Mechanism for a suppression of Auger recombination in type-II heterostructures

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The mechanism for Auger recombination in type-II heterostructures is studied theoretically for the first time. The rate of this recombination is a power-law function of the temperature, not an exponential function, as it is in the bulk material. A suppression of Auger recombination in type-II heterostructures is predicted. This suppression would stem from the short-range nature of the Coulomb interaction of the electrons involved in the recombination. A suppression of Auger recombination at type-II heterostructures has recently been observed experimentally.
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Type-II heterostructures have the following distinctive features:[1] 1) There are offsets of the conduction band (V_c) and of the valence band (V_v), which go in the same direction (Fig. 1) and which differ in sign ($V_c>0$, $V_v=-|V_v|<0$). 2) The electrons and holes are spatially separated, in contrast with the situation in type-I heterostructures, so they can recombine only if there is a mutual tunneling through the heterojunction barrier. To the best of our knowledge, the literature has no reports of a theoretical study of Auger recombination in type-II heterostructures. As is shown in the present letter, however, Auger recombination must be taken into account in (for example) an analysis of the lifetime of nonequilibrium carriers in type-II heterostructures. As was shown in Ref. 2, the mechanisms for Auger recombination in heterostructures and in bulk semiconductors are quite different. In a heterostructure, Auger recombination does not require the attainment of a threshold, because of the interaction of carriers with the heterojunction, and because there is no requirement that the quasimomentum component perpendicular to the heterojunction be conserved. The rate of the recombination is a *power-law* function of the temperature. We recall that in a bulk semiconductor the rate of Auger recombination is an *exponential* function of the temperature.[3] We show below that the rate of Auger recombination in a type-II heterostructure is again a power-law function of the temperature, but the mechanisms for the recombination are fundamentally different in heterostructures of types I and II.

Our purpose in this letter is to theoretically examine Auger recombination in type-II heterostructures.

There are two important mechanisms for Auger recombination in type-II heterostructures. 1) There is the Auger process involving two electrons and one hole (the CHCC process). 2) There is the Auger process involving an electron and a hole, with a transition of a second hole into the SO (spin–orbit) band (the CHHS process). We restrict the

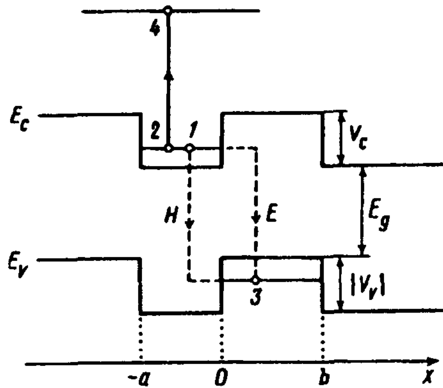

FIG. 1. Schematic energy-band diagram of a type-II heterostructure with quantum wells. 1, 2—Initial states of the particles; 3, 4—final states; H, E—two possible mechanisms for the recombination of electron 1 and hole 3.

present letter to the discussion of the CHCC process (Fig. 1), since it outweighs the CHHS process under the condition $(E_g-\Delta_{SO}/E_g>m_c/m_{SO}$, where Δ_{so} is the spin–orbit splitting constant, E_g is the effective width of the band gap (Fig. 1), and m_c and m_{SO} are the effective masses of an electron and an SO hole, respectively.

The rate of Auger recombination is calculated in first-order perturbation theory in the electron–electron interaction:

$$G=\frac{2\pi}{\hbar}\frac{1}{S}\sum_{1,2,3,4}|M|^2\delta(E_1+E_2-E_3-E_4)f_c(E_1)f_c(E_2)f_h(E_3)[1-f_c(E_4)], \tag{1}$$

where $f(E_i)$ is the distribution function of particle i $(i=1,2,3,4)$, E_1 and E_2 are the energies of the initial states, E_3 and E_4 are those of the final states, S is the area of the heterojunction, and M is a matrix element of the electron–electron interaction. The summation in (1) is over the initial states (1 and 2) and the final states (3 and 4) of the particles. After an average is taken over the spin states of the particles, the square of the matrix element becomes

