

Gamma Radiation Nose System Based on $\text{In}_2\text{O}_3/\text{SiO}$ Thick-Film Sensors

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Abstract—A prototype gamma radiation monitoring system based on $\text{In}_2\text{O}_3/\text{SiO}$ thick-film sensors array was designed. Four sensors had an identical pn-heterojunction structure with different material compositions. These sensors were subjected to gamma radiation emitted by ^{137}Cs source with an activity of 370 kBq. Changes in their current-voltage characteristics were recorded and compared. The performance parameters of the devices, such as sensitivity to γ radiation exposure and working dose region, were found to be highly dependent on the composition of the materials used. To cover a wider range of radiation and improve the overall sensitivity, an approach of using sensor arrays was utilized. A dynamic selection of the multiple sensors of various sensitivities and working dose ranges was implemented by applying a pattern recognition analysis.

Index Terms—Metal oxides, pattern recognition (PR), sensor arrays, thick films, γ radiation.

I. INTRODUCTION

REAL-TIME radiation sensors are essential in a wide range of applications, including nuclear power production, industry, and medicine (health treatment and product sterilization) [1]. The choice of proper detector depends on application requirements, expected working radiation dose range, sensitivity, size, stability, and cost. Considerable research into new sensors is underway, including efforts to enhance the sensors' performance through both material properties and manufacturing technologies.

Metal oxides and their mixtures in different proportions are considered as suitable materials for radiation sensing layers. Mixing oxides was found to control the properties of semiconductor films [2], [3]. The interaction of γ rays with materials mainly occurs by means of electronic excitation, electronic ionization, and, primarily, atomic displacement of the orbital electrons [4]. It is believed that ionizing radiation causes structural defects (called color centers or oxygen vacancies in oxides) leading to their density change on the exposure to γ rays [5]. The influence of radiation on the material depends on dose rate and the parameters of the films, including their thickness and composition: The degradation is more severe for the higher dose and the thinner films [6]–[8]. Radiation produces a change in the density of charge carriers in semiconducting material, which alters its properties. This measurable change provides information on the dose absorbed by the sensing layer.

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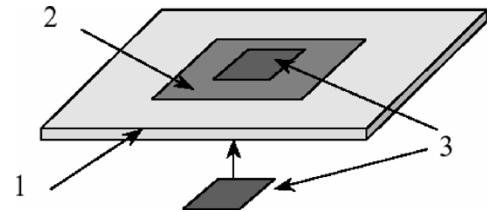


Fig. 1. Layout of manufactured pn-heterojunctions, where 1 is the p-type silicon wafer, 2 is the $\text{In}_2\text{O}_3/\text{SiO}$ layer, and 3 is the Ag electrodes.

In this paper, a number of pn-heterojunctions based on thick films with four different mixtures of In_2O_3 and SiO components are incorporated into a single radiation monitoring system. These sensors were exposed to gamma radiation in an identical way, so one can compare the performance of these devices and trace the influence of composition on the response characteristics. The values of radiation damage in the manufactured devices were estimated from changes in their current-voltage characteristics. It was found that the composition of the sensing layers plays a vital role in determining the sensitivity and working dose range of the dosimeter. In most cases, the sensitivity and maximum level of radiation that the device would sustain are in compromise. To cover a wider range of radiation and to enhance the overall sensitivity of radiation monitoring system, the approach of using sensor arrays is utilized, where sensors differ in their material composition. A dynamic selection of multiple sensors of various sensitivity and working dose range can be implemented by applying a pattern recognition (PR) analysis. The data-processing unit of the presented radiation monitoring system receives information from each sensor and based on their reading, a sensor with highest sensitivity in given dose range is chosen, providing the most accurate estimation of the radiation dose.

