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# Hydrostatic Pressure Dependence of the Threshold Current in 1.5 μm Strained Quantum Well Lasers

By

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Results are presented which show that the radiative current in 1.5 μm quantum well lasers obeys simple theory, but that the total current through the device at room temperature is dominated by Auger recombination. The measured temperature and pressure dependencies of the threshold current show that it is phonon-assisted Auger recombination that is operative. This is less sensitive than band-to-band Auger processes to the exact form of the band structure and explains why inbuilt strain has little effect on the temperature sensitivity of the threshold current and why there is little change in threshold current as one goes from 1.5 to 1.3 μm devices.

## 1. Introduction

Despite the commercial importance of the 1.5 μm lasers used in optical fibre communications, considerable uncertainty continues to exist about the causes of the large observed threshold current and its extreme temperature sensitivity. It had been hoped that the introduction of strain into quantum well lasers would almost eliminate direct band-to-band Auger recombination and intervalence band absorption [1], two proposed loss mechanisms that can be very temperature sensitive. However, although either compressive or tensile strains of about 1% greatly improve the laser performance and more than halve the threshold current [2], it remains stubbornly temperature sensitive. This has led some authors to propose that the problem stems from an unusually large temperature dependence of the differential gain [3, 4] or from the temperature dependence of a large stimulated emission component below threshold [5]. In this paper we provide direct evidence that, in fact, the radiative component of the threshold current in 1.5 μm quantum well lasers is perfectly well behaved and that the high values of the threshold currents observed are due to the presence of phonon-assisted Auger recombination [6]. While this itself only has a weakly temperature dependent coefficient, it depends on the carrier density cubed and greatly amplifies temperature variations of the carrier density.

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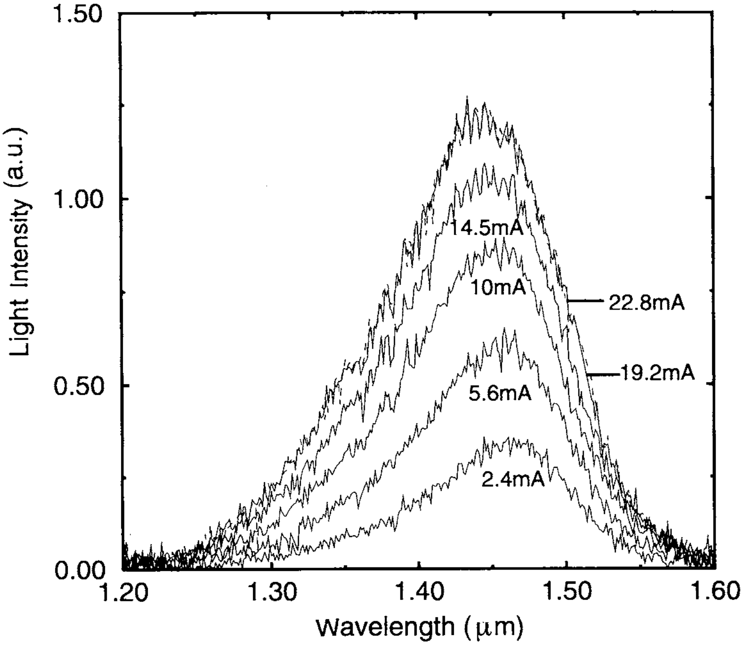


Fig. 1. The variation of the spontaneous emission spectrum with current for a 1% compressively strained laser

## 2. The Temperature Sensitivity of the Radiative Current

### *2.1 Experimental*

We have undertaken a study of the temperature sensitivity of the radiative current $I_{rad}$ in a range of 1.5 μm devices by measuring the temperature variation of the spontaneous emission through a small window etched in the substrate electrode or through the side of buried heterostructure devices where there is also no reabsorption of the light.

