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APPLICATION OF SILICON-POLYMER COMPOSITE VARISTORS TO PROTECT SENSITIVE MEDICAL IMAGING CIRCUITS AND PERFORMING BETTER VOLTAGE BIAS FOR SiPMs*

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Nowadays, Silicon photomultipliers (SiPM) become a reasonable choice for Time-of-Flight Positron Emission Tomography (TOF-PET). To achieve the best performance of SiPMs, it is necessary to adjust a suitable voltage bias. In this article, we are using varistors which protect SiPM from voltage fluctuations. The silicon-polymer composite varistors prepared using hot press method have been investigated. Research on (current-voltage) characteristics of samples shows that by increasing silicon content in the mixture, the breakdown voltage decreases from 110 V to 70 V. The results also show that increasing silicon content decreases the potential barrier height from 0.29 eV to 0.26 eV, however, leakage current increases. Increasing silicon content increases nonlinear coefficient from 4.1 to 4.8. Using these techniques gives us ability to produce suitable surge protector for medical imaging modalities.

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1. Introduction

Rapid development of electronic and medical equipment has resulted in growing concern about how to protect them against voltage fluctuations,

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since nowadays most of the electronic devices contain many sensitive elements such as transistors which can be damaged by voltage fluctuations [1]. One of the electronic devices that is very sensitive to voltage fluctuations is SiPM. SiPM is a semiconductor device built as an array of avalanche diodes connected together in parallel [2]. Each array detects photons identically and independently. Some advantages of SiPM such as low voltage operation and insensitivity to magnetic field make it the main choice in most of the Positron Emission Tomography (PET) constructions [3, 4].

A good strategy to protect sensitive medical imaging and electronic circuits is using over-voltage protectors with proper nonlinear current-voltage (I–V) characteristics, namely "varistors" [5–8]. A varistor is an electroceramic passive component, strongly dependent on voltage, whose (I–V) characteristics are Ohmic at the pre-breakdown region, while its resistance drops drastically at the breakdown region. This behavior makes them suitable for protecting electronic devices and electric circuits against surges and over-voltages. A varistor is used parallel with the sensitive part of the circuits. At lower voltages, resistance of a varistor is high but when the voltage increases suddenly, the resistance of varistor decreases and the varistor behaves like a conductor [6]. Breakdown voltage in varistors is strongly dependent on the type and amount of primary materials, thickness, the active area between the two electrodes, and most importantly their preparation conditions. By changing these factors, a varistor with different electrophysical properties is produced for use in different circuits [7, 8]. Nowadays, there is a high request for manufacturing low-voltage varistors. The silicon-PolyAniline-Polyethylene composite varistors can be another low-voltage composite varistors. Silicon is a hard, relatively inert tetravalent metalloid which is very brittle in crystalline form and has a marked metallic luster. Its unique properties make it important in micro- and nano-electronic industry. Silicon forms the backbone of modern microelectronics, and is widely used in optoelectronics due to its 1.12 eV indirect band gap [9].

Among conductive polymers, special attention has been paid to polyaniline (PANI) because it has various forms leading to different physical properties (*i.e.* doped and de-doped polyaniline), low production cost and good environmental stability [10–13]. One of the major problems related to the low mechanical properties of PANI to overcome is its frangibility. The solution is to combine it with a thermoplastic polymer, *e.g.* polyethylene (PE) [14]. PE is one of the most widely used thermoplastics with excellent thermal and electrical insulation properties [15]. Among all types of PEs, the high-density polyethylene (HDPE) is a commonly used thermoplastic with a high degree of crystalline structure [16, 17]. In this experimental work, we produce silicon-polymer-based composite varistors that can be use in new devices such as medical diagnosis devices [18, 19].

