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Leakage current in 808 nm laser diodes analyzed using high hydrostatic pressure and temperature

Artem Bercha[1], Yurii Ivonyak[1], Mariusz Klimczak[1], Filip Dybala[1], Bernard Piechal[1], Witold A. Trzeciakowski[*,1], Elzbieta Dabrowska[2], Marian Teodorczyk[2], and Andrzej Malag[2]

[1] Institute of High Pressure Physics, Polish Academy of Sciences "UNIPRESS", Sokołowska 29/37, 01-142 Warsaw, Poland
[2] Institute of Electronic Materials Technology, Wólczyńska 133, 01-919 Warsaw, Poland

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[*] Corresponding author: e-mail wt@unipress.waw.pl, Phone: +4822 876 0346, Fax: +4822 876 0452

Threshold current in 808 nm GaAsP/AlGaAs laser diode has been measured as a function of pressure (up to 1.8 GPa) and temperature (from 80 to 300 K). The results have been analyzed in order to separate leakage current from radiative current and to determine the effective barrier for leakage and its pressure dependence. Our data indicates that both *X* and *L* minima in the barriers and in the claddings contribute to leakage.

1 Introduction Reduction of leakage currents is important for improving laser diode characteristics [1]. Leakage increases temperature sensitivity of threshold current [2]. For AlGaInP laser diodes leakage is the main obstacle for extending their operation into the orange and yellow spectral range. In our efforts of using pressure for wavelength tuning of laser diodes [3–5] leakage in short-wavelength lasers lead to increased threshold currents and limited their tuning range. For all these reasons it is important to optimize the design of heterostructures so as to increase effective barriers for leakage. In nitride lasers it is common to design electron-blocking layers. Sometimes the quantum wells can be made deeper by choosing appropriate materials for barriers or claddings, the acceptor doping profile may affect the effective barrier height for electrons. It is therefore important to develop characterization methods allowing to determine barriers for leakage. In the present paper we demonstrate such method using the 808 nm GaAsP/AlGaAs laser diode manufactured in the Institute of Electronic Materials Technology in Warsaw. Since the AlGaAs barriers and claddings may be indirect (with L or X minima coming into play) high pressure may be used to distinguish between Γ, L, and X barriers since they have very different pressure coefficients [6, 7].

2 Experimental Our samples were grown by MOVPE on GaAs:Si substrates. The active layer was a single 15 nm $GaAs_{0.88}P_{0.12}$ quantum well with $Al_{0.4}Ga_{0.6}As$ barriers and $Al_{0.7}Ga_{0.3}As$ claddings. Carbon doping was used in the *p*-cladding (concentration $7 \times 10^{17}\,cm^{-3}$) while Si-doping was used in the *n*-cladding (concentration $1 \times 10^{17}\,cm^{-3}$). The waveguide was asymmetric in order to reduce the beam divergence in the fast-axis direction. Mirror coatings reflected about 95% on the high-reflecting side and about 1% on the low-reflecting side. Threshold currents were high (above 1200 mA at ambient conditions) due to low reflectivity of the output mirror and to the large width of the stripe (180 μm). Chips were 3 mm long. They were mounted on Cu heatsinks with a clamp in order to avoid strains caused by soldering. This, however, restricted our measurements to pulsed operation of the laser diode; we used 500 ns pulses with 0.1% duty cycle.

Clamped lasers were mounted in an optical pressure cell together with a graded-index collimating lens. The cell and the details of our setup have been described in previous work [3–5, 8]. The cell was placed in an optical cryostat operating in the 80–300 K range. For each pressure (or rather for each fixed position of the piston) we measured *L*–*I*–*V* characteristics and the emission spectra as a function of temperature. Actually at lower temperatures the pressure in the cell dropped but this effect was taken into account (*i.e.*, pressure was determined at each temperature using the InSb pressure gauge).

3 Results Room temperature variation of threshold currents with pressure is shown in Fig. 1 for three different laser diodes. The sample studied in the present paper is represented by the red circles. For comparison, we also show the (normalized) threshold current for the 645 nm GaInP/AlGaInP laser and for the 808 nm GaAs/AlGaInP commercial laser. For shallow quantum wells typical for red lasers leakage increases rapidly with pressure [5]. The 808 nm sample with AlGaInP barriers shows a very small increase of threshold current with pressure. This demonstrates that for a given emission wavelength it is possible to reduce leakage by the proper design of the heterostructure.

In Fig. 2 we present the schematic conduction-band diagram for a separate-confinement heterostructure showing the Γ, *L*, and *X* band edges. We neglect hole leakage since it is believed to be negligible due to large hole masses and low mobilities. The band diagram is significantly modified by space charge effects due to doping and due to high concentration of electrons and holes in the quantum well. Therefore the barriers for leakage (the distance from the quasi-Fermi level in the well to the band-edge in the barrier or cladding) are not easy to calculate. Moreover, there are several barriers for leakage into *X* and *L* minima in the barriers and in the claddings so we can speak of some effective barrier for leakage representing the average of multiple recombination channels. In the present paper we do not attempt to develop theoretical description of *I*–*V* characteristics of laser diodes but we discuss a simple experimental method for the determination of effective barriers for leakage.

