Effect of p-Doping on the Temperature Dependence of Differential Gain in FP and DFB 1.3-μm InGaAsP–InP Multiple-Quantum-Well Lasers

G. Belenky, C. L. Reynolds, Jr., L. Shterengas, M. S. Hybertsen, D. V. Donetsky, G. E. Shtengel, and S. Luryi

***Abstract*—The temperature dependence of differential gain dG/dn for 1.3-μm InGaAsP–InP FP and DFB lasers with two profiles of p-doping was obtained from RIN measurements within the temperature range of 25 °C–65 °C. Experiments showed that the change of the active region doping level from $3 \cdot 10^{17}$ cm^{-3} to $3 \cdot 10^{18}$ cm^{-3} leads to a 50% increase of the differential gain for FP lasers at 25 °C. Heavily doped devices also exhibit more rapid reduction of the differential gain with increasing temperature. The effect of active region doping on the energy separation between the electron Fermi level and electronic states coupled into the laser mode explains the observations. The temperature dependence of differential gain for DFB devices strongly depends on the detuning of the lasing wavelength from the gain peak.**

I. Introduction

THE EFFECT of doping on the performance of InGaAsP–InP lasers has been discussed in literature as an attractive method of controlling the device performance for various commercial applications [1]–[7]. Optimization of the doping profile of the p-cladding–waveguide interface and the laser waveguide improves the device temperature performance [1], [2]. It was shown experimentally that doping of the active region leads to enhancement of the modulation bandwidth and an increase in the differential gain of 1.55-μm InGaAsP multiple-quantum-well (MQW) lasers [3], [5], [6]. Theoretical aspects of the effect of doping on device high-frequency performance were discussed in [7].

In this work, we studied experimentally the changes in the value and temperature dependence of the differential gain of 1.3-μm InGaAsP–InP MQW lasers with the increase of acceptor concentration (Zn) within the active region from $3 \cdot 10^{17}$ cm^{-3} to $3 \cdot 10^{18}$ cm^{-3}. The device static characteristics, including gain and loss, were also studied.

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G. Belenky is with the State University of New York at Stony Brook, Stony Brook, NY 11794 USA. and also with Lucent Technologies, Bell Laboratories, Murray Hill, NJ 07974 USA.

C. L. Reynolds, Jr., and G. E. Shtengel are with Lucent Technologies, Bell Laboratories, Breinigsville, PA 18031 USA.

L. Shterengas, D. V. Donetsky, and S. Luryi are with the State University of New York at Stony Brook, Stony Brook, NY 11794 USA.

M. S. Hybertsen is with Lucent Technologies, Bell Laboratories, Murray Hill, NJ 07974 USA.

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II. Experiment and Discussion

InGaAsP–InP heterostructures were grown at 650 °C by low-pressure (80 mbar) metalorganic chemical vapor deposition (MOCVD) on (100) n^+-InP substrates. Standard CMBH lasers were grown. A strained MQW active region consists of nine 70-Å wells and 100-Å barriers in which the wells are mismatched by ~1% and are surrounded by 500-Å separate-confinement heterostructure (SCH) layers ($\lambda = 1.15$ μm). In our experiments, we used devices having a cavity length of 300 μm and a mesa width of about 1 μm. A typical secondary ion mass spectrometry (SIMS) active region concentration depth profile of the structures used in this work is shown in Fig. 1. Lasers with two different p-doping profiles were studied: 1) a moderately ($3 \cdot 10^{17}$ cm^{-3}) Zn doped active region and 2) a heavily ($3 \cdot 10^{18}$ cm^{-3}) doped active region. The As signal was used to denote the placement of the SCH–active region. The threshold current was about 9 mA for lasers with a heavily doped active region and about 7 mA for lasers with a moderately doped one. The parameter T_0, indicating the temperature sensitivity of the threshold current, was in the range 55 K–65 K for all the devices studied.

The relative intensity noise (RIN) spectrum was detected with a high-speed InGaAs p-i-n photodetector (cut-off frequency of over 15 GHz) and low-noise preamplifier. The noise signal was measured by a spectrum analyzer. The measured RIN spectra for DFB devices with different dopings taken at 25 °C are plotted in Fig. 2(a) and (b). As the current increases, the peak frequency (resonance frequency f_r) shifts to a higher level. The RIN frequency (f) spectra (see Fig. 2) were approximated by [8]

$$\mathrm{RIN} = \frac{4}{\pi}\delta f_{st}\frac{f^2 + (\gamma^*/2\pi)^2}{(f_r^2 - f^2)^2 + f^2(\gamma/2\pi)^2} \tag{1}$$

where δf_{st} is the Schawlow–Townes linewidth, f_r is the electron–photon resonance frequency, and γ is the damping factor. All these parameters were determined by fitting (1) to the measured RIN spectra. The agreement was satisfactory. We approximated $\gamma^* = \gamma$ in our fitting procedure since the difference between γ and γ^* is much smaller than the resonance frequency. The fitted values of the parameters and the measured value of the threshold current I_{th} allow for determination of the values of the differential gain dG/dn. We estimated the K factor from the slope of γ/f_r^2 and the effective differential gain $(1/\chi)dG/dn$ from [8]

$$f_r^2 = \frac{v_g\Gamma}{4\pi^2}\cdot\frac{dG}{dn}\cdot\frac{1}{\chi}\cdot\frac{\eta_i(I - I_{\mathrm{th}})}{eV} \tag{2}$$

