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МОДЕЛЮВАННЯ ПРОЦЕСІВ ТА ЯВИЩ

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PHOTON COUNT DYNAMIC RANGE DETERMINATION FOR OPTICALLY STIMULATED LUMINESCENCE DECAY MEASUREMENTS IN YAP:Mn

D. Afanassyev[1], S. Ubizskii[1], V. Rabyk[2], V. Paslavsky[2]

[1]*Lviv Polytechnic National University,*
12 Bandera Street, 79013 Lviv, Ukraine
denisna64@gmail.com,sergii.b.ubizskii@lpnu.ua

[2]*Ivan Franko National University of Lviv,*
107Tarnavskogo St., 79017 Lviv, Ukraine
rabykv@ukr.net, v.i.paslavsky@ukr.net

Margins of photon counting dynamic range have been determined experimentally for a photomultiplier tube operating in a setup for pulsed optically stimulated luminescence measurement. An effect of light exposure on the dark count has been taken into account as an addition limitation for the upper limit of light flux. The experiments have revealed that the dispersion of individual dark count readings is weakly affected by light exposure up to $6{\cdot}10^5$ s^{-1},while the mean dark count is increasing. These results are used for optimizing the measurement procedure for luminescence decay.

Key words: photon counting, pulse pair resolution, dark count fluctuations, optically stimulated luminescence (OSL), pulse mode OSL.

Introduction. The yttrium aluminum perovskite activated by Mn (YAP: Mn) is considered a promising detector material for passive OSL dosimetry [1,2] using the optically stimulated luminescence excited by short light pulses (P-OSL) for absorbed dose assessment [3]. The successful application of the P-OSL technique requires the development of dedicated instrumentation and OSL response readout method, taking into account peculiarities of the detector material and its OSL glow decay. The OSL of this material is not yet fully studied.The preliminary experiments have revealed a rather complex behavior of luminescence decay kinetics. Therefore it is necessary to measure the OSL response not only in a wide time scale but also in a wide dynamic range of light intensity. The latter reaches several orders of magnitude from the start of the decay process to the end of the time scale of interest (up to 500 s). The accurate recording of such responses requires an extension of light detection dynamic range for both high and low light intensities.

The light flux low end of the OSL response is so weak, that even the application of single photon counting technique requires certain background reduction. The authors have successfully applied the synchronous background subtraction to tackle this problem obtaining the residual dark count below 20 s^{-1} for the 1 s dwell time and even less for further increase of the latter [4,5].

From another side, the OSL emission intensity immediately after the excitation pulse in these experiments exceeded the linear range of photon counting, which is usually less than 10^6 s^{-1}.The measured photon count deviates from the linear dependence of input flux due to finite pulse pair resolution in time scale which depends on the photomultiplier tube (PMT) together with the signal conditioning electronics (amplifier, comparator, counters) and introduces some dead time into data acquisition process. If the pulse pair resolution parameter τ is known, the count nonlinearity can be corrected by a simple expression [6-8]:

$$N = M(1 - M\tau), \tag{1}$$

Where N and M are the real and measured photon counting rate respectively. This expression is a linearized solution of the following equation [6,8]:

$$M = N\exp(- N\tau). \tag{2}$$

Expressions (1) and (2) give sufficiently close results for $N\tau < 0.2$ with residual error within 1…2%[8], which may be comparable with noise spread. The linear response range can therefore be extended up to about 10^7 s^{-1} or even further [6], while using more elaborated model based on (2).

Unlike the conventional procedure based on the use of a calibrated light source or attenuator, which provides several different light intensities with known ratios [7], we extract the information on pulse pair resolution from the actually measured experimental data. Therefore a major complication of the instrumentation is avoided. Our approach for correct determination of τis based on assumption that the decay behavior of the OSL glow process under study remains the same over the whole sequence of excitation pulses, up to complete bleaching of the sample. Thus, the decay behavior of the YAP:Mn crystal played a role of calibration tool for our nonlinearity correction procedure. The procedure itself consisted in determination of the τ parameter for which the spread of normalized decay curves for the first excitation pulses and the last measured ones is minimize das described in[6].

Although a reasonable extension of the photon count dynamic range of about an order of magnitude can be achieved by the technique, another issue arises. The exposure of a PMT photocathode to light increases the dark count. The initial low dark count restores after quite long period of storage in darkness. Therefore the detection limit for weak light fluxes is affected. The experimental procedure for recording a variable light flux, like the OSL kinetics, should take into account this effect too. Thus, the goal of this study is the experimental determination of a reasonable upper limit of light intensity for extension of photon counting dynamic range by means of study of influence of a relatively high light flux on the dark count level as well as the lowest flux detection level being insensitive to mentioned influence.