$$|M|^2=|M_{\rm I}|^2+|M_{\rm II}|^2-M_{\rm I}M_{\rm II}^*, \tag{2}$$

$$M_{\rm I}=\int \psi_2^*(\mathbf{r})\psi_4(\mathbf{r})\frac{e^2}{\kappa_0|\mathbf{r}-\mathbf{r}'|}\psi_1^*(\mathbf{r}')\psi_3(\mathbf{r}')d^3rd^3r', \tag{3}$$

where κ_0 is the dielectric constant of the medium. We find $M_{\rm II}$ from (3) by making the interchange $1\rightleftharpoons 2$. In (3) we expand $1/|\mathbf{r}-\mathbf{r}'|$ in a Fourier integral; we find

$$M_{\rm I}=\frac{4\pi e^2}{\kappa_0}\int\frac{d^3q}{(2\pi)^3}\frac{I_{24}(\mathbf{q})I_{13}(-\mathbf{q})}{q^2}, \tag{4}$$

where

$$I_{ij}(\mathbf{q}) = \int d^3r \psi_i^*(\mathbf{r}) \psi_j(\mathbf{r}) e^{i\mathbf{q}\cdot\mathbf{r}}. \tag{5}$$

We calculate the matrix element M from Kane's model.[4,5] At the heterojunction, the wave functions satisfy certain boundary conditions.[6] The mutual transformation of holes (light and heavy) and their interaction with the heterojunction should be taken into account. For a highly excited electron, it is particularly important to incorporate the nonparabolicity of the spectrum.[2,3,7]

The integration over q in the plane of the heterojunction in (4) leads to a conservation law for the longitudinal component of the quasimomentum: $\mathbf{k}_\parallel^{(1)} + \mathbf{k}_\parallel^{(2)} = \mathbf{k}_\parallel^{(3)} + \mathbf{k}_\parallel^{(4)}$, where $\mathbf{k}^{(i)} = (k_x^{(i)}, \mathbf{k}_\parallel^{(i)})$ is the quasimomentum of particle i. In the integration over q_x in (4) we then use the theorem of residues, finding that there are two types of poles in the complex q_x plane: 1) poles corresponding to a small momentum transfer in a Coulomb interaction (an effective long-range Coulomb interaction), $q_x = |\mathbf{k}_\parallel^{(2)} - \mathbf{k}_\parallel^{(4)}| \simeq 1/\lambda_T$, where $\lambda_T = \sqrt{\hbar^2/(2m_h T)}$; 2) poles corresponding to a large momentum transfer, an effective short-range Coulomb interaction, $q_x \simeq Q$, where $Q = 1/(\sqrt{2}\lambda_g)$, $\lambda_g = \sqrt{\hbar^2/(2m_c E_g)}$, and $\lambda_T \gg \lambda_g$. The matrix element of the Auger transition thus breaks up into two parts:

$$M = M^{(1)} + M^{(2)}. \tag{6}$$

Here $M^{(1)}$ is the part of the matrix element M which corresponds to a small momentum transfer in the course of the Coulomb interaction, and $M^{(2)}$ is the part of M which corresponds to a large momentum transfer. An effective long-range Coulomb interaction is possible in the course of Auger recombination only at heterostructures, by virtue of the interaction of carriers with the heterojunction.[2]

In heterostructures of type I, the matrix element is dominated by the term $M^{(1)}$, which corresponds to a small momentum transfer. In this case we have $M^{(2)}/M^{(1)} \approx (T/V_c)\sqrt{m_c/m_h} \ll 1$. In homogeneous semiconductors, the only contribution to the matrix element of the Coulomb interaction in the course of the Auger transition is that corresponding to a large momentum transfer.

In type-II heterostructures, the relation between $M^{(1)}$ and $M^{(2)}$ depends strongly on the parameters of the heterostructure, namely, the heights of the heterostructure barriers, V_c and V_v, and the widths of the quantum wells for electrons, a, and holes, b (Fig. 1). The following cases are possible, depending on the relation between V_c and V_v: $M^{(1)} \gg M^{(2)}$, $M^{(1)} \sim M^{(2)}$, $M^{(1)} \ll M^{(2)}$.

