The nonmonotonic dose dependence of optically stimulated luminescence in $Al_2O_3:C$: Analytical and numerical simulation results

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Nonmonotonic dose dependence of optically stimulated luminescence (OSL) has been reported in a number of materials including $Al_2O_3:C$ which is one of the main dosimetric materials. In a recent work, the nonmonotonic effect has been shown to result, under certain circumstances, from the competition either during excitation or during readout between trapping states or recombination centers. In the present work, we report on a study of the effect in a more concrete framework of two trapping states and two kinds of recombination centers involved in the luminescence processes in $Al_2O_3:C$. Using sets of trapping parameters, based on available experimental data, previously utilized to explain the nonmonotonic dose dependence of thermoluminescence including nonzero initial occupancies of recombination centers (F^+ centers), the OSL along with the occupancies of the relevant traps and centers are simulated numerically. The connection between these different resulting quantities is discussed, giving a better insight as to the ranges of the increase and decrease of the integral OSL as a function of dose, as well as the constant equilibrium value occurring at high doses. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2168266]

I. INTRODUCTION

Optically stimulated luminescence (OSL) is the effect of light emission during exposure of a solid sample to stimulating light (usually of different wavelength) following an irradiation by, say, β rays, γ rays, or x rays. The effect is understood to be the result of absorption of energy during the ionizing radiation exposure, part of which can be released in the form of measurable light while illuminating the sample by light of a different wavelength. The effect is similar to thermoluminescence (TL), in which the excitation stage is exactly the same, but the trigger for releasing the absorbed energy is the heating of the sample. Both TL and OSL are used for dosimetry, which can be employed when the measured luminescence is a simple increasing monotonic function of the dose, preferably linear. The possible superlinearity and sublinearity of these effects have been discussed elsewhere.[1] In several materials, the dose dependence of TL has been found to be an increasing function at low doses, reached a maximum at a certain dose, and declined at higher doses, sometimes leveling off at a certain high dose. Some authors ascribed this effect to "radiation damage" though no details were given. A review of the experimental evidence of this effect in TL as well as a theoretical account has been given by Lawless *et al.*[2] The explanation of the nonmonotonic dose dependence in TL was given in terms of competition between transitions into active and competing traps or between radiative and nonradiative recombination centers. Competitions during the excitation stage or the heating, readout stage have been considered.

Schulman *et al.*[3] described the changes in photoluminescence due to prior γ excitation in organic solids, which in our present terms can be understood to be OSL. For example, in naphthalene, the dependence of 464 nm emission stimulated by 365 nm UV light depended nonlinearly on the previous γ-excitation dose, reaching a maximum at $\sim 10^5$ Gy and decreasing at higher doses. Since the stimulating wavelength is shorter than that of the emitted light, one might think that this is simply photoluminescence; however, this is obviously not the case since the role of the initial γ irradiation is crucial. Freytag,[4] Tesch,[5] and Böhm *et al.*[6] described the γ-dose dependence of silver-activated phosphor glass which is used for dose measurements. The effect was termed by these authors radiophotoluminescence (RPL). A visible orange light stimulated by 365 nm UV light was found to increase linearly with the prior applied γ dose between 10^{-2} and 10^2 Gy, reached a maximum at $\sim 3\times 10^3$ Gy, and declined by nearly three orders of magnitude at higher doses up to 10^8 Gy. The strict linearity with the dose between 10^{-2} and 50 Gy enables the evaluation of the dose in this region. Freytag[4] has pointed out that the region of decreasing RPL could also be used for dose measurements, provided a well-determined curve is available. Zeneli *et al.*[7] have further studied the behavior of radiophotoluminescent glasses which, as they report, is being used for high-level dosimetry around the particle accelerators. These authors also studied the light emission by 365 nm stimulation following γ irra-

