Analysis of thermally stimulated luminescence and conductivity without quasi-equilibrium approximation

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Abstract
Thermally stimulated luminescence (TSL) and conductivity (TSC) are considered using the classical insulator model that assumes one kind of active trap, one kind of inactive deep trap and one kind of recombination centre. Kinetic equations describing the model are solved numerically without and with the use of quasi-equilibrium (QE) approximation. The QE state is characterized by the parameter \(q_I = \frac{(dn_c/dt)}{I_e}\), where \((dn_c/dt)\) is the rate of change of free electron density, and \(I_e\) is the TSL intensity. The QE state parameter \(q_I\), the relative recombination probability \(\gamma = I_e/(I_e + I_t)\) (\(I_t\) is the trapping intensity) and a new parameter called a quasi-stationary (QS) state parameter \(q^*_I = q_I \gamma\) are used for the analysis of the TSL and TSC. The QE and QS states are determined by conditions \(|q_I| \ll 1\) and, respectively, \(|q^*_I| \ll 1\). The TSL and TSC curves and the temperature dependences of \(q_I\), \(q^*_I\), \(\gamma\) the recombination lifetime and the occupancies of active traps and recombination centres are numerically calculated for five sets of kinetic parameters and different heating rates. These calculation results show that (1) the upper limit of the heating rate for the presence of the QS state appears at a higher heating rate than that for the QE state when the retrapping process is present, and (2) the TSL (TSC) curves in the QS state have properties similar to those for the TSL (TSC) curves in the QE state. Approximate formulae for calculation of the parameters \(q_I\) and \(q^*_I\) in the initial range of the TSL and TSC curves are derived and used in the heating-rate methods, proposed in this work, for determination of those parameters from the calculated TSL curves.

1. Introduction

It is well known that thermally stimulated luminescence (TSL, or thermoluminescence) and thermally stimulated conductivity (TSC) are phenomena that appear when a crystal of insulator or semiconductor previously photoexcited at low temperature is next heated in the dark. The generally accepted explanation of the phenomena assumes thermal release of photoexcited charge carrier captured by trap to the delocalized band (TSC) following radiative recombination (TSL) of the carrier with the opposite-sign carrier in the recombination centre (e.g. [1, 2]). In the pioneering theories of TSL and TSC it was assumed that the thermally released carriers are in quasi-equilibrium (QE) in the delocalized band [3–7]. The assumption makes it possible to derive analytical description of the TSL and TSC curves. Later the QE assumption was often used by many authors (e.g. [8–12]) for description of the TSL and TSC processes. However, numerical solutions of the basic kinetic equations describing the TSL and TSC processes showed that the QE approximation can be questioned. Kelly et al [13] compared the results of numerical solutions of the kinetic equations with the ones obtained from the analytical expressions. They found that the QE approximation is not adequate for the low trap density (<10^{15} cm^{-3}). Later several more authors carried out numerical solutions of the kinetic equations and calculated the TSL and TSC characteristics [14–25]. Shenker and Chen [14]
found that the QE approximation in the description of TSL is true both in the weak and in the strong retrapping cases and that the level of QE deteriorates in the high temperature part of the TSL peak calculated for the strong retrapping case. Lewandowski and McKeever [15] introduced new parameters \( Q = q_1 + 1 \), and \( P \) for analysis of the validity of the QE assumption, where \( q_1 \) is the QE level parameter and \( P \) is the ratio of the retrapping rate to the recombination rate. They calculated the TSL and TSC characteristics without the QE approximation. On the basis of the results they concluded that the use of the QE approximation in the description of TSL and TSC in the case of strong retrapping is without merit. They also concluded that the slow retrapping case (first-order kinetics) satisfies the requirements of a realistic system, and this in turn may explain the apparent dominance of first-order kinetics in nature. They suggested an experimental method for determining the shape of the \( q_1(T) \) function using simultaneously measured TSL and TSC curves. The analysis of TSL and TSC without the QE approximation was developed in later works of Lewandowski and coworkers [16, 17]. However, the conclusions of Lewandowski and coworkers [15–17] are not in agreement with the results of numerical solutions of kinetic equations published by Shenker and Chen [14], Opanowicz [18, 19] and Opanowicz and Przybyszewski [20]. Elsewhere [19, 20] the TSL and TSC characteristics were calculated without the use of the QE approximation and the results were compared with the corresponding results obtained using the QE approximation. The results are as follows: (1) The QE approximation is correct with accuracy 1% when the density of the recombination centres and traps is higher than \( 10^{14} \text{ cm}^{-3} \) and the recombination coefficient is higher than \( 10^{-12} \text{ cm}^3 \text{ s}^{-1} \). (2) The QE assumption is valid for the strong retrapping case. (3) The TSL curve calculated for the strong-retrapping case can have the first-order shape. These results were later confirmed by the results of Sunta et al who analysed the TSL processes using different models [22–25]. Sunta et al [24] also found that the level of QE during the TSL emission depends on the heating rate of a sample, and that near the turning point from the QE to the non-QE state the TSL curve begins to change its shape. They used this property for the derivation of the experimental method to test whether or not the TSL emission occurs under the QE state.

In this work we report TSL and TSC curves calculated numerically (with and without the use of the QE approximation) for an insulator model with one kind of recombination centres and two kinds of traps (active shallow and inactive deep). The curves calculated at different heating rates are analysed to understand the TSL and TSC processes when the QE conditions are not fulfilled. In order to attain it we calculated and discussed other characteristics of the TSL and TSC: the temperature dependences of the recombination probability, the recombination lifetime, the occupancy of active traps, the QE parameter \( q_1 \) and the thermal generation rate from the active traps. A new parameter \( q \ast \) is introduced, it takes into account the participation of both recombination and retrapping in producing the quasi-stationary (QS) state of the TSL and TSC. Methods for determination of the QS level from the TSL and TSC curves are proposed and examined.

2. Theoretical description of the TSC and TSL without quasi-equilibrium approximation

In order to describe the TSC and TSL we consider an n-type insulator model with one kind of recombination centre and two kinds of electron traps (e.g. [9–12]). At low temperature the recombination centres and traps are empty (ionized). At this temperature the insulator is subjected to external photo-excitation (with photon energy greater than the band gap) that produces free electrons and holes. The holes are captured by the recombination centres while the electrons are captured by different kinds of traps. It is assumed that there are the shallow (active) traps that are partly or fully filled with electrons during photo-excitation and the thermally disconnected (inactive) deep traps that are fully filled with electrons. After the removal of excitation the insulator is heated in the dark according to the linear heating rate \( \omega = \frac{dT}{dt} = \text{Const}(T) \) (\( T \) is the temperature, and \( t \) is the time). The heating provides thermal energy to the captured electrons in the active traps that are excited to the conduction band giving an increase in the conductivity (TSC). The excited electrons recombine radiatively (TSL) in the recombination centres or are retrapped by empty active traps. The electrons in deep traps stay immobilized. According to the model the TSC and TSL processes can be described by the neutrality condition

