Performance of a Junction Termination Extension Avalanche Photodiode for Use with Scintillators

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Abstract. An avalanche photodiode with a ring structure called junction termination extension (JTE) was built and tested. It has three diffused rings around the main junction to avoid early breakdown at the surface. The JTE rings have less doping than the main junction and can be built by well controlled single ion-implantation through a single mask. Avalanche photodiodes with two mm diameter active area have been built by implantation of boron with a dose of 2, 3, 4 and 5 $\times 10^{12}$ cm$^{-2}$, followed by deep diffusion of the junction up to 14 $\mu$m. The dark current is strongly dependent on the implantation dose, decreasing with decreasing charge. For the APDs with implanted dose of $5 \times 10^{12}$ cm$^{-2}$ a gain of 8 is obtained at 1120 V. The energy resolution from a $^{137}$Cs source was measured to be 24.4% FWHM with a 2 x 2 x 2 mm3 BGO scintillator. We have also performed simulations of the gain and breakdown voltage that correlate well with the results.

1. Introduction
Avalanche photodiodes (APDs) have advantages over normal silicon detectors or photomultiplier tubes when used in specific applications[1]. They are insensitive to magnetic fields, they are very small, its size can be tailored easily for a specific application and they have fast response with higher gain than normal PIN photodiodes. For PET instrumentation APD detectors may reduce the cost of the detector/scintillator ring, and it may allow to build smaller rings with better resolution[2]. One of the structures that has the lowest noise is the "beveled edge" photodiode. These detectors have a structure that is similar to the high voltage diodes and thyristors and have mechanical grooves or bevel edges built in[3]. In spite of efforts by various groups these devices found very limited application because of poor stability, low production yield, high device-to-device variations and early breakdown due to local variations in resistivity. The bevel structure has a 15º angle that has to be contoured, polished or etched[4]. Subsequently, this edge has to be passivated and cured to avoid high surface currents. The bevel is very large (~ 2 mm from the active surface) preventing the manufacturing of small devices and limiting the packing fraction that can be obtained in an array.

An improvement in the reliability of the devices and a decrease in cost can be achieved if the APD does not need a bevel or grooves to reduce the electric field at the surface. A common technique requiring no additional processing steps are field-plate and floating guard ring terminations[3]. In the present work, a new type of junction termination is investigated, named junction termination extension[5]. These detectors have a structure that is similar to avalanche photodiodes built previously[6]. These detectors were built on lower resistivity wafers to obtain lower breakdown
voltage, and the implantation dose was reduced. They were built at the facilities of the Institute of Semiconductor Physics, Siberian Branch of RAS, Novosibirsk, Russia

2. Gain simulation

One dimension computer modeling of the JTE-APD structure was performed to estimate the width of the depleted region and breakdown voltage and to help understand the dark current and gain characteristics. By solving the Poisson equation[3], it is possible to obtain the gain for a given bias:

$$M(x) = \frac{1}{1 - \int_0^W \alpha_n \exp\left[ -\int_x^W (\alpha_n(y) - \alpha_p(y))dy \right] dx}$$

where $W$ width of the depleted region, is the $\alpha_n$ and $\alpha_p$ are the impact ionization coefficient for electrons and holes [3], which are strongly dependent on the electric field.

3. Results

The dark current as function of bias was measured in several devices with different implanted doses. The variability in the dark current for each implantation depth was found to be low, which is an indication that the performance of the devices is not very dependent on the process. As seen in Figure 1, the device to device variation in dark current is less than 100 nA at 800 V. However, the dark current of the APDs was found to be very sensitive to the implantation dose. The dark current for several devices with four implantation doses is shown in Figure 1. It is clear that the lower dose gives lower dark current. A possible reason for this behavior is that as the dose is increased, the peak electric field near breakdown increases. When the peak electric field increases at the junction, the increase at the curved part of the depletion region surface is even higher [5] and may induce early breakdown. The devices with implantation doses of $5 \times 10^{12}$ cm$^{-2}$ do not reach more than 600 V, but it is clear that lower dark currents would be obtained by optimizing the amount of implanted charge.

![Figure 1. Dark current for several APD detectors with different implantation doses as function of bias.](image)

To measure the gain, the APD was illuminated with a yellow LED (~ 550 nm), which was driven with a pulse generator at 3 kHz. A 40 µs square pulse was used to generate the incident light. The output of the APD was connected to a 1000 Ω resistor and the voltage in the resistance was measured directly with a fast oscilloscope. The gain is obtained by normalizing the amplitude of the pulse at the desired voltage with the amplitude at 500 V (gain = 1). A gain up to 8 was obtained at 1120 V for
devices with implanted dose of \(2 \times 10^{12}\) cm\(^{-2}\) (just before breakdown). The measured gain is shown in figure 2 along with the modeled results from equation 1.

![Figure 2. Measured and modeled gain for APDs implanted with a dose of \(2 \times 10^{12}\) cm\(^{-2}\)](image)

To have an estimate of the performance of the detector, it was coupled to a \(2 \times 2 \times 2\) mm\(^3\) BGO scintillator, and the energy spectrum of a \(^{137}\)Cs source was measured. The APD was biased at 1100 V, the cathode was biased with positive voltage and the output was AC coupled to a charge sensitive preamplifier (eV 5092 from eV Products). The output from the preamplifier was connected to a shaping amplifier (0.25 μs shaping time), subsequently it was connected to an ADC and a multichannel analyzer. To calculate the resolution, the 662 keV peak was fitted to a gaussian curve (continuous line in figure 3). The resolution obtained was 24.4% FWHM for the 662 keV peak.

![Figure 3. Energy resolution from a \(^{137}\)Cs source of the APD coupled to a BGO scintillator.](image)
4. Conclusions
The data for the planar JTE avalanche photodiode show that very repeatable results can be obtained for the dark current because standard single-ion implantation process has been used. After optimization of the implanted charge, the structure has the potential to make very low noise detectors with high reliability. The dark current of the APDs was found to be very sensitive to the implantation dose and the dark current increases with higher implanted charge. The lowest current is obtained with a dose of $2 \times 10^{12}$ cm$^2$. A gain of 8 was obtained at 1120 V, which is not high compared to other APDs, but it is enough to obtain a 24.4% resolution from a $^{137}$Cs source. More work is needed to increase the breakdown voltage to bulk values, which will be accomplished by re-designing the rings structure.

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