Auger Recombination in Quantum-Well InGaAsP Heterostructure Lasers

L. C. CHIU AND AMNON YARIV

Abstract—**Interband nonradiative Auger recombination in quantum-well InGaAsP/InP heterostructure lasers has been calculated. It is found that the Auger rate is much reduced in the quasi two-dimensional quantum-well lasers. This suggests that the temperature sensitivity of quantum-well InGaAsP lasers is much less than ordinary structures with much higher values of T_o at around room temperatures.**

A CONTINUING problem with lasers and light emitting diodes (LED) based on the quaternary compound $In_{1-x}Ga_xAs_yP_{1-y}$ lattice matched to InP is their temperature sensitivity. In LED's, the optical output power saturates at high current densities and, in lasers, the threshold current increases rapidly with temperatures above 220–250 K.

In the case of lasers, the threshold current has been found empirically to vary with temperature T as $I_{\text{th}} \sim \exp(T/T_o)$. The quantity T_o determines the temperature sensitivity of the device. In InGaAsP lasers, the log (I_{th}) versus T plot exhibits a break-point temperature below which the T_o is typically about 110 K, whereas above the break-point temperature, T_o has a low value of ~50–60 K [1]–[3]. The break-point typically occurs at around 220–250 K. The T_o in GaAlAs/GaAs lasers, on the other hand, remains at about 120–170 K over the same temperature range [4]. Many mechanisms have been proposed to account for the low T_o of the quaternary lasers. Among the various mechanisms considered, the interband Auger recombination has been found to be a dominant factor [5]–[7].

Although it has been demonstrated that GaAlAs/GaAs quantum-well lasers exhibit higher T_o's [8], it is unclear whether InGaAsP quantum-well lasers would be free from a break-point in the threshold current versus temperature characteristics. In this paper, we present an analysis of the nonradiative Auger recombination in the quantum-well lasers. It is found that the rate of Auger recombination is greatly reduced in such quasi two-dimensional structures. It is thus suggested that the log (I_{th}) versus T plot for such lasers would be free from a low temperature break-point and the T_o for temperatures above 220–250 K should remain above ~120 K. Experimental confirmation of this prediction will also serve as a check on the importance of Auger recombination in ordinary InGaAsP lasers. The data in [9] for multiple quantum-well lasers do indicate that the breakpoint is ~300 K, which is considerably higher than ordinary quaternary lasers.

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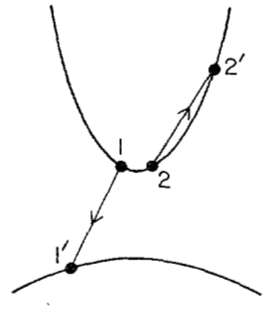

Fig. 1. The CHCC Auger recombination processes. 1, 2 and 1′, 2′ are the initial and final states, respectively.

In this paper, only the CHCC (see Fig. 1) process will be considered. The rate of Auger transition can be written as [10]

$$P = \frac{2\pi}{\hbar}(2\beta)\,2\left(\frac{V}{(2\pi)^3}\right)^3\left(\frac{e^2}{\epsilon V}\right)^2 \iiint \frac{|F_1F_2|^2}{(|\boldsymbol{k}_1 - \boldsymbol{k}_{1'}|^2 + L_D^{-2})^2} \times [f_1 f_2(1-f_{1'})(1-f_{2'}) - (1-f_1)(1-f_2)f_{1'}f_{2'}] \cdot \delta(E_f - E_i)\,d\boldsymbol{k}_1\,d\boldsymbol{k}_{1'}\,d\boldsymbol{k}_2. \quad (1)$$

In the above, the f's are the Fermi factors, $E_{f,i}$ are the final and initial energies of the particles, respectively, e is the electronic charge, V is the volume, L_D is the screening length, and $2 < 2\beta < 3$ due to spin symmetry. The overlap integrals $|F_1F_2|^2$ are given by [11]

$$|F_1F_2|^2 \approx \frac{\hbar^2}{2m_eE_g} f_{cv}\,|\boldsymbol{k}_1 - \boldsymbol{k}_{1'}|^2 \quad (2)$$

where m_e is the electron mass, E_g is the bandgap energy, and f_{cv} is the oscillator strength. The screening length is calculated from [12]

$$\frac{1}{L_d^2} = \frac{e^2}{\epsilon_r\epsilon_o k_B T}\,\frac{2}{(2\pi)^3}\int f(k)(1-f(k))\,d\boldsymbol{k} \quad (3)$$

where ϵ_r is the relative dielectric constant, ϵ_o is the permittivity of free space, k_B is the Boltzmann constant, and T is the temperature.

