TẠP CHÍ KHOA HỌC VÀ CÔNG NGHỆ ĐẠI HỌC DUY TÂN
DTU Journal of Science and Technology 05(78) (226) 63-74

ĐẠI HỌC DUY TÂN
DUYTAN UNIVERSITY

Relationship between TL Peaks and OSL Signal Components with Different Thermal Stability and Bleaching Rates in Vietnamese Quartz

Mối quan hệ giữa các đỉnh TL và các thành phần tín hiệu OSL có độ ổn định nhiệt và tốc độ tẩy trắng khác nhau trong thạch anh Việt Nam

Tran Ngoc[a*, b], Phan Van Do[c]
Trần Ngọc[a*, b], Phan Văn Độ[c]

[a]*Institute of Research and Development, Duy Tan University, Da Nang, 550000, Vietnam*
[a]*Viện Nghiên cứu và Phát triển Công nghệ cao, Đại học Duy Tân, Đà Nẵng, 550000, Việt Nam*
[b]*Faculty of Environment and Natural Sciences (ENS), School of Engineering and Technology, Duy Tan University, Da Nang, 550000, Vietnam*
[b]*Khoa Môi trường và Khoa học tự nhiên, Trường Kỹ thuật và Công nghệ, Đại học Duy Tân, Đà Nẵng, 550000, Việt Nam*
[c]*Thuyloi University, 175 Tay Son Street, Dong Da, Hanoi, Vietnam*
[c]*Trường Đại học Thủy lợi, 175 Tây Sơn, Đống Đa, Hà Nội, Việt Nam*

(Date of receiving article: 13/06/2025, date of completion of review: 24/08/2025, date of acceptance for posting: 17/09/2026)

Abstract

This paper presents experimental results obtained by combining optical absorption (OA), thermoluminescence (TL), and optically stimulated luminescence (OSL) measurement techniques to understand the physical nature of the components in the OSL signal and their relationship to different photosensitive and thermally stable charge traps in natural quartz. Analysis of the experimental results shows that the OSL signal contains at least three components with different attenuation characteristics. The OSL signal mainly originates from photosensitive traps (at 325ºC), partly from photoluminescence transport (PTTL) thermal luminescence traps at 110ºC and deep traps above 600°C. The curve fitting from data of OSL measurements (LM-OSL) can be described by the superposition of three first-order components with the peak position at t_{m1} = 68.8s, t_{m2} = 182.1s, and t_{m3} = 337.8s. The values of the photoionization cross-sections and the decay constant of the "fast", "medium", and "slow" components ranging from as high as $2.5x10^{-17}$ (the fast component) to as low as $2.3x10^{-19}$ (for the slow component), and 4.8 s, 34.6 s, and 487.7s, respectively. Each component has different thermal stability and bleaching rate. The fast and medium components appear to be associated with TL peaks in the temperature range from 250ºC to 350ºC and, and they can be bleached quickly by blue light, whereas the slow component remains stable until at least 600ºC.

Keywords: thermoluminescence, optically stimulated luminescence (OSL), modulation of intensity, photoionization

Tóm tắt

Bài báo trình bày các kết quả thực nghiệm thu được bằng sự kết hợp các kỹ thuật đo hấp thụ quang học (OA), nhiệt phát quang (TL) và phát quang cưỡng bức quang (OSL) nhằm mục đích hiểu rõ bản chất vật lý của các thành phần trong tín hiệu OSL và mối quan hệ của chúng với các bẫy điện tích nhạy quang và ổn định nhiệt khác nhau trong thạch anh tự nhiên. Phân tích các kết quả thực nghiệm cho thấy tín hiệu OSL chứa tối thiểu ba thành phần với các đặc tính suy giảm khác nhau. Tín hiệu OSL chủ yếu bắt nguồn từ các bẫy nhạy quang (tại 325ºC), một phần từ các bẫy nhiệt phát quang chuyển tải quang (PTTL) ở 110ºC và các bẫy sâu trên 600 ºC. Dữ liệu đo OSL (LM-OSL) có thể được làm khớp bằng sự

*Corresponding author: Tran Ngoc
Email: tranngoc11@duytan.edu.vn

chồng chất của ba thành phần bậc nhất với vị trí đỉnh tại t_{m1} = 68.8s, t_{m2} = 182.1s, and t_{m3} = 337.8s. Các giá trị cho tiết diện quang ion hóa và hằng số phân rã của các thành phần "nhanh", "trung bình" và "chậm" dao động từ mức cao nhất là $2{,}5x10^{-17}$ (thành phần nhanh) đến mức thấp nhất là $2{,}3x10^{-19}$ (đối với thành phần chậm), và lần lượt là 4,8s, 34,6s và 487,7s. Mỗi thành phần có độ ổn định nhiệt và tốc độ tẩy trắng khác nhau. Các thành phần nhanh và trung bình dường như liên quan đến các đỉnh TL trong phạm vi nhiệt độ từ 250°C đến 350°C và có thể bị tẩy trắng nhanh chóng bởi ánh sáng xanh lam (450 nm), trong khi thành phần chậm vẫn ổn định cho đến ít nhất 600°C.

