Characterization of Very Large Silicon Avalanche Photodiodes

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Abstract— In this paper, we discuss recent advances in the high gain, very large area silicon avalanche photodiode technology. Very large area APDs (square and octagonal design, up to 45 cm\(^2\) area) have been built using the planar process. These APDs have been successfully operated as scintillation spectrometers. When cooled to –40 °C, the energy resolution of 5.9 keV X-rays (\(^{55}\)Fe source) upon direct interaction with the 45 cm\(^2\) APD was measured to be 2.4 keV (FWHM). The APD was coupled to a CsI(Tl) scintillator and irradiated with 662 keV gamma rays from \(^{137}\)Cs source and the energy resolution was measured to be ~10% (FWHM) at the temperature of –40 °C. A rise time of < 2 ns was measured with the 40 cm\(^2\) APD upon irradiation with 5.5 MeV alpha particles. A new packaging design has been developed to allow cooling of these large APDs to liquid nitrogen temperature. Evaluation of the 45 cm\(^2\) APD has been conducted at LN\(_2\) temperatures. Its gain was found to be as high as \(10^4\), while the noise was measured to be ~0.8 electrons (rms). Detection of low intensity optical signal (<8 photons/pulse) with the 45 cm\(^2\) APD has also been accomplished.

I. INTRODUCTION

Large area avalanche photodiodes (APDs) are versatile sensors of X-rays, visible light and gamma rays. The potential benefits that could be derived from using avalanche photodiodes have been recognized for over three decades [1] – [4]. The high internal gain of an APD (up to \(10^4\) at cooled temperatures) significantly improves the signal-to-noise ratio that can be achieved for detecting photons. Important features of these APDs are their high quantum efficiency, having a peak quantum efficiency of 60-80% at optical wavelengths, and wide spectral response, which are far greater than those for PMTs.

APDs are now fabricated using a planar processing method without any manual beveling steps. The resulting APDs have performance similar to the previous beveled edge devices but can be manufactured with very high yields at a much lower cost. Using this process, APDs sizes have been increased to over 40 cm\(^2\) as single element detectors, as pixelated arrays [5] and as position sensitive devices [6].

Figure 1 shows a 45 cm\(^2\) single element APD packaged on ceramic substrate. The packaging design allows cooling of the large APDs to LN\(_2\) temperature without any mechanical damage due to thermal stresses.

These compact, large area APDs with their high gain, relatively high QE, low light sensitivity, and magnetic insensitivity provides a unique opportunity to replace PMTs in those applications which could benefit from the properties offered by our large area APDs. Due to the large active area of these detectors, their associated large capacitance and resulting noise, requires some amount of cooling to meet the needs of a given experiment.

There are many potential applications for our large area APDs. Large scale physics experiments that use water Cherenkov detectors could employ large area APDs. While the integration of these APDs into a water environment would need to be addressed, the experiment would benefit from the high QE at blue wavelengths, the fast response, and low light level sensitivity. Scintillation spectroscopy for nuclear physics research, optical tomography, optical detection of biological and chemical molecules, direct X-ray detection, and charge particle detection are all potential applications of large area APD technology. Low background, low level counting radiochemistry experiments are also possible with such large APDs.

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II. LARGE AREA APD FABRICATION

In order for APDs to have the desired high gain property, a sufficiently strong electric field must be applied across the device. The relatively large distance involved requires a wide depletion region. RMD uses a depletion region that is 150 µm near breakdown. This in turn requires a deep p-n junction that can only be created with a deep diffusion. The high reverse bias that is applied across the device in turn creates strong electric fields that are a concern along the edge of the device where electrical breakdown could be less than in the bulk. To mitigate this problem APDs were beveled manually however this limited the yield and raised the APD cost. The manual bevel process is shown in Figure 2. We now use a planar producing method to create the deep-diffused profiles needed to fabricate an ultra-high gain APDs. This approach involves cutting grooves in a n-type 4-inch diameter NTD silicon wafers that are then used for the APD fabrication. The shape of the groove is used to influence the profile of the subsequent p-diffusions. The presence of grooves creates a curved diffusion profile. The resulting p-n junction profile, which is contoured, acts as a planar bevel that can be terminated at a required angle using etching and polishing methods. Figure 2 outlines the steps involved in this process that is very amenable to low cost fabrication of large area APDs [5].