In type-II heterostructures, in contrast with type-I heterostructures, the CHCC process is realized by two mechanisms (Fig. 1): 1) An electron tunnels through the heterostructure barrier and recombines with a hole in a quantum well (this is mechanism E). 2) A hole tunnels through the heterostructure barrier and recombines with an electron in a quantum well (this is mechanism H). The contributions of these two mechanisms to the matrix element are on the same order of magnitude, because of the mutual transformation of light and heavy holes as they interact with the heterojunction. These contributions differ in sign; when added together, they cancel out. As a result, the matrix element for the Auger transition in a type-II heterostructure acquires an additional factor on the order of $[Tm_h/(V_c m_c)]^{3/2} < 1$, which distinguishes it from the matrix element for an Auger

transition in a type-I heterostructure. Accordingly, a destructive interference of the two mechanisms (E and H) for electron–hole recombination occurs in type-II heterostructures. This interference leads to a decrease in the matrix element and thus a decrease in the rate of Auger recombination.

Substituting the explicit expression for the matrix element M into (1), and summing over the initial and final states of the particles, we find

$$G=\tilde{G}[g_1+g_2+g_3]\equiv G_1+G_2+G_3. \tag{7}$$

Here

$$\tilde{G}=32\sqrt{2}\pi^2\frac{E_B}{\hbar}\frac{T^2}{V_cE_g}\frac{m_h^2}{m_c^2}n^2p\lambda_g^4\frac{\kappa^4\lambda_g^5}{b}\frac{\cos^4(ka/2)}{(1+\kappa a)^2}, \tag{8}$$

$$g_1\simeq\left(\frac{3V_c-|V_v|}{4V_c}\right)^2,\quad g_3\simeq\frac{m_h}{m_c}\frac{|V_v|}{8E_g}; \tag{9}$$

$$g_2\simeq\left(\frac{m_hT}{m_cV_c}\right)^{1/2}\frac{5V_c-|V_v|}{8E_g}\left[4g_1^{1/2}+\left(\frac{m_hT}{m_cV_c}\right)^{1/2}\frac{5V_c-|V_v|}{2V_c}\right], \tag{10}$$

$E_B=m_ce^4/(2\hbar^2\kappa_0^2)$ is the Bohr energy of an electron, $k^2=2m_cE_{0c}/\hbar^2$, $\kappa^2=2m_c(V_c-E_{0c})/\hbar^2$, where E_{0c} is the energy of the ground quantum-well level of the electrons, and n and p are the 2D concentrations of electrons and holes, respectively. The quantities G_1 and G_2 in (4) stem from that component ($M^{(1)}$) of matrix element M which corresponds to a small momentum transfer in the Coulomb interaction of electrons, while G_3 stems from that component ($M^{(2)}$) of M which corresponds to a large momentum transfer. Under the condition $V_c>|V_v|$ we find $G_1\sim G_2\gg G_3$ from (7)–(9). Here we have made use of the conditions $T<V_c<E_g$. We should stress that under the condition $3V_c\approx|V_v|$, i.e., $(3V_c-|V_v|)/V_c\ll 1$, we have $G_1\ll(G_2,G_3)$. Under the condition $4V_c\approx|V_v|$ we instead have $G_2\ll(G_1,G_3)$. This means that G_1 and G_2 have a minimum at the specified values of the ratio $|V_v|/V_c$ (Fig. 2). The rate of Auger recombination thus has a minimum at certain values of $|V_v|/V_c$: $G^{\min}\approx G_3$. The minimum rate of Auger recombination, $G^{\min}$, is thus determined by the matrix element of the Coulomb interaction, $M^{(2)}$, at a large momentum transfer. This statement means that there is an effective suppression of Auger recombination in type-II heterostructures, since under the condition $V_c>|V_v|$ we have $G_3\ll(G_1,G_2)$, as mentioned above.