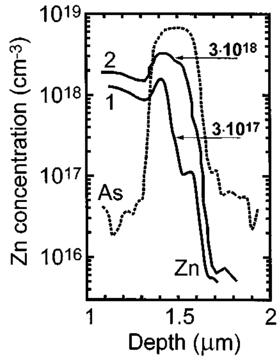

Fig. 1. SIMS data for (1) moderately and (2) heavily doped structures. The As signal shows the position of the active region.

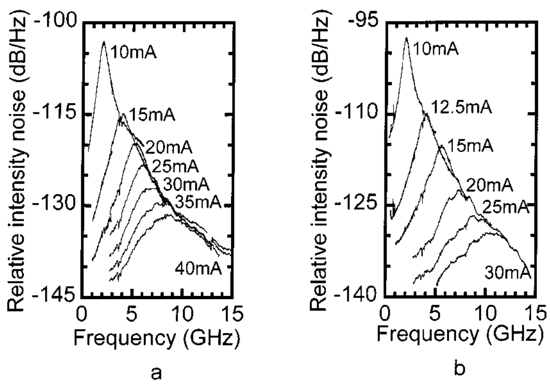

Fig. 2. RIN spectra at different bias currents (a) for moderately doped and (b) for heavily doped DFB devices at 25 °C.

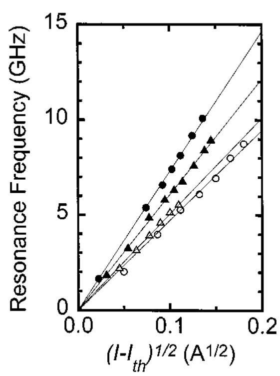

Fig. 3. RIN maximum frequency versus square root of pumping current for FP (triangles) and DFB (circles) devices at 25 °C. Open and solid symbols represent data for moderately and heavily doped lasers, respectively.

TABLE I
TYPICAL PARAMETERS FOR THE DEVICES STUDIED AT 25 °C. Zn CONCENTRATION N_{Zn} IS SHOWN FOR THE MIDDLE OF THE ACTIVE REGION ACCORDING TO THE DATA IN Fig. 1

		N_{Zn} 10^{18}cm^{-3}	I_{th} mA	$(dg/dN)/\chi$ 10^{-16}cm^2	K ns	Total Loss cm^{-1}
Moderately doped	DFB	≈0.3	7.5	3.78	≈0.37	65
	FP		6	4.18		
Heavily doped	DFB	≈3	9.5	8.66	≈0.30	83
	FP		9	6.04		

where v_g is the group velocity, η_i is the injection efficiency, γ is the confinement factor, I is the current, V is the active region

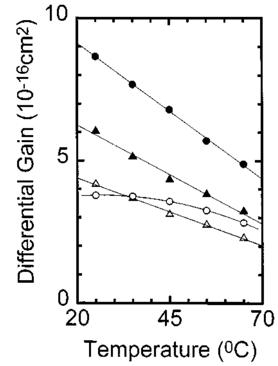

Fig. 4. Temperature dependence of the differential gain for moderate (open symbols) and heavy (solid symbols) doping for FP (triangles) and DFB (circles) lasers.

(MQW) volume, S is the photon density, and e is the electron charge. χ is a factor which approximates the impact of carrier transport: $\chi = 1 + \tau_d/\tau_e$ with τ_d-effective carrier capture time including diffusion across SCH and τ_e-thermionic emission lifetime from the QWs. We observed linear dependencies of the resonance frequency on the square root of the current (Fig. 3) in the whole injection range. Table I summarizes the results of the measurements at room temperature. The value of the group refractive index ($n = 3.7$) and injection efficiency ($\eta_i = 1$) used were appropriate for CMBH lasers. The total optical losses were measured near threshold from the intersection of the gain curves in TE and TM polarizations [9] with 10% accuracy. Corresponding measurements of the optical gain were performed using the Hakki–Paoli technique [10]. Amplified spontaneous emission spectra of the lasers were recorded with an optical resolution better then 1 Å. For the DFB lasers studied, spectral measurements showed that, at 25 °C, the lasing mode was placed at the short-wavelength slope of the gain spectra for heavily doped devices (negative detuning) and at the long-wavelength slope for moderately doped ones (positive detuning). In the general case, the sign of the detuning is defined by the stop-band position, not by the active region doping profile. As the temperature rose, the DFB lasing mode position changed by about 1 Å–K but the gain peak shifted by about 4 Å–K. For moderately doped devices, the detuning changed sign from positive to negative at about 40 °C.