The direct bandgap at the Γ point increases with pressure about 10 meV kbar^{-1}. The indirect Γ–*X* bandgap decreases with pressure about 1 meV kbar^{-1}. The indirect Γ–*L* bandgap increases with the rate of about 5 meV kbar^{-1}. We assume that these pressure rates are the same in the well, in the barrier and in the cladding. This means that the Γ–Γ barriers will remain unchanged under pressure, the Γ–*X* barriers will decrease about 11 meV kbar^{-1} and the Γ–*L* barriers will decrease 5 meV kbar^{-1}. Therefore, pressure measurements should help identify the main channels for leakage.

The pressure dependence of threshold currents at different temperatures is shown in Fig. 3. We can see an exponential increase at higher temperatures (typical for leakage) and moderate increase at lower temperatures

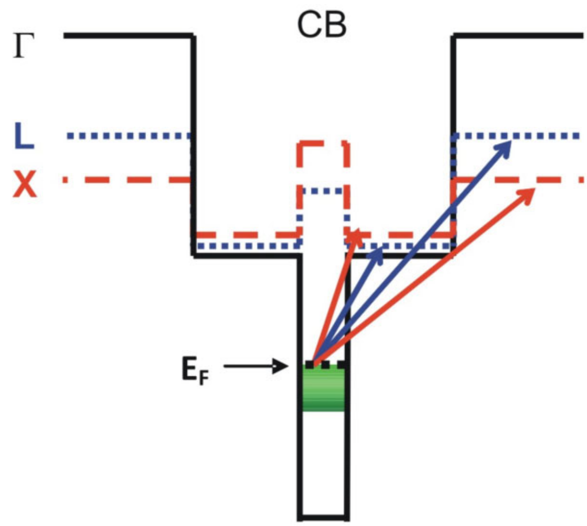

Figure 2 Schematic conduction-band profile for a GaAsP/AlGaAs separate-confinement heterostructure. Band edges are shown for the Γ, *L*, and *X* minima. Please note that the waveguide and cladding is often indirect. Each band-edge moves with a different pressure coefficient which makes pressure a valuable tool in distinguishing between them.

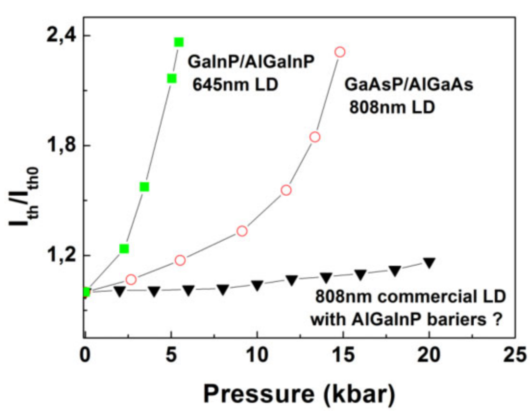

Figure 1 Room temperature variation of threshold currents with pressure for three different laser diodes: GaInP/AlGaInP structure showing a rapid increase of leakage, 808 nm sample studied in this paper with moderate increase of leakage, 808 nm diode with AlGaInP barriers characterized by small increase of leakage.

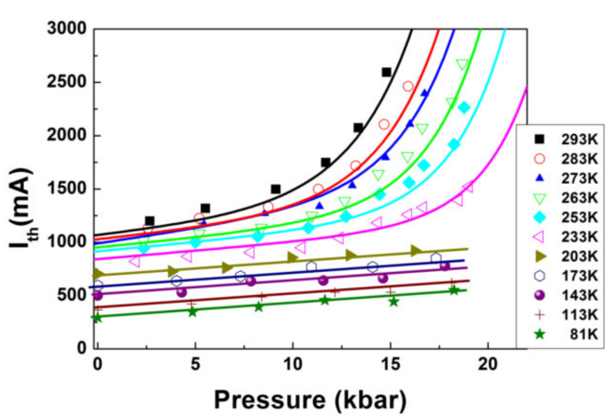

Figure 3 Threshold currents for the 808 nm GaAsP/AlGaAs laser diode as a function of pressure for different temperatures. Theoretical curves are described in the text.

(where leakage should be negligible). The theoretical curves will be explained in the next section.

4 Analysis of results Threshold current may contain contributions from different recombination channels

$$I_{\mathrm{th}} = I_{\mathrm{nr}} + I_{\mathrm{rad}} + I_{\mathrm{Auger}} + I_{\mathrm{leakage}}, \tag{1}$$

where the Auger recombination I_{Auger} should be negligible in 808 nm lasers [9, 10]. The nonradiative recombination I_{nr} should also be negligible for a high quality material.

This leaves us with radiative recombination I_{rad} and with I_{leakage}. The radiative current dominates at low temperatures and it is usually proportional to kT,

$$I_{\mathrm{rad}}(p, T) = B(p) \times kT. \tag{2}$$

The ambient-pressure value of B is obtained from the low-temperature part of $I_{\mathrm{th}}(T)$, as shown in Fig. 4. This figure shows how we can separate the radiative current from the total current. The remainder is due to leakage.