II. EXPERIMENTAL PROCEDURE

Polymer pastes of In_2O_3 and SiO mixtures in various proportions were made of 92 wt.% of functional material and 8 wt.% of polyvinyl-butyril (PVB), while ethylenglycolmonobutylether was used as a solvent, following standard preparation procedure for polymer thick-film pastes [9], [10]. Four various compositions were used. These are only In_2O_3 ; 75 wt.% of In_2O_3 and 25 wt.% of SiO; 50 wt.% of In_2O_3 and 50 wt.% of SiO; 25 wt.% of In_2O_3 and 75 wt.% of SiO [9]. These polymer pastes were screen printed using DEK RS 1202 automatic screen printer on p-type silicon wafers to form pn-heterojunctions. A silicon wafer P(100) had a dopant level of 10^{15} cm^{-3} on polished side and 10^{18} cm^{-3} on unpolished side. Afterward, printed films were cured in Telco Model 6 laboratory oven at a temperature of 100°C for 2 h. The active area of the diodes was $8 \times 4 \text{ mm}^2$,

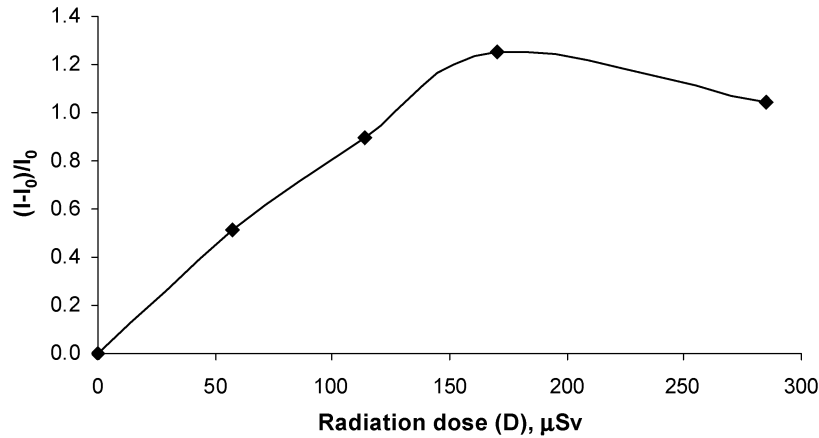


Fig. 2. Dependence of normalized current $(I - I_0)/I_0$ with γ dose under the applied voltage of +2 V for $\text{In}_2\text{O}_3/\text{Si}$ diode.

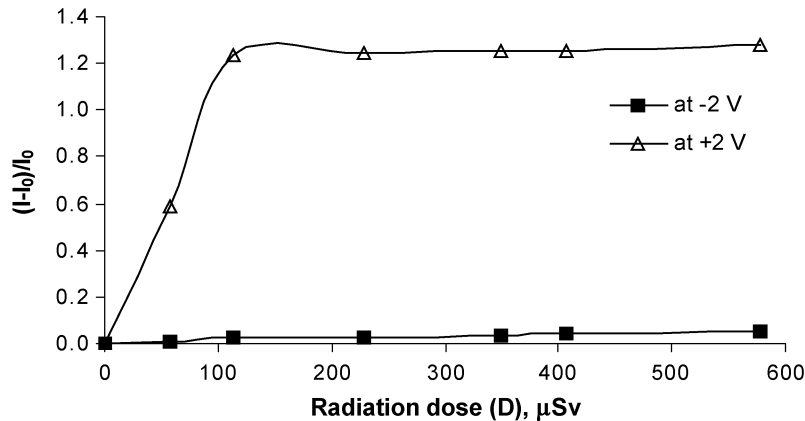


Fig. 3. Dependence of current $(I - I_0)/I_0$ with γ dose under the applied voltages of ± 2 V for diode made with 75 wt.% of In_2O_3 and 25 wt.% of SiO .

whereas all radiation-sensitive layers were $30 \mu\text{m}$ in thickness. Commercial DuPont 4929 silver paste was used to manufacture the electrical contacts. The layout of manufactured pn-heterojunctions is shown in Fig. 1.

The ^{137}Cs (0.662 MeV) disk-type source was used to expose the samples to γ radiation (provided by AEA Technology QSA GmbH as a standard reference gamma radiation source). The radioactive gamma-emitting element ($3.18 \times 5 \text{ mm}$) was encapsulated into 2-mm-thick high-strength epoxy resin (diameter 25 mm) to shield any accompanying β radiation. The source was distanced 1 cm from the device under investigation at an angle of incidence of 0° . The dose rate of the source was $5.7 \mu\text{Sv}/\text{min}$. A set of irradiations were performed changing the exposure time and, hence, the dose. The changes in I - V characteristics for the samples were monitored after each dose to estimate its effect.

