Temperature dependence of long wavelength semiconductor lasers

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We compare the temperature dependent characteristics of multiple quantum well semiconductor laser diodes and light emitting diodes operating at a wavelength, $\lambda = 1.3$ μm. No model in which Auger recombination is the dominant temperature sensitive parameter can explain our experimental observations. We suggest that net gain is the appropriate temperature dependent variable which determines laser diode performance at elevated temperatures.

The practical use of long wavelength semiconductor laser diodes is impaired by an extreme sensitivity of threshold current to temperature. It is commonly believed that, at room temperature and above, nonradiative Auger recombination is the dominant physical mechanism responsible for such sensitivity. On that basis, it was suggested that quantum well lasers[1] and, more recently, strained layer quantum well lasers[2–4] should show a reduced temperature sensitivity due to suppression of Auger recombination channels in these structures. Empirically however, the temperature sensitivity of lasers derived from these sophisticated layer structures is not significantly improved compared to devices made from bulk active layers.[5,6] Clearly, it is appropriate to reappraise the importance of Auger recombination in determining the temperature sensitivity of laser threshold.

In this letter we examine the role of Auger recombination in *both* semiconductor laser diodes (LDs) *and* light emitting diodes (LEDs). We measure the performance of LDs and LEDs in the temperature range $100\ \mathrm{K} < T < 365$ K. Our results cannot be explained by a standard semiconductor rate equation model in which Auger recombination is the limiting temperature sensitive parameter. We suggest that the importance of Auger recombination in determining high-temperature performance of long wavelength lasers has been overestimated and that, in fact, net optical gain is the relevant parameter determining such performance.

We characterize sensitivity of semiconductor laser threshold current, I_{th}, to changes in temperature by a parameter, T_Δ^{LD}, via a phenomenological relationship, $I_{\mathrm{th}} = I_0 \exp(T/T_\Delta^{\mathrm{LD}})$, where T_Δ^{LD} is evaluated over small ($\sim$4 K) temperature increments. This definition recognizes that the temperature sensitivity of I_{th} varies continuously with temperature and is not accurately described by a single number such as the more commonly used T_0^{LD}. We are similarly motivated in characterizing temperature dependence of LED emission with the phenomenological exponential relationship $P^{\mathrm{LED}} = P_0 \exp(-T/T_\Delta^{\mathrm{LED}})$.

In the experiments to be discussed, the laser devices used are as-cleaved buried heterostructure InGaAs/InP multiple (8) quantum well (MQW) Fabry–Pérot lasers of cavity length 250 μm. The emission wavelength is $\lambda = 1.3$ μm and diodes are mounted on a copper heat sink whose temperature may be varied between $T = 100$ and 365 K. The device material was grown by low pressure metalorganic vapor phase epitaxy on a n-type InP substrate with InGaAsP quantum well and barrier thicknesses of 30 and 50 Å, respectively.[7] Laser threshold current, is $I_{\mathrm{th}} = 8.5$ mA at a temperature $T = 20$ °C. As in previous work,[8] in order to ensure validity of our study, LED devices were laser chips from the same wafer which had antireflection coated ($R < 0.1\%$) facets.

In Fig. 1(a) we show a semilogarithmic plot of experimentally determined LED light emission, P_{LED} with temperature, T, for a constant LED bias current $I^{\mathrm{LED}} = 2.0$ mA. P^{LED} increases with decreasing temperature. For $T \lesssim 140$ K superluminescence due to the presence of optical gain in the LED causes P_{LED} initially to increase rapidly and then saturate for $T \lesssim 100$ K. Also shown is variation of T_Δ^{LED} with T. The maximum value of T_Δ^{LED} is about 120 K for $T = 310$ K. With decreasing temperature T_Δ^{LED} *decreases* and reaches a minimum of $T_\Delta^{\mathrm{LED}} \sim 34$ K at $T \sim 140$ K when superluminescence (due to optical gain) dominates emission intensity, P^{LED}. With further decrease in T, saturation in P^{LED} causes T_Δ^{LED} to rapidly increase. The results of this simple experiment immediately show that optical gain plays a key role in determining the temperature dependence of emission of edge emitting LEDs.