Từ khóa: Nhiệt phát quang, phát quang cưỡng bức quang (OSL), điều chỉnh cường độ, quang ion hóa

1. Introduction

Compared to other minerals, quartz usually exists in the single crystal form, it is one of the mineral that accounts for the largest proportion of the Earth's mantle composition [1, 2, 3]. Nominally, quartz is a pure SiO_2 oxide; natural quartz still contains a variety of defects in its crystal structure because of the different geological conditions in crystal formation. For this reason, the luminescence of quartz is complex with its diverse physical properties. This luminescence feature is explained by the abundance of defects in quartz. These defects usually relate to impurity atoms (e.g., Al, Ti, Ge, or metal alkali), which are in an interstitial position or replace the site of a Si atom [4, 5, 6]. The concentration of impurity-related defects is dependent on the conditions of mineral formation or subsequent alteration. Because of the appearance of these impurities, the quartz can absorb some kinds of ionizing radiation strongly [7, 8, 9]. The information about the radiation can be recorded as a latent signal within the quartz crystal lattice. This information may be erased by certain events, such as daylight exposure, heat, or high pressure. There are two ways to obtain a latent signal from the quartz crystals, which are thermoluminescence (TL) and optically stimulated luminescence (OSL). Both signals result from the measurement of trapped electrons held within the crystals via the light emitted by quartz when it is exposed to light (OSL) or heat (TL). Consequently, quartz can be used as a natural dosimeter for quantifying the radiation history of a material [10, 11, 12]. In terms of their nature, electron traps are generally classified into two main types: optically sensitive traps and traps that are neither optically sensitive nor thermally coupled. For the latter type, the optical stimulation (OSL) process has little effect on the kinetics of the trapped electrons; consequently, these traps do not contribute to the OSL signal generated during stimulation. In the case of colorless quartz, two electron traps are of particular interest: (1) the 110°C trap, known as the PTTL trap (used for dating), and (2) the 325°C trap, known as the optically sensitive trap (used for OSL dosimetry). The kinetic processes occurring within these two traps during irradiation and stimulation are subjects of significant interest in the context of geological dating.

In this paper, we present the experimental data obtained by combining methods: optical absorption, TL, and OSL on laboratory irradiation of natural quartz samples. The physical nature of the components involved in the luminescent signal and their relationship to the charge traps has been determined based on their thermal stability and bleaching properties. The thermal and/or photosensitivity properties of charge traps and their relationship with the components of the luminescent signal are also discussed in detail.

2. Experiments and methods

The colorless natural quartz crystals from Phong Nha Ke Bang (Quang Binh province, Vietnam (17°21'N, 105°46'E)) were used in this study. The crystals were first cleaned and dissolved in other symbiotic minerals in corrosive solvents such as HF (0,1M), HCl

(0,1M). After that, a part was cut into sheets of 5x3x3 mm^3 and polished on both sides with aluminum oxide powder; the rest was ground and sieved to select particles with sizes from 90 µm to 150 µm. All were thermally treated at 500ºC for 2 hours to remove all the charges in TL traps caused by irradiation in the natural environment. The irradiation process was carried out at room temperature using an X-tube with Cu target operated at 30 kV-20 mA (dose rate: 1.16 Gy/s) (YPC1 X-ray generator, X-tube with Cu target, specifications: Vmax: 50 kV, Imax: 20 mA). Between irradiation and OSL readout, a delay of 60 s was kept. The TL and OSL emission was observed with a 9635Q EM1 PMT fitted with ΦC6 (320 nm–450 nm), CC5 (340 nm–500 nm), and ЗC7 (520 nm–750 nm) filters, allowing the use of argon laser excitation light (514.5 nm) with a power of 4 W or wide range lamp D2 (100 W). The total power at the sample as used in the CW-OSL measurement was 100mW cm^{-2}. The excitation light intensity modulation increases linearly using a neutral schott with a fast scanning motor at a rate γ = 0.021 mW cm^{-2} s^{-1} used in LM-OSL measurements.

3. Results and discussion

3.1. Optical absorption properties

To evaluate the change in density of absorbent centers during the OSL process, it is possible to perform an absorption spectroscopic measurement for a monochromatic radiation (maximum in the absorption spectrum) simultaneously with the change in temperature of the sample. The carrier concentration changes during heating depend on the position of each trap level and the nature of the trap, so the absorption curve of a monochromatic radiation with temperature will reflect this change [13, 14]. Fig. 1(a) shows a monochromatic 450 nm light absorption curve during heating (previously irradiated sample with D_X=1044 Gy). The absorption curve has the form of horizontal segments alternating with rapidly declining segments over a temperature range. If we compare the temperature ranges where the rapid decline on the absorption curve is compared with the TL curve measured at the same temperature (Fig. 1(b)), we see that the absorbance decreases in the 80ºC-140ºC and 250ºC-350ºC, these temperature ranges coincide with the corresponding temperature ranges at 110 ºC and 325ºC on the TL curve (curve a). This shows a relationship between the 450 nm light absorption line and the absorption center concentration in the two charge traps corresponding to these temperature peaks, which are called optically sensitive traps. The above experimental observations can be explained as follows: During light stimulation of the sample (OSL process), the intensity of the OSL depends on the charge concentration captured on the photosensitive trap and the probability of releasing them: $n = n_0\exp(-\lambda.t)$ (where n is the amount of charge remaining on the trap levels at each moment, n_0 is the number of charges at time t_0, and λ is the probability of releasing the charge from the trap). In other words, the intensity of the OSL is defined as the rate of attenuation of electrons captured on the trap or the hole in the recombination center during stimulation: $I_{OSL} = -dm/dt \approx -dn/dt$ (where m is the concentration of holes in the recombination center and n is the electron concentration in the trap) [15, 16, 17, 18, 19, 20]. Then the absorbance is described by the equation: $A = \varepsilon.d.m$ (where ε is the absorption coefficient, d is the thickness of the absorbing medium (both ε and d are constants for a sample), m is the absorption center concentration) [20].

