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Alpha radiation induced space charge stability effects in semi-insulating silicon carbide semiconductors compared to diamond[☆]

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ABSTRACT

Although the use of semi-insulating silicon carbide material for radiation detection purposes has been previously demonstrated, its use in practical applications has been inhibited by space charge stability issues caused by defect concentrations within the material, the so called *polarisation effect*, by which the count rate and resultant spectrum changes with irradiation time.

This is a result of the charge carriers generated during irradiation filling deep level defects within the material, causing space charge buildup and de-activating that trap level until the trapped charge is re-emitted. Consequently, the time dependence of the polarisation effect has been determined by a combination of parameters that can be influenced during operation, namely the incident radiation intensity, ambient light, temperature and bias. The material properties have also been considered through the use of materials with different defect capture cross sections, concentrations and energy level.

A thorough characterisation of the alpha irradiation induced polarisation phenomenon in semi-insulating silicon carbide has been conducted to demonstrate that stable operation detectors are in fact possible with this material. The effects were compared to single crystal diamond and polycrystalline diamond, which are known to exhibit similar polarisation issues.

The polarisation rate as an effect of incident flux, bias and temperature was determined, with the depolarisation rate as a function of ambient light and bias also demonstrated. Consequently it has been shown that stable operation can be maintained for detectors made from semi-insulating SiC material of active thickness 350 μm at incident alpha radiation fluxes of < 0.7 alphas per second per mm^2 with high operating biases ($> \pm 400$ V). Furthermore, polarisation can be suitably *managed* or reduced through the use of light illumination and elevated temperatures (373 K).

1. Introduction

The use of silicon carbide (SiC) semiconductor material has been on the increase since the 1990's following a drive for electronics which could withstand high temperatures and radiation doses. As such high quality, low defect material is now commercially available for applications such as high-voltage electronics, ultra-violet photodiodes and light emitting diodes.

In addition to this, a lot of work has been conducted to investigate the performance of this material in detecting radiation [1–5]. This work has predominantly been conducted on thin epitaxial detectors, but work has also demonstrated that semi-insulating SiC (SiC-SI) materials have favourable particle and neutron detection properties [1,6-9] providing a potentially thicker and more cost effective detection alternative.

However, at the time of writing most semi-insulating SiC still suffers from relatively low charge collection efficiencies ($<$ 50%) [9,10] and issues with stability, namely the polarisation effect by which the count rate and resultant spectrum changes with irradiation time [6,7,9]. These issues are primarily a result of high defect concentrations within the material.

A study has been conducted to fully characterise the polarisation effect within semi-insulating SiC radiation detectors and demonstrate methods to manage it. These management methods allow for the stable use of semi-insulating SiC material in practical radiation detection applications. As a benchmark, similar studies were carried out on single crystal diamond (D-SC) and polycrystalline diamond (D-PC), both of which have well documented polarisation phenomena for radiation detection applications [11–14].

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2. Theory

The so called *polarisation effect* in semiconductor detectors made from wide band gap material is a phenomenon by which the spectrum and/or count rate varies and typically reduces during the irradiation [15]. It is generally accepted that polarisation occurs when trapped charge carriers remain immobilised for relatively long periods of time, such that the rate of charge trapping is greater than the rate of detrapping [15], although it is worth mentioning that polarisation occurs in thallium bromide (TlBr) semiconductor detectors due to the physical movement of ions in the material when a bias is applied [16,17].

Charge carrier traps are a result of growth defects or impurities introduced into the material during growth, fabrication and/or operation. They act to capture created charge (electrons or holes) and immobilise them for a period of time or even neutralise them completely. Lost or delayed charge carriers result in a reduced signal pulse due to incomplete charge induction on the electrodes during the integration time of the system. Furthermore, the emissions of detrapped electrons and holes outside of the integration time of their associated event, may also add to the noise of the system [18].

A further consequence of trapped charge carriers is the creation of an ionised centre with a localised space charge region around it (Fig. 1). While the rate of trapping is greater than the rate of detrapping, there will be a resulting buildup of trapped charge carriers and the space charge region will change throughout the material.

For *localised* charge carrier generation, by which the charge creation and subsequent trapping predominantly occurs within a localised region (e.g. alpha particle irradiation, where charge carrier generation is concentrated near the irradiated surface due to the short range of alpha particles in the material), the space charge build up can create a localised reduction of the electric field seen by the carriers, thus reducing the local charge drift velocity, leading to an increased probability of trapping and hence reduced resultant pulse height (Fig. 1).

Uniform trapping occurs when charge carrier creation occurs throughout the material (e.g. gamma ray irradiation) resulting in a diluted build-up of space charge throughout the detector. Subsequently, subject to the number of traps present, stable operation can be achieved following an initial period of variation as all the traps are filled. However, a stable detector may not necessarily yield optimum counting efficiencies or resolutions and may also require increased applied electric field to compensate for the space charge build-up.

