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Spark Sensor Based on Lithium-Potassium-Aluminophosphate Borate Glass Doped with Eu

V.A. Spiridonov[1,*], L.V. Azina[1], D.I. Panov[1], A.L. Kolesnikova[1,2]

[1] Institute of Advanced Data Transfer Systems, ITMO University, Kronverkskiy pr. 49, St. Petersburg 197101, Russia
[2] Institute for Problems in Mechanical Engineering, V.O., Bolshoj pr., 61, Russian Academy of Sciences, St. Petersburg, 199178, Russia

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Abstract

We demonstrate the concept of a spark sensor operating in UV range of the electromagnetic spectrum. The design of the device and the results of measurements of its most important characteristics are presented. Response time of the sensor is 3.8 ms and response threshold is 0.4 mW/m^2. For the sensing element of the device glass material with the composition $10Li_2O$-$15K_2O$-$15Al_2O_3$-$35B_2O_3$-$25P_2O_5$ doped with 5 at.% Eu is used. The peak of luminescence of the material corresponds to 611 nm when excited by a wide band (with wavelengths from 300 to 400 nm) of UV radiation that guarantees the high operation ability of the designed sensor.

Keywords: Spark sensor; Glass material; Luminescence; Safety of electrical equipment

1. INTRODUCTION

Spark breakdown poses a serious threat, because it can cause huge damages in a short time, so it is important to have devices capable detecting it in the shortest possible period and turning off the power of the damaged equipment. The main disadvantage of the traditional fuses used for a short circuit detection is their response speed, which reaches several seconds in the event of a jump in the circuit (exceeding the current in the circuit by less than 3 times according to GOST IEC 60898-1-2020). Such duration of the response period is enough to cause irreversible damage and even cause a fire. In addition, a strong electromagnetic field generated by a spark can disable electrical current sensors [1]. The principle of operation of the optical arc protection device is to register a flash of light inside the switchgear when a spark occurs. Existing devices offered on the market are based on the registration of a flash of light in the visible range [2-4]. However, as shown in Fig. 1, most of the spark discharge occurs in ultraviolet (UV) range of electromagnetic spectrum [5] and remains invisible to silicon photodetectors used in the standard sensors [6].

Another disadvantage of using the visible range is a possibility for false alarms. Sunlight or light from fluorescent lamps used to illuminate rooms where high-power devices are located can easily cause a false alarm and a termination of the device operation, which will cause a power outage. The re-activation of the control panel can take several minutes [7], which can lead to huge financial losses, for example in production, for no reason. Existing devices solve this problem by reducing sensitivity, reacting only to strong flashes. This may cause these devices to operate too late to prevent an irreversible damage. Thus, detecting UV radiation will significantly increase the sensitivity of the device, as well as protect against false alarms.

In this paper, the design of a device operating in UV range of electromagnetic spectrum is proposed. There are several reports on the use of phosphors in spark sensors [8–12]. However, their design does not imply the use of UV light range only. To register UV radiation, our proposed device uses a sensitive element made of lithium-potassium-aluminophosphate borate glass doped with Eu atoms, as well as a light filter that transmits UV radiation and absorbs the visible part of the spectrum.