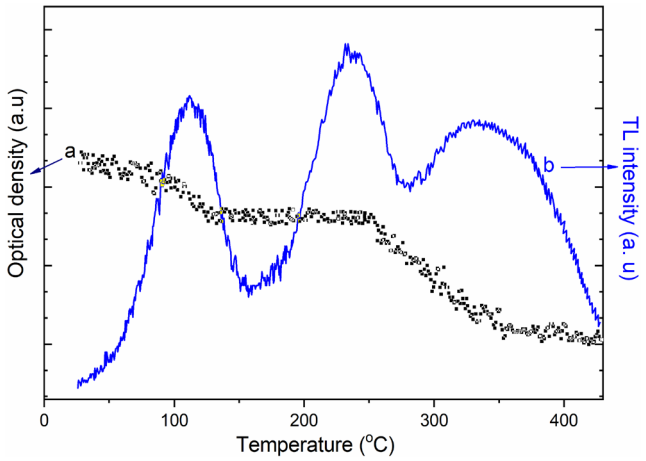


Fig. 1. Monochromatic 450 nm light absorption curve during heating (a) and TL glow curve (b) of quartz sample irradiated D_X =1044 Gy, β = 2°C/s.

In this experiment, at the initial time of heating, the carrier concentration in the absorption centers is greatest, so the absorption intensity reaches the maximum value for a monochrome light. As the temperature increases, the charges on the optically sensitive traps are released, resulting in a decrease in the absorbing center concentration, and a decrease in absorption band strength is observed. The absorbance band strength reaches a constant value when the charge is released. If the sample is stimulated with constant intensity monochromatic light, the change in concentration of absorbed light over time will be: dA/dt = ε.d.dm/dt. Then the intensity of OSL will be I_{OSL}=1/εd(-dA/dt). These experimental results show that the OSL process occurs concurrently with the bleaching of the absorbent center produced in the irradiation process and is involved in the absorption process, which is a very important suggestion in the process dating by the quartz inclusion technique [18, 19, 20, 21, 22, 23].

3.2. Optically stimulated luminescence properties

The OSL decay curve from a natural quartz sample (X-ray irradiation-1044 Gy) measured at room temperature, excited by 514.5 nm light from the argon laser, is shown in Fig. 2 (the excitation light intensity is kept constant). A monotonically decreasing signal with an excited time is usually observed. However, it can be seen that the OSL decay is not a simple exponential decay: first, a rapid decay (during the first 50 s of excitation), then a slower decay (to 150 s next), and finally a very slow decay (not yet about zero) prolongs the 460 s as the measurement proceeds. There are two possible interpretations for the observation that the OSL decay is not a single exponential. In the first interpretation, the excited light initially releases charge from a single type of trap, with bleaching capacity depending on the rate of charge release captured on this trap. However, due to re-trapping of charges after being released, they are considered the cause of the simple non-exponential decay of the OSL [22, 23, 24]. The second interpretation is to consider that the effect of the non-first-order processes on the observed OSL decay is minor, and that the decay represents the release of charge from traps with different rates of charge loss. If the first interpretation is correct, it seems unlikely that the occurrence of partial bleaching could be detected. However, the second interpretation would suggest that the observed form of OSL decay would change depending on the degree of bleaching, and that partial bleaching should be detectable [13, 14, 15]. To determine the origin, the number of components involved in the OSL,

and their relationship with the electronic traps on the TL curve. We performed simultaneous TL and OSL measurements on the same samples. Before performing these measurements, the samples were irradiated with X-rays with a dose of 1044 Gy, then preheated at 30ºC, 150ºC, 250ºC, 300ºC, 350ºC, 400ºC, 450ºC, 600ºC and 650ºC for 10s before measuring OSL and TL.

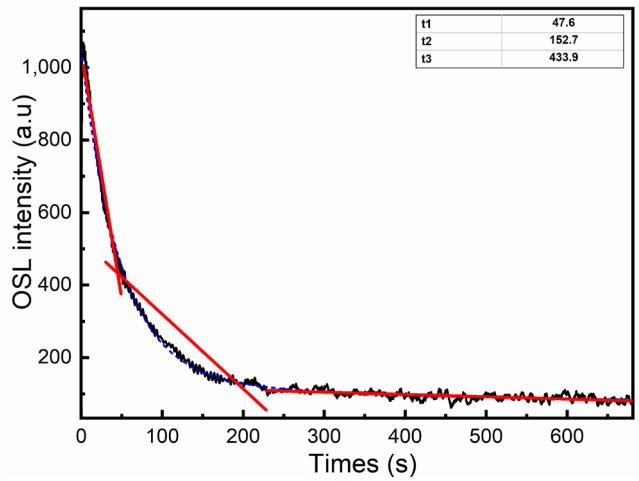


Fig. 2. The OSL decay curve from a natural quartz sample (X-ray irradiation-1044 Gy, excited by 514.5 nm light)

The results shown in Fig. 3(A, B), respectively. Fig. 3A shows that when the sample is preheated from 30^0C to 150^0C (curves a, b), there is no significant change in the OSL signal.

