Study of the Proton Irradiation Effects in n-FZ DSSD for the Si Tracker at R3B Experiment

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Abstract. The R3B collaboration aims to assemble an experimental setup with high resolution and efficiency to perform kinematically complete measurements of reactions with high-energy RIBs (radioactive ion beams). In the R3B experimental setup, the silicon tracker is positioned closest to the target region and can provide high-resolution position measurements of light-charged particles like protons. The three layers of the silicon tracker are constructed with a total of 30 Si double-sided strip detectors (DSSD). In this paper, as an option of 23 MeV proton irradiated n-type Float-Zone (Fz) Si double-sided strip detector (DSSD) have been considered, and by taking the two-trapproton irradiation damage model, the bulk damage effect and the macroscopic performance of the Si double-sided strip detector (DSSD) have been discussed. The detector is irradiated with three values of proton fluences (equivalent to 1 Mev neutron fluence): 2×10^{14}, 5×10^{14} and 8×10^{14} cm^{-2}. By using the Shockley-Read-Hall recombination (SRH) formulation, the full depletion voltage and leakage current have been measured as a function of the irradiation dose, finally the device and process parameters and specifications for the Si double-sided strip detector (DSSD) used in the R3B silicon tracker experiment have been proposed.

Keywords: Double sided strip detector, Float zone, Full depletion voltage, Leakage current, Bulk damage.

1. Introduction

FAIR (Facility for Antiproton and Ion Research) is an accelerator facility at GSI, Darmstadt, Germany [1-2]. FAIR can deliver ion beams of all elements up to Uranium. At FAIR we get high energy and high intensity of primary ion beams because of the addition of heavy-ion synchrotron (SIS 100/300) with previous GSI facility. After exiting from SIS 100/300 synchrotron, the primary ion beams will incident on a thin isotopic production target (positioned after the double ring synchrotron) can generate secondary rare isotopic ion beams up to 1.5AGeV [3], which will be delivered to R3B (Reactions with Radioactive Relativistic Beams) experimental setup at FAIR. In R3B, the high-energy rare isotopic beams /radioactive ion beams (RIBs) incident on a fixed target and will emit different particles like protons, neutrons, gamma rays, heavy ions, etc [4-6]. In the R3B experimental setup, the silicon tracker is positioned closest to the target region within a vacuum vessel [7]. When the Ion beams will pass through the three layers of the silicon tracker, it can provide high-resolution position measurement of light charged particles like protons [1]. The three layers of the silicon tracker are constructed with a total of 30 Si double-sided strip detectors (DSSD), 6 Si DSSD are required for the inner layer and 12 Si DSSD are required for each outer layer of the Si tracker as shown in figure 1 [8-12].
The choice of the material for the DSSD is n-Fz (float-zone) silicon for the Si tracker[12]. The electrical performances of the detectors were needed to be tested for the designing, development, and optimization of the detectors for the high energy physics (HEP) experiments[13-14]. Within NUSTAR Collaboration for R3B silicon tracker, the n-FzDSSD is exposed by proton irradiation[1]. The macroscopic and microscopic performance of the detector can be measured using current-voltage (I/V), capacitance-voltage (C/V), Thermally Stimulated Current (TSC), Deep Level Transient Spectroscopy (DLTS) and Transient Current Technique (TCT). The induced radiation causes some damages, which overall affects the electrical performance of the detector. In order to study the radiation damages impact on the irradiated Si detectors several research groups have proposed the n-Fz proton irradiation damage models [12]. In this paper, by using SRH (Shockley Read-Hall) calculations the bulk damage effect and the macroscopic performance of proton irradiated n-FzSi DSSD have been discussed for three different values of proton fluences. For the SRH calculations, the experimentally verified two trap n-Fz proton radiation damage model[12] have been considered; this model is useful to explain the macroscopic performance of the n-Fz Si DSSD in the low irradiation environment. Finally design idea, process and device parameter for DC coupled Si DSSD and AC coupled Si DSSD have been proposed.

