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Possibilities for Thick, Simple-Structure Silicon X-Ray Detectors Operated by Peltier Cooling

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Abstract. We have proposed two types of simple-structure silicon (Si) X-ray detectors with 1.5-mm-thick high-resistivity Si substrates, which are able to be operated at reasonably low negative bias and cooled by Peltier cooling. Since the device structures are simple and the detectors require only one high voltage, the cost of the X-ray detection system can be reduced very much. Moreover, the absorption of cadmium X-ray fluorescence (energy: 23.1 keV) in 1.5-mm-thick Si is approximately 65%, whereas in commercial silicon drift detectors (Si thickness: approximately 0.3 mm), it is approximately 19%. We have simulated the electric potential distribution within the proposed detectors and carried out fundamental experiments towards the realization of the detectors.

Introduction

Various types of X-ray detectors, such as silicon (Si) pin diode detectors or silicon drift detectors (SDD) [1,2], are used for measuring the energies and counts of incoming X-ray fluorescence photons. Although a pin diode can be used for collecting charge carriers that are proportional in number to the energy of the X-ray photon, the capacitance of the detector becomes large, which degrades its performance. To reduce the capacitance, the SDD was proposed. An SDD has a small anode (n layer), relative to the anode of the pin diode, at one surface of the n^--type Si substrate (i layer) and a large entrance window layer (cathode or p layer) at the opposite surface of the substrate. The anode is surrounded by multiple p-type rings (p ring), which are biased in such a way that they result in an electric field which causes electrons to flow towards the anode. The p rings are electrically coupled within the prior art SDD using metal-oxide-semiconductor field-effect-transistors (MOSFET) or implanted resistors in order to form an adequate electric field in the SDD. Although the SDD can have reduced electronic noise compared with the pin diode, SDDs with MOSFETs or implanted resistors can be costly to manufacture. Therefore, the authors have proposed simple-structure SDDs without MOSFETs or implanted resistors [3-7].

To detect a trace of hazardous elements in foods and soil, the absorption of cadmium (Cd) X-ray fluorescence (energy: 23.1 keV) should be higher than 50%. Because the i layer in commercial SDD is approximately 300 μm, however, the absorption of Cd X-ray fluorescence is approximately 19% [8]. Therefore, thick Si X-ray detectors have been investigated [8-10].

Besides low cost and high sensitivity to high-energy X-rays, detectors should be transportable. This means that the cooling mechanism should also be compact and transportable, as is the case with a Peltier cooler. In this study, therefore, we investigate the possibilities for thick, simple-structure Si X-ray detectors operated by Peltier cooling.

Proposed Thick, Simple-Structure Si X-Ray Detectors

Figure 1 shows the schematic half structure of a simple SDD without MOSFETs or implanted resistors, hereafter SSDD [3,4,7]. The same negative voltage bias is applied to the cathode and the outermost p ring, and the other p rings are floating. The anode is connected to the junction FET (JFET) in a pre-amplifier.

Figure 2 shows the schematic cross section of a gated SDD with only one p ring, hereafter GSDD [5,6]. In the figure, an oxide layer is used as a passivation layer, which is adopted in almost all Si devices. Since gates (i.e., metals) are formed on the oxide layer during metallization of the anode and the p ring, there are no special processes required to form the MOS structures. The same negative voltage bias is applied to the cathode, the p ring, and all the gates, and the anode is connected to the JFET.

To meet the requirement of high sensitivity to X-rays with energies up to 25 keV as well as reasonably low bias operation, the Si substrate should be thicker than or equal to 1 mm and should have resistivity higher than 5 kΩ·cm (that is, a donor density lower than 10^{12} cm^{-3}).

The fabrication processes of both SSDD and GSDD are the same, and are much simpler, compared with the prior art SDD. Moreover, these detectors require only one high voltage bias. Therefore, the cost of the X-ray detection system can be reduced very much.

Fabrication Processes

To investigate whether higher-resistivity Si substrates can be used to fabricate thick SSDD and GSDD, these SDDs were fabricated using 300- or 625-μm-thick n^- Si substrates with a resistivity of 2 kΩ·cm, 6.5 kΩ·cm, or 10 kΩ·cm. To fabricate 2.5-μm-thick p rings for the formation of an adequate potential gradient in the i layer, boron (B) ions of 1×10^{15} cm^{-2} were implanted at 60 keV to one side of the substrate, and then the substrate was annealed at 1100°C for 50 min in an O_2 atmosphere. To produce a 2-μm-thick anode with 80 μm in radius at the center of the SDD, phosphorus ions of 6×10^{15} cm^{-2} were implanted at 60 keV to the same side of the surface, and then the sample was annealed at 1000°C for 40 min in O_2. To form a 0.3-μm-thick p layer at the opposite surface, B ions of 1×10^{14} cm^{-2} were implanted at 50 keV through a 60-nm-thick oxide layer, and then the sample was annealed at 900°C for 30 min in O_2. In these processes, approximately 1.5-μm-thick SiO_2 passivation layers were formed on the surface. Finally, the anode and the cathode were metalized. At the same time, the gates were formed in the case of GSDD.

