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Nai Shyan Lai  
*University of New South Wales*

Wee Han Lim  
*University of New South Wales*

Amy L. Ziebell  
*University of Wollongong, alz97@uow.edu.au*

Mark I. Reinhard  
*Australian Nuclear Science and Technology Organisation*

Anatoly B. Rosenfeld  
*University of Wollongong, anatoly@uow.edu.au*

See next page for additional authors

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Recommended Citation
Lai, Nai Shyan; Lim, Wee Han; Ziebell, Amy L.; Reinhard, Mark I.; Rosenfeld, Anatoly B.; and Dzurak, Andrew S.: Development and fabrication of Cylindrical Silicon-on-Insulator Microdosimeter Arrays 2009, 1637-1641.  

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Development and Fabrication of Cylindrical Silicon-on-Insulator Microdosimeter Arrays

Nai Shyan Lai, Student Member, IEEE, Wee Han Lim, Student Member, IEEE, Amy L. Ziebell, Student Member, IEEE, Mark I. Reinhard, Member, IEEE, Anatoly B. Rosenfeld, Senior Member, IEEE, and Andrew S. Dzurak

Abstract—Recent developments in the fabrication and simulation of prototype silicon-on-insulator (SOI) microdosimeter arrays are presented. A new planar array design has been proposed which has a number of advantages over the previous elongated parallelepiped and cylindrical mesa array designs. This novel planar array design, which incorporates a guard ring, is based upon 2500 planar cylindrically shaped p-i-n detectors and was fabricated via dopant diffusion and ion implantation. The dopant-diffused arrays were successfully fabricated and tested using 2 μm and 10-μm-thick SOI substrates. Technology computer-aided design modeling of the ion-implanted structure is presented which includes the electrostatic potential profile, showing possible avalanche signal multiplication around the n+ core of the microdosimeter. The alpha particle charge transient response was simulated to determine the charge collection in the sensitive region.

Index Terms—Avalanche signal multiplication, microdosimeter, p-i-n detectors, silicon-on-insulator (SOI), SOI substrates, technology computer-aided design (TCAD) modeling.

I. INTRODUCTION

In microdosimetry, which is based on the measurement of the stochastic energy deposition events on cellular level in contrast to deterministic effect described by absorbed dose, the dose equivalent and relative biological effectiveness (RBE) of therapeutic and mixed radiation fields can be accurately estimated. In principle, RBE can be assumed to be dependent upon the spectra of lineal energy \( f(y) \), events measured on the micrometer scale. The dose equivalent can be calculated by multiplying the absorbed dose with the radiation quality factor \([1, 2]\). The experimental measurements of the spectrum \( f(y) \) require a radiation detector with a well-defined sensitive volume, a known mean chord length, equivalent to the size of a biological cell. Gas proportional counters can be used for this purpose by varying the counting gas density to obtain the equivalent density volume \( (pV) \) value of a cell. These detectors have an advantage of excellent tissue equivalency of the gas. However, this approach causes detrimental effects introduced by event pile up in the large physical volume as well as wall effects.

In the 1980s, solid-state microdosimeters were presented but the lack of tissue equivalency of the detection medium and the large size of the silicon detector lead to different chord length distributions compared to the tissue-equivalent spherical proportional counter \([3]\). The regulations for silicon microdosimeter designs are highlighted in \([4]\).

In more recent research, the Centre for Medical Radiation Physics (CMRP), University of Wollongong, Australia, has developed a planar diode array with sensitive volumes (SV) in the shape of elongated rectangular parallelepiped that utilizes silicon-on-insulator (SOI) technology. These devices have been successfully tested for applications in radiotherapy \([5, 6]\), radiation protection \([7]\), and deep space environments \([8]\). It was reported that this array design has a poorly defined charge collection volume that can be taken into account by the introduction of a charge collection efficiency (CCE) coefficient \([4–6]\).

The current state of research has demonstrated the proof-of-principle operation of a prototype microdosimeter array based upon a SOI substrate in which a novel 3-D cylindrically shaped p-i-n detector provides a well-defined SV and electric field profile with 100% charge collection efficiency \([9]\). However, a significant amount of low energy charge collection was observed across the outer mesa structure \([10]\).

To overcome this problematic mesa structure, a novel new design of microdosimeter arrays is detailed in this paper.