* Corresponding author: V.A. Spiridonov, e-mail: vladspiridonov@itmo.ru

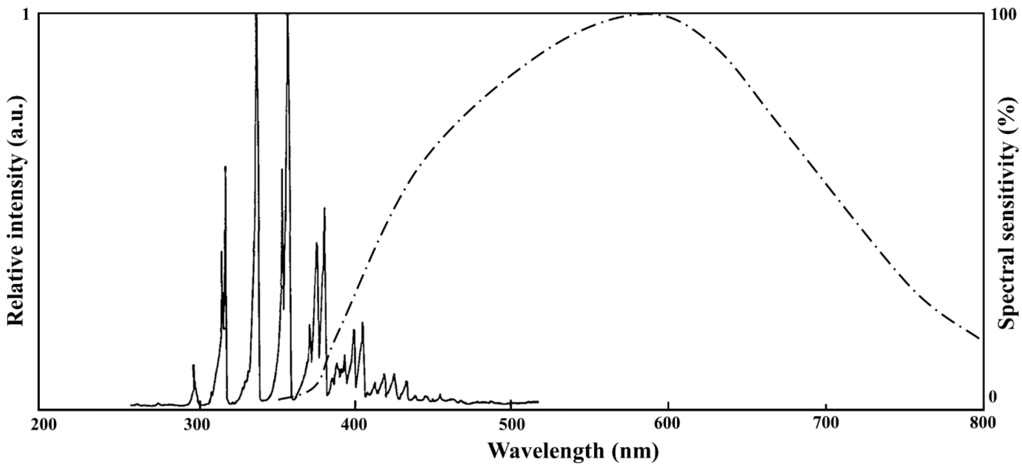

Fig. 1. Arc discharge spectrum (solid line), compared to the sensitivity of the silicon photodetector (dash-dotted line). Adopted from Refs. [5,6].

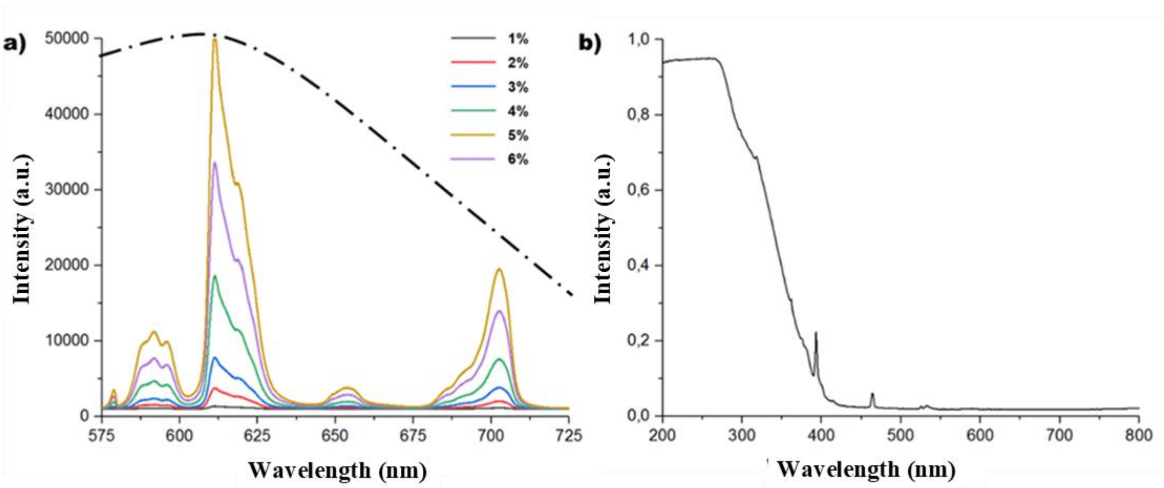

Fig. 2. (a) Luminescence spectrum of $10Li_2O$-$15K_2O$-$15Al_2O_3$-$35B_2O_3$-$25P_2O_5$ glass material doped with varying atomic % of Eu. Dash-dotted line shows sensitivity of silicon photodetector. (b) Absorption spectrum of glass material with 5 at.% of Eu.

2. EXPERIMENTAL SETUP AND METHODOLOGY

For sensing element fabrication, glass of the composition $10Li_2O$-$15K_2O$-$15Al_2O_3$-$35B_2O_3$-$25P_2O_5$ doped with 5 at.% Eu was synthesized. The choice of such a composition was due to the need to obtain a transparent, chemically stable, easily synthesized matrix for europium (Eu) ions, which provide the conversion of UV radiation in the visible light. Potassium-aluminoborate glass is transparent in the region of 300–800 nm [13,14], with a synthesis temperature of 1450 °C [15]. Lithium promotes better dissolution of ions in the glass matrix and, as a consequence, increases quantum efficiency of photoluminescence [16]. The conducted experiments demonstrated that the addition of europium to the charge did increase the synthesis temperature. To work with simple resistive heaters, it was necessary to reduce the temperature to acceptable for the operation of a standard heater (below 1400 °C). For this purpose, 10% phosphorus oxide was added to the matrix, which made it possible to reduce the synthesis temperature and preserve the chemical stability of the material. The Eu amount in the material was determined experimentally by synthesizing several glass samples of different compositions. Atomic % of europium in glass varied from 1 to 6. Luminescence spectra of obtained glasses and absorption spectrum of glass with 5 at.% of Eu are given in Fig. 2.