Experimental. The simplified arrangement of experiment is shown in Fig. 1. The apparatus is described in more detail in [5]. The OSL is excited by light pulses with a maximum wavelength at λ=470 nm, generated by the high-power LED 1. Its excitation spectral range is further narrowed by an optional bandpass filter 2 installed before the sample under study 3. The electromechanical shutter 4 allows the emission light to pass via another bandpass filter 5to the detector 6 (Hamamatsu H9305-04 PMT module) only at 1 s long time intervals following the excitation pulses, after a fixed delay of 46 ms. The electronics module contains pulse preamplifier, amplitude discriminator, counters, as well as the microcontroller, drivers and USB interface. The dedicated software runs on the PC to set all the parameters of the experiment, start the measurement procedure and record the data.

The measurement procedure for OSL response [6] is modified in respect to one described in [5] to provide just one excitation pulse before the sequence of 128 time intervals of 1 s duration each, with repetition period of 3.1 s for response counting. Each 1 s interval is divided by 250 channels of 4 ms duration each, while identical 1 s intervals are provided for dark counts, accordingly to synchronous subtraction procedure described in [4]. The total duration of this recording was 397 s. It was considered enough for full elimination of OSL glowing after the single excitation pulse, at least for samples under study. The duration of each excitat ion pulse 100 ms and the LED current pulse amplitude was constant at 200 mA. The measurement sequence for each excitation pulse was started manually. The time interval between subsequent pulses was kept constant at 7 minutes. Each OSL decay curve was recorded in a separate data file. The 1 s data intervals were merged together over the common time scale.

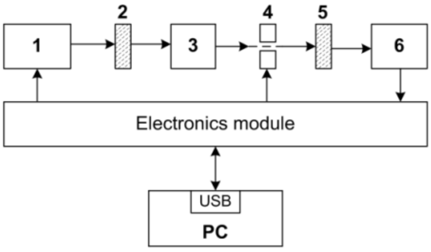

Fig.1. Experimental arrangement for recording the OSL response excited by solitary light pulses.

The samples were the 3?3 mm^2 polished square cuts of a YAP:Mn single crystal irradiated to different doses from different sources, after annealing at 500 °C for 30 min. The sample #1 has been irradiated by 30 KeVX-rays to a dose of approximately 2Gy, the #2 one has got 1 Gy dose from a ^{137}Cs gamma rays source.

Result and Discussion. A sample #1 exhibiting a strong OSL glow with initial light flux above $2\cdot10^4$ counts per bin (cpb), or $>5\cdot10^6 s^{-1}$has been measured to determine the photon count nonlinearity correction at high light intensity. This sample was subjected to 20 subsequent solitaryexcitation pulses resulting in a reduction of initial OSL response by factor of about 2. Only responses for 1st, 10th and 20th pulses are shown in Fig. 2 to demonstrate a trend. These response curves were fitted by Becquerel decay function (BDF) (see Fig. 2), known also as generalized hyperbola [10-12]:

$$I(t) = a + b(1 + ct)^{-1/d}, \tag{3}$$

where a, b, c, d are fitting parameters.

The pulse pair resolution parameter $\tau = 35$ ns has been determined using an approach outlined in [6] bringing the residual spread of normalized fitted responses to less than 5% (see Fig. 3). Based on this correction, a reasonable upper limit for photon count rate was determined at $5\cdot10^6$s^{-1}.This limit results in a residual error of corrected readout under 1%, according to [7,9].

From the other hand, the mean dark count rate and its fluctuations may be affected by exposing the photocathode to intense light flux. In fact, certain increase in dark count has been observed while measuring the above OSL responses of sample #1.

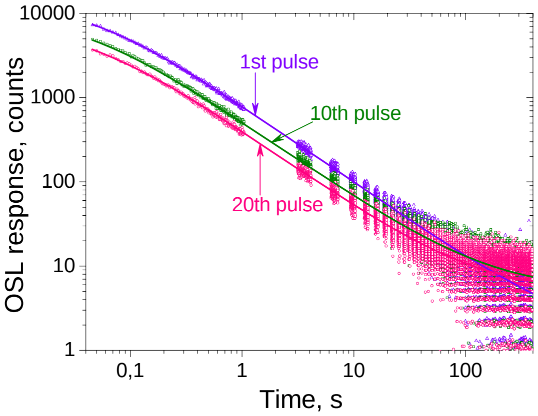

Fig.2.OSL decay curves for the #1 sample (points) recorded after the 1st, 10th and 20th sequential pulses together with their fits by mean of Becquerel decay function (3).