III. RESULTS AND DISCUSSION

A. $\text{In}_2\text{O}_3/\text{SiO}$ Thick-Film Structures as Radiation Sensors

Morphology and structural properties of four $\text{In}_2\text{O}_3/\text{SiO}$ were studied [9]. A fine-grained uniform surface of In_2O_3 films with flake-shaped particles measuring 0.2 – $0.5 \mu\text{m}$ was revealed with SEM analysis. The surface of the films made with 25 wt.% of In_2O_3 and 75 wt.% of SiO possessed large-scale uniformity. The openings between the larger particles of SiO were filled

with much smaller particles of In_2O_3 , leaving no big pores [9]. Both the X-ray diffraction and Raman spectroscopy data indicated the presence of indium-oxide crystal phase in all compositions, whereas none of the silicon-oxide-based crystalline phases, such as quartz, stishovite, cristobolite, or quartz, were identifiable. Furthermore, the intensity of the In_2O_3 peaks decreases and the intensity of the amorphous halo increases as the amount of silicon oxide is increased. This indicates that SiO must be present in the amorphous state [9].

Figs. 2–5 show dependences of the normalized current $(I - I_0)/I_0$ with γ dose for various $\text{In}_2\text{O}_3/\text{SiO}$ diodes, where I_0 is the value of current of nonirradiated sample, and I is the value of current of irradiated sample at the same applied voltage.

As one can see, all samples showed the most increase in the values of current up to a dose of $114 \mu\text{Sv}$, except pure In_2O_3 samples ($170 \mu\text{Sv}$). Beyond these doses, the values of normalized current were found to be highly dependent on the material composition. The threshold levels were:

- $170 \mu\text{Sv}$ for films made with 100 wt.% of In_2O_3 ;
- $578 \mu\text{Sv}$ for films made with 75 wt.% of In_2O_3 and 25 wt.% of SiO ;
- $700 \mu\text{Sv}$ for films made with 50 wt.% of In_2O_3 and 50 wt.% of SiO ;
- $2100 \mu\text{Sv}$ for the films made with 25 wt.% of In_2O_3 and 75 wt.% of SiO .

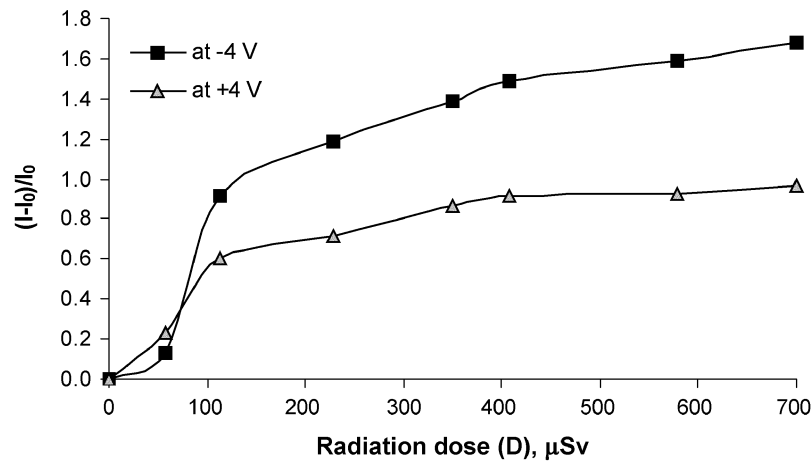


Fig. 4. Dependence of current $(I - I_0)/I_0$ with γ dose under the applied voltages of ± 4 V for diode made with 50 wt.% of In_2O_3 and 50 wt.% of SiO .

