RADIATIVE EFFICIENCY IN LOW-DIMENSIONAL SEMICONDUCTOR STRUCTURES

Indexing terms: Semiconductor devices and materials, Quantum-well structures

The ratio of the spontaneous emission and Auger recombination rates for quantum wells and wires is compared theoretically with that for bulk structures. Dramatic improvements in radiative efficiency are not predicted for these novel structures unless carrier densities are greatly reduced.

Introduction: An important parameter for semiconductor lasers for optical-fibre communication systems is the temperature sensitivity of the threshold current.[1] In the absence of nonradiative recombination, it has been predicted[2] that the temperature sensitivity of the threshold current is reduced as the degrees of freedom for motion of the carriers in the active region is reduced. Indeed, such a reduction has been found in GaAs quantum-well lasers (see, for example, Reference 3) and a further reduction is expected in a quantum-wire structure.[2] However, in the lower-bandgap materials, such as are used in the active regions of semiconductor lasers for long-wavelength optical-fibre communication systems, band-to-band Auger recombination, a nonradiative process, will be present to some extent.[1] It is well known that this nonradiative process is considerably more sensitive to temperature than spontaneous emission. It is important therefore to be able to determine how the ratio of the spontaneous emission rate to the Auger recombination rate varies with the number of degrees of freedom.

Unfortunately, while spontaneous emission rates can be reasonably estimated, the determination of absolute Auger recombination rates is beset with difficulties, for example the estimation of overlap integrals[4] or the incorporation of realistic band structures.[5] However, trends in Auger recombination rates, for example the ratio of quantum-well and bulk Auger recombination rates,[6] as the number of degrees of freedom of the carriers is reduced can probably be more reliably estimated. Given that trends in the spontaneous emission rate and the Auger recombination rate as the degrees of freedom are reduced can be separately estimated, it is clear that trends in the ratio of these rates can also be obtained. It is the purpose of this letter to show how the ratio of spontaneous emission to Auger recombination rates changes as the number of degrees of freedom is reduced.

Trends in spontaneous emission rates: Denote by $R_{sp}^{(v)}$ the total spontaneous emission rate per unit volume of the active region in a 'v-dimensional' laser structure. $v = 3$ refers to a conventional bulk DH structure, $v = 2$ to a quantum well and $v = 1$ to a quantum wire (the case $v = 0$ is excluded). Assuming intrinsic material, the wavevector selection rule and Boltzmann statistics one finds using standard theory that

$$R_{sp}^{(v)} = An^2/N^{(v)} \tag{1}$$

A is the Einstein coefficient averaged over all allowed transitions and over all polarisations of the emitted light, and may reasonably be expected to be roughly independent of v for III-V materials. n is the carrier density per unit volume. $N^{(v)}$ is an effective density of states per unit volume given by

$$N^{(v)} = \frac{2}{L^3}\left(\frac{(m_c + m_v)k_B T L^2}{2\pi\hbar^2}\right)^{v/2} \tag{2}$$

m_c and m_v are the conduction-band and valence-band effective masses, T is the absolute temperature and L the width of the active region in each of the v dimensions in which the carrier is confined (i.e. an active region with square cross-section of side L is used for the quantum wire). It has been assumed that the carriers have been confined to their lowest respective subbands in the quantum-well and quantum-wire cases. It follows that, for equal carrier concentrations,

$$R_{sp}^{(v-1)}/R_{sp}^{(v)} = \left[\frac{(m_c + m_v)k_B T L^2}{2\pi\hbar^2}\right]^{1/2} \tag{3}$$

