# Forbidden Auger process in strained InGaSb/AlGaSb quantum wells

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Carrier loss due to Auger recombination has been known to be the major factor limiting the performance of long-wavelength semiconductor lasers. We show for the first time that the dominant Auger process in InGaSb/AlGaSb and InGaAs/InP strained quantum well structures can be suppressed because of the conversation of energy and crystal momentum with the sufficient reduction of the in-plane heavy hole masses. As a result, low-threshold currents and good temperature performance can be achieved in strained quantum well semiconductor lasers. An analytic expression for the in-plane effective hole masses in a strained quantum well is derived and used to calculate the hole masses of InGaSb/AlGaSb strained quantum wells.

Auger recombination has been imposing difficulties in the advance of semiconductor lasers. Lasers, such as InGaAsP/InP lasers, for long-wavelength fiber communication systems suffer from severe Auger recombination carrier loss.[1] Compared to the GaAs/AlGaAs lasers used in 0.8 $\mu$m fiber communication systems they have higher threshold currents and lower quantum efficiencies. In addition, they are very sensitive to temperature changes. GaAs/AlGaAs lasers with novel structures, such as short-cavity high-speed lasers[2] and vertical-cavity surface-emitting lasers,[3] have threshold current densities far higher than those of conventional lasers. It is likely that the performance of these lasers is eventually limited by the rapid increase of Auger recombination loss.

The ability to grow quantum well and superlattice structures using techniques such as molecular beam epitaxy and metalorganic chemical vapor deposition opens the new dimension of semiconductor energy-band engineering. The recent interest in growing strained quantum well lasers is an example.[4]

In a strained quantum well, the in-plane effective heavy hole mass is reduced because of the heavy hole and light hole band mixing. This reduction has been shown to increase the in-plane mobility of the $p$-channel pseudomorphic modulation-doped field-effect transistors,[5] and to reduce the threshold currents, and increase the modulation speed in strained quantum well lasers effectively.[4-7]

In this work we investigate the effect of the heavy hole mass on the Auger recombination process. We derive the analytic expression for the in-plane heavy and light hole masses in a strained quantum well. We find that it is possible to eliminate the dominant band-to-band Auger recombination in InGaSb/AlGaSb strained quantum wells.

Band-to-band Auger recombinations in InGaAsP and InGaSb bulk and quantum well structures are dominated by the CHHS process,[8] where an electron 1′ (C) recombines with a heavy hole 1 (H), and excites a heavy hole 2 (H) to a split-off band at 2′ (S), as shown in Fig. 1.

The conservation of momentum and energy requires

$$\mathbf{k}_i - \mathbf{k}_f = \mathbf{k}_{1'} + \mathbf{k}_{2'} - \mathbf{k}_1 - \mathbf{k}_2 = 0 \qquad (1)$$

and

$$E_i - E_f = E(1') + E(2') - E(1) - E(2) = 0. \qquad (2)$$

The wave vectors k's are three dimensional in bulk material and two dimensional in the quantum well structures. $E_g$ and $\Delta$ in Fig. 1 are, respectively, the band gap and the spin split-off gap in the bulk material, and the effective band gap and the effective spin split-off gap in the quantum well structures. Assume the bands are parabolic with effective masses $m_c$, $m_h$, and $m_s$ for the electrons, the heavy hole, and the spin split-off hole, respectively. The left-hand side of Eq. (2) becomes

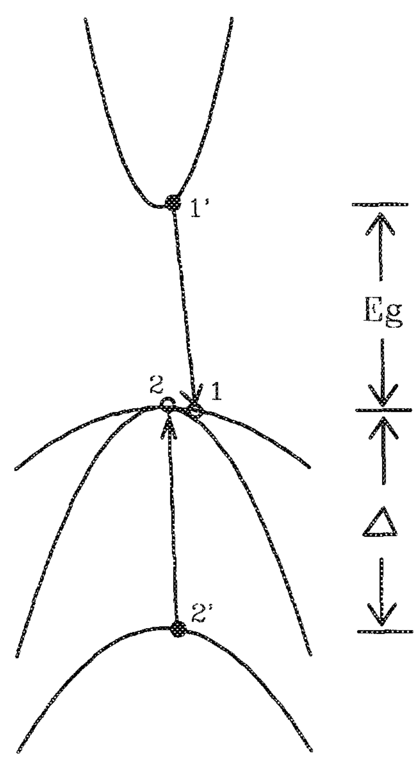


FIG. 1. CHHS Auger process. The $E_g$ and $\Delta$ are respectively the band gap and the spin split-off gap in bulk material, or the effective band gap and the effective spin split-off gap in a quantum well structure.

