Vol. 31, No. 10 Journal of Semiconductors October 2010

Dose-rate dependence of optically stimulated luminescence signal*

Wei Pingqiang(卫平强)$^{1, 2, 3}$, Chen Zhaoyang(陈朝阳)$^{1, 2, †}$, Fan Yanwei(范艳伟)$^{1, 2}$,
Sun Yurun(孙玉润)$^{1, 2, 3}$, and Zhao Yun(赵云)$^{1, 2, 3}$

(1 Xinjiang Technical Institute of Physics and Chemistry, Chinese Academy of Sciences, Urumqi 830011, China)
(2 Xinjiang Key Laboratory of Electronic Information Materials and Devices, Urumqi 830011, China)
(3 Graduate University of the Chinese Academy of Sciences, Beijing 100049, China)

Abstract: Optically stimulated luminescence (OSL) is the luminescence emitted from a semiconductor during its exposure to light. The OSL intensity is a function of the total dose absorbed by the sample. The dose-rate dependence of the OSL signal of the semiconductor CaS doped Ce and Sm was studied by numerical simulation and experiments. Based on a one-trap/one-center model, the whole OSL process was represented by a series of differential equations. The dose-rate properties of the materials were acquired theoretically by solving the equations. Good coherence was achieved between numerical simulation and experiments, both of which showed that the OSL signal was independent of dose rate. This result validates that when using OSL as a dosimetry technique, the dose-rate effect can be neglected.

Key words: optically stimulated luminescence; dose-rate; numerical simulation; radiation measurement
DOI: 10.1088/1674-4926/31/10/102001 **PACC:** 8760M; 8760P; 2880

1. Introduction

It is well-known that ionizing radiation, such as in a nuclear power station and a synchrotron radiation laboratory, can badly damage human tissue, especially where high doses exist. So, precise control of dosage is needed in radioactive medicine to avoid damage to the human body. Human space exploration has to face a harsh radiation environment, and the electronic equipment of spacecraft will be damaged by radiation, which affects the life of the spacecraft. Obviously, it is of great significance to study the radioactive properties of materials used in a monitoring system to acquire reliable measurement results. Compared to other radiation dosimeters, optically stimulated luminescence dosimeters (OSLDs) have many advantages: for example, good radiation dosage sensitivity, wide measurement range, low energy consume, and blenched by light, which attracts much attention[1−5].

During exposure of a semiconductor or insulator to ionizing radiation, the valence electrons are ionized and electron–hole pairs are created. Some of these are trapped in preexisting defects in the materials through non-radiative trapping transitions. Upon stimulation with photons appropriate energy, the electrons can be released from the localized trap and recombine with localized holes at recombination centers. Recombination of the freed electrons with localized holes results in radiative emission and luminescence. According to the stimulation source, OSLD can be divided into three models: (a) the "continuous-wave OSL" (CW-OSL) method in which the stimulation light intensity is kept fixed and the OSL signal monitored continuously throughout the stimulation period, (b) the so-called "linear-modulation" OSL (LM-OSL) method in which the stimulation intensity is ramped linearly while the OSL is measured, and (c) the "pulsed OSL" (POSL) method in which the stimulation source is pulsed and the OSL is monitored only between pulses. The intensity of OSL signal is proportional to the dose of absorbed radiation. There are many reports in the literature on the superlinear dose dependence of OSL signal[6−10]. In nearly all the reports on OSL and its applications, it is assumed that there was no dose-rate effect. But some accounts of dose-rate effects in TL are given in Refs. [11, 12]. In the present work, we deal with the problems of dose-rate dependence of OSL by numerical simulation and experiments. Alkaline earth metal sulfide material CaS:Ce,Sm was chosen as the OSL material for experiment. The CW-OSL model and one trap and one center model were chosen for numerical simulation.

2. Experiments and numerical simulation

Figure 1 shows our measurement system. The system included a sense probe, a Y-chart fiber, a laser, a photodiode, an amplifier circuit, and an oscilloscope. In order to avoid interference with natural light and electromagnetic waves, the whole system was sealed in a metal box because the dosage

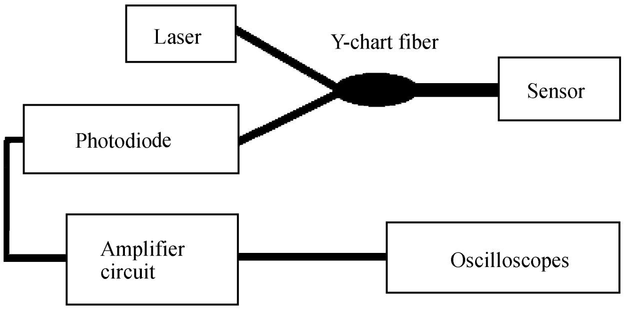

Fig. 1. Principle picture of OSL measurement system.