II. DESIGN AND FABRICATION

The new design consists of cylindrical SV microdosimeter arrays, in addition to a guard ring (GR), used to prevent charge collection outside the sensitive regions. Fig. 1 shows the schematic design of the individual p-i-n diode. There are two different approaches in designing the GRs: 1) a simple ring (or defined guard ring) around the outer collector and 2) a guard electrode covering all areas (or guard ring everywhere) that are not part of the SV as illustrated in Fig. 2(a) and (b), respectively. The new arrays are comprised of 2500 individual p-i-n detectors, maximizing the total SV to provide a significant increase in the signal to noise over previous designs. The array of detectors has the capability to observe delta electrons of high energy ions by connecting the detectors in an odd-even arrangement. This design permits dual-channel readout to identify further ionization in the surrounding sensitive regions, obtaining information about the
spatial distribution of energy cluster. From here, high energy charged particles, typical for space environments of the same linear energy transfer (LET), can be detected based on their differing track structure. These designs use 2-μm and 10-μm-thick SOI substrates in which dopants are incorporated via diffusion and implantation. Ion implantation allows smaller feature sizes to be achieved within the individual p-i-n detectors, opening the possibility of achieving avalanche signal multiplication to further improve signal to noise as well as increase the total SV.

The overall design specifications for different versions are summarized in Table I. The designs consist of eight different array versions where versions 1–4 and versions 5–8 are incorporated via dopant diffusion and via ion implantation, respectively on an array size of approximately 2.3 × 2.3 mm². For versions 1–4, the sensitive region widths for each p-i-n detector are approximately 2 μm which gives the sensitive surface area of approximately 50 μm² and the total area for 2500 p-i-n detectors is 125 000 μm². As for versions 5–8, the sensitive width is estimated to be 6 μm, the single detector sensitive surface area is 169 μm² and the total area is 422 500 μm².

Versions 1–4 cylindrical microdosimeter arrays were successfully fabricated at the Semiconductor Nanofabrication Facility (SNF), University of New South Wales, Australia, using standard microfabrication processes. SOI wafers with 10 kΩ - cm p-type high-resistivity superficial silicon, crystal orientation of ⟨100⟩, were used. Two SOI wafer thicknesses were used in this experiment: 1) 2 μm superficial silicon, 2 μm buried oxide, 500- μm handle oxide and 2) 10- μm superficial silicon, 2- μm buried oxide, 500 μm handle oxide. A standard positive/negative photoresistor was utilized throughout the photolithography processes and versions 1–4 were fabricated on a different batch of SOI wafers. The wafers were diffused via high concentration phosphorus and boron diffusion, producing a peak density of approximately 10¹¹ cm⁻³. Using 300-nm-thick thermal oxide as the mask, phosphorus dopants were diffused into the superficial silicon at a temperature of 1000 °C for 60 min and boron dopants were diffused at a temperature of 1100 °C for 60 min. The projected and lateral diffusion for both dopants are about 2 μm. The array is passivated with 100-nm silicon dioxide followed by the evaporation of 200-nm aluminum as the electrodes for the n+-core, p+ region, and n+ GR contacts. The final fabrication step is the annealing process. This was done in a forming gas, with a mixture of 95% N₂ and 5% H₂, at 400°C for 15 min to significantly reduce the trap charge density at the superficial silicon and the silicon–dioxide interface.

Prior to any test and ion beam-induced charge collection (IBIC) measurements, the different versions of microdosimeter arrays were cleaved into single arrays and packaged onto a
<table>
<thead>
<tr>
<th>Version</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOI Substrate Thickness</td>
<td>2 μm</td>
<td>10 μm</td>
<td>2 μm</td>
<td>10 μm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Guard Ring Type</td>
<td>DGR</td>
<td>GRE</td>
<td>DGR</td>
<td>GRE</td>
<td>DGR</td>
<td>GRE</td>
<td>DGR</td>
<td>GRE</td>
</tr>
<tr>
<td>Fabrication Method</td>
<td>Via Dopant Diffusion</td>
<td>Via Ion Implantation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sensitive Region Width</td>
<td>≥ 2 μm</td>
<td>≥ 6 μm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single Detector Sensitive Area</td>
<td>≥ 50 μm²</td>
<td>≥ 169 μm²</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Sensitive Area</td>
<td>≥ 125,000 μm²</td>
<td>≥ 422,500 μm²</td>
<td></td>
<td></td>
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</tbody>
</table>

**TABLE I**

**SUMMARY OF EIGHT DIFFERENT VERSIONS OF MICRODOSIMETER ARRAYS WHICH INCLUDE SOI SUBSTRATE THICKNESS, GUARD RING TYPE, FABRICATION METHOD, SENSITIVE REGION WIDTH, SINGLE DETECTOR SENSITIVE AREA, AND TOTAL SENSITIVE AREA FOR EACH VERSION**

DGR: Defined Annulus Guard Ring  
GRE: Guard Ring Everywhere

Fig. 3. Scanning electron micrographs (SEMs) showing completed dopant-diffused microdosimeter arrays with: (a) defined guard ring (DGR) and (b) guard ring everywhere (GRE). Each shows the zoomed-in version of the single diode.

