

Mid infrared range laser based on intersubband transitions and resonant Auger processes in quantum wells

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Abstract. A new type of mid infrared semiconductor laser based on intersubband optical electron transitions in type II quantum wells with electrical or optical pumping is suggested. Inversion of population is created due to special shape of quantum well and resonant Auger recombination providing additional pumping of excited level.

Semiconductor lasers of mid infrared range (MIR, $\lambda > 4 \mu\text{m}$) have a large number of applications. Development of MIR injection lasers based on interband electron-hole optical transitions comes up against the fundamental problems. The main difficulty is the increase of Auger recombination with decrease of forbidden gap. Because of this in last years the possibility of development of MIR lasers based on intersubband (intraband) optical electron transitions in quantum wells (QWs) is intensively explored. Up to now, among the numerous ideas only two was realized. It is the unipolar quantum cascade laser (QCL) [1] based on idea of Kasarinov and Suris [2] and the unipolar fountain laser (FL) with optical pumping [3]. However, the fabrication of QCL needs a complicated technology. The necessity of powerful optical pumping at wavelength closed to the one of generation restricts the practical use of FL.

The interband cascade lasers (ICL) based on interband electron transitions in type II quantum wells [4] represent a special class of lasers. QWs in them include Sb-containing semiconductor solid solutions. Up to now lasers of this type have emission wavelength not exceeding $4 \mu\text{m}$. Nevertheless, the threshold current of ICL J_{th} is significantly less in comparison with QCL, so they seem more perspective.

In the present work a new type of laser based on intersubband carrier transitions and resonant Auger processes in Sb-based type II QWs is offered. Usually, nonradiative Auger recombination plays a negative role in injection lasers but for the first time in this laser the resonant Auger recombination is the important positive factor.

The mechanism of creation of population inversion (PI) is illustrated in Fig. 1. QW for electrons has a shape of asymmetrical funnel. The energy differences $E_{e3} - E_{e2}$ and $E_{e2} - E_{e1}$ exceed the energy of optical phonon $\hbar\omega_{\text{LO}}$. So, the electron lifetime τ_3 on level e_3 genetically coupled with wide part of QW is great due to weak overlapping wave functions of levels $e_3 - e_2$ and $e_3 - e_1$. At the same time the wave functions of levels e_2 and e_1 are strongly overlapped. The electron lifetime τ_2 on level e_2 is approximately equal to the time of intersubband electron transition with emission of optical phonon. As it follows from calculations, τ_3 is approximately an order more. This difference between lifetimes assists the creation of population inversion between levels e_3 and e_2 ($n_3 > n_2$, where n_i is the electron concentration on level i). PI can be destroyed due to $e - e$ interaction if the concentration n_1 becomes great. It may be prevented by fast depopulation of level e_1

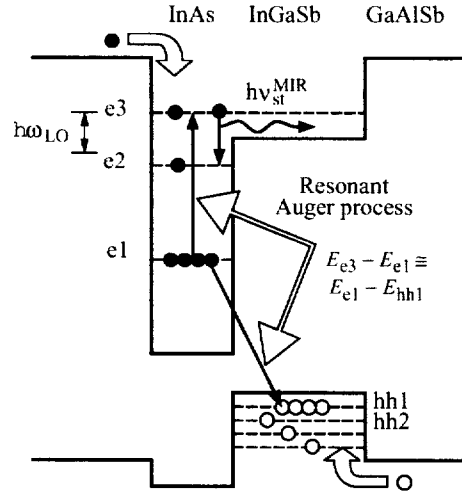


Fig. 1. The potential profile of quantum well and diagram of Auger processes.

connected with Auger recombination. Under the resonance the Auger recombination related lifetime can be sufficiently small. Moreover, the resonant Auger processes additionally pump the level $e3$ (as it is shown by vertical arrows in Fig. 1). So, there are two positive factors arising due to resonant Auger processes: concentration pinning at lowest energy level and additional pumping of excited level.

