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To cite this article: M K Mjagkih *et al* 2021 *J. Phys.: Conf. Ser.* **2103** 012159

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Development of a method for quantitative comparison of the luminance of self-glowing crystals – the basic elements of a low current source

M K Mjagkih¹, P A Dementev², M V Zamoryanskaya³

¹ Laboratory Assistant, Ioffe institute, St. Petersburg, Russia

² Junior Researcher, Ioffe institute, St. Petersburg, Russia

³ Head of the Laboratory of Diffusion and Defect Formation in Semiconductors, Ioffe institute, St. Petersburg, Russia

E-mail: maxim.mjagkih@gmail.com

Abstract. This work is devoted to the development of a method for the quantitative comparison of the luminosity of weakly luminous samples, such as self-glowing crystals. A self-glowing crystal is an efficient scintillator, whose self-luminescence is due to the decay of a radioactive isotope introduced into the crystal matrix during its growth. Such crystals can be used as low current sources with a service life of 50 years or more. This technique takes into account the luminescence spectra of the samples under study, the spectral functions of the spectrometer and photodetector. Information on the luminescence spectra of samples can be obtained based on their cathodoluminescence spectra. Thanks to the calculations performed according to this technique, it becomes possible to estimate the optical radiation power of a self-glowing crystal, which can be converted into an electric current using a photodiode. Also, the proposed technique can be applied to assess the luminosities of any materials under the influence of radioactive radiation.

1. Introduction

Many modern electronic devices (most often microprocessors and memory modules) require not only the main source of energy in the form of mains power or high-capacity storage batteries, but also constant power from low-current sources (such as small chemical power supplies). The main problem of using chemical energy sources is their relative fragility (no more than 10-15 years), which leads to the need for their regular replacement throughout the entire operation time of the electronic device. When using electronic devices in conditions of limited accessibility (space, the Arctic, etc.), it is desirable to use batteries with a service life of up to 50 years.

A promising solution to this problem is the development of an energy source based on a «self-glowing» crystal and a photoelectric converter. The self-glowing crystal is an efficient scintillator activated by an alpha radioactive isotope such as Am²⁴¹ or Pu²³⁸. self-glowing of a crystal is due to the decay of a radioactive isotope introduced into the crystal matrix during its growth.

2. Experimental stand

The aim of this work is to develop a method for quantitative comparison of the luminosity of weakly luminous samples. The proposed technique is necessary for studying the properties of self-glowing crystals or other materials that glow under the action of high-energy radiation (scintillators, etc.). To



measure the luminosity of weakly luminous samples, a special stand was developed and manufactured. It is a light-tight box, inside which a sample holder and an optical radiation detector based on a silicon photodiode are installed on an optical rail. The silicon photodetector was developed at the Ioffe Institute [1]. A deflection flap is installed between the self-glowing crystal sample and the detector to measure the dark signal of the photodetector. The scheme of the stand is shown in Figure 1.

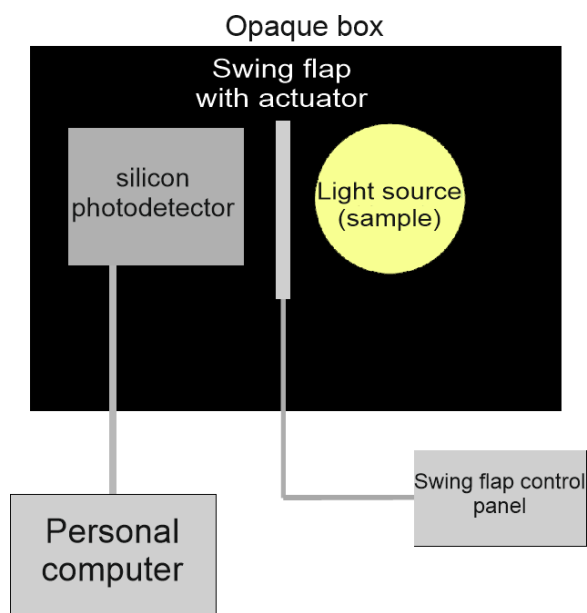


Figure 1. Schematic diagram of the stand for measuring the luminosity of weakly luminous samples.

The developed technique consists in the acquisition of the self-glowing spectra of the samples using special optical stand, their integration and subsequent processing of the obtained data using the spectral dependence of the sensitivity of the photodetector. Thanks to the calculations performed according to this technique, it becomes possible to estimate the optical radiation power of a self-glowing crystal, which can be converted into an electric current using a photodiode. For the investigated sample, the spectrum of its self-glowing was obtained on a special optical stand. The self-glowing spectrum was similar to the cathodoluminescence spectrum of the same sample, not activated by radionuclide. In this regard, in this work, to estimate the optical power of self-glowing, we used the cathodoluminescence spectrum of the sample under study. As a result, it is also necessary to take into account the spectral function of the cathodoluminescence spectrometer.