\[
n_e + n_i + M = p_i, \tag{1}
\]

and the kinetic equations

\[
\frac{dn_e}{dt} = n_s \exp\left(-\frac{E}{kT}\right) - n_e \alpha p_i - n_e \beta (N_t - n_i), \tag{2}
\]

\[
\frac{dn_i}{dt} = n_s \beta (N_t - n_i) - n_s \exp\left(-\frac{E}{kT}\right), \tag{3}
\]

\[
\frac{dn_e}{dt} + \frac{dn_i}{dt} = \frac{dp_i}{dt}, \tag{4}
\]

where \( n_e \) is the density of free (in the conduction band) electrons representing TSC, \( n_i \) is the density of electrons captured by the active traps with the density \( N_t \), \( M \) is the density of electrons in the inactive deep (thermally disconnected) traps, \( \alpha \) is the recombination coefficient for the free electron with the hole in the recombination centre, \( p_i \) is the density of holes in the recombination centres, \( s \) is the frequency factor for the active trap and \( \beta \) is the trapping coefficient for the free electron by the active trap. It is assumed that \( \alpha \), \( \beta \) and \( s \) are independent of the temperature and the luminous efficiency is equal to one.

The TSL intensity is represented by equations

\[
I_e = -\frac{dp_i}{dt} = n_e \alpha p_i = \frac{n_e}{\tau_e}, \tag{5}
\]

where

\[
\tau_e = \frac{1}{\alpha p_i} \tag{6}
\]

is the free electron recombination lifetime.

The equation system (1)–(4) can be solved assuming that free electrons are in the QE state with the recombination centres that is mathematically expressed by condition (e.g. [9–11])

\[
\frac{dn_e}{dt} \ll \frac{dn_i}{dt} \approx \frac{dp_i}{dt}, \tag{7}
\]
Additionally, it is assumed that (e.g. [9, 15])

\[ n_e \ll n_i + M. \]  

(8)

The approximations (7) and (8) are called the QE approximation. We will consider the TSL and TSC processes without the QE approximation applying the QE parameter [15]:

\[ q_1 = \frac{\frac{dn_e}{dT}}{\frac{dn_i}{dT}}. \]  

(9)

Using the QE parameter in equation (2) we can derive the equation for the TSC intensity in the form:

\[ n_e = \frac{n_i s \exp\left(\frac{E}{kT}\right)}{\alpha p_i (q_i + 1) + \beta (N_i - n_i)}. \]  

(10)

Putting expression (10) for the TSC intensity in equation (5) we have

\[ I_e = \frac{\alpha p_i n_i s \exp\left(\frac{E}{kT}\right)}{\alpha p_i (q_i + 1) + \beta (N_i - n_i)}. \]  

(11)

For the description of the TSL and TSC we can use the recombination parameter [11, 12]

\[ \gamma = \frac{\alpha p_i}{\alpha p_i + \beta (N_i - n_i)} = \frac{I_e}{I_e + I_t}, \]  

(12)

where

\[ I_t = n_i \beta (N_i - n_i) \]  

(13)

is the free electron trapping time we can present the parameter \( \gamma \) in the form:

\[ \gamma = \frac{\tau_e^{-1}}{\tau_e^{-1} + \tau_i^{-1}} = \frac{P_e}{P_e + P_i}, \]  

(15)

where \( P_e = \tau_e^{-1} \) and \( P_i = \tau_i^{-1} \) are the probabilities (per second) of the recombination and, respectively, trapping. The parameter \( \gamma \) can have values from 0 to 1. 0.5 < \( \gamma \) < 1 is for the weak-retrapping case, and \( \gamma < 0.5 \) corresponds to the strong retrapping case. Now using the parameter \( \gamma \) we can present equation (11) in simpler form

\[ I_e = \frac{\gamma G}{\gamma q_1 + 1}. \]  

(16)

where

\[ G = n_i s \exp\left(\frac{E}{kT}\right) \]  

(17)

is the thermal excitation rate of electrons from the active (shallow) traps to the conduction band. When \( |q_1| \ll 1 \) equation (16) takes a form typical for the QE state [11, 12]

\[ I_e = \gamma G. \]  

(18)

However, when there is the non-QE state, equation (16) may also take the form (18) because the condition \( |\gamma q_1| \ll 1 \) can be realized for strong retrapping (i.e. \( \gamma \ll 1 \)).

The condition for the QE state can also be expressed in the form

\[ \left| \frac{dn_e}{dT} \right| \ll \left| \frac{dn_i}{dT} \right| = |I_t - G|, \]  

(19)

where \( \frac{dn_e}{dT} < 0 \) because \( G > I_t \) (see equation (2)). So it follows from inequality (19) that the retrapping process counteracts the reaching of the QE state. On the other hand, formula (9) transformed (using relations \( I_e = n_e / \tau_e \) and \( \omega = dT / \tau_e \) into the form

\[ q_1 = \omega \tau_e \frac{dn_e}{dT} \]  

(20)

suggests that \( \tau_e \) strongly influences the QE level. Using the parameters \( \tau_e, \gamma, q_1 \) and \( G \), equation (10) for the TSC intensity can be presented in the form corresponding to equation (16) for the TSL intensity:

\[ n_e = \frac{\tau_e \gamma G}{\gamma q_1 + 1}. \]  

(21)

Let us introduce a new parameter:

\[ q^* = \gamma q_1. \]  

(22)

Putting the formulae for \( \gamma \) (12), \( q_1 \) (9), \( I_e \) (11) and \( I_t \) (13) in equation (22) we obtain

\[ q^* = \frac{dn_e}{dT} = \frac{dn_i}{dT} \frac{\tau_e R N_i s \exp\left(\frac{E}{kT}\right)}{(q^* + 1)kT^2}. \]  

(23)

From equation (23) we see that the parameter \( q^* \) describes the state of the free electrons in relation to the sum of the recombination and trapping processes. The state determined by condition

\[ |q^*| \ll 1 \]  

(24)

call the QS state because the state corresponds to \( dn_e/dT \approx 0 \) as it follows from equation (2). The stationary state of free electrons appears at the TSC peak-maximum position where \( dn_e/dT = 0 \). Of course, from equation (22) it is clear that \( q^* \leq q_1 \) because \( \gamma \leq 1 \).