A typical result for the variation of the spontaneous emission spectrum with current is shown in Fig. 1. These results are for a 1% compressively strained quantum well laser at room temperature. The light was collected by a 100 μm diameter multimode fibre and fed directly to an optical spectrum analyser. Since we took care that $R$, the collection factor and detector response of the system was kept constant during each series of measurements, the area under the spontaneous emission curve, $RL$, is directly proportional to $I_{rad}$. Here $L$ is the total spontaneous emission rate. It is interesting to note that above the threshold current of 19 mA, which was determined by studying the radiation from the end facet, the area under the curve becomes constant. This is because the carrier concentration becomes pinned by the stimulated emission and so the spontaneous emission current also becomes pinned. This effect is clearer in Fig. 2 where we have plotted $RL$ as a function of total current $I$ through the device at 294 and 333 K for a) an unstrained and b) a 1% compressively strained device. The threshold current value, $I_{th}$, is indicated by the vertical dotted lines. As can be seen, both $I_{th}$ and $I_{rad}$ at threshold increase with increasing temperature but $I_{rad}$ is much less temperature sensitive than $I_{th}$.

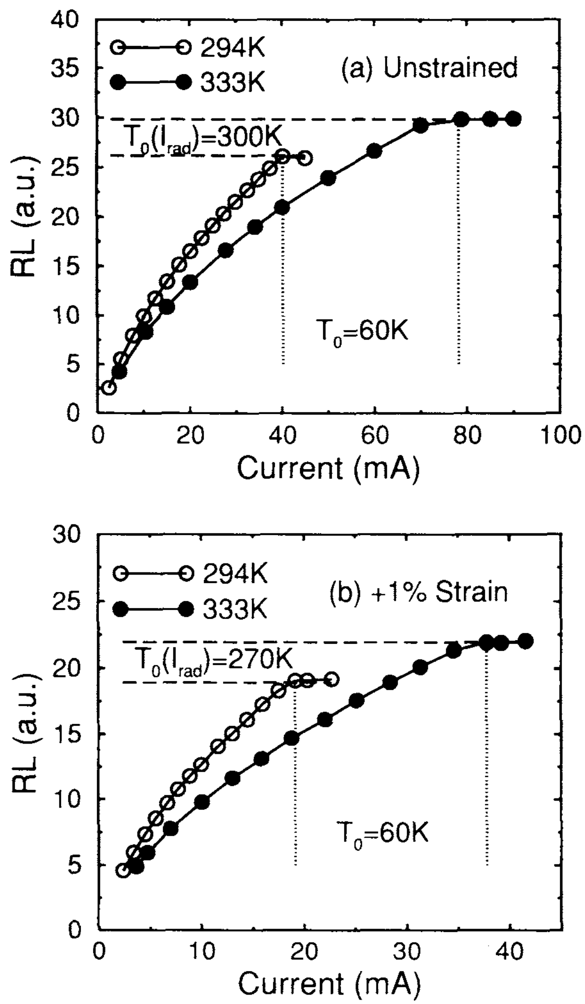


Fig. 2. Integrated spontaneous emission rate as a function of current for a) an unstrained laser and b) a 1% compressively strained laser, at 294 and 333 K. The $T_0$ values for the threshold current, $T_0$, and for the radiative current, $T_0(I_{\rm rad})$, are given

### *2.2 Theoretical model and analysis*

The variation of the total spontaneous emission as a function of total carrier density in the quantum well laser structures was calculated using the quantum well band structure generated from a three-band $\mathbf{k}\cdot\mathbf{p}$ Hamiltonian, including the heavy-hole, light-hole, and spin-split-off contributions [7]. Both the valence and conduction band structures were calculated by solving Poisson's and Schrödinger's equations self-consistently using a five-point finite difference method which can take account of spillover into the barrier region. We also took account of carriers in the separate confinement region. These band structures were then used to calculate both the spontaneous emission rate and the gain spectra for single quantum wells using the density matrix formulation including Lorenzian type broadening. In order to determine the threshold condition for multiple quantum well lasers, the optical confinement factor and hence the threshold gain value required to overcome cavity and mirror losses was calculated. The other material parameters required can be found elsewhere [7].