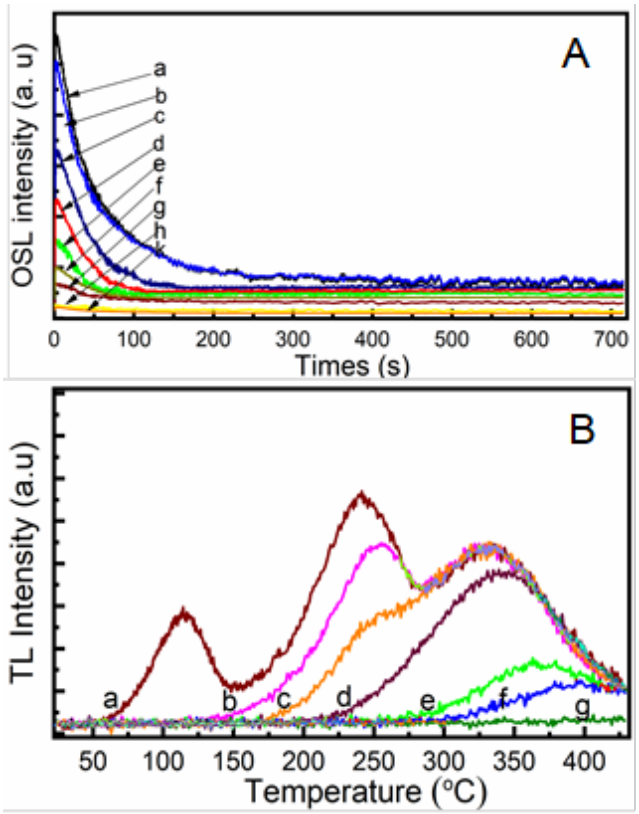


Fig. 3. OSL attenuation curves (A) and TL glow curves (B) of a natural quartz sample (the sample was previously irradiated D_X =1044 Gy, and preheated for 10 seconds at temperatures (a) 30°C, (b) 150°C, (c) 250°C, (d) 300°C, (e) 350°C, (f) 400°C, (g) 450°C, (h) 600°C and (k) 650°C

However, preheating the sample to a temperature between 250ºC and 350ºC (curves c, d) produced a rapid decrease in the OSL signal over a period of 250s of excitation (especially in the range from 50 s to 250 s of excitation), and the portion of the signal after stimulation for 250 s remains unchanged during excitation. When the sample preheat is in the temperature range from 350ºC to below 600ºC, the OSL signal after excitation for 250s remains stable (see curves e, f, g against curves c, d), but when the sample is preheated to 650ºC, the entire OSL signal decreases rapidly to zero (h, k curves). Analysis of Fig 3(A, B), in conjunction with references [14, 17], reveals that the OSL signal comprises at least three components: a rapid decay during the first 50 s, a medium-rate decay over the subsequent 200 s, and a slow decay during prolonged stimulation with the latter component remaining relatively stable provided the sample treatment temperature does not exceed 600°C. The correlation between the OSL signal components and the TL peaks is shown in Fig. 3B. The preheat of the sample to 300ºC completely emptied the TL traps corresponding to release charges temperature below 300ºC with T_{max} at 110ºC and 240ºC (curves b, c, and d). When the sample was preheated to 350ºC (curve e), the trap was emptied between 300ºC and 350^0C (with a T_{max} = 325ºC). If the preheat of the sample is continued to 400ºC, then only traps corresponding to charge release temperatures above 400ºC will exist (curve f). Since TL measurements are usually only possible up to temperatures below 450ºC, preheating samples to 450ºC has completely cleared the signal of detectable TL traps (curve g). The correlation between the components involved in the OSL signal and the charge traps that produce the TL signal, discussed by us as follows: The preheat to 350ºC is sufficient to remove the fast and medium components (curve c, d, e of Fig. 3A), indicating that charge traps in the temperature range 250ºC to 350ºC (maximum at 325ºC) are related to these components (curve e, f, g of Fig. 3B). Furthermore, experimental results show that the OSL signal is still present during the first 50 seconds of excitation (in curves c, d, and e (Figure 3A)), which may be related to another optical process occurring during excitation to perform the OSL measurement, and can be explained as follows: During optical excitation, there may be transfer of charges from traps with high thermal stability to traps with lower thermal stability (including optically sensitive traps) (phototransfer thermoluminescence process-PTTL). In other words, there is charge redistribution, a portion of which can reconstruct the optically sensitive traps that had previously been bleached by preheat, this process is known as "trapping recovery" [14, 20]. OSL measured subsequently would in this case contain fast. The OSL signal decay curve to zero observed in the preheat of the sample between 600ºC and 650ºC is the result of a decrease in the concentration of the charge in traps above 600ºC when the sample is preheated to this temperature. This shows that the slow component displays considerable thermal stability, given that some fraction of the signal remains after heating to 600 ºC, and this stability is far in excess of the signal traditionally used for optical dating. These observations are quite consistent with the proposal of Bailey et al (1997), that the fast and average components of the OSL signal are associated with the TL 325ºC peak, while the slow component remains stable to less than 650ºC [5, 8, 9, 13, 14, 22, 24, 25]