3. Methods for determination of the parameters of the QE and QS states

In this section we will consider the TSC and TSL in their initial temperature ranges. Using formulae (17) and (22) and a new parameter \( R = \gamma m_i / N_i \) we can present formula (21) for the TSC intensity in the form

\[ n_e(T) = \frac{n_i(T) s \exp\left(\frac{E}{kT}\right)}{(q^* + 1)kT^2}. \]  

(25)

We assume that \( R, \gamma, q^* \) and \( M \) are independent of the temperature in the initial range of TSL, i.e. for \( I(T) / I_{em} < 0.5 \) where \( I_{em} = I_e(T_{ma}) \) is the TSL peak-maximum intensity. In this case differentiation of equation (25) gives

\[ \frac{dn_e}{dT} = \frac{\tau_e R N_i s E \exp\left(\frac{E}{kT}\right)}{(q^* + 1)kT^2}. \]  

(26)
where

\[ \text{Formula describing variation of the parameter } q \text{.} \]

Using this equation we can find the ratio of the TSL intensities \( I \) (i.e. parameter values of relative TSL (or TSC) intensity corresponding to two different this formula. Using formula (27) for two equal values of the \( \omega \) initial range of TSL (or TSC):

\[ q_{\text{rel}} = q_{\text{rel}}^{(1)} T_1^2 / q_{\text{rel}}^{(2)} T_2^2, \tag{28} \]

where \( q_{\text{rel}}^{(1)} = q_{\text{rel}}^{(1)}(T_1) \) and \( q_{\text{rel}}^{(2)} = q_{\text{rel}}^{(2)}(T_2) \).

In order to derive the formula for determination of the QS parameter \( q^* \) we use equation (16) for the TSL intensity in the form corresponding to equation (25) for the TSC:

\[ I_{\text{TSL}}(T) = R N_s \exp \left( - \frac{E}{kT} \right). \tag{29} \]

Using this equation we can find the ratio of the TSL intensities \( I_{\text{rel}}(\omega_1) \) and \( I_{\text{rel}}(\omega_2) \) at two different heating rates \( \omega_1 \) and \( \omega_2 > (\omega_1) \)

\[ I_{\text{rel}}(\omega_1) = \frac{R_1(q_{\text{rel}}^* + 1) \exp \left( - \frac{E}{kT_1} \right)}{R_2(q_{\text{rel}}^* + 1) \exp \left( - \frac{E}{kT_2} \right)}. \tag{30} \]

Assuming that \( I_{\text{rel}} \) and \( R_1(\omega_1) = R_2(\omega_2) \) correspond to equal values of the relative TSL intensities at two heating rates (i.e. \( I_{\text{rel}}(\omega_1)/I_{\text{rel}}(\omega_2) = I_{\text{rel}}(T_2)/I_{\text{rel}}(T_1) \)) in the initial range of TSL we obtain

\[ \frac{I_{\text{rel}}(\omega_1)}{I_{\text{rel}}(\omega_2)} = \frac{(R_1/q_{\text{rel}}^* + 1) \exp \left( - \frac{E}{kT_1} \right)}{(R_2/q_{\text{rel}}^* + 1) \exp \left( - \frac{E}{kT_2} \right)}. \tag{31} \]

Approximate equations (28) and (31) are the system with two unknowns \( q_{\text{rel}}^* \) and \( q_{\text{rel}}^* \). The solution of the system is

\[ q_{\text{rel}}^* = Z - 1 \]

\[ q_{\text{rel}}^* = q_{\text{rel}}^* Y, \tag{32} \]

where

\[ Y = \frac{\omega_1 T_1^2}{\omega_2 T_2^2}. \tag{34} \]

\[ Z = \frac{I_{\text{rel}}(\omega_1 e^T) \exp \left( - \frac{E}{kT_2} \right)}{I_{\text{rel}}(\omega_2 e^T) \exp \left( - \frac{E}{kT_1} \right)}. \tag{35} \]

Formulae (32), (33), (34) and (35) may be used for the determination of the values of \( q_{\text{rel}}^* \) and \( q_{\text{rel}}^* \) when the values of \( T_1, T_2, \) and \( I_{\text{rel}} \) are known from the initial ranges of the TSL curves measured at two heating rates \( \omega_1 \) and \( \omega_2 \).

Another method for the determination of \( q^* \) in the initial range of the TSL curve can be derived assuming that the slower heating rate \( \omega_1 = (\omega_2) \) is sufficient to obtain the QS state, i.e. \( |q_1^*| 
3, 10Ks

Table 1. Kinetic parameters of traps used in calculations: The density of active traps \((N_a)\), the initial density of electrons in the active traps \((n_0)\), the trapping coefficient \((\beta)\), the frequency factor \((s)\), the density of the deep inactive traps \((M)\), the recombination coefficient \((\alpha)\), the initial density of holes in the recombination centres \(p_0 = M + n_0\), and the active trap depth \(E = 0.3\text{ eV} \).

| Set | \(N_a\) (cm\(^{-3}\)) | \(n_0\) (cm\(^{-3}\)) | \(\beta\) (cm\(^{-3}\) s\(^{-1}\)) | \(s\) (s\(^{-1}\)) | \(M\) (cm\(^{-3}\)) | \(\alpha\) (cm\(^3\) s\(^{-1}\)) |
|-----|----------------|----------------|----------------|-------------|--------|----------------|
| A   | 10\(^{11}\)   | 10\(^{11}\)   | 10\(^{-11}\)   | 10\(^{-7}\)  | 10\(^{8}\) | 10\(^{-12}\) |
| B   | 10\(^{12}\)   | 10\(^{11}\)   | 10\(^{-12}\)   | 10\(^{-8}\)  | 10\(^{9}\) | 10\(^{-13}\) |
| C   | 10\(^{11}\)   | 10\(^{10}\)   | 10\(^{-12}\)   | 10\(^{-10}\) | 10\(^{12}\) | 3\times10\(^{-13}\) |
| C1  | 10\(^{11}\)   | 10\(^{10}\)   | 10\(^{-12}\)   | 10\(^{10}\)  | 5\times10\(^{10}\) | 5\times10\(^{-13}\) |
| D   | 10\(^{11}\)   | 10\(^{10}\)   | 10\(^{-11}\)   | 10\(^{10}\)  | 10\(^{13}\) | 10\(^{-12}\) |

4. Analysis of thermally stimulated luminescence and conductivity

In order to analyse the QE and QS problems we numerically calculated temperature dependences of different TSL and TSC characteristics: \( I_{\text{TSL}}(T), n_{\text{TSL}}(T), n_1(T), n_2(T), p_1(T), p_2(T), \) where \( T \) is the temperature, \( \omega_1(\omega_2) \) is the peak-maximum intensity and \( T_1(\omega_1) \) are the temperatures at the intensity of TSL (TSC) equal to 0.5 of the peak-maximum intensity. For the calculations we solved numerically (without the QE approximation (NQE)) the kinetic equations (1)–(4) using the Runge-Kutta [26] and Gear [27] procedures and Pentium computer. The TSL and TSC characteristics were also calculated using equations (1)–(4) approximated under QE conditions (7) and (8) and the method described in our previous paper [11]. The calculations were performed for values of the sample heating rate in the range \( \omega = 10^{-3}.10\text{ K s}^{-1} \). For discussion we present example results of the TSL and TSC characteristics calculated for five sets of traps and recombination centres parameters listed in table 1.
Two values of heating rate intensity (peak-maximum intensity temperatures at the TSL (TSC) intensity equal to 0.5 of the calculated for ω from figures 1(1) that it is the case of decreasing recombination probability retrapping (see, e.g, [2,11,12] and table 2). Figure 1 for the set A using the QE approximation in the case of weak heating rate (Figures 1(a)–(b)). The intensity of the TSL peak at ω = 1 K s⁻¹ in the non-QE case (Iem = 2.27 × 10⁶ cm⁻³ s⁻¹) is lower than that for the QE case (Iem = 3.66 × 10⁶ cm⁻³ s⁻¹) and the intensity of the TSL at the higher temperatures (T > 200 K) is higher for the non-QE case than for the QE case. These results are the consequence of the fact that the recombination intensity falls behind the strong generation rate of free electrons even in low temperature range. Consequently part of the holes accumulated in the recombination centres recombine only at the high temperatures (figure 1(c)). The results of q₁(T) for ω = 1 K s⁻¹ (figure 1(d)) show that the rate of change of free electrons (dνₑ/dτ) is relatively higher in relation to the TSL intensity (Iₑ) than at ω = 10⁻² K s⁻¹ causing that the QE state is not present in this case. In the high temperature range (T = 250–300 K) of the TSL and TSC the parameters QE and QS reach approximately constant values, |q₁| ≈ 1, and |q₉| ≈ 0.5 (figure 1(d)). It means that the rate of change of free electron density is approximately equal to the TSL intensity and the trapping intensity, |dνₑ/dτ| ≈ Iₑ ≈ Iₑ.

