Origin of the High Temperature Performance Degradation of 1.5µm InGaAs(P)/InP Quantum Well Lasers

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Abstract

High temperature degradation of the efficiency of 1.5µm InGaAs(P) lasers is shown to be due to strong coupling between Auger recombination and internal absorption. This is explained using a simple analytical model.

Summary

Semiconductor lasers in the 1400-1600nm band are key components of telecommunications systems where they may be used as signal or pump sources. InGaAs(P)/InP is the traditional alloy used for the production of devices at these wavelengths, however, due to the strong temperature dependence of the threshold current (Ith) in these devices there is currently much activity in searching for an alternative, more thermally stable material. This will eliminate the requirement for thermoelectric cooling and lead to a significant component cost reduction. Most practical applications require stable operation over the temperature range, -20°C to +80°C. To assist in the development of thermally stable materials requires a detailed understanding of the thermal factors influencing device performance over this range. It has previously been demonstrated that the strong increase in threshold current observed for 1.5µm InGaAs(P)/InP lasers is due to non-radiative Auger recombination such that at room temperature it accounts for ~80% Ith with the remaining 20% Ith due to radiative recombination.

Using a combination of Auger- (IAug) and radiative-recombination (Irad) currents, one can obtain good agreement with the measured Ith from low temperatures up to room temperature (Figure 1a). However, for further increases in temperature it is clear that this model begins to fail and severely underestimate Ith. This is particularly evident from an equivalent plot of the characteristic temperature, Tc (figure 1b) where Tc is defined as 1/Ith=d(Ith)/dT. In the simple model, it is assumed that the threshold carrier density, nth is equal to the transparency carrier density, nT. Under the Boltzmann approximation, Ith=bn and IAug=cn where n is the carrier density, b is the bimolecular recombination coefficient and c is the Auger coefficient. For a quantum well, at transparency, nT(kT)−1, where T is the absolute temperature. In addition we can write that B=CT where C is the Auger coefficient. Consequently, at transparency, we derive expressions for the temperature dependencies of each current path as Tc(IAug)=T and Tc(Ith)=T/(1+Fe/kT)[1]. Up to room temperature these expressions agree well with experiment. However they fail to predict the decrease in Tc observed above room temperature since both Tc(IAug) and Tc(Ith) continue to increase with increasing temperature.

Figure 1. Simple transparency model fit to (a) Ith and (b) Tc for a 1.5µm InGaAs(P) device. Above 300K, the simple model underestimates Ith and hence overestimates Tc.
In Figure 2 we plot the temperature variation of the internal absorption, $\alpha_i$, measured for the same devices as determined from the slope of the inverse differential efficiency versus cavity length. Over the temperature range 300-360K $\alpha_i$ increases from 10cm$^{-1}$ to $\sim$20cm$^{-1}$ due to increasing inter-valence band absorption$^3$. This manifests itself as both a decrease in the differential efficiency and a further increase in $I_{th}$ (and hence a decrease in $T_o$). One can quantify the effect of $\alpha$ on $I_{th}$ and $T_o$ as follows. For a quantum well$^4$, assuming that the gain varies logarithmically with $n$, one can write that $n_m=n_0\exp(g_m/g_o)$ where $g_m$ is the threshold material gain and $g_o$ is the gain coefficient. $g_m=(\alpha_t+\alpha_m)/\Gamma$ where $\alpha_m$ is the mirror loss and $\Gamma$ is the optical confinement factor. At threshold we can write that

$$I_{th}=Bn_0^2\exp\left(\frac{2}{g_m}\right)\left(\alpha_t+\alpha_m\right)$$

and

$$I_{sat}=Cn_0^2\exp\left(\frac{3}{g_m}\right)\left(\alpha_t+\alpha_m\right).$$

Assuming that $\alpha_m$ and $g_o$ are approximately temperature insensitive and substituting our previously defined temperature variations of $B$, $C$ and $n_0$, gives

$$T_o(I_{th})=\frac{T}{1+2\frac{d\alpha_i}{\Gamma g_o}dT}$$

and

$$T_o(I_{sat})=\frac{T}{3+E_\alpha+\frac{3T}{kT}\frac{d\alpha_i}{\Gamma g_o}dT}$$

where $d\alpha/dT$ is the temperature dependence of $\alpha_i$. Note that if $d\alpha/dT=0$, these expressions reduce to the simple form as discussed earlier. It is clear from these expressions how the increase in $\alpha_i$ with temperature couples strongly into the radiative, and in particular, the Auger recombination current$^3$.

From measurements of $I_{th}$ versus cavity length we deduce that $g_m=4500$ cm$^{-1}$ over this temperature range. Furthermore from ref. 2, $E_\alpha=62$ meV and using a simple effective index model we calculate $\Gamma=0.016$ for this structure. Using these parameters together with the measured $\alpha_i(T)$, Figure 3 shows the measured $I_{th}$ and $T_o$ (circles) together with the calculated $I_{th}(T)$ and $T_o(T)$ which includes the effect of temperature dependent absorption (solid line). For comparison, the dotted lines show the calculated $I_{th}$ and $T_o$ without including absorption. These data clearly show that temperature dependent absorption coupled with Auger recombination explains the dramatic fall off in $T_o$ above room temperature and can readily be explained with a simple analytical model. These results highlight the extent to which Auger recombination degrades the performance of 1.5$\mu$m InGaAs(P) lasers and emphasises the importance of minimising absorptive losses in lasers operating in the Auger regime.

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