In Fig. 1(b) we show a semilogarithmic plot of an experimentally determined I_{th} versus T characteristic of a typical laser device. We note that above room temperature, pulsed (mark/space = 1μs/1 ms) light versus current data are used in order to preclude the possibility of thermal runaway from excessive heating of the laser active region by the drive current. It is noteworthy that laser temperature performance, as measured by T_Δ^{LD}, deteriorates rapidly with increasing temperature in contrast to the increased (improvement) of T_Δ^{LED} over much of the same temperature range. Also indicated in Fig. 1(b) are best-fit lines which yield T_0^{LD} (the more commonly used measure of laser temperature performance). In the low-temperature range ($100\ \mathrm{K} < T < 180\ \mathrm{K}$) $T_0^{\mathrm{LD}} \sim 80$ K and around room temperature ($290\ \mathrm{K} < T < 330\ \mathrm{K}$) $T_0^{\mathrm{LD}} \sim 42$ K. The break point in T_0^{LD} is normally ascribed to Auger recombination. A consequence of this assumption is that the Auger recombination rate (which is proportional to n^3, where n is the carrier density) determines laser threshold current at high temperatures.

The temperature sensitivity of LD and LED are related quantities, linked via the rate equations for carrier and photon numbers;

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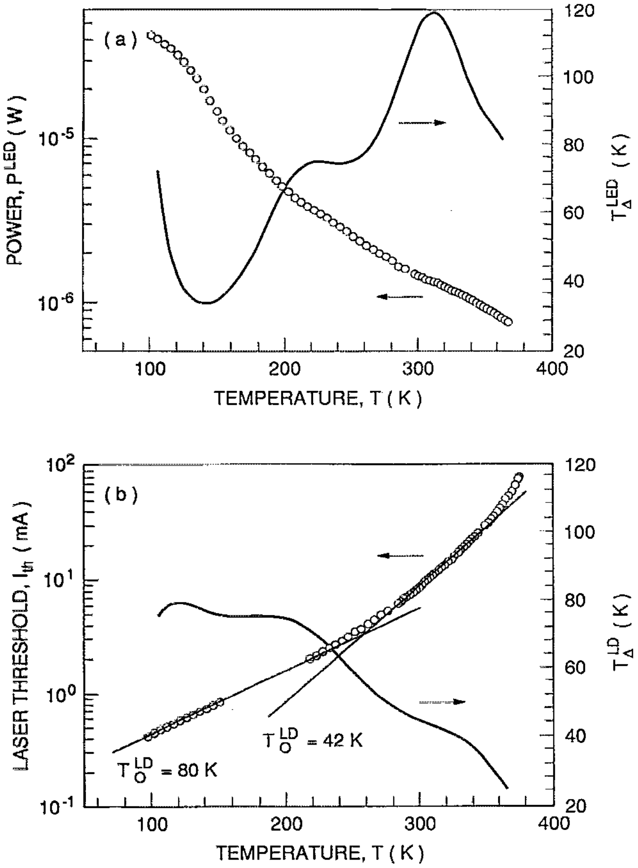

FIG. 1. (a) Measured temperature dependence of LED emission, P^{LED}, vs substrate temperature, T. Also shown is corresponding T_Δ^{LED} vs T. (b) Measured I_{th} vs substrate temperature, T for a MQW laser operating at $\lambda = 1.3$ μm. Also shown is corresponding T_Δ^{LD} vs T.

$$\frac{dn}{dt} = \frac{I}{eV} - R_{us} - GS, \tag{1}$$

and

$$\frac{dS}{dt} = [G - \kappa]S + R_{sp}, \tag{2}$$

where n, I, V, e are the carrier density, pumping current, active region volume, and electronic charge, respectively. S is the photon density, κ is the generalized loss of the laser and $G = A(n - n_0)(1 - \epsilon S)$ is the gain function where n_0 is the carrier density for transparency, ϵ is the gain saturation parameter, and A is the gain coefficient. R_{us} is the total unstimulated recombination rate, given explicitly in terms of n by

$$R_{us} = (A_{nr}n + Bn^2 + Cn^3), \tag{3}$$

where A_{nr} and C describe nonradiative recombination due to traps or surfaces and Auger processes respectively, while B is the radiative recombination coefficient. $R_{sp} = \Gamma\beta Bn^2$, where Γ is the confinement factor and β is the fraction of spontaneous emission coupled into the lasing mode. Standard values (see Table I) are used for all parameters in these equations. We use the conventional assumption that high temperature performance is limited by Auger recombination. For simplicity of exposition, the calculations presented assume that temperature dependence of I_{th} is only determined by a temperature sensitive Auger parameter, $C(T) = C_{293}\exp(T - a)/T_{Aug}$ where C_{293} is the commonly adopted Auger recombination coefficient at room temperature and the value of a and T_{Aug} are chosen to approximately reproduce the observed T_0^{LD} around room temperature ($273\text{ K} < T < 340\text{ K}$).

