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3D simulations and modeling of new low capacitance silicon pixel detectors

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ABSTRACT

With signal to noise ratio (S/N) being a key parameter of a high performance detector, reducing the detector noise has been one of the main tasks in detector development. A new low capacitance silicon pixel detector is proposed, which is based on a new electrode geometry with reduced effective electrode area while keeping the sensitive volume unchanged. Detector electrical characteristics including electrostatic potential, electric field, full depletion voltage, and capacitance have been simulated in detail using a 3D TCAD tool. From these simulations and calculations, we confirm that the new detector structure has a much reduced capacitance (by a factor of 3) as compared to the traditional pixel detectors with the same sensitive volume. This reduction in detector capacitance can certainly improve the detector signal to noise ratio. However, the full depletion voltage for the new structure is larger than that of the traditional one due to the small electrode effect.

1. Introduction

Nowadays, pixels detectors are widely used in high-energy physics experiments, such as the ATLAS' inner detectors at the Large Hadron Collider (LHC) [1–3], and X-ray spectroscopy with good energy resolution [4,5]. One of the key parameters of a pixel detector is the pixel capacitance. The pixel capacitance determines the noise performance of a pixel detector and it is an important input parameter for the design of pixel read-out electronics [6].

The capacitance of a traditional pad/pixel detector, with the signal electrode covering the entire detector area, is high. Low capacitance has been a critical requirement for designing a new detector. In this work, we propose a structure of the signal electrode to reduce its effective area while keeping the sensitive volume unchanged. We also keep the symmetry of the electrode so that one can get more uniform distributions in electric field and electric potential. Comparing with the traditional pad/pixel detectors in capacitance and full depletion voltages, we can find that the new detector's structures/geometries with lower detector capacitance can provide better design program for silicon pixel detectors [7]. In this paper, we mainly presented two kinds of newly designed electrode shapes: Kidney shape and Open Square Ring shape.

2. Structure of new design pixel detector

Using the Silvaco TCAD simulation tool, we can simulate Kidney shape and Open Square Ring shape detector structures. Shown in Fig. 1a and b are a single cell of the Kidney shape and Open Square Ring shape respectively. A large area detector can be made by an array of these individual cells. In the simulation of the structure of a unit cell, the bulk silicon is n-type high resistivity silicon doped with phosphorus of 8×10^{11} cm^{-3}. The detector thickness d is 500 μm. There are 1 μm thick p^+-implanted areas (boron, the peak concentration is 1×10^{19} cm^{-3}, only under the Kidney shape or the Open Square Ring shape areas) on the front surface and an 1 μm thick n^+-implanted layer on backside surface. On the front surface, p^+-implanted areas are covered by 1 μm thick aluminum to form the Kidney shape or the Open Square Ring shape cathodes. On the bottom (the backside), the n^+-implanted layer (phosphorus, the peak concentration is 1×10^{19} cm^{-3}) is covered by 1 μm thick aluminum acts as the anode. Cathodes are separated by a silicon dioxide layer with an oxide charge density of 4×10^{11} cm^{-3}. From the preliminary 2D simulations we learned that non depleted space would generate if the gap between p^+-implants is set too large [8,9]. We chose a maximal distance of 233 μm between two neighboring p^+ implants of the kidney shapes or open square shapes in order to keep a reasonable detector full depletion voltage of 240 V. This is due to the trade off between pixel capacitance and detector full depletion voltage. This distance can be larger (therefore smaller pixel capacitance) if we chose, e.g. a detector full depletion voltage of 300 V. In practice,

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this can be varied according to application needs. In order to maintain a uniform detector full depletion voltage, the distance between cells (in any direction) in the detector should be kept less or equal to the distance (in our case, 233 μm) between two neighboring p^+ implants of the kidney shapes or open square shapes.The maximum distance between two p^+-implants of Kidney shape is 233 μm and the minimum distance between pixels is 110 μm for 500 μm thick detectors. The maximum distance between two p^+-implants of Open Square Ring shape is 233 μm and the minimum distance between pixels is 190 μm for 500 μm thick detectors.

3. Electric potential characteristics

Shown in Fig. 2 are the electric potential distributions of the kidney shape and open square ring shape detectors in 2D cross section views. The bias voltage is set at 150 V. Fig. 2(a) and (b) is the y–z slices of the face of the detectors and sectional drawing (see Fig. 1).

4. Electric field characteristics

Fig. 3 shows the results of the electric field distribution of the Kidney shape and Open Square Ring shape detectors at a bias voltage of 150 V. Fig. 3(a) and (b) is the y–z slices of the face of the detectors and sectional drawing (see Fig. 1).

5. Capacitance–voltage characteristics

The capacitance is a sensitive parameter in the operation of a silicon tracking detector, as it directly affects the noise and crosstalk [10]. The capacitance-voltage characteristics are obtained by using a small signal analysis (AC analysis, frequency is 1×10^6 Hz) [11]. The capacitance of the newly designed detectors (Kidney and Open Square Ring) is plotted in Fig. 4. They are reduced by about a factor of 3 as compared to conventional pixel detectors with cathode electrode filling the whole cell area.