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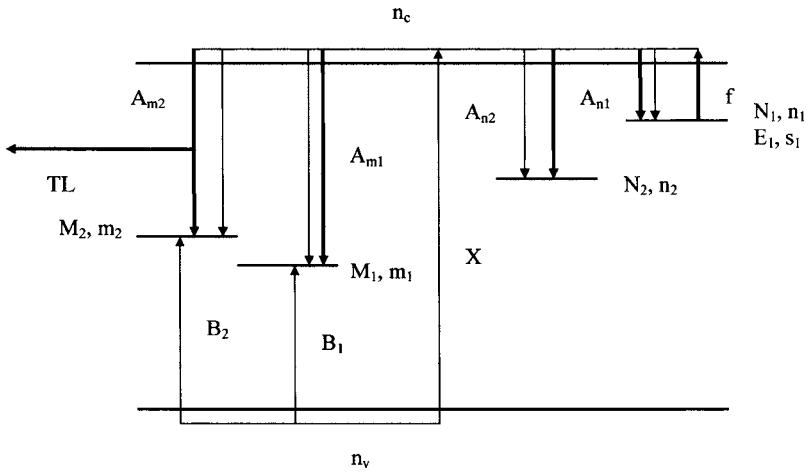

FIG. 1. The energy-level diagram of two electron trapping states and two kinds of hole recombination centers. Transitions occurring during excitation are given by the solid lines, and transitions taking place during the optical readout stage are shown by the thick lines.

diation. They reported on a γ-dose dependence which was a nearly linear function between 10^{-1} and 10^{2} Gy, reached a maximum at $\sim 10^{3}$ Gy, and declined substantially at doses up to 10^{6} Gy at all the temperatures used, namely, 4.6, 77, and 300 K. The authors ascribed the decline to the self-absorption of the luminescent light.

An important material in which the nonmonotonic effect of both TL and OSL has been observed is Al_2O_3 with or without C impurities. Bloom *et al.*[8] studied pulsed OSL (POSL) in Al_2O_3 single crystals and reported a small decline of POSL at β doses above ~ 10 Gy. Yukihara *et al.*[9] described a model of two trapping states and two kinds of recombination centers pertinent to $Al_2O_3:C$ and discussed the character and concentrations of the traps and centers. In particular, the concentration of preexisting F^+ centers which is likely to be many orders of magnitude higher than the radiation-induced F^+ centers appears to be of great importance.[10] Yukihara *et al.*[11,12] reported on the nonmonotonic dose dependence of OSL in β-irradiated $Al_2O_3:C$. Both integrated cw-OSL and initial OSL were found to reach a maximum which, depending on the sample, often occurred at ~ 35 Gy of β excitation, the effect being somewhat stronger in the latter than in the former. In parallel, the measurements revealed a maximum in the dose dependence of TL at about the same dose. Pagonis *et al.*[13] simulated the nonmonotonic dose dependence of TL in $Al_2O_3:C$ using different sets of trapping parameters, some of which previously suggested by McKeever *et al.*[10] and Yukihara *et al.*[11,12] For three different $Al_2O_3:C$ samples labeled "chip 101," "B1040," and "D320," the TL results varied to some extent, and the parameters were adjusted to fit these results. The dependence of the linear absorption coefficient on the dose was also simulated and compared to the data by Yukihara *et al.*[9]

In the present work, we simulate the dependence of the integrated OSL on the dose with the same set of parameters related to the sample labeled chip 101 mentioned by Pagonis *et al.*[14] The calculations follow a previous work by Chen and Leung[15] dealing with a much simpler model of one trapping state and one kind of recombination center, and with pulsed OSL. Preliminary results have been given by Pagonis *et al.*,[14] but in the present work we get a much better insight into the conditions between the active center occupancy before and after the stimulation and the peak shape of the OSL dependence on the dose. The initial increase and later decrease of the integral OSL with the dose are explained in terms of the relation between the concentrations of trapping states, recombination centers, and the initial, radiation-independent, concentration of the active luminescence center (F^+). Also, the constant plateau value of the integral OSL reached at high doses is also explained using the same concentrations.

II. THE MODEL AND RELEVANT SET OF PARAMETERS

The model used is shown in Fig. 1, and is rather similar to that given by Yukihara *et al.*[9] Two trapping states are taken into consideration, N_1 which is an "active" dosimetric trap, meaning that the stimulating light is capable of releasing electrons from it, and N_2, a competitor in which electrons can be trapped, but the stimulating light cannot release electrons from it. Two recombination centers are assumed to exist, M_1 which is radiative and M_2, a nonradiative competitor. The set of six coupled differential equations governing the process during excitation is

