SWNTs effect on the charge collection during gamma irradiation at different voltages

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A new method of radiation detection using two charge collecting electrodes (CCEs) coated by single wall carbon nanotubes (SWNTs) is being introduced. In this study the charge collection behaviour is considered as a function of voltage applied to the two electrodes. The ^{60}Co gamma radiation is used as ionizing radiation source. The collected charge in the as-prepared SWNT detectors is much more in comparison with the standard parallel plate ionization chamber (Roos chamber) at the same applied potential. An ion collection efficiency of higher than 0.99 is obtained at about 5 Volts.

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1. Introduction

Carbon nanotubes (CNTs) due to their excellent mechanical (i.e., Young's modulus 10^3 GPa), chemical and physical properties [1-3] have been considered as new materials nowadays. It is believed that the single walled tubes are the most conductive form of carbon fibre ever, with resistivity probably an order of magnitude lower than their multi-walled counterparts [4]. SWNTs present better electrical properties than multiwall carbon nanotubes (MWNTs) [4]. SWNTs with a length of 1μm and a radius of about 1 nm which generate a very high electric field at relatively low voltage could be a suitable candidate for fabrication of a miniaturised gas ionization sensor and ionization chamber. Some attempts have been made to use CNTs in radiation detectors [5-8]. The results were far from the predicted requirement, maybe because of the device structure or the existence of impurities such as catalyst within the CNTs, as reported by the authors but the miniaturised gas ionization sensor showed little sensitivity to temperature and humidity [9].

When gamma rays enter in the air, produce ion pairs. The negative ions drift to anodes. In the strong electric field in the vicinity of the SWNTs on the electrodes surface, a number of ion pairs are produced in avalanche process. [10]

Usually, the best efficiency of charge collecting occurs at high voltages between 200 – 400V in common materials such as graphite. In this work, following our previous work [8] we were interested to use purified SWNTs as the charge collecting electrodes (CCEs). The CCEs were made of poly-methylmethacrylate (PMMA) substrate as sensing elements coated by purified SWNTs. Effect of different voltages on charge collecting of constructed electrodes for gamma radiation have been investigated.

2. Materials and methods

PMMA materials were used as SWNT substrates for fabricating two parallel electrodes. The electrodes consist of a PMMA rings of 43 mm external diameter, 28 mm internal diameter and of 8 mm thickness. The purchased SWNT powder (Ionic Liquids Technologies Co.) was characterized with purity higher than 95%, 2-5 nm diameter and 2-5 μm length. Two milligrams of the SWNTs were pressed using a hydraulic press (Beckman 00-25 Glenrothes, Fife, Scotland) and a clean stainless steel mold under 8,000 kg pressure. The pressing of the SWNT powder was performed on one side of each two PMMA circular plates with 28 mm diameter and 1 mm thickness already cut and machined to be readily mounted on the PMMA ring. The thickness of the pressed SWNTs was estimated to 100 μm by an optical microscope evaluation. The distance between the two plates used as electrodes has been fixed at two millimetres. One of the disks on which the SWNTs were pressed, was divided into two concentric circles by removing the SWNTs (in circle shape) from the coated surface using a milling machine. The inner circle diameter is 16 mm and that of the outer circle is 26 mm. The connection of different parts of this device has been shown schematically in figure 1. The effective volume between the electrodes was calculated to be about 0.402 ml.

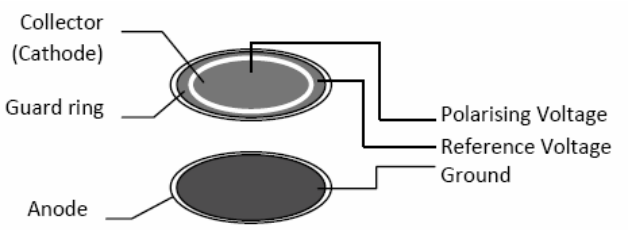

Fig. 1. Schematic of the designed charge collecting electrodes and its connections.

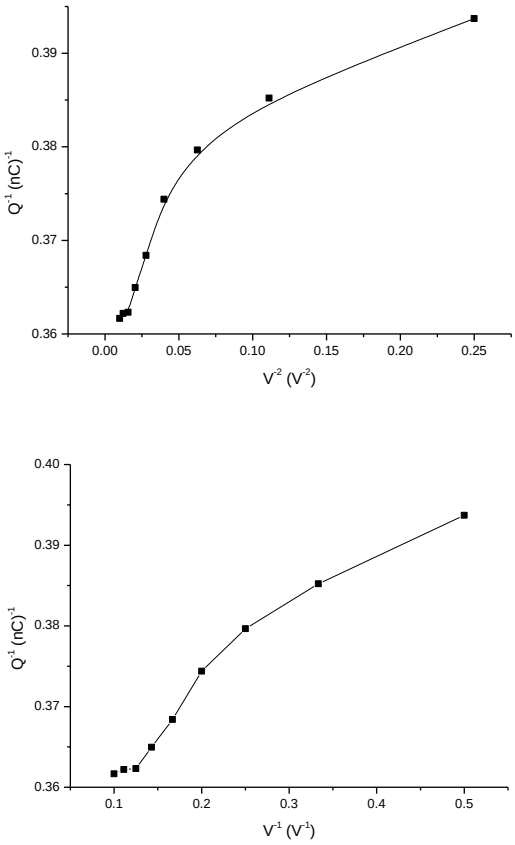

Fig. 2. Plot of a) 1/Q vs. 1/V^2 and b) 1/Q vs. 1/V (so-called Jaffe plot) at constant dose.