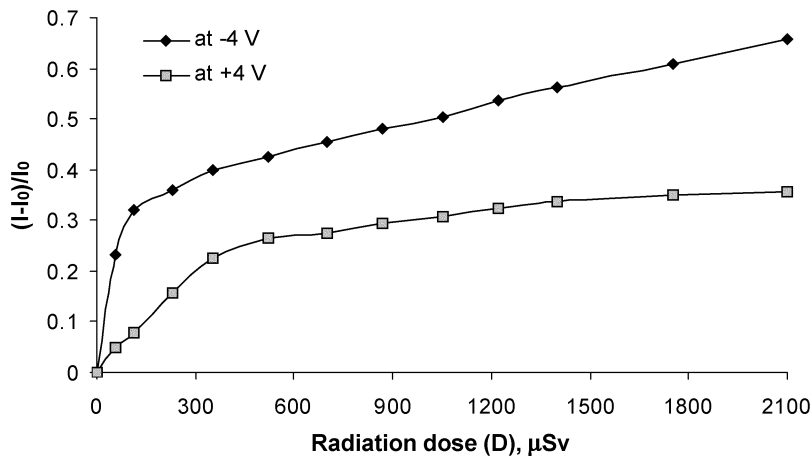


Fig. 5. Dependence of current $(I - I_0)/I_0$ with γ dose under the applied voltages of ± 4 V for diode made with 25 wt.% of In_2O_3 and 75 wt.% of SiO .

Samples made with only pure In_2O_3 are recommended for the detection of low levels of radiation. Counterpart samples made with 25 wt.% of In_2O_3 and 75 wt.% of SiO are recommended for high-dose applications, as they sustained a higher dose of up to 2100 μSv [11].

It is believed that in all tested pn-heterojunctions, the increase in values of currents with radiation was caused by the grain boundaries, which serve as current paths resulting in poor leakage current characteristics. Another reason for worsening the electrical properties is that the films were damaged by the creation of radiation defects in the form of broken Si-O and In-O bonds. It is reasonable to assume that the increase in the leakage current after the influence of γ radiation is partially attributed to the lowering of the barriers height at $\text{Ag}/(\text{In}_2\text{O}_3 + \text{SiO})$ interface. Similar effects of γ rays were observed in the $\text{Al}/\text{Ta}_2\text{O}_5$ interface because of building up a charge in Ta_2O_5 near this contact [6]. During the irradiation process, a modification of the $\text{Si}/(\text{In}_2\text{O}_3 + \text{SiO})$ interface takes place as a result of the oxidation of the silicon wafer, leading to an enlargement in the mixed-transition region, where SiO_2 and the intermediate oxidation states of Si coexist. The latent defects, which are activated during irradiation, are in the form of oxide traps and are also responsible for deterioration of the device characteristics [6], [12].

B. Radiation Nose System Design

To cover more than one energy or type of radiation, the approach of using devices with a combined structure, such as sensor arrays, can be utilized, where the sections of the radiation nose system could differ in material thickness or composition [13]. The most important aspect of utilizing multiple radiation sensors is choosing the most accurate one for a given radiation dose. Additionally, the detection of damaged sensors is a critical task necessary for ensuring the maximum possible accuracy in measuring radiation doses. The characteristics of a radiation sensor exposed to a radiation dose higher than its working dose range will permanently change, making the sensor unreliable. Therefore, damaged sensors should be excluded from further usage. For example, a sensor based on pure In_2O_3 is damaged if exposed to a radiation dose level higher than 170 μSv .

Fig. 6 shows the dependences of normalized values of currents versus radiation dose for four sensors with different $\text{In}_2\text{O}_3/\text{SiO}$ constituent, which are built in as sensor arrays for radiation monitoring. The process of the detection always starts from the analysis of the radiation dose readings from sensor 4, which is capable of measuring highest radiation doses without being damaged. If sensor 4 reports the detection of radiation dose of more than 700 μSv , then sensors 1, 2, and 3