$$\frac{dm_1}{dt} = -A_{m_1} m_1 n_c + B_1 (M_1 - m_1) n_v, \tag{1}$$

$$\frac{dm_2}{dt} = -A_{m_2} m_2 n_c + B_2 (M_2 - m_2) n_v, \tag{2}$$

$$\frac{dn_1}{dt} = -sn_1 \exp(-E/kT) + A_{n_1}(N_1 - n_1) n_c, \tag{3}$$

$$\frac{dn_2}{dt} = A_{n_2}(N_2 - n_2) n_c, \tag{4}$$

$$\frac{dn_v}{dt} = X - B_2 (M_2 - m_2) n_v - B_1 (M_1 - m_1) n_v, \tag{5}$$

$$\frac{dn_c}{dt} = \frac{dm_1}{dt} + \frac{dm_2}{dt} + \frac{dn_v}{dt} - \frac{dn_1}{dt} - \frac{dn_2}{dt}. \tag{6}$$

Here, M_1 (cm^{-3}) is the concentration of radiative hole centers with instantaneous occupancy of m_1 (cm^{-3}), M_2 (cm^{-3})

is the concentration of nonradiative hole centers with instantaneous occupancy of m_2 (cm^{-3}), N_1 (cm^{-3}) is the concentration of the electron active trapping state with instantaneous occupancy of n_1 (cm^{-3}), and N_2 (cm^{-3}) is the concentration of the trapping state with instantaneous occupancy of n_2 (cm^{-3}). n_c and n_v are the concentrations (cm^{-3}) of the electrons and holes in the conduction and valence bands, respectively. X ($cm^{-3}\ s^{-1}$) is the rate of production of electron-hole pairs, which is proportional to the excitation dose rate, and B_1 and B_2 ($cm^3\ s^{-1}$) are the trapping probability coefficients of free holes in centers 1 and 2, respectively. A_{m_1} and A_{m_2} ($cm^3\ s^{-1}$) are the recombination probability coefficients for free electrons with holes in centers 1 and 2, and A_{n_1} ($cm^3\ s^{-1}$) is the retrapping probability coefficient of free electrons into the active trapping state N_1. A_{n_2} ($cm^3\ s^{-1}$) is the trapping probability coefficient of the free electrons into the competing trapping state N_2. If we denote the time of excitation by t_D and the rate of production of electron-hole pairs per cm^3 by X, then Xt_D represents the total concentration of electrons and holes produced, which is proportional to the total dose imparted.

Concerning the values of the relevant parameters in Al_2O_3:C, these have been evaluated by Pagonis *et al.*,[14] based on the results by Yukihara *et al.*,[9] and will be used here for OSL. We selected a four-level model of alumina that includes one dosimetric trap (N_1), one deep electron trap (N_2), one radiative recombination center (M_1), and one radiationless center (M_2). Measurements on chip 101 show that, before irradiation, the recombination center has a nonzero initial carrier concentration and that this concentration decreases
at doses above 10 Gy. We were able to reproduce this and other observed behaviors of this sample[14] with the following parameter set: $M_1=10^{17}\ cm^{-3}$, $M_2=2.4\times10^{16}\ cm^{-3}$, $N_1=2\times10^{15}\ cm^{-3}$, $N_2=2\times10^{15}\ cm^{-3}$, $A_{m_1}=4\times10^{-8}\ cm^3\ s^{-1}$, $A_{m_2}=5\times10^{-11}\ cm^3\ s^{-1}$, $B_1=10^{-8}\ cm^3\ s^{-1}$, $B_2=4\times10^{-9}\ cm^3\ s^{-1}$, $A_{n_1}=2\times10^{-8}\ cm^3\ s^{-1}$, $A_{n_2}=2\times10^{-9}\ cm^3\ s^{-1}$, $X=1.7\times10^{15}\ cm^{-3}\ s^{-1}$, and $m_{10}=9.4\times10^{15}\ cm^{-3}$. The rest of the initial carrier concentrations in the model are taken equal to zero. The chosen values for M_1 and m_{10} are in agreement with independent measurements inferred from optical-absorption data (Yukihara *et al.*[9]). Note also that the selected rate constant values were all chosen to be within the range of commonly observed electron capture in solids (see, e.g., Lax[16]).

