Simulations of electrical properties of cylindrical 3d-trench electrical si detectors under different radiation fluences and mip incident position

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Abstract. In this work, we investigate the dependence of charge collection on the MIP(minimum ionizing particle) incident position for cylindrical 3D-Trench electrode Si detectors being irradiated to various fluences. Simulation results are: (1) For non-irradiated detectors, detector charge collection does not depend on the MIP incident position, i.e. the charge collection is always a constant, there is no effect of trapping; (2) For irradiated detectors, detector charge collection depends on the MIP incident position; (3) As radiation fluence increases, detector charge collection decreases, regardless of MIP incident position. This is due to the fact that charge trapping by radiation induced defects also increases with radiation fluences, resulting in less charge collection.

1. Introduction
Semiconductor detectors are devices used for the detection of photons, charged particles, or other electric magnetic radiation [1]. It can transform radiation energy into electrical current or electrical voltage, with external readout electronics, a detector signal can be constructed to determine the property of the incident particle, such as its energy or position [2-4]. Silicon detectors, in particular, are the dominant member in semiconductor detector family due to it is abundance in nature \mature processing technology and excellent electrical properties near room temperature. Silicon detectors have been used widely in the large hadron collide (LHC) in CERN as inner and tracking detectors [5].

In the lasting years, proton radiation fluences have reached $1 \times 10^{16} \text{ n}_{eq}/\text{cm}^2$ in the LHC [6, 7]. This has caused serious radiation damage effect for Si detectors especially for inner detector properties. In particular, strong radiation can cause significant increase in charge trapping, resulting in the reduction in the detector charge collection efficiency [8].

It is therefore important to study the effect of radiation on the detector properties. In this work, we will carry out the research of the dependence of charge collection on the MIP incident position for cylindrical 3D-Trench electrode Si detectors being irradiated to various fluences [9].
2. Dependence of charge collection on MIP incident position

2.1. Non-irradiated detectors

Shown in Figure (1) is the simulation of the charge collection for a non-irradiated cylindrical 3D-Trench electron detector [10]. We used a TCAD simulation to SILVACO [11] which includes physics models of generation-recombination, carry transport, scattering and ionization, tunneling, and carrier statistics. With an applied bias voltage of 100V. As shown in Figure 1 a), the radius of the collection column is \( r_0 = 5\mu m \), and the radius of the trench electrode is \( R = 40\mu m \). The MIP incident position is at \( r_1 \).

At a bias voltage of 100V, the total collected charge (combined contribution of electrons and holes), is 21000 electrons. Since the full depletion voltage for our cylindrical 3D-Trench electron detector is only a few volts, the total collected charge will be the same (21000), as long as the bias voltage is more than a few volts, larger than the full depletion voltage for non-irradiated detectors [12].

Collected charge in time interval \( dt \) by drifting electrons holes \( (dQ_{e,h}) \) generated by MIP are [13]:

\[
dQ_{e,h} = q \cdot v_{e,h}(r) \cdot E_w(r) \cdot dt
\]

Where \( q \) is the charge generate by MIP in the detector for electrons or holes, \( v_{e,h}(r) \) are the drift velocities at radius point \( r \) for electrons and holes, respectively, and \( E_w(r) \) is the weighting field at radius point \( r \).

In time interval \( dt \) carries drift distance \( dr \) are:

\[
dr = v_{e,h}(r) \cdot dt
\]

**Figure 1.** Illustration of the structure of 3D-Trench electron detector and the MIP incident position \( (r_1) \) (a); and the simulated charge collection as a function of the MIP incident position (b).

Eq (1) can be therefore rewritten as the following

\[
dQ_{e,h} = q \cdot v_{e,h}(r) \cdot E_w(r) \cdot \frac{dr}{v_{e,h}(r)} = q \cdot E_w(r) \cdot dr
\]

Under the electric field \( E (r) \) in the detector, electrons drift from the MIP incident point \( r_1 \) to \( R \), the total contribution to the collected charge by electrons is:

\[
Q_e = \int_{r_1}^{R} qE_u(r) \cdot dr
\]

And holes drift from \( r_1 \) to \( r_0 \), the total contribution to the collected charge by holes is :

\[
Q_h = \int_{r_1}^{r_0} qE_u(r) \cdot dr
\]
The total collected charge is therefore :

\[ Q = Q_e + Q_h = \int_0^R qE_w(w) \, dr + \int_0^r qE_w(r) \cdot dr = q\int_0^R E_w(r) \cdot dr \quad (6) \]

From the definition of the weighting field, we have :

\[ \int_0^R E_w(r) \cdot dr = 1 \quad (7) \]

From Eq.(6), we have that the total collected charge without radiation damage is :

\[ Q = Q_0 = q \text{ (no radiation)} \quad (8) \]

Therefore, for a non-irradiated 3D-Trench-Electrode detector, the total collected charge is a constant that equals the generated charge by MIP (q), and it is independent of the MIP incident position \( r_1 \).