---

* Project supported by the National Natural Science Foundation of China (Nos. 10875168, 10475112).

† Corresponding author. Email: czy@ms.xjb.ac.cn

Received 5 March 2010, revised manuscript received 27 April 2010

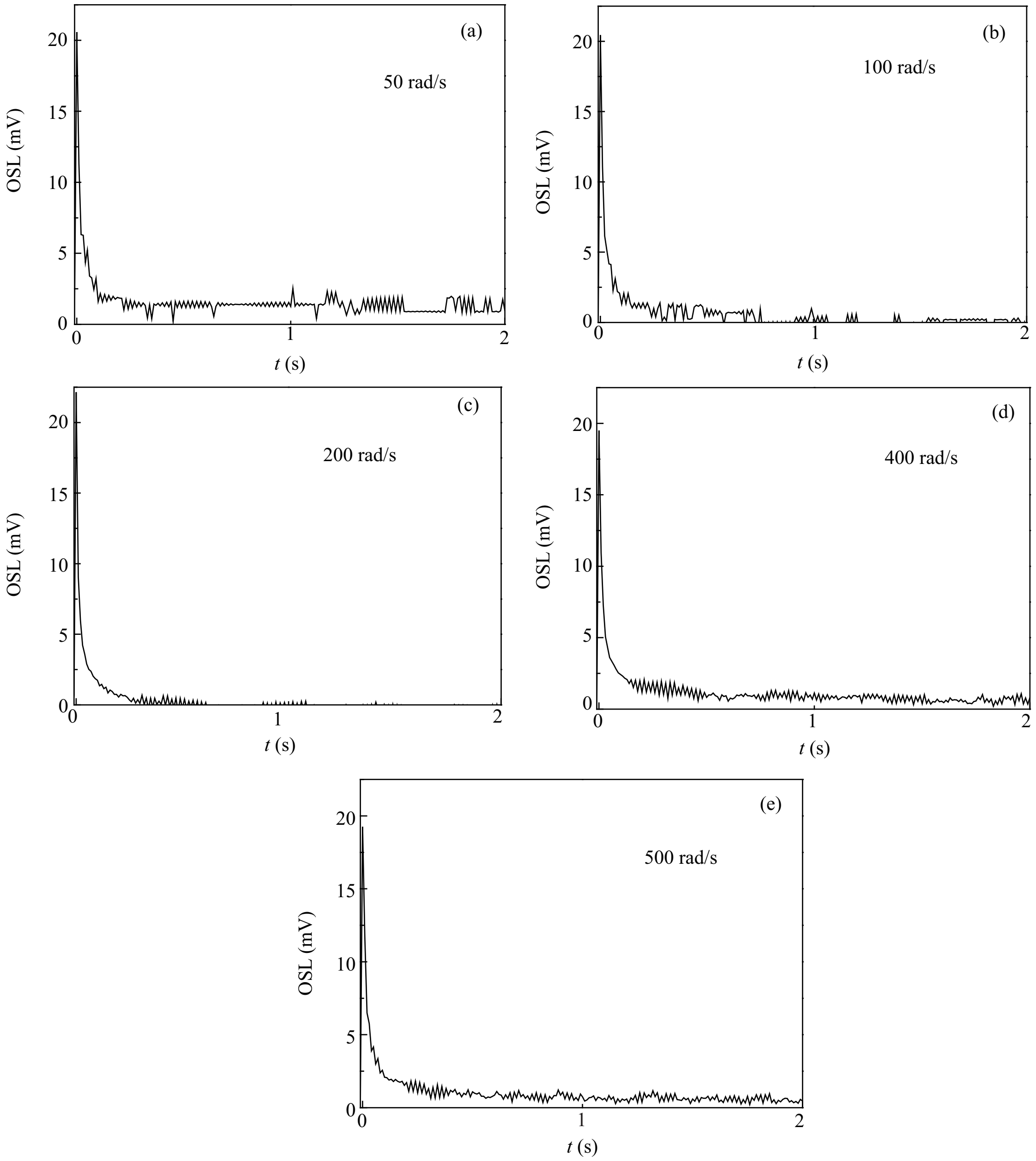

Fig. 2. Experimental results of OSL curves under various dose-rates for a constant total dose.