In the next stage of the process, a relaxation period has been simulated by setting the excitation dose rate to zero and solving the same set of equations for a certain period of time so as to have the concentrations of the free electrons, n_c, and free holes, n_v, go to negligible values; the initial values of the concentration functions for the relaxation stage are the final values at the excitation stage. Finally, the following five simultaneous equations are to be solved for the stimulation stage:

$$\frac{dn_1}{dt} = -fn_1 + A_{n_1}(N_1 - n_1)n_c, \tag{7}$$

$$\frac{dn_2}{dt} = A_{n_2}(N_2 - n_2)n_c, \tag{8}$$

$$\frac{dm_1}{dt} = -A_{m_1}m_1n_c, \tag{9}$$

$$\frac{dm_2}{dt} = -A_{m_2}m_2n_c, \tag{10}$$

$$\frac{dn_1}{dt} + \frac{dn_2}{dt} + \frac{dn_c}{dt} = \frac{dm_1}{dt} + \frac{dm_2}{dt}. \tag{11}$$

Here, $f(s^{-1})$ is a magnitude proportional to the stimulating light intensity, and has been given the value of $1/60\ s^{-1}$. The model assumes that the stimulating light does not raise electrons from the competing trap N_2. The OSL intensity is associated with the recombination into m_1, therefore, the intensity $I(t)$ is

$$I(t) = A_{m_1}m_1n_c. \tag{12}$$

It should be noted that, whereas in the work on TL, the maximum intensity was usually taken as the TL signal, here we prefer to follow the experimental practice in which one usually considers the integral on the decaying OSL curve over a certain period of time. It should be noted that the dose dependence may be different when a response to a short pulse of light is considered as discussed by Chen and Leung.[15]

The MATLAB ode23s solver as well as the MATHEMATICA solver have been used to solve numerically the relevant sets of equations, and the results reached with both were in excellent agreement. In order to evaluate the area under the OSL decaying curve, one should usually perform a numerical integration for a certain period of time along the curve. In order to bypass this step, we chose the following method. If we assume, as we did, that m_1 is the hole concentration in the luminescent center, obviously the OSL intensity is $I(t) = -dm_1/dt$. The integral over time between zero and the chosen final time t_f yields

$$\int_0^{t_f} I(t)dt = m_{10} - m_{1f}. \tag{13}$$

We can, therefore, perform the simulation along the stimulation time, but instead of integrating over $I(t)$, just take the difference between the initial and final values of m_1. This method, which saves computation time, also enables a better understanding of the results as discussed below.

III. NUMERICAL RESULTS

With the set of parameters relevant, in particular, to the Al_2O_3:C samples mentioned above, we have performed the following simulations. Different lengths of excitation were used and n_1, n_2, m_1, and m_2 were recorded at the end of excitation plus relaxation, and plots of these magnitudes as a function of dose were made. For m_1, its value following the next stimulation stage was found for each dose, as well as the value of the integral OSL as described above [Eq. (13)].

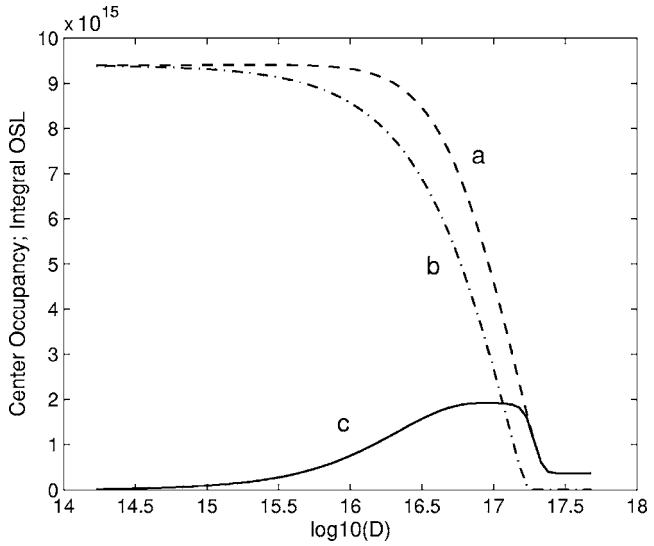

FIG. 2. Simulated dose dependence of the concentration of the occupancy of the radiative center at the end of irradiation plus relaxation (a) and the end of light stimulation (b). Curve (c) shows, under the same circumstances, the integral OSL as a function of the dose. The relevant set of parameters is given in the text and includes an initial concentration of radiative center, $m_{10}=9.4\times10^{15}$ cm^{-3}.