A set of rate equations describing the variation of electron concentration at levels $e1$, $e2$ and $e3$ under pumping current density J has a form:

$$\frac{dn_3}{dt} = \eta \frac{J}{e} A_3 - \frac{n_3}{\tau_{32}} - \frac{n_3}{\tau_{31}} + \frac{n_1}{\tau_A} \quad (1)$$

$$\frac{dn_2}{dt} = \eta \frac{J}{e} A_2 + \frac{n_3}{\tau_{32}} - \frac{n_2}{\tau_{21}} + n_1 \beta \quad (2)$$

$$\frac{dn_1}{dt} = \eta \frac{J}{e} A_1 + \frac{n_2}{\tau_{21}} + \frac{n_3}{\tau_{31}} - 2 \frac{n_1}{\tau_A} - n_1 \beta. \quad (3)$$

Here η is the electron (hole) loss factor due to $e-h$ recombination beyond the QWs ($\eta < 1$); A_i determine the capture of electrons on levels ($A_1 + A_2 + A_3 = 1$, accordingly to calculations $A_3 \gg A_1, A_2$); τ_{ij} are the electron lifetimes related with intersubband $i \rightarrow j$ transitions with emission of LO phonons (it should be noted that intrasubband lifetimes $\tau_{ii} \ll \tau_{ij}$); τ_A is the lifetime related to the resonant Auger process ($\tau_A^{-1} \propto n_1 p_1 \approx n_1^2$). Last terms in (2),(3) describe thermal excitation ($\beta \propto \tau_{21}^{-1} \exp[-(E_{e2} - E_{e1})/k_B T]$).

Stationary solution of (1-3) gives for PI value and for concentration n_1 :

$$n_3 - n_2 = \eta \frac{J}{e} \left[(A_1 + A_2 + 2A_3) \frac{\tau_{31}(\tau_{32} - \tau_{21})}{\tau_{32} + \tau_{31}} - A_2 \tau_{21} - n_1 \exp\left(-\frac{E_{e2} - E_{e1}}{k_B T}\right) \right] \quad (4)$$

$$n_1 = \tau_A \eta \frac{J}{e}. \quad (5)$$

Amplification coefficient due to intersubband optical electron transitions $e3 \rightarrow e2$ is given by:

$$\alpha_{32} = \frac{4\pi^2 e^2 (n_3 - n_2) \omega_{32}}{c \sqrt{\varepsilon} L_W} |Z_{32}|^2 \frac{1}{\pi} \frac{\gamma}{\gamma^2 + (\hbar\omega - \hbar\omega_{32})^2}, \quad (6)$$

where ε is high frequency dielectric permittivity, L_W is QW width, Z_{32} is the coordinate matrix element, γ is line broadening.

To obtain MIR stimulated emission the following condition has to be satisfied:

$$\Gamma \alpha_{32} = \frac{1}{l_R} \ln \left(\frac{1}{R} \right) + \alpha_{\text{loss}}, \quad (7)$$

where Γ is optical confinement factor, l_R is resonator length, R is mirror reflection coefficient, α_{loss} describes losses in waveguide and active layers.

Calculations give the value of α_{32} approximately 68 cm^{-1} for 10 layers of QWs embedded in i -layer of the structure (waveguide for $\lambda \cong 10 \mu\text{m}$ with $\Gamma \cong 0.1$) under losses $\alpha_{\text{loss}} = 0$, $R \cong 0.36$, $l_R = 1.5 \text{ mm}$. Let now estimate the threshold current J_{th} or threshold intensity of interband ($h\nu > E_{e3} - E_{hh3}$) optical pumping P_{th}^v for stimulated MIR emission. Accordingly to calculations the electron lifetimes in QW are: $\tau_{32} \cong 6 \text{ ps}$, $\tau_{21} \cong 0.4 \text{ ps}$, $\tau_{31} \cong 20 \text{ ps}$. Assuming the temperature is low (thermal excitation is negligible: $E_{e2} - E_{e1} \gg k_B T$) we obtain: $\eta J_{\text{th}} \cong 2 \cdot 10^3 \text{ A/cm}^2$ or $P_{\text{th}}^v \cong 4 \cdot 10^3 \text{ W/cm}^2$ at $\lambda^{\text{pump}} = 0.5 \mu\text{m}$. The last value is rather small. For structure area $S = 1.5 \text{ mm} \times 200 \mu\text{m}$ the threshold intensity $P_{\text{th}}^v \cdot S = 12 \text{ W}$. This intensity can be provided with semiconductor laser.

