Proceedings of the XXXII International School of Semiconducting Compounds, Jaszowiec 2003

The Effect of Pressure and Temperature on AlGaInP and AlGaAs Laser Diodes

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InGaP/AlGaInP lasers (emitting from 630 to 690 nm) and GaAs/AlGaAs lasers (emitting at 780 nm) were studied under hydrostatic pressure up to 20 kbar and at temperatures from 240 to 300 K. The electrical characteristics, the power-current dependencies and the emission spectra were measured. The emission spectra shifted in agreement with the pressure/temperature variation of the band gaps in active layers of the laser. Since at high pressure the $\Gamma - X$ separation in the conduction band is strongly reduced (both in AlGaInP and AlGaAs), the dominant loss mechanism of the lasers is the electron leakage to X minima in the p-claddings. This, in turn, leads to high sensitivity of threshold currents to temperature. The dependence of threshold currents on pressure and on temperature is in good agreement with the simple theoretical analysis taking into account the carrier leakage and the radiative and nonradiative recombination. Better agreement between the theory and the experiment is obtained assuming drift rather than diffusion leakage. This indicates that threshold currents could be further reduced if the p-doping is improved in the claddings.

PACS numbers: 42.55.Px, 42.60.–v, 78.45.+h

1. Introduction

It is well known that both for AlGaInP and for AlGaAs short wavelength laser diodes threshold current increases rapidly with temperature and the differential quantum efficiency decreases with increasing temperature [1–3]. This increase in threshold occurs due to small $\Gamma - X$ separation which allows thermally activated electrons to leak from active region to p-cladding layer through X minima [4–6].

Hydrostatic pressure modifies the band structure of semiconductors and usually increases the direct band gap of most III–V and II–VI semiconductors with the rate of about 7–12 meV per kbar. We have used this effect for wavelength tuning of different lasers in a wide spectral range. The separation between direct (Γ) and indirect (X) minima in AlGaAs and in AlGaInP decreases with pressure with the rate of 10–12 meV per kbar. We have found that for the GaAs/AlGaAs laser diodes emitting in the 780–840 nm range and for the red emitting InGaP/AlGaInP lasers (635–690 nm range) thresholds significantly increased with pressure. We decided to study the effect of both pressure and temperature on different laser diodes. Our main motivation was to compensate the increase in threshold with pressure by decreasing the temperature of the laser. This allowed us to extend the tuning range of laser diodes for two reasons: (i) we were able to apply higher pressures without increasing the threshold, (ii) the decreasing temperature shifted emission wavelength in the same direction as the increasing pressure. We were also motivated by the need to obtain yellow laser light for different applications.

We start by describing our experiment and the optical pressure cell (Sec. 2). In Sec. 3 we discuss the pressure and temperature effect on threshold currents and we derive simple equations that we used for fitting our experimental results. In Sec. 4 we present our experimental results for GaAs/AlGaAs and InGaP/AlGaInP diode lasers. Section 5 contains major conclusions.

2. Experimental

Our pressure cell is schematically shown in Fig. 1. It is made of high quality maraging steel with an insert. The pressure is increased by pushing the piston. The pressure is calibrated with the resistance of InSb sensor which gives about 0.1 kbar sensitivity in the 20 kbar range (the absolute accuracy of pressure determination depends on the proper calibration of the sensor and is typically 1 kbar).

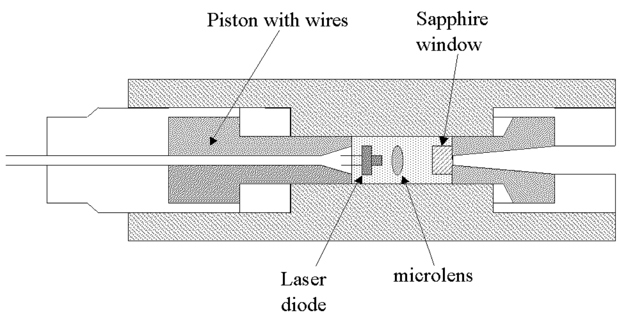

Fig. 1. Schematic view of the pressure cell.

