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Optically stimulated exoelectron emission processes in quartz: comparison of experiment and theory

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ABSTRACT

Recent experiments have demonstrated that it is possible to measure optically stimulated exoelectron emission (OSE) signals simultaneously with optically stimulated luminescence (OSL) from quartz samples. These experiments provide valuable information on the charge movement in quartz grains. Two specific experiments measured the temperature dependence of the OSL and OSE signals on preheat and stimulation temperature. This paper provides a quantitative description of these experiments by using a previously published theoretical model for photostimulated exoelectron emission (PSEE). The experimental data yield a value of $\chi \sim 1.2$ eV for the work function of quartz. The experimental temperature dependence of the OSE signals is interpreted on the basis of a photo-thermostimulated (PTSEE) process involving the main OSL trap at $\sim 320\,^{\circ}$C; this process takes place with a thermal assistance energy estimated at $W \sim (0.29 \pm 0.02)$ eV. Good quantitative agreement is obtained between theory and experiment by assuming a thermal broadening of the thermal depletion factor for the OSL traps, described by a Gaussian distribution of energies.

1. Introduction

The study of exoelectron emission yields useful information on the trapped charge populations in solids. This phenomenon results from the emission of electrons which absorb enough excitation energy to overcome the work function of the material; these electrons may originate directly from traps, or from the conduction band. Ankjærgaard et al. [1] used a flow-through Geiger-Müller pancake electron detector to simultaneously measure optically stimulated electrons (OSE) and optically stimulated luminescence (OSL) from a sedimentary quartz sample. These authors demonstrated that OSE signals from natural quartz grains are easily detectable and reproducible, although they are not as frequent as the OSL signals. Their experiments studied the thermal stability of the OSE and OSL signals, as well as their dependence on the stimulation temperature. The OSL and OSE dose response was also measured, and conclusions were drawn on the movement of electrons in a sample of sedimentary quartz (WIDG8), which has been the subject of several previous experimental studies (e.g. [2,3]).

Ankjærgaard et al. [1] found that the OSE and OSL signals behave differently as a function of the preheat temperature (the temperature the sample is heated to after irradiation but prior to the stimulation). The OSE signal decreases steadily between 120 and 400 °C. They suggested that this temperature dependence does not represent the thermal depletion of the OSL traps in quartz, because the OSE experimental curve decays much more gradually and over a larger temperature range than the expected thermal depletion of the OSL traps at ~320 °C. At the same time, the OSL signal initially increases with the preheat temperature and subsequently decreases rapidly in this temperature range. The OSL results were consistent with previous measurements of this sample by Wintle and Murray [2], with the decrease in the OSL signal apparently due to thermal depletion of the 320 °C OSL trap. The behavior of the OSE signals was interpreted as being inconsistent with thermal detrapping of the electrons, because it is much slower and takes place over a much wider temperature range.

In a second experiment, Ankjærgaard et al. [1] studied the behavior of the OSE and OSL signals as a function of the

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stimulation temperature. The OSL signal decreased between room temperature and 400 °C, in agreement with previous measurements which were explained on the basis of thermal quenching [3]. On the other hand, the OSE signal exhibited a peak-shape temperature dependence starting at ~100 °C, with a maximum at ~280 °C. This peak-shaped behavior was found for both the initial 0.5 s of the OSE signal, and for the total OSE signal integrated over 100 s. Ankjærgaard et al. [1] interpreted the initial increase of the OSE signal as due to the increased mean energy of electrons in the conduction band at higher temperatures. They also suggested that thermal erosion of the OSE trap becomes dominant at temperatures above ~280 °C.

This paper makes use of a previously published model for photostimulated exoelectron emission (PSEE) processes in solids to explain the experimental data of Ankjærgaard et al. [1]. The experimental data yield an estimated value of $\chi \sim 1.2$ eV for the work function of quartz, and also an estimated value for the energy of thermal assistance equal to $W \sim (0.29 \pm 0.02)$ eV. A photo-thermostimulated (PTSEE) process is proposed here to explain both the stimulation temperature dependence of the OSE signals, and the dependence of OSE on the preheat temperature. By assuming a broadening of the thermal depletion factor for the OSL traps due to a random Gaussian distribution of energies, good quantitative agreement is obtained between theory and experiment.

1.1. The OSE model of Oster and Haddad (2003)

Oster and Haddad [4] developed a mathematical model to describe non-stationary photostimulated exoelectron emission in solids. This phenomenon consists of the emission of low-energy electrons from the surface of the solid during photostimulation, after excitation by ionizing radiation. One such possible transition of interest in this paper is shown in Fig. 1. Additional phenomena described by Oster and Haddad [4] are photo-photostimulated emission (PPSEE), thermo-photostimulated emission (TPSEE), and finally thermo-thermostimulated emission; these additional phenomena are not relevant to this study.

In transition (1) shown in Fig. 1, the electron release is caused by photons, while the emission from the surface is caused by thermal excitation. This is termed photo-thermostimulated emission in Oster and Haddad [4].