3.3. The correlation between TL peaks and OSL signal components and the role of heat in the OSL process.

During the OSL process, when optically stimulated, only charges in optically sensitive traps are released. The carrier kinetics when released in optically sensitive traps are considered to be the cause of non-single

exponential decay. To clarify this problem, we have performed experiments to establish the relationship between optically sensitive traps and components in the OSL. The effect of bleaching curves optically sensitive traps with blue light (450 nm) on the shape of the resulting OSL decay is shown in Fig. 4A. The OSL decay curve is measured immediately after irradiation with X-rays (curve a), measured after the sample was illuminated with blue light (450 nm) for 100 seconds (curve b), for 300 seconds (curve c), and 720 seconds (curve d). The results showed that the signal intensity decreased rapidly in the 0s to 200s interval, but there was no significant change between 200s and 700s (excitation time). Correlation between TL optically sensitive traps with OSL components is shown in Fig. 4B. TL glow curve obtained after irradiation with X-rays at room temperature (with a heating rate of $5^oC.s^{-1}$) (curve a), after illumination with blue light (450 nm) for the previous 100 seconds when measuring TL (curve b), for 300 seconds (curve c), and 720 seconds (curve d). Results showed that exposing the sample to blue light for 100s before TL measurement led to a change of emission band in the temperature range 50°C to 150°C (maximum at 110°C) and range from 280°C to 350°C (maximum at 325°C). Compared with curve a, the peak at 110°C (on curve b) has a slight increase, but the peak at 325°C has a rather large signal decline. When the lighting time was increased to 300s (curve c), the peak at 325°C was almost bleached, leaving the slow bleaching component of the peak at 375°C together with the peak at 240°C.

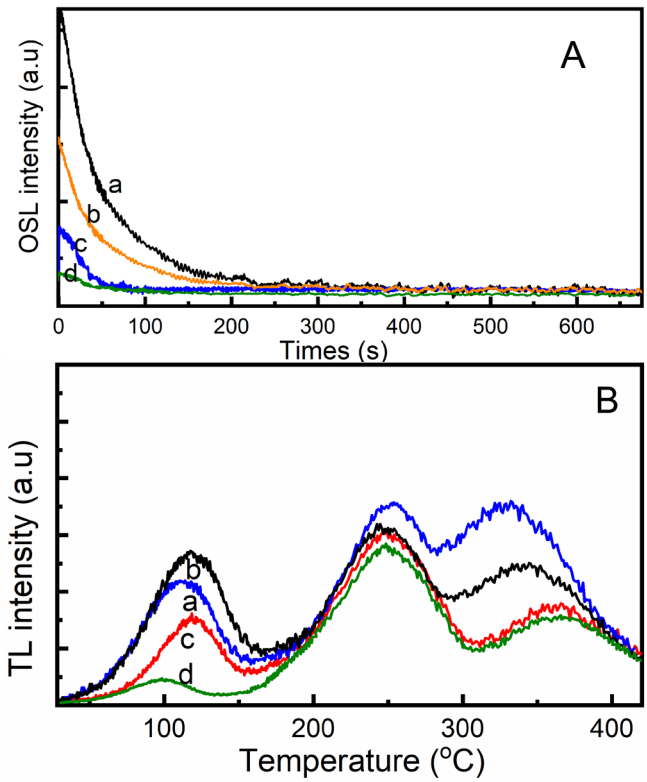


Fig. 4. OSL attenuation curves (A) and TL glow curves (B) of a natural quartz sample (the sample was previously irradiated DX =1044 Gy, and was illuminated with blue light (450 nm) for 100 seconds (b), for 300 seconds (c), and 720 seconds (d))

In addition, the peak at 110°C observed a significant decrease in intensity. These results show that the TL peak at 325°C corresponds to a very optically sensitive electron trap but is thermally stable. The electron trap at 110°C is not only a photosensitive trap, but it can also capture electrons released from deeper photosensitive traps through the PTTL effect.

This is why the TL signal increases when the sample is illuminated for 100s (curve b versus curve a). Subsequent signal degradation (curve c) as illumination time increased to 300s, the electrons in the deeper optically sensitive traps (mainly 325ºC peak) may have been reduced, causing the rate of PTTL entering the trap to decrease [1, 2, 6, 7, 8, 14]. In addition, the trap itself is bleached due to the illumination, and the temperature increases with long lighting time. These results are completely consistent with the suggestion that the PTTL signal at a 110ºC peak is closely related to a TL 325ºC peak [2, 8, 13, 14].

One question that arises is how the role of heat in the OSL process, with or without thermal assistance? With the help of heat, when electrons move from the ground state of the trap to the conduction zone usually do not occur directly, but through an intermediate excited state, they accumulate here and are released gradually, depending on the energy depth E_A of the excited state and the temperature of the sample [4, 7, 8].

To clarify this, we carried out quantitative measurements of PTTL intensity when samples were excited by monochromatic light at different temperatures; the intensity values are listed in Table 1.

Table 1. The dependence of the PTTL intensity on the sample illumination temperature.

T_{UV}(K)	1/T_{UV}(K)	I_{PTTL}(nA)	LnI_{PTTL}
313	0,0032	3,21	1,17
323	0,0031	3,72	1,31
333	0,0030	4,12	1,42
343	0,0029	4,57	1,58

The dependence of lnI according to 1/T (according to Arrhenius) is presented in Fig. 5. The energy of releasing electrons from the excited state is determined by the equation: $\ln I_{PTTL} = A + B.x_{(1/T)}$, from the fitting line has the value ΔE = 0.11 eV. Thus, the electron release mechanism of the optically sensitive traps must go through an excitation level near the bottom of the conduction band with an activation energy of 0.11 eV. The observed experimental results are quite consistent with those of the authors in [7, 9, 12, 20, 26], who have proposed a model for the assisted charge transfer process temperature in the presence of an E_A stimulating state near the bottom of the conduction band. And perhaps this also contributes to explaining the complexity of the Quartz OSL signal decay curve.

