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Development of high-resolution silicon-based particle sensor with integrated amplification

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ABSTRACT

The electronic noise of the front-end preamplifier can potentially limit the energy and position resolutions of radiation sensors, a detrimental effect that can be diminished by the use of on-chip amplification. The implementation of an avalanching structure upon a direct-conversion semiconductor-based radiation detector is modeled and demonstrated using high-resistivity silicon. The avalanche particle sensor configuration is designed analytically, and we validated the design with numerical process and device simulations. Process and device simulation results from the sensors modeled with various geometries, doping profile arrangements, and fabrication conditions are reported. We tested the refined numerical design by fabricating and testing diagnostic sensors. Multiplication junctions, based on a junction termination extension design, were created from micrometer-scale highly-doped layers on silicon wafers using both diffusion and ion implantation techniques. For <100 keV energy depositions, our modeling has shown that a gain of ~ 8 is ideal if one is attempting to optimize the SNR, which is realized in the experimental detectors at an excess bias of 3 V. At that voltage, the energy resolution for 81 keV gamma-rays can, in principle, be reduced from 2.12% to 0.96% (for a $k_\alpha = 0.2$ device), the degree of improvement limited by the leakage current of the devices, and within a factor of 2 of the ultimate Fano limit (0.53%).

1. Introduction

For solid-state devices that convert energy directly into charge carriers, the noise floor is typically provided by the thermally-generated current fluctuations in the detector and the preamplifier electronics. The detector's surface-leakage current can be mitigated by guard rings and surface passivation [1–3]. The bulk leakage current can be quenched by either gettering the mobile impurities [4] or by employing fabrication techniques that reduce the frequency of the phonon-electron scattering. Specifically, one can use the environmental interface as a sink for longitudinal acoustic phonon modes [5] or one can employ nanostructured semiconductors for which the strength of the carrier–carrier coupling exceeds that in the equivalent bulk semiconductor [6,7].

Upon the successful quenching of the detector's noise, the noise floor is not typically set by the statistical counting limit associated with the stochastic charge-creation process during a radiation interaction as desired, but rather by the gate noise of the preamplifier ("preamp"). For instance, Fig. 1 shows the ^{133}Ba gamma-ray spectrum for a small silicon PIN diode, the fabrication of which is described in [3]. If one calculates the Fano noise that results from the deposition of 81 keV in silicon (using a Fano factor of 0.115) then the energy uncertainty is 0.53% (0.432 keV), compared with a measured uncertainty of 2.1% (1.7 keV). One can cool the front-end amplifier and develop advanced amplification methods to reduce the noise contribution of the preamp; however, if one can increase the signal size from the detector itself, then a higher preamp noise can be tolerated.

In optical photon devices, avalanche multiplication is used to produce internal device gain and enhanced signal-to-noise ratio (S/N) in the form of avalanche photodiodes (APDs), but on-chip avalanching is not typically employed in direct-conversion nuclear radiation detectors for two reasons. First, an avalanche particle detector, termed an APaD, requires that the multiplication junction be developed across a relatively small voltage (<1 V typically) because the depletion junction width of a nuclear detector may be

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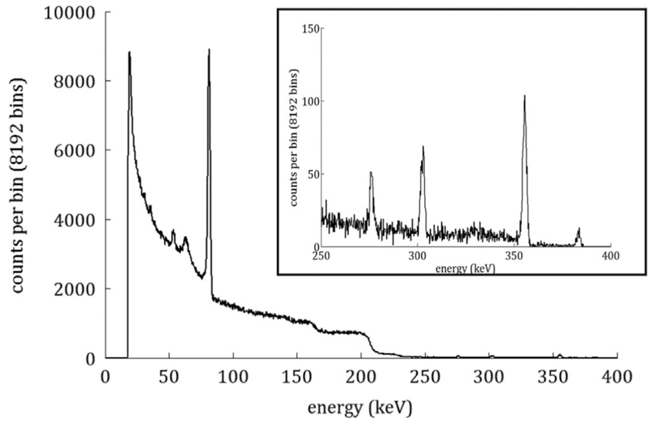

Fig. 1. ^{133}Ba gamma-ray spectra, derived from Ag-bounded circular diodes Si PIN detectors operated at 100 $V_{reverse}$ in which the number of 1 mm diameter circular diodes on the 1 × 1 cm^2 die is maximized. The inset shows an expanded view of the 250–400 keV region, where most of the photopeaks reside. The peak resolution is 2.12% (1.72 keV) at 81 keV and 0.48% (1.71 keV) at 356 keV; in fact, the noise is sufficiently low that the charge-sensitive readout noise characteristics dominate the peak widths.

hundreds of micrometers to centimeters thick in order to efficiently stop a high-energy or incident neutral particle, compared with the few micrometers needed to highly attenuate optical photon flux. The consequence on the fabrication is that highly doped junctions must be formed to realize a high enough field to produce impact ionization near the surface.