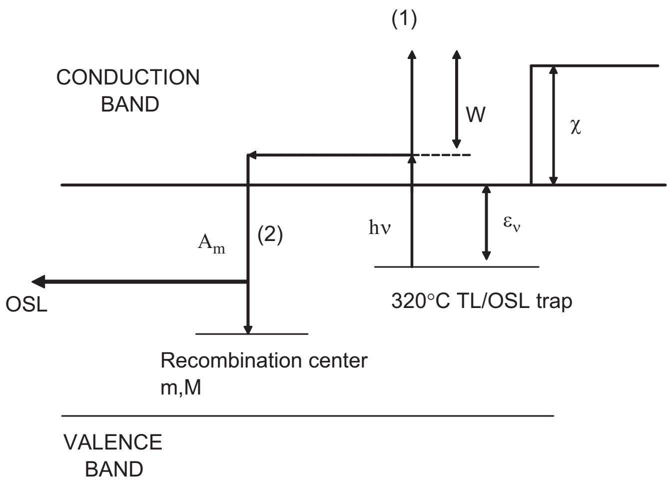

Fig. 1. A model describing the origins of OSE and OSL signals in quartz. Photon absorption gives rise to electron escape to the conduction band, followed either by transition (1) where electron emission from the surface is caused by thermal excitation (this is termed photo-thermostimulated emission) in Oster and Haddad (2003), or by transition (2) where electron recombination with a trapped hole gives rise to luminescence.

The model is developed by solving the following set of differential equations:

$$\frac{dn}{dt} = -P_v n = -\zeta E_s n \tag{1}$$

and

$$\frac{dN}{dt} = P_v n - (A_R + \Omega_T) N. \tag{2}$$

Here A_R is the recombination probability (in s^{-1}), n is the electron concentration in the traps (cm^{-3}), $P_v = \zeta E_s$ is the probability of electron ejection from the trap by photons (in s^{-1}), Ω_T is the probability of electron emission from the conduction band by thermal stimulation (in s^{-1}), ζ is the light absorption cross section for the OSL trap (in cm^{-2}), E_s is the quantum intensity for the OSL trap (in eV). N is the electron concentration in the conduction band (in cm^{-3}), and t is the time in s.

It is noted that the recombination probability A_R appearing in Eq. (1) with units of s^{-1} is given by the following expression (Chen and McKeever, [5]):

$$A_R = m A_m, \tag{3}$$

where m is the instantaneous concentration of holes in the recombination center (in cm^{-3}), and A_m is the recombination coefficient (in units of $cm^3\,s^{-1}$).

In the model of Oster and Haddad [4] the recombination probability A_R is treated as a constant by assuming that the hole concentration m does not vary significantly during the OSE/OSL experiment. As will be shown in a later section, in some of the OSE experiments of Ankjærgaard et al. [1] the recombination probability A_R actually varies with the preheat temperature.

If I_x is the number of electrons emitted per cm^2 per second from a layer at a depth between x and $x+dx$, then the contribution to OSE from this layer will be given by

$$I_x = N \Omega_x \, dx = N \Omega_T D g_x \, dx, \tag{4}$$

where Ω_x is the probability of electron emission from the conduction band, which is a function of the distance x between the electron and the surface. In this equation, g_x is the probability for electrons in the conduction band to move from depth x to the surface, and D is the average transparency of the surface barrier for hot electrons. Ω_T is the probability of thermal electron emission from the conduction band.

The probability Ω_T of thermal electron emission from the conduction band is given by the Boltzmann factor

$$\Omega_T = \Omega_o \exp\left\{\frac{(-\varepsilon_v + \chi - h\nu)}{kT}\right\}, \tag{5}$$

where Ω_o is a dimensionless coefficient, χ the work function (in eV), $h\nu$ = energy of the stimulating photons (in eV), T the temperature (in K), k = Boltzmann constant and ε_v is the depth of the optically sensitive trap (in eV). These energy levels are shown schematically in Fig. 1.

By solving Eqs. (1) and (2) using the quasiequilibrium assumption $dN/dt = 0$, and by integrating over the layer l of the sample, Oster and Haddad [4] obtained the following expression for the instantaneous OSE intensity

$$I = f(\lambda) D n_o \zeta E_s \frac{\Omega_T}{A_R + \Omega_T} \exp(-\zeta E_s t), \tag{6}$$

where the function $f(\lambda)$ is given by

$$f(\lambda) = 1 - e^{l/\lambda}, \tag{7}$$

and where l is the entire excited layer and λ represents the effective depth of the emission layer (Oster et al., [6]). The quantity n_o represents the initial electron concentration in the traps.

1.2. Photo-thermostimulated emission

In the case of transition (1) shown in Fig. 1, the trapped electrons can be excited optically to the conduction band, and subsequently will be emitted from the surface via a thermally assisted process. In this case, the energy of the photon is such that

$$\varepsilon_v < h\nu < \varepsilon_v + \chi, \tag{8}$$

and one obtains the following simplified expression for the OSE signal (Oster and Haddad, [4], their Eq. (9)):

$$I = B\,\exp\left\{\frac{(-\varepsilon_v + \chi - h\nu)}{kT}\right\}\exp(-\zeta E_s t) = I_o\,\exp(-\zeta E_s t), \tag{9}$$

where

$$B = f(\lambda) D n_o \zeta E_s \frac{\Omega_o}{A_R}, \tag{10}$$

and n_o represents the initial concentration of trapped electrons at time $t = 0$.

