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# Threshold current temperature dependence of GaInP/$(Al_yGa_{1-y})InP$ 670 nm quantum well lasers

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The temperature dependence of threshold current of $(Al_yGa_{1-y})InP$/GaInP quantum well lasers ($y=0.3$, 0.4, and 0.5) has been investigated and used to characterize thermally activated loss mechanisms above room temperature. We show good agreement between activation energies measured by Arrhenius analysis and those expected for the loss of electrons from the well to the $X$-conduction band minima in the barrier. Our analysis uses measured band gaps of the actual structures, avoiding assumptions about the alloy compositions, spontaneous emission data to subtract radiative and other direct gap processes, and recent band gap data for this alloy system. This provides convincing experimental confirmation of the loss of electrons from the indirect minima as the preferred process causing the rise in current at high temperature in these lasers. © *1995 American Institute of Physics.*

In this letter we describe investigations of the temperature dependence of the threshold current of 670 nm GaInP/AlGaInP quantum well lasers between 200 and 400 K. Below about 300 K we see a linear temperature dependence due to recombination within the quantum well, while at higher temperatures an exponential increase sets in. Using spontaneous emission measurements we show that recombination from the Γ conduction band of the barrier/waveguide material does not account for the observed current behavior and that this exponential rise is chiefly due to carrier loss via $X$-conduction band minima. Our measured activation energies are in excellent agreement with recent new data for the band gaps of this alloy system and provide the strongest direct experimental evidence thus far for carrier loss by this mechanism.

We have studied devices with different aluminum contents in the $(Al_yGa_{1-y})InP$ waveguide/barrier region ($y=0.3$, 0.4, and 0.5) of a separate confinement structure comprising two 68 Å wide, compressively strained, $Ga_{0.41}In_{0.59}P$ quantum wells separated by a 250 Å wide barrier, all set in a waveguide of $(Al_yGa_{1-y})_{0.51}In_{0.49}P$, of total width approximately 2200 Å. This was clad with 1 μm wide layers of $(Al_{0.7}Ga_{0.3})_{0.51}In_{0.49}P$, doped to $5\times10^{17}$ cm$^{-3}$ using zinc on the $p$ side and $1\times10^{18}$ cm$^{-3}$ with silicon on the $n$ side. The temperature dependence of threshold current ($I_{th}$) measured pulsed on oxide isolated 50 μm wide stripe geometry lasers between 200 and 400 K, shown in Fig. 1, exhibits linear behavior below about 270 K with an exponential increase setting in at higher temperatures. The devices with $y=0.3$ barriers have the weakest temperature dependence of threshold current, despite their low-gap barrier,and have a value of $T_0$ (measured between 20 to 70 °C) of 144 K for the 450 μm long device.

We have observed spontaneous emission spectra through a narrow (≈4 μm) window etched through the top metallization (AuZn) and the 0.5 μm thick $p$-GaAs contact layer,[1] recorded at threshold injection between 280 and 400 K at 20 K intervals and with a fixed collection geometry. By this means we can determine the relative recombination rates per unit area in the well and barrier. In Fig. 2 we have plotted as a function of temperature the area under each spectrum due to emission in the well (in arbitrary units). The figure shows that the spontaneous recombination rate in the well at threshold increases approximately linearly with temperature as expected for the constant density of states of one pair of subbands in a quantum well. We have also plotted the area under each spectrum for photon energies associated with emission from the "bulk" barrier material and this contribution increases approximately exponentially with temperature. An Arrhenius plot of these latter data in the form [emission rate]/$T^{3/2}$ versus $1/T$ gives an activation energy of 198±25 meV from a least-squares fit and this should correspond to the difference between the barrier band gap and the quasi-Fermi level separation ($E_b-\Delta E_f$). This quantity is temperature dependent and it is straightforward to show that the measured activation energy is the linear extrapolation of ($E_b-\Delta E_f$) over the range of measurement to $T=0$. At $T=0$ the quasi-Fermi levels move to the edges of the $n=1$ subbands and, since $\Delta E_f$ moves approximately linearly with respect to the band edges as $T$ increases and providing the temperature dependence of well and barrier band gaps are the same, then we can identify the measured activation energy with ($E_b-E_{well}$), where $E_{well}$ is the energy of the $e1$-hh1 transition. Photovoltage absorption spectroscopy (PVS)[2] performed on this material at room temperature showed three distinct absorption peaks which can be assigned to the $e1$-hh1, $e1$-lh1, and $e2$-hh2 excitonic transitions within the quantum well. We determined the ($e1$-hh1) transition to be 1.856 eV±2.8 meV and similarly measured the direct band gap energy of the $(Al_{0.3}Ga_{0.7})_{0.51}In_{0.49}P$ barrier to be $E_b=2.081$ eV±3.5 meV. Taking the exciton binding energy to be about 15 meV,[3] we obtain $E_b-E_{well}=210$ meV±6.3 meV, which is in good agreement with the measured activation energy of 198 meV±25 meV for radiative barrier emission.

