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

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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 (ρV) 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

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Fig. 1. Single 3-D cylindrical microdosimeter version 3 incorporating diffused $n+$ and $p+$ regions. (a) Top view without silicon dioxide overlayers and aluminum metallization. (b) Cross-section view with all the dimensions in micrometers.

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 $2\text{-}\mu\text{m}$ and $10\text{-}\mu\text{m}$ -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 $2.3 \times 2.3 \text{ mm}^2$. For versions 1–4, the sensitive region widths for each p - i - n detector are approximately $2 \mu\text{m}$ which gives the sensitive surface area of approximately $50 \mu\text{m}^2$ and the total area for 2500 p - i - n detectors is $125\,000 \mu\text{m}^2$. As for versions 5–8, the sensitive width is estimated to be $6 \mu\text{m}$, the single detector sensitive surface area is $169 \mu\text{m}^2$ and the total area is $422\,500 \mu\text{m}^2$.

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 $10 \text{ k}\Omega\text{-cm}$ p -type high-resistivity superficial silicon, crystal orientation of $\langle 100 \rangle$, were used. Two SOI wafer thicknesses

Fig. 2. $2.3 \times 2.3 \text{ mm}^2$ microdosimeter array consists of 2500 cylindrical diodes with: (a) a simple ring (or defined guard ring) around the outer collector and (b) guard electrode covering all areas (or guard ring everywhere) that are not part of the SV.

were used in this experiment: 1) $2 \mu\text{m}$ superficial silicon, $2 \mu\text{m}$ buried oxide, $500\text{-}\mu\text{m}$ handle oxide and 2) $10\text{-}\mu\text{m}$ superficial silicon, $2\text{-}\mu\text{m}$ buried oxide, $500 \mu\text{m}$ 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 10^{20} 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 $2 \mu\text{m}$. 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% N_2 and 5% H_2 , 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 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

Version	1	2	3	4	5	6	7	8
SOI Substrate Thickness	2 μm		10 μm		2 μm		10 μm	
$n+$ Guard Ring	DGR	GRE	DGR	GRE	DGR	GRE	DGR	GRE
Fabrication Method	Via Dopant Diffusion				Via Ion Implantation			
Sensitive Region Width	$\approx 2 \mu\text{m}$				$\approx 6 \mu\text{m}$			
Single Detector Sensitive Area	$\approx 50 \mu\text{m}^2$				$\approx 169 \mu\text{m}^2$			
Total Sensitive Area	$\approx 125,000 \mu\text{m}^2$				$\approx 422,500 \mu\text{m}^2$			

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

Fig. 4. Single 3-D cylindrical 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 microns. The depth of the implanted $n+$ and $p+$ is approximately $0.57 \mu\text{m}$ and $0.56 \mu\text{m}$, respectively.

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. This model includes the 2-D aluminum electrodes and 100-nm-thick silicon-dioxide overlayers where the electrical contacts were located on top of the

Fig. 5. (a) Electrostatic potential profile and (b) electric-field profile calculated by using TCAD for device version 7 with a reverse bias voltage sweep from 10 V to 50 V at room temperature.

implanted central n^+ , implanted p^+ , and implanted n^+ DGR regions. The width of the sensitive volume is approximately 6 μm, 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 2.5×10^5 V/cm 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

Fig. 6. Charge transient response of the microdosimeter version 7 with an applied reverse bias voltage of 10 V accelerated with 3-MeV alpha particles toward the sensitive region at: (a) 1 ps, (b) 10 ps, (c) 100 ps, and (d) 1 ns.

Fig. 7. Reverse bias leakage current test on different rows of the microdosimeter array version 1 in dark at room temperature.

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

Fig. 8. IBIC median energy map of 3 MeV He^{2+} (196 keV/ μm) for microdosimeter version 1 at -5 V.

performed on the ANSTO Heavy Ion Microprobe at Lucas Heights, Australia. A spatially resolved beam of 3 MeV He^{2+} ions, of diameter $\sim 0.8 \mu\text{m}$ was raster scanned across the surface of the device. The response of the device to each ion was recorded in coincidence with the X- and Y-beam coordinates. A 3-MeV He^{2+} ion deposits 196 keV/ μm within silicon. In Fig. 8, the resulting median energy map of the collected charge in response to the He beam is shown, revealing almost 100% CCE for ions incident within the annulus region of the device. This measurement was performed under grounded $p+$ and guard-ring conditions with 5-V bias applied to the $n+$ core contact.

It is very difficult to control the voltage applied to the $n+$ guard ring since the metallization of the Al electrode connecting the diodes in series is imperfect due to the width being at the limit of available microfabrication techniques. A protective film is required to prevent further damage to the metallization of the electrodes after the final fabrication step. Intermediate Coating IC1-200 spin-on-glass has been proposed as the passivation layer and preliminary tests have been undertaken. IC1-200 is a high transparency polysiloxane-based spin-on dielectric material with highly uniform thin-film thickness of approximately 170 nm, which can also act as the tissue converter.

As for the ion-implanted TCAD model, the simulation results are promising when compared to the dopant-diffused model due to its much smaller $n+$ core size. This only requires reverse biasing voltage of 40 V to produce avalanche multiplication in the SV, rather than 500 V [9]. The electric field in the SV can be increased further by introducing a lightly doped boron ($p-$) diffusion layer around the $n+$ core, which acts as a $p+$, i , $p-$, and $n+$ avalanche diode. This $p-i-n$ avalanche structure provides internal amplification of deposited charge. The resulting increase in the signal to noise allows events associated with lower lineal energies to be observed, increasing the dynamic range of the microdosimeter. To allow the measurement of events associated with low lineal energies requires a high signal-to-noise ratio. The noise of the device and signal-processing electronics as obtained by using the electronic pulser method equated to a full width at half maximum (FWHM) of 4.6 keV, that allow the microdosimeter to distinguish events with lineal energy of approximately 0.5 keV/ μm . In addition to this, the total sensitive area is also important in determining the signal-to-noise of the microdosimeter array. Arrays of size $1 \times 1 \text{ cm}^2$ are suitable for most applications in space and terrestrial radiation protection.

V. CONCLUSION

Novel new designs of the well-defined SV cylindrical SOI microdosimeter arrays and results have been presented by showing that they can potentially overcome the shortcomings of previous microdosimeter array designs. Microdosimeter array versions 1–4 were successfully fabricated and the preliminary results show a low reverse bias leakage current. ISE TCAD modeling results have shown that the avalanche signal amplification is possible in the SV of ion-implanted microdosimeters which are important for silicon microdosimetry.

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