2. Double-sided silicon strip detector for R3B Silicon tracker

The Si double-sided strip detector is constructed by segmenting the electrodes on both sides of the bulk. Both sided strips are angled orthogonally with each other (see figure 2). A Si DSSD allows both types of charge carriers to be collected at the segmented electrode [9] and can provide two-dimensional position measurements of the incident particle. After the incidence of radiation electron-hole pair will generate in the active volume of the detector and will move towards the segmented electrodes under the influence of an external electric field and these charges can be collected and processed by the readout electronics [9].
Figure 2. Cross-sectional view of a 3-D Si double-sided strip detector [10].

As we know from the basic principle of the detector, the incident radiation ionizes the charge particle in bulk as well as the silicon oxide layer of the detector. However, for the carriers in the insulating layer, some of them cannot escape from this layer and these remaining charges forms the fixed oxide charges. These positive charges attract electrons and form an accumulation layer of negative charges in the n-type bulk silicon. This electron accumulation layer can cause the shortening of the adjacent n strips. Hence, a medium doped p-type region was introduced between two n strips to disrupt the electron accumulation layer to isolate the neighbouring strips [9]. This technique is called p-spray. An alternative technique to p-spray that is used for isolation is p-stop. A p-stop uses a highly doped p+ implant positioned between adjacent n+ strips to achieve strip isolation.

2.1. Bulk damage model

The incident radiation introduces some damage into the detector which results in degradation of detector performance. Bulk damage was incorporated by introducing some trap levels inside the forbidden energy levels having energy $E_t$ [11]. Trap levels are characterized by some parameters like introduction rate, energy and capture cross-section. By the introduction of this trap level some macroscopic properties of the detector change like full depletion voltage will increase, the leakage current will increase and the charge collection efficiency will decrease [11].

Here in this paper, as an option of 23MeV proton irradiated n-type float-zone Si double-sided strip detector have been considered. Typical linear dimensions are: $556 \times 29460 \mu m \times 200/250/300 \mu m$. The bulk damage effect induced by incident radiation as a function of three proton fluences: $2 \times 10^{14}, 5 \times 10^{14}$, and $8 \times 10^{14} \text{cm}^2$ (equivalent to 1MeV neutron fluence) are discussed here. Hence, an approximate bulk damage model incorporating just two trap levels, one acceptor and one donor trap, is devised for proton irradiated detectors are shown in table 1 [12]. By using SRH calculations the resulting bulk damage model can account for various macroscopic measured properties of proton irradiated silicon detectors i.e, increase of leakage current, increase of full depletion voltage and the decrease of charge collection efficiency with an increase of proton fluences.
Table 1. Two deep trap proton irradiation damage model for n-Fz Si DSSD. Providing energy level distance from the conduction band edge $E_c$ and valence band edge $E_v$. The fluence $F$ is given in $n_{eq}$ cm$^{-2}$ [12].

| Type of defect | Level (eV) | $\sigma_e$ (cm$^2$) | $\sigma_h$ (cm$^2$) | Concentration (cm$^{-3}$) |
|---------------|-----------|---------------------|---------------------|---------------------------|
| Deep acceptor | $E_c-0.525$ | $1.0 \times 10^{-14}$ | $1.0 \times 10^{-14}$ | $1.189 \times F + 0.65 \times 10^{14}$ cm$^{-3}$ |
| Deep donor    | $E_v+0.48$ | $1.0 \times 10^{-14}$ | $1.0 \times 10^{-14}$ | $5.89 \times F - 3.96 \times 10^{14}$ cm$^{-3}$ |

This is an experimentally verified “two trap proton irradiation damage model” for n-Fz Si DSSD consisting one acceptor trap and one donor trap defect. The model is valid only for fluences higher than $10^{14}$ $n_{eq}$ cm$^{-2}$ [12].

2.2. Detector model and Shockley-Read-Hall theoretical calculations

In this section the proposed device model, specifications and the device and process parameters have been mentioned and by using the two-trap proton irradiation damage model the theoretical SRH calculations have been explained.

