Development of Low-resistivity Silicon Drift Detector Arrays for Soft X-rays

W. Chen, G. De Geronimo, J. A. Gaskin, S. Li, Z. Li, B. D. Ramsey, and G. Smith

Abstract— New silicon drift detector (SDD) arrays are being developed for use as extraterrestrial X-ray spectrometers. For the first time these SDDs have been produced on low resistivity, n-type silicon, with a thinner thickness than normal, effectively ensuring their radiation hardness in anticipation of operation in potentially harsh radiation environments (such as those found around Jupiter). To achieve low-energy X-ray response, a thin entrance window was produced using a double implantation technology. The design, fabrication and performance of these detectors are presented here.

I. INTRODUCTION

Over the past several years, our group has developed Silicon Drift Detectors (SDDs) [1] on high resistivity silicon for the detection of X-rays. A high resistivity material enables the detector to reach full depletion of the silicon bulk with a reasonably low biasing voltage. Our present task is to develop SDD arrays for X-ray spectrometers that can be operated in mild to harsh radiation environments (e.g. protons) around planetary bodies such as the Moon, and Europa in the Jovian system.

The development of such detector arrays is an on-going collaboration between the NASA Marshall Space Flight Center (MSFC) and Brookhaven National Laboratory (BNL). These arrays are designed for detecting the light elements C to Fe, which are dominant on planetary bodies and whose emission X-rays span the energy ranges of ~0.2 to 10 keV. By measuring the spectrum of emitted X-rays and by identifying lines in the spectrum, the elements on planetary bodies can be identified. A significant challenge is detection of the low energy *K* lines of the low *Z* elements such as C. Low energy detection requires the use of a thin-entrance window that must be able to block ultraviolet light, while allowing X-ray transmission. Past experience has shown that a 110 - 120 nm aluminum layer is not only sufficient to eliminate surface charging while allowing better than 65% X-ray transmission for 280 eV X-rays, but also has negligible impact on the SDD leakage current. The silicon under this aluminum layer should be efficient for detecting X-rays right at the aluminum-silicon interface, and therefore any realistic implantation will result in a “dead” layer depth. The power requirement is the dominant constraint in the choice of the detector design and the read-out technology. The detectors are also required to operate at an extremely high rate of up to one million counts/s cm² with a power budget, excluding cooling, of 10 W. These detectors

should also be radiation tolerant to several Mrad with shielding, and at least 250 krad without shielding. This requires the detector and its readout electronics not only to have a low equivalent noise charge (ENC) of better than 10 e but also to be radiation hard.

The ambient radiation in Jovian environments can increase the detector effective resistivity (with n-type bulk), leading to the space-charge-sign-inversion (SCSI), or “type-inversion” point. This causes the SDDs to cease functioning, and the usage of a low resistivity material becomes desirable to extend the detector’s lifetime. However, lowering the resistivity of the detector material can increase operating voltage, compared with that for the same thickness for high resistivity SDD. This requires a reduction in silicon thickness to keep the operation voltage reasonable.

II. DESIGN AND FUNCTION OF THE DETECTOR

The basic building block (or cell) consists of a single spiral hexagonal SDD [2, 4] which, when tiled into an array, results in continuous coverage over a large detection area. The decision to choose a spiral SDD as an elementary cell for XRS was a consequence of the power constraints combined with the economical production of the SDDs. The spiral is made of a rectifying p-type implant on relatively low resistivity n-type silicon material, chosen to anticipate the usage of these detectors in a radiation harsh environment. Following formula shows the relationship of the effective doping concentration to radiation fluence [5, 6]:

$$N_{\text{eff}} = N_{\text{id}} e^{-\gamma\Phi_n} - \beta\Phi_n \quad (1)$$

where N_{eff} is the effective doping concentration or space charge concentration, N_{id} is the initial doping concentration, and Φ_n is the radiation fluence equivalent to 1 MeV neutron. For non-irradiated silicon, the doping concentration N_{id} is inversely proportional to resistivity: $N_{\text{id}} = 1/e\mu\rho$. It can be seen from Eq. (1) that:

1) as radiation fluence Φ_n increases, N_{eff} decreases, and it eventually changes sign from positive to negative, the SCSI onset point being given by $N_{\text{eff}} = 0$,

2) For a given radiation fluence Φ_{ns} , we require $N_{\text{eff}} > 0$ to ensure the proper operation of the SDD. Therefore silicon material with initial resistivity $\rho_{\text{id}} < e^{-\gamma\Phi_{\text{ns}}} / (e\mu\beta\Phi_{\text{ns}})$ is required. For a higher given radiation fluence (in a more harsh radiation environment), lower resistivity silicon would be needed initially. For an SDD application in Europa, the maximum radiation dose is about 1 Mrad (or about 2×10^{13}

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n_{eq}/cm^2), and a low resistivity silicon material with an initial resistivity $< 2 \text{ k}\Omega\text{-cm}$ is required.

However, while the silicon resistivity is lowered, the operation voltage for silicon bulk to reach full depletion (U_{fd}) will be increased if the thickness of the detector remains the same:

$$U_{fd} = d^2 / (2\mu_{pd} \epsilon_s \epsilon_0) \quad (2)$$

where d is wafer thickness, ϵ_s is silicon permittivity, and ϵ_0 is vacuum permittivity. Thus, U_{fd} is proportional to the square of the detector thickness, illustrating why relatively thinner silicon is required to keep the operation voltage at a reasonable level.

One side of the SDD array, called the window (W) or entrance side, is continuous, thin, rectifying junction, through which X-rays enter the detector. On the W side, a p-implant contact provides a rectifying junction for each cell, which enables depletion into the silicon bulk. The opposite side, called the device side, contains arrays of identical SDD cells, each cell containing an electron collecting anode as well as all other electrodes needed to generate the drift field and to sink leakage current produced at the Si-SiO₂ interface. For each SDD cell (20 mm²), a hexagonal-spiral shaped p-implant cathode surrounds a central hexagonal shaped n-implant anode (0.01 mm²). The drift voltage inside the detector is generated by this hexagonal spiral cathode. This spiral cathode produces the main valley where signal electrons drift as well as the voltage divider to produce the drift field. There is a single hexagonal shaped p-implant cathode (E1) located between the spiral cathode and the central anode. The electrode contacts at each end of the spiral are called E2 (inner contact) and Ot (outer contact). The spiral's function provides a depletion voltage for the silicon bulk and supplies a near-constant drift field for electrons in the SDD. Therefore, the designated voltages U_{ot} , U_w , U_{E2} , and U_{E1} are the biases for operating this SDD (fig. 1). On both sides of the detector array there is a system of guard rings which smoothly adjusts the voltage of the boundary cells to the ground potential of the silicon outside the sensitive volume.

Fig. 1. Schematic of a 3-dimensional, single SDD is shown.

Optimum performance of the SDD is obtained with the following constraints:

$$|U_{Ot}| \leq U_{fd} + |U_w|, |U_w| \leq U_{fd} + |U_{E1}|, |U_{E1}| < |U_{E2}| \quad (3)$$

If these expressions are not satisfied, a reach-through and/or redirection, or even reverse direction, of the drift channel conditions could occur. Again, according to Eq. (2), the SDD resistivity and the thickness influence the depletion voltage U_{fd} and therefore affect the operation constrain conditions in Eq. (3).

Fig. 2. Central region of the 2 dimensional design of the SDD where the sink anode, anode, electrodes E1 and E2 are visible.

To reduce the noise to the requirement of not more than 10 electrons, it is necessary to lower the leakage current to below the level of 5 pA for 20 mm² SDD area. We approach this in two ways:

- 1) the detectors are cooled to a temperature below -50 °C to reduce the bulk leakage current;
- 2) an additional feature called the sink anode is introduced (fig. 2), which ensures that the surface current, generated at the Si-SiO₂ interface under the oxide spiral, is directed towards the sink anode and removed through the E1 contact. This prevents the surface current from contributing to the leakage current on the main anode and is accomplished via a small bridge connection between the E1 and the sink anode.