2.2. Detector charge collection at different radiation fluences conditions

For the cylindrical 3D-Trench-Electrode detector shown in Figure 1 a), we have simulated the effect of MIP incident position \( r_1 \) on the charge collection for different proton radiation fluences.

As shown in Figure 2 for a detector irradiated to \( 1 \times 10^{15} \text{ n}_{eq}/\text{cm}^2 \) (\( \text{neq: 1MeV neutron equivalent} \)) the total collected charge changes with incident with MIP incident position \( r \), it has highest value when \( r_1=r_0 \). In this case, only electrons contribute to the total induced charge, since they drift across the entire distance between the two electrodes from \( r_0 \) to \( R \). Holes do not contribute at all, since they don’t drift at all. The maximum value of the total collected charge is only about 19500 electrons, which is about 1500 electrons less than the case of non-irradiation. This is mainly due to the trapping by radiation induced defects. On the other hand, when the MIP incident position \( r_1=R \), only holes contribute to the total induced charge (16000 electrons), since they drift the entire distance between the two electrodes from \( R \) to \( r_0 \). The total collected charge here is minimum because the hole mobility is less than the electron mobility, leading to larger trapping rate inside the detector [14].

![Figure 2](image-url)

**Figure 2.** Dependence of charge collection on the MIP incident position for a cylindrical 3D-Trench Electrode detector, The detector bias voltage is 100V, and the proton fluence is: \( 1 \times 10^{15} \text{ n}_{eq}/\text{cm}^2 \).

As proton fluence increases to a fluence of \( 5 \times 10^{15} \text{ n}_{eq}/\text{cm}^2 \), the maximum collected charge is about 16000 electrons, which occurs at a MIP incident position \( r_1=10\mu m \) as shown in Figure 3. Now the radiation induced trapping increases to about 5000 electrons. Also we note that the effect of MIP incident position \( r_1 \) on the total collected charge becomes more significant. Again the minimum charge collection at a value of 7500 electrons, which occurs also at \( r_1=R \).
Figure 3. Dependence of charge collection on the MIP incident position for a cylindrical 3D-Trench Electrode detector. The detector bias voltage is 100V, and the proton fluence is: $5 \times 10^{15} \text{n}_{\text{eq}}/\text{cm}^2$.

At the maximum proton fluences of $1 \times 10^{16} \text{n}_{\text{eq}}/\text{cm}^2$, as shown in Figure 4, the maximum charge collection again occurs at a MIP incident position $r_1=10\mu$m, at a value of 13500 electrons. The charge trapping now is significant with a trapped charge of 7500 electrons. Again the minimum charge collection occurs at $r_1=R$, at a value of 4000 electrons. The difference between the maximum charge collection (13500, $r_1=10\mu$m) and the minimum one (4000, $r_1=R=40\mu$m) is 9500 electrons, close to the value of maximum charge collection. This gives maximum effect of the MIP incident position ($r_1$) on the total charge collection.

Figure 4. Dependence of charge collection on the MIP incident position for a cylindrical 3D-Trench Electrode detector. The detector bias voltage is 100V, and the proton fluence is: $1 \times 10^{16} \text{n}_{\text{eq}}/\text{cm}^2$.

3. Summary and conclusions

In summary, from our simulations, we can conclude that for non-irradiated cylindrical electrode detectors, there is no charge loss due to trapping. The total collected charge does not depend on the MIP incident position $r_1$, and it equals the total charge generate by MIP incident inside detector. The charge collection efficiency is 100%. The total charge collection decrease with radiation fluences regardless of the MIP incident position, the maximum charge collection efficiency reduces to about...
92.9% at a fluences of \(1\times10^{15}\) \(n_{eq}/cm^2\) to about 76.2% at a fluences of \(5\times10^{15}\) \(n_{eq}/cm^2\), and to about 64.3% at the maximum fluence of \(1\times10^{16}\) \(n_{eq}/cm^2\). For irradiated detectors, they total charge collection depends on the MIP incident position \(r_1\). The minimum charge collection always occurs at \(r_1=R\), where only holes contribute to the total charge collection. This is due to the fact that holes have larger trapping rate (7.7\(\times10^{-7}\) cm\(^2\)/s) and smaller drift mobility (450 cm\(^2\)/Vs, 1450 cm\(^2\)/Vs) [14-16]. The effect of MIP incident position \(r_1\) on the detector total charge collection becomes more significant as radiation fluence increases. The differences between maximum and minimum charge collection at different \(r_1\) are: 0 electrons for no radiation, 3500 electrons for \(1\times10^{15}\) \(n_{eq}/cm^2\), 8500 electrons for \(5\times10^{15}\) \(n_{eq}/cm^2\), and 9500 electrons for \(1\times10^{16}\) \(n_{eq}/cm^2\).

Acknowledgments
The authors would like to thank the financial supports from the Key Project of National Natural Science Foundation of China under Grant No. 11835008, the National Key R&D Program of China under Grant No.2017YFF0105000, and the Special Project of Changsha-Zhuzhou-Xiangtan National Independent Innovation Demonstration Area under Grant Nos. 2017GK2293 and 2018XK2303.

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