Auger carrier capture kinetics in self-assembled quantum dot structures

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We establish rate equations to describe Auger carrier capture kinetics in quantum dot structures, calculate Auger capture coefficients for self-assembled quantum dots, and analyze Auger capture kinetics using these equations. We show that Auger capture times can be of the order of 1–100 ps depending on barrier carrier and dot densities. Auger capture rates depend strongly on dot diameters and are greatest at dot diameters of about 10–20 nm. © *1998 American Institute of Physics.* [S0003-6951(98)01501-0]

Self-assembled quantum dot semiconductor lasers were realized during the past few years,[1–6] and continue to attract much attention due to their interesting physics and potential applications. In these lasers, carriers are pumped into barriers around the self-assembled dots (SADs) and are then captured by the SADs, and relax via 0D energy levels to the low-lying lasing ones. These relaxation processes can strongly affect laser characteristics such as threshold current, efficiency, and modulation characteristics, and are currently under intense study.[7–12] While in quantum well lasers, fast carrier capture and relaxation are mediated by carrier-LO phonon interactions, in quantum dot (QD) structures, carrier relaxation via LO phonon scattering is highly improbable due to the discrete feature of the QD energy levels and the fixed energies of LO phonons. Nevertheless, fast relaxation with characteristic times of the order of 10–100 ps has been observed experimentally,[9,10] the relaxation being ascribed to multiphonon-carrier interactions and to carrier-carrier Coulomb interactions (Auger processes). The importance of Auger relaxation in QDs has already been discussed.[13,14] In this letter, we study Auger carrier capture in SAD structures, formulate Auger carrier kinetics equations, obtain simple expressions for the Auger coefficients, and estimate various characteristic times for Auger capture.

We consider Auger carrier capture processes in InAs/GaAs self-assembled quantum dot structures. Generally in experiments, the carriers which are injected electrically or optically into the GaAs barriers, and are free to move in 3D, are captured very rapidly by the lower-band gap 2D wetting layer (WL). We may therefore assume that the carriers are effectively injected directly into the WL, and then they are captured by the SADs or recombine in the wetting layer. In the following analysis, we consider only Auger capture events involving electron and hole ground states in the SADs. (This simple model can readily be generalized to take into account other SAD energy levels.) The binding energies of the electron and hole states (see Fig. 1) are represented by ϵ_{De} and ϵ_{Dh}, respectively. In typical InAs/GaAs SADs, $\epsilon_{\mathrm{Dh}} > \epsilon_{\mathrm{De}}$, and $(\epsilon_{\mathrm{Dh}} - \epsilon_{\mathrm{De}}) = 0.1 - 0.2$ eV.[9] In the WL, the electron and hole binding energies are ϵ_{We} and ϵ_{Wh} (~0.05–0.1 eV), hence the binding energies relative to the wetting layer are $\Delta\epsilon_e = (\epsilon_{\mathrm{De}} - \epsilon_{\mathrm{We}})$ and $\Delta\epsilon_h = (\epsilon_{\mathrm{Dh}} - \epsilon_{\mathrm{Wh}})$, with $\Delta\epsilon_h > \Delta\epsilon_e$. We consider two types of Auger capture processes: in process I, for instance, a 2D electron (Fig. 1) or 2D hole [Fig. 2(a)] in the wetting layer collides with a 2D electron and is captured by the SAD, the other 2D electron being scattered into a 2D state in the WL with higher energy. Similar processes of this type occur involving 2D holes. In process II, a 2D hole is captured by the SAD due to Coulomb scattering with a previously captured electron, the electron being excited into a 2D state in the WL [Fig. 2(b)]. Let us note that since $\Delta\epsilon_h > \Delta\epsilon_e$, the process when a 2D electron is captured with simultaneous excitation of a hole from a 0D state in the SAD to a 2D state in the WL is a process of thermal excitation of the system. We assume further that the characteristic energies $\Delta\epsilon_e$, $\Delta\epsilon_h$, $(\Delta\epsilon_h - \Delta\epsilon_e)$ in the Auger processes under study are much larger than the thermal energy $k_B T$ (where T is the *carrier* temperature in the WL) and the Fermi levels in the WL, and consequently we neglect the effects of thermal excitation processes.

