponding ER spectra $\Delta R/R$. No separate QW feature can be seen, and there appears to be only a simple feature which follows E_{CM} . However, closer examination reveals subtle changes in the ER amplitude and symmetry as T is varied. As explained later, we interpret this as the interaction between the QW and CM, as E_{QW} crosses from below E_{CM} at high T to above it at low T . In general, the $\Delta R/R$ lineshape of a coupled QW-CM feature is complicated, [4], [6], [7], [9], but we showed previously that, in circumstances where only a single simple feature is observed at E_{CM} , its amplitude A and symmetry (described in terms of some phase angle θ) can be parameterised by fitting an appropriate empirical lineshape [7]. Several approximate descriptions are possible, but here we follow [7] and use

$$\frac{\Delta R}{R} = \text{Re} \left\{ \frac{A\Gamma^3 e^{i\theta}}{(E - E_{\text{CM}} + i\Gamma)^3} \right\} \quad (1)$$

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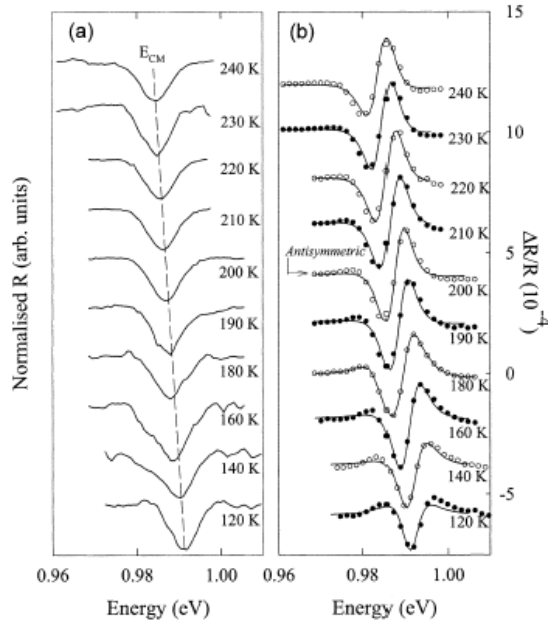


Fig. 1. (a) Representative normalized R spectra of the dilute-N GaInNAs VCSEL structure at different T . (b) Corresponding ER spectra. Circles: experiment (not all data points shown). Curves: fits using empirical lineshape function (1).

where E is the photon energy and Γ a broadening parameter.¹

Fig. 1(b) shows good fits and Fig. 2 summarizes the results. In Fig. 2(a), at 200 K, A has an obvious maximum. In Fig. 2(b), at 200 K, $\theta \approx 0^\circ$ (signifying (1) is perfectly anti-symmetric about $E = E_{CM}$). In Fig. 2(c), the E_{CM} from fitting (1) agrees well with that obtained directly from the R spectra. As explained next, the fact that the lineshape is both anti-symmetric and of maximum amplitude at 200 K, indicates that $E_{QW} = E_{CM}$ (≈ 0.987 eV), and so suggests that the VCSEL will perform best at this T_{opt} .

IV. ORIGIN OF THE ER LINESHAPE CHANGES

The applied ac electric field periodically modulates the QW via the quantum confined Stark effect, causing small variations in the real and imaginary parts, $\Delta\varepsilon_1$ and $\Delta\varepsilon_2$, of its dielectric function, predominantly near E_{QW} . A general modulated R spectrum is defined by [10]

$$\frac{\Delta R}{R} = \alpha \Delta\varepsilon_1 + \beta \Delta\varepsilon_2 \quad (2)$$

where α and β are the Seraphin coefficients $(1/R)(\partial R/\partial\varepsilon_1)$ and $(1/R)(\partial R/\partial\varepsilon_2)$, which are the fractional changes in R due to the modulation of ε_1 and ε_2 , respectively [6], [9]. In conventional ER of bulk or single heterostructure layers, the R spectrum is smooth and almost featureless. Thus, its derivatives, α and β , also vary slowly with photon energy, and the $\Delta R/R$ lineshape is dominated by $\Delta\varepsilon_1$ and $\Delta\varepsilon_2$, which vary rapidly near a transition energy: α and β provide essentially only phase information. In contrast, for VCSELs, the R spectrum is detailed and its derivatives in (2) contain sharp features, especially near E_{CM}

¹Although formally identical to the Aspnes's PR model, (1) is used here, only empirically, to obtain the amplitude and phase of the CM feature.