20-pin dual-in-line cavity while the pads were bonded with aluminum wires to the respective pins. Fig. 3 illustrates the scanning electron micrograph (SEM) images of the completed dopant-diffused microdosimeter arrays with defined guard ring (DGR) and guard ring everywhere (GRE).

**III. TCAD MODELING**

The most critical design parameters for optimizing devices for microdosimetry as well as single event upset (SEU) studies are the diode structure sizes [11]. In recent research, ion implantation has been the preferred fabrication method in designing smaller structures and it is important to achieve the optimal 1/r electric field distribution in the SV. The ion implantation design schematic as illustrated in Fig. 4(a) is to be used for the cylindrical microdosimeter arrays version 5–8. Proof of concept of these structures has been shown by performing 3-D numerical device simulations using the DESSIS code in the ISE-TCAD software package [12]. The objective of the simulations was to investigate the electrical profiles and the characteristics of the charge collection efficiency.

The simulation setup includes a drift-diffusion model that self-consistently solves the Poisson equation and the electron-hole continuity equations to obtain the charge transient response of the microdosimeter array model. The TCAD model incorporates dominant Shockley–Read–Hall (SRH) recombination and Auger recombination models. These models were used to absorb the differences in momentum between the carriers at the impurity state in superficial silicon and excite the third carrier to a higher energy level without moving to another energy band at an unstable high-energy state, respectively.

Fig. 4(b) and (c) depicts the actual dimensions used in the modeling of the microdosimeter version 7, incorporating ion-implanted n+ and p+ regions. (a) The schematic design. (b) Top view without silicon-dioxide overlayers and aluminum metallization. (c) Cross-section view with all of the dimensions in micons. The depth of the implanted n+ and p+ is approximately 0.57 μm and 0.56 μm, respectively.
implanted central $n^+$, implanted $p^+$, and implanted $n^+$ DGR regions. The width of the sensitive volume is approximately 6 $\mu$m, giving a higher total sensitive area and better detection sensitivity than the dopant-diffused arrays. The effect of the bias voltage on the electric-field profile was observed by sweeping the reverse bias voltage from 10 V to 50 V at room temperature, as shown in Fig. 5. The radial electric field is in the range of $10^5$ V/cm at the core of the microdosimeter and decreases sharply outward showing a $1/r$ electric-field distribution. This simulation results confirm that the avalanche amplification will occur at the reverse bias voltage of 40 V which shows the electric-field peaks above the avalanche threshold of around the $n^+$ core [13].

In the SEU study, accidental triggering of the device caused by low energy ions can be simulated by using a heavy ion model [12]. In this case, 3-MeV alpha particles are accelerated into the SV and the space charge is calculated as a function of time, as illustrated in Fig. 6. The response of the model shows that the charge is fully collected after approximately 1 ns when the reverse bias voltage is set to 10 V.

**IV. RESULTS AND DISCUSSION**

For the microdosimeter mesa array design, there are concerns over the high reverse bias leakage current associated with the low energy charge collection in the SV caused by the parasitic charge surrounding the SV. The parasitic charge occurrence is mainly generated from the remaining thin silicon crumb in between the mesa diodes which are not fully etched. The solution to this problem is to incorporate a guard ring around each SV in the new microdosimeter planar array design. This method attracts the parasitic charge to the diffused $n^+$ guard ring region when the reverse bias voltage is applied to the guard ring electrode. As a preliminary test, design version 1 was chosen. The reverse bias leakage current for 250 diodes when the guard ring is grounded is approximately 200 pA at 5 V at room temperature in a dark environment. The leakage current for different rows is present in Fig. 7. As for the other versions, version 2 shows less reverse bias leakage current than version 1 but versions 3 and 4 show higher reverse bias leakage currents than version 1 and 2. Both surface and bulk effects contribute to the total leakage current of the device. At lower temperatures, the leakage current is reduced in accordance with carrier generation processes within the bulk.

The IBIC technique was used to obtain an image of the charge collection region across the device structure. IBIC was
ACKNOWLEDGMENT

The authors would like to thank E. Gauja for his technical advice and helpful support on the microfabrication processes as well as to C. Escott for ongoing support and discussions in TCAD modeling. They would also like to thank the National Space Biomedical Research Institute (NSBRI), V. Pisacane, Prof. J. Dicello (of the U.S. Naval Academy), and M. Zaider (MSKCC) for their support, useful discussion, and collaboration on the development and space application of silicon microdosimetry.

REFERENCES