The Physics Controlling the Sensitivity of Semiconductor Lasers to High Temperatures

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The temperature dependence of the gain and loss processes in uncooled 1.3 μm and 1.55 μm quantum-well and quantum-dot lasers are discussed and the performance of various materials combinations and structures are compared and contrasted.

Temperature stable, cheap, semiconductor lasers working in the wavelength range from about 1.3 μm to 1.6 μm would be ideal light sources for optical fibre communications. Unfortunately their threshold current density, J_{th} , tends to increase quickly and their quantum differential efficiency decreases above room temperature (RT). Here we discuss the fundamental causes of this behaviour and its possible reduction by improved device structure and materials combinations.

We can characterize the rate of increase of J_{th} at any temperature by $d(\ln J_{\text{th}})/dT = 1/T_0$ (1). Thus J_{th} would increase by a factor “e” over the temperature interval T_0 . A simple model for an ideal quantum-well laser predicts that the threshold current density due to radiative transitions alone may be written as $J_{\text{rad}} = Bn_{\text{th}}^2$ where $B = B_0/T$ and the carrier concentration at threshold $n_{\text{th}} = n_0 T$. Hence $J_{\text{rad}} \propto T$ and $T_0 = T$ [1]. Thus we would expect T_0 to be about 300K at RT and to increase at higher temperatures. Studies of J_{rad} in 1.3 μm and 1.55 μm GaInAsP/InP compressively strained quantum well lasers show this holds remarkably well, probably because the distribution of holes in the valence band remains non-degenerate. Fig. 1 shows the measured variation of the integrated light intensity, L , collected from a small window milled in the substrate electrode of a 1.5 μm GaInAsP/InP laser. At currents above threshold n_{th} is kept pinned by the lasing process resulting in a constant value of $L = L_{\text{th}}$ which is proportional to J_{rad} .

Figure 1 Determination of T_0 and $T_0(J_{\text{rad}})$ for a 1.5 μm laser.

L_{th} does indeed have a characteristic temperature $T_0(J_{\text{rad}}) \approx T$, however the variation of J_{th} , indicated by the vertical lines is closer to a $T_0(J_{\text{th}}) = T/5$ indicating an additional strongly temperature sensitive non-radiative recombination process.

Fig 2 shows that at low temperatures J_{th} for a 1.3 μm and 1.5 μm lasers behaves ideally and increases linearly. For clarity J_{th} for the devices is shown normalised at low temperatures, although high pressure measurements have shown that $J_{\text{th}} \propto E_g^2$ so J_{th} for the 1.5 μm device is actually lowest at low temperature. The dashed curve is normalised variation of J_{rad} . J_{th} for the 1.5 μm device starts to increase super-linearly at about 150K and J_{th} is about $5 \times J_{\text{rad}}$ at 300K indicating that non-radiative recombination constitutes about 80% of J_{th} near RT. For the 1.3 μm device the corresponding values are 200K with J_{th} about

Figure 2 Temperature dependence of J_{th} for a 1.3μm and 1.5μm laser together with J_{rad} (dashed line).

$2 \times J_{rad}$ at 300K. Thus the non-radiative recombination process decreases swiftly with increasing E_g . Also, writing $J \sim n^Z$, since $L = Bn^2$, a plot of $\ln(J)$ vs $\ln(L^{1/2})$ has a gradient of Z . Figure 3, shows that the measured values of Z at threshold are close to 2 at low temperatures but increase to $Z \approx 3$ where the non-radiative transitions dominate, indicating the presence of Auger recombination which involves three carriers and results in a current $J_{Aug} = Cn^3$.

If Auger recombination dominates we may write $J_{th} = Cn_{th}^3 = C(n_0 T)^3$ and equation (1)

Figure 3 Temperature dependence of Z -parameter for a 1.3μm and 1.5μm laser.

yields $T_0 = T/3$ or $T_0 \approx 100K$ at RT. If the Auger process has a thermal activation energy E_a then T_0 is reduced further to $T_0 = T/(3 + E_a/kT)$ so this and/or a degree of inter-valence band absorption would explain very well the measured value of T_0 . More evidence is obtained from the decrease of J_{th} [1] with increasing hydrostatic pressure shown in Figure 4. This is fit best by assuming a CHSH Auger process, which involves the excitation of a hot hole and so $J_{Aug} = Cn_{th}p_{th}^2$.

Figure 4 Photon energy dependence of J_{th} over the wavelength range 1.3-1.6μm showing the characteristic decrease associated with Auger recombination.

Armed with this information the following steps may be taken to reduce J_{th} and its temperature sensitivity.

- (1) Since $J_{Aug} = Cn_{th}^3$ and $J_{rad} = Bn_{th}^2$ it is clearly advantageous to reduce n_{th} . Previous work has shown the influence on J_{th} of varying the number of wells in GaInAsP lasers at RT [2]. The number at which J_{th} is a minimum will increase with increasing temperature and so can be chosen for the temperature range of importance.
- 2) Introduce compressive or tensile strain in the wells as discussed in detail elsewhere [3].
- 3) Change the relative conduction and valence band offsets. Figure 6 shows qualitatively the band alignment of single InGaAsP/InP, InGaAlAs/InP and InGaAsN/GaAs quantum wells before current

Figure 5 Schematic band alignments (at zero bias) for InGaAs/InP, InGaAlAs/InP and InGaAsN/GaAs 1.3 μm lasers.

injection. The faster thermal excitation of the carrier type with the smallest confinement will cause the build up of an electrostatic field until the rate of escape of electrons and holes are equal and governed by the sum of the confinement energies. This tends to increase the radiative current density but may decrease the Auger current of the form $J_{\text{Aug}} = C n_{\text{th}} p_{\text{th}}^2$. In GaInAsP/InP $n_{\text{th}} < p_{\text{th}}$ and J_{Aug} is increased. In GaAlInAs/InP n_{th} remains $= p_{\text{th}}$ and J_{Aug} remains unaltered. This explains the observed lower temperature sensitivity of InGaAlAs/InP devices compared with InGaAs(P)/InP devices, as shown in Figure 6 for lasers emitting at 1.5 μm .

Figure 6 Temperature dependence of J_{th} for a 1.5 μm InGaAs and InGaAlAs laser.

In GaInAsN/GaAs $n_{\text{th}} > p_{\text{th}}$ and J_{Aug} and J_{th} is expected to be reduced. Unfortunately, in the GaInAsN/GaAs material presently available, J_{th} is dominated by recombination through defects [4] and its full potential has not been demonstrated.

Figure 7 Temperature dependence of J_{th} and J_{rad} for intrinsic and p-doped 1.3 μm QDot lasers.

There has been considerable effort to produce 1.3 μm lasers with superior threshold characteristics based on the 3D quantum confinement provided by semiconductor quantum dots (QDs). The radiative and non-radiative components of the threshold current in 1.3 μm , p-doped and undoped quantum-dot semiconductor lasers were studied between 20 K and 370 K (Figure 7) [5]. The complex behaviour can be explained simply assuming that the radiative recombination and non-radiative Auger recombination rates are strongly modified by thermal redistribution of carriers between the dots. The large differences between the devices arise due to the trapped holes in the p-doped devices. These both greatly increase Auger recombination involving hole excitation at low temperatures and decrease electron thermal escape due to their Coulombic attraction. The model explains the high T_0 values observed near room temperature and shows that by increasing the p-doping an almost infinite T_0 can be achieved over a selected temperature range, but at the expense of an increased J_{th} and a decreased quantum differential efficiency.

References

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