The measured threshold current (Fig. 1) shows an exponential increase at high temperatures which we ascribe to the leakage of carriers from the quantum well. An Arrhenius

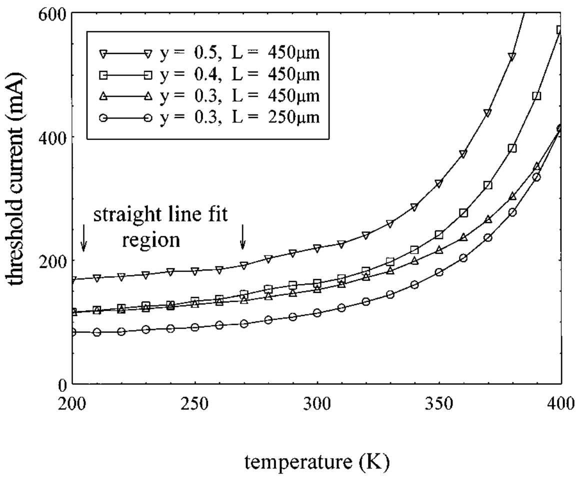


FIG. 1. Threshold currents measured pulsed as a function of temperature for 670 nm devices with $y=0.3$ (250 and 450 $\mu$m long), 0.4 (450 $\mu$m long), and 0.5 (450 $\mu$m long).

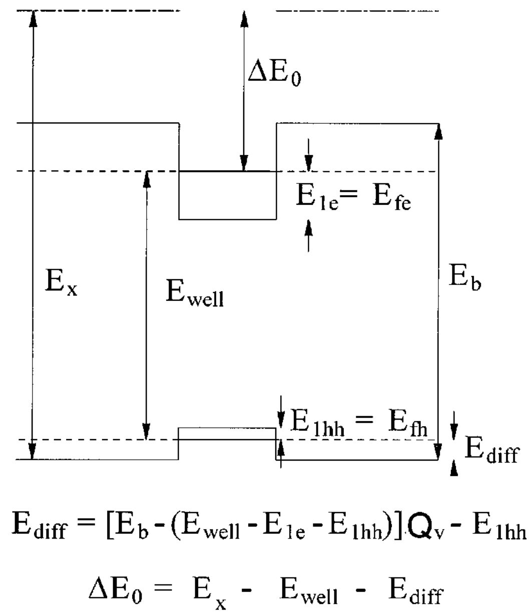


FIG. 3. Energy band diagram of the quantum well and waveguide/barrier region to illustrate the calculation of the predicted activation energy.

analysis of this excess current, obtained by subtracting a linear extrapolation of $I_{th}$ between 200 and 270 K to higher temperatures, gives activation energies between 300 and 400 meV as we move from $y=0.3$ to 0.4 to 0.5. Since the activation energy for the total current is significantly greater than that for the observed radiative processes in the barrier we conclude that there are important current contributions from nonradiative processes having higher activation energy. An obvious process is the loss of carriers from the $X$ minima of the barrier or cladding layers.

To determine the activation energy of this process we have subtracted from the threshold current the current associated with recombination in the well and the direct gap of the barrier by scaling the total spontaneous emission rate as a function of temperature, measured in arbitrary units, to the measured threshold current in the linear region below about 270 K, the difference between this and the measured current at higher temperatures being the excess nonradiative current. The scaling factor represents the internal efficiency and a calibration factor and in effect we have assumed that the wells and barrier have the same internal efficiency. While this is not easy to justify, we find that the activation energy derived below is insensitive to uncertainties in the scaling factor. The excess current was obtained in this way for those samples for which spontaneous emission data could be measured, and we determined activation energies of 333±13 meV ($y=0.3$;250 $\mu$m long), 316±24 meV ($y=0.3$; 450 $\mu$m) and 320±18 meV ($y=0.4$;450 $\mu$m) over the range 300–400 K.