The severity of these effects is subject to the type, concentration and location of the traps, as well as the primary charge carrier. These traps exist at specific energy levels within the band gap region, the energy of which the trapped charge carriers must subsequently overcome in order to once again freely move through the material. As given by Lutz [18], the average emission time of a trapped charged carrier, or the *detrapping time*, (t_t) is dependent upon both the temperature (T) and the energetic location of the trap within a specific material's bandage,

$$t_t = \frac{1}{\sigma_c \cdot v_{th} \cdot n_i \cdot e^{\frac{E_i - E_t}{kT}}} \tag{1}$$

where σ_c is the capture cross-section, v_{th} is the thermal velocity of the charge carriers, n_i is the intrinsic carrier concentration and k is the Boltzmann constant. E_i and E_t are the intrinsic (or Fermi) level and defect energy level respectively.

Therefore shallow traps (typically < 0.4 eV) are quite close to the allowed energy bands and charge carriers tend to easily migrate between the energy levels quickly. However, deep traps tend to exist near the mid-point of the forbidden region and as such the amount of energy required for the trapped carriers to migrate back to the allowed energy band may be large.

A direct consequence of wide band gap material detectors is that the deep level trap energy value can be relatively large (typically > 0.7 eV) and subsequently thermal excitation of the trapped charge carrier is unlikely, leading to a long detrapping time. For example, in diamond traps within the band gap have been identified at 1.23 eV [19] and 1.86 eV [20] leading to an estimated room temperature detrapping time of ≈76 days and $\approx 2 \times 10^9$ years respectively, where as the main defects in SiC are around 0.63 eV and 0.97 eV [21] and can last several hours, as shown in Table 1.

A further consequence of wide band gap material is that even the shallow traps can result in long periods of trapping relative to the integration time of the system (as shown in Table 1) resulting in transient stability issues. As such trap induced polarisation is quite prevalent in wide band gap materials such as diamond (D) [22], SiC [23], CZT [24] (Cadmium Zinc Teluride) and CdTe [25] (Cadmium Teluride).

An indication of the concentration of traps within a material can be gained from the mobility lifetime ($\mu\tau$) product for each respective charge carrier, which is a combination of the charge carrier drift mobility (μ) within the material and the mean carrier lifetime (τ), that being the average period of time the created carriers exist and hence can travel before they are trapped, assuming free charge carrier recombination is negligible. This characteristic value defines the mean drift length (λ) of the charge carriers through a material for a given electric field (E) [15]

$$\lambda_e = \mu_e \tau_e E \tag{2}$$

$$\lambda_h = \mu_h \tau_h E \tag{3}$$

such that λ needs to be greater than the sensitive region of the detector so that the charge carriers can travel the width of the detector and maximise the contribution to the signal output. Therefore when $\mu\tau$ is small it is more likely that charge carriers will be trapped.

Clearly one way to address polarisation effects within the material is to improve the growth, processing and fabrication techniques of the detectors in order to minimise the concentration of defects and impurities, which is by no means a simple task. However, there are several demonstrated methods to manage the polarisation in semiconductor detectors in order to make them suitable for practical detection

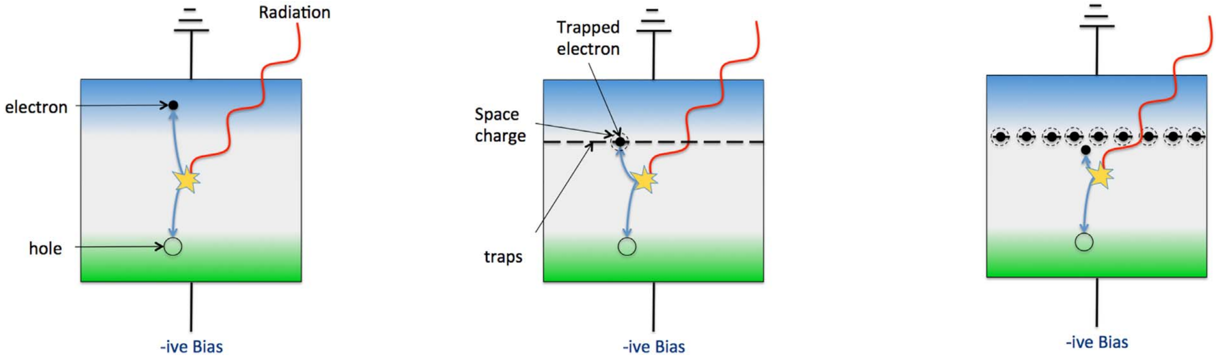

Fig. 1. Concept of signal creation and localised polarisation in semiconductors.