$$E_i - E_f = E_g + \frac{\hbar^2}{2m_c}k_{1'}^2 + \frac{\hbar^2}{2m_h}k_1^2 + \frac{\hbar^2}{2m_h}k_2^2 - \Delta - \frac{\hbar^2}{2m_s}k_{2'}^2$$

$$= E_g - \Delta + (1+\mu_1)\frac{\hbar^2}{2m_h}\left(k_{1'} - \frac{\mathbf{p}}{1+\mu_1}\right)^2 + \left(2 - \frac{1}{1+\mu_1}\right)\frac{\hbar^2}{2m_h}\left(\mathbf{p} + \frac{\mathbf{k}_{2'}}{2-1/(1+\mu_1)}\right)^2 + \left(\frac{\mu_1 - \mu_2 - 2\mu_1\mu_2}{1+2\mu_1}\right)\frac{\hbar^2}{2m_h}k_{2'}^2, \tag{3}$$

where

$$\mathbf{p} = \mathbf{k}_{1'} - \mathbf{k}_1 = \mathbf{k}_2 - \mathbf{k}_{2'} \tag{4}$$

and

$$\mu_1 = m_h/m_c \text{ and } \mu_2 = m_h/m_s. \tag{5}$$

In direct band-gap bulk III-V semiconductors $m_h$ is always greater than $m_s$ and the coefficient

$$C = (\mu_1 - \mu_2 - 2\mu_1\mu_2)/(1+2\mu_1), \tag{6}$$

is always negative. However, in two-dimensional structures, such as strained quantum well structures,[9] it is possible to have $m_h$ sufficiently smaller than $m_s$ so that the coefficient $C$ is positive. If $C$ is positive, depending on the sign of $E_g - \Delta$, two unusual phenomena may occur. If $\Delta > E_g$ the Auger process has an antithreshold[10] and the Auger recombination rate is greater than that in a structure with $C$ negative. If $\Delta < E_g$ Eq. (3) is always positive and can never equal zero, as required by energy conservation. In other words the Auger process is forbidden.

The $k\cdot p$ model of heavy hole and light hole bands of a strained quantum well starts with the Luttinger–Kohn Hamiltonian[11,12] for the bulk material:

$$H = H(k_x,k_y,k_z) = \begin{pmatrix} 4P+Q+S & 0 & R & -T \\ 0 & P+Q+S & T^* & R^* \\ R^* & T & P-Q-S & 0 \\ -T^* & R & 0 & P-Q-S \end{pmatrix}, \tag{7}$$

where

$$P = -\gamma_1\frac{\hbar^2}{2m}(k_x^2 + k_y^2 + k_z^2), \tag{8}$$

$$Q = -2\gamma_2\frac{\hbar^2}{2m}(k_x^2 + k_y^2 - 2k_z^2), \tag{9}$$

$$R = \sqrt{3}\frac{\hbar^2}{2m}[\gamma_2(k_x^2 - k_y^2) - 2i\gamma_3 k_x k_y], \tag{10}$$

$$T = 2\sqrt{3}\gamma_3\frac{\hbar^2}{2m}(k_x - ik_y)k_z, \tag{11}$$

and $S$ is the strain potential. $m$ is the free-electron mass and $\gamma_i$ are the Luttinger–Kohn parameters.

We proceed to follow the procedure used in the unstrained quantum well problem.[13] Assuming that the barrier height of the strained quantum well is infinite and the well width is $d$, we find the eigenenergy $\epsilon(\mathbf{k}_t)$ is the solution of the equation

$$\sin(k_1 d)\sin(k_2 d)\{(|R|^2 + |T_1|^2)(|R|^2 + |T_2|^2) + (P_1 + Q_1 + S - \epsilon)(P_2 - Q_2 - S - \epsilon) \times [(P_2 + Q_2 + S - \epsilon)(P_2 - Q_2 - S - \epsilon) - 2R^2]\} = 2[1 - \cos(k_1 d)\cos(k_1 d)](P_1 + Q_1 + S - \epsilon) \times (P_2 - Q_2 - S - \epsilon)T_1 T_2, \tag{12}$$

where $P_i$, $Q_i$, and $T_i$ are the $P$, $Q$, and $T$ with $k_z$ substituted by $k_i(\epsilon)$, $i = 1, 2$. $k_1$ and $k_2$ are respectively solutions of the equations

$$P_1 - \epsilon = \sqrt{(Q_1 + S)^2 + T_1^2}$$

and

$$P_2 - \epsilon = -\sqrt{(Q_2 + S)^2 + T_2^2}. \tag{13}$$

Equation (12) gives the in-plane dispersion relation of the strained quantum well. At $k_t = 0$, the heavy and light hole $n$th subband levels are

$$\epsilon_{h,l}^{(n)} = \pm S \mp (\gamma_1 - 2\gamma_2)\frac{\hbar^2}{2m}\left(\frac{n\pi}{d}\right)^2, \quad n = 1,2,..., \tag{14}$$

where the upper signs are for the heavy hole subbands, the lower signs for the light hole subbands.