By taking the natural logarithm of Eq. (9), one obtains the expression

$$\ln I_o = \ln B - \frac{\varepsilon_v + \chi}{kT} + \frac{h\nu}{kT}. \tag{11}$$

From Eq. (9) it is clear that the initial emission intensity I_o depends on the temperature T and also on the frequency of the stimulating light ν. The total intensity I depends on I_o, and decreases exponentially with time. The rate of exponential decay of the OSE signal from Eq. (9) is equal to ζE_s. This is the same as the time decay rate of the OSL signal, in agreement with the experimental findings of Ankjærgaard et al. [1].

It must be noted that the initial concentration of trapped electrons n_o will be a function of the stimulation temperature and/or the preheat temperature of the sample.

2. Comparison of the model and experimental data

2.1. Dependence of the OSE signal on the stimulation temperature

The dependence of OSE signal on stimulation temperature was recorded using a single aliquot of sedimentary quartz (WIDG8). The aliquot was given a beta dose of 44 Gy from a ^{90}Sr/Y source and preheated to 260 °C for 10 s before blue (470 nm) LED stimulation at some temperature. This was followed by a test dose measurement where the same aliquot was given a dose of 18 Gy, preheated to 260 °C and blue light stimulated at 125 °C. This cycle was repeated for different stimulation temperatures. The OSE and OSL signals were recorded simultaneously; the electrons were emitted into a counting gas (99% argon and 1% isobutane) and detected by a Geiger-Müller counter, the photons measured through an U-340 glass filter using a PM-tube.

Note that the experimental uncertainties in the data shown in Figs. 3, 5, 7–9 are based only on counting statistical errors (the square-root of the total number of counts per channel). They are smaller than the size of the symbols used in these figures, and are thus not visible.

The experimental dependence of the OSE signal $I(T)$ on the stimulation temperature is shown in Fig. 2a. According to Eq. (11), a graph of $\ln I$ against $1/kT$ should yield a straight line at low temperatures T, with a negative slope of $W = h\nu - \varepsilon_v - \chi$. Fig. 2b

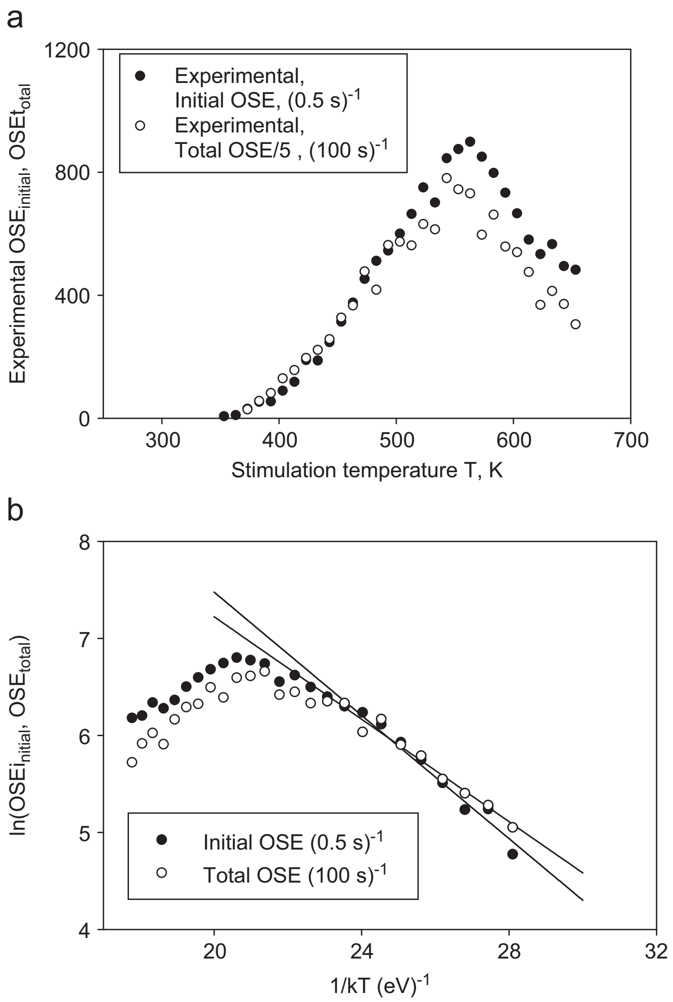

Fig. 2. (a) The experimental OSE dependence on stimulation temperature data of Ankjærgaard et al. (2008) are redrawn here. (b) Analysis of the data in (a). A graph of $\ln I$ against 1/kT yields a straight line at lower temperatures, T, with a negative slope of $W = h\nu - \varepsilon_v - \chi$. This slope represents the thermal activation energy for thermally assisted emission of electrons from the conduction band, and gives a value of $W = -(0.29 \pm 0.02)$ eV.

shows that the initial rise part of this graph is indeed linear, with a negative slope of $W = -(0.26 \pm 0.02)$ eV for the initial OSE data, and with a slope of $W = -(0.32 \pm 0.2)$ eV for the total OSE data. This slope represents the thermal activation energy for thermally assisted emission of electrons from the conduction band. We conclude that the OSE dependence on stimulation temperature is consistent with a thermal assistance process with an average thermal activation energy of $W = -(0.29 \pm 0.02)$ eV. By using the value $h\nu = 2.64$ eV (corresponding to the photon energy for the blue-stimulating light at 470 nm), $W = -0.29$ eV and by substituting a typical value of $\varepsilon_v = 1.75$ eV for the OSL trap at ~320 °C (Bailey, [7]), we obtain the following estimate of the work function χ for quartz:

$$\chi = h\nu - \varepsilon_v - W = 2.64 - 1.75 + 0.29 = 1.2\,\text{eV}. \tag{12}$$

To the best of our knowledge, there are no previously published values for the work function χ of quartz samples in the literature.