All calculations are performed using the Origin numerical data analysis environment and MS Office Excel. The initial data are the cathodoluminescence spectrum of the sample under study, the instrumental function of the cathodoluminescence spectrometer, and the spectral dependence of the photodetector sensitivity.

The cathodoluminescence spectrum of the sample is the dependence of the number of photons recorded by the photomultiplier of the spectrometer at a given wavelength for a time interval of 0.1 s on the radiation wavelength. The operating wavelength range of the spectrometer is in the range from 350 nm to 750 nm.

The instrumental function of the cathodoluminescence spectrometer used in this technique is an approximation of the real instrumental function obtained experimentally using a third-degree polynomial. The approximation is necessary in order to get the opportunity to calculate the value of the instrumental function of the spectrometer for any value of the wavelength (for any point on the cathodoluminescence graph). The used spectral dependence of the photodetector sensitivity is also an

approximation of the dependence obtained experimentally using a polynomial of degree 3 in order to be able to calculate it for any wavelength.

3. Stages of the self-glowing power estimation technique

3.1. Division by the spectral function of CL spectrometer

The cathodoluminescence spectra of the sample is divided by the value of the instrumental function of the spectrometer at each point.

3.2. Calculation of the cathodoluminescence energy spectrum of the sample

The formula (1) is used to calculate the energy contribution of each part of the spectrum lying between adjacent points (Figure 2):

$$E(\lambda) = 10 \times I(\lambda) \frac{hc}{\lambda} \quad (1)$$

where $E(\lambda)$ is the approximate value of the energy supplied from the luminescent sample in the interval between the wavelength $\lambda = \lambda_1$ and the subsequent wavelength λ_2 , for which the spectrum is specified, for a time interval of 1 s (calculated for λ corresponding to the beginning of the interval under consideration); $I(\lambda)$ is the number of photons registered by PMT of spectrometer in 0.1 seconds for the wavelength λ (PMT works in the photon counting mode); h is Planck's constant; c is the speed of light; 10 – coefficient for converting the energy value into the SI system.

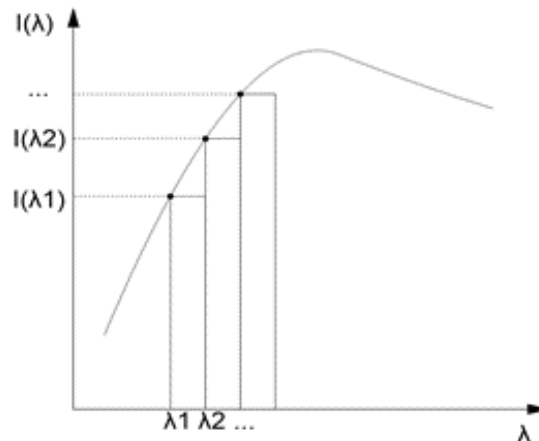


Figure 2. Splitting of the cathodoluminescence spectrum into intervals according to wavelengths.

3.3. Estimation of the current arising in the photodetector under the action of the optical radiation of a self-glowing crystal

According to formula (2), the current J_c arising under the action of radiation from the sample with the investigated luminescence spectrum in a silicon photodetector [1, 2]:

$$J_c = \int s(\lambda) E(\lambda) d\lambda \quad (2)$$

where $E(\lambda)$ is the spectral distribution of the luminescence energy (paragraph 3.2); $s(\lambda)$ – spectral dependence of the photodetector sensitivity.

For each wavelength $\lambda = \lambda_1$ for which the spectrum is indicated, the length of the interval (in nanometers) between it and the next indicated wavelength λ_2 is calculated for further integration of the spectrum.

Based on these data, the numerical value of the integral (2) is calculated. For this, the energy values for each wavelength interval are multiplied by the interval length and by the value of the instrumental function of the photodetector for the wavelength corresponding to the beginning of the interval.

3.4. Determination of the conversion factor of optical power into a signal recorded by a photodetector

The need to determine this coefficient is because the geometry of the collection of radiation when recording the spectrum of cathodoluminescence or X-ray luminescence differs significantly from the collection of the signal when measuring the photocurrent. This is primarily due to the different size of the investigated region (diameter and depth of generation of optical radiation). This coefficient can be calculated based on the geometric parameters of the system under study. In addition, acquisition of cathodoluminescence and self-glowing spectra is carried out in relative units.

4. Experiment results

Based on the described technique, the current J_c , induced by cathodoluminescent radiation of a ZrSiO_4 sample doped with Tb^{3+} rare earth ions, has been estimated. The emission spectrum of this sample is shown in Figure 3.