TABLE I. Parameters used to model MQW InGaAs/InP LDs and LEDs.

Parameter	Value
A	1.5×10^{-6} cm^3 s^{-1}
n_0	1.0×10^{18} cm^{-3}
ϵ	4.0×10^{-17} cm^3
A_{nr}	1.0×10^{8} s^{-1}
B	1.2×10^{-10} cm^3 s^{-1}
C_{293}	3.0×10^{-29} cm^6 s^{-1}
T_{Aug}	35.0 K
a	263.0 K
κ	57 cm^{-1}
Γ	0.05
β	1.0×10^{-5}
V	4.8×10^{-12} cm^3

In Fig. 2(a) we plot the calculated LED emission and T_Δ^{LED} with T for a fixed bias current $I^{LED} = 2.0$ mA. LED emission is calculated by neglecting superluminescence and setting $G = 0$. Figure 2(b) shows the calculated value of I_{th} with T together with the associated T_Δ^{LD}. At low temperatures Auger recombination has little effect on laser threshold and consequently T_Δ^{LD} is large. At high temperatures I_{th} increases rapidly with change in temperature as in the experiment. It must be noted that temperature dependence of the calculated LED emission and T_Δ^{LED} [Fig. 2(a)] are solely due to variation of the nonradiative Auger component with T. Physically therefore, the effect of a highly temperature sensitive nonradiative (Auger) recombination will be apparent in both LD and LED and, in the limit of high temperatures and absence of a more temperature sensitive phenomenon, will dominate the temperature dependence of emission for both.

The consistency of description of Auger recombination in LD and LED may be assessed by determining the temperature variation of the ratio $\zeta = T_\Delta^{LED}/T_\Delta^{LD}$. In Fig. 3 we show the experimental and calculated temperature variation of ζ. Experimentally, for a constant LED bias current $I^{LED} = 2.0$ mA, ζ increases to ~ 3. The kink in ζ around $T = 300$ K is due to the departure of P^{LED} from exponential-like behavior at high temperatures. We also show experimental data for a LED with $I^{LED} = 10.5$ mA where, for clarity, we only show data for the temperature range $280\text{ K} < T < 370\text{ K}$. At $I^{LED} = 10.5$ mA, ζ increases to ~ 4.5. In the calculation, for both values of I^{LED}, the maximum numerical value of ζ is ~ 1.5. If $C(T)$ is the only temperature dependent term in Eqs. (1) and (2) then ζ can never exceed approximately 1.5. The fact that experiment contradicts an Auger biased calculation is important because it shows that Auger recombination cannot simultaneously explain the high-temperature behavior of laser threshold and LED emission. No model in which Auger