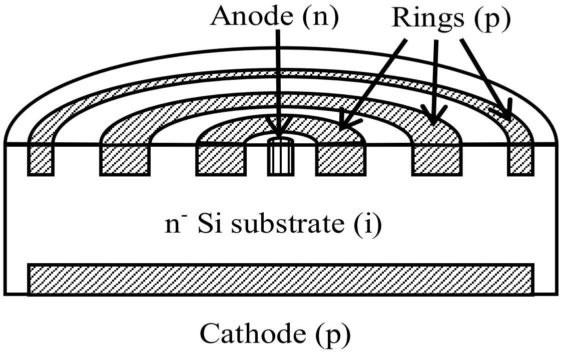

Fig. 1 *Schematic half SDD structure with a few p rings which are not connected by MOSFETs or implanted resistors (SSDD). The same negative voltage is applied to the cathode and the outermost p ring, while the other p rings are floating.*

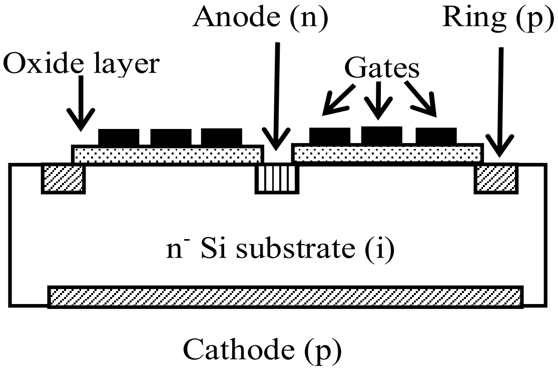

Fig. 2 *Schematic cross section of SDD structure with one p ring and a few gates (GSDD). The same negative voltage is applied to the cathode, p ring, and all the gates.*

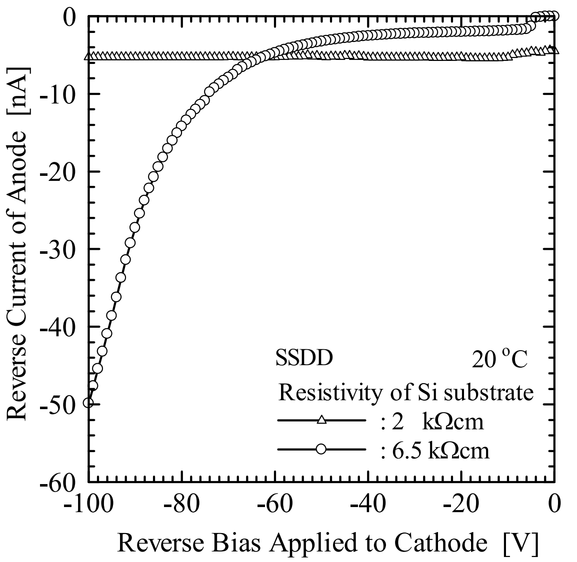

Fig. 3 *Leakage current of anode in 300-μm-thick SSDD with different voltages applied to three p rings.*

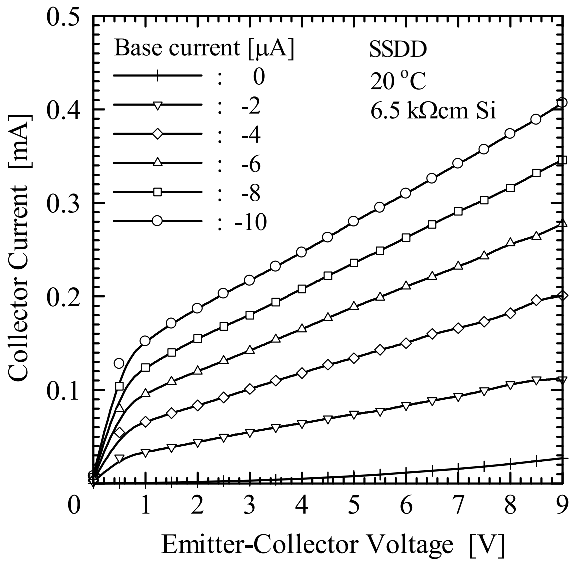

Fig. 4 *Characteristics of collector current vs. emitter-collector voltage when SSDD with 300-μm-thick 6.5-kΩ·cm Si is regarded as pnp transistor.*

Results and Discussion

Figure 3 shows the dependence of the leakage current of the anode on the bias of the cathode in SSDDs with 300-μm-thick 2-kΩ·cm and 6.5-kΩ·cm Si, when – 5 V, – 42.5 V, and – 80 V were applied to the innermost, middle, and outermost p rings, respectively. At higher than – 60 V, the leakage current in the 6.5 kΩ·cm case was higher than in the 2 kΩ·cm case. The leakage current of the cathode in the 6.5 kΩ·cm case is of the order of mA, although it in the 2 kΩ·cm case was of the order of nA. This is because in the 6.5 kΩ·cm case, a large hole current flowed between the cathode and the p rings [7]. Figure 4 shows the current-voltage characteristics of a pnp transistor with the p ring as an emitter, the anode as a base, and the cathode as a collector using 300-μm-thick 6.5-kΩ·cm Si. To block the hole current between the cathode and the p ring, the same negative voltage should be applied to the cathode and the outermost p ring, and the other p rings should be floating. Otherwise, all the inner p rings should be omitted in Fig. 1 [4].

