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Study of induced current of 3D-open-shell-electrode detector

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ABSTRACT

Interactions between neighboring cells often occur in a semiconductor silicon detector array. That is, there are high-energy particles incident on one cell of the detector that generate an electric signal for the cell, while weak signals are also generated in other neighboring cells. Therefore, isolation of the detector cells is an important factor in the performance of the detector, particularly for its energy resolution. To eliminate the dead space in the 3D-trench-electrode detector proposed by Brookhaven National Laboratory, a novel three-dimensional (3D) detector, the 3D-Open-Shell-Electrode Detector (3DOSED), was proposed in 2018, in which good isolation between cells was achieved. To verify this and determine the optimal structure design, a Silvaco technology computer-aided design simulation tool was used to simulate the electrical characteristics of the detector in 3D. The distributions of the electric field and the weighting field of 3DOSEDs were obtained with different opening gap angles. A single minimum ionizing particle was used that was incident vertically on the middle of the central collection electrode and peripheral trench electrode of the detector cell, according to the Ramo theorem of the principle of induced-current generation, and the mathematical software MATLAB was employed to calculate the induced current and carrier drift time. The interference current between the neighboring cells of a 3DOSED was obtained. Good isolation was found between neighboring cells in the 3DOSED.

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I. INTRODUCTION

Due to its small bandgap width, high carrier mobility, and easy processing, silicon has rapidly become one of the most widely used semiconductor detector materials in the world. It often appears in the manufacture of detectors of ultraviolet, visible, and infrared radiation, which are widely used in high-energy physics, astrophysics, nuclear medicine, and other fields. Researchers have designed and developed silicon detectors with different structures as suited to their fields. Common two-dimensional (2D) silicon detectors include silicon microstrip detectors, silicon pixel detectors, and silicon drift detectors. To improve the performance of these detectors, in 1997, the first generation of 3D column electrode detectors was proposed by Parker and co-workers. The 3D column electrode detector was the first three-dimensional silicon detector developed with a three-dimensional deep etching process. In this deep etching process, the electrode spacing of the detector can be made much smaller than that of 2D detectors, meaning that 3D column electrode detectors have better radiation tolerance, shorter charge collection times, and lower full depletion voltage than 2D detectors. However, a region of high electric field appears near the column electrode and a low electric field region appears in the symmetrical center of the neighboring four electrodes, which limit its use in environments with extremely harsh radiation.

To enhance the radiation tolerance of the detector, in 2009, the scientists at Brookhaven National Laboratory proposed a new type of 3D silicon detector, the 3D-trench-electrode detector. In this device, one type of electrode (cathode or anode) is made into a trench shape that surrounds the other column-shaped electrode (anode or cathode), which isolates the detector cells from each
other and makes the electric field of the cell more uniform. However, the 3D-trench-electrode detector retains 10% of the bulk of the silicon on the bottom unetched to prevent the cell from falling off the wafer. This unetched region cannot be fully depleted, giving rise to a region with a low electric field, generally called the dead space. To eliminate this dead space and increase the isolation of the cells, Li’s team proposed a new detector structure called the 3D-Open-Shell-Electrode Detector (3DOSED), shown in Fig. 1, where two narrow openings appear in the peripheral trench electrode in one cell of the 3DOSED. These openings connect neighboring cells to the silicon bulk of the wafer, ensuring the mechanical stability of the detector on the wafer. It also eliminates the unetched region in the bottom of the 3D-trench-electrode detector, which isolates the detector cells from each other.

II. FULL-3D SIMULATION

For our simulation, we chose a $1 \times 2$ array of square 3DOSED cells as the study object. The detectors had a thickness of 300 $\mu$m and a width and length of 230 $\mu$m. The bulk silicon was high resistivity n-type ($1 \times 10^{19}$ cm$^{-3}$). The central collection electrode was n$^+$ doped ($1 \times 10^{19}$ cm$^{-3}$), with a side length of 10 $\times$ 10 $\mu$m. The square shell electrodes are formed as two complementary p$^+$ doped ($1 \times 10^{19}$ cm$^{-3}$) silicon trenches, with widths of 10 $\mu$m. As shown in Figs. 1 and 2, we kept the width of the opening gap $b$ to 7 $\mu$m and changed the angle of the opening gap (after calculation, the change in angle was represented by the value $a$), as shown in Fig. 2.