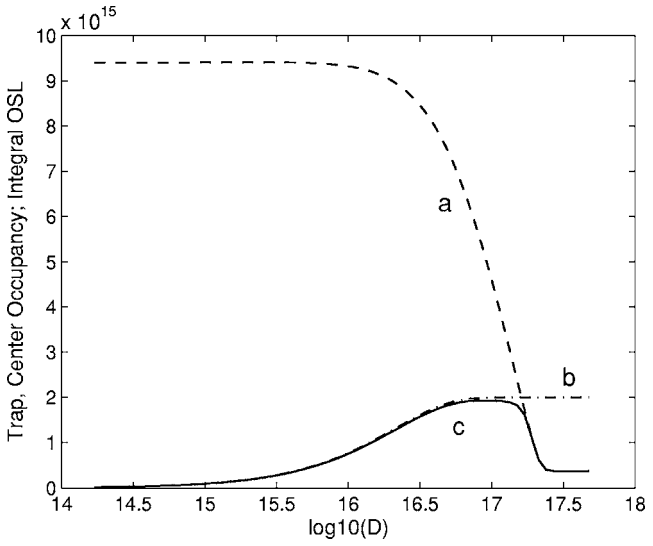

FIG. 3. With the same parameters as in Fig. 2, the occupancy of the radiative center following excitation and relaxation is shown in (a), and that of active trap in (b). Curve (c) shows the simulated integral OSL in the same range of doses.

Figure 2 depicts, in curve (a), the dependence of the occupancy of the radiative center, m_1, at the end of the relaxation period, on the dose. At low doses, the concentration starts at the initial value of 9.4×10^{15} cm^{-3}, reduces at higher doses due to recombinations that take place during excitation, and gets to an equilibrium final value of $\sim3.7\times10^{14}$ cm^{-3} at high doses. The significance of this equilibrium value will be discussed below in connection with the other relevant parameters of the given problem. Curve (b) shows the values of m_1 for the same problem and the set of parameters, but at the end of the stimulation stage. Note that at high doses, the m_1 value here reduces to practically zero, in agreement with the experimental findings of Yukihara *et al.*[11] for chip 101. Curve (c) depicts the difference between the values of (a) and (b), and as explained above, it represents the area under the OSL curve as a function of the dose. The peak shape resembles, at least qualitatively, the behavior reported by Yukihara *et al.*[11] for chip 101. At high doses, the OSL intensity reaches a plateau, again similarly to the experimental results. The equilibrium OSL value reached is the same value of $\sim3.7\times10^{14}$ cm^{-3}, and the reason for this is that m_1 reduces to very small values following the stimulation period.

While considering these results, we would like to compare from a different point of view the filling of the trapping states and recombination centers with the dose, with the total OSL dose dependence. Curve (a) in Fig. 3 shows, again, the dependence of the concentration of the active center at the end of relaxation as a function of dose. Curve (b) shows the increase of the active trap concentration n_1 at the end of relaxation, with the dose, from an initial value of zero to a full saturation at 2×10^{15} cm^{-3}. n_1 reaches a saturation at a "dose" of $\sim10^{17}$ cm^{-3}. Not shown here is the approach to saturation of the competitor at high doses; n_2 reaches a saturation value ($n_2\approx N_2$) of 2×10^{15} cm^{-3} at a simulated dose of $\sim2.5\times10^{17}$ cm^{-3}. The calculated values of the integral OSL are repeated in curve (c); the relation between these three quantities will be discussed in the next section.

Although the present work deals mainly with the behavior of the Al_2O_3:C samples, more simulations have been performed which help in getting a better insight into the processes taking place and the inter-relation between the trapping states and recombination centers. Figure 4 shows the dose dependence of n_1 and m_1 as a function of the dose in the same system with the same trapping parameters, except that the initial value of m_1 is set to zero. This is similar to the case of sample B1040 reported by Yukihara *et al.*[9] In curve (a), m_1 gets to a maximum value at $\sim1.6\times10^{16}$ cm^{-3} and then declines and remains at a plateau level of $\sim6.13\times10^{13}$ cm^{-3} at high doses. In curve (b), n_1 is seen to increase from zero to its saturation value of 2×10^{15} cm^{-3}. Curve (c)