film is very sensitive to natural light and the amplifier circuit is sensitive to electromagnetic waves. The photodiode is only sensitive to visible light, and in order to avoid the interference from the laser, a lens was put in front of it. The photodiode and laser were fixed by a bracket to keep collimation of the optics system, which fiercely affected the reliability of the measurement results. The measurement process begins with infrared light sent by laser through the optical fiber, stimulating OSL emission in the sealed sensor. The OSL emission, which is proportional to the radiation dose absorbed by the crystal, travels back through the other fiber and is detected by the photodiode.

To study the dose-rate dependence of OSL, the total dose was kept fixed. At first, the dosage films were blenched by a laser of 200 mW and packaged with a dark paper packet. It was then irradiated at a distance of 40 cm from an electron accelerator (the energy of electrons was 1.1 MeV). The dose-rate of the electron accelerator depends on the electron energy, the distance from the electron source, and the velocity of the electron beam. In this paper, the distance and electron energy were kept fixed. The dose-rate was adjusted by changing the velocity of the electron beam. The velocity of the electron beam was adjusted from 0.01 to 0.1 mA, the dose-rates were 50, 100, 200, 400, and 500 rad/s. The samples were irradiated for 20, 10, 4, 2.5 and 2 s, respectively, to keep the total dose fixed. So the total dosage was 10 Gy. Finally they were taken out of the electron accelerator and put in our measurement system to measure the intensity of the OSL signals.

The calculation model used was put forward by Chen and Leung[13]. The whole OSL process was divided into there parts: irradiation, time annealing and stimulation. Each of them was represented by a series of differential equations. The dose rate dependence properties of the materials were acquired theoretically by solving the equations. The equations representing the irradiation stage are shown as follows:

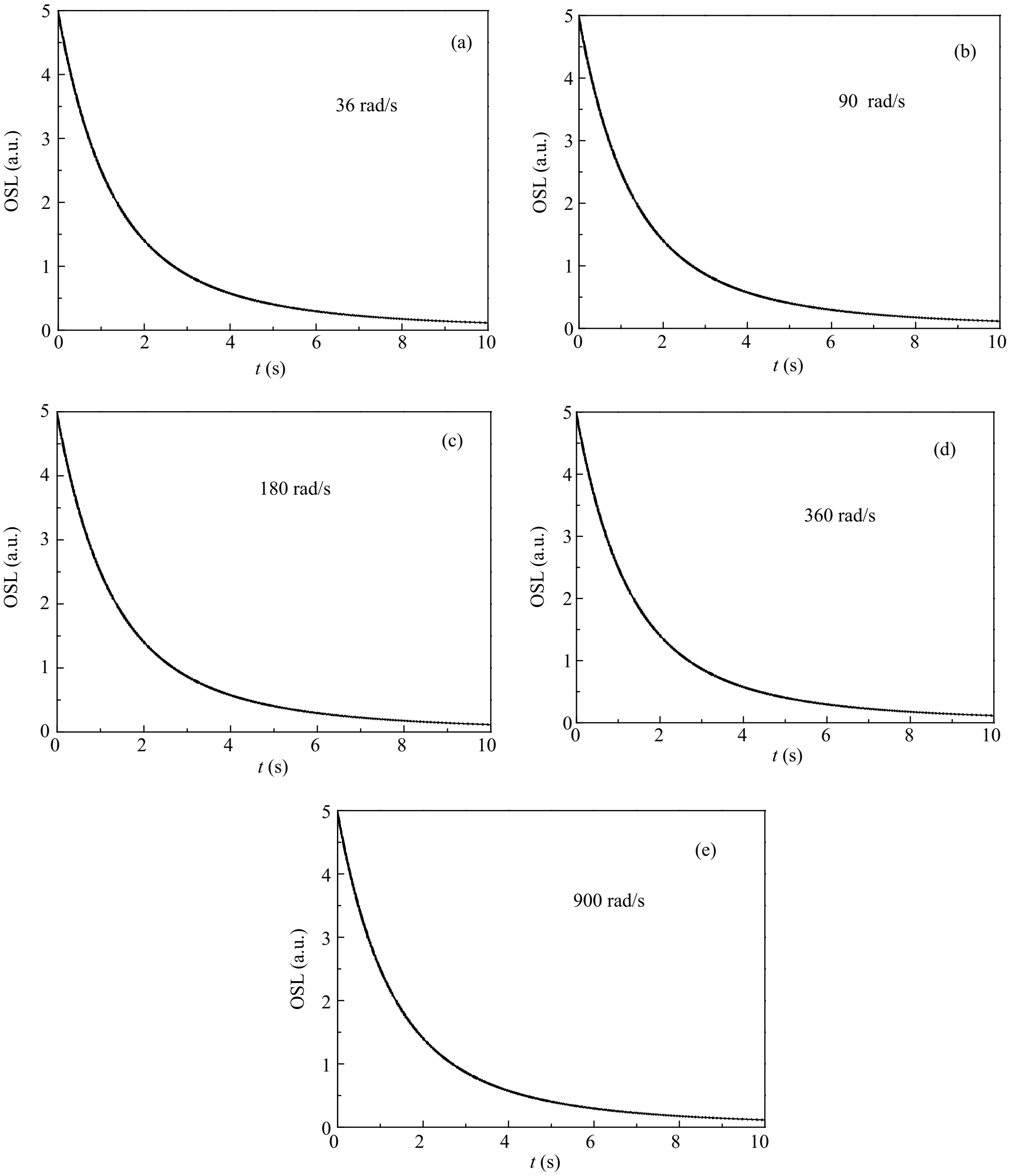

Fig. 3. Numerical simulation results of OSL curves under various dose-rates for a constant total dose.

$$\mathrm{d}n_{\mathrm{v}}/\mathrm{d}t = X - B(M - m)n_{\mathrm{v}}, \tag{1}$$

where n_{v} is the concentration of holes in the valence band, X is the creation rate of electron/hole pairs, B is the probability of holes being trapped by the holes trap center, M is the concentration of trap center of holes, and m is the concentration of holes in the trapped state.

$$\mathrm{d}m/\mathrm{d}t = -A_{\mathrm{m}}mn_{\mathrm{c}} + B(M - m)n_{\mathrm{v}}, \tag{2}$$

where A_{m} is the recombination probability of holes and electrons, and n_{c} is the concentration of electrons in the conduction band.

$$\mathrm{d}n/\mathrm{d}t = A_{\mathrm{n}}(N - n)n_{\mathrm{c}}, \tag{3}$$

where N is the concentration of trap center of electrons, n *is* the concentration of electrons in the trapped state, and A_{n} is the probability of electron being trapped by the electron trap center.

$$\mathrm{d}n_{\mathrm{c}}/\mathrm{d}t = \mathrm{d}m/\mathrm{d}t + \mathrm{d}n_{\mathrm{v}}/\mathrm{d}t - \mathrm{d}n/\mathrm{d}t. \tag{4}$$

At the annealing stage, the semiconductor CaS doped Ce and Sm are taken away from the radiant point, so the X turns to zero. And the holes in the valence band decrease quickly. At the last stage, the trapped electrons are excited from the trap center to the conduction band, then recombined with the holes in the recombination center. So at the last stage, Equation (3) turns to:

$$\mathrm{d}n/\mathrm{d}t = A_{\mathrm{n}}(N - n)n_{\mathrm{c}} + fn, \tag{5}$$

where f is the light activation probability. The intensity of OSL signals is equal to:

$$I_{\mathrm{OSL}} = A_{\mathrm{m}} m n_{\mathrm{c}}. \tag{6}$$

3. Results and discussion

The experimental results of the OSL curves under different dose-rates are shown in Fig. 2. From these curves, it can be found that the typical exponential decay was seen when using a constant power and constant wavelength stimulation light, and the OSL signal decayed to a minimum value in 2 s. The total dose was 1000 rad(CaS). Of all the OSL curves, the peaks are at 0.02 mV. That is to say, there is no dose-rate effect in OSL, according to our experiments.

