Temperature Performance of 1.3-μm InGaAsP–InP Lasers with Different Profile of p-Doping

G. L. Belenky, *Senior Member, IEEE,* D. V. Donetsky, C. L. Reynolds, Jr., R. F. Kazarinov, G. E. Shtengel, *Member, IEEE,* S. Luryi, *Fellow, IEEE,* and J. Lopata

***Abstract*—Temperature dependencies of the threshold current, device slope efficiency, and heterobarrier electron leakage current from the active region of InGaAsP–InP multiquantum-well (MQW) lasers with different profiles of acceptor doping were measured. We demonstrate that the temperature sensitivity of the device characteristics depends on the profile of p-doping, and that the variance in the temperature behavior of the threshold current and slope efficiency for lasers with different doping profiles cannot be explained by the change of the measured value of the leakage current with doping only. The entire experimental data can be qualitatively explained by suggesting that doping can affect the value of electrostatic band profile deformation that affects temperature sensitivity of the output device characteristics. We show that doping of the p-cladding/SCH layer interface in InGaAsP–InP MQW lasers leads to improvement of the device temperature performance.**

***Index Terms*—Doping, electron emission, heterojunctions, nonlinearities, optical losses, semiconductor lasers.**

I. Introduction

OPTIMIZATION of the p-doping profile of 1.3-μm multiquantum-well (MQW) InGaAsP–InP lasers is an important problem of the design and manufacturing of low-cost transmitters for different telecommunication applications. Experimental and modeling results obtained by different groups show that changes of acceptor concentration within different regions of the laser structure significantly affect device characteristics. It was shown theoretically and experimentally that p-doping of the active region in strained MQW InGaAsP–InP lasers can be attributed to a substantial increase in the differential gain leading to greater maximum modulation frequency [1]–[3]. It was also predicted theoretically and shown experimentally [4]–[6] that an increase of acceptor concentration in the p-cladding layer adjacent to the active region in 1.3-μm bulk active InGaAsP–InP lasers allows to minimize the voltage drop at the p-cladding/SCH interface and to avoid a substantial reduction of the barrier for thermionic emission of electrons from the active region. Experiments [7] carried out within the range of injection current densities below 2 kA/cm^2 shows that carrier leakage current of 1.3-μm MQW InGaAsP–InP lasers can be minimized by utilizing a p-doped SCH layer.

Since the leakage current affects internal $\eta_{\rm int}$ and external device efficiency $\eta_{\rm ext}$ as well as the device threshold current $I_{\rm th}$, it was important to study the temperature dependencies of laser characteristics $\eta_{\rm ext}$ and $I_{\rm th}$ together with $I_{\rm L}$ value under high-injection current densities for devices with different profiles of the p-doping in the vicinity of the active region.

In this letter, the temperature dependencies of the threshold current, device slope efficiency and heterobarrier electron leakage current from the active region of InGaAsP–InP MQW lasers with different profiles of acceptor doping were measured under pulse injection within the temperature range of 10 °C–80 °C and the range of injection current densities up to 10 kA/cm^2. This level of the injection is close to operating conditions of 1.3-μm MQW InGaAsP–InP buried heterostructure devices.

II. Experiment and Discussion

We have fabricated and measured broad-area laser devices which incorporate an electron collector [6], [7] for leakage measurements with the cavity length of 500 μm, mesa width of 20 μm, and collector area about 5 μm $\times$ 5 μm. For measurements of the device slope efficiency, we used broad-area lasers with 60-μm stripe width and the same cavity length. Lasers with three different p-doping profiles in the vicinity of the active region were studied: with an *undoped* p-cladding/SCH interface, with *moderately Zn-doped* interface ($\sim$5 $\times$ 10^{17} cm^{-3}) and *doped interface* (1.5 $\times$ 10^{18} cm^{-3}). Zn concentration at the SCH/active region interface was about 10^{16} cm^{-3} for the first type of devices and did not exceed 10^{17} cm^{-3} for both latter types. The laser active region consists of nine 70-Å-thick quantum wells separated by 100-Å barriers and is surrounded by 500-Å separate confinement layers ($\lambda =$ 1.15 μm). The device structure and its doping profiles were not different from those described in [7]. In our studies, the injection current pulses have a 50-ns width and a 100-kHz repetition rate.