The light emitted by the laser comes out of the cell through the sapphire window (after being collimated by a special microlens) or through the multimode optical fiber. We obtained about 75% of the laser power outside the cell in both coupling systems. The optical fiber and wires are inserted into the plug which is screwed into the pressure cell. As a pressure medium in the cell the special kind of gasoline or a pentane–hexane mixture was used. The gasoline we are using is transparent and provides hydrostatic pressure up to 20 kbar in the temperatures range from 220 to 300 K. For the experiments at lower temperatures we used two types of cooling systems. Three Peltier elements (with fans) attached to the cell allowed to cool it down to 0°C. This system is compact and requires only simple power supply with a controller. For lower temperatures we passed the nitrogen gas through the copper tube wound around the cell; this method allowed to cool it down to about 120 K. The temperature was measured by a thermocouple placed inside the pressure cell. The cell with cooling elements is placed under a small hydraulic press so that the pressure can be varied at lower temperature. For each pressure we measured the current–voltage and the power–light characteristics together with the spectra at different currents under pulsed or cw operation. We used 200 ns pulses with 0.1% duty cycle. The spectra were measured using SPEX 1000M monochromator with liquid-nitrogen cooled CCD. With 10 micron slits we have got the resolution of about 0.01 nm.

Our laser diodes were commercial devices produced by Hitachi (690 nm, 30 mW, 45 mA threshold), Sharp (780 nm, 10 mW, 45 mA threshold), Sanyo (780 nm, 5 mW, 43 mA threshold) and by Semiconductor Laser International (660 nm, 200 mW, 570 mA threshold). The manufacturers were not willing to reveal the compositions of the layers or other technological information.

3. Theory

The lasers which we studied emitted at 780 nm and in the 630–690 nm range (at ambient pressure and temperature). For such wide band gaps we can neglect the effect of Auger recombination and we can consider only three contributions to the threshold current: radiative recombination, nonradiative recombination, and leakage. Let us consider leakage current first. The dominant contribution to leakage comes from electrons diffusing and drifting into the p-claddings. The energy barrier ΔE for this process is the distance from the quasi Fermi level in the active region to the X minima in the p-cladding (due to high Al content in the cladding the lowest minima in the conduction band are at the X points in the Brillouin zone). This energy barrier is very sensitive to pressure because the $\Gamma - X$ separation decreases under pressure with the rate of about 10 meV per kbar in AlGaInP and about 12 meV per kbar in AlGaAs. The general formula for the leakage current density is [4]:

$$J_{\mathrm{L}} = qD_nN_0\left[\sqrt{1/L_n^2 + 1/(4z^2)}\,\mathrm{cth}\sqrt{1/L_n^2 + 1/(4z^2)}\,x_p + 1/(2z)\right], \tag{1}$$

where q is the electronic charge, x_p is the p-cladding layer thickness, and L_n is the minority electron diffusion length. D_n is the minority electron diffusion coefficient given by $D_n = \mu_n(kT/q)$, where μ_n is the minority electron mobility, k is the Boltzmann constant, and T is the absolute temperature. The quantity z is a length characteristic of drift leakage, given by

$$z = \left(\frac{kT}{q}\right)\frac{\sigma_p}{J_{\text{tot}}}, \tag{2}$$

where σ_p is the electrical conductivity of the p-cladding layer and J_{tot} is the total diode current density.

N_0 in Eq. (1) is the concentration of minority electrons at the edge of the p-cladding layer, given by

$$N_0 = 2\left(\frac{m_X kT}{2\pi\hbar^2}\right)^{3/2}\exp(-\Delta E/kT), \tag{3}$$

where m_X is the density-of-states effective mass of electrons in the X valley of the cladding layer and ΔE is the potential barrier for electron leakage. ΔE is affected by the doping density in the cladding because the quasi-Fermi level for holes in the active layer has to match the Fermi level at the edge of the p-cladding. For low p-doping there are two reasons for increased leakage: drift component of J_{L} increases and ΔE is reduced. For high p-doping the electric field in the p-cladding $(J_{\text{tot}}/\sigma_p)$ will be low and J_{L} will be dominated by diffusion

$$J_{\text{L}}^{\text{diff}} = \frac{\mu_n kTN_0}{L_n}. \tag{4}$$

For high currents and low σ_p, J_{L} will be dominated by drift

$$J_{\text{L}}^{\text{drift}} = \frac{q\mu_n N_0 J_{\text{tot}}}{\sigma_p}. \tag{5}$$