Equation (1) has been modified [see (5)] to calculate the rate of Auger recombination in a quantum-well structure. It is well known that when the active layer thickness L_z of a semiconductor laser is of the order of the carrier de Broglie wavelength, quantum size effects arise [13]. The nonradiative band-to-band Auger process then changes in a fundamental

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way. For a quasi two-dimensional layer, it is usually assumed that the single-particle Hamiltonian can be separated into a quantized component normal to the layer and continuous components in the plane of the layer [14]. In such a case, the energy spectrum is given by [15]

$$E(k_{zn}, k_x, k_y) = \frac{\hbar^2 k_{zn}^2}{2m^*} + \frac{\hbar^2}{2m^*}(k_x^2 + k_y^2) \tag{4}$$

where n denotes the nth quantized state of k_z, m^* is the effective mass of electrons or holes, and k_x, k_y are the continuous components of the crystal momentum. We recognize that the actual band structure of quantum-well structures has not been established and the parabolic band approximation is employed here. However, in the case of the CHCC process, taking nonparabolicity into account would lead to slower Auger rate [16] and thus, even longer lifetime. Also, possible anisotropy in the effective masses has been neglected, and the effective masses of the electrons and holes in the direction perpendicular and parallel to the plane of the layer have been taken to be the same. This would not affect the transition rate significantly unless the anisotropy factor is bigger than ~1.5. The Auger rate for such quasi two-dimensional systems becomes

$$P = \frac{2\pi}{\hbar}(2\beta)\, 2\left(\frac{V}{(2\pi)^3}\right)^3 \left(\frac{e^2}{\epsilon V}\right)^2 \mathbf{S} \frac{|F_1 F_2|^2}{(|\boldsymbol{k}_1 - \boldsymbol{k}_{1'}|^2 + L_D^{-2})^2} \times [f_1 f_2 (1 - f_{1'})(1 - f_{2'}) - (1 - f_1)(1 - f_2) f_{1'} f_{2'}] \cdot \delta(E_f - E_i)\, d\boldsymbol{k}_1\, d\boldsymbol{k}_{1'}\, d\boldsymbol{k}_{2'} \tag{5}$$

where $\mathbf{S}$ denotes summing over discrete states and integrating over continuous states.

In this work, all the calculations have been performed for $In_{0.72}Ga_{0.28}As_{0.60}P_{0.40}$ for which the emission wavelength is about 1.3 μm. To find the confined quantized states, the discontinuities are taken to be ~0.31 and ~0.15 eV in the conduction and valence bands, respectively [17]. The quantum-well is assumed to be a finite square well and the summation is extended only over the confined states in (5). The small Fermi factors at the top of the well ($\sim 10^{-5}$-10^{-6}) justify this approximation. The rate is then calculated numerically and the Auger lifetime is obtained from the expression

$$\tau_A = \frac{\Delta n}{P} \tag{6}$$

where Δn is the injected carrier density at threshold. It is assumed here that the injection level is high, so that $\Delta n \doteq n_{\text{th}}$, an assumption which is excellent in the case of injection lasers.

The results of the calculation are presented in Figs. 2-4. In Fig. 2, $1/\tau_A$ is plotted against the electron density at a temperature of 300 K and for a quantum-well with width 100 Å. The slope of 2.45 (>2) is typical of the nonradiative process in degenerate materials [6]. In Fig. 3, the nonradiative Auger lifetimes of the quantum-well and ordinary laser structures are compared under the same injection conditions and temperatures. A well with width 100 Å has also been assumed for the quantum-well laser. It shows that the Auger lifetime is about two orders of magnitude longer in the quasi two-dimensional system. In Fig. 4 the lifetime versus width of well at a temperature of 300 K is plotted. It can be seen that the lifetime decreases rapidly with increasing well width. This is expected since the number of confined states increases and the energy separation between states decreases when the width of the well increases. Moreover, the quantum size effect would have to disappear gradually as the width increases.

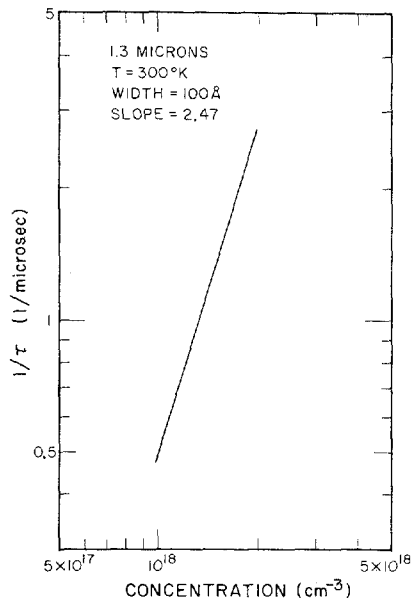

Fig. 2. The inverse of Auger lifetime as a function of carrier concentration for a 1.3 μm quantum-well (width = 100 Å) InGaAsP laser at 300 K.

