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Experimental characterization of Silicon Drift Detector for X-ray spectrometry: Comparison with theoretical estimation

M. Shanmugam [a,*], Y.B. Acharya [a], S.V. Vadawale [a], H.S. Mazumdar [b]

[a] Physical Research Laboratory, Ahmedabad, Gujarat, India
[b] Dharmsinh Desai University, Nadiad, Gujarat, India

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ABSTRACT

Reverse saturation current and the ideality factor (η) are the main parameters that affect the performance of a radiation semiconductor detector in different space environmental conditions. We have measured both of these parameters for the Silicon Drift Detector (SDD) used as a radiation detector in the X-ray spectrometry for space borne applications having the active area of 40 mm^2 and 109 mm^2 with 450 μm thick silicon. The measured reverse saturation current is compared with the theoretically estimated values using diode equation for various detector operating temperatures and shown that there is a strong dependence of reverse saturation current with ideality factor. Subsequently, using the reverse saturation current ratio method, the slope ratio for small area to the large area SDD is derived and compared with the theoretical slope ratio obtained using the measured ideality factor. It is shown that the slope ratios closely match with the diode equation of the form which has the ideality factor in both the product and exponential terms for these SDDs. The measured spectral energy resolution is ~150 eV at 5.9 keV for both small and large area SDDs when operated at −40 °C and −65 °C respectively. The noise performance of the spectrometer is also measured in terms of Equivalent Noise Charge (ENC) for various detector operating temperatures and shown that the value of ENC in rms noise electrons is minimal for the pulse shaping time of 3.3 μs.

1. Introduction

The electrical characteristics of a semiconductor radiation detector degrade under the harsh space environmental conditions and this is the most important limiting factor for their application. The electrical processes in the semiconductor device depend on the temperature and the radiation environments in which they are used. Any change in the electrical characteristics such as reverse saturation current and the ideality factor will have adverse effects on its use for the space application. It is therefore important to study the change in the electrical characteristics of semiconductor junction parameters, which could reveal possible changes in the output characteristics of the device. In this study, we measured the reverse saturation current and the ideality factor (η) for Silicon Drift Detector (SDD) [1–4] with different active areas. The device level reverse saturation current gives the direct correlation with spectral performance and it varies with the temperature and the radiation dose encountered by the detector. The ideality factor is a direct indicator of the output parameter dependence on the electrical transport properties of a P-N junction [5]. Generally, the reverse saturation current and the ideality factor are measured using the forward *I–V* characteristics of the P-N junction devices such as Light Emitting Diode (LED), silicon PIN diode, Schottky diode and solar cell [6–8]. Since the radiation detectors are operated in the reverse bias mode for detecting the photons of desired energy, we used the novel approach of measuring reverse saturation current in the SDD and its ideality factor. SDD is a state-of-art new technology semiconductor detector which is widely used in the laboratory [9–11] as well as space experiments [12–14] for detecting photons in the low energy X-ray region. SDD is functionally similar to a Si-PIN photodiode but has different electrode structure resulting in very low detector capacitance and therefore, under similar operating conditions, the SDD gives better energy resolution than a Si-PIN diode of same size. SDD is a type of PIN junction diode consisting of n$^+$ point anode surrounded by multiple p$^+$ rings, n$^-$ bulk intrinsic layer and planer p$^+$ cathode [15]. SDDs with such electrodes are commercially available for various applications [16,17] and research still continues for further improvements [18–20].

The reverse saturation current in the SDD is measured using a simple novel technique which involves counting the reset

* Corresponding author.
E-mail address: shansm@prl.res.in (M. Shanmugam).

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frequency of the reset type charge sensitive pre-amplifier which is used for the charge readout. The ideality factor is derived by measuring the slope of natural logarithm of reverse saturation current against inverse of temperature plot. The exact value of reverse saturation current cannot be computed theoretically due to non availability of some device parameters and hence the ratio of reverse saturation current at two different temperatures are analytically verified with experimental measurements. Theoretical background and the experimental measurements are described in subsequent sections. The energy resolution and the noise performance for both small and large area SDD based spectrometer are measured and the results are discussed.

2. Theoretical background

The forward current of the P-N junction diode depends on the term $\exp(qV/\eta kT)$ [21]. The diode equation contains two temperature dependant terms; one is exponential term ($qV/\eta kT$) and another is reverse saturation current (I_o). The forward current–voltage relation is given by the equation

$$I = I_o\left[\exp\left(\frac{qV}{\eta kT}\right) - 1\right] \tag{1}$$

where I is the forward current, I_o is the reverse saturation current, q is the electronic charge, V is the junction voltage, k is the Boltzmann's constant, η is the ideality factor and T is the temperature in K.