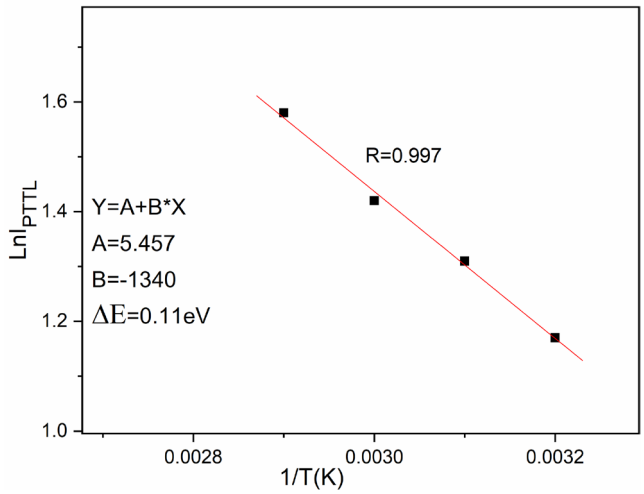


Fig 5. The dependence of LnI_{PTTL} on 1/T of the PTTL peak was at 110 ^{0}C.

3.4. The dependence of OSL on stimulated light intensity

The components in the OSL have different properties depending on the release rate and recombination rate of the carriers from capture traps, or in other words, depend on the excitation rate in optically sensitive traps. When the excitation light intensity is modulated linearly during OSL recording (LM-OSL), it is possible to separate the different OSL components as a function of time. (i.e., on the curve, some vertices will appear) [13, 16, 17]. In this experiment, the samples were irradiated with a dose of D_x=1044 Gy before measurement. The excitation light intensity is modulated to produce an output beam so that the light power at the sample surface changes from zero to a maximum of about 15 mW over the duration of stimulation (rate $\gamma = 0.021$ mW $cm^{-2}s^{-1}$). The LM-OSL curve measured at room temperature is shown in Fig. 6. We see the signal spectrum distributed in a wide band over stimulation time, with the maximum occurring after nearly 100 seconds of stimulation. The signal LM-OSL does not originate from zero at the initial stimulus, which is explained by the effect of the phosphorescence of the shallow traps (this can be overcome by taking the following measurements: the sample was heat treated to 120 ºC (preheat) or measured after irradiation for at least a few days).

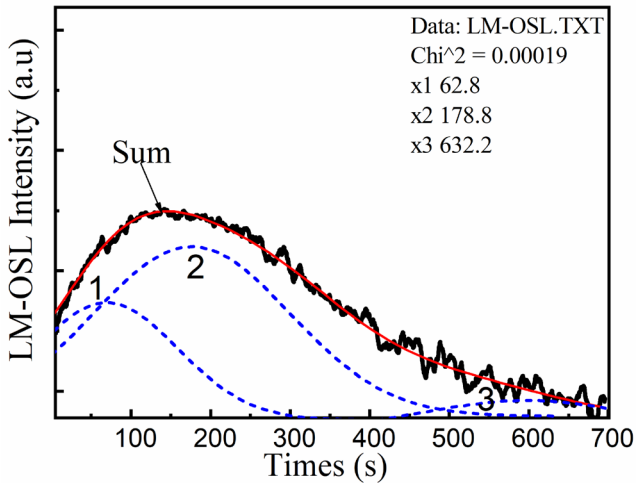


Fig.6. The LM-OSL curve of natural quartz, excited by 514.4 nm argon laser light for 720 s (excitation power density modulated linearly from 0 to 15 mW), and the three OSL components (1,2,3) were found by fitting the optimal curve according to a first kinetic order.

3.5. Determine the kinetic parameters

Determining the characteristic kinetic parameters for each participant is a difficult task because of their overlap on the curve. For simplicity in the calculation, we assume that participating in the OSL process of quartz has at least 3 components, and the OSL signal attenuation curve is a superposition of these first-order kinetic attenuation components. Then, if the excitation intensity is linearly modulated (LM - OSL): $f(t,\lambda) = \sigma(\lambda)\Phi(t) = \sigma(\lambda)\gamma t$, then the signal curve is given by [16, 17, 19, 20, 21]:

$$I_{LM}(t,\lambda) = n_0\sigma(\lambda)\gamma \exp\left\{\frac{-\sigma(\lambda)\gamma t^2}{2}\right\} \quad (1)$$

Thus, the LM - OSL curve will start at zero at t = 0 and increase to the maximum at $t_m = 1/\sqrt{\sigma(\lambda)\gamma}$, so if we know the excitation rate $\gamma = d\Phi(t)/dt$, we can determine the cross-section of ionized photons at the wavelengths used for excitation. At the time at $t = t_f$ such that $\Phi(t_f) = \Phi$ then we have:

$$\tau(\lambda) = \frac{1}{\sigma(\lambda)\gamma\tau_f} \text{ or } \tau(\lambda) = \frac{t_m(\lambda)^2}{\tau_f} \quad (2)$$

On the other hand, the photo-ionization cross-section depends on temperature according to the expression:

$$\sigma(T,\lambda) = \sigma_0(\lambda)\exp\left(-\frac{E_A}{kT}\right) \quad (3)$$

where E_A is the thermal activation energy of the trap and $\sigma_0(\lambda)$ is the initial photo-ionization cross-section given by: $\sigma_0(\lambda) = K\sqrt{E_0}\,\frac{(h\upsilon - E_0)^{3/2}}{h\upsilon(h\upsilon - \delta E_0)^2}$; (K is a normalization constant, hν is the energy of the incident light at wavelength λ, E_0 is the photo-ionization energy of the trap, and δ is a constant (for quartz, δ = 0.559) [17, 19].

