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TEMPERATURE DEPENDENCE OF DIFFERENTIAL GAIN CONSTANT
AND CARRIER DENSITY AT TRANSPARENCY FOR InGaAsP/InP
SEMICONDUCTOR LASER DIODES

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One of the most important parameters for the active layer of a laser
diode is the differential gain constant $g_0 (cm^2/sec)$ and the transparency
carrier density $N_T (cm^{-2})$ at which the peak-gain coefficient $g=0$. The
particular composition In$_{0.72}$Ga$_{0.28}$As$_{0.6}$P$_{0.4}$ of undoped active layer
which lattice matches InP, is chosen because its bandgap ($E_g = 0.96$ eV
at $\lambda = 1.3 \mu m$) is at a region of low-loss and minimum dispersion in
optical fibers[1]. Based on the parabolic model of the peak-gain
which relates the peak-gain coefficient, $g$, of the laser diode to the
injected carrier density $N$[2], one can calculate the parameters $g_0$. 
and $N_T$ at different temperatures for undoped InGaAsP active layer.

The dependence of the laser diode peak-gain coefficient, $g$, of an undoped quaternary InGaAsP material with injected carrier density $N$ at 1.3 $\mu$m band wavelength can be well approximated by a parabolic model of the form [2]

$$g = aN^2 + bN + \gamma,$$  \hspace{1cm} (1)

where $N$ is the injected carrier density and $a$, $b$, and $\gamma$ are the gain parameters and are functions of temperature, band wavelength and doping of the active layer. The solid curve in Fig.1 shows the superlinear relationship between the gain $g$ and the injected carrier density $N$ neglecting the low gain region. The commonly used linear approximation model is of the form [2]

$$g = A(N - N_T),$$  \hspace{1cm} (2)

where $A ( = dg/dN)$ is the gain constant (cm$^2$) and $N_T$ is the transparency value of carrier density illustrated by broken lines in Fig.1.

Neglecting the low gain region, we can fit Eq.(2) with Eq.(1) to get the constants $A$ and $N_T$ in terms of $a$, $b$, and $\gamma$. We can express the relationship between the differential gain constant $g_o$ and the constant $A$ in the following form

$$g_o = vA,$$  \hspace{1cm} (3)
where \( v \) is the speed of light in the active medium that is defined as

\[
v = \frac{c}{n_r},
\]

(4)

with \( c \) the light speed in vacuum and \( n_r \) the refractive index of the active medium given by \( \text{[2]} \)

\[
n_r = 3.4 + 0.256 y - 0.095 y'^2,
\]

(5)

with \( y (=0.6) \) the As composition in the active layer. The dependence of peak gain coefficient on injected carrier density at different temperatures ranging from \(-10^\circ\text{C}\) to \(50^\circ\text{C}\) is illustrated in Fig. 2 for undoped InGaAsP material at a wavelength \( \lambda = 1.3\mu\text{m} \).

Based on the data given in Ref. [2] and using a curve fitting computer program, we have obtained general forms for the temperature dependence of the three parameters \( \alpha \), \( \beta \) and \( \gamma \) as

\[
\alpha = 4.29467 \times 10^{-29} \exp \left(-0.00329828 T\right),
\]

(6)

\[
\beta = -7.75887 \times 10^{-16} \exp \left(0.002097630 T\right),
\]

(7)

\[
\gamma = 347.373 \exp \left(0.00761227 T\right).
\]

(8)

Using these forms in Eq. (1), one can get the temperature dependence of the peak gain coefficient \( g \). Then using again the curve fitting computer program to approximate the gain \( g \) to a linear dependence on the injected carrier density \( N \), as given in Eq. (2), one can get \( N_T \) the carrier density at transparency and the constant \( A \) as functions
of temperature. The transparency carrier density $N_T$ has been obtained as

\begin{align}
N_T &= 10^{18} \times \left( 1.47369 + 0.00212129 T + 8.43604 \times 10^{-6} T^2 \\
&\quad + 5.97474 \times 10^{-8} T^3 + 1.74918 \times 10^{-10} T^4 \right). \tag{9}
\end{align}

From the obtained relation for the constant $A$, and using Eqs. 3 - 5, we have obtained the differential gain constant, $g_\omega$, as a function of temperature in the form

\begin{align}
g_\omega &= (8.93472 - 0.0651316 T + 6.43553 \times 10^{-5} T^2 \\
&\quad + 1.00126 \times 10^{-7} T^3 + 1.05953 \times 10^{-9} T^4) \times 10^{-6}. \tag{10}
\end{align}

Figures 3(a, b and c) show the variations of parameters $\alpha, \beta$ and $\gamma$ with temperature ranging from $-200^\circ C$ up to $150^\circ C$.

Figure 4 displays the variation of both the differential gain constant $g_\omega$ and the carrier density of transparency $N_T$ with temperature. The results obtained have a good agreement with the experimental one [3] and show that the differential gain constant, Fig.4, increases with cooling the laser in consistence with that reported in Ref.4.

References

Fig. 1. Variation of peak-gain coefficient with injected carrier density for undoped 1.3 μm band wavelength semiconductor laser diode.

Fig. 2. Variation of peak-gain coefficient with injected carrier density in an undoped InGaAsP quaternary alloy at different temperatures.
Fig. 3-a. Variation of the parameter $\alpha$ with temperature.

Fig. 3-b. Variation of the parameter $\beta$ with temperature.

The parameter $\beta$ (cm$^2$ s$^{-1}$ x $10^{-14}$)
Fig. 3-c. Variation of the parameter $\gamma$ with temperature.

Fig. 4. Variation of the differential gain constant $g_*$ and the carrier density of transparency $N_t$ with temperature.