4.1. Case A

Figures 1(a)–(d) show the TSL and TSC characteristics numerically calculated without the QE approximation for set A of kinetic parameters (weak-retrapping case) and two values of heating rates ω = 10⁻² K s⁻¹ (1) and 1 K s⁻¹ (2). It is seen from figures 1(a) and (b) that the TSL and both TSC peaks calculated for ω = 10⁻² K s⁻¹ have shapes similar to that typical for the corresponding TSL and TSC curves calculated for the set A using the QE approximation in the case of weak retrapping (see, e.g. [2,11,12] and table 2). Figure 1(c) shows that it is the case of decreasing recombination probability (γ(T)) and increasing recombination lifetime (τₑ(T)) with increasing temperature.

Analysis of the temperature dependence of the QE level parameter q₁ for ω = 10⁻² K s⁻¹ (figure 1(d)) suggests that the TSL and TSC occur in the approximate QE state (|q₁| < 1.7 × 10⁻³) except for high temperatures (T > 160 K). On the other hand, the values of the QS parameter (|q₉| = |γq₁| = 1.1 × 10⁻² at T < 160 K and |q₉| < 5 × 10⁻² at T > 160 K) show that the QS state is may be assumed to be present in the whole interesting temperature range. This is because the retrapping probability increases with increasing temperature (γ < 0.5 at T > 165 K).

The TSL and TSC peaks calculated for ω = 1 K s⁻¹ are shifted towards the higher temperatures and they are wider in relation to the TSL and TSC peaks for ω = 10⁻² K s⁻¹ (figures 1(a) and (b)). The intensity of the TSL peak at ω = 1 K s⁻¹ in the non-QE case (Iem = 2.27 × 10⁶ cm⁻³ s⁻¹) is lower than that for the QE case (Iem = 3.66 × 10⁶ cm⁻³ s⁻¹) and the intensity of the TSL at the higher temperatures (T > 200 K) is higher for the non-QE case than for the QE case. These results are the consequence of the fact that the recombination intensity falls behind the strong generation rate of free electrons even in low temperature range. Consequently part of the holes accumulated in the recombination centres recombine only at the high temperatures (figure 1(c)). The results of q₁(T) for ω = 1 K s⁻¹ (figure 1(d)) show that the rate of change of free electrons (dνₑ/dτ) is relatively higher in relation to the TSL intensity (Iₑ) than at ω = 10⁻² K s⁻¹ causing that the QE state is not present in this case. In the high temperature range (T = 250–300 K) of the TSL and TSC the parameters QE and QS reach approximately constant values, |q₁| ≈ 1, and |q₉| ≈ 0.5 (figure 1(d)). It means that the rate of change of free electron density is approximately equal to the TSL intensity and the trapping intensity, |dνₑ/dτ| ≈ Iₑ ≈ Iₑ.

4.2. Case B

The TSL and TSC characteristics for case B calculated without the QE approximation for ω = 10⁻² and 1 K s⁻¹ are presented in figures 2(a) to (d) and table 3. The TSL and TSC curves for ω = 10⁻² K s⁻¹ (figures 2(a) and (b)) have the shape typical for the strong retrapping and the recombination lifetime increasing with the temperature (figure 2(c), and [2,11]). The values of the QE parameter (|q₁| < 10⁻³ at T < 190 K) figure 2(d) suggest that the QE state is present. This conclusion is confirmed by

Table 2. Values of parameters of the TSL and TSC curves (Tₘₒₗ, μₘₒₗ = (T₂₃ₒₗ − T₁ₘₒₗ)/(T₂₃ₒₗ − T₃ₒₗ), Iₘₒₗ and nₘₒₗ) calculated for set A of kinetic parameters without the QE approximation and for two values of heating rate ω. Tₘₒₗ and T₂₃ₒₗ are the temperatures at the TSL (TSC) intensity equal to 0.5 of the peak-maximum intensity Iₘₒₗ(nₘₒₗ) at Tₘₒₗ.

| ω (K s⁻¹) | Tₘₒₗ (K) | μₘₒₗ | Iₘₒₗ (cm⁻³ s⁻¹) |
|------------|-----------|------|------------------|
| TSL 10⁻²   | 192.5     | 5.26 × 10⁻¹ | 2.27 × 10⁸      |
|            | 1 (2)     |                   |                  |
| TSC 10⁻²   | 198.7     | 6.58 × 10⁻¹ | 4.00 × 10¹      |
|            | 1 (2)     |                   |                  |

Figure 1. Temperature dependences of TSL and TSC characteristics calculated for set A of kinetic parameters and for two values of the heating rate (ω = 10⁻² K s⁻¹ (1) and 1 K s⁻¹ (2)): (a) the relative TSL intensity (Iₑ(T)) (a.u. means arbitrary units), (b) the relative TSC intensity (nₑ(T)) (c) the relative recombination probability (γ(T)) and the recombination lifetime (τₑ(T)) and (d) the QE (q₁(T)) and QS (q₉(T)) parameters. q₁ > 0 and q₉ > 0 at T < Tₘₒₗ, q₁ < 0 and q₉ < 0 at T > Tₘₒₗ, and q₁ = q₉ = 0 at Tₘₒₗ.
relative recombination probability (\( \gamma(T) \)) and with the QE approximation (QE) and for different values of heating rate \( \omega \) and temperatures in relation to the TSL and TSC curves for parameters calculated for the QE approximation listed in table 3. The dominating strong retrapping (\( \gamma < 0.1 \), figure 2(c)) improves on the QS state at \( \omega = 1 \text{ K s}^{-1} \) similarly as for \( \omega = 10^{-2} \) and \( 10^{-1} \text{ K s}^{-1} \), but the condition for the presence of the QE state (\( |q| \approx 10^{-2} \)) occurs only at high temperatures (\( T > 210 \text{ K} \), figure 2(d)). In the high temperature range (\( T = 270-320 \text{ K} \)) the parameters QE and QS achieve the values \( |q| \approx 1 \) and \( |q| \approx 1 \times 10^{-2} \) (figure 2(b)), whereas the recombination probability reaches the value \( \gamma \approx 1 \times 10^{-2} \) (figure 2(c)). These results mean that the rate of change of free electron density is approximately equal to the recombination intensity, but those are much lower than the intensity of retrapping, \( \frac{dn_e}{dt} \approx I_c \approx I_e \).