III. FABRICATION OF THE DETECTOR

The production of radiation-hard SDD arrays at BNL utilized both our previously developed method [7, 10] for the entrance window fabrication and lower resistivity, thinner, n-type silicon material.

We use $n<100>$, $1\sim 2\text{ k}\Omega\text{cm}$, $280\mu\text{m}$ thick, 100 mm diameter silicon wafers. The processing of these SDD arrays at BNL was as follows: On the window side, we used 10 keV ($1\times 10^{14}/\text{cm}^2$) boron ions and 50 keV ($4\times 10^{12}/\text{cm}^2$) phosphorus ions implanted through a 500 Å silicon dioxide layer to produce the thin entrance window of the SDD. Fig. 3 shows simulation of this implantation and electric field near the silicon surface. This 500 Å of oxide was removed first by wet etching, and then the native oxide was removed by back

sputtering before deposition of a 1100 – 1200 Å thick aluminum layer. Therefore, the entrance window is radiation-hard due to the lack of silicon dioxide between the thin-junction and the aluminum layer. A partial cross-section of the detector is shown on fig. 4.

Fig. 3. A simulation of the implantation profiles and electric field distribution near the silicon surface is shown.

Fig. 4. A partial cross-section of single spiral SDD is shown. The material is n-type <100> silicon with a thickness of 280 μm and a resistivity of 1~2 kΩ·cm.

On the device side, the original 4700 Å of silicon dioxide was etched down to 500 Å at the E1, the spiral and the guard rings. A 45 keV ($1 \times 10^{15}/\text{cm}^2$) boron-implantation through 500 Å of silicon dioxide generates the p⁺ E1, spiral and guard rings. Then the silicon dioxide was removed completely at the central anode and at the sink anode for a 45 keV ($1 \times 10^{14}/\text{cm}^2$) phosphorus ion implantation while the entire p⁺ region was covered by an aluminum mask. After the implantation and removal of the aluminum mask, we annealed the SDD array at 700 °C for 17 hours. Back-sputtering was then performed to remove the native oxide after the 500 Å silicon dioxide layer was first removed by wet etching from the spiral where the metal-contacts' were to be placed. A layer of 2500 Å aluminum was deposited following the back-sputtering. The entire process of fabricating the SDD array involves seven masks and entails eight mask steps. Fig 5 shows a finished low resistivity wafer containing two larger SDD arrays, each containing 64 SDD pixels, two smaller sets of 16 SDDs and 5 SDDs. There are also some test structures on the rest of the wafer.

Fig. 5. Finished 100 mm diameter wafer contains SDD arrays and testing structures.

IV. TEST RESULTS AND DISCUSSION

A few of 16 array of low-resistivity, thinner-silicon SDD were mounted into PC board and bonded to the application specific integrated circuit (ASIC) [11, 12] which were designed in BNL and were fabricated at the Taiwan Semiconductor Manufacturing Company (TSMC). We call the final assemblies of SDD arrays and ASICs as hybrid-SDD detectors. Fig. 6 shows a spectrum we obtained from an ⁵⁵Fe source with one of low-resistivity, thinner-silicon hybrid-SDD detector. Its energy resolution is 162 eV FWHM at 5.9 keV at a temperature of T= -50 °C (counting rate: 50 kcps), which is similar to that of a high resistivity hybrid SDD detector fabricated together at BNL.

Fig. 6. A spectrum we obtained from an ⁵⁵Fe source displayed in a logarithmic scale.

In order to test the radiation effects of this hybrid-SDD detector, we exposed two new hybrid-SDD detectors to high-energy 203 MeV protons, with doses of 0.25 Mrad and 1 Mrad, at the RERS1 beamline at the Indiana University Cyclotron Facility. In addition, one hybrid-SDD detector produced by KETEK on n-type, high-resistivity (6-7 kΩ·cm), thicker (450 μm) silicon wafer, was irradiated to 1 Mrad. Both types of hybrid-SDD detectors were tested before and after irradiation. All hybrid-SDD detectors were kept in a freezer (~-8°C) after irradiation to avoid any thermal annealing

effects before testing took place. The corresponding radiation doses and the material used to produce SDD chips are listed in table I.