Luminescence spectra (Fig. 2a) showed that the maximum of the re-emitted light was at 611 nm wavelength with several side peaks in the region of 575–600 nm wavelength. The luminescence intensity increased with an increase in the number of europium ions up to 5 at.%. Further increase in Eu concentration led to microcrystallization of europium ions, loss of optical transmission, and, therefore, to a decrease in the intensity of the

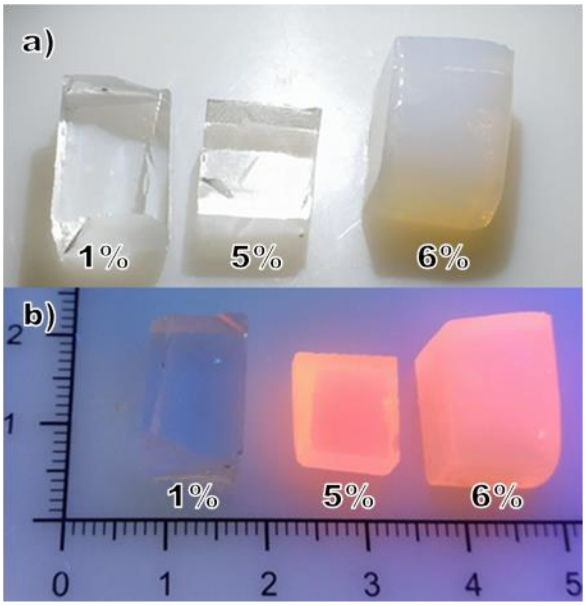

Fig. 3. Photographs of samples with various Eu at.%: (a) under daylight, (b) irradiated with UV light (UV lamp, 12 W, 365 nm).

luminescence of the sample and a loss of the effectiveness of the device. Figure 3 shows a photo of samples under daylight and irradiated with UV radiation.

The charge after homogenizing by stirring was loaded into heated up to 1350 °C crucible. The synthesis duration in the melt was 120 min. After that the composition was placed into metal molds. Then the produced glass was placed in the muffle heated to 400 °C followed by cooling to room temperature at a rate of (i) 10 degrees per hour first three hours, and (ii) 30 degrees per hour after that. To obtain the device active element, a 25x25x5 mm parallelepiped was cut out of the resulting glass sample using IsoMet 1000 precision sectioning saw. The active element was then grinded with aluminum oxide abrasive powder and polished with cerium oxide polishing powder.

The spectral-luminescent characteristics were examined using a luminescence measurement unit based on monochromator MDR-41, xenon light source and photomultiplier tube FEU-100. A light filter was placed in front of the monochromator to remove the luminescence excitation wavelength of MDR-41 and FEU-100 that were controlled from a computer. The MDR-41 performed scanning over the visible wavelength range with 0.2 nm steps. The UV radiation power density required for the device to operate was measured by the TKA-PCM UV radiometer. The response time was measured by the Tektronix MDO3032 oscilloscope.

3. RESULTS AND DISCUSSION

Schematic representation of an optical spark breakdown sensor is shown in Fig. 4. The sensing head and the transceiver module were connected to each other by a fiber optic cable. Sensing head consisted of light filter UG11 for visible light cut-off, active element made of the described above material, housing, collimator, and mounting elements.

Transmission spectrum of the light filter is shown in Fig. 5. As can be seen from the figure, the filter completely cuts off the visible range passing the UV radiation necessary to excite luminescence in the glass of the active element (Fig. 2b).

As is seen from luminescence spectrum of lithium-potassium-aluminophosphate borate glass doped with Eu, presented in Fig. 2a, the re-emitted light peaks are close to the maximum sensitivity of a silicon photodetector. Thus, the device can work with cheap silicon photodiodes that are protected from unwanted influence of daylight without the need to artificially raise the threshold of operation, because the work of the designed spark sensor is based on registering the re-emitted light from the active element.

Measurements of the response rate and sensitivity of the device showed a response time of 3.8 ms with a response threshold of 0.4 mW/m^2, which is superior to the characteristics of analogues on the market now [18–20].