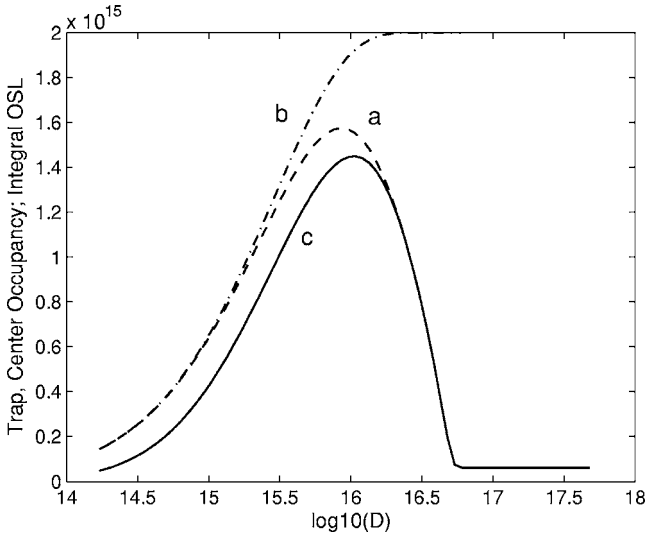

FIG. 4. Same as Fig. 3, but with $m_{10}=0$. Curves (a) and (b) show, respectively, the occupancies of m_{10} and n_{10} at the end of relaxation, and (c) depicts the simulated integral OSL.

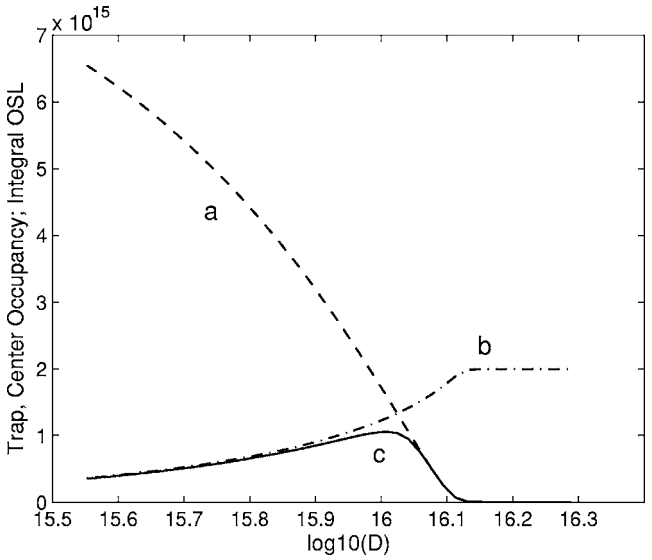

FIG. 5. Similar to Fig. 3, but the total concentration of competing centers is set to be $M_2=2.4\times10^{18}$ cm^{-3}.

represents the integral OSL which, roughly speaking, has a similar peak shape as m_1, but slightly shifted to higher doses. The OSL also reaches the same plateau level of $\sim 6.13\times10^{13}$ cm^{-3} as can easily be understood. These relations will also be discussed below.

Figure 5 shows the same magnitudes as Figs. 3 and 4 but the capacity of the competitor center is increased by two orders of magnitude to be 2.4×10^{18} cm^{-3}; the initial value of m_1 is 9.4×10^{15} cm^{-3} as in Fig. 3. Here too, the behavior at low doses resembles that of the dose dependence of n_1, whereas the behavior at high doses is the same as that of m_1. The equilibrium value reached at high doses is significantly smaller; its simulated value is 1.75×10^{12} cm^{-3}, nearly three orders of magnitude smaller than the maximum occurring at a dose of $\sim10^{16}$ cm^{-3}. This behavior of a significant decline in the OSL intensity resembles that reported by Freytag,[4] Tesch,[5] and Böhm *et al.*[6]