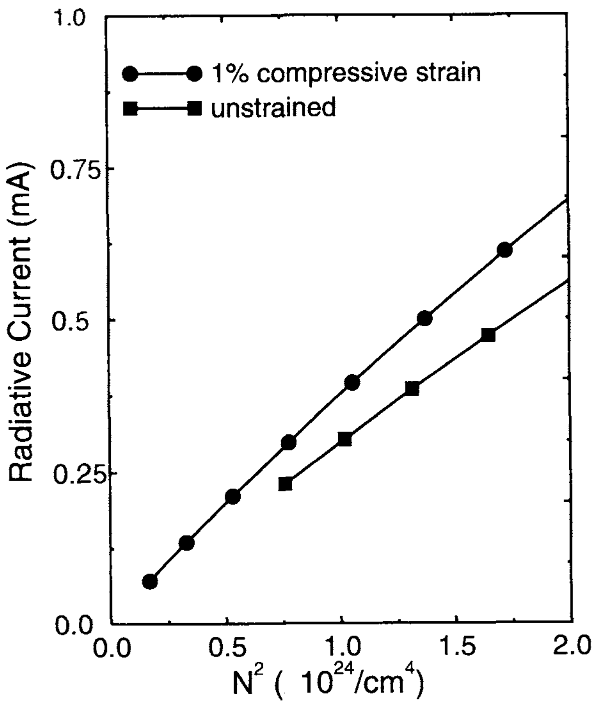


Fig. 3. The calculated variation in radiative current as a function of the square of the carrier density. The squared threshold carrier density $N_{th}^2$ is $0.75 \times 10^{24}\,cm^{-4}$ in the strained device and $1.2 \times 10^{24}\,cm^{-4}$ in the unstrained device

Fig. 3 shows the calculated variation in the radiative current which is proportional to the total spontaneous emission $L$ as a function of the square of the averaged carrier density $N$ for some representative samples up to threshold. As can be seen, despite the band filling and degeneracy effects we require to reach threshold, $L$ remains closely proportional to $N^2$. From these results we believe we are justified to use the simple Boltzmann relationship

$$I_{rad} = eBN^2\,, \tag{1}$$

where $B$ is independent of $N$ even at the threshold carrier density, $N_{th}$.

$T_0$, the characteristic temperature normally used to describe the temperature sensitivity, is defined as

$$T_0 = \left[\frac{1}{I_{rad}}\,\frac{dI_{rad}}{dT}\right]^{-1}\,. \tag{2}$$

Now in an ideal quantum well [8] $B \propto T^{-1}$ while $N_{th} \propto T$. Thus, $T_0 = T$ the temperature around which the measurement is made and therefore one would expect a $T_0$ for $I_{rad}$ close to 300 K at room temperature as is observed. One can therefore conclude that the radiative component of the threshold current is behaving just as theory would predict.

## 3. The Dominance of the Auger Recombination Current Path

Firstly it should be observed that the measured values of the threshold currents corresponding to the values of $I_{th}$ shown in Fig. 2 are almost an order of magnitude greater than the radiative currents calculated using the model described above. It is therefore