The size of Si DSSD that we have used in the calculations is $55610 \mu m \times 29460 \mu m \times 200/250/300 \mu m$ (see figure 3) and the device and process parameters of the detector have been mentioned in table 2 and specifications have been mentioned in table 3. The Si DSSD that we are proposing is a DC-coupled and AC coupled sensor that consists of an n-stripe, an n bulk, and a p-stripe. Though the p-strips on the backside are placed orthogonal to the n-stripe on the frontside, the direction of the readout strips is the same. This requires a double metal structure. The first metal and the second metal are electrically connected by a via-hole process [9]. The p-strips and the n bulk region just act as a p-n junction diode. The diode is operated in reverse bias condition. Figure 3(a) describes the two-dimensional view of a DC-coupled n-FzSi DSSD irradiated with proton irradiation and figure 3(b) describes the two-dimensional view of an AC coupled n-FzSi DSSD irradiated with proton irradiation. In AC coupled Si DSSD for electrical insulation, a very thick oxidation layer is deposited between two metals, and the electrical connection between the two metals is established by the via-hole process. There has a nitride layer after the oxide layer to prevent physical damages [9].

![Figure 3](image-url)

**Figure 3.** (a) Schematic of a two-dimensional view of single metal layer DC-coupled Si DSSD, (b) Schematic of a two-dimensional view of double metal layer AC-coupled Si DSSD.
Table 2. Device and process parameters of n-Fz Si DSSD for proton irradiation.

| Sl. No | Physical parameters          | Values                                      |
|--------|-----------------------------|--------------------------------------------|
| 1      | Doping concentration (N_D)  | 1 × 10^{12}, 3 × 10^{12}, 5 × 10^{12} cm^{-3} |
| 2      | Device depth (W_N)          | 200μm, 250μm, 300μm                        |
| 3      | Junction depth (X_J)        | 2.5μm                                      |
| 4      | Width of the metal over hang (W_MO) | 5μm                                   |
| 5      | Thickness of the Al layer   | 1μm or 1.5μm                               |
| 6      | Thickness of the oxide layer| 300 nm                                     |
| 7      | Thickness of the nitride layer| 50 nm                                   |
| 8      | p-spray                     | 10^{12}μm – 10^{15}μm                      |

Table 3. Specifications of n-Fz Si DSSD for proton irradiation.

| Sl. No. | Specifications          | Values            |
|---------|-------------------------|-------------------|
| 1       | Leakage current(I_L) per strip | <10 nA          |
| 2       | Interstrip capacitance   | <1.2 pF          |
| 3       | Breakdown voltage        | <1000 V          |

By using the Shockley Read Hall recombination formula the effective doping concentration(N_{eff})/full depletion voltage(V_{FD}) and the leakage current(I_L) can easily be calculated;

\[ N_{eff} = N_D + \sum n_T^{\text{donor}} - \sum n_T^{\text{acceptor}} \]  \hspace{1cm} (1)

\[ n_T = \frac{n_T^{e_n,p}}{e_n + e_p} \]  \hspace{1cm} (2)

\[ e_p = C_p N_V \exp \left( \frac{-e_p - E_F}{kT} \right) \]

\[ e_n = C_V N_C \exp \left( \frac{e_n - E_F}{kT} \right) \]

Here, N_D is the doping concentration, n_T is the steady state occupancy of defect level, N_T is the defect concentration, e_n,p is the emission rate of electron or holes, C_n,p is the capture coefficient of electron or holes, V_th is the thermal velocity.

After calculating the effective doping concentration, the V_{FD} can be calculated by using the formula;

\[ V_{FD} = \frac{W_N^2 N_D q}{2 \varepsilon_{Si}} \]  \hspace{1cm} (3)

Here, W_N is the thickness of the detector and \( \varepsilon_{Si} \) is the dielectric constant of silicon.

By using Shockley Read Hall recombination formula the generation leakage current (I_L) can be calculated;

\[ I_L = q A d (\sum n_T^{\text{acceptor}} e_n + \sum n_T^{\text{donor}} e_p) = \frac{q n_i A W_N}{\tau_g} \]  \hspace{1cm} (4)

Here, I_L is generation leakage current, q is elementary charge, A is the area of the detector, d is the thickness of the detector, n_i is the intrinsic carrier concentration and \( \tau_g \) is the generation lifetime.