Assuming the OSL signal is the sum of three single-decay components described by the expression $I_{CW}(t,\lambda) = n_0 f(\lambda)\exp\left\{\frac{-t}{\tau(\lambda)}\right\}$. By combining the values obtained from fitting the CW-OSL and LM-OSL curves shown in Fig 2 and Fig 6 with equations (1), (2) and (3), the kinetic parameters of the components involved in the quartz OSL process can be calculated. Using a maximum excitation power density of 15 mW/cm² at the sample surface and a measurement duration of t_f = 720 s, the analysis of the LM-OSL curve yields t_{m1} = 62.8 s, t_{m2} = 178.8s, and t_{m3} = 632.2s, excitation wavelength λ = 514.5 nm, the results are listed in Table 2.

Table 2. The σ(λ) and τ(λ) parameters can be extracted from the fitted data of the CW-OSL and LM-OSL curve

Component	σ(λ) (cm^2)	τ(λ) (s)
1	$2{,}5.10^{-17}$	4,8
2	$7{,}6.10^{-18}$	34,6
3	$2{,}3.10^{-19}$	487,7

Values for the photoionization cross-sections for components 1, 2, and 3 corresponding to the "fast", "medium", and "slow" components in the natural quartz crystal, ranging from as high as $2.5\text{x}10^{-17}$ (the fast component) to as low as $2.3\text{x}10^{-19}$ for the slow component, and the decay constants are 4,8s, 34,6s, and 487,7s, respectively [16, 17, 19, 20, 21]. However, as previously analyzed, certain experimental conditions result in significant errors in the obtained data. Specifically, these errors arise because: (i) the optical stimulation rate at any given moment cannot be precisely determined; (ii) calculations rely on the assumption that the OSL process follows first-order kinetics, whereas in reality, the contributing components depend complexly on charge retrapping rates; and (iii) ignore the influence of irradiation dose on the nature of the physical processes occurring in the sample. Consequently, most components do not strictly follow first or second-order kinetics but rather exhibit intermediate kinetic behavior; this causes the actual peak positions (t_m) to differ from those derived from optimal curve fitting, thereby leading to discrepancies in the calculated results. In summary, the results obtained here are hypothetical and semi-quantitative in nature.

4. Conclusion

By combining optical absorption (OA), thermoluminescence (TL), and optically stimulated luminescence (OSL) measurement techniques, the physical nature of the components in the OSL signal and their relationship to various photosensitive and thermally stable charge traps in natural quartz have been elucidated. The OSL signal originates primarily from photosensitive traps (at 325°C), partly from PTTL traps at 110°C, and deep traps

above 600°C. Experimental results show that the OSL (or LM-OSL) signal can be identified by the superposition of three first-order components with peak positions at t_{m1} = 62,8s, t_{m2} = 178,8s, and t_{m3} = 632,2s, corresponding to the "fast", "medium", and "slow" components, respectively. The photoionization cross-sections of the "fast," "medium," and "slow" components range from a high of $2.5x10^{-17}$ (fast component) to a low of $2.3x10^{-19}$ (slow component), and the decay constants are 4.8s, 34.6s, and 487.7s, respectively. Each component exhibits different thermal stability and decolorization rates. The fast and medium components appear to be associated with TL peaks in the temperature range of 250°C to 350°C and can be rapidly decolorized by blue light (450 nm), while the slow component remains stable up to at least 600°C. During optical stimulation, the transfer of charges from traps with high thermal stability may occur to traps with lower heat resistance, including optically sensitive traps. This is useful information for using natural quartz samples as dosimeters in age calculation problems in archeology and geology.

References

[1] L. Boetter-Jensen. (2000). "Development of optically stimulated luminescence techniques using natural minerals and ceramics and their application to retrospective dosimetry". *Riso-R*-1211(EN),74 - 85.

[2] R. M. Kaylor, J. Feathers, W.F. Hornyak, A. D. Franklin. (1995). "Optically stimulated luminescence in Kalahari quartz: Bleaching of the 325 °C peak as the source of the luminescence". *J. of Luminescence*. 65, 1-6. https://doi.org/10.1016/0022-2313(95)00048-U.

[3] F. Preusser, M. L. Chithambo, T. Götte, M. Martini, K. Ramseyer, E. J. Sendezera, G. J. Susino, A. G. Wintle. (2009). "Quartz as a natural luminescence dosimeter". *Earth-Science Rev*. 97. https://doi.org/10.1016/j.earscirev.2009.09.006.

[4] M. Martini, F. Meinardi. (1997). "Thermally stimulated luminescence: New perspectives in the study of defects in solids". *Riv. del Nuovo Cim. della Soc. Ital. di Fis.* 20, 1–71. DOI:10.1007/BF02897907.

[5] M. Martini, M. Fasoli, A. Galli. (2009). "Quartz OSL emission spectra and the role of [AlO4]° recombination centres". *Radiat. Meas.* 44, 458–461. DOI:10.1016/j.radmeas.2009.04.001

[6] O.M. Williams, N.A. Spooner. (2018). "Defect pair mechanism for quartz intermediate temperature thermoluminescence bands". *Radiat. Meas.* 108, 41–44.