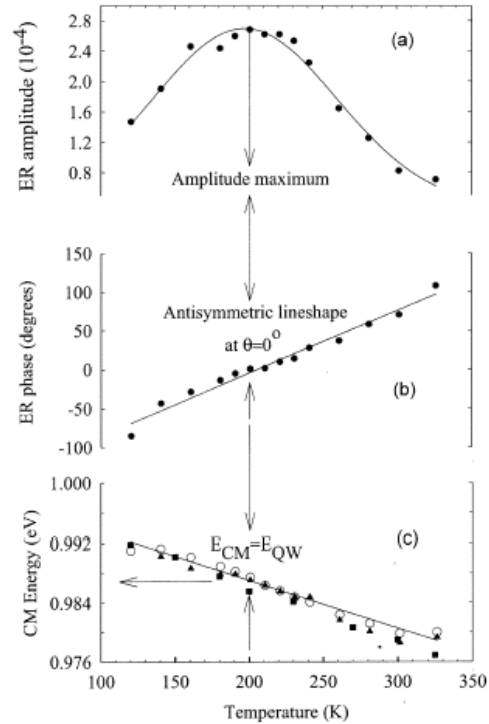


Fig. 2. Results of fitting the ER spectra in Fig. 1(b) with the empirical (1). (a) ER amplitude. (b) Symmetry (phase) of ER lineshape. (c) CM energy. Triangles: from the R spectra [Fig. 1(a)]. Circles: ER fits [Fig. 1(b)]. Squares: lasing photon energy from the optical pumping experiments. The curve and lines are guides to the eye.

[4], [6], [7], [9]. For α , the modulation of the QW ε_1 and, thus, refractive index, alters the active region optical thickness and, thus, E_{CM} , and leads to an *anti-symmetric* first-derivative-like dispersive lineshape for α , centred on E_{CM} . For β , the modulation of the QW ε_2 and, thus, absorption, alters the CM depth, giving a symmetric peak-like (or dip-like) absorptive lineshape, centred on E_{CM} . Thus, in general all four parameters in (2) have a role in the lineshape of the coupled CM-QW feature.

In the most favorable situations, the top DBR reflectivity is not very high and the width of the CM dip, Γ_{CM} , is larger than, or comparable to, Γ_{QW} , the inhomogeneous broadening of E_{QW} . Then, if E_{QW} and E_{CM} are reasonably well separated, independent QW and CM features can be seen in $\Delta R/R$, centred on E_{QW} and E_{CM} , respectively [4], [6], [9]. Furthermore, provided $\Gamma_{CM} \approx \Gamma_{QW}$ and are small, then, if E_{QW} and E_{CM} can be made to cross by tuning T (as here, or via pressure, incidence angle, or wafer position), we can observe a resonance in the $\Delta R/R$ amplitude when $E_{QW} = E_{CM}$ [4]–[6], [9].

However, when the top DBR reflectivity is high and $\Gamma_{QW} \gg \Gamma_{CM}$ (as we believe occurs here), one observes no independent QW feature, but only a single feature centred on E_{CM} , thus, apparently precluding a measurement of E_{QW} using the above techniques. Nevertheless, it may still be possible to infer E_{QW} : in the coupled CM-QW lineshape, when E_{QW} and E_{CM} are nearby, α and β now play the dominant role, as they vary more rapidly in energy than $\Delta\varepsilon_1$ and $\Delta\varepsilon_2$, which determine essentially only the sign and relative contribution of α and β to the spectrum [7]. It is well known that $\Delta\varepsilon_2$ has a zero at E_{QW} , while