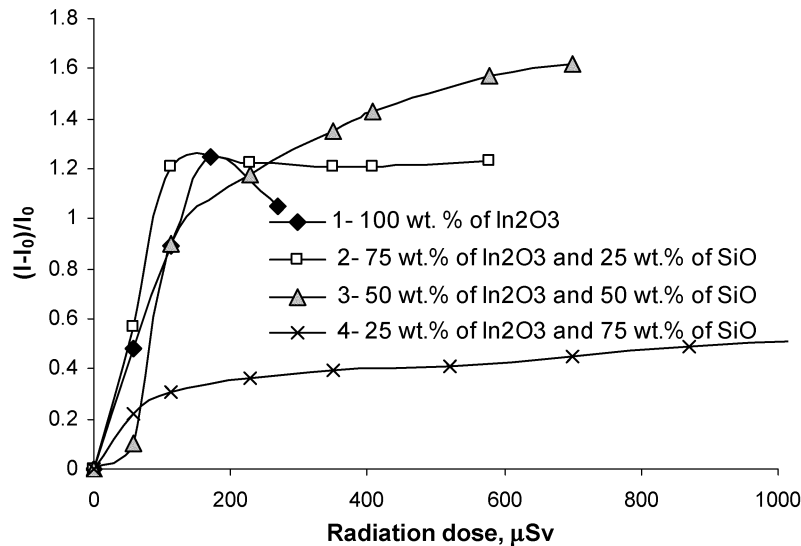


Fig. 6. Dependences of normalized values of currents versus radiation dose for four sensors with different $\text{In}_2\text{O}_3/\text{SiO}$ constituent.

TABLE I
COMPARISON OF RADIATION DOSE MEASUREMENT ACCURACY/SENSITIVITY

Radiation range (μSv)	0	170	578	700
	170	578	700	2100
The most accurate sensor	1	2	3	4
Second most accurate sensor	2	3	4	
Sensors damaged		1	1,2	1,2,3

should be classified as damaged. When sensors 3 and 4 report radiation dose higher than $578 \mu\text{Sv}$, then sensors 1 and 2 are damaged. Analysis starts from sensor 4 and if it does not detect damage in sensor 3, then sensor 3 is used (as more accurate) to detect whether sensors 1 or 2 are damaged. If sensor 3 reports radiation dose higher than $578 \mu\text{Sv}$, then sensors 1 and 2 are considered as damaged. Otherwise, if sensor 3 reports radiation dose higher than $170 \mu\text{Sv}$, then only sensor 1 is damaged.

Once it is known which sensors are operational at a given dose, a selection of the most accurate/sensitive among them should take place, as summarized in Table I.

The above-proposed radiation monitoring system has two main advantages, e.g., wider working dose range and increased overall sensitivity. This approach may be compared with gas-sensing electronic nose system, which finds its application not only in food industry, but also in healthcare, military, and space exploration [14]. The analysis of gas mixtures requires the use of multiple gas sensors, each one sensitive to a different gases or gas concentration. Only then can the information be properly evaluated to recognize a specific pattern. The main goal of the PR algorithm is to classify set of input values into one of available classes. In the case of the electronic nose, input values consist of readings from each sensor in the array, while the class recognized by the PR algorithm reflects a type of odour [14]. PR covers a very rich family of different algorithms. Performance of a particular algorithm can be measured in terms of flexibility, efficiency, and reliability. The accuracy of measurement classification by PR algorithms is the most common problem in real applications of sensor arrays systems [14].

Theoretically, the proposed radiation monitoring system design approach can be applied for more complex systems, for mainly industrial applications, where few types of radiation sources are used. These sources can have different parameters, such as an activity and dose rate. Moreover, resultant radiation exposure could be of a complex nature, e.g., it can include α , β , γ rays, etc. In this case, radiation-sensitive materials should be carefully chosen. Similarly, an array of sensors can be implemented, with each sensor having different sensitivity to various radiation types or energies. Based on a set of the output readings from these sensors, a specific PR algorithm should be applied so that the radiation nose system will accurately determine radiation dose and type.

IV. CONCLUSION

A novel approach to monitoring a radiation dose was presented. A number of $\text{In}_2\text{O}_3/\text{SiO}$ radiation sensors with different compositions were fabricated using thick-film technology. The sensitivity of these devices and their working dose range were found to be highly dependent on the combination of the materials used. It was proposed to combine these sensors as an array into the radiation monitoring system to ensure the highest overall sensitivity and widest working dose range.

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