Table I. List of hybrid-SDD detectors made on various materials and irradiated to various doses.

	Fluence (p/cm ²) 203 MeV protons		Notes
Device	4.26x10 ¹² (0.25Mrad)	1.7x10 ¹³ (1.0Mrad)	
B1 SDD hybrid		X	1~2kΩcm, 280μm
B2 SDD hybrid	X		1~2kΩcm, 280μm
K SDD hybrid		X	6~7.5kΩcm, 450μm
Exposed t(min)	4.3	17.4	

After 0.25 Mrad irradiation, the tests of the low-resistivity hybrid-SDD detector showed (fig.7) that the energy resolution is 298 eV FWHM at 5.9 keV (T= -75 °C, 50 kcps), which is higher than the value measured prior to irradiation. After 1 Mrad irradiation the spectrum is much broader (T= -50 °C, 50 kcps) for the same low-resistivity hybrid-SDD detector. Since the leakage current is increased due to irradiation, the estimated value of the temperature, which could bring the leakage current down to the pre-irradiation level, is -100°C for 0.25 Mrad and -106°C for 1 Mrad. Although our measurement was limited by our current temperature constraint of -75°C, we can still clearly see the radiation hardness of the low-resistivity material by comparing to high-resistivity material in fig. 8, where both hybrid-SDD detectors had 1 Mrad irradiation.

Actually after irradiation, the silicon material underwent significant damage, which generated many trapping sites. The trapping time calculation is $\tau_t^{-1} \sim 5 \times 10^{-7} \Phi_{\text{eff}}[13]$. For the 1 Mrad dose, the applied fluence is $1.7 \times 10^{13} \text{ n}_{\text{eq}}/\text{cm}^2$ (1 Mrad), which gives a calculated trapping time of just 0.1 μs. This is significantly less than ~0.3 μs for the regular drift time of our SDD with drift distance of 2.5 mm and drift bias (U_{ot}) of 130V without irradiation. Thus after irradiation it is very likely that significant trapping is taking place.

To overcome this we can increase the drift bias U_{ot} , which however has a limit according to Eq. (3), and may necessitate further cooling to offset the resulting increase in leakage current. We can also attempt holding the device at elevated temperatures to anneal out the trapping defect levels. Both these changes are planned for the future. A final obvious solution would be to redesign the radiation-hard version of the SDD pixels to reduce the drift distance of the charges (much smaller pixel size, < 1 mm, ~0.5 mm drift distance), so that the drift time will be smaller than the trapping time. One may also use p-type material to avoid the inversion problem (the trapping problem still demanding small pixel size though), which requires an entirely new design of a hybrid SDD detector including new ASICs and new SDD detectors, and therefore a much larger effort and longer development time.

Fig. 7. The FWHM of the spectrum broadens as the radiation dose increases.

Fig. 8. The spectra were obtained by hybrid-SDDs which both made of low-resistivity and high-resistivity material, both irradiated by 1 Mrad 203 MeV protons.

V. CONCLUSION

New low-resistivity, thin-window, thinner-silicon, n-type SDD arrays have been designed, produced and tested. For the first time these SDDs were produced on lower resistivity, thinner-silicon material. This new SDD build with thin-entrance window has shown good energy resolution (FWHM of 162 eV) for detecting ⁵⁵Fe X-rays, which is equivalent to the performance of a high-resistivity SDD detector. Lower resistivity SDD has shown improved radiation hardness up to at least 0.25 Mrad of 203 MeV proton radiation. Further study on irradiation up to 0.5 Mrad to this low-resistivity SDD detector is needed. Ultimately for operating in the Jovian system it is necessary to redesign the radiation-hard version of the SDD pixels to reduce the drift distance of the carriers, so that the drift time will be smaller than the trapping time. But the charge sharing between neighboring pixels, for the smaller pixel array, needs to be considered.

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