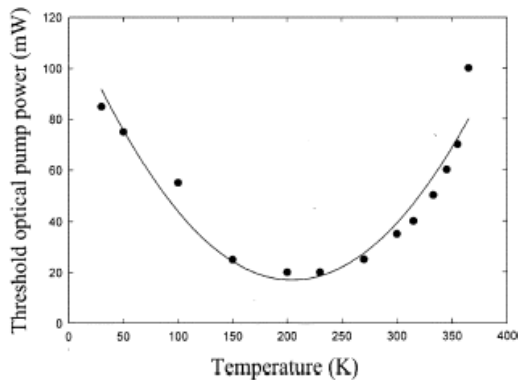


Fig. 3. T -dependence of threshold optical pumping power, required for the VCSEL to lase. The curve is a guide to the eye.

$\Delta\varepsilon_1$ is at an extremum [7]. Here, since $\Gamma_{QW} \gg \Gamma_{CM}$, it is reasonable to approximate that in the neighborhood of E_{QW} , $\Delta\varepsilon_1$, and $\Delta\varepsilon_2$ are both constant, with $\Delta\varepsilon_1 \gg \Delta\varepsilon_2$. Thus, when $E_{QW} = E_{CM}$, $\Delta\varepsilon_2$ is negligible near E_{CM} and (2) shows that the lineshape assumes essentially the anti-symmetry of the α Seraphin coefficient alone. When $E_{QW} \neq E_{CM}$, the lineshape is no longer anti-symmetric about E_{CM} as $\Delta\varepsilon_1$ is now not approximately constant near E_{CM} . Also, $\Delta\varepsilon_2$ may no longer be negligible near E_{CM} , so lineshape nonanti-symmetry could also arise because of admixture of α and β terms. If $\alpha \gg \beta$, the lineshape will essentially be given by the first term in (2) and, in addition to the anti-symmetry when $E_{QW} = E_{CM}$, an amplitude resonance may also be seen because $\Delta\varepsilon_1$ at E_{CM} falls off as the QW moves away either side of E_{CM} . Since $\Delta\varepsilon_1 \gg \Delta\varepsilon_2$ over quite a wide energy range about E_{QW} , this amplitude resonance may even be seen when $\alpha \approx \beta$. The actual magnitudes of α and β depend on sample details, but we showed earlier that their lineshapes can be accurately parameterised by expressions like (1) [7]. To summarize, in these circumstances, the lineshape of the coupled QW-CM ER feature becomes anti-symmetric about E_{CM} when $E_{QW} = E_{CM}$, and, depending on sample details, may also exhibit an amplitude resonance.

Here, the R spectra [Fig. 1(a)] show the CM width $\Gamma_{CM} \approx 10$ meV. From measurements on QWs grown under similar conditions, but without DBRs, we estimate $\Gamma_{QW} \sim 40$ meV, which tallies with the fact that N incorporation increases Γ_{QW} [2]. Thus, since $\Gamma_{QW} \gg \Gamma_{CM}$, the lineshape is certainly expected to be anti-symmetric when $E_{QW} = E_{CM}$. Moreover, the optically pumped device should consequently lase over a large photon energy range and, thus, a large T range. The emitted photon energy should essentially follow E_{CM} in the R spectrum. Since the anti-symmetry and amplitude resonance are both observed for the present VCSEL at the T_{opt} where $E_{QW} = E_{CM}$ (Fig. 2), we surmise from the above arguments that either $\alpha \gg \beta$ or $\alpha \approx \beta$.

V. DEVICE VERIFICATION

To test our ER predictions, the same wafer piece was optically excited. Fig. 3 shows the measured T -dependence of lasing threshold optical pump power: minimum average pump power is 20 mW and occurs at ~ 200 K, the same T_{opt} predicted by the ER where $E_{QW} = E_{CM}$. Fig. 2(c) confirms the other pre-

dictions: lasing photon energy equal to E_{CM} , and broad operating T -range. The full physical origin of the latter aspect is explored elsewhere but is due to an intrinsic property of dilute-N GaInNAs, namely the existence of discrete band gaps arising from five different possible nearest-neighbor N-configurations, which significantly broadens the QW gain spectrum [2].