The calculation results of \( \gamma(T) \) (figure 2(c)) and \( q(T) \) (figure 2(d)) at \( \omega = 10^{-2} \text{ K s}^{-1} \) demonstrate that the QE state can be realized for the case of strong retrapping. On the other hand, the QE state is not present in the TSL and TSC at \( \omega = 1 \text{ K s}^{-1} \). However, as it follows from our calculation results, the QE state is reached (\( |q| < 10^{-2} \)) at \( \omega = 1 \text{ K s}^{-1} \) for the set of kinetic parameters (B1) with the densities of the recombination centres and traps that are much higher (\( N_i = 10^{15} \text{ cm}^{-3} \), \( M = 10^{12} \text{ cm}^{-3} \)) and the other parameters

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**Table 3.** Values of parameters of the TSL and TSC curves calculated for set B of kinetic parameters without the QE approximation (NQE) and with the QE approximation (QE) and for different values of heating rate \( \omega \).

| TSL | \( \omega \) (K s\(^{-1}\)) | \( T_{rn} \) (K) | \( T_{re} \) (K) | \( T_{2n} \) (K) | \( \mu_{\beta} \) | \( I_{cm} \) (cm\(^{-3}\) s\(^{-1}\)) |
|-----|-----------------|-----------------|-----------------|-----------------|-------------|------------------|
| NQE | 10\(^{-2}\)     | 168.9           | 156.3           | 182.4           | 5.26 \times 10\(^{-1}\) | 3.31 \times 10\(^{7}\) |
| QE  | 10\(^{-1}\)     | 168.9           | 156.4           | 182.8           | 5.26 \times 10\(^{-1}\) | 3.33 \times 10\(^{7}\) |
| NQE | 10\(^{-1}\)     | 187.7           | 172.3           | 205.2           | 5.32 \times 10\(^{-1}\) | 2.59 \times 10\(^{8}\) |
| QE  | 10\(^{-1}\)     | 187.9           | 172.6           | 205.1           | 5.28 \times 10\(^{-1}\) | 2.71 \times 10\(^{8}\) |
| NQE | 1              | 210.3           | 190.7           | 236.4           | 5.71 \times 10\(^{-1}\) | 1.64 \times 10\(^{9}\) |
| QE  | 1              | 211.4           | 192.3           | 233.0           | 5.31 \times 10\(^{-1}\) | 2.16 \times 10\(^{9}\) |

| TSC | \( \omega \) (K s\(^{-1}\)) | \( T_{rn} \) (K) | \( T_{re} \) (K) | \( T_{2n} \) (K) | \( \mu_{\mu} \) | \( n_{cm} \) (cm\(^{-3}\)) |
|-----|-----------------|-----------------|-----------------|-----------------|-------------|------------------|
| NQE | 10\(^{-2}\)     | 184.8           | 164.8           | 213.2           | 5.88 \times 10\(^{-1}\) | 8.96 \times 10\(^{8}\) |
| 1   | 222.0           | 197.3           | 274.9           | 6.82 \times 10\(^{-1}\) | 2.83 \times 10\(^{10}\) |
remain as those in the set B. In case B1, similarly as in case B, the retrapping process is very strong ($\gamma \approx 0.1$) in the whole interesting temperature range. But in case B1 the QE state appears at $\omega = 1$ K s$^{-1}$ because of the much lower value of the recombination lifetime ($\tau_e \approx 10^{-2}$ s in the initial range of the TSL intensity $I_e/I_{em} \approx 0.1$) than in case B ($\tau_e \approx 10$ s at $I_e/I_{em} \approx 0.1$). In these two cases the value of $n_c^{-1} d\omega_c/dT$ is approximately equal to $1.1 \times 10^{-1}$ and, of course, it does not change the value of $q_l$ (see equation (20)).

The results of $q_l(T)$ at $\omega = 10^{-2}$ K s$^{-1}$ for case B show that the QE level deteriorates at temperatures higher than those at the TSC peak-maximum, $T > T_{ms} = 185$ K (figure 2(d)). This behaviour of the $q_l(T)$ dependence can be explained using equation (16) in the form $q_l = G/I − 1/\gamma$. It follows from this equation that $q_l > 0$ when $G/I_e > 1/\gamma$ at $T < T_{ms}$, and $q_l < 0$ when $G/I_e < 1/\gamma$ at $T > T_{ms}$. At $T > T_{ms}|q_l|$ increases when $\gamma$ decreases (i.e. the retrapping increases) with increasing $T$ (figures 2(c) and (d)). The temperature dependences of $\gamma$ and $\tau_e$ (figure 2(c)) at $\omega = 1$ K s$^{-1}$ for case B show similar behaviour as for case A: $\gamma$ decreases and $\tau_e$ increases with increasing temperature than in the approximate QE state at $\omega = 10^{-2}$ K s$^{-1}$. It suggests that the density of holes in the recombination centres at $\omega = 1$ K s$^{-1}$ decreases more slowly than at $\omega = 10^{-2}$ K s$^{-1}$.

4.3. Cases C and C$_1$

The TSL curves calculated without the QE approximation for case C at $\omega = 10^{-2}$ and 1 K s$^{-1}$ are presented in figure 3(a). In this case the recombination probability ($\gamma \approx 0.5$) and the recombination lifetime ($\tau_e \approx 10$ s) are approximately constant in the temperature range of the TSL calculated for the two values of $\omega$. At $\omega = 10^{-2}$ K s$^{-1}$ the TSL curve has the first-order shape with the symmetry factor $\mu_g = 0.427 [2, 7, 11]$. It is interesting to see that the first-order shape can be observed for the case of moderate retrapping ($\gamma \approx 0.5$). The results of $q_l(T)$ calculated for $\omega = 10^{-2}$ K s$^{-1}$ show that there is the approximate QE state ($|q_l| < 2.5 \times 10^{-5}$) in the temperature range $T = 105–165$ K (figure 3(b)). In this temperature range the condition for the QS state is better fulfilled ($|q_l| < 1.2 \times 10^{-3}$). It results in the well-formed first-order shape of the TSL curve (see equation (18)). The upper limit value of the heating rate for the presence of the QS state (with $|q_l| \leq 3.8 \times 10^{-2}$ and $|q_l| \leq 7.2 \times 10^{-2}$) seems to be at $\omega = 3 \times 10^{-2}$ K s$^{-1}$ because the values of the parameters of the NQE and QE TSL curves are in good agreement up to this heating rate value. The TSL curve calculated for $\omega = 1$ K s$^{-1}$ presents strong deviation from the typical first-order shape of the QE state (as seen at $\omega = 10^{-2}$ K s$^{-1}$): it has approximately the second-order shape ($\mu_g \approx 0.5$). In this case neither the QE nor the QS states are present (figure 3(b)).