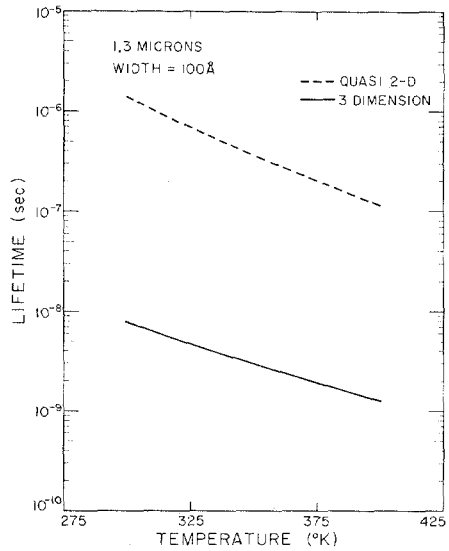

Fig. 3. Comparison of calculated Auger lifetimes for a 1.3 μm quantum-well (width = 100 Å) and ordinary InGaAsP lasers under the exact same injection conditions.

The dramatic increase in lifetime in a quasi two-dimensional system as compared to the three-dimensional system is due to the nature of the difference in the density of states, and, more importantly, the decrease in the number of configurations that can satisfy the requirement of both momentum and energy conservation simultaneously. Although the calculation is carried out for a single quantum-well only, the energy band within the well for a multiple quantum-well as well as superlattice structure can be shown to be very narrow [18], [19]

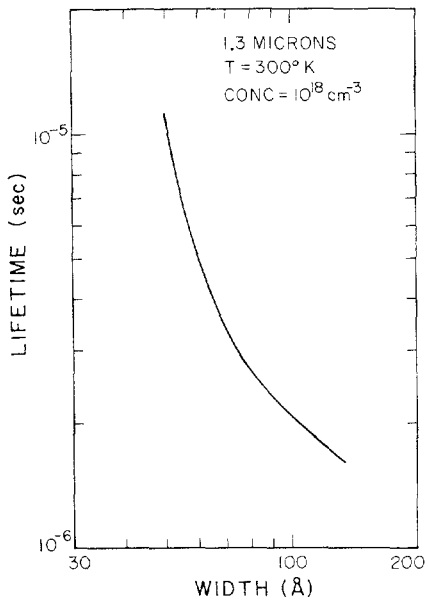

Fig. 4. Calculated Auger lifetime for a 1.3 μm quantum-well laser as a function of well width at 300 K.

and the results given here will approximately be valid in these cases too.

The threshold current density can be written as

$$J_{\text{th}} = \frac{n_{\text{th}} ed}{\tau} \tag{7}$$

for ordinary lasers and single quantum-well lasers, and

$$J_{\text{th}} = \frac{n_{\text{th}} eNd}{\tau} \tag{8}$$

for multiple quantum-well lasers [15]. In the above equations, e is the electronic charge, d is the active layer thickness, n_{th} is the injected carrier density at threshold, N is the number of quantum wells, and τ is the carrier lifetime. In lasers, it is the existence of competitive nonradiative processes which shorten the carrier lifetime [5]-[7]. From (7) and (8), it is obvious that a decrease in τ causes a corresponding increase in the threshold at the same n_{th}. Although the nonradiative Auger lifetime is longer in the quantum-well lasers, it is the relative magnitude between the radiative and nonradiative lifetimes that is important.

In quantum-well lasers, it can be shown that the ratio of the radiative lifetime in a three-dimensional structure and a quasi two-dimensional system under the constant matrix element assumption can be written as (neglecting light and split-off hole bands)

$$\frac{\tau_{q2d}}{\tau_{3d}} \approx \left(\frac{2m_r}{\hbar^2}\right)^{1/2} \frac{L_z}{\pi} (\hbar\omega - E_g)^{1/2} \times \frac{1}{n} \tag{9}$$