For the simulations described below, we selected six cases with the following $a$ values: $a = 0$ $\mu$m, where the angle of the opening gap was the smallest; $a = 20$ $\mu$m; $a = 40$ $\mu$m; $a = 60$ $\mu$m; $a = 80$ $\mu$m; and $a = 101.5$ $\mu$m, where the angle of the opening gap was a right angle.

A. Electric field simulation

Full 3D simulation was performed for the detectors, using the Silvaco technology computer-aided design (TCAD) tool. The bias voltage here was 100 V. The voltage added to the anode electrode was 100 V and that added to the cathode electrode was 0 V, to make sure the detector was fully depleted. As shown in Fig. 3, at the top and bottom of the detector, electrodes were covered by a 1 $\mu$m thick aluminum layer, and the rest were covered by a 1 $\mu$m thick silicon dioxide layer. A 2D cut at $Z = 150$ $\mu$m of the 3DOSED is shown in Fig. 4, for which simulated electric field profiles are displayed in Figs. 5(a)–5(f).

It can be seen from the simulation results that the electric field distributions of the detector were uniform, which indicated that the openings in the peripheral trench electrode had little effect on the distributions of the electric fields. We placed a cutline between the central collection electrodes of cells A and B, with data on the electrical fields on the cutline shown in Fig. 6. The electrical field values for cells A and B were similar and symmetrical. In addition, the values near the central collection electrode of both cells were the largest and decreased gradually from the central collection electrode to the peripheral trench electrode.
B. Weighting field simulation

Weighting field distributions were again obtained using 3D simulation. Beginning with our previous simulation of electric field, we replaced the peripheral trench electrode and the central collection electrode with metal (such as Al), and we replaced the silicon bulk between them with insulating material (such as SiO$_2$). In the simulation, 1 V was applied to the central collection electrode of cell A and 0 V was applied to all other electrodes. A 2D cut at Z = 150 μm of the 3DOSED is shown in Fig. 7, for which the simulated weighting field profiles are displayed in Figs. 8 (a)–8(f).

The profile of the simulated weighting field indicated that the weighting field distributions were relatively uniform in cell A, and the values of the weighting field in cell B were small. Similarly, we described a cutline between the central collection electrodes of cells A and B. The weighting field data for the cutline are shown in Figs. 9(a) and 9(b). We can clearly see that the weighting field values were the largest near the central electrode and decreased gradually from the central collection electrode to the peripheral trench electrode in cell A. For cell B, the weighting fields were much smaller than those in cell A and were very different due to their different opening gap angles. Therefore, we took the logarithm of the y-coordinate values to better separate the weighting field curves. Figure 9(b) clearly shows that as the value of a decreased, the weighting field rapidly decreased. The weighting field values decreased gradually from the peripheral trench electrode to the central collection electrode in cell B.

III. MODELING AND CALCULATION METHOD

The induction of electrical signals on detector electrodes was generally based on the Ramo theorem:}

$$\mathbf{I} = q \cdot \mathbf{E}_w \cdot \mathbf{v}_{de} = q \cdot \left( |E_{wx}|i + |E_{wy}|j + |E_{wz}|k \right) \cdot \left( v_{w, x}^h i + v_{w, y}^h j + v_{w, z}^h k \right)$$

$$= q \cdot \left( |E_{wx}|v_{x}^h + |E_{wy}|v_{y}^h + |E_{wz}|v_{z}^h \right).$$

(1)
FIG. 5. Electric field profiles at $Z = 150 \, \mu m$ of the 3DOSED for (a) $a = 0 \, \mu m$, (b) $a = 20 \, \mu m$, (c) $a = 40 \, \mu m$, (d) $a = 60 \, \mu m$, (e) $a = 80 \, \mu m$, and (f) $a = 101.5 \, \mu m$.

where $I$ is the induced current, $q$ is the charge generated by the minimum ionizing particle (MIP), $E_w$ is the weighting field ($E_{wx}$, $E_{wy}$, and $E_{wz}$ are the weighting field components along the x, y, and z directions, respectively, which can be obtained from Silvaco TCAD), and $v_{dr}$ is the carrier drift velocity that depends on the internal electric field of the detector ($v_x$, $v_y$, and $v_z$ are the components of carrier drift velocity in the x, y, and z directions, respectively),

$$
\vec{v}_{dr}^{e,h} = \mu^{e,h} \frac{\vec{E}}{v_s},
$$

(2)

$$
|\vec{E}| = \sqrt{|E_x|^2 + |E_y|^2 + |E_z|^2},
$$

(3)

where $\mu$ is the carrier mobility for electrons (e) or holes (h) ($\mu^e = 1450 \, cm^2/V \, s$ and $\mu^h = 450 \, cm^2/V \, s$) and $v_s$ is the saturation drift velocity ($\sim 10^7 \, cm/s$). $E_x$, $E_y$, and $E_z$ are the electric field components along the x, y, and z directions, respectively, which can also be obtained from Silvaco TCAD.