2. Preparation of the varistor

The first stage of varistor production is preparing its primary compounds. High-purity silicon crystal (99.9%), high-density polymer have been ground and sifted using a No. 200-mesh sieve to guarantee that the size of chosen particles is less than 74 μm. High-density polyethylene (HDPE) was sieved with the same sieve because its large particles may cause the nonuniformity of composition [20]. On the other side, small particles have higher effective interaction surface. In the meantime, doped PANI in the form of emeraldine salt has been obtained from aniline monomer [21]. To study the effect of primary compound amounts on varistor properties, specified amounts of each material have been picked up according to Table I. Primary compounds have been mixed according to their mass percentage and weighed with the accuracy of 10^{-4} g. By using a ball mill, each mixture has been mixed for 2 h to hand in a uniformly mixture. Hot pressing method has been used to prepare varistor disks. Each varistor disk has been formed to be of 10 mm in diameter and 220 μm in thickness at pressure of 60 MPa and temperature of 130°C. Finally, after checking for their qualities such as uniform thickness and lack of any cracks, the electrical properties of the disks could be studied. To study electro-physical properties like current-voltage characteristics, each varistor disk has been sandwiched between two copper electrodes of 6 mm diameter. Then by applying voltage between the two copper disks, circulated current has been measured. All measurements were performed at room temperature.

TABLE I

Breakdown voltage, nonlinear coefficient and potential barrier height of samples at different percentage of silicon and polymer.

Sample	Amount silicon [%]	Amount polymer [%]	Bearkdown voltage [V]	Nonlinearity coefficient	Potential barrier [eV]
1	60	40	110	4.1	0.29
2	65	35	90	4.3	0.265
3	70	30	70	4.8	0.264

3. (I–V) characteristics and nonlinear coefficient

The (I–V) characteristics of a varistor strongly depend on the content of materials that we used to produce it, so different samples were produced according to Table I. First stage of research comprised finding the best fraction of the silicon and polymer. The criterion to determine this fraction is the breakdown voltage and nonlinearity coefficient.

Studying (I–V) characteristics of samples at 25°C shows that this composite has varistor behavior (Fig. 1). By increasing Si content, breakdown voltage of varistor samples decreases whereas nonlinearity of the samples increases (Table I). This behavior continues until the amount of Si reaches 70% of the whole. Bigger increase in Si content results in higher leakage current. These results can be explained regarding grain boundary analysis. A varistor consists of inter-granular nonconductive layers and conductive grains. For Si-polymer varistors, inter-granular layer is made of PANI and HDPE. Since HDPE is a fully insulated polymer and PANI is used in a doped state, PANI and HDPE in single-phase state have completely linear (I–V) characteristics [22], therefore, these elements alone do not show the behavior of a varistor. However, using HDPE and PANI with Si results in completely different behavior [23, 24]. The (I–V) characteristics of a varistor in its nonlinear region is defined by

$$\mathrm{I(V)} = KV^{\alpha} \quad \text{or} \quad \alpha = \mathrm{d}(\ln \mathrm{I})/\mathrm{d}(\ln \mathrm{V})\,,$$

where α is a nonlinear coefficient and K is a constant which is related to the microstructure of the varistor. By plotting the (ln I–ln V) diagram for nonlinear region and calculation of the tangent of (ln I–ln V) diagram, it is possible to obtain the nonlinear coefficient for the varistors. It is clear from Fig. 1 that by increasing Si content, nonlinear coefficient values increase from 4.1 to 4.8 and breakdown voltages are reduced from 110 V to 70 V, which indicates an increase in the quality of the varistor (see Table I).