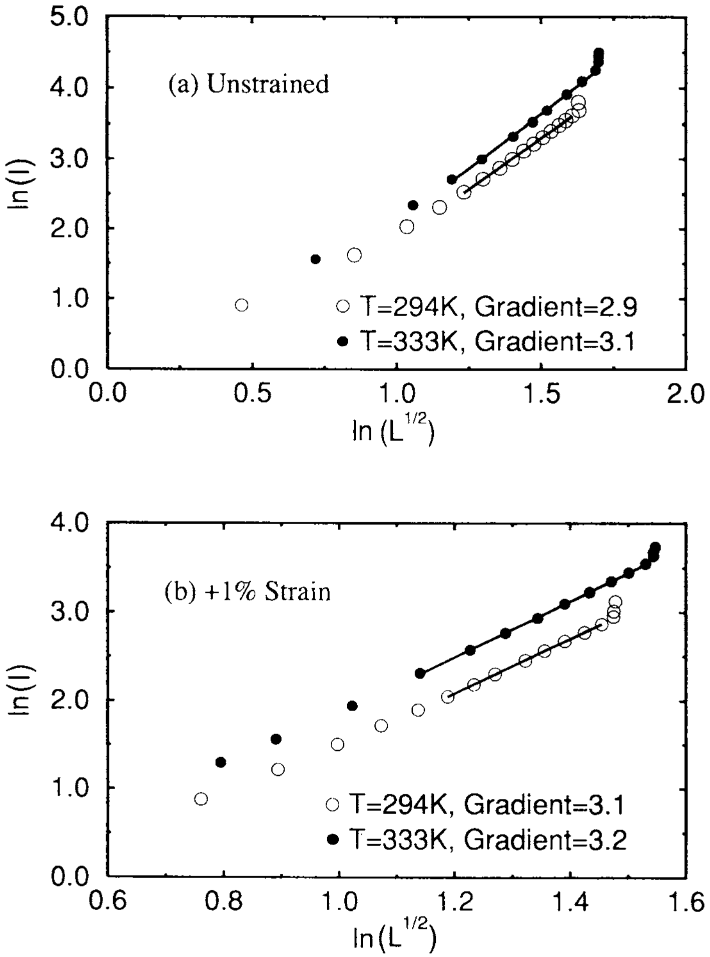


Fig. 4. ln $(I)$ against ln $(L^{1/2})$ for a) unstrained and b) 1% compressively strained lasers. The gradients of each line are shown, and are close to 3 in both cases

clear that there is a nonradiative current path which is dominant in these devices. The second thing to notice is that in both the devices shown in Fig. 2, the spontaneous emission varies sublinearly with total current $I$ and therefore $I$ does not vary as $N^2$.

For further analysis of the spontaneous emission results let us assume that $I \propto N^z$. Now, since $L \propto I_{rad} = eBN^2$ it follows that $N \propto L^{1/2}$. We therefore have $I \propto (L^{1/2})^z$ or that

$$\ln(I) = Z \ln(L^{1/2}). \tag{3}$$

Fig. 4 shows plots of ln $(I)$ against ln $(L^{1/2})$ for the lasers in Fig. 2 and it is clear that (3) holds well in the current range from about $I_{th}/3$ to $I_{th}$. The gradient $Z$ of each line is marked on the figure and, as can be seen, in both cases it is close to 3. It is therefore clear that, while the radiative current, which is a two-particle process, varies as $I_{rad} \propto N^2$ the total current $I$, which is almost an order of magnitude larger, varies as

$I \propto N^3$ which is typical for a three-particle process. In the Auger recombination process the energy and momentum of the recombining electron–hole pair is transferred to a third carrier by either lifting an electron high into the conduction band or by putting a hole deep into the valence band. We therefore believe that the plots in Fig. 4 give a clear indication that in the 1.5 μm devices we have studied, Auger recombination forms the dominant current path.

## 4. Identification of the Type of Auger Recombination

### *4.1 Temperature dependence of the threshold current*

Since Auger recombination dominates the threshold current we may simply write it in the form $I_{th} = eCN^3$, where $e$ is the electronic charge and $C$ is the 2D, areal Auger coefficient which has the form $C = C_0 \exp(-E_a/kT)$, where $E_a$ is the activation energy.

For quantum well devices we may write, as in Section 2, that $N_{th} \propto T$. It therefore follows that [10]

$$T_0 = \frac{T}{3 + \frac{E_a}{kT}} . \tag{4}$$

This means that even if the Auger coefficient is totally independent of temperature, i.e. $E_a = 0$, the expected value of $T_0$ is $T/3$, or about 100 K at room temperature! Turning now to Fig. 2 we observe that $T_0$ for the total threshold current density as indicated by the vertical dotted lines is about 60 K at 300 K. It therefore follows from equation (4) that $E_a/kT \approx 2$. Thus, the activation energy for the Auger process in operation is much smaller than one would calculate for a direct band-to-band process but is closer to that for phonon-assisted processes. In phonon-assisted Auger recombination the phonon involved allows momentum and energy conservation even for holes close to the valence band maximum and does not need the hot holes at large $k$-values involved in direct band-to-band Auger recombination. What is more, the phonon reduces the sensitivity of the process to the exact form of the band structure.

### *4.2 Pressure dependence of the threshold current density*

When hydrostatic pressure is applied to any III–V compound or alloy, the direct band gap $E_g$ increases at about 10 meV/kbar. We have measured [9] the exact pressure coefficients of the range of alloys used in 1.5 μm lasers and also showed that the valence band and Γ minimum conduction band offsets are almost constant with pressure. Therefore, the main effect of pressure is to increase $E_g$ and, according to $\mathbf{k} \cdot \mathbf{p}$ theory, to increase the electron effective mass $m_c$ by the same proportion. Fig. 5 shows the measured rate of change of $I_{th}$ with pressure for different 1.5 μm laser structures. Although there is some variation in the results, all devices showed a decrease in $I_{th}$ of between about 30% and 40% at 10 kbar. Since we have established that Auger recombination dominates the threshold current we can calculate the variation of $I_{th}$ with pressure ignoring the effects of the radiative current. The results of such calculations for the unstrained device are shown in Fig. 5 and, as can be seen, the variation predicted for either the CHSH or the CHCC phonon-assisted Auger processes (solid lines) are in much better agreement with the experimental results than the direct band-to-band processes (dashed lines). Also, at

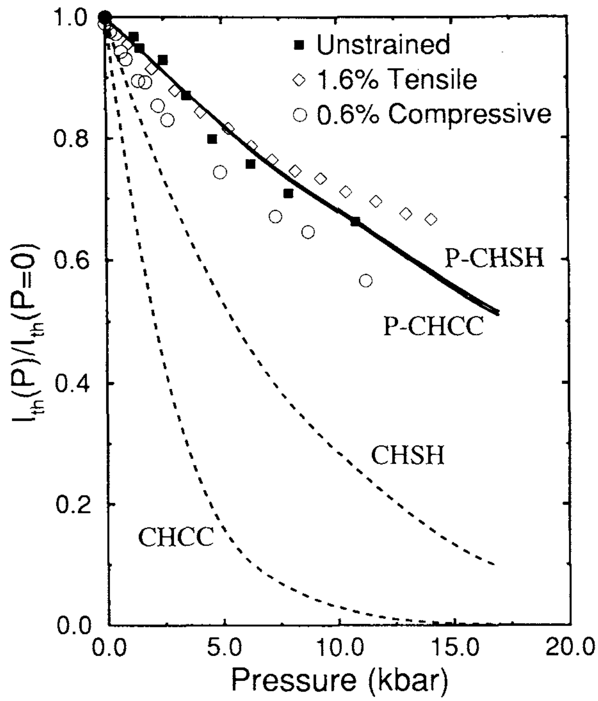


Fig. 5. Normalised measured rate of change of the threshold current with hydrostatic pressure for unstrained, 0.6% compressively strained, and 1.6% tensiley strained devices. The calculated rates of change of the threshold current due to Auger recombination for the unstrained device are also shown. In the CHCC Auger process, an electron and hole recombine across the band gap, exciting an electron to higher in the conduction band. CHSH: A hole is excited from the heavy-hole to the spin-split-off band. P-CHSH, P-CHCC: Phonon-assisted processes

10 kbar the operating wavelength of the lasers shown in Fig. 5 is approximately 1.3 μm which would predict that, if direct band-to-band Auger recombination is occurring, the threshold current should have reduced by one to two orders of magnitude. In fact it is observed that the threshold current of lasers grown to operate at 1.3 μm is in a very similar range to that of 1.5 μm devices as expected assuming phonon-assisted Auger recombination.

## 5. Conclusion

The results presented here show that the radiative current in 1.5 μm quantum well lasers is well behaved but that the total current through the device at room temperature is dominated by Auger recombination. The measured temperature and pressure dependencies of the threshold current show that it is phonon-assisted Auger recombination that is operative. Since phonon-assisted processes are much less sensitive to the exact band structure than direct band-to-band processes, this conclusion also explains why in-built strain has little effect on the temperature sensitivity of the threshold current and why there is little change as one goes from 1.5 to 1.3 μm devices.

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