Fig. 1 shows the temperature dependence of threshold current density $J_{\rm th}$ for devices with the different profiles of p-doping. One can see that the values of threshold currents in 1.3-μm InGaAsP–InP lasers and their temperature dependencies are different for devices with different Zn-doping profiles. In lasers with undoped p-cladding/SCH interface, the threshold

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

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

C. L. Reynolds, Jr. is with the Lucent Technologies Bell Laboratories, Breinigsville, PA 18031 USA.

R. F. Kazarinov, G. E. Shtengel, and J. Lopata are with the Lucent Technologies Bell Laboratories, Murray Hill, NJ 07974 USA.

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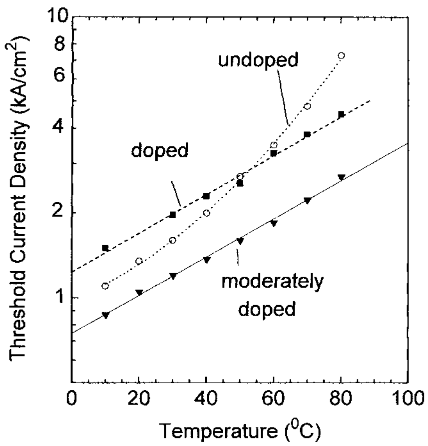


Fig. 1. Dependencies of threshold current density on temperature for three lasers with different doping profiles: with undoped p-cladding/SCH interface (dotted curves, circles), with moderately doped interface (solid lines, triangles) and with doped SCH region (dashed lines, squares).

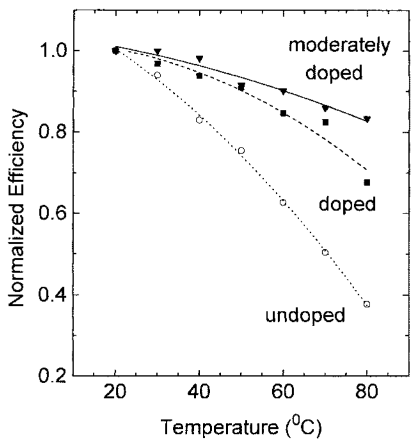
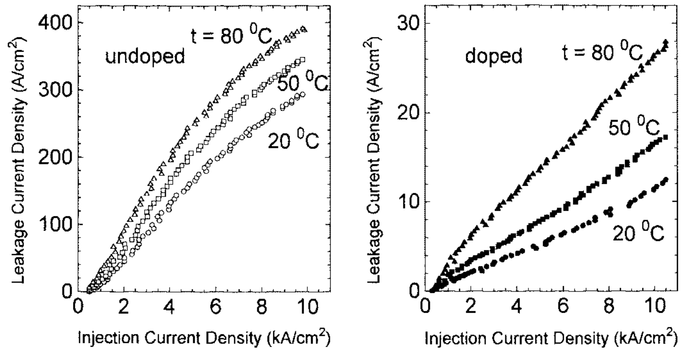


Fig. 2. Normalized slope efficiency as a function of temperature for lasers with three different doping profiles: with undoped p-cladding/SCH interface (dotted curves, circles), with moderately doped interface (solid lines, triangles) and with doped SCH region (dashed lines, squares).

current rapidly increases with temperature above 40 °C. The temperature dependence of $J_{\rm th}$ for devices with a moderately doped p-cladding/SCH interface or with a doped interface are characterized by one slope with typical $T_0 = 60$ K. Thickness of the cladding layers of the devices studied in this work was 0.65 μm, almost twice thinner than necessary to avoid absorption of the optical field by alloyed contacts. Thus the design of our lasers aimed at leakage measurements was not optimized for maximum external efficiency. Measured at 20 °C, the value of $\eta_{\rm ext}$ for devices with moderately doped and doped p-doping/SCH interface was about 25% and for devices with undoped interface 20%. Fig. 2 presents the results of measurements of temperature dependencies of external efficiency for devices with different doping profiles. We observed a strong dependence of $\eta_{\rm ext}$ temperature sensitivity on doping profile.

The results of measurements of the heterobarrier carrier leakage current $J_{\rm L}$ are presented in Fig. 3(a) and (b) for devices with undoped and doped interfaces correspondingly. We used a purely electrical technique [4] to measure the leakage of electrons from the active region of a InGaAsP–InP MQW laser. The obtained results in their entirety demonstrate



(a) (b)

Fig. 3. Measured heterobarrier leakage current versus injection current for the lasers with (a) undoped p-cladding/SCH interface and (b) doped SCH region at 20 °C (circles), 50 °C (squares) and 80 °C (triangles).

unambiguously that optimization of the p-doping profile allows to decrease the electron leakage current in InGaAsP–InP lasers by about one order of magnitude. However, the results of the $J_{\rm L}$ measurements cannot explain the difference in the dependencies $\eta_{\rm ext}(T)$ for devices with different doping profiles presented in Fig. 2. As shown in Fig. 3, the measured value of $J_{\rm L}$ does not exceed 4% of the total injection current densities even for devices with an undoped p-cladding/SCH interface at 80 °C. Taking into account that the collection efficiency of leakage current density by the electron collector on the top of the p-contact is at least 80% [6], we can estimate that the maximum possible contribution of the effect of heterobarrier leakage to the reduction of internal efficiency is about 5%. For lasers with doped interface, the corresponding values are less than 1% at 80 °C. Comparison of the results presented in Figs. 1 and 2 with Fig. 3 allows us to conclude that the rapid increase of the threshold current and the decrease of efficiency with temperature for 1.3-μm InGaAsP–InP MQW lasers with an undoped p-cladding/SCH interface cannot be explained by the increase of leakage current. The qualitative understanding of the results presented in Figs. 1–3 can be achieved in the framework of the model of electrostatic band profile deformation developed in [8], [9] for MQW InP based lasers.

At high injection, electrons can spill over into the SCH region from the QW's, while holes remain localized within the QW. This separation of charges creates electrostatic band profile deformation making the energy of the effective barrier for conduction band larger, and that for valence band smaller compared with the initial one. At elevated temperatures, hole density within the SCH can increase leading to an increase in loss and recombination in the SCH, and as a result causing the rise of the threshold current and the decrease of the slope efficiency [8], [10]. The results of calculation of the dependencies $\eta_{\rm ext}(T)$ and $I_{\rm th}(T)$ carried out in the framework of the model of the electrostatic band profile deformation appear to be in good agreement with measured $\eta_{\rm ext}(T)$ and $I_{\rm th}(T)$ for MQW InGaAsP–InP lasers [10]. It was shown that the rapid rise of the $I_{\rm th}$ with temperature within the region 40 °C–80 °C, which is a common phenomenon for undoped lasers (Fig. 1), is caused mostly by the effect of electrostatic band profile deformation and not by the increase with temperature of the intensity of Auger processes. The

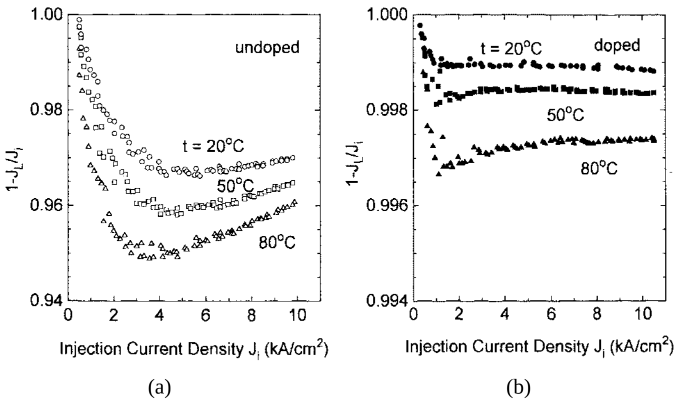


Fig. 4. Dependencies of $1 - J_{\mathrm{L}}/J_I$ versus injection current for the lasers with undoped p-cladding/SCH interface (a) and doped SCH region (b).

conclusion [8] about accumulation of holes in the SCH layer at elevated temperatures is supported by the results of spectrally resolved measurements of the spontaneous emission from SCH layer of 1.3-μm InGaAsP–InP MQW lasers [11]. It was shown that above the threshold, in agreement with prediction [8]–[10], the intensity of radiative recombination in SCH layer of 1.3-μm InGaAsP–InP MQW increases with the drive current and this increase correlates quantitatively with the decrease of the device slope efficiency.

To explain the difference in measured dependencies $\eta_{\mathrm{ext}}(T)$ and $I_{\mathrm{th}}(T)$ for devices with different doping shown in Figs. 1 and 2 in the framework of the model [8]–[10], we have to assume that the doping profile affects the charge distribution within the SCH, thus suppressing the influence of the band bending effect on the device performance. The difference in dependencies $\eta_{\mathrm{ext}}(T)$and $I_{\mathrm{th}}(T)$ for devices with a *moderately Zn-doped* interface and *doped interface* can be also explained by the difference in optical loss caused by the degree of p-doping. Assumption about the suppression of the effect of the electrostatic band bending by incorporation of acceptors into SCH layer allows to understand the difference in dependencies $J_{\mathrm{L}}(J_I)$ presented in Fig. 3(a) and (b) for devices with different doping profiles. Increase of the electron energy barrier for thermionic emission caused by the electrostatic band bending effect can be responsible for sublinear character of the dependencies $J_{\mathrm{L}}(J_I)$ registered in case of undoped structure [Fig. 3(a)]. Fig. 4(a) and (b) shows the dependencies of coefficient $(1 - J_{\mathrm{L}}/J_I)$ versus current density J_I for devices with an undoped and doped interfaces correspondingly. The value of this coefficient characterizes the contribution of heterobarrier leakage current change with injection current into the dependence of the device internal quantum efficiency on injection current. The parameter σ defined by equation: $\eta_{\mathrm{int}}(I_{\mathrm{inj}}) = \eta_{\mathrm{int}}^{\mathrm{th}} - \sigma(I_{\mathrm{inj}} - I_{\mathrm{th}})$ characterizes the contribution of the total leakage current (in the case of the buried heterolasers it is the sum of the heterobarrier and blocking layer leakage) in the change of the device internal efficiency with injection current, here $\eta_{\mathrm{int}}^{\mathrm{th}}$ is internal quantum efficiency at threshold. For 1.3 μm InGaAsP–InP MQW buried heterostructure devices, the common value of the σ is about 0.5 Å^{-1} [12]. Our experiments show that for devices with moderately doped and doped p-doping/SCH interface the contribution of the heterobarrier leakage in σ does not exceed 0.1 Å^{-1} even at 80 °C. We can conclude that optimization of p-doping allows to minimize the contribution of heterobarrier leakage effect into σ.

III. Conclusion

We demonstrate that the temperature sensitivity of the device characteristics depends on the profile of p-doping, and that variance in the temperature behavior of the device threshold current and slope efficiency for lasers with different doping profiles cannot be explained by the change of the measured value of the leakage current with doping only. The obtained experimental results can be qualitatively explained by suggesting that doping can affect the value of electrostatic band profile deformation which affects temperature sensitivity of the output device characteristics. We demonstrate that utilizing a p-doped p-cladding/SCH layer interface in InGaAsP–InP MQW lasers leads to improved device temperature performance even at 80 °C and high-injection current densities.

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