This value of χ is now used to obtain a quantitative fit to the experimental data of OSE dependence on stimulation temperature shown in Fig. 2a. Ankjærgaard et al. [1] interpreted the descending part of the data in Fig. 2a as due to thermal depletion of the main OSL traps at ~320 °C. For a first-order kinetic process, the thermal depletion of a single thermoluminescence (TL) or OSL trap is given by the well-known first-order expression

$$n = n_o \exp(-\lambda t) = n_o \exp(-s \exp(-E_1/kT)t), \tag{13}$$

where n is the concentration of electrons at time t (in cm^{-3}), n_o the initial concentration at time $t = 0$, $\lambda = s\exp(-E_1/kT)$ represents the decay constant at temperature T (in s^{-1}), E_1 the energy depth of the trap below the conduction band (in eV), and s the frequency factor of the trap (in s^{-1}). The time t is the duration of heating of the sample at the temperature T and k is the Boltzmann constant.

The decrease in the concentration of electrons due to the increased temperature T is, therefore, given by the depletion factor $D(T)$ expressed by

$$D(T) = n/n_o = \exp(-s \exp(-E_1/kT)t_p). \tag{14}$$

This depletion factor $D(T)$ is shown in Fig. 3a. The values of the constants in this expression are taken as $E_1 = 1.75$ eV for the 320 °C OSL trap, $s = 5 \times 10^{13}\,s^{-1}$ and $t_p = 10$ s is the preheat time used in experiments of Ankjærgaard et al. [1]. The thermal assistance factor $\exp(-W/kT)$ is also shown in Fig. 3a; the product of the increasing function $\exp(-W/kT)$ and of the decreasing function $D(T)$ yields a broad peak shape with a maximum at ~580 K (~307 °C). This broad peak shape is shown superimposed on the experimental data in Fig. 3b. Inspection of Fig. 3b shows a general qualitative agreement of theory and experiment, but the overall calculated temperature dependence of the OSE signal is narrower than indicated in the experimental data. This suggests a possible thermal broadening of the observed temperature dependence of the OSE data, possibly due to interactions with the lattice vibrations.

This thermal broadening can be expressed by using a normalized random Gaussian distribution of the energy E given by

$$g(E) = \exp\left(-\frac{(E-E_1)^2}{2\sigma^2}\right), \tag{15}$$

where $E_1 = 1.75$ eV and σ represents the standard deviation or width parameter of the Gaussian distribution. The effect of this energy distribution will be to produce an effective depletion factor $D_{eff}(T)$, which can be calculated by integrating the expression $D(T)$ in Eq. (14) over all possible energies E

$$D_{eff}(T) = \int_{-\infty}^{+\infty} g(E)D(T)\,dE. \tag{16}$$

By substituting the value of $D(T)$ from Eq. (14), this becomes

$$D_{eff}(T) = \int_{-\infty}^{+\infty} g(E)\exp(-s \exp(-E/kT)t_p)\,dE. \tag{17}$$

This integral can be calculated numerically rather easily to yield a graph of the effective depletion factor $D_{eff}(T)$ as a function of the stimulation temperature T, as shown in Fig. 4, for several values of the Gaussian width parameter σ. As may be expected on physical grounds, increasing of the Gaussian width parameter σ leads to an overall thermal broadening of the depletion factor $D_{eff}(T)$. Fig. 5a shows the optimal $g(E)$ distribution with $E_1 = 1.75$ eV and $\sigma = 0.14$ eV; this $g(E)$ distribution gives a good quantitative fit to the experimental data, as shown in Fig. 5b.

2.2. Dependence of the OSE signal on the preheat temperature

In a second experiment, Ankjærgaard et al. [1] studied the dependence of the OSE signal on the preheat temperature by using a single aliquot of sample WIDG8. The aliquot was irradiated with a dose of 330 Gy, preheated to a given preheat temperature for 10 s, and optically stimulated at 125 °C using blue LEDs. This cycle was repeated for different preheat temperatures using the same aliquot, and the results of the experiment are shown in Fig. 6. Ankjærgaard et al. [1] found that the OSE signal decreases continuously with the preheat temperature between 130 and 400 °C. They suggested that there may be a discrepancy between this temperature dependence and the thermal depletion