Current damage constant (\( \alpha \)) can be calculated by using the formula:

\[ \alpha = \frac{A}{\Phi_{eq} \times V} \]  \hspace{1cm} (5)

Here, \( \alpha \) is current-damage constant, \( \Phi_{eq} \) is equivalent fluence and V is the volume of the detector.
3. TCAD device simulation for Double-Sided Strip Detector
To study the radiation damage effect in the double-sided silicon strip detector TCAD (technology computer aided design) device modelling approach can be used. The microscopic model can be fed into the TCAD program to simulate the macroscopic performance in the irradiated detectors. The Cogenda (Visual TCAD)[13] or SilvacoATLAS device simulator tool can be used to optimize the electrical performance of the detector[14,15]. Atlas is a simulator tool that can perform DC, AC and transient analysis for semiconductor devices. This device takes a grid mesh made of discrete elements as an input structure and solves the Poisson’s equation, carrier continuity, drift-diffusion equation for electrons and holes at every grid point of the mesh to calculate physical quantities such as electric field distribution and carrier mobility inside the device and electrical properties such as current and capacitance. The physical models that are used in the simulation are: Shockley-Read-Hall recombination, concentration dependent mobility, Auger recombination accounting for high-level injection effects, band gap narrowing and field dependent mobility[16].

4. Results and discussions
In this section, we have analysed the macroscopic performance of the irradiated n-FzSi DSSD for the R3B Si tracker. The n-FzSi DSSD detector is irradiated with the proton fluences (equivalent to 1MeV neutron fluence): $2 \times 10^{14}, 5 \times 10^{14}$ and $8 \times 10^{14} \text{n}_{\text{eq}} \text{cm}^{-2}$. By using the Shockley-Read-Hall (SRH) model, the full depletion voltage and leakage current have been measured as a function of the irradiation dose for the different doping concentrations and device depths, finally the device and process parameters and specifications for the DC/AC Si DSSD used in the R3B silicon tracker experiment are proposed. The macroscopic results on $V_{\text{FD}}$ are shown in figure 4 for the different doping concentration in the irradiated n-FzSi DSSD.

In the irradiated detectors, it has been observed that the charge carriers (e/h) are trapped by the defects/deep-traps (Donor/Acceptor), leading to increase in the effective doping concentration, changing the electric field distribution and shifts the full depletion voltage. In figure 4, it has been shown that the full depletion voltage $V_{\text{FD}}$ increases with the increase of proton irradiation fluences for three sets of n-Fz Si DSSD detectors having device depth 200μm, 250μm and 300μm for the different doping concentrations of the n-Fz bulk of the Si DSSD (see figure 4). All the irradiation proton doses have been normalized to 1MeV neutron equivalent doses using the appropriate hardness factor.

The generation leakage current is not a major issue in many radiation damage detection systems even it increases the overall noise of the full detector system. In irradiated detector, the leakage current can be controlled using cooling.

The leakage current at full depletion voltage is directly proportional to the fluence and it will increase with the increase of device depth. From the figure 5, we can see that the generation leakage current increases with the proton irradiation fluences at 300 K. The lowest leakage current obtained in 200μm thin DSSD irradiated with $2 \times 10^{14} \text{ cm}^{-2}$. 
5. Conclusions

In the R3B experiment at GSI, Darmstadt, Germany, a low proton dose ($10^{14}$ cm$^{-2}$) single metal or double metal radiation hard (DC/AC coupled) Si DSSD requires for the Si Tracker. Here, we have...
used a two-deep trap proton irradiation damage model to analyse the macroscopic performance of the Si DSSD in the Si tracker. The detectors irradiated with sufficiently high doses with a safety margin of neutron equivalent fluences; $2 \times 10^{14}$, $5 \times 10^{14}$ and $8 \times 10^{14}$ cm$^{-2}$. The variation of full depletion voltage and leakage current of the irradiated n-FzSi DSSD as a function of proton fluences for the different bulk doping concentrations and device depths showed. We have used SRH recombination formulation for the full depletion voltage and leakage current calculation at 300K.

It shows that for 200μm AC coupled irradiated n-Fz double metal layer Si DSSD with a proton fluence $2 \times 10^{14}$ cm$^{-2}$ shows the low full depletion voltage of 970 V at a doping concentration of $5 \times 10^{12}$ cm$^{-3}$.

Finally, we have proposed the single metal layer DC coupled and double metal layer AC coupled Si DSSD design for the R3B Si tracker as a first option. The device, process parameters and specifications are shown for the proposed design. The TCAD device simulation using Silvaco ATLAS is underway to get the optimal design of DSSD for the Si tracker at R3B.

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