This effective *suppression* of the rate of Auger recombination in type-II heterostructures stems from the large overlap integral $I_{24}(q)$ for an electron in initial state 2 and final state 4 in the case of a small momentum transfer q. This overlap integral consists of three regions: two regions of electron tunneling ($x<-a$ and $x>0$) and the quantum-well region ($-a<x<0$). When the contributions from these three regions are added together, it turns out that in the case of a type-II heterostructure, as in the case of type-I heterostructures, the contributions from the tunneling regions and the quantum-well region cancel out. The resultant overlap integral decreases to an extent depending on the value of $(3V_c+V_v)/E_g$. For a type-I heterostructure we have $V_v>0$, while for a type-II structure we have $V_v=-|V_v|<0$. As a result, we find that under the condition $3V_c\simeq|V_v|$ in a type-II heterostructure there is a pronounced decrease in the overlap integral $I_{24}(q)$, for

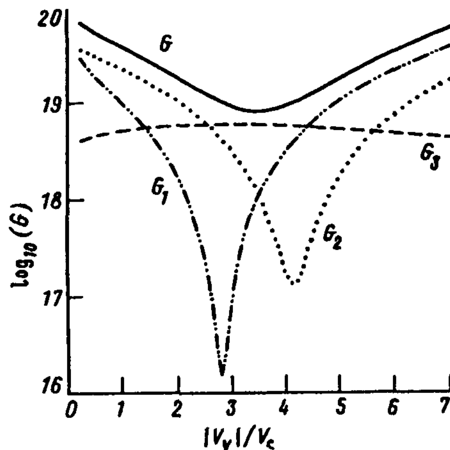

FIG. 2. Logarithm of the rate of Auger recombination, $\log_{10}(G)$, versus $|V_v|/V_c$ at $T=290$ K. Dotted and dashed curves—The components G_1, G_2, and G_3 of the total rate of Auger recombination, G; solid curve—G itself. Parameter values characteristic of an InGaAsSb/GaSb structure were used in the calculation:[1] $E_g=0.6$ eV, $V_c=0.25$ eV, $m_c=0.04m_0$, $m_h=0.4m_0$, and $n=p=7\times10^{11}$ cm^{-2}.

an electron in the initial and final states at a small momentum transfer q. This is the result of the cancellation of the contributions of the regions mentioned above to $I_{24}(q)$.

Figure 2 shows the rate of Auger recombination as a function of the ratio $|V_v|/V_c$ as calculated from (7) with the help of the exact expressions for g_1, g_2, and g_3. We found a result of fundamental importance: There is a minimum in the rate of Auger recombination at $3V_c \simeq |V_v|$. The ratio of the rate at the minimum, $G^{\min} \equiv G(3V_c \sim |V_v|)$, to that at $V_c \geqslant |V_v|$ is small: $G^{\min}/G(V_c \geqslant |V_v|) \ll 1$. The reason why this result is of fundamental importance is that it demonstrates the possibility of *suppressing* Auger recombination in type-II heterostructures. This effective suppression of Auger recombination in type-II heterostructures is a consequence of the nature of the Coulomb interaction of electrons in the course of an Auger transition. Under certain conditions ($|V_v| \leqslant V_c$) the Coulomb interaction between electrons is basically an effective long-range interaction (the momentum transfer is small), with the result that the rate of Auger recombination is large. Under other conditions ($3V_c \approx |V_v|$), the Coulomb interaction between electrons is predominantly of a short-range nature (the momentum transfer is large), so there is a sharp decrease in the recombination rate).

The suppression of Auger recombination in type-II heterostructures is of fundamental importance to the fabrication of optoelectronic devices with improved characteristics. We know that Auger recombination leads to a decrease in the internal quantum yield of quantum-well semiconductor lasers, and it also leads to a sharp increase in the threshold current density at high temperatures.[7] The mechanism predicted here for the suppression of Auger recombination in type-II heterostructures would make it possible, in particular, to solve the problem of developing long-wave lasers ($\lambda > 4$ μm); specifically, this effect would make it possible to raise their working temperatures to room temperature and above.