IV. DISCUSSION

The obvious relation between m_1 at the end of relaxation, at the end of stimulation, and the integral of the OSL has been explained above with relation to Fig. 2. The nonmonotonic dose dependence of the integral OSL has been previously[14] associated with competition during either excitation or readout (or, perhaps, both). In the present simulation, m_1 (Fig. 2) is decreasing with the dose and n_1 is increasing with the dose, and therefore, obviously, competition during excitation is not the leading factor for the nonmonotonic dependence. Competition during readout may have an important role; however, the apparent effect may be explained in a different way as follows. On p. 169 of Ref. 1, it is shown that for TL, the area under the glow peak depends on $\min(n_0,m_0)$, where n_0 and m_0 are, respectively, the occupancies of active traps and centers at the end of irradiation and prior to heating. The same considerations hold for n_1 and m_1 at the end of excitation in the present case of integral OSL. Considering Fig. 3, it is obvious that at relatively low doses, $n_1<m_1$, and therefore, the simulated OSL behaves like n_1 (curve b), i.e., increasing with the dose. In fact, since OSL is given in the same units as the concentration, the two curves practically coincide at low doses. At high doses, $n_1>m_1$, and therefore, the OSL (curve c) behaves like m_1 (curve a), namely, decreases with the dose, and at high enough doses, the two curves coincide. One might expect that the maximum will occur when $n_1=m_1\approx2\times10^{15}$. In fact, the maximum signal occurs at a dose of $\sim10^{17}$, whereas the maximum OSL takes place at $\sim1.6\times10^{17}$. This slight discrepancy should be attributed to nontrivial dynamic effects that have to do with the variations which take place in n_2 and m_2 in the same dose range.

As for the results of Fig. 4, where the radiative recombination center m_1 is initially nil, curve (a) for the concentration of these centers and (c) for the OSL are similar, peak-shaped functions, but not identical. The similarity between the curves points to an effect of competition during excitation. The slight shift of the OSL peak to higher doses than that of m_1 can be explained, taking into consideration the n_1 curve (b) which is an increasing function at the same dose range. Roughly speaking, the integrated OSL can be considered as the product of n_1 and m_1 and when a peak-shaped function is multiplied by an increasing function, the result is usually a peak-shaped function, the maximum of which occurring at higher values of the argument.

We would like to discuss now the nonzero plateau values of the OSL, which are not saturation values, observed at high doses both in some experimental results as mentioned above and in Figs. 2–4 as a result of the simulations. For illustration, let us start by considering the set of parameters yielding Figs. 2 and 3. Note that at high doses, the simulation yielded an equilibrium value of 3.7×10^{14} for m_1, from which the same value was found for the OSL, and 1.303×10^{16} for m_2. We will show now how these values are associated with the set of parameters chosen for the simulation. Note that initially, we have $m_{10}=9.4\times10^{15}$. This necessarily means that there is another entity in the sample, an entirely disconnected trapping state that does not participate in the exchange of carriers during excitation or readout, but should be assumed to exist due to neutrality considerations and hold 9.4×10^{15} electrons. During a given excitation, the same number of electrons is accumulated in N_1 and N_2 as holes in M_1 and M_2, and those accumulated in M_1 and M_2 are in addition to the initial m_{10} mentioned above; therefore if we consider points in time following excitation, we have

$$n_1+n_2+9.4\times10^{15}=m_1+m_2. \tag{14}$$

If we consider high enough dose such that both N_1 and N_2 are saturated, a situation that can take place only if N_1+N_2 is smaller than M_1+M_2, than we can write for this range

$$N_1+N_2+9.4\times10^{15}=m_1+m_2. \tag{15}$$

The mentioned nonzero plateau results from a state of dynamic equilibrium in which the net change of both m_1 and m_2 is nil. In other words, the number of holes trapped per second in each center is equal to the number of holes recombining with electrons in the same center per second, i.e.,

$$A_{m_1} m_1 n_c = B_1 (M_1 - m_1) n_v, \tag{16}$$

$$A_{m_2} m_2 n_c = B_2 (M_2 - m_2) n_v. \tag{17}$$

Dividing the two equations by one another, one gets

$$\frac{A_{m_1} m_1}{A_{m_2} m_2} = \frac{B_1 (M_1 - m_1)}{B_2 (M_2 - m_2)}. \tag{18}$$

With the given set of parameters, Eqs. (15) and (18) are two equations in the two unknown parameters m_{1e} and m_{2e}, the equilibrium values of the centers concentration, which can be solved, say, by inserting m_{2e} from Eq. (15) into (18), thus yielding a quadratic equation in m_{1e}. Out of the two possible solutions, one is found to be negative, and therefore, nonphysical. The positive equilibrium value is $\sim 3.7 \times 10^{14}$ cm^{-3}, which is exactly the plateau level seen on the right-hand side of curves (a) and (c) of Fig. 2. The equilibrium value of the competing center m_{2e} can immediately be found from that of m_{1e} using Eq. (15) and the value found is $m_{2e} = 1.303 \times 10^{16}$ cm^{-3}. It should be noted that this consideration applies to the equilibrium *during* excitation, and the relevant occupancies may be somewhat different at the end of relaxation. With the examples given here, however, it has been found that the additional contribution to the concentration of the traps and centers is minor, less than 1%, and therefore, the evaluated numbers are valid.