III. CHARACTERIZATION & RESULTS

A. Large area APD gain & noise

While the 45 cm² APD was cooled to -40°C the gain and noise was measured as a function of the applied bias. In the test chamber with the APD, light from a 565 nm LED illuminated the detector. As the bias was increased the output pulse amplitude was recorded as well as the noise. At a bias of 200V, the gain is defined to be unity. At -40°C the maximum gain of the device is approximately 5000 while its noise is 70 electrons (rms). These gain and noise curves as a function of bias are typical of our planar processed APDs.

B. Energy resolution

The energy resolution from direct photon interactions and scintillation interaction was measured. Upon cooling the 45 cm² APD to -40 °C and irradiating it with 5.9 keV X-rays ($^{55}$Fe source), an energy resolution of 2.4 keV (FWHM) was achieved (see figure 4). The spectroscopic scintillation was also measured. A CsI(Tl) scintillator (38 mm diameter, 25 mm tall) was coupled to the APD while it was cooled to -40°C and irradiated with $^{137}$Cs (662 keV). The photopeak energy resolution is 10% (FWHM) (see figure 5).
C. APD timing response

The timing response of the 40 cm$^2$ APD has been measured. The APD was irradiated with 5.5 MeV alpha particles ($^{241}$Am source) and its response was captured directly on a digital scope (with 50 Ω input impedance) without any amplification or shaping. The rise time of the APD response was measured to be <2 ns, which is encouraging (see figure 6).

D. APD operating properties at LN$_2$ temperatures

The gain, noise and optical detection characteristics of the 45 cm$^2$ APD was extensively evaluated at LN$_2$ temperature. A cryostat assembly was built to cool the large APD to LN$_2$ temperature and a fiber optic cable was placed in the cryostat assembly to optically irradiate the device at 590 nm. The gain of the device was measured as a function of operating bias and was found to be as high as $10^4$ (see figure 7). The optimal operating gain (where the noise is minimized and the device operates in a stable manner) was ~1000. The operating gain was maintained constant while the APD was cooled by correspondingly lowering the applied bias (see figure 8). The dark current of the device was measured at LN$_2$ temperature. While at a gain of 1000, the leakage current was measured to be 30 pA (see figure 9).
A pulse height spectrum was then recorded with the 45 cm$^2$ APD cooled to LN$_2$ temperature upon exposure to an optical pulse along with an injected electronic pulse on a calibrated energy scale. From the broadening of the peak corresponding to the injected electronic pulse, the electronic noise of the device was estimated to be ~0.8 electrons (rms) (see figure 10). Furthermore, as can be seen in figure 10, the detection of low intensity optical signal (<8 photons/pulse) has been accomplished with the large 45 cm$^2$ APD cooled to LN$_2$ temperature.

IV. SUMMARY AND CONCLUSIONS

Large area APDs have been fabricated at RMD using planar processing techniques. These devices, when cooled to cryogenic temperature have a gain as high as 10$^4$ and a noise of approximately 0.8 electrons (rms). They also have a fast response. A rise time < 2 ns was measured with direct $\alpha$-interactions. Direct photon and scintillation detection was demonstrated when the detector was cooled to -40°C. When coupled to a CsI(Tl) scintillator, the energy resolution is 10% (FWHM) at 662 keV at that temperature. Our APDs have a very high QE at optical wavelengths and in the UV region. These results indicate that large APDs can be applied to optical and UV detection in such applications as water Cherenkov and liquid noble gas calorimetry. In addition, scintillation spectroscopy is a possible application for the very large APDs for use in medical imaging and astronomy. A wide variety of experiments that need large area detection for direct photon or charge particle interactions would also benefit from this technology.

V. REFERENCES