A similar case ($C_1$) of TSL and TSC is obtained when the values of the density of deep traps and the recombination coefficient are changed in relation to those for case C (table 1). This is the case ($C_1$) of strong retrapping with very weakly temperature-dependent recombination lifetime and recombination probability ($\tau_e = 5.6 \times 10^{-1}$ s and $\gamma = 1.7 \times 10^{-1}$ at $I_e(T)/I_{em} = 10^{-2}$ and $T < T_{ms}$, and $\tau_e = 6.7 \times 10^{-1}$ s and $\gamma = 1.3 \times 10^{-1}$ at $I_e(T)/I_{em} = 10^{-2}$ and $T > T_{ms}$). The parameters of the TSL curves calculated for case $C_1$ with and without the use of the QE approximation and for three values of the heating rate ($\omega = 10^{-2}$ K s$^{-1}$ (1) and 1 K s$^{-1}$) (2) the relative TSL intensity ($I_e(T)$), and (b) the parameters $q_l(T)$ and $q^*(T)$. Figure 4(a) presents the TSL curves calculated for set D of kinetic parameters and $\omega = 10^{-2}$ K s$^{-1}$. In this case the recombination lifetime increases very weakly with increasing temperature from $\tau_e = 9$ to 10 s within the temperature range of the TSL curve. The recombination probability shows even weaker temperature dependence and its value is typical for the weak-retrapping process ($\gamma \approx 0.9$). The TSL and TSC curves calculated for $\omega = 10^{-2}$ K s$^{-1}$ have the first-order shape with the symmetry factor $\mu_g = 0.426$. Figure 4(b) shows that the TSL and TSC processes at $\omega = 10^{-2}$ K s$^{-1}$ are realized under the approximately fulfilled QE condition ($|q_l| < 2 \times 10^{-2}$ at $T = 130–177$ K). Because of the value of $\gamma \approx 0.9$ the values of the parameters $q_l$ and $q^*$ differ only by about 10%.
TSL intensity $I$ is given for the first time by Sunta [24]. A proposition of the method for estimation of the QE level is based on the dependence of the symmetry factor of the TSL curve from the turning point of the $gI(\omega)$ curve on the related reciprocal temperature $1/T$. Analysis of the results of analysis of thermally stimulated luminescence and conductivity shows that the approximate linear dependence $I_m(\omega)$ calculated for sets A, B, C and D of kinetic parameters (section 4). Similarly, the turning point for case C is seen at $\omega_0 \approx 3 \times 10^3 K s^{-1}$ but the QE limit is at $\omega_0 \approx 2 \times 10^3 K s^{-1}$ (section 4). The QE state for case C1 is present at lower heating rates ($\omega_0 \leq 2 \times 10^{-3} K s^{-1}$) than the turning point that is at $\omega_0 \approx 2 \times 10^{-3} K s^{-1}$.

We also analysed the dependences of the peak-maximum intensity of the TSL and TSC on the heating rate and the reciprocal peak-maximum temperature. Analysis of the $I_m(\omega)$ curves shows that the approximate linear dependence of $I_m(\omega)$ on $\omega$ ($I_m \propto \omega^k$ with $k \approx 0.9$, figure 6) is observed in a wide range of $\omega$ in all four cases A, B, C and D. A similar dependence of the peak-maximum intensity of the TSC on the heating rate ($n_m \propto \omega^k$ with $k \approx 0.9$) is valid in these cases. The values of the factor $k$ becomes lower ($k < 0.9$) at high heating rates (figure 6). Analysis of the results of $I_m(\omega)$, $q_0(\omega)$ and $q^*(\omega)$ shows that the dependence of $I_m(\omega)$ on $\omega^k$ is present in the range of $\omega$ corresponding to the QE state. For example, the QE state of the TSL peak-maximum intensity in case B occurs up to $\omega_0 = 5 \times 10^{-3} K s^{-1}$, whereas the upper limit of $\omega$ for the QE state is at $\omega_0 \approx 2 \times 10^{-3} K s^{-1}$ (figures 2(a) and (c)).

Figure 7 shows the dependence of the TSL peak-maximum intensity $I_m(1/T_{ml})$ on the related reciprocal temperature $T_{ml}$ calculated for cases A, B, C and D and for different heating rates $\omega_0$. It is seen from the figure that for the weak-retrapping cases (A and D) the functions of $I_m(1/T_{ml})$ have exponential dependence. Consequently the shapes of the TSL and TSC curves (with $\mu_g = 0.473$, figure 4(a)) differ from the typical first-order kinetic shape.

### 5. Determination of the QE and QS parameters

A proposition of the method for estimation of the QE level was given for the first time by Sunta et al [24]. The method is based on the dependence of the symmetry factor of the TSL curve on the heating rate $\mu_g(\omega)$. According to the method, the upper limit value of $\omega_0$ for the presence of the QE state can be determined from the turning point of the $\mu_g(\omega)$ curve from the weak to the strong dependence of $\mu_g$ on $\omega$. Figure 5 shows the dependence of $\mu_g$ on $\omega$ for the TSL curves calculated for the above-described cases A, B, C and D. It is seen from figure 5 that the turning point on the $\mu_g(\omega)$ curve for the weak retrapping case A appears approximately at $\omega_0 = 10^{-2}$, which corresponds to the end of presence of the QE and QS states determined by $|q_1| \approx |q_2| \approx 10^{-2}$ (section 4). For the weak-retrapping case D the turning point on the $\mu_g(\omega)$ curve is seen at $\omega \approx 10^{-1}$ K s$^{-1}$ whereas the upper limit for presence of the QE and QS states is at $\omega_0 \approx 10^{-2}$ (section 4). For the moderate and strong retrapping cases (C, and B and C1) the turning point appears at higher values of $\omega$ than the upper limit of the presence of the QE state. The results of $q^*(\omega)$ for the strong retrapping case B show that the turning point on the dependence $\mu_g(\omega)$ is at the limit of the presence of the QE state that appears at $\omega_0 \approx 10^{-1}$ K s$^{-1}$ whereas the limit for the QE state is at $\omega_0 \approx 10^{-2}$ K s$^{-1}$ (section 4). Similarly, the turning point for case C is seen at $\omega_0 \approx 3 \times 10^3 K s^{-1}$ but the QE limit is at $\omega_0 \approx 2 \times 10^3 K s^{-1}$ (section 4). The QE state for case C1 is present at lower heating rates ($\omega_0 \leq 2 \times 10^{-3} K s^{-1}$) than the turning point that is at $\omega_0 \approx 2 \times 10^{-3} K s^{-1}$.