Second and more importantly, the signal size associated with a nuclear radiation event is orders-of-magnitude larger per quanta compared with optical-photon events, thus reducing the relative influence of the fixed noise source provided by the preamplifier. Instead, the multiplication noise associated with the stochastic process can become dominant. The range of energy depositions over which avalanche multiplication improves the SNR is presented in Section 3, in which we quantify the degree of improvement in the energy resolution for various multiplication factors and excess noise factors depending on carrier injection condition.

We designed the avalanche particle sensor configuration analytically and validated the design with numerical process and device simulations, as summarized in Section 2. The modeling indicates that effective multiplication junctions composed of thin n+/p+ layers can be confined to the central part of the diode if a junction termination extension (JTE) configuration is employed.

Finally, we tested the numerical design by fabricating and testing diagnostic sensors, the results from which are summarized in Section 3. The high-speed, high-resolution particle sensor consists of a high-resistivity p-type silicon substrate, in which electrons are injected into an n+/p+ multiplying junction, in which a drift field is created across the bulk of the detector and an amplifying field is created at the n+/p+ interface, the gradient and width of which governed the gain of the device. This configuration can enhance the direction and energy measurements of ions, electrons, and low-energy photons, and is therefore applicable to detailed studies of the heliosphere, the Earth's magnetosphere, rare-isotope beams, as well as general particle sensors that require improved energy resolution.

2. Detector modeling and fabrication

2.1. Device modeling and simulation

In order to analytically design a diode-sensor that contains: 1) a thick stopping layer for incident particles (electrons, ions, and photons), and 2) an avalanche junction that amplifies the number

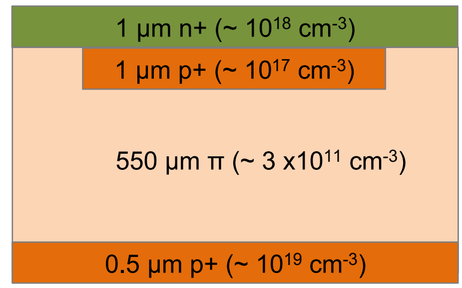

Fig. 2. Schematic of the analytical layer design of avalanche particle detector with JTE structure.

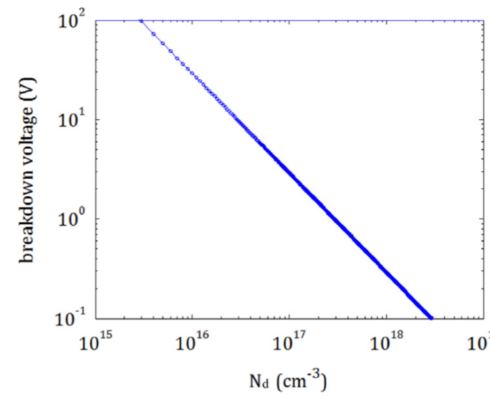

Fig. 3. Variation in the breakdown voltage as the doping is varied, assuming a one-sided step junction and a critical field of 3 × 10^5 V/cm.

of charge-carriers as they drift toward the collecting electrode, we modeled variations on the n+/p+/π/p+ structure shown in Fig. 2. Since the APaD has a much larger depletion region than an APD (0.5–2 mm thick, compared with a few micrometers for an APD), only a few volts or even a fraction of a volt drops across the amplifying junction. That is, one biases the sensor such that the physical thickness of the silicon substrate is fully depleted and no more, because higher bias can result in higher leakage-current noise. For high-resistivity ($\rho > 10$ kΩ cm) silicon, only 70 V is required to deplete 550 μm, which distributes uniformly in depth.

For a given doping concentration, the bias voltage ($V_{breakdown}$) needed to produce a critical breakdown field (E_c) of 3 × 10^5 V/cm is shown in Fig. 3, assuming a one-sided step junction [8]:

$$V_{breakdown} = \frac{\varepsilon_s E_c^2}{2qN_d}, \quad (1)$$

where ε_s is the semiconductor permittivity, q is the unit charge, and N_d is the doping concentration. If less than a volt drops across the amplification junction, then the lower doped side of the junction must be doped to greater than 10^{17} cm^{-3}. Such calculations result in the baseline design shown in Fig. 2, from which numerical simulations can validate the design.

Note in Fig. 2 that the bottom p+ layer has two purposes, first as an ohmic contact layer for the bottom metal (Cr/Au) electrode, and second, we make the p+ layer polycrystalline in order to serve as a sequestration layer during ionic-impurity gettering. The n+ layer is also extended beyond the p+ layer in order to realize a junction termination extension (JTE) design, noting that the field at the n+/π interface is much lower than that at the n+/p+ layer, thus confining the highest field region to the interior of the n+/p+ junction. This analytical n/p junction design analysis can be buttressed by numerical simulations using the Sentaurus Device Toolkit, which can provide guidance on the corner behavior and the process recipe needed to realize the JTE design.