With these simplifying assumptions, the Auger carrier capture kinetics in the SAD structure can be described by the rate equations:

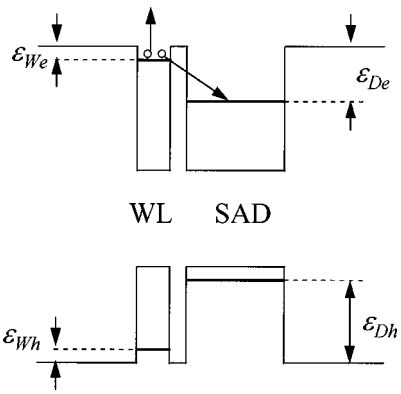

FIG. 1. Schematic energy band diagram of a SAD structure. The self-assembled dot (SAD) is separated from the wetting layer (WL) by a thin barrier. For example, two 2D electrons (open circles) collide in the WL, resulting in one of them being captured by the SAD and the other being promoted to higher energy in the WL (type I process, see the text). This process is characterized by the Auger capture coefficient C_{ee}.

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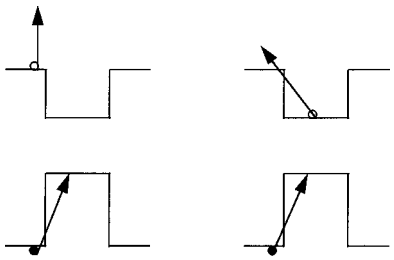

FIG. 2. (a) Auger capture process of type I represented by the coefficient C_{he}: a 2D hole collides with a 2D electron, and is captured by the SAD, the 2D electron remaining in the WL; (b) Auger capture of type II characterized by the coefficient B_{he}: a 2D hole is captured by the SAD due to Coulomb interaction with a previously captured 0D electron; the latter is excited from the SAD into the WL.

$$\frac{dn_e}{dt}=-B_W^{\mathrm{rec}}n_e n_h+B_{\mathrm{he}}n_h f_e(1-f_h)N_D-C_{\mathrm{ee}}n_e^2(1-f_e)N_D-C_{\mathrm{eh}}n_e n_h(1-f_e)N_D+J, \tag{1}$$

$$\frac{df_e}{dt}=-B_D^{\mathrm{rec}}f_e f_h-B_{\mathrm{he}}n_h f_e(1-f_h)+C_{\mathrm{ee}}n_e^2(1-f_e)+C_{\mathrm{eh}}n_e n_h(1-f_e), \tag{2}$$

$$\frac{dn_h}{dt}=-B_W^{\mathrm{rec}}n_e n_h-B_{\mathrm{he}}n_h f_e(1-f_h)N_D-C_{\mathrm{hh}}n_h^2(1-f_h)N_D-C_{\mathrm{he}}n_h n_e(1-f_h)N_D+J, \tag{3}$$

$$\frac{df_h}{dt}=-B_D^{\mathrm{rec}}f_e f_h+B_{\mathrm{he}}n_h f_h(1-f_h)+C_{\mathrm{hh}}n_h^2(1-f_h)+C_{\mathrm{he}}n_h n_e(1-f_h). \tag{4}$$

Here n_e and n_h are the 2D densities of electrons and holes in the WL respectively, f_e and f_h the respective occupation probabilities of the electron and hole levels in the SAD. J is the pumping rate and N_D is the number of SADs per unit area. The first terms on the right side of Eqs. (1)–(4) describe the recombination of electrons and holes in the WL and in the SADs, the second terms describe Auger hole capture of type II, while the third and fourth terms describe type I Auger capture. The terms with the coefficients C_{cs} (where c or $s=e,h$, where e represents electrons and h holes) describe Auger processes in which a 2D carrier (the captured carrier c) collides with another 2D carrier (the scattering carrier s) and is captured by the SAD, the scattered carrier gaining energy but remaining in the WL. In general, the Auger capture coefficients B_{he} and C_{cs} depend on the carrier densities n_e and n_h but within our assumption of moderate carrier temperatures and densities these dependences may be ignored. In effect, the above representation of the Auger capture rates can be considered as a truncated expansion in powers of the carrier densities, and in this form it may have very general significance for the description of Auger carrier kinetics in quantum dot structures. Next, we provide the results of our calculations of the Auger capture coefficients.