Table 4. Values of parameters of TSL curves calculated for set C1 of kinetic parameters without the QE approximation (NQE) and with the QE approximation (QE) and for three values of heating rate $\mu$.

| TSL $\omega$ (K s$^{-1}$) | $T_{em}$ (K) | $T_i$ (K) | $T_{sl}$ (K) | $\mu_qi$ | $I_m$ (cm$^{-3}$s$^{-1}$) |
|--------------------------|-------------|-----------|-------------|----------|-------------------|
| NQE $2 \times 10^{-3}$   | 155.2       | 145.5     | 162.8       | $4.37 \times 10^{-1}$ | $1.07 \times 10^6$ |
| QE $2 \times 10^{-3}$    | 155.2       | 145.5     | 162.7       | $4.35 \times 10^{-1}$ | $1.08 \times 10^6$ |
| NQE $1 \times 10^{-2}$   | 166.2       | 155.0     | 175.2       | $4.46 \times 10^{-1}$ | $4.59 \times 10^6$ |
| QE $1 \times 10^{-2}$    | 166.1       | 155.1     | 174.7       | $4.37 \times 10^{-1}$ | $4.74 \times 10^6$ |
| NQE $10^{-1}$            | 185.0       | 170.4     | 199.7       | $5.03 \times 10^{-1}$ | $3.09 \times 10^6$ |
| QE $10^{-1}$             | 184.5       | 170.0     | 195.1       | $4.39 \times 10^{-1}$ | $3.87 \times 10^6$ |

![Figure 4](image-url) **Figure 4.** Temperature dependences of TSL and TSC characteristics calculated for set D of kinetic parameters and for two values of the heating rate ($\omega = 10^{-3}$ K s$^{-1}$ (1) and 1 K s$^{-1}$ (2)): (a) the relative TSL intensity $I(T)$, and (b) the parameters $q_0(T)$ and $q^*(T)$.

$\omega = 1$ K s$^{-1}$ the QE state and the QS state are not realized. Consequently the shapes of the TSL and TSC curves (with $\mu_g = 0.473$, figure 4(a)) differ from the typical first-order kinetic shape.
cases A, B, C and D and for different heating rates in the range of reciprocal peak-maximum temperature \( \omega \). The result shows the dependence of heating rate \( \omega \) corresponding to \( I \) states \( (i) \) in the range of the validity of the QE and QS character in the range of the occurrence of the QS state.

At the values of \( \omega \) are exponential in the range of occurrence of the QS state. Table 6 presents the values of the ratio \( q_{12}/q_{11} \) (27), where \( q_{11} \) and \( q_{12} \) are the QE parameters for equal values of \( I_1/I_{em} \) (or \( n_e/n_{em} \)) in the initial range of the TSL (TSC) at two values of the heating rate \( \omega_1 \) and, respectively, \( \omega_2 \). The formula was derived under the assumption that the parameters \( \tau_\omega, R \) and \( q^* \) are independent of the temperature in the initial part of the TSL or TSC curve and that \( \tau_\omega \) corresponding to the fixed value of \( I_{em}/I_{em} \) is independent of the heating rate.

We therefore calculated the values of \( \tau_\omega, R \) and \( q^* \) for sets A, B, C and D of kinetic parameters and different values of the relative TSL intensity \( (I_c/I_{em}) \) and different values of the heating rate \( \omega \). The resulting values of \( R, \tau_\omega \) and \( q^* \) calculated for \( I_c/I_{em} = 5 \times 10^{-2} \) and \( 3 \times 10^{-4} \) (at \( T < T_{ml} \) and \( \omega = 10^{-3} \) and \( 1 \text{ K s}^{-1} \) are given in table 5. The values of \( R \), \( \tau_\omega \) and \( q^* \) show that in the TSL initial range these parameters are weakly dependent on the temperature. The parameters \( R \) and \( \tau_\omega \) are also very weakly dependent on the heating rate. Table 6 presents the values of the ratio \( q_{12}/q_{11} \) determined with the above-mentioned method (equation (28)). They are in good agreement with the corresponding results of \( q_{20}/q_{10} \) calculated using equation (9).

6. Conclusion

In this work we have also proposed the method for the determination of two values of the QS parameter, \( q_{1*} \) and \( q_{2*} \), from the initial parts of two TSL curves measured at two different heating rates, \( \omega_1 \) and \( \omega_2 \) (section 2). The method uses equations (32) and (33) that are derived under the assumptions that the parameters \( \tau_\omega \) and \( R \) corresponding to equal values of the relative TSL intensity (in the TSL initial range) are independent of the value of \( \omega \). Table 7 presents the values of \( q_{1*} \) and \( q_{2*} \) determined by applying the ‘two equations method’ to the initial range of the TSL curves calculated for sets A, B, C, C1 and D of kinetic parameters and two values of the heating rate. These results of \( q^* \) are compared with the corresponding results, \( q_0^* \), calculated using formula (23). Relative error of the values of \( q^* \) determined with the ‘two equations method’ is lower than 17% when the method is applied to the relative TSL intensity of \( I_c/I_{em} = 0.15 \), and the error is not higher than 50% when \( I_c/I_{em} = 0.3 \).

A similar method for the determination of the value of \( q^* \) is also based on the analysis of the initial parts of the TSL curves measured at two different heating rates. The method uses equation (36) that is derived from equation (31) under the assumption that the slower heating rate is sufficiently low to obtain the QS state \((\omega_1 = \omega_2)\). The values of \( q^* \) were calculated by applying equation (36) to the initial parts of the TSL curves computed for the sets A, B, C, C1 and D of kinetic parameters and two values of the heating rate. On the basis of the results presented in this section and in section 4 we assume that the TSL generated at \( \omega_1 = 10^{-2} \text{ K s}^{-1} \) is in the QS state. The results of the determination of \( q^* \) are presented in table 8. It is seen from the table that the above-described method provides the values of \( q^* \) with an accuracy better than 11% when evaluated for \( I_c/I_{em} = 0.15 \), and with lower accuracy (<25%) for \( I_c/I_{em} = 0.3 \).
and TSL intensity $(I_L/I_{m})$ in its initial range and for two values of heating rate $\omega$.