Because the drift path is consistent with the electric field line, for any point on the drift path, the following equations are valid:

$$
\begin{align*}
\frac{dy}{dx} &= \frac{E_y}{E_x}, \\
\frac{dz}{dx} &= \frac{E_z}{E_x}, \\
\frac{dy}{dx} &= \frac{E_x}{E_x}, \\
\frac{dz}{dx} &= \frac{E_z}{E_x}, \\
\frac{dy}{dx} &= \frac{E_x}{E_x}, \\
\frac{dz}{dx} &= \frac{E_z}{E_x}.
\end{align*}
$$

(4)

$$
\begin{align*}
\frac{v_{dx}^e}{v_{dr}^e} &= \frac{|E_x|}{|E_x|} = \frac{|v_{dx}^e|}{|v_{dr}^e|} \cdot \frac{|E_x|}{\sqrt{|E_x|^2 + |E_y|^2 + |E_z|^2}}, \\
\frac{v_{dx}^h}{v_{dr}^h} &= \frac{|E_y|}{|E_x|} = \frac{|v_{dx}^h|}{|v_{dr}^h|} \cdot \frac{|E_y|}{\sqrt{|E_x|^2 + |E_y|^2 + |E_z|^2}}, \\
\frac{v_{dz}^e}{v_{dr}^e} &= \frac{|E_z|}{|E_x|} = \frac{|v_{dz}^e|}{|v_{dr}^e|} \cdot \frac{|E_z|}{\sqrt{|E_x|^2 + |E_y|^2 + |E_z|^2}}, \\
\frac{v_{dz}^h}{v_{dr}^h} &= \frac{|E_z|}{|E_x|} = \frac{|v_{dz}^h|}{|v_{dr}^h|} \cdot \frac{|E_z|}{\sqrt{|E_x|^2 + |E_y|^2 + |E_z|^2}}.
\end{align*}
$$

(5)
The carrier real-time position on the drift path is

\[ \begin{align*}
  y &= \int_{x_0}^{x} \frac{E_y}{E_x} \, dx + y_0, \\
  z &= \int_{x_0}^{x} \frac{E_z}{E_x} \, dx + z_0,
\end{align*} \tag{6} \]

where \(x_0, y_0, z_0\) are the carrier initial position, and \(x, y, z\) are the carrier real-time position.

According to Eqs. (1)–(6), we can obtain the induced current at any point on the drift path,

\[ I = q \cdot \bar{E}_0 \left( x, \int_{y_0}^{y} \frac{E_y}{E_x} \, dy + y_0, \int_{x_0}^{x} \frac{E_z}{E_x} \, dx + z_0 \right) \times \psi_{dr} \left( x, \int_{y_0}^{y} \frac{E_y}{E_x} \, dy + y_0, \int_{x_0}^{x} \frac{E_z}{E_x} \, dx + z_0 \right). \tag{7} \]

For carrier drift time, we have

\[ ds = \sqrt{dx^2 + dy^2 + dz^2} = \sqrt{1 + \left( \frac{dy}{dx} \right)^2 + \left( \frac{dz}{dx} \right)^2} \, dx \]

\[ = \sqrt{1 + \left( \frac{E_y}{E_x} \right)^2 + \left( \frac{E_z}{E_x} \right)^2} \, dx. \tag{8} \]

Since \( \psi_{dr} = \frac{d}{dt} \rightarrow t = \int \frac{1}{\psi_{dr}} ds \), according to Eq. (8), we obtain immediately

\[ t = \int \frac{1}{\psi_{dr} \left( x, \int_{y_0}^{y} \frac{E_y}{E_x} \, dy + y_0, \int_{x_0}^{x} \frac{E_z}{E_x} \, dx + z_0 \right)} \sqrt{1 + \left( \frac{E_y}{E_x} \right)^2 + \left( \frac{E_z}{E_x} \right)^2} \, dx. \tag{9} \]

We obtain a relationship between induced current \(I\) and carrier drift time \(t\) from Eqs. (1)–(9), both of which are related to position values.