[7] A. D. Franklin, J. R. Prescott, R. B. Scholefield. (1995). "The mechanism of thermoluminescence in an Australian sedimentary quartz". *J. Lumin*. 63, 317–326. https://doi.org/10.1016/0022-2313(94)00068-N.

[8] G. Vaccaro, L. Panzeri, A.M. Monti, M. Martini, M. Fasoli. (2019). "Optical bleaching of the 375 °C TL peak, $[GeO_4/Li^+]^0$ EPR center and OSL signal in irradiated natural quartz", *J. Lumin.* 205, 61–65. https://doi.org/10.1016/j.jlumin.2018.08.046.

[9] N. Itoh, D. Stoneham, A.M. Stoneham. (2002). "Ionic and electronic processes in quartz: Mechanisms of thermoluminescence and optically stimulated luminescence". *J. Appl. Phys.* 92, 5036–5044. https://doi.org/10.1063/1.1510951.

[10] W.J. Rink, H. Rendell, E.A. Marseglia, B.J. Luff, P.D. Townsend. (1993). "Thermoluminescence spectra of igneous quartz and hydrothermal vein quartz". *Phys. Chem. Miner.* 20, 353–361. https://doi.org/10.1007/BF00215106.

[11] C. Schmidt, C. Woda. (2019). "Quartz thermoluminescence spectra in the high-dose range". *Phys. Chem. Miner.* 46, 861–875. https://doi.org/10.1007/s00269-019-01046-w.

[12] A. Rashad, A. E. Helal, G. Ahmed, S. Kassem, R. Fahim, S. Salem, S.E.D. Mohamed, A. Gamal. (2020). "Spectroscopic Analysis of Irradiated Natural Quartz and ESR Dating Aspects". *Arab J. Nucl. Sci. Appl.* 0, 1–13. https://doi.org/10.21608/ajnsa.2020.22502.1321.

[13] E. Bulur, L. Boetter-Jensen, and A. S. Murray. (2000). "Optically stimulated luminescence from quartz measured using the linear modulation technique". *Radiation Measurements*. 32, 407-411. https://doi.org/10.1016/S1350-4487(00)00115-3.

[14] R. M. Bailey, B. W. Smith, E. J. Rhodes. (1997). "Partial bleaching and the decay form characteristics of quartz OSL". *Radiat. Meas*, 27,123–136. DOI:10.1016/S1350-4487(96)00157-6

[15] M. Jain, A. S. Murray, L. Boetter-Jensen. (2003). "Characterisation of blue-light stimulated luminescence components in different quartz samples: implications for dose measurement". *Radiation measurements*. 37, 441-449, DOI:10.1016/S1350-4487(03)00052-0.

[16] C. K. Kuhns, N. A. Larsen, S. W. S. Mc. Keever. (2000). "Characteristics of LM-OSL from several different types of quartz". *Radiation Measurements*.

32, 413-418. https://doi.org/10.1016/S1350-4487(00)00065-2.

[17] E. Bulur, L. Boetter-Jensen, and A. S. Murray. (2001). "LM-OSL signals from some insulators: an analysis of the dependency of the detrapping probability on stimulation light intensity". *Radiation Measurements*. 33, 715-719. https://doi.org/10.1016/S1350-4487(01)00089-0.

[18] A.G. Wintle, G. Adamiec.(2017). "Optically stimulated luminescence signals from quartz: A review". *Radiat. Meas,* 98, 10–33. https://doi.org/10.1016/j.radmeas.2017.02.003.

[19] N. A. Spooner, O. M. Williams, J. E. Moffatt. (2019). "Pulsed optically stimulated luminescence for mechanisms studies in quartz". *Radiat. Meas*, 128. DOI:10.1016/j.radmeas.2019.106176.

[20] R. Chen, S.W.S. McKeever. (1998). *Theory of Thermoluminescence and Related Phenomena*, World Scientific. https://doi.org/10.1142/2781.

[21] R. Chen. J. L. Lawless, V. Pagonis. (2020). "Competition between long-time excitation and fading of thermoluminescence (TL) and optically stimulated luminescence (OSL)". *Radiat. Meas*, 15, 136-142. https://doi.org/10.1016/j.radmeas.2020.106422.

[22] O.M. Williams, N. A. Spooner. (2020). "Quartz optically stimulated luminescence configurational coordinate model". *Radiat. Meas*, 15. 132-138. DOI: 10.1016/j.radmeas.2020.106259.

[23] R. Chen, X.H. Yang, S.W.S. McKeever. (1998). "The strongly superlinear dose dependence of thermoluminescence in synthetic quartz". *J. Phys. D. Appl. Phys.* 21, 1452–1457. https://doi.org/10.1088/0022-3727/21/9/021.

[24] R. M. Bailey. (2000). "The slow component of quartz optically stimulated luminescence". *Radiation Measurements*. 32, 233-246. https://doi.org/10.1016/S1350-4487(99)00285-1.

[25] M. L. Chithambo, R.R. Dawam. (2020). "Phototransferred thermoluminescence of annealed synthetic quartz: Analysis of illumination-time profiles, kinetics and competition effects". *Radiat. Meas*. 131. https://doi.org/10.1016/j.radmeas.2019.106236.

[26] E. H. M. Nunes, F.S. Lameiras, M. Houmard, W.L. Vasconcelos. (2013). "Spectroscopic study of natural quartz samples". *Radiat. Phys. Chem.* 90, 79–86. DOI:10.1016/j.radphyschem.2013.05.003.