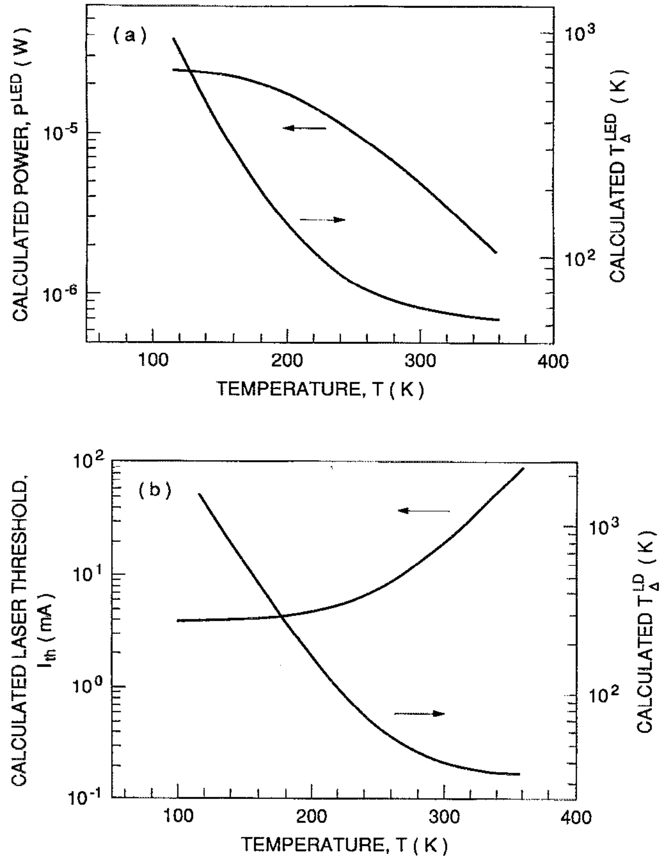

FIG. 2. (a) Calculated variation of LED emission P^{LED} with temperature, T, for a $\lambda = 1.3$ μm laser diode using a standard rate equation model. The model assumes Auger recombination dominates temperature dependence of laser threshold current at high temperatures. Also shown is corresponding T_{Δ}^{LED} vs temperature, T. (b) Calculated variation in threshold current, I_{th}, with temperature T using the same parameters as in (a). Also shown is corresponding T_{Δ}^{LD} vs temperature T.

recombination is the dominant temperature sensitive parameter can explain our experimental observations.

Previously we have suggested that the influence of optical gain on the temperature dependence of I_{th} in long wavelength lasers has been underestimated.[8] This suggestion is reinforced by the measured large variations in T_{Δ}^{LED} and ζ at low temperature (where Auger processes are generally acknowledged to be unimportant) due to superluminescence (i.e., gain) in the LED. We note that these observations are corroborated by previous studies of edge emitting and surface emitting LEDs (SELEDs).[9–11] T_0^{LED} for $\lambda = 1.3$ μm SELEDs are large ($T_0^{LED} \gtrsim 120$ K) and are reportedly insensitive to changes in temperature or drive current[9,10]. This insensitivity is probably because the thin active region, together with the absence of optical confinement, suppresses superluminescence. Above room temperature, edge emitting LEDs at low injection levels have T_{Δ}^{LED} similar to that of SELEDs. At high drive levels, however, T_{Δ}^{LED} approaches that of injection lasers[11] due to the onset of superluminescence.

Obviously, to explain the empirical data, it is necessary to identify a temperature dependent variable for the LD that does not influence the LED spontaneous emission, R_{sp}. Inspection of Eqs. (1) and (2) and the experimental results suggest the appropriate temperature dependent variable is net gain. This should not be too surprising since the energy (temperature) scale of many processes which determine the value of peak optical gain in direct band-gap semiconductors (separation of electron and hole chemical potential, exciton binding energy, band-gap shrinkage, etc.) is similar to T_{Δ}^{LD}.

In conclusion, we have measured the temperature dependence of optical emission from long wavelength LDs and LEDs in the range 100 K$\leqslant T \leqslant$365 K. The experimental results cannot be explained by a model in which Auger recombination is the limiting recombination mechanism. The prominence previously ascribed to Auger recombination in determining the high-temperature behavior of long wavelength semiconductor lasers is misplaced. We suggest that the appropriate temperature dependent variable is most likely net optical gain.

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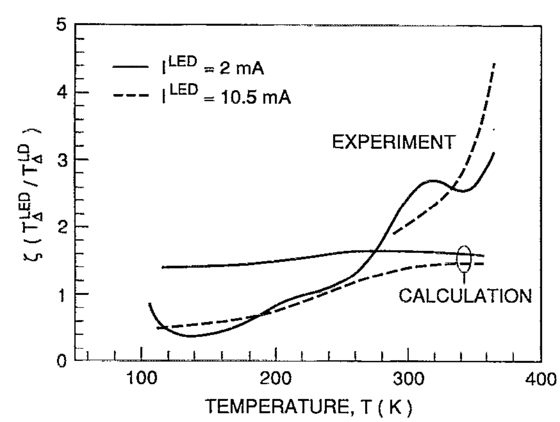

FIG. 3. Plot of measured ratio $\zeta = T_{\Delta}^{LED}/T_{\Delta}^{LD}$ vs temperature T, where T_{Δ}^{LED} has been determined for two values of bias current I^{LED}. Also shown is calculated value of ζ assuming an Auger recombination dominated temperature dependence.

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