As for the numerical simulation, some parameters were set differently from those of Chen. The dose rate and total dose were given here in units of rad. CaS has a density of 2200 kg/m^3 and an average of 20 eV is required for the heavy charged particles to produce electron-hole pairs by γ rays. 100 rad(CaS) equals 1 J/kg, and 1 J equals 6 $\times 10^{18}$ eV. The number of pairs produced per kilogram is about 3 $\times 10^{17}$. Therefore, the number of pairs produced in cm^3 is 6.6 $\times 10^{14}$. In conclusion, if the dose rate is 100 rad/s, X equals 6.6 $\times 10^{14}$ cm/s. In our simulation, X was set as 2.37 $\times 10^{14}$ cm/s, 5.92 $\times 10^{14}$ cm/s, 1.18 $\times 10^{15}$ cm/s, 2.37 $\times 10^{15}$ cm/s and 5.92 $\times 10^{15}$ cm/s. The dose rate was 36, 90, 180, 360, 900 rad/s, respectively. To keep the total dose fixed, the irradiation time was set as 50, 20,10, 5 and 2 s. So the total dose was 1800 rad. The doped Ce and Sm used were at a mass fraction of 0.3%, and the Avogadro constant is 6.02 $\times 10^{23}$ mol^{-1}, so M equals 2.84 $\times 10^{19}$ cm^{-3}, and N equals to 2.65 $\times 10^{19}$ cm^{-3}. The doped Ce acts as the hole trap and doped Sm acts as the electron trap. The numerical simulation results of OSL curves under different dose-rates are shown in Fig. 3. The typical exponential decay was also seen in the numerical curves. All the OSL decay curves overlapped, which indicated that there was no dose-rate effect in OSL by numerical simulation. The conclusions we achieved were in opposition to those of Chen on the dose-rate properties of OSL. This was good news regarding the use of OSL technology for radiation measurement.

4. Conclusions

Following some reports in the literature of the dose-rate properties of POSL signals of Al_2O_3, and basing on the one-trap/one-center model, the dose-rate properties of the CW-OSL signal of alkaline earth metal sulfide material CaS:Ce, Sm have been studied. The experimental and numerical simulation results had a good coherence, both showing that there was no dose-rate effect in a CW-OSL of alkaline earth metal sulfide material CaS:Ce, Sm when the total dose was kept fixed. This demonstrates that when using OSL technology for radiation measurement, the dose-rate effect can be ignored and the dose-rate can be determined by dividing the total dose by the irradiation time. However, the calculation model and parameters need to be further improved. The decay time of experiments was 2 s, but the numerical simulation result was 10 s.

References

[1] Dusseau L, Plattard D, Vaille J R, et al. An integrated sensor using optically stimulated luminescence for in-flight dosimetry. IEEE Trans Nucl Sci, 2000, 47(6): 2412

[2] Klein D M, Yukihara E G, Bulu E, et al. An optical fiber radiation sensor for remote detection of radiological materials. IEEE Sense J, 2005, 5(4): 581

[3] Garcia P, Vaille J R, Benoit D, et al. Study of the thermal behavior of the OSL integrated sensor response. IEEE Trans Nucl Sci, 2007, 54(6): 2272

[4] Liu Y P, Chen Z Y, Fan Y W, et al. The study on optically stimulated luminescence dosimeter based on the SrS:Eu,Sm and CaS:Eu,Sm. Chin Phys B, 2008,17(8): 3156

[5] Thompson J W. Accuracy, precision, and irradiation time for Monte Carlo simulations of single aliquot regeneration (SAR) optically stimulated luminescence (OSL) dosimetry measurements. Radia Meas, 2007, 42(10): 1637

[6] Liu Y P, Chen Z Y, Fan Y W, et al. A study on the real-time radiation dosimetry measurement system based on optically stimulated luminescence. Chin Phys C, 2008, 32(5): 381

[7] Polf J C, Yukihara E G, Akselrod M S, et al. Real-time luminescence from Al_2O_3 fiber dosimeters. Radia Meas, 2004, 38(2): 227

[8] Yukihara E G, Mittani J C, Vanhavere F, et al. Development of new optically stimulated luminescence (OSL) neutron dosimeters. Radia Meas, 2008, 43(2–6): 309

[9] Sawakuchi G O, Yukihara E G, McKeever S W S, et al. Optically stimulated luminescence fluence response of Al_2O_3:C dosimeters exposed to different types of radiation. Radia Meas, 2008, 43(2–6): 450

[10] Pinto T N O, Cecatti S G, Gronchi P C, et al. Application of the OSL technique for beta dosimetry. Radia Meas, 2008, 43(2–6): 332

[11] Valladas G, Ferreira J. On the dose-rate dependence of thermoluminescence response in quartz. Nucl Instrum Methods, 1980, 175(1): 216

[12] Chen R, McKeever S W S, Durrani S A. Solution of the kinetic equations governing trap filling consequences concerning dose dependence and dose-rate effects. Phys Rev B, 1981, 24(9): 4931

[13] Chen R, Leung P L. Dose dependence and dose-rate dependence of the optically stimulated luminescence signal. J App Phys, 2001, 89(1): 259