The collected charges were measured by reference level electrometer (SUN Nuclear Corporation), which was connected to the electrodes via a low noise triaxial cable and a TNC connector. The triaxial cable wires were connected to the electrodes with graphite paste. The voltages from 2 V to 400 V were applied to electrodes as external voltage by a power supply via the electrometer. The electrodes were settled in a rectangular slab of PMMA with 20 mm thickness at the same level (figure 1).

A Picker V9 ^{60}Co machine was used to irradiate the CCEs with 1.25 MeV ^{60}Co gamma rays at a maximum dose rate in water ($\dot{D}_{W_{max}}$) 0.17 Gy/min at source to electrodes distance 80 cm and field size 10×10 cm^2. A set of measurements were performed to evaluate and characterize the prototype chamber as follows:

- Chamber leakage currents were tested as an indication of real currents induced by radiation.
- A stability test was carried out with a ^{60}Co field size of 10×10 cm^2, source to surface distance of 80 cm and depth=0.4 g cm^{-2} of PMMA.
- Charge collection as a function of applied voltage.
- Determination of ion collection efficiency

3. Results and discussion

The CCE leakage currents were tested as an indication of real currents induced by radiation. The measured leakage current was 1.8×10^{-14} A. The mean value of the CCE readings for 10 runs, with five consecutive readings in each run, has been performed to study the stability of measurement in the short term. The mean reading was 2.404 nC and standard deviation values in each run were, <±0.9%.

The ion collection efficiency, *f*, in a continuous radiation beam has been calculated using graphical method according to Boag's theory as follows:

$$f = \frac{Q}{Q_{sat}} \tag{1}$$

and

$$\frac{1}{Q} = \frac{1}{Q_{sat}} + \left(\frac{\lambda_g / Q_{sat}}{V^2} \right) \tag{2}$$

where Q and V are the charge reading and applied voltage respectively, Q_{sat} is the saturation value of Q and λ_g is constant

The plot of 1/*Q* versus 1/V^2 (equation 2) permits the calculation of the Q_{sat} by extrapolation, see figure 2a. The strong deviation of empirical curve from Boag's theory predicting linearity at high voltages indicates that the shape of the saturation curve does not correspond to a true saturation curve. It is worth knowing that extrapolation of the experimental curve to infinite voltage (1/V^2) does not in general correspond to the true saturation curve. One valuable tool for analysing the performance of the chamber is the use of the Jaffe plots in which 1/*Q* is plotted as a function of 1/*V* in pulsed beams as shown in Fig. 2b. According to this figure a pronounced curvature at the higher voltages is observed. The theoretical calculation of the total collection efficiency, *f*, by Böhm [11] based on the recombination process considers the ion loss due to the initial recombination and diffusion depending on 1/*V* and the ion loss due to volume recombination depending on 1/V^2. The deviation of the predicted curves in figure 2 from the linearity is probably due to the fact that other effects should be considered for the mentioned processes. Among the other effects cited in Ref. [12] the emission of electrons from the carbon nanotube tips can also be pointed out. The correction for the lack of charge collection due to ion recombination should be performed according to the TRS-277 [13] recommendation. The recombination correction factor is obtained from

$$k_s = a_o + a_1\left(\frac{Q_1}{Q_2}\right) + a_2\left(\frac{Q_1}{Q_2}\right)^2 \tag{3}$$

where the constants a_i are given in ref [14] for pulsed radiation and the Q_i are collected charges at the voltage V_i. The value of k_s is estimated to be 1.1 for V_1/V_2=5.

Fig. 3 shows the ion collection efficiency, *f*, for the CCEs as a function of applied voltage during which the ^{60}Co beam energy is 1.25 MeV with a maximum dose rate of 0.17 Gy/min. This figure shows that the ion collection efficiency of CCEs for the ^{60}Co gamma radiation is higher than 0.99 at the voltage about 5 V. This voltage is very low with respect to the voltage reported by Arbabi et al [8,15] and Ma et al [5], when MWNTs were used (about 300 V). This difference is due to the better conductivity of SWNTs in comparison with MWNTs. When low voltages are applied to the SWNT electrodes, local high intensity electric field created on SWNT tips can provide enough electrical fields in medium for collecting charges [16]. The electron mobility in MWNTs is perturbed by the interaction with the potential created by different carbon walls and also side-wall defects. These results permit to envisage the fabrication of this type of the radiation sensor which works at low voltage leading an increase in their life time due to the lower energy of impacted ions on the detection surface.

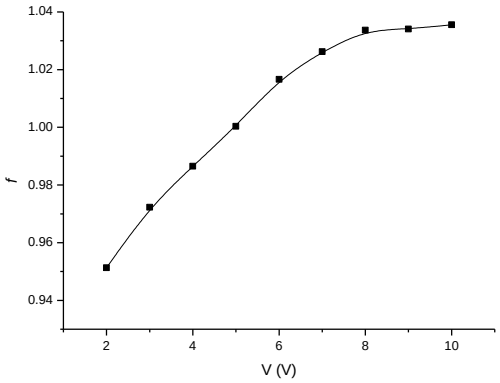

Fig. 3. Ion collection efficiency, f, of chambers vs. applied voltage for ^{60}Co radiation.

4. Conclusion

According to the obtained results this study represents that the SWNTs can be used as materials for covering the electrode surfaces in parallel plate radiation sensor. Having an ion collection efficiency of 0.99 at 5 V bias voltages, indicating a better conductivity of SWNTs, in comparison with MWNTs results, in the enhancement of the sensor life time.

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