Table I demonstrates that p-doping of the active region leads to enhancement of the differential gain and the device modulation bandwidth for both FP and DFB devices. Measurements of the differential gain were carried out within the temperature range from 25 °C to 65 °C (Fig. 4). The results for the FP devices show that heavy doping of the active region enhances the temperature sensitivity of the differential gain.

The dependence of differential gain on doping and temperature can be qualitatively understood based upon a simplified expression for the peak optical gain (G) in a QW [11]

$$G \propto \left(1 - \exp\left(-\frac{n}{N_c}\right) - \exp\left(-\frac{p}{N_v}\right)\right) \quad (3)$$

where n and p are the two-dimensional (2-D) electron and hole concentrations in the QWs and N_c and N_v are the corresponding effective densities of states. In the 2-D case, N_c and N_v are directly proportional to temperature T. For simplicity, assuming quasi-neutrality in the laser active region, we can write $n + N_A = p$, where N_A is the acceptor concentration. For an increase in doping, a smaller injected carrier density n is required to obtain the same gain in (3). The differential gain based on (3) is

$$\frac{\partial G}{\partial n} \propto \frac{1}{T} \cdot \left(\frac{1}{m_e} \exp\left(-\frac{n}{N_c}\right) + \frac{1}{m_h} \exp\left(-\frac{n}{N_v}\right) \cdot \exp\left(-\frac{N_A}{N_v}\right)\right) \tag{4}$$

where m_e and m_h are electron and hole effective masses. For InGaAsP-based QWs used here, it remains the case that $m_h \gg m_e$, even with compressive strain. Therefore, the first term dominates the differential gain and any reduction in the injected carrier density n leads to increased differential gain. However, since the leading dependence of the differential gain on temperature is just $1/T$, the negative slope is also larger, as seen in Fig. 4. Furthermore, it can be shown that the next order in the temperature dependence also becomes negative with doping in the active region: $\partial/\partial T(T \cdot (\partial G/\partial n)) = 0$ for an undoped active region, and $\partial/\partial T(T \cdot (\partial G/\partial n)) < 0$ for a p-doped one. This is under the simplifying assumption of temperature-independent optical loss.

The simplified analysis in (3) and (4) can be generalized. It reflects the fact that the rise of carrier concentration with temperature is more pronounced for heavily doped devices. The energy positions of states coupled into a laser mode are located closer to the quasi-fermi levels than in moderately doped lasers. Detailed simulations show that carrier transport is quite important to understand quantitatively the effective differential gain and its temperature dependence in multi-quantum well (MQW) lasers [12], [13].

The temperature dependence of the differential gain for DFB devices is further influenced by the position of the lasing wavelength relative to the wavelength of the gain peak. First, for a particular operating carrier density in the active layer, the differential gain is a strong function of wavelength, being smaller on the long-wavelength side of the gain peak and larger on the short-wavelength side. This explains the larger difference in measured differential gain between the moderately (positively detuned) and the heavily doped (negatively detuned) DFB lasers in comparison to the FP lasers. Second, if the lasing wavelength is detuned from the gain peak, then the operating carrier density must be larger which leads to a lower differential gain overall. For the devices studied, the operating carrier density changes with temperature due both to the intrinsic dependence of gain on temperature and to the change in the spectra position of the lasing mode relative to the gain peak. For devices with negative detuning (heavily doped lasers in our case), the rise of temperature leads to additional increase of the operating carrier density due to an increase of the detuning value. Increased detuning also contributes to lowering the T_0 value for heavily doped DFB devices. The measured values of T_0 were about 63 K for FP and 55 K for DFB heavily doped lasers. In moderately doped devices, the increase of temperature decreases positive detuning, thus suppressing the temperature dependence of the differential gain up to about 40 0°C. After this temperature, the effect of negative detuning becomes apparent again.

III. Conclusion

To summarize, we carried out measurements of the differential gain values for 1.3-μm InGaAsP–InP MQW DFB and FP lasers with two different doping profiles. It was shown that an increase of Zn concentration in the middle of the active region from $3 \cdot 10^{17}$ cm^{-3} to $3 \cdot 10^{18}$ cm^{-3} leads to a 50% differential gain increase for FP lasers at 25 °C. However, the differential gain drops with temperature more quickly for heavily doped devices. We have shown that these two effects are directly linked. The position of the laser wavelength relative to the gain peak is another critical factor influencing the temperature dependence of the differential gain for the DFB devices.

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