VI. CONCLUSION

We have shown that ER measurements, using an ITO-on-glass electrode is useful for postgrowth characterization of VCSELs, does not require destructive deposition of metal contacts, and is well suited to predicting the device optimum working temperature. In contrast, PR has sample-dependent constraints on the wavelength and power of the pump laser, for it to reach the VCSEL active region, and PR spectra can be distorted by photoluminescence backgrounds, especially at low T .² We have shown that, despite a large inhomogeneous broadening of the GaInNAs QW exciton, and the absence of any QW feature in the ER, our technique is capable of accessing the excitonic ground-state transition and its resonance with the CM. This work extends the potential of electro-modulation as a postgrowth characterization measurement of the CM and QW in structures such as VCSELs and resonant-cavity light-emitting diodes.

REFERENCES

- [1] C. Ellmers, F. Höhnsdorf, J. Koch, C. Agert, S. Leu, D. Karaiskaj, M. Hofmann, W. Stolz, and W. W. Rühle, "Ultrafast (GaIn)(NAs)/GaAs vertical-cavity surface-emitting laser for the 1.3 μ m wavelength regime," *Appl. Phys. Lett.*, vol. 74, pp. 2271–2273, 1999.
- [2] S. A. Choulis, T. J. C. Hosea, P. J. Klar, M. Hofmann, and W. Stolz, "Influence of varying N-environments on the properties of (GaIn)(NAs) vertical-cavity surface-emitting lasers," *Appl. Phys. Lett.*, vol. 79, pp. 4277–4279, 2001.
- [3] T. E. Sale, *Vertical Cavity Surface Emitting Lasers*. New York: Wiley, 1995.
- [4] S. A. Choulis and T. J. C. Hosea, "Growth characterization of In_xGa_{1-x}As/GaAs/AlAs vertical-cavity surface-emitting laser structure using photomodulated reflectance," *Proc. Inst. Elect. Eng.—Optoelectron.*, vol. 14, pp. 49–53, 2001.
- [5] T. E. Sale, T. J. C. Hosea, and P. J. S. Thomas, "Photo-modulated reflectance as a valuable nondestructive process analysis tool for VCSELs," *IEEE Photon. Technol. Lett.*, vol. 12, pp. 1328–1330, Oct. 2000.
- [6] S. A. Choulis, S. Ghosh, and T. J. C. Hosea, "Resonances between the cavity mode and five excitonic transitions in an In_xGa_{1-x}As/GaAs/AlAs/AlGaAs vertical-cavity surface-emitting laser structure using photomodulated reflectance," *J. Appl. Phys.*, vol. 88, pp. 5547–5553, 2000.
- [7] S. Ghosh, T. J. C. Hosea, and S. Constant, "Photoreflectance lineshape symmetry and quantum-well ground-state exciton energy in vertical-cavity surface-emitting lasers," *Appl. Phys. Lett.*, vol. 78, pp. 3250–3252, 2001.
- [8] S. Ghosh and T. J. C. Hosea, "Non-destructive electroluminescence characterization of as-grown semiconductor optoelectronic device structures using indium-tin-oxide coated electrodes," *Rev. Sci. Instrum.*, vol. 71, pp. 1911–1912, 2000.
- [9] P. J. Klar, G. Rowland, P. J. S. Thomas, A. Onischenko, T. E. Sale, T. J. C. Hosea, and R. Grey, "Photomodulated reflectance study of InGaAs/GaAs/AlAs VCSEL structures in the weak coupling regime: The cavity/ground-state-exciton resonance," *Phys. Rev. B*, vol. 59, pp. 2894–2901, 1999.
- [10] B. O. Seraphin and N. Botka, "Band structure analysis from electroreflectance studies," *Phys. Rev.*, vol. 145, pp. 628–636, 1966.

²In samples with a p-n junction, ER may also show luminescence backgrounds at low T .