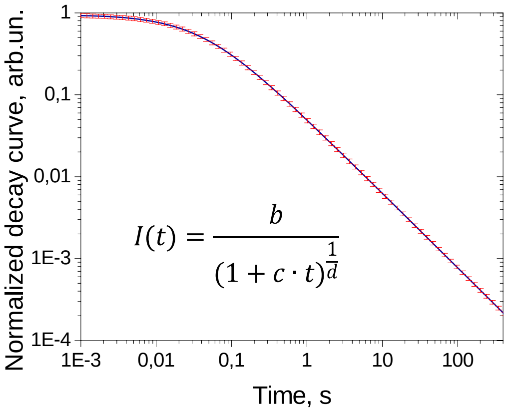

Fig.3. The averaged normalized BDF fit for all of 20 single pulse responses of the #1 sample after nonlinearity correction with τ = 35 ns. Error bars height is about 5% of the signal value and corresponds to the standard deviation of the fit points of all 20 decay curves from the average one.

To determine a light intensity less influencing the dark count rate, the further experiments were carried out on a sample #2, which featured a lower OSL glow intensity. This sample was subjected to multiple series of excitation pulses providing the PMT to be exposed to light of lower intensity than that observed at determining the upper limit of photon count.

The dark count rate was first measured immediately after the PMT was energized by bias voltage. The mean dark count increased slightly after turning the instrument, and then it was stabilized during some warm up. Possibly this increase was due to the heat released inside the PMT module, which also contains the DC/DC converter and voltage divider. The histograms of dark count readings (128 mean values for 250 bins of 4ms each) recorded after turning the PMT on and after 20 min. of warm up areshown in Figs.4*a* and 4*b*.

Then an irradiated sample of YAP: Mn was inserted into the reader chamber and a large number of excitation pulses was applied and the OSL responses together with dark counts were recorded according to experimental procedure [6]. The initial readings of the OSL response at 46ms delay after the end of excitation pulse were in the range of 2000–2500 counts per bin, or $(5–6)\cdot10^5$ s^{-1}. The histograms of dark count level for pulses #72 – #199 and #459 – #586 are shown in Figs. 4*c* and 4*d*, respectively.

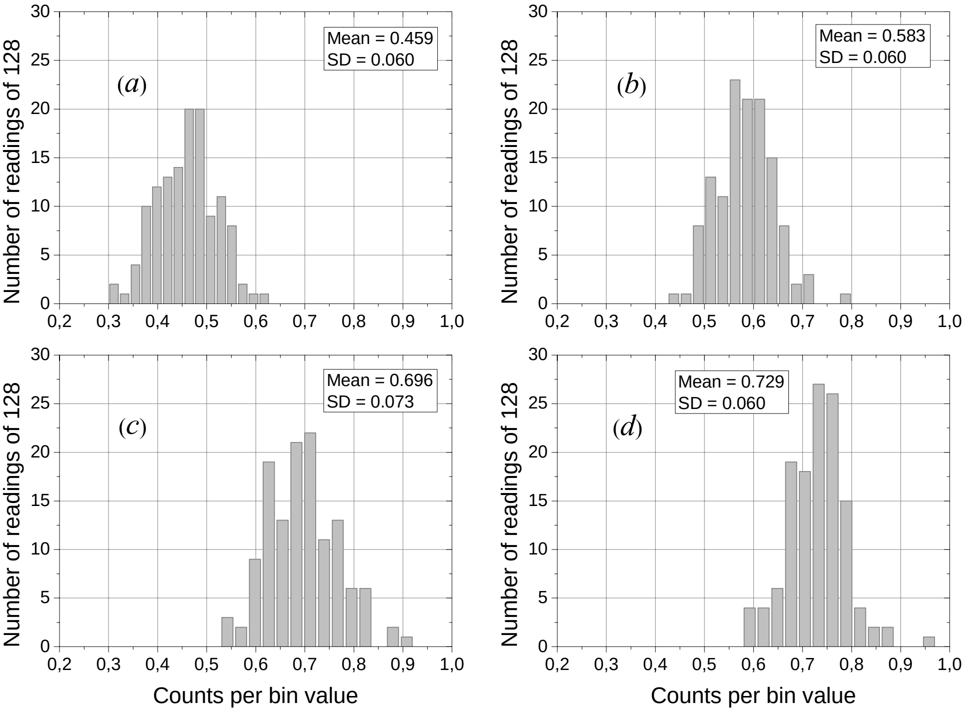

Fig.4.Dark count level histograms for 128 subsequent readings of 250 bins of 4 ms each, recorded just after the PMT has been turned on (*a*), after 20 minutes of PMT warmup (*b*), at recording the responsesthe #2 sample from excitation pulses #72–#199 (*c*) and #459–#586 (*d*). The mean values of counts per bin as well as their standard deviations are given in the insets.