The effective masses of the heavy hole and the light hole at the zone center can also be derived from Eq. (12). In the [100] or [010] direction they are

$$\frac{m}{m_{h,l}^{(n)}} = -\gamma_1 \mp \left[\gamma_2 - \frac{6\gamma_3^2 K^2}{S/(\hbar^2/2m) + 2\gamma_2 K^2}\right] - (\gamma_1 \mp 2\gamma_2) \times \frac{12\gamma_3^2 K^2 K'}{d[S/(\hbar^2/2m) + 2\gamma_2 K^2][S/(\hbar^2/2m) + 2\gamma_2 K'^2]} \times \frac{\cos(K'd) + (-1)^{n+1}}{\sin(K'd)}, \tag{15}$$

where

$K = n\pi/d$ and

$$K' = \sqrt{[(\gamma_1 \mp 2\gamma_2)K^2 - 2S/(\hbar^2/2m)]/(\gamma_1 \pm 2\gamma_2)}. \tag{16}$$

Under the isotropic band assumption ($\gamma_3 = \gamma_2$), Eq. (15) applies in other directions as well. When $S = 0$ and $\gamma_3 = \gamma_2$ Eq. (15) is identical to the results given by Nedorezov.[13,14] When $d$ increases to infinity, Eq. (15) gives the effective hole masses in the strained bulk material.[14]

Figure 2 shows the in-plane dispersion relation of $In_xGa_{1-x}Sb$/AlGaSb strained quantum wells with $x = 0.15$ and $x = 0.25$. The parabolic approximation is good to about $2k_BT$ below the first heavy hole subband edge at room temperature. Figure 3 shows the $C$ coefficient and $\delta E = E_g - \Delta$. The CHHS Auger process is forbidden

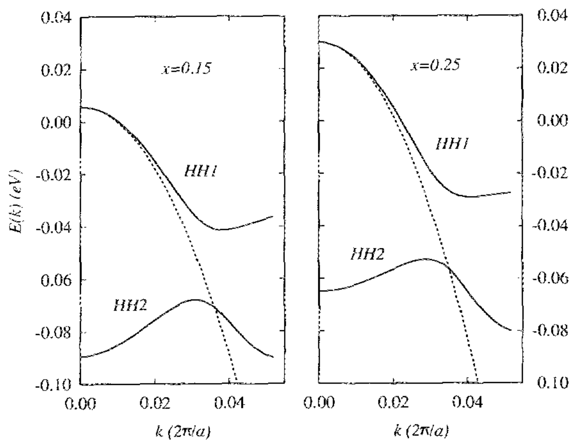


FIG. 2. In-plane dispersion relations of strained $In_xGa_{1-x}Sb/AlGaSb$ quantum wells, $d = 60$ Å. Only the first and second heavy hole subbands calculated from Eq. (12) (solid curves) are shown. The dotted curves are the parabolic fit to the first heavy hole subband with the effective masses calculated from Eq. (15).

when they are both positive. These conditions are satisfied when the well width $d < 75$ Å for $x = 0.2$ and when $d < 70$ Å for $x = 0.25$. If we make the strained quantum well lasers within the thickness limit obtained above so that the CHHS Auger recombination is forbidden, the lasers should show low threshold currents and good temperature performance. Our results can obviously be applied to strained quantum wells with finite barrier height as well.[15]

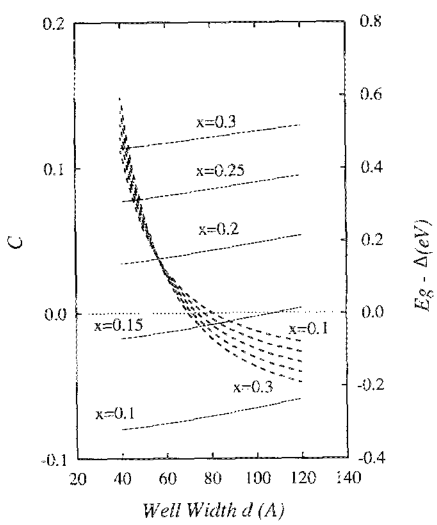


FIG. 3. $C$ coefficient (solid curves) and $\delta E = E_g - \Delta$ (dashed curves) with various values of the well width $d$ for $x = 0.1$, 0.15, 0.2, 0.25, and 0.3.

In conclusion, we have shown that the CHHS Auger recombination process can be suppressed in strained quantum wells. As a result, low threshold and good temperature performance can be achieved in strained quantum well lasers. We provide a criterion for the band structure parameters to achieve the suppression and also the analytic expression for the in-plane effective masses in a strained quantum well. InGaSb/AlGaSb strained quantum wells have been used as the principal example. The phenomenon of forbidden Auger process can occur in the InGaAs/InP strained quantum well structures as well.

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