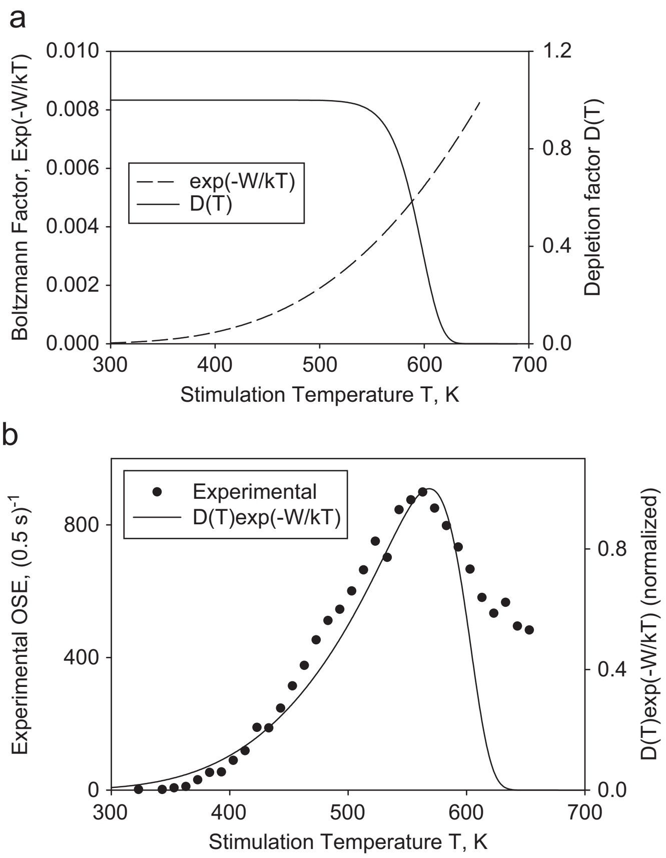

Fig. 3. (a) The depletion factor $D(T)$ for the OSL traps at ~320 °C as a function of the stimulation temperature T. The thermal assistance factor $\exp(-W/kT)$ is also shown. In (b), the experimental data from Fig. 2a is shown together with the product of the increasing function $\exp(-W/kT)$ and of the decreasing function $D(T)$ is shown; the latter yields a broad peak with a maximum at ~580 K (~307 °C).

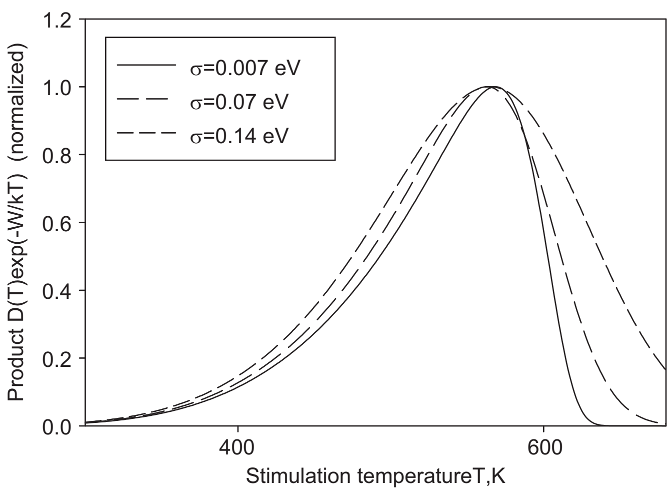

Fig. 4. The product of the effective depletion factor $D_{eff}(T)$ and the thermal assistance factor $\exp(-W/kT)$ is shown as a function of the stimulation temperature T for several values of the Gaussian width parameter σ. Increasing the Gaussian width parameter σ leads to an overall thermal broadening of the factor $D(T)\exp(-W/kT)$.

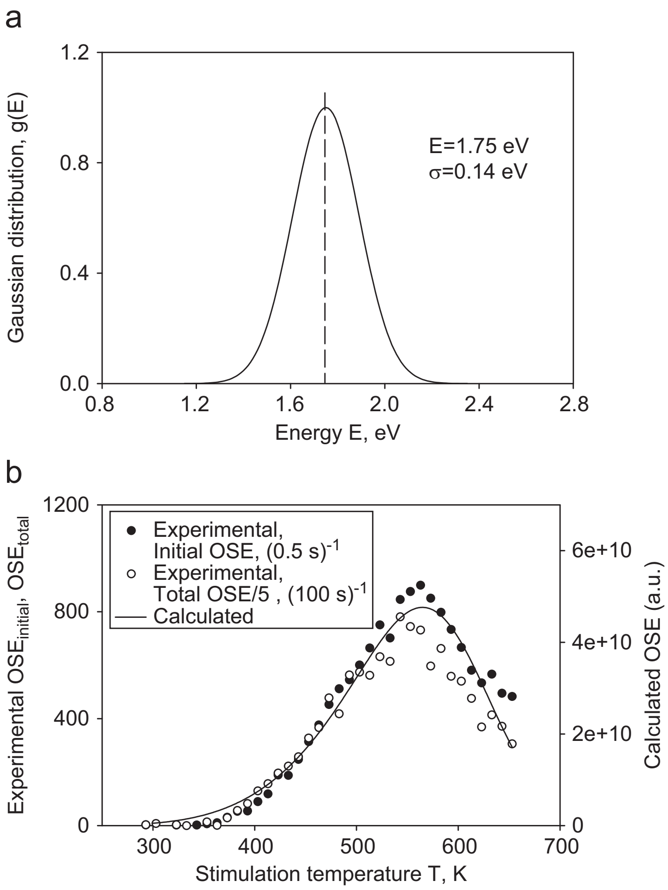

Fig. 5. (a) The Gaussian energy distribution $g(E)$ obtained using $E_1 = 1.75\,\text{eV}$ and $\sigma = 0.14\,\text{eV}$ gives rise to the predicted OSE signal shown in (b), where it is compared to the experimental data of Fig. 2a.

