A Novel Silicon Geiger-Mode Avalanche Photodiode

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Abstract

Dark count non-linearity in CMOS compatible, single photon counting, Geiger-mode avalanche photodiodes (GM-APD) has been investigated. A novel structure was designed, fabricated, and characterized to allow dark count optimization. Dark count levels for the proposed structure are shown to scale linearly with area.

Introduction

The detection of single photons of light is important for a wide range of emerging scientific applications from single molecule fluorescence (1) to quantum cryptography (2). The International Technology Roadmap for Semiconductors: System-on-a-Chip (SOC), predicts the need for electro-optical sensors and electro-biological sensors to be incorporated into CMOS compatible processes by 2004 and 2006 respectively (3) and the NEXUS roadmap for