Table 5.

| $I_L/I_{m}$ case | $5 \times 10^{-2}$ | $3 \times 10^{-1}$ |
|------------------|-------------------|-------------------|
| $\omega$ (K s$^{-1}$) | $R$ ($\tau_2$ s) | $q^*$ ($\gamma q_1$) | $R$ ($\tau_2$ s) | $q^*$ ($\gamma q_1$) |
| A 10$^{-2}$ | 9.86 $\times 10^{-1}$ | 1.01 $\times 10^1$ | 2.05 $\times 10^{-2}$ | 9.01 $\times 10^{-1}$ | 1.09 $\times 10^1$ | 1.88 $\times 10^{-2}$ |
| 1 10$^{-2}$ | 9.79 $\times 10^{-1}$ | 1.00 $\times 10^1$ | 1.45 | 8.64 $\times 10^{-1}$ | 1.06 $\times 10^1$ | 1.19 |
| B 10$^{-2}$ | 9.91 $\times 10^{-3}$ | 9.99 | 1.75 $\times 10^{-2}$ | 8.82 $\times 10^{-3}$ | 1.06 $\times 10^1$ | 1.40 $\times 10^{-2}$ |
| C 10$^{-2}$ | 9.88 $\times 10^{-1}$ | 9.96 | 1.24 $\times 10^{-1}$ | 8.65 $\times 10^{-1}$ | 1.04 $\times 10^1$ | 9.28 $\times 10^{-2}$ |
| D 10$^{-2}$ | 9.21 $\times 10^{-2}$ | 9.90 | 7.08 $\times 10^{-1}$ | 4.43 $\times 10^{-2}$ | 9.91 | 5.22 $\times 10^{-2}$ |
| 1 10$^{-2}$ | 9.12 $\times 10^{-2}$ | 9.10 | 1.41 $\times 10^{-2}$ | 8.34 $\times 10^{-2}$ | 9.17 | 1.11 $\times 10^{-2}$ |

Table 6.

Table 7.

| $I_L/I_{m}$ case | $1.5 \times 10^{-1}$ | $3 \times 10^{-1}$ |
|------------------|-------------------|-------------------|
| $\omega$ (K s$^{-1}$) | $q_1/\gamma q_1$ | $q_1/\gamma q_1$ | $q_1/\gamma q_1$ | $q_1/\gamma q_1$ |
| A 6.76 $\times 10^4$ | 6.72 $\times 10^4$ | 6.34 $\times 10^4$ | 6.43 $\times 10^4$ | 1.30 | 1.30 | 1.19 | 1.24 |
| B 6.81 $\times 10^3$ | 6.90 $\times 10^3$ | 6.54 $\times 10^3$ | 6.80 $\times 10^3$ | 1.07 $\times 10^{-2}$ | 1.16 $\times 10^{-1}$ | 1.12 $\times 10^{-1}$ |
| C 6.95 $\times 10^3$ | 6.75 $\times 10^3$ | 6.78 $\times 10^3$ | 6.67 $\times 10^3$ | 1.20 $\times 10^{-2}$ | 1.02 $\times 10^{-1}$ | 8.50 $\times 10^{-3}$ | 1.10 |
| D 6.68 $\times 10^3$ | 6.42 $\times 10^3$ | 6.54 $\times 10^3$ | 6.33 $\times 10^3$ | 8.34 $\times 10^{-1}$ | 8.63 $\times 10^{-1}$ | 7.23 $\times 10^{-1}$ | 8.10 $\times 10^{-1}$ |

Table 8.

| $I_L/I_{m}$ case | $1.5 \times 10^{-1}$ | $3 \times 10^{-1}$ |
|------------------|-------------------|-------------------|
| $\omega$ (K s$^{-1}$) | $q_1^*$ | $\gamma q_1^*$ | $q_1^*$ | $\gamma q_1^*$ |
| A 1.30 | 1.30 | 1.19 | 1.24 |
| B 1.07 $\times 10^{-2}$ | 1.16 $\times 10^{-1}$ | 9.28 $\times 10^{-2}$ | 1.12 $\times 10^{-1}$ |
| C 6.10 $\times 10^{-1}$ | 6.48 $\times 10^{-1}$ | 5.22 $\times 10^{-1}$ | 6.16 $\times 10^{-1}$ |
| D 1.02 | 1.13 | 8.50 $\times 10^{-3}$ | 1.10 |

kinds of electron traps (active (shallow), and non-active (deep-thermally disconnected)), and one kind of recombination centres. The kinetic equations describing the model are solved without and with the QE approximation. The TSL and TSC processes are analysed using the QE parameter $q_1$ and a new parameter $q^* = \gamma q_1$ describing the relation between the rate of change of free electrons density and the intensities of recombination and trapping ($\gamma \leq 1$ is the relative recombination probability). The QE and QS states are determined by $|q_1| \ll 1$, and, respectively, $|q| \ll 1$. Approximate formulas ((28), (32), (33) and (36)) for calculation of the relative QE parameter $q_1/\gamma q_1$, and the QS parameter $q^*$ from the initial range of the TSL or TSC are derived and used in the heating rate methods, proposed in this work, for determination of those parameters.

The TSL and TSC curves and other characteristics (the QE and QS parameters, the recombination lifetime, the recombination probability, the density of electrons trapped in the active traps, the densities of holes captured by the recombination centres) are calculated for five sets of kinetic parameters and different heating rates. The characteristics calculated at low heating rates have the properties typical for the QE state. The properties of the TSL and TSC characteristics calculated at high heating rates deviate from those typical for the QE state. The deviation of the properties appears when the heating rate is higher than that corresponding to the limit of validity of the QS state.

In the case of weak re trapping ($\gamma \approx 1$) the QE and QS states appear in approximately the same range of the heating rate, i.e. the upper limit of the heating rate is approximately the same for the presence of both the QE and QS states. However, in the case of the non-negligible re trapping ($\gamma < 1$) the limit of the validity of the QS state appears at a higher heating rate than the highest one permitting the presence of the QE state.

The QE state of the TSL and TSC can appear both in the weak and in the strong retrapping processes. It means that the strong re trapping is not in contradiction to the QE state. It is so because the value of the recombination lifetime is fundamental for reaching of the QE state. The QS TSL curves for the case of strong re trapping have the so-called first-order shape (typical for the weak re trapping) when the recombination lifetime is independent of the temperature. These conclusions concerning the influence of the retrapping process on the TSL and TSC properties are in agreement with the corresponding conclusions in the earlier works [19, 20, 22–24].

Our results suggest that the range of the heating rate of a crystal allowing the occurrence of the QS state of TSL.

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and TSC processes can be approximately estimated from
the dependences: (1) very weak increase of the symmetry
factor of the TSL (TSC) curve with increasing heating rate
(2) approximately linear dependence of the TSL (TSC) peak-
maximum intensity on the heating rate and (3) exponential
dependence of the TSL (TSC) peak-maximum intensity on the
reciprocal peak-maximum temperature.

The above-mentioned methods for the determination of
the parameters \( q_1 / q_2 \) and \( \gamma \) in the initial range of TSL and
TSC were examined by applying them to the TSL and TSC
curves calculated without the use of the QE approximation
for five sets of kinetic parameters. The results of the
examination show that the methods yield reasonable values of
the parameters (error < 30%) when applied to the initial range
of the TSL (or TSC) with an intensity not higher than 30% of
the maximum intensity. It should be noticed that in the case
of weak retrapping (\( \gamma \approx 1 \)) the methods for the determination
of the QS parameter \( q^* \) also yield the approximate value of the
QE parameter \( q_I \) because of the relation \( q^* = q_I \gamma \). Having
the values of the initial parameter \( q^* \) one can roughly estimate
its values decreasing with the increasing temperature up to the
TSC peak-maximum position where \( q_I = q^* = 0 \).

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