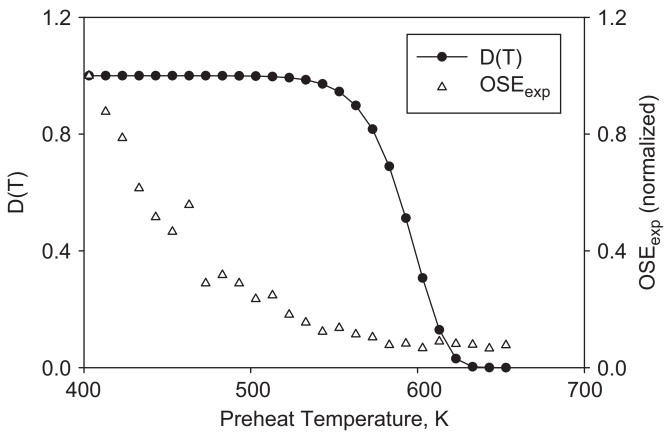

Fig. 6. Comparison of the expected thermal depletion factor $D(T)$ for the 320 °C OSL trap, with the experimental OSE dependence on preheat temperature data from Ankjærgaard et al. (2008). The OSE experimental data decays more gradually than expected.

of the OSL traps in quartz, because the experimental curve decays much more gradually and over a larger temperature range than the expected thermal depletion of the OSL traps. This is shown clearly in Fig. 6, where the predicted depletion factor $D(T)$ of the 320 °C trap in quartz is also shown together with the experimentally measured OSE intensity.

By applying the model of Oster and Haddad [4], we will show that the apparent discrepancy in Fig. 6 between the experimental data and the depletion factor $D(T)$ can be explained within the same photo-thermal mechanism discussed in the previous section.

We first combine Eqs. (9) and (10) to obtain the complete expression for the instantaneous OSE intensity:

$$I = f(\lambda) D n_o \zeta E_s \frac{\Omega_o}{A_R} \exp\left(\frac{-\varepsilon_v + \chi - h\nu}{kT_{stim}}\right) \exp(-\zeta E_s t). \quad (18)$$

Here T_{stim} is the temperature of the sample during the optical stimulation; during the experiment of Fig. 6, the stimulation temperature is fixed at $T_{stim} = 125\,°\text{C}$. The only two quantities in Eq. (18) which are dependent on the preheat temperature T_p are the initial concentration of electrons in the trap n_o at the beginning of the optical stimulation, and the recombination probability A_R. The initial concentration n_o will depend on the preheat temperature according to the thermal depletion factor $D(T_p) = \exp(-s\exp(-E/kT_p))$ from Eq.(14). From Eq. (3), the recombination probability A_R is proportional to the concentration of holes in the recombination center $m(T_p)$, which in turn is a function of the preheat temperature T_p. More specifically, it is possible during the preheat stage to thermally transfer holes from the Zimmerman hole reservoirs (levels 6 and 7) into the recombination center; this thermal transfer of holes leads to an increase of the concentration of holes in the recombination center $m(T_p)$, and to corresponding increase of the OSL recombination probability A_R; this increased competition will reduce the number of electrons contributing to the OSE signal. This thermal transfer phenomenon has been documented widely both by experiments and by simulations (see for example, Pagonis et al. [8] and references therein).

While it is not possible to measure directly the quantity $m(T_p)$, one can measure by proxy the sensitivity $S(T_p)$ of the sample to a small test dose, which is proportional to $m(T_p)$. By substituting $A_R \propto m(T_p) \propto S(T_p)$ into Eq. (18), we obtain

$$I(T_p) \propto D(T_p) \frac{1}{S(T_p)}. \quad (19)$$

This equation indicates that the experimentally measured OSE intensity $I(T_p)$ should be proportional to the ratio of the two factors $D(T_p)/S(T_p)$. We now offer two possible ways of estimating the temperature-dependent sensitivity $S(T_p)$, firstly by using experimental data and secondly by using simulation. Wintle and Murray [2] measured the sensitivity $S(T_p)$ of WIDG8, the same sample used in the OSE experiments of Ankjærgaard et al. [1]. During the pulse-annealing experiments of Wintle and Murray [2], an aliquot of WIDG8 was irradiated with 56 Gy, then was preheated for 10 s at progressively higher temperatures from 160 to 500 °C, each time measuring the OSL at 125 °C using a short 0.1 s stimulation. The 110 °C thermoluminescence peak was measured at each step by delivering a small test dose of 0.1 Gy. The sensitivity $S(T_p)$ was measured by the response of the 110 °C TL peak to the small test dose.

The experimental results of Wintle and Murray [2] are reproduced in Fig. 7a of this paper, together with the thermal depletion factor $D(T_p) = \exp(-s\exp(-E/kT_p))$. The ratio of these two temperature-dependent factors $D(T_p)/S(T_p)$ is shown in Fig. 7b, together with the normalized OSE data of Ankjærgaard et al. [1]. Fig. 7b shows that the two quantities are indeed proportional to each other in the temperature range for which the Wintle and Murray data are available.