A similar calculation can be made for the situation in which the initial filling of the radiative center is zero, as shown in Fig. 4. Here, the left-hand side of Eq. (15) includes only $N_1 + N_2$, or 4×10^{15} cm^{-3} with the given parameters. Solving the analog of Eq. (15) with this value along with Eq. (18) yields $m_{1e} = 6.13 \times 10^{13}$ cm^{-3}, which is the plateau level shown in curves (a) and (c) of Fig. 4. The resulting value for m_{2e} is 3.94×10^{15} cm^{-3}. A similar calculation performed for the parameters yielding Fig. 5, namely, the same as in Fig. 3 but with $M_2 = 2.4 \times 10^{18}$ cm^{-3}, yielded $m_{1e} = 1.75 \times 10^{12}$ cm^{-3} which, indeed, is the value reached for high doses in Fig. 5. This value is more than three orders of magnitude smaller than the maximum of the scale, and therefore looks like zero on the figure.

In conclusion, the present work has shown, using simulations as well as intuitive physical considerations, the main features seen in the dose dependence of integral OSL, namely, the occurrence of a peak-shaped curve followed by an equilibrium plateau at high doses, in the framework of a model with two trapping states and two kinds of recombination centers. The relation between the concentrations of the active center at different stages of the process and the OSL integral has been discussed. Also, the direct connection between the relevant parameters chosen for simulation and the high dose equilibrium value has been established.

[1] R. Chen and S. W. S. McKeever, *Theory of Thermoluminescence and Related Materials* (World Scientific, Singapore, 1997).
[2] J. L. Lawless, R. Chen, D. Lo, and V. Pagonis, J. Phys.: Condens. Matter **17**, 737 (2005).
[3] J. H. Schulman, H. W. Etzel, and J. G. Allard, J. Appl. Phys. **28**, 792 (1957).
[4] E. Freytag, Health Phys. **20**, 93 (1983).
[5] K. Tesch, Radiat. Prot. Dosim. **6**, 347 (1983).
[6] M. Böhm, E. Pitt, and A. Scharmann, Radiat. Prot. Dosim. **8**, 139 (1984).
[7] D. Zeneli, M. Tavlet, and F. Coninckx, Radiat. Prot. Dosim. **66**, 59 (1996).
[8] D. Bloom, D. E. Evans, S. A. Holmstrom, J. C. Polf, S. W. S. McKeever, and V. Whitley, Radiat. Meas. **37**, 141 (2003).
[9] E. G. Yukihara, V. H. Whitley, J. C. Polf, D. M. Klein, S. W. S. McKeever, A. E. Akselrod, and M. S. Akselrod, Radiat. Meas. **37**, 627 (2003).
[10] S. W. S. McKeever, M. S. Akselrod, L. E. Colyott, N. Agersap Larsen, J. C. Polf, and V. Whitley, Radiat. Prot. Dosim. **84**, 163 (1999).
[11] E. G. Yukihara, V. H. Whitley, S. W. S. McKeever, A. E. Akselrod, and M. S. Akselrod, Radiat. Meas. **38**, 317 (2004).
[12] E. G. Yukihara, R. Gaza, S. W. S. McKeever, and C. G. Soares, Radiat. Meas. **38**, 59 (2004).
[13] V. Pagonis, R. Chen, and J. L. Lawless (unpublished).
[14] V. Pagonis, R. Chen, and J. L. Lawless, presented at the 11th International Conference on Luminiscence and ESR Dating, Köln, Germany, July 2005, Radiat. Meas. (in press).
[15] R. Chen and P. L. Leung, J. Appl. Phys. **89**, 259 (2001).
[16] M. Lax, Phys. Rev. **119**, 1502 (1960).