Measuring reverse saturation current gives vital information on the contribution of the current noise by the SDD in the overall spectrometer system performance. The device level reverse saturation current in the SDD detector largely depends on the local defects [22], leakages due to Si–SiO_2 interface trap [23] and detector edge effects [24]. The reverse saturation current (I_o) is directly proportional to temperature and exponentially related to ($-qE_g/\eta kT$) [25]. The reverse saturation current is given by Eq. (2)

$$I_o = BT^{3/\eta}\exp\left[\frac{-qE_g}{\eta kT}\right] \tag{2}$$

where B is the constant, E_g is the band gap energy which varies with temperature [26] and hence cannot be considered as constant. Researchers have also used $BT^{3/2}$ [27], BT^2 [28] and $BT^{5/2}$ [21] terms instead of $BT^{3/\eta}$ for estimating the reverse saturation current in various P-N junction diodes. Substituting the values of k and q in Eq. (2), we obtain

$$I_o = BT^{3/\eta}\exp\left[-\frac{1000}{T}\times 11.59\times\frac{E_g}{\eta}\right] \tag{3}$$

Using Eq. (3), the value of ideality factor (η) can be derived by measuring the reverse saturation current for various device operating temperatures and plotting natural logarithm of I_o against $1000/T$ and equating the slope of the fitted line to $(11.59\times(E_g/\eta))$. The temperature dependence of band gap E_g is derived using Varshni equation [26] for estimating the reverse saturation current, which is given by

$$E_g(T) = E_g(0) - \frac{\alpha T^2}{(T+B)} \tag{4}$$

where E_g (T) is the band gap energy at temperature T, E_g (0) = 1.17 eV, the band gap at temperature 0 K, $\alpha = 4.73\times 10^{-4}$ eV/K and β = 636 K for silicon semiconductor [29].

The value of B which includes junction area is generally not known and also not specified by the manufacturer. By dividing reverse saturation current at one temperature with its value at another temperature will eliminate the B term and the ratio equation is given by

$$\frac{I_r(T_2)}{I_r(T_1)} = \left(\frac{T_2}{T_1}\right)^{3/\eta}\exp\left[-\frac{E_g}{\eta K}\left(\frac{T_1-T_2}{T_1T_2}\right)\right] \tag{5}$$

where $I_r(T_1)$ is the reverse saturation at temperature T_1 and $I_r(T_2)$ is the reverse saturation current at temperature T_2. Rewriting Eq. (5) in linear form and plotting $\ln\left[\frac{(I_r(T_2)/I_r(T_1))}{(T_2/T_1)^{3/\eta}}\right]$ against $\left(\frac{T_1-T_2}{T_1T_2}\right)$ gives slope which is independent of the parameter B.

$$\ln\left[\frac{(I_r(T_2)/I_r(T_1))}{(T_2/T_1)^{3/\eta}}\right] = -\frac{E_g}{\eta K}\left(\frac{T_1-T_2}{T_1T_2}\right) \tag{6}$$

The theoretical slope $E_g/\eta K$ derived from Eq. (6) is compared with the experimentally measured slope values for small and large area SDDs. It is observed that the dependence of the slope on ideality factor varies from detector to detector of same area as well as between small and large area SDDs. The measured slope ratio between the small and large area SDDs are compared with the theoretically estimated slope ratio and shown that the change in the reverse saturation current in SDDs with temperature closely follows the diode equation of the form $BT^{3/\eta}$. The experimental design, experimental setup and the measurement results are presented in the subsequent sections.

3. Experimental design and setup

3.1. Experimental design

The experimental design consist of a SDD detector interfaced with a hybrid Charge Sensitive Pre-Amplifier (CSPA) for charge to voltage conversion followed by CR-$(RC)^2$ type hybrid shaping amplifier with base line restorer. These hybrids are designed to improve the signal/noise ratio in the spectroscopic measurements. The design also consists of a voltage multiplier based High Voltage (HV) generation circuit which provides necessary HV biases to the SDD detector for charge collection. The spectral data is collected using AMPTEK make Multi Channel Analyzer (MCA).

3.1.1. Silicon Drift Detector

SDDs used in the measurement are having the total silicon area of 40 mm^2 (small area) and 109 mm^2 (large area) with 450 μm thick silicon. These SDDs are available in the form of modules having SDD chip mounted on a Peltier cooler and a temperature monitor (thermistor/diode). SDD module also consists of JFET, f/b capacitor (charge integrating feedback capacitor) and a reset diode interfaced with SDD chip and these modules are procured from KETEK, GmbH. The small area SDDs are provided with thermistor and the large area SDDs are provided with temperature diode as temperature sensing device [30]. These SDDs provide good spectroscopic performance when cooled to −40 °C and −65 °C for small and large area detectors respectively. At these temperatures, the current noise contribution by the SDD to the spectroscopic performance is negligible and solely depends on the spectrometer system noise. The required SDD operating temperature is achieved by applying suitable power to the inbuilt Peltier element.

3.1.2. Charge sensitive pre-amplifier and shaping amplifier

Charge Sensitive Pre-Amplifier (CSPA) is widely used to convert the charge carriers induced in the detector active volume to voltage pulse in the spectroscopic applications by applying suitable high voltage bias to the detector electrodes. There are two types of CSPAs, one is "RC feedback type" and another is "reset type". The reset type CSPA directly integrates the reverse saturation current from the SDD into the charge integrating f/b capacitor in the absence of any photon interacting with the detector. The output of reset type CSPA is in the form of ramp signal consisting of