Our calculations have followed the approach of Uskov *et al.*[15] in calculating Auger carrier relaxation via 0D energy levels in SADs, but unlike Ref. 15 we are not restricted to the dipole approximation in calculating the transition matrix elements. Starting with Fermi's Golden Rule we obtain the differential cross sections for Coulomb scattering of the carriers, the integrated cross sections, and finally the Auger capture rates. In accordance with our assumption of moderate carrier temperatures and densities, we neglect the initial energies of scattered carriers in comparison with the characteristic energies of the Auger processes. We have also assumed[9] that the SADs have uniform cylindrical shapes with height H and diameter D. As result of these simplifications, we derived the following expressions for the Auger capture coefficients:

$$B_{\mathrm{he}}=\frac{m_e e^4}{4\xi_{01}^4\hbar^3\epsilon_0^2\epsilon^2}\cdot\frac{D^2}{H^2}\cdot\frac{(\kappa_D+\kappa_W)^2}{\kappa_D^4\kappa_W^2}\times\frac{J_0^2(q_{\mathrm{he}}D/2)}{[(q_{\mathrm{he}}D)^2/(4\xi_{01})^2-1]^2}\cdot F^2, \tag{5}$$

$$C_{\mathrm{cs}}=\frac{\pi m_s e^4}{4\xi_{01}^2\hbar^3\epsilon_0^2\epsilon^2}\cdot\frac{D^2}{H}\times\frac{\kappa_W(\kappa_D+2\kappa_W+2q_s)^2}{q_s^2(\kappa_W+q_s)^2(\kappa_D+\kappa_W+q_s)^2}\times\frac{J_0^2(q_sD/2)}{[(q_sD)^2/(4\xi_{01})^2-1]^2}, \tag{6}$$

where m_s represents the effective masses of scattered carriers in the WL (with $s=e,h$); ϵ_0 is the vacuum permittivity; ϵ is the relative permittivity; $J_0(x)$ is the zero order Bessel function of the first kind and $\xi_{01}=2.4$ is the value of its first root; $q_{\mathrm{he}}=\sqrt{2m_e(\Delta\epsilon_h-\Delta\epsilon_e)}/\hbar$ is the wave number of an electron excited into the WL as a result of a process of type II, while $q_s=\sqrt{2m_s\Delta\epsilon_c}/\hbar$ is the wave number of a scattered carrier which has received an energy increment $\Delta\epsilon_c$ from a captured carrier (with $c=e,h$), W is the thickness of the WL, κ_D and κ_W are the, respective, characteristic decay constants of the wave functions in the GaAs barriers surrounding the SAD and WL, which depend on the carrier binding energies. Finally, the function F is given by the integral

$$F=\int_0^\infty du\cdot\frac{J_0(u)}{(u/\xi_{01})^2-1}\times\frac{1+[2u/(\kappa_D+\kappa_W)]D}{[1+(2u/\kappa_D D)][1+(2u/\kappa_W D)]}. \tag{7}$$

From Eqs. (5) and (6), we find that the Auger coefficients depend strongly on the SAD diameter D: they oscillate and decrease as $1/D^3$ at large D (see Figs. 3 and 4). These results were plotted for $H=5$ nm, $\epsilon_{\mathrm{De}}=0.2$ eV, $\epsilon_{\mathrm{Dh}}=0.3$ eV, $\epsilon_{\mathrm{We}}=0.03$ eV, $\epsilon_{\mathrm{Wh}}=0.05$ eV. Values of the effective masses have been taken from Ref. 9. Figure 3 shows that Auger capture due to scattering by electrons (represented by the coefficients C_{ee} and C_{he}) are more effective than those involving hole scattering (coefficients C_{eh} and C_{hh}). For $D=10$–15 nm,[9,10] where the Auger coefficients are close to their maximum value, $B_{\mathrm{he}}=3\times10^{-4}$ m^2/s and $C_{\mathrm{ee}}=2\times10^{-20}$ m^4/s.