The level of concentration n_1 is very important for threshold current (or threshold intensity of optical pumping). This concentration can be calculated from (5).

Let now calculate τ_A . In order to determine the probability of Auger recombination or Coulomb electron excitation from ground state ($e1$) to excited state ($e3$) we used 4-band Kane model. The electron and hole wave functions are found in terms of superposition of band states of s - and p -types. Rate of electron Auger excitation is calculated in frames of second order of perturbation theory on electron-electron interaction:

$$G = \frac{2\pi}{\hbar} \sum |M|^2 \delta(E_{e1} + E'_{e1} - E_{e3} - E_{hh1}) f_{e1}(\mathbf{k}) f_{e1}(\mathbf{k}') f_{hh1}(\mathbf{k}), \quad (8)$$

where f_{e1} , and f_{hh1} are the electron and hole distribution functions, E_{e1} , E'_{e1} are the initial electron states and E_{e3} , E_{hh1} are the final ones. The summation is over all initial and final states. The matrix element of Coulomb electron interaction can be expressed as

$$M = \frac{4\pi e^2}{\kappa_0} \int \frac{d^3 q}{(2\pi)^3} \frac{1}{q^2} I_{12}(\mathbf{q}) I_{34}(-\mathbf{q}), \quad (9)$$

where

$$I_{12}(\mathbf{q}) = \int \psi_{e1}^*(\mathbf{r}) \psi_{e3}(\mathbf{r}) e^{i\mathbf{q}\mathbf{r}} d^3 r, \quad (10)$$

$$I_{34}(-\mathbf{q}) = \int \psi_{e1}^*(\mathbf{r}') \psi_{hh1}(\mathbf{r}') e^{-i\mathbf{q}\mathbf{r}'} d^3 r'$$

and \mathbf{q} is the momentum transferred at Coulomb interaction. It should be noted that $I_{12}(\mathbf{q})$ is proportional to overlap integral of localized electron states and $I_{34}(-\mathbf{q})$ is proportional to overlap integral of localized electrons and holes.

Taking in (9) integration over \mathbf{q} and using an explicit form of electron and hole wave functions we can obtain the final expression for matrix element. Let us next substitute the expression obtained for matrix element in (8). Taking in (8) integration over initial and final particle states we obtain the expression for inverse time of electron Coulomb excitation under resonant conditions:

$$\frac{1}{\tau_A} = \frac{G}{n_1} = 8\pi \frac{E_B}{\hbar} \left(\frac{E_{e1}}{k_B T} \right)^2 \frac{m_c}{m_h} \lambda_{E_g}^2 |\mathbf{d}_{13}|^2 n_1 p_1. \quad (11)$$

Here n_1 and p_1 are the concentrations of 2D electrons and holes; m_c and m_h are effective masses of electrons and holes; \mathbf{d}_{13} is dipole matrix elements of electron transition from ground state ($e1$) to excited state ($e3$); $E_B = m_c e^4 / 2\hbar^2 \kappa_0$ is Bohr energy of electron; $\lambda_{E_g} = \hbar / (2m_c \tilde{E}_g)^{1/2}$, $\tilde{E}_g = E_{e1} - E_{hh1}$.

Using (5), (11) and substituting the parameters for InAs/GaSb QW for J_{th} or P_{th}^n we obtain $\tau_A \approx 10^{-11}$ s and $n_1 \cong 2.3 \cdot 10^{11}$ cm $^{-2}$. It is rather small value allowing do not take into account influence of electron collisions from different subbands on PI formation.

It should be noted that the dependence of τ_A upon resonance detuning is weak if detuning $(E_{e3} - E_{e1}) - (E_{e1} - E_{hh1}) < k_B T$. So, it is not necessary to satisfy precisely the resonance conditions what simplifies structure growth.

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