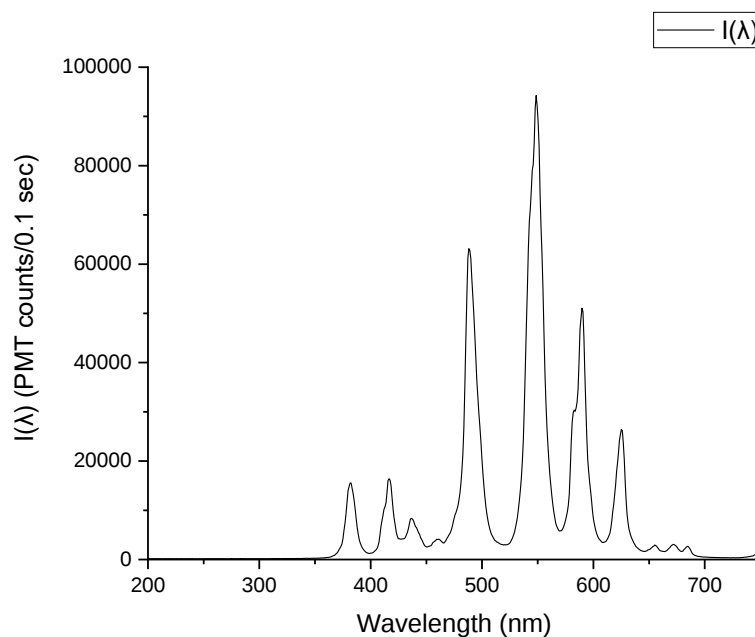


Figure 3. Cathodoluminescence spectrum of the $\text{ZrSiO}_4: \text{Tb}^{3+}$ sample.

The calculated values of the current J_c generated by the photodetector when it is illuminated by the luminescence of the sample: $\text{ZrSiO}_4: \text{Tb}^{3+}$, amounted to $1,02 \times 10^{-24} \text{ (A)}$.

After calculating the luminosity of the sample using this technique, the photocurrent J_f was measured using a silicon photodetector and an opaque box. The graph of the dependence of the photocurrent ($n\text{A}$) generated at the photodetector versus time is shown in Figure 4. The measurement was carried out for 418 seconds. The opening of the shutter separating the detector from the sample was performed 111 seconds after the start of the measurement. The distance between the detector and the sample is strictly fixed and is 3 cm. The mean value of the photocurrent J_f obtained for this sample was $2,695 \times 10^{-8} \text{ (A)}$.

The proportionality coefficient C for converting the measured current into the real optical power of the sample in this experiment is calculated by the formula (3):

$$C = \frac{J_f}{J_c} \quad (3)$$

For this sample, $C = 2,78 \times 10^{16}$.

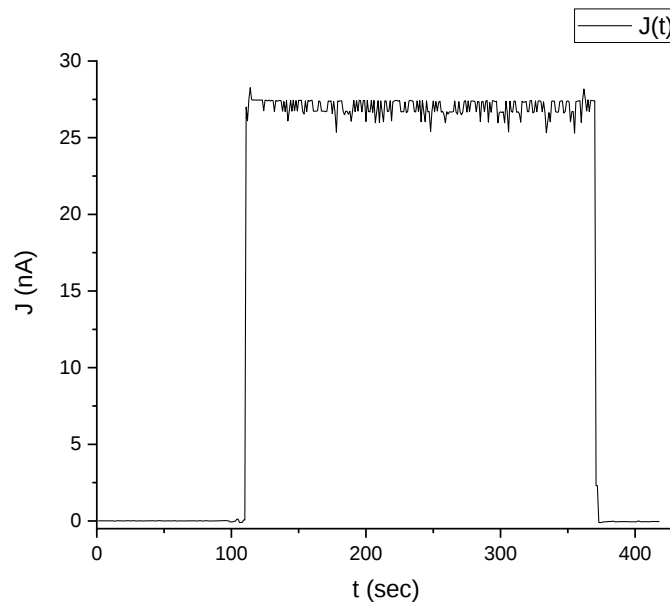


Figure 4. Time dependence of the photocurrent measured with a silicon photodetector in an opaque box (sample $\text{ZrSiO}_4: \text{Tb}^{3+}, \text{Pu}^{238}$).

5. Conclusion

In the course of the work, a stand was developed for measuring the photocurrent of self-glowing samples. The photocurrent induced by optical radiation of a $\text{ZrSiO}_4: \text{Tb}^{3+}, \text{Pu}^{238}$ sample in a silicon photodetector is measured. A technique has been developed for assessing the optical radiation power of samples using the radiation spectrum. The developed stand can also be used to assess the luminosity of any samples when excited by an external high-energy source. It will be used to determine the scintillation properties of various solid materials.

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