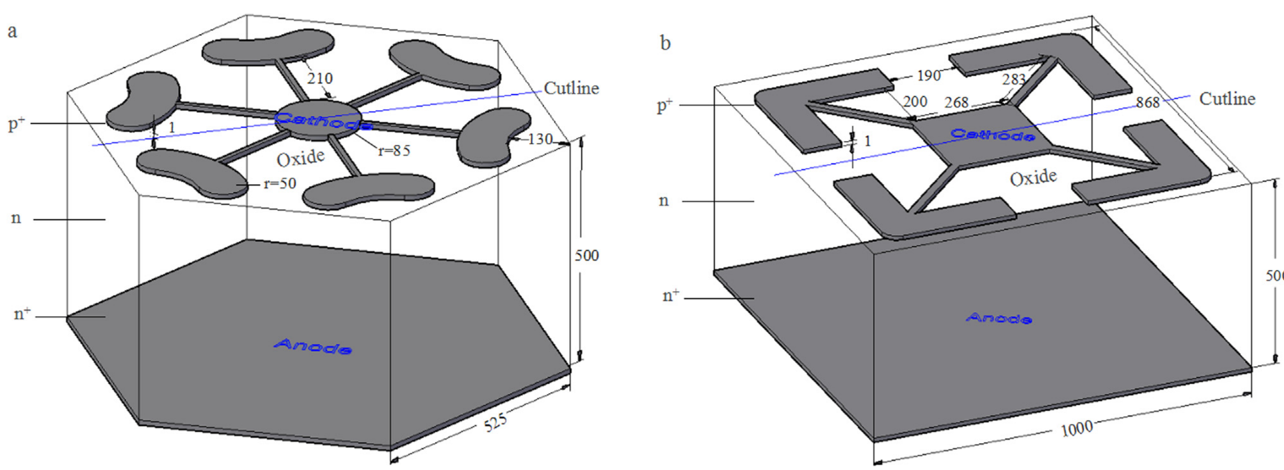

Fig. 1. (a) Structure of the kidney shape detector. (b) Structure of the open square ring shape detector.

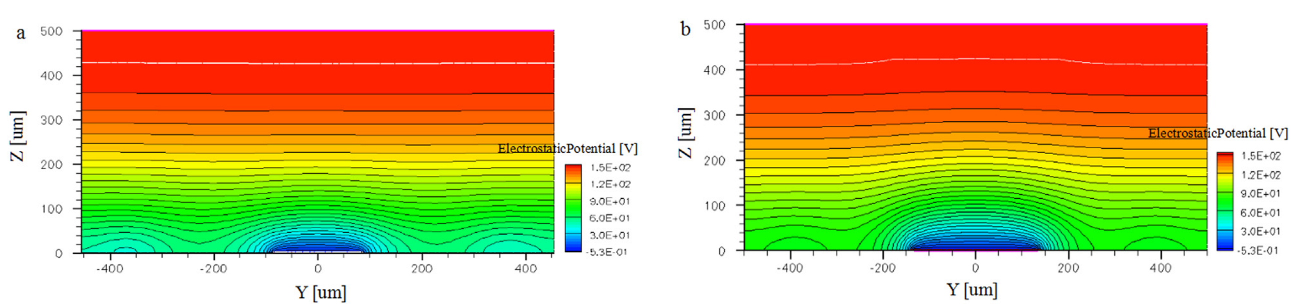

Fig. 2. (a) Potential profile of the kidney shape detector. (b) Potential profile of the open square ring shape detector.

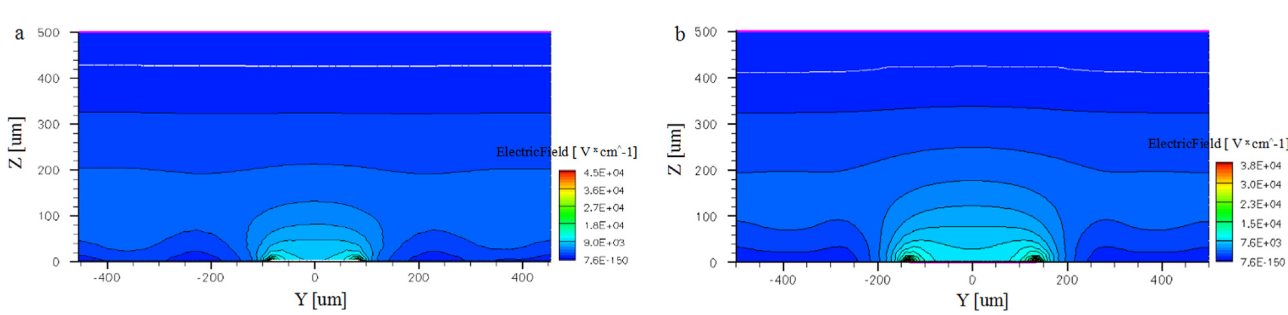

Fig. 3. (a) Electric field profile of the kidney shape detector. (b) Electric field profile of the open square ring shape detector.