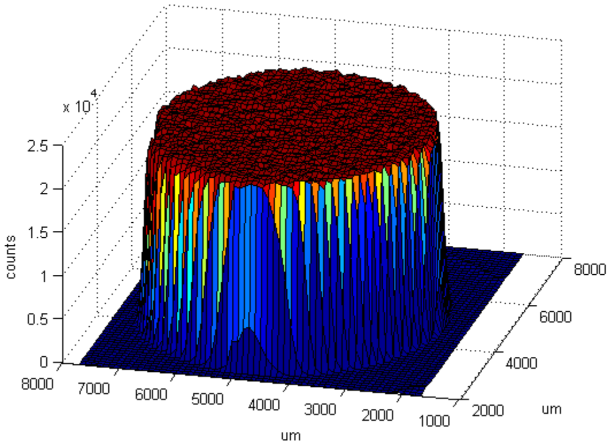

Fig. 5 *Mapping of counts produced in 625-μm-thick GSDD with 10-kΩ·cm Si substrate to which X-rays were incident through 100-μm- diameter pinhole, by moving the detector in 100-μm increments. The active area is approximately 18 mm^2.*

As shown in Fig. 2, the GSDD has only one p ring. To form an adequate electric field between the anode and the p ring, gates are added. The performance of a 625-μm-thick GSDD with a 10-kΩ·cm Si substrate was investigated with – 90 V applied to the cathode, the p ring, and all the gates. At a peaking time of 5 μs and temperature of – 35 °C, a resolution of 145 eV at 5.9 keV was measured from the ^{55}Fe source. The peak-to-background was 2208 to the background level at 2 keV, which is not good because the entrance window had not been optimized for a high peak-to-background. Using a 100-μm-diameter pinhole and moving the detector in 100-μm increments, the active area was mapped out, which is shown in Fig. 5. The active area was approximately 18 mm^2, which is consistent with simulation.

The electric potential distribution in the SSDD and GSDD shown in Figs. 1 and 2 with 1.5-mm-thick 10-kΩ·cm Si substrate were simulated. Figure 6 shows the electric potential distribution within the Si substrate of a GSDD when – 400 V was applied to the cathode, p ring, and three gates. Here, the positive fixed charge in SiO_2 near the SiO_2/Si interface was assumed to be 10^{10} cm^{-2}. It is clear from the simulated electric potential distribution that electrons produced by incident X-rays can flow smoothly to the anode.

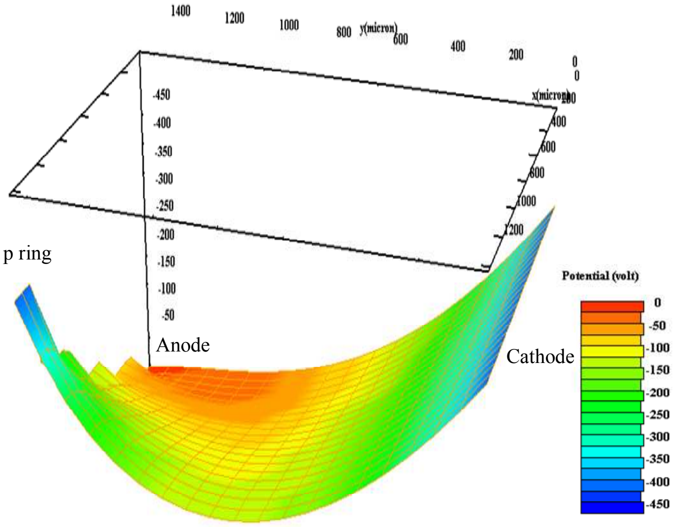

Fig. 6 *Simulated electric potential distribution within 1.5-mm-thick GSDD with 10-kΩ·cm Si substrate. The cathode, p ring, and three gates are biased at – 400 V. The positive fixed charge in* SiO_2 *near the* SiO_2*/Si interface is assumed to be* 10^{10} *cm*$^{-2}$.

Conclusions

For transportable and simple-structure Si X-ray detectors that can be operated at reasonably low reverse bias by Peltier cooling and can be sensitive to X-rays with energies up to 25 keV, two types of detector structures (SSDD and GSDD) were proposed. To search whether SSDD and GSDD with thick Si substrate can be operated by Peltier cooling, these detectors with high-resistivity Si substrate were fabricated and investigated. The results indicated that SSDD and GSDD with thick high-resistivity Si substrate are feasible. By device simulation, moreover, adequate electric potential distributions in detectors with 1.5-mm-thick Si substrate were obtained.

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