4. SUMMARY

The presented materials have shown the concept for a spark sensor operating in the UV range of electromagnetic

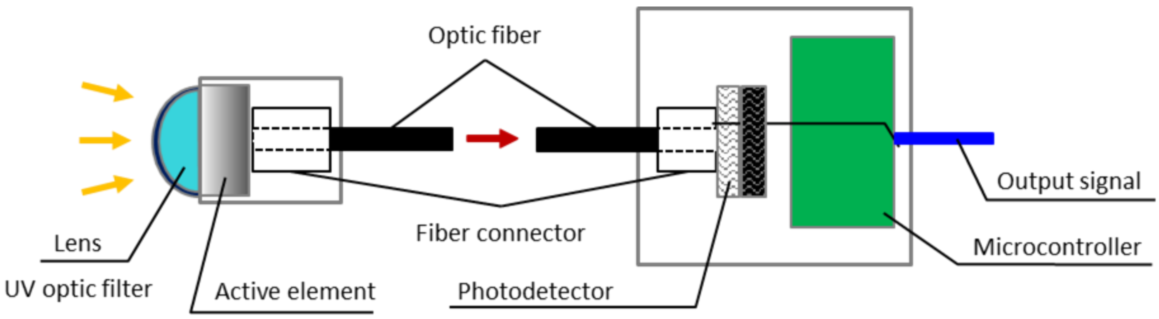

Fig. 4. Schematics for the optical spark breakdown sensor.

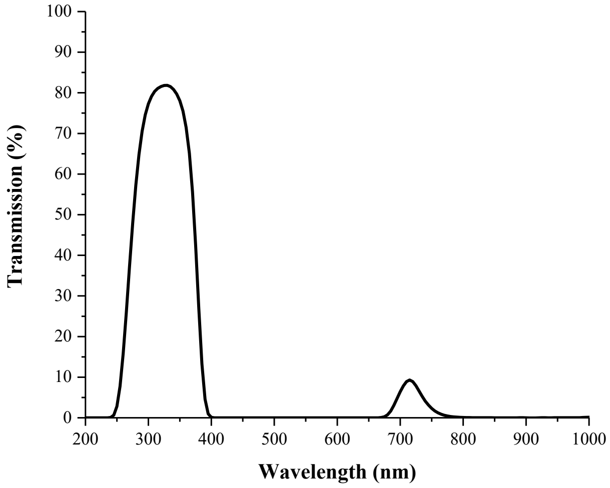

Fig. 5. Transmission spectrum of UG11 light filter. Adopted from Ref. [17].

radiation. The design of the device provides high sensitivity and protection against unwanted external triggering. For the sensitive element of the device the glass with composition $10Li_2O$-$15K_2O$-$15Al_2O_3$-$35B_2O_3$-$25P_2O_5$ doped with 5 at.% Eu has been synthesized. The peak of luminescence for the fabricated material has been determined at 611 nm wavelength when being excited by a wide band of UV radiation in the range from 300 to 400 nm.

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Датчик искрового пробоя на основе литий-калий-алюмофосфатноборатного стекла, легированного ионами Eu

В.А. Спиридонов[1], Л.В. Азина[1], Д.Ю. Панов[1], А.Л. Колесникова[1,2]

[1] Институт перспективных систем передачи данных Университета ИТМО, Кронверкский пр., д. 49, лит А, Санкт-Петербург 197101, Россия

[2] Институт проблем машиноведения РАН, В.О., Большой пр., д. 61, Санкт-Петербург, 199178, Россия

Аннотация. В работе продемонстрирована концепция датчика искрового пробоя, работающего в ультрафиолетовом диапазоне электромагнитного спектра. Представлена конструкция устройства и результаты измерений его наиболее важных характеристик. Время срабатывания датчика составляет 3,8 мс, а порог срабатывания – 0,4 МВт/м2. Для чувствительного элемента устройства используется стеклянный материал с составом $10Li_2O$-$15K_2O$-$15Al_2O_3$-$35B_2O_3$-$25P_2O_5$, легированный 5 ат.% Eu. Пик люминесценции материала соответствует 611 нм при возбуждении широкой полосой (с длинами волн от 300 до 400 нм) ультрафиолетового излучения, что гарантирует хорошую работоспособность разработанного датчика.

Ключевые слова: датчик искрового пробоя; стекло; люминесценция; безопасность электрооборудования