The temperature-dependent sensitivity $S(T_p)$ can also be estimated by simulation of the pulse-annealing experiment of Wintle and Murray [2]. Such a simulation was carried out recently by Pagonis et al. [8], who showed that it is possible to simulate the changes in sensitivity $S(T_p)$ by using the comprehensive quartz model of Bailey [7]. The simulated sensitivity $S(T_p)$ was shown in Fig. 6b and e of Pagonis et al. [8]. We have repeated the simulation

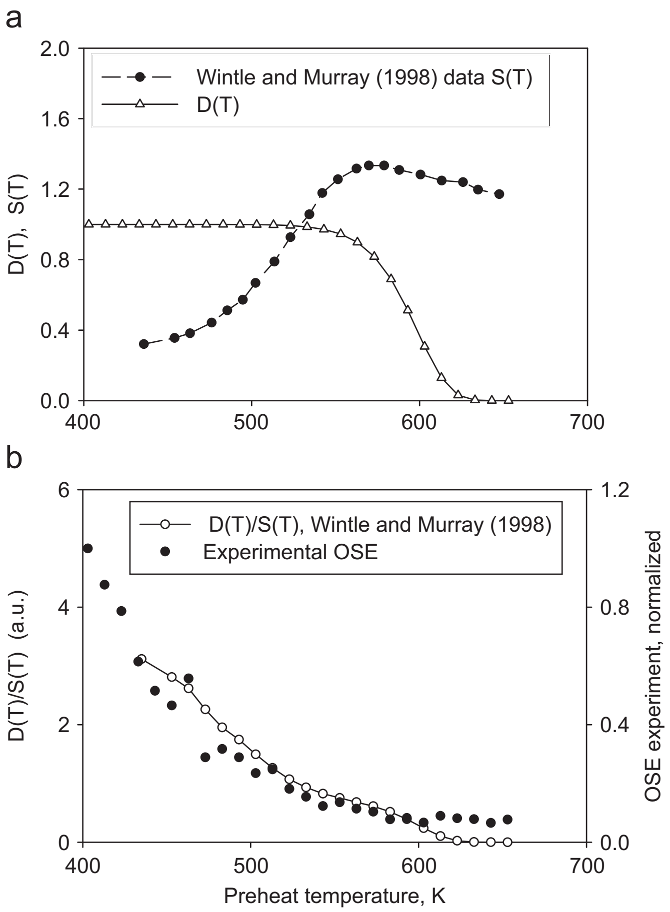

Fig. 7. (a) The sensitivity data $S(T)$ from the pulse-annealing experiment of Wintle and Murray (1998) are shown together with the expected thermal depletion factor $D(T)$ calculated from Eq. (14). (b) The ratio $D(T)/S(T)$ calculated from the data in (a) is shown to be proportional to the experimental OSE intensity measured by Ankjærgaard et al. (2008) as a function of preheat temperature.

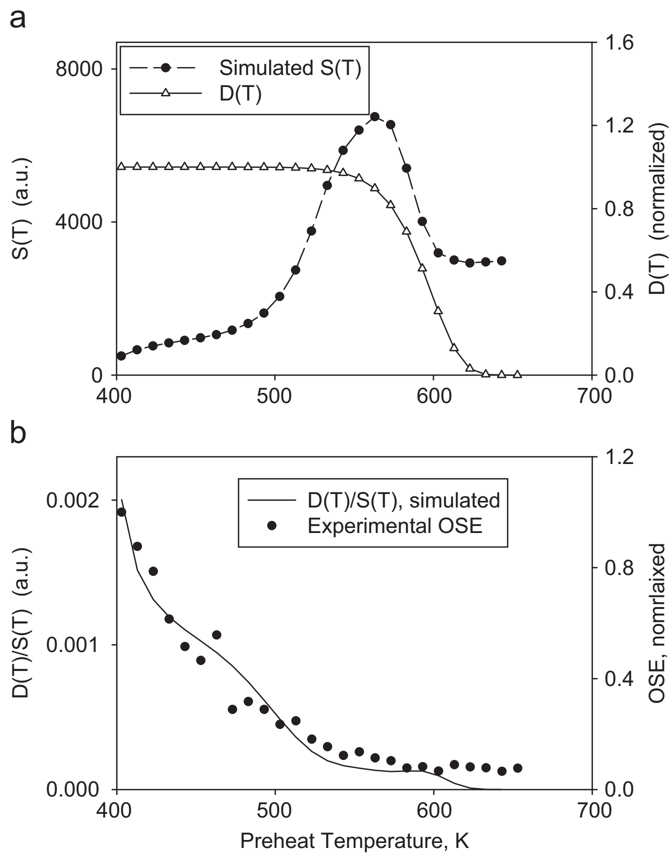

Fig. 8. (a) The sensitivity data $S(T)$ from the simulated pulse-annealing experiment, obtained using the simulation procedure of Pagonis et al. (2007), are shown together with the expected thermal depletion factor $D(T)$ calculated from Eq. (14). (b) The ratio $D(T)/S(T)$ calculated from the data in (a) is shown to be proportional to the experimental OSE intensity measured by Ankjærgaard et al. (2008) as a function of preheat temperature.

by using the rather large beta dose of 330 Gy employed in the OSE experiments of Ankjærgaard et al. [1], and the results of the simulated $S(T_p)$ are shown in Fig. 8a. The ratio of the two simulated factors $D(T_p)/S(T_p)$ is shown in Fig. 8b together with the normalized OSE data. Fig. 8b shows again that the two graphed quantities are indeed proportional to each other, as expected from Eq. (19).

In conclusion, this section has shown that the experimentally measured OSE intensity $I(T_p)$ during the preheat experiment of Ankjærgaard et al. [1], can be explained satisfactorily by using the photo-thermostimulated process shown in Fig. 1. By using either simulation or previously published experimental data, it is found that there is no discrepancy between the results of the preheat experiment of Ankjærgaard et al. [1] and the thermal depletion rate of the 320 °C trap in quartz; the OSE signal decreases more rapidly than the OSL signal because of a change in competition between the two processes of luminescent recombination and electron ejection from the surface.