From these values, we can estimate various Auger capture times, a very important consideration for luminescence

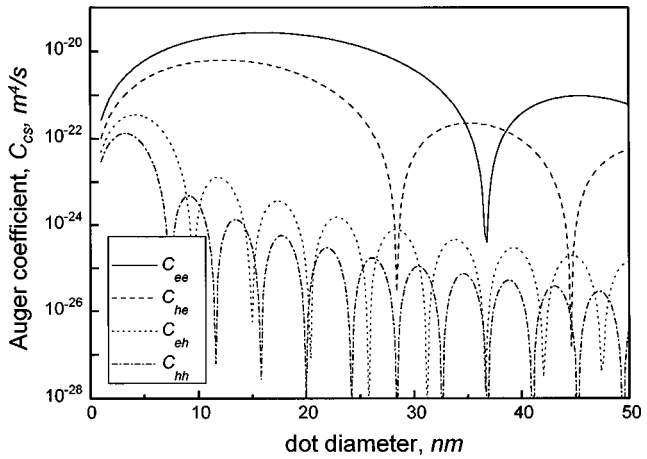

FIG. 3. The dependence of the Auger capture coefficients C_{ee}, C_{he}, C_{eh}, and C_{hh} on the diameter D of cylindrical quantum dots for given binding energies of carriers in the SAD.

and laser dynamics. The luminescence rise time as found in time resolved experiments[9,10] is defined by the QD level population rise time which can be expressed in accordance with (2) and (4) as

$$\tau_{\mathrm{rise}}=\frac{1}{Cn_{\mathrm{in}}^2}, \tag{8}$$

(where $C\sim C_{\mathrm{ee}}\sim C_{\mathrm{he}}$) and hence this time should be limited only by the initial carrier density n_{in} in the WL. Assuming a typical range, $n_{\mathrm{in}}\approx 10^{15}-10^{16}\ \mathrm{m}^{-2}$ gives a characteristic time of 1–100 ps depending on the pump power.[9,10] On the other hand, in lasing experiments such as those of Ref. 16, the effective capture time which is given accordingly to (1) and (3) as

$$\tau_{\mathrm{capt}}=\frac{1}{CnN_D} \tag{9}$$

(where we assume $n\sim n_e\sim n_h$), influences laser dynamics, and this time also depends on the number density N_D of SADs per unit area. Assuming $N_D=10^{15}-10^{16}$ and $n=10^{15}-10^{16}\ \mathrm{m}^{-2}$, we obtain $\tau_{\mathrm{capt}}\sim 1-100$ ps.

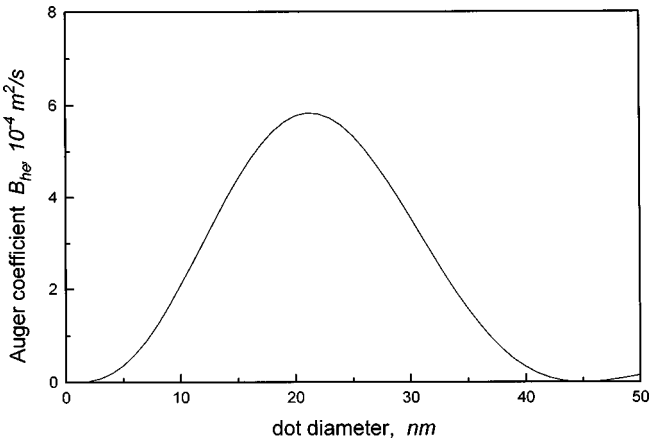

FIG. 4. The dependence of the Auger capture coefficients B_{he}, on the quantum dot diameter for given binding energies of carriers in the SAD.

Finally, the efficiency of Auger carrier capture by SAD can be characterized by the ratio η of the capture rate to the full rate of carrier removal (capture plus recombination) from the wetting layer. Our present model gives

$$\eta=\frac{CN_D}{B_W^{\mathrm{rec}}+CN_D}, \tag{10}$$

which again depends on N_D. Inserting $B_W^{\mathrm{rec}}\sim 10^{-6}\ \mathrm{m}^2/\mathrm{s}$ and $N_D=10^{15}-10^{16}\ \mathrm{m}^{-2}$ into (10) gives $\eta=0.9$–0.99, indicating that there should be no carrier capture ''bottleneck'' in a dense array of SADs.

In conclusion, we have formulated kinetic equations to describe Auger carrier capture in SAD structures and obtained simple expressions for the Auger coefficients. We have estimated the importance of the various processes, and found characteristic capture times for time resolved luminescence and lasing experiments, and the efficiency of carrier capture by the SADs. The latter estimates have shown the possibility of highly efficient Auger carrier capture in SAD structures.

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