One can see in Fig. 4 that the dark count level is changing after warm up of the PMT as well as after a lot of OSL emission pulses illuminating PMT cathode. At the same time the standard deviation of dark count level is almost the same remaining at 0.06–0.07 cpb, corresponding to 15–18 s^{-1}. Because of the dark count level estimated in the time interval preceding the OSL signal recording interval is subtracted from response signal in each measurement period the standard deviation of dark count (but not dark count level) determines the lowest level of signal which can be detected in described in [4] measurement procedure. It means that the dynamic range determined from these experiments spreads from about 15 s^{-1} to $6{\cdot}10^5$ s^{-1}, or more than 4 orders of magnitude for recording the OSL responses from solitary excitation pulses. At the same time we cannot exclude that even more high light flux level exceeding $6{\cdot}10^5$ s^{-1} can be measured correctly by our OSL system because it needs additional experiments.

Conclusion. The photon count dynamic range in measurements of the YAP: Mn OSL decay kinetics has been found to be weakly affected by dark count increase due to PMT exposure to the light flux with intensity up to $6{\cdot}10^5$ s^{-1}. The standard deviation of the dark count which determines the lowest limit of photon counting dynamic range was quite stable over several hundreds of excitation pulses applied to the sample, although the mean value of dark count has increased in the course of experiment. It seems desirable to design the automated measurement algorithm of the P-OSL reader to prevent the PMT photocathode from receiving the light fluxes above $6{\cdot}10^5$ s^{-1}.The further studies are necessary to elucidate the sensitivity of PMT dark count mean rate and fluctuations at higher OSL emission intensity.

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ВИЗНАЧЕННЯ ДИНАМІЧНОГО ДІАПАЗОНУ ВИМІРЮВАННЯ КІНЕТИКИ ЗГАСАННЯ ОПТИЧНО СТИМУЛЬОВАНОЇ ЛЮМІНЕСЦЕНЦІЇ YAP:Mn

Д. Афанасьєв[1], С. Убізський[1], В. Рабик[2], В. Паславський[2]

[1]*Національний університет “Львівська політехніка”*,
вул. Степана Бандери, 12, Львів, 79013, Україна
denysna64@gmail.com, sergii.b.ubizskii@lpnu.ua

[2]*Львівський національний університет імені Івана Франка,*
вул. ген. Тарнавського107, 79017Львів, Україна
rabykv@ukr.net,v.i.paslavsky@ukr.net

Границі динамічного діапазону ліку фотонів визначені експериментально для вимірювання кінетики відгуку збудженої імпульсами оптично стимульованої люмінесценції (ОСЛ)опромінених зразків YAP:Mn. Як фотоприймач був застосований модуль ФЕП HamamatsuH9305-04.Нелінійність ліку фотонів від світлового потоку високої інтенсивності за рахунок скінченого часового розділення імпульсів була скоригована з використанням часової константи встановленої безпосередньо з даних вимірювання кінетики ОСЛ в YAP:Mn. Цим можна забезпечити верхню межу динамічного діапазону світлових потоків до близько $5{\cdot}10^6 с^{-1}$. Однак, світловий потік такої інтенсивності впливає на рівень фонового ліку фотонів. Для визначення додаткового обмеження динамічного діапазону був досліджений вплив світлових потоків дещо меншої інтенсивності, у діапазоні до $6{\cdot}10^5$ $с^{-1}$, протягом вимірювання близько 600 послідовних записів кінетики згасання ОСЛ. Знайдено, що середнє значення фонового ліку знаходиться в інтервалі від 115 – 183 $с^{-1}$. Причому воно зростає на протязі 20 хв. після подавання напруги на ФЕП приблизно на 20%, а також внаслідок освітлення фотокатоду відносно інтенсивними імпульсами ОСЛ. Початкове підвищення темнового фону ймовірно викликане підвищенням температури фотокатоду за рахунок нагріву ФЕП електронними компонентами, що знаходяться у модулі. При цьому середньоквадратичне відхилення окремих відліків фонового ліку, яке саме визначає найменші вимірювані значення світлового потоку при використанні синхронного віднімання фону, становить від 15 до 18 $с^{-1}$ та слабо залежить від експозиції до світлового потоку з інтенсивністю $6 \cdot 10^5$ с$^{-1}$, включно з періодом початкового прогріву модуля ФЕП. Визначений за цими даними динамічний діапазон ліку фотонів становить більше 4 порядків. Враховуючі ці результати, алгоритм автоматизованого зчитування відгуку у прототипі зчитувача ОСЛ має обмежувати світловий потік, що потрапляє на фотокатод ФЕП до приблизно $6 \cdot 10^5$ с$^{-1}$ для уникнення впливу на нижню границю динамічного діапазону. Уточнення цього обмеження вимагає подальших досліджень.

Ключові слова: лік фотонів, динамічний діапазон, роздільність пар імпульсів, флуктуації фонового ліку, оптично стимульована люмінесценція (ОСЛ).

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