2.3. Dependence of the OSL signal on the preheat temperature

In a recent modeling study, Pagonis et al. [8] modeled the dependence of the OSL signal from quartz on the preheat temperature, using the comprehensive kinetic model by Bailey [7]. A description of the model of the parameters used and of the equations in the model was given in Pagonis et al. [8], and will not be repeated here. However, it is important to realize that this type of simulation involves optical and thermal stimulation of electrons and holes through both the conduction and the valence band, and is of a very different nature from the OSE processes shown in Fig. 1 of this paper.

We have simulated the experimental protocol of Ankjærgaard et al. [1] using the Bailey model [7]. In their protocol an aliquot of sample WIDG8 was irradiated with a dose of 330 Gy, preheated to a given preheated temperature for 10 s, and optically stimulated at 125 °C. This cycle was repeated for different preheat temperatures using the same aliquot, and the experimental data are shown in Fig. 9, together with the results of the model. The shape of the modeled data is very similar to that of the experimental data; the small differences can be easily accounted for by making small adjustments in the thermal kinetic parameters for the OSL traps in the model.

2.4. Dependence of the OSL signal on the stimulation temperature

We have also simulated the second experimental protocol of Ankjærgaard et al. [1] in which a variable stimulation temperature is used by using the Bailey [7] model. In this protocol, an aliquot was given a dose of 44 Gy and a preheat temperature of 260 °C was used, followed by blue light stimulation at a variable stimulation temperature. The same aliquot was then given a test dose of 18 Gy, preheated to 260 °C and stimulated at 125 °C. Finally, the aliquot was optically stimulated at 280 °C for 100 s. The experimental data of Ankjærgaard et al. [1] are shown

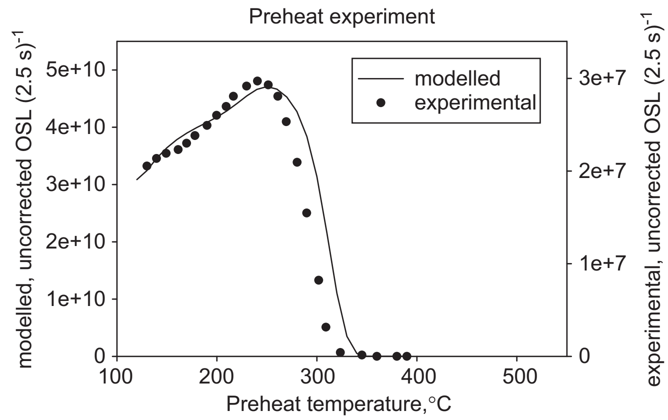

Fig. 9. The simulated dependence of the OSL signal on the stimulation temperature. The experimental data of Ankjærgaard et al. (2008) are compared with the results of the model by Bailey (2001), which involves optical and thermal stimulation of electrons and holes through both the conduction and the valence band.

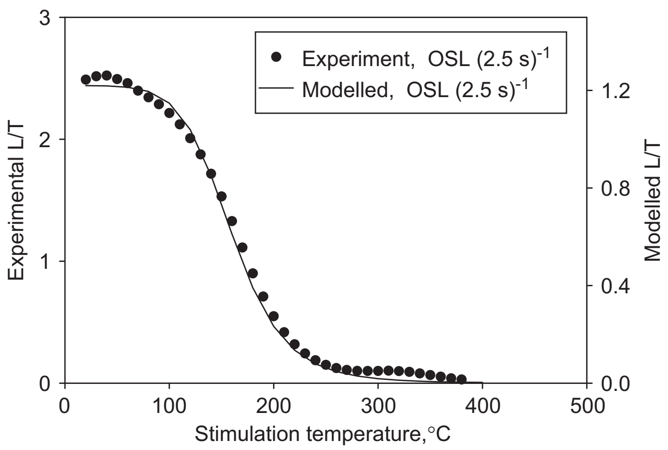

Fig. 10. Simulated dependence of the OSL signal on the preheat temperature. The experimental data of Ankjærgaard et al. (2008) are compared with the results of the model by Bailey (2001).

in Fig. 10, together with the results of the model. Apart from a factor of 2 difference for the value of the overall OSL intensities, the modeled data show the exact same behavior as the experimental data.

3. Conclusions

The model of Oster and Haddad [4] provides a quantitative description of the exoelectron emission measurements of Ankjærgaard et al. [1]. The experimental data are consistent with a value of $\chi\sim1.2$ eV for the work function of quartz, and a thermal assistance energy of $W\sim(0.29\pm0.02)$ eV. Within this model, both the variable preheat and variable stimulation temperature dependences of the OSE signal were shown to involve the same photo-thermostimulated process associated with the main OSL trap at $\sim$320 °C.

On the other hand, the corresponding OSL processes taking place in the same samples were explained using the comprehensive model of Bailey [7]. Within this model, the dependence of the OSL signal on the preheat and stimulation temperatures are explained on the basis of electron and hole transitions taking place through the conduction and valence bands. The two models used in this paper, namely the Oster and Haddad model for OSE and the Bailey model for OSL, are completely consistent with each other, and help elucidate the mechanisms involved in the charge movement in quartz samples.

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