With increasing pressure $B(p)$ may increase, decrease or remain constant for the following reasons: The transparency current for quantum-well lasers is proportional to E_g^2, as shown in Ref. [11]. This should lead to increase of I_{rad} with pressure. However, the confinement factor Γ multiplying the material gain G in the threshold equation:

$$\Gamma G = \alpha_{\mathrm{opt}} + (1/2L) \cdot \log(1/R_1R_2), \tag{3}$$

increases with pressure because the extension of the optical mode decreases with decreasing wavelength (α_{opt} represents the optical losses). This should lead to a decrease in I_{rad}. Finally, the mirror reflectivities R_1 and R_2 may increase or decrease with pressure, depending on the dielectric mirror coatings. Therefore, in our phenomenological approach we approximate the pressure variation of radiative current with a linear dependence, taken from the low-temperature $I_{\mathrm{th}}(p)$ dependence (as shown in Fig. 3). The radiative current is taken in the form:

$$I_{\mathrm{rad}}(p, T) = B_0(1 + \beta p) \times kT, \tag{4}$$

where β is obtained from the data in Fig. 3 for temperatures below 200 K. At higher temperatures leakage comes into play. We assume diffusion leakage (which should be dominant for high doping concentration in the p-cladding) of the form [12]:

$$I_{\mathrm{leakage}} = A(kT)^{3/2}\exp[(\alpha p - \Delta E)/kT], \tag{5}$$

where A is a constant (depending on the band-edge masses), ΔE the effective barrier for leakage at ambient pressure, and α is the pressure coefficient of this barrier. A possible linear temperature dependence of ΔE could be introduced into A. The total threshold current is a sum of (4) and (5).

Having determined the B_0 and β from low temperature data we can subtract Eq. (4) from the total threshold current and fit the pressure variation of the leakage current in the form

$$I_{\mathrm{leakage}} = C(kT)^{3/2} \times \exp(\alpha p/kT), \tag{6}$$

where

$$C = A\exp(-\Delta E/kT). \tag{6a}$$

In such way we only fit two parameters for each experimental curve: $C(T)$ and α. The best agreement (shown in Fig. 3) was obtained for $\alpha = 8$ meV kbar^{-1}. Then we fit the $C(T)$ plotted in a logarithmic scale in Fig. 5 as a function of $1/kT$. The slope yields ΔE and the intersection with ordinate yields A. The linearity of the points is rather good which supports our simple model. We obtained $\Delta E = 380$ meV. Under the pressure of 20 kbar this barrier would be reduced to 220 meV.

5 Summary and conclusions The effective barrier obtained from our procedure is much greater than in red InGaP/AlGaInP lasers [5] which is also evident in Fig. 1. The

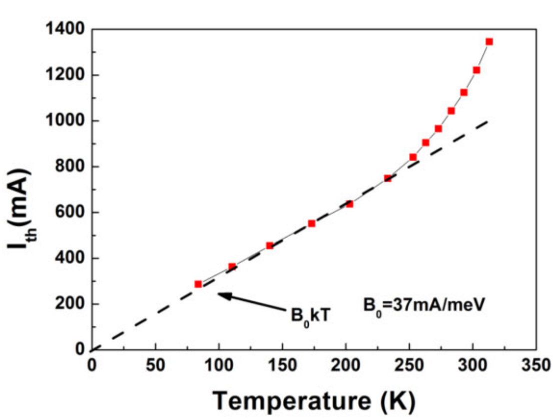

Figure 4 Temperature dependence of threshold current. The linear part is treated as radiative contribution, the rest is due to leakage.

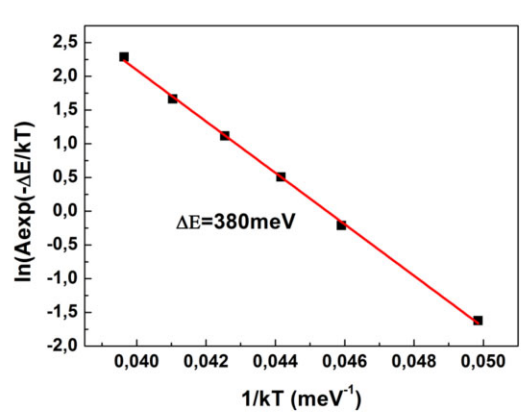

Figure 5 Plot of the temperature-dependent parameter ln$C$ as a function of $1/kT$. The slope determined the value of $\Delta E = 380$ meV.

average pressure coefficient is between the value for Γ–L separation (5 meV kbar^{-1}) and the value for Γ–X separation (11 meV kbar^{-1}). This means that both L and X minima in the barriers and in the claddings contribute to leakage.

We hope that pressure/temperature measurements will help characterize leakage in laser diodes and optimize the design of short wavelength AlGaAs and AlGaInP lasers.

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