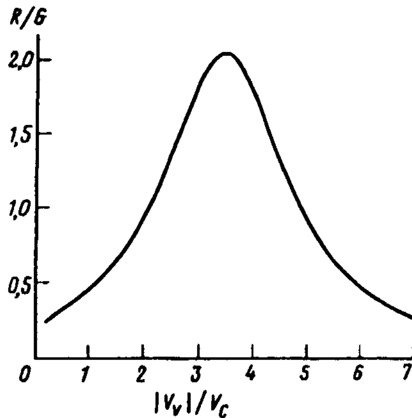

FIG. 3. Ratio of the rates of radiative recombination, R, and Auger recombination, G, versus the ratio $|V_v|/V_c$ at $T=290$ K. The parameter values of the heterostructure are the same as in Fig. 2.

Yet another important assertion can be made here. The rate of radiative recombination in type-II heterostructures, $R\equiv R_{\text{II}}$, and the rate of this recombination in type-I heterostructures, R_{I}, are on the same order of magnitude. However, the rate of Auger recombination at the minimum, $G_{\text{II}}^{\min}$, in type-II heterostructures is much lower than the rate of Auger recombination in type-I heterostructures, G_{I} (Ref. 7), for given parameter values of the heterostructure:

$$\frac{G_{\text{II}}^{\min}}{G_{\text{I}}}\sim\left(\frac{T}{V_c}\frac{m_h}{m_c}\right)^3\frac{V_c}{E_g}\ll 1. \tag{11}$$

We have calculated the rate of radiative recombination in type-II heterostructures. We allowed for the circumstance that the electrons and holes are spatially separated. Using the same method to calculate the rate of radiative recombination ($R\equiv R_{\text{II}}$) as in the case of type-I heterostructures,[7] we find

$$R_{\text{II}}\simeq\frac{\pi}{2}\frac{\varepsilon_\infty}{\sqrt{\kappa_0}}\frac{e^2}{\hbar c}\frac{E_g}{\hbar}\frac{E_g}{m_c c^2}\frac{\hbar^2 np}{2(m_c+m_h)T}\left(\frac{T}{V_c}\frac{m_h}{m_c}\right)^2, \tag{12}$$

where ε_∞ is the high-frequency dielectric constant of the medium. Using the expression for R_{I} from Ref. 7, we find a ratio $R_{\text{II}}/R_{\text{I}}\simeq[Tm_h/(V_c m_c)]^2<1$. Consequently, R_{II} and R_{I} are on the same order of magnitude.

Interestingly, the ratio of the rate of radiative recombination to the rate of Auger recombination in type-II heterostructures has a sharp maximum as a function of $|V_v|/V_c$ (Fig. 3). An important point is that for type-II heterostructures with a small effective gap width E_g the ratio R/G may be greater than one at its maximum. By optimizing the parameters of the heterostructure (to maximize the ratio R/G), we can thus achieve a maximum internal quantum yield for a long-wave laser based on a type-II heterostructure. The threshold current for such a laser would be controlled primarily by radiative recombination.

The mechanism predicted here for the suppression of Auger recombination has been observed experimentally[8] in the fabrication of a laser of a new type using a single type-II InAs/GaSb heterojunction. A suppression of Auger recombination in a type-II heterostructure with an In(As, Sb)-based superlattice has been observed in another experimental study.[9]

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[1]M. P. Mikhailova and A. N. Titkov, Semicond. Sci. Technol. **9**, 347 (1994).
[2]G. G. Zegrya and V. A. Kharchenko, Zh. Éksp. Teor. Fiz. **101**, 327 (1992) [Sov. Phys. JETP **74**, 173 (1992)].
[3]B. L. Gel'mont, Sov. Phys. JETP **48**, 268 (1978).
[4]E. O. Kane, J. Phys. Chem. Solids **1**, 249 (1957).
[5]A. V. Sokol'skii and R. A. Suris, Sov. Phys. Semicond. **21**, 529 (1987).
[6]R. A. Suris and G. G. Zegrya, Semicond. Sci. Technol. **9**, 347 (1994).
[7]G. G. Zegrya, A. D. Andreev, N. A. Gun'ko, and E. V. Frolushkina, Proc. SPIE **2399**, (1995) (to be published).
[8]M. P. Mikhailova, G. G. Zegrya, K. D. Moiseev *et al.*, Proc. SPIE **2397** (1995) (to be published).
[9]P. J. P. Tang, M. J. Pullin, S. J. Chung *et al.*, Proc. SPIE **2397** (1995) (to be published).

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