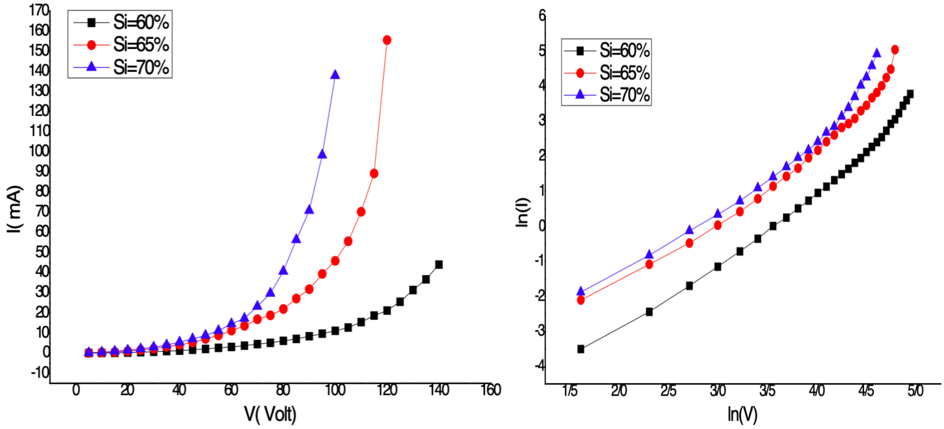

Fig. 1. Left: (I–V) characteristics of the samples. Right: ln(I)–ln(V) plot for calculation of the nonlinear coefficient.

4. Potential barrier height

To calculate the potential barrier height, the Pianaro model is considered in the Schottky-type conduction mechanism [25]. According to this model, the relation between current density and potential barrier is as follows:

$$J = AT^{\frac{1}{2}} \exp\left[\left(\beta E^{\frac{1}{2}} - \phi_{\mathrm{B}}\right)/k_{\mathrm{B}}T\right],$$

where A is the Richardson's constant, ϕ_{B} is the interface voltage barrier height, T is temperature, k_{B} is the Boltzmann's constant and β is a constant related to the potential barrier width. By plotting the $[\ln(\mathrm{I}) - V^{\frac{1}{2}}]$ curve, it is possible to calculate the potential barrier height. It will be obtained by intersection of voltage axis and extrapolated line of the plot (Fig. 2). The figure shows that $\ln \mathrm{I}$ increases almost linearly as a function of $V^{\frac{1}{2}}$, and that barrier height decreases almost linearly as Si content increases [6]. Calculated barrier heights are summarized in Table I. Potential barrier at grain boundaries results in nonlinear characteristics of the varistor. This potential barrier, called Schottky barrier, is formed due to trapping of electrons at grain boundaries. The Schottky barrier reduces the mobility of the carriers by increasing the effective resistivity of the grains. By decrease of the potential barrier height, charge carriers will be able to tunnel with low voltage, reducing breakdown voltage [23–25]. Therefore, the double Schottky barrier model is applicable for Si-polymer composite varistors.

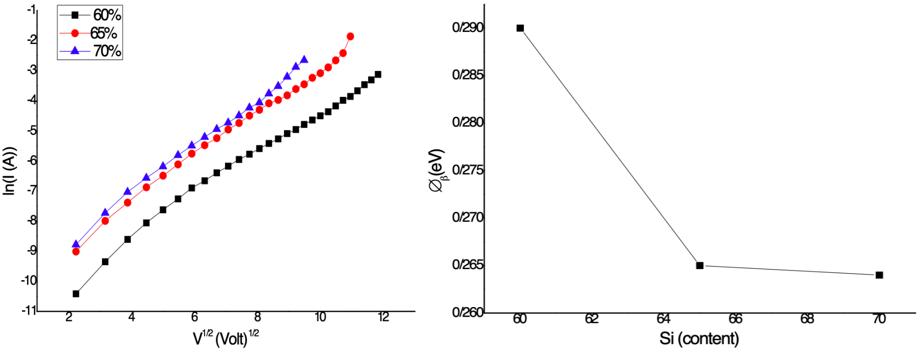

Fig. 2. Left: $\ln(\mathrm{I})$–$V^{\frac{1}{2}}$ plot for calculation of potential barrier height. Right: potential barrier height of samples for different Si content in mixture.

5. Conclusions

By increasing silicon content in the mixture, varistor breakdown voltage and potential barrier height of sample decreases, but leakage current and nonlinear coefficient of sample increases. According to properties of circuits, we can produce varistors with properties required to protect circuits from voltage fluctuations.

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