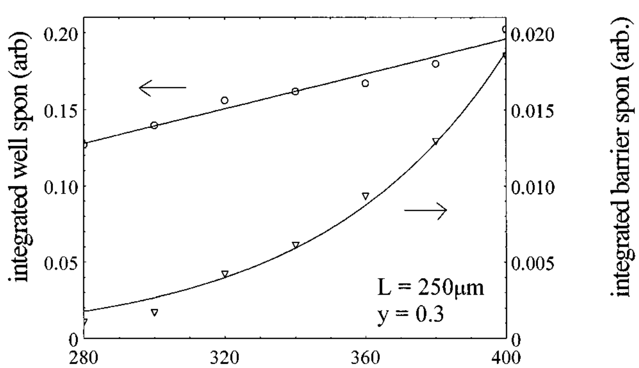


FIG. 2. Spectrally integrated spontaneous emission rates corresponding to the quantum well and barrier/waveguide regions as functions of temperature in the same arbitrary units for the structure with $y=0.3$. Similar data have been obtained for other structures.

The band gap of the indirect $X$ minimum in (AlGa)InP has a very weak dependence on aluminum composition[4] and has a value of 2.25 eV at room temperature (subtracting 80 meV from the 4 K value of Ref. 4). Nonradiative processes are usually controlled by the concentration of one carrier type, and following previous studies of AlGaAs lasers[5] we assume these to be electrons. The activation energy of the electron density is the linear extrapolation of the separation between the electron quasi-Fermi level and the $X$-conduction band edge to $T=0$ and this is given by the energy separation of the lowest electron confined state in the well to the $X$ minimum. With reference to Fig. 3 we see that this is

$$\Delta E_0 = E_x - \{(E_b - E_{\rm well} - E_{1e} - E_{1\rm hh})] \times Q_v - E_{1\ \rm hh}\} - E_{\rm well}, \quad (1)$$

where $E_x$ is the indirect barrier band gap (=2.25 eV, Ref. 4), $E_{1e}$ and $E_{1\ \rm hh}$ are the lowest confined electron and hole states relative to the bottom of the conduction and valence quantum wells, respectively, and $Q_v$ the valence band offset ratio [0.30 (Ref. 6)]. $E_{1e}$ and $E_{1\ \rm hh}$ are found using a simple envelope function calculation with effective electron and hole masses for well and barrier of $m_e=0.0993$, $m_{\rm hh}=0.4513$ and $m_e=0.1186$, $m_{\rm hh}=0.4489\times m_0$, respectively[7] and where the effects of strain have been implemented as described in Ref. 6, leading to values of $E_{1e}=37$ meV and $E_{1\rm hh}=12$ meV. These values are consistent with the PVS measurements. We used our experimental values of the direct barrier band gap ($E_b$) and the transition energy ($E_{well}$) as determined from PVS spectra, corrected for the exciton binding energy. From Eq. (1) we obtain a predicted activation energy of 339 meV ($y=0.3$) and 322 meV ($y=0.4$) for processes involving electrons in the $X$ minimum. This agrees within experimental error with the activation energies determined above. Previous attempts to correlate the high temperature current with band gap data [for example, Refs. 8 and 9] have not been particularly satisfactory, leaving a lack of experimental confirmation of the precise mechanisms involved.

Convincing correspondence has been obtained between the high-temperature activation energy of the threshold current and the energy band diagram. This is due to the use of measured (PVS) band gaps of the actual structures, avoiding assumptions about the alloy compositions, the use of spontaneous emission data to subtract radiative and other direct gap processes, and the use of recent band gap data for this alloy system. The analysis presented here provides the strongest direct experimental evidence thus far for loss of carriers from the indirect minimum being responsible for the excess thermally activated threshold current in these devices. Since the indirect gap is only weakly dependent on composition we are not able to distinguish between recombination in the barrier and recombination or drift in the $p$-type cladding layer, though other work suggests that the most likely route for carrier loss is the cladding layer.[9]

In summary, we have measured the threshold current of 670 nm $Ga_{0.41}In_{0.59}P/(Al_yGa_{1-y})_{0.51}In_{0.49}P$ lasers for temperatures between 200 to 400 K. An Arrhenius analysis of the spontaneous emission from the barrier gives an activation energy of 198±25 meV which is in excellent agreement with the value predicted for band-to-band recombination across the $\Gamma$ gap of the barrier/waveguide. We have determined an activation energy in the region of 320 meV for the excess high-temperature current and this agrees well with that predicted for loss of electrons from the $X$ minimum, providing direct experimental evidence for large contribution of these carriers to the high-temperature threshold current of these devices.

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