where m_r is the reduced mass of the electron and hole, L_z is the width of the well, ω is the frequency of light, E_g is the bandgap energy, and n is the number of pairs of levels where optical transition can take place. Taking $n = 1$, it can easily be verified that the ratio is less than one for $(\hbar\omega - E_g)^{1/2} < 0.275$. Since under ordinary laser operation $(\hbar\omega - E_g)^{1/2} \ll 0.275$, the radiative lifetime in a quantum-well laser is even shorter than in a conventional laser. This can be verified in the GaAs-GaAlAs system from the data in [8]. Thus, the radiative lifetime at threshold for quantum-well lasers remains in the nano or subnanosecond regime. For a *single* quantum-well laser, despite the higher gain [see (9)], the carrier density at threshold is about 1.3 times that of a conventional laser due to the small optical confinement factor. However, it can be seen from Fig. 2 that even at densities of several times that of ordinary lasers, the Auger lifetime is still much longer than the radiative lifetime. Thus, in the quantum-well lasers, the nonradiative Auger processes are no longer competitive with the radiative process. Therefore, it is predicted that such lasers will not have a low temperature break-point above which the T_o decreases considerably. If such behavior can be confirmed by experimental observation, the case for the importance of Auger recombination in ordinary InGaAsP lasers will also be strengthened.

In conclusion, the nonradiative Auger lifetimes in a quantum-well InGaAsP laser have been calculated and found to be much longer than the radiative lifetime. It is thus predicted that the quantum-well laser will not be characterized by a low T_o and, as a result, will not be as temperature sensitive as the ordinary lasers. In ordinary lasers, the rate constant for Auger recombination is material dependent and, at a given temperature, is fixed [20]. Thus, it is difficult to obtain lasers with high T_o's. However, the results of this work suggest that InGaAsP lasers with high T_o's could be obtained by employing the single or multiple quantum-well structures.

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CW Laser Action in Ethyl Chloride

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Abstract—**We have observed far infrared output at 447, 698, 1306, and 1669 μm in ethyl chloride using a metallic-waveguide laser and a CO_2 pump laser. The measurements were made with a metal-mesh Fabry–Perot interferometer and, together with the pump assignments, they are in disagreement with previously published values.**

ETHYL chloride, C_2H_5Cl, is a particularly useful active medium in optically pumped far infrared (FIR) lasers since it provides radiation at several wavelengths in the sparse region around 1 mm [1]. We report here new measurements of the FIR wavelengths and CO_2 pump line assignments for this molecule which are at variance with those appearing in the literature [2].

Our FIR laser consisted of a 2.0 m long cylindrical copper waveguide of 19 mm inside diameter and plane polished aluminum end mirrors. Input and output coupling was through circular holes of diameter 1.5 and 2.0 mm, respectively. The output mirror could be translated 4 mm with ±1 μm resolution. The CO_2 pump laser was grating tuned and delivered about 20 W on each line concerned. FIR radiation was detected with a Golay cell and a lock-in amplifier.

Using a plane parallel inductive metal-mesh free space Fabry-Perot interferometer whose plate separation could be varied by 12 mm, we measured FIR output wavelengths of 447 ± 1 μm, 698 ± 1 μm, 1306 ± 2 μm, and 1669 ± 2 μm. Wavelength uncertainties are determined by the finesse of the interferometer for the shorter lines and by the available scanning range at longer wavelengths. Fig. 1 shows a typical Fabry–Perot interferogram for the 1306 μm line. The performance of the interferometer was checked by measuring the wavelength of the well-known 570.57 μm methanol line.

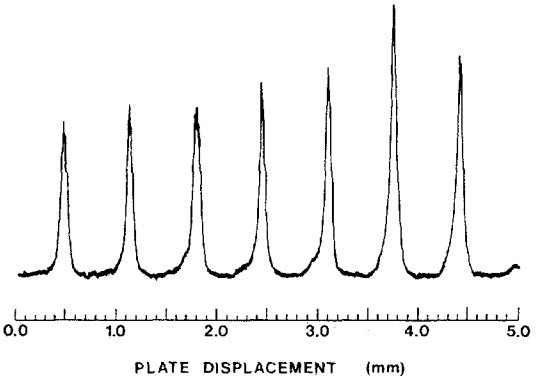

Fig. 1. Segment of a Fabry–Perot interferogram for the 1306 μm line. Measurement of the full 34 transmission maxima yields a wavelength accuracy of about 0.1 percent.

Previous wavelength measurements on ethyl chloride [2] were apparently made by translating the end mirror of the waveguide laser cavity. When we did this for the $10R(28)$ pumped lines we found, in addition to wavelengths of 447 and 1306 μm, a periodicity corresponding to a wavelength of 1346 ± 5 μm (see Fig. 2). However, measurement of the free space wavelength of this feature yielded a value of 1306 μm. We believe this line to be the same as that reported earlier as having a wavelength of 1350 μm [2].

Calculations indicate that a TE_{03} circular waveguide mode would account for this longer guide wavelength in a laser whose end mirror is close to the end of the waveguide. In our laser the output mirror was kept between 1 and 5 mm from the end of the guide in order to reduce losses. While losses

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