Trends in Auger recombination rates: An analogous analysis can be made for trends in Auger recombination rates, although here it has to be assumed that the effective overlap integral[4] does not vary greatly with the number of degrees of freedom v. Such an analysis has already been reported for the CHCC Auger process for the case of quantum wells and bulk.[6] This analysis has been extended to give the ratio of Auger recombination rates in quantum wells and the bulk for all the band-to-band processes that can occur in III-V materials† and also to quantum wires with square geometry.§ Neglecting factors of the order unity, all these results can be expressed in the simple formula

$$R_{Aug}^{(v)}/R_{Aug}^{(v-1)} \simeq (E_a/\pi k_B T)^{1/2} \tag{4}$$

where $R_{Aug}^{(v)}$ is the recombination rate per unit volume for the Auger process under consideration with activation energy E_a, and the v index has the same significance as in the earlier discussion of spontaneous emission. In deriving eqn. 4 the same assumptions have been made as in earlier work,[6,7] i.e. wavevector conservation, equal carrier concentrations, Boltzmann statistics, all carriers restricted to their lowest sub-bands, spherically symmetric band structure and the omission of processes involving higher sub-bands and the continuum states. It must be stressed that eqn. 4 only holds over a limited range of values of L. On the one hand, L must be large enough (50 Å in most cases of practical interest) for the wide well limit†[8] to be applicable and yet narrow enough for most of the carriers to be in their lowest sub-bands at thermal equilibrium.

Trends in the ratio of spontaneous emission and Auger recombination rates: Define the ratio $\xi^{(v)}$ of spontaneous and Auger recombination rates as

$$\xi^{(v)} = R_{sp}^{(v)}/R_{Aug}^{(v)} \tag{5}$$

and consider the variation in this parameter with v, i.e.

$$\xi^{(v-1)}/\xi^{(v)} = [R_{sp}^{(v-1)}/R_{sp}^{(v)}][R_{Aug}^{(v)}/R_{Aug}^{(v-1)}] \tag{6}$$

If we assume that one type of band-to-band Auger process, with activation energy E_a is dominant regardless of v, then, using eqns. 3, 4 and 6,

$$\xi^{(v-1)}/\xi^{(v)} = L/\lambda \tag{7}$$

where

$$\lambda = 2\pi\left[\frac{\hbar^2}{2(m_c + m_v)E_a}\right]^{1/2} \tag{8}$$

A rough estimate of λ for III-V materials of potential interest in long-wavelength optical-fibre communication systems using $m_c + m_v \sim 0\cdot5$ m and $E_a \sim 0\cdot1$ eV gives $\lambda \sim 50$ Å. Since L is likely to be of the same order in semiconductor lasers, we do not expect large changes in ξ as the number of degrees of freedom in the active layer is reduced. Indeed, recent measurements of the temperature sensitivity of the threshold current of long-wavelength GaInAs quantum-well lasers show no significant improvement over those for corresponding bulk devices.[9,10]

Summary and conclusions: It has been shown (subject to certain caveats) that once the ratio of spontaneous emission rate to the Auger recombination rate is known in the bulk it can be estimated in a quantum-well or a quantum-wire structure using a simple formula. This is a useful result because a

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† TAYLOR, R. I., ABRAM, R. A., BURT, M. G., and SMITH, C.: 'Auger recombination in a quantum well heterostructure', *IEE Proc. J, Optoelectron.*, to be submitted

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measurement of the above-mentioned ratio in a conventional double-heterostructure device can be used to predict this ratio for quantum-well and quantum-wire devices with active regions made of the same material. Assuming the same carrier density at threshold, we do not expect the ratio to be dramatically different in a quantum well or a quantum wire from that of a conventional double-heterostructure laser. However, if a quantum-well or a quantum-wire laser were designed to have a threshold carrier density much less than the corresponding quantity in a conventional double-heterostructure laser, then indeed we would expect to see significant improvements in the spontaneous emission efficiency. This conclusion follows from the fact that the spontaneous emission rate varies as the square of the carrier density, whereas the Auger recombination rate varies as the cube.

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M. G. BURT *13th June 1985*

British Telecom Research Laboratories
Martlesham Heath
Ipswich, Suffolk IP5 7RE, United Kingdom

R. I. TAYLOR

Department of Applied Physics & Electronics
University of Durham
Science Laboratories, South Road, Durham DH1 3LE, United Kingdom

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