In this work, the simulated electric field and weighting field data have been obtained using a Silvaco TCAD tool, and we imported these data into MATLAB. Then, the electric field and weighting field distributions of the detector were constructed using MATLAB’s curve fitting tool. The above model and calculation method were used to create code for MATLAB. For these program codes, a single MIP was used to incident vertically on the middle of the central collection electrode and the peripheral trench electrode (other types of incident will be studied in the future). The roughly 24 000 electron–hole pairs generated by MIP incidence were divided into 300 drift clusters. Each drift cluster contained 160 electrons or 160 holes. Under the action of the electric field, electron clusters drift to the central collection electrode (n+ doped), and the hole clusters drift to the peripheral trench electrode (p+ doped). The induced current and drift time for each drift cluster were calculated. Finally, all of the results were compiled to obtain the curve of the induced current and the carrier drift time. The flowchart for these operations is shown in Fig. 10.

IV. CALCULATION RESULTS

Using the model and the calculation method described above, we calculated the MIP-induced currents and the carrier drift time. The results of the calculation are shown as follows.

With MIP vertically incident on cell A (Fig. 2), the induced current that was collected in cell A was generated in cell A of the detector. Figure 11(a) shows the curve of the electron current, Fig. 11(b) shows that of the hole current, and Fig. 11(c) shows that of the total induced current. The electron current was clearly larger than the hole current because the electrons drifted toward the central collection electrode, and the holes drifted toward the peripheral trench electrode, while the electric field and the weighting field were much larger near the central collection electrode than those near the peripheral trench electrode [Figs. 6 and 9(a)]. According to Eqs. (1) and (2), the induced electron current should be larger than the induced hole current. For the total induced current curve, the initial peak current was mainly the induced electron current, while the long tail of the curve was the induced hole current. The total
FIG. 8. Weighting field profiles at Z = 150 μm of the 3DOSED for (a) a = 0 μm, (b) a = 20 μm, (c) a = 40 μm, (d) a = 60 μm, (e) a = 80 μm, and (f) a = 101.5 μm.

FIG. 9. Weighting field between the central collection electrodes of (a) cell A and (b) cell B.

induced current duration time was about 2.5 ns, dominated by slow hole drifting. The integration for each total induced current curve was about 24 000, which represented the total charge generated by an MIP incident.
When MIP2 was vertically incident on cell B, the induced current collected in cell A was due to the charges generated by the incident MIP in cell B. We termed this type of induced current the interference current. We judged the degree of isolation between neighboring cells of the detector by the magnitude of the interference currents. To better display the $I-t$ curves, we took the logarithm of the y-coordinate to better separate interference current curves. Figure 12(a) shows the curve of the electron interference current.
current, Fig. 12(b) shows that of the hole interference current, and Fig. 12(c) shows that of the total interference current. A comparison of Figs. 11(c) and 12(c) clearly shows that the interference currents [Fig. 12(c)] are much smaller [at least four orders of magnitude less than the induced currents, as seen in Fig. 11(c)]. From Fig. 12(c), it is clear that the 3DOSED with \( a = 101.5 \) \( \mu m \) generates the greatest interference in the neighboring cells, and the interference current reached \( 10^4 \). As the \( a \) value decreased, interference currents decrease dramatically as well. When \( a = 0 \) \( \mu m \), there was little interference in neighboring cells, only on the order of \( 10^1 \). This means that the 3DOSED with \( a = 0 \) \( \mu m \) exhibited nearly complete cell isolation, resulting in nearly no interference between neighboring cells. Therefore, \( a = 0 \) \( \mu m \) was determined to be the best configuration for the 3DOSED cell.

V. CONCLUSION

This work proposed a new model and method of calculation for the induced current and carrier drift time. Using a Silvaco TCAD tool to simulate the electric field and weighting field distributions of the square 3DOSED and using MATLAB for induced and interference current calculations, we obtained curves for induced current and carrier drift time. We found that interference currents were much smaller than induced currents in our detector. As the \( a \) value decreased, the interference current also decreased. For \( a = 0 \) \( \mu m \), the square 3DOSED had the best (nearly complete) cell isolation and showed almost no interference between neighboring cells. The square 3DOSED with \( a = 0 \) \( \mu m \) was obviously an optimal structural design scheme. To conclude, there was good isolation between neighboring cells in our square 3DOSED, with \( a = 0 \) \( \mu m \), and optimal isolation was achieved, which is very beneficial to the energy resolution of detectors.

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