In our analysis of the data we shall use the above formulae for J_{L} i.e. we shall consider two extreme cases. The intermediate case (described by Eq. (1)) contains too many parameters which we do not know. For red emitting lasers it was shown in Ref. [4] that the drift current dominates the leakage while for GaAs/AlGaAs lasers high hole concentration in the p-cladding can be achieved so that the diffusion current should be more important. We shall be only concerned with the dependence of J_{L} on pressure and on temperature. The only pressure-dependent quantity in J_{L} is (to a good approximation) the energy barrier $\Delta E = \Delta E_0 - \alpha p$, where ΔE_0 is the ambient pressure value of ΔE and α is the pressure coefficient of the $\Gamma - X$ separation (taken as 10 meV per kbar in AlGaInP and as 12 meV per kbar in AlGaAs). Thus we obtain the following expressions for the leakage current $I_{\text{L}} = J_{\text{L}}S$ in the two extreme cases:

$$I_{\text{L}}^{\text{diff}} = A(kT)^{5/2}\exp\left(\frac{\alpha p - \Delta E_0}{kT}\right), \tag{6}$$

or

$$I_{\text{L}}^{\text{drift}} = A(kT)^{3/2} I_{\text{tot}}\exp\left(\frac{\alpha p - \Delta E_0}{kT}\right), \tag{7}$$

where we treat A and ΔE_0 as fitting parameters, independent of pressure and temperature. This involves the assumption that μ_n, L_n, and σ_p do not depend on temperature (which might not be the case).

Let us now discuss the two remaining contributions to threshold currents: the radiative and nonradiative recombination. The radiative current $J_{\mathrm{r}} = qB_0 n_{\mathrm{th}}^2$, where n_{th} is the electron concentration (which clamps at threshold) and B_0 is the bimolecular recombination coefficient. As shown in Ref. [7], the pressure/temperature variation of B_0 arises from the term E_{g}/kT, where E_{g} is the band gap of the active region (which we take to be the emission energy of the laser). The threshold concentration and its pressure dependence due to the increase in the effective mass and to the increase in the optical confinement factor have been discussed in Ref. [7]. In most cases the radiative threshold current increased with pressure, in some cases it decreased but the changes were rather weak (a few percent in the 10 kbar range). It can be shown that the electron concentration at transparency is proportional to kT. We assume the same proportionality for the threshold concentrations. Due to the experimental observation in InGaAs/GaAs lasers that the thresholds were independent of pressure we assume that the radiative current is constant with pressure and proportional to kT. Since the nonradiative current is proportional to n_{th}/τ, where τ is the lifetime for nonradiative recombination (assumed constant), we can also expect the proportionality to kT. Therefore in our simple analysis we assume the radiative and nonradiative contribution to the threshold current as BkT, where B is a constant.

Summarizing, for the analysis of the threshold current at different pressures and temperatures we shall use the following expressions:

$$I_{\mathrm{tot}}^{\mathrm{diff}}(p,T) = A(kT)^{5/2}\exp\left(\frac{\alpha p - \Delta E_0}{kT}\right) + BkT, \tag{8}$$

or

$$I_{\mathrm{tot}}^{\mathrm{drift}}(p,T) = \frac{BkT}{1 - A(kT)^{3/2}\exp\left(\frac{\alpha p - \Delta E_0}{kT}\right)}, \tag{9}$$

where A, B, and ΔE_0 will be three fitting parameters independent of pressure and temperature. The parameter α (pressure coefficient of the $\Gamma - X$ separation) will be taken as 10 meV per kbar in AlGaInP and as 12 meV per kbar in AlGaAs.

4. Results

4.1. GaAs/AlGaAs laser diodes

We studied the 780 nm diodes by Sharp and Sanyo with threshold currents 45 mA (10 mW optical power) and 43 mA (5 mW optical power), respectively. The emission shifted with pressure with the rate of 9.8 meV per kbar for the Sharp laser and 9.5 meV per kbar for Sanyo laser while temperature shift is about 0.45 meV per degree kelvin for both lasers.

Let us discuss the pressure dependence of threshold currents for 10 mW laser diode. This is shown in Fig. 2 for different temperatures. At room temperature I_{th} starts to increase sharply above 6 kbar while the curves at low temperatures are almost flat. In order to fit this data with formulae (8) or (9) we proceed in the following way. First we fit the pressure dependencies at fixed temperatures (with formulae (8) or (9)). In this case the term $A\exp(-\Delta E_0/kT)$ can be treated as constant C. Thus we only fit with two parameters B and C. B stayed the same for all curves i.e. indeed B is independent of temperature (and pressure). Then we plotted the parameter C as a function of $1/kT$ in a logarithmic scale and we obtained ΔE_0 and A. This is illustrated in Fig. 3 for both the diffusion and the drift approximations. We can see that $\log C$ is indeed a linear function of $1/kT$. Linearity is better in Fig. 3a. However, the parameter ΔE_0 is surprisingly large in Fig. 4a (480 meV). The drift approximation (Fig. 3b) yields $\Delta E_0 = 300$ meV which is a more reasonable value for the separation between the electronic Fermi level in the active layer and the X minima in the AlGaAs p-cladding. Thus in

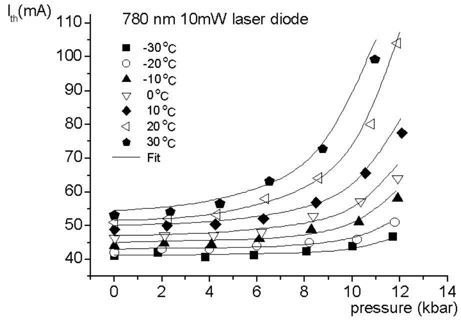

Fig. 2. Threshold currents for the 780 nm laser vs. pressure at different temperatures. Fitted lines were obtained from Eq. (9) with $\Delta E_0 = 300$ meV and A and B listed in Table.

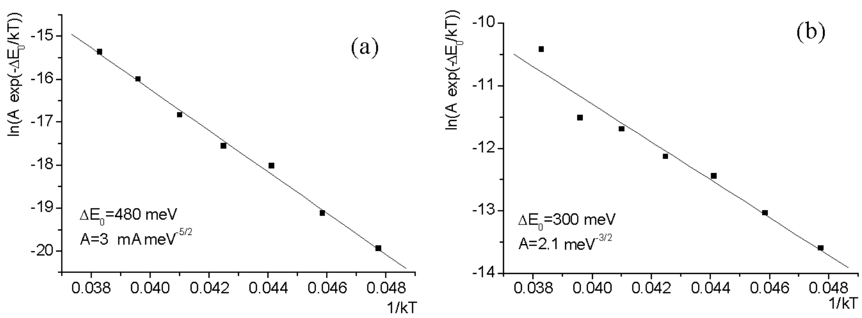

Fig. 3. Coefficient $C = A\exp(-\Delta E_0/kT)$ obtained from fitting the $I_{\text{th}}(p)$ dependencies with diffusion leakage given by Eq. (8) (a) or with drift leakage given by Eq. (9) (b).

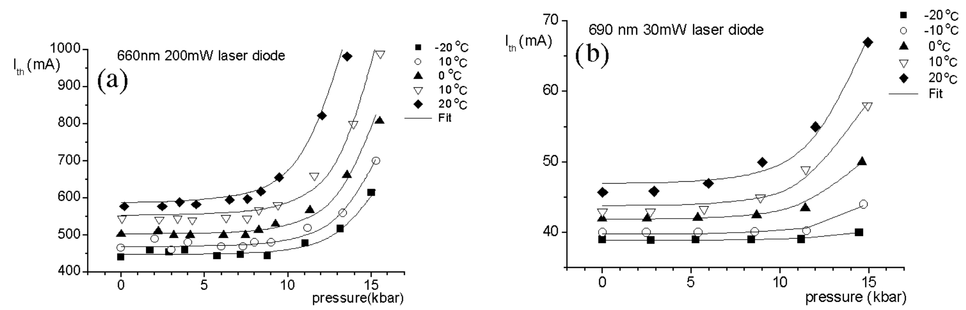

Fig. 4. Threshold currents for the 660 nm (a) and 690 nm (b) laser vs. pressure at different temperatures. Fitted lines were obtained from Eq. (9) with $\Delta E_0 = 215$ meV (a) and $\Delta E_0 = 282$ meV (b), respectively. Parameters A and B are listed in Table.

TABLE

Fitting parameters A, B, and ΔE_0 obtained from the fits to $I_{\text{th}}(p,T)$ using Eq. (10)[a].

Laser diode	A [meV$^{3/2}$]	B [mA/meV]	ΔE_0 [meV]
780 nm	2.09	2.0	300
	36.23	1.78	353
690 nm	0.46	1.78	282
660 nm	0.047	21.3	214

[a]Please note that the absolute values of A and B should not be compared for different lasers since we fitted the currents, not the current densities.

Fig. 2 we show the theoretical curves obtained from Eq. (9) with $\Delta E_0 = 300$ meV and the parameters A and B given in Table. Since in our model the pressure variation is entirely due to leakage terms, it is easy to compare the contributions from radiative and nonradiative currents to the exponentially increasing leakage currents. The latter are negligible in the pressure/temperature range when the threshold curves are flat in Fig. 2. Carrying out similar operations on 5 mW diode laser we obtained comparable results. Also in this laser we found that the parameter ΔE_0 has a more reasonable value using the drift approximation. We obtained $\Delta E_0 = 353$ meV.

4.2. InGaP/AlGaInP laser diodes

660 nm is typical wavelength for unstrained InGaP/AlGaInP structures while 690 nm is the longest commercially available wavelength from InGaP/AlGaInP diode lasers. The pressure shift is about 7.9 meV per kbar which is in agreement with the literature data for the pressure coefficient of the direct band

gap in quaternary alloys based on AlGaInP material. The temperature shifts were approximately 0.45 meV per degree kelvin. As in the previous cases, for 660 nm laser we can see sharp increase in $I_{\mathrm{th}}(p)$ at higher temperatures and slower increase at lower temperatures (Fig. 4a) whereas for 690 nm laser this increase in $I_{\mathrm{th}}(p)$ is much slower and for low temperatures (at $-20°$C) remained constant even for high pressures (Fig. 4b) . Fitting each curve with two parameters B and C and then extracting ΔE_0 and A from the logarithmic plot of C versus $1/kT$ (the same as in Fig. 3) we obtained from the fits $\Delta E_0 = 386$ meV using Eq. (8) and $\Delta E_0 = 215$ meV using Eq. (9) for 660 nm laser and $\Delta E_0 = 507$ meV using Eq. (8) and $\Delta E_0 = 282$ meV using Eq. (9) for 690 nm laser. For both lasers the lower values seem more reasonable. Therefore in Fig. 4a and Fig. 4b we show the theoretical curves obtained from Eq. (9) with $\Delta E_0 = 215$ meV and $\Delta E_0 = 282$ meV, respectively. The A and B parameters are given in Table. The fact that the drift approximation seems more likely is consistent with the conclusions of Ref. [4] where it was argued that the drift term dominates the leakage currents in red lasers because of poor p-type conductivity in AlGaInP.

5. Conclusions

The temperature and pressure variation of the threshold current for four commercial laser diodes was measured and fitted with a very simple formula taking into account the leakage to X minima in the claddings plus the radiative and nonradiative recombination. More reasonable values for the leakage barrier were obtained assuming drift rather than diffusion leakage. If indeed the drift dominates the leakage it should be possible to reduce the thresholds by increasing the

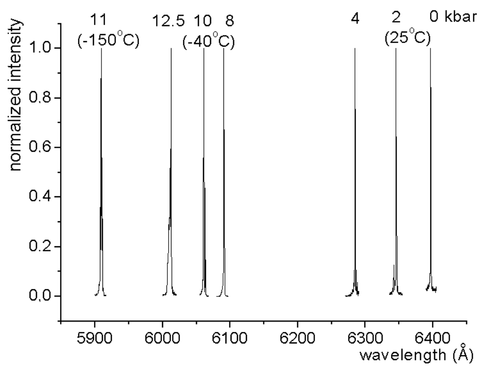

Fig. 5. Emission spectra of the 640 nm laser diode showing how we can extend the wavelength tuning range if we compensate for the pressure increase in the threshold current by lowering the temperature.

doping in the p-claddings. Our simple analysis was motivated by the fact that by controlling the pressure and temperature of the laser diodes we are able to increase the wavelength tuning range in GaAs/AlGaAs and InGaP/AlGaP devices towards shorter wavelengths. This can be illustrated in Fig. 5 where we show the spectra of the 640 nm laser diode at different pressures and temperatures. At room temperature we found the sharp increase in the threshold current with pressure so that we could not exceed 4 kbar. When we cooled the diode down to $-40°$C we were able to increase the pressure and reach 600 nm without increasing the operating current. Further cooling allowed us to reach yellow emission at 590 nm. In order to determine precisely the pressure/temperature tuning limits we have to understand the mechanisms of leakage to X minima which also determine the short-wavelength limits of AlGaAs and AlGaInP lasers.

Acknowledgments

This work was sponsored by NATO through the Science for Peace Program (grant no. 972443) and by the European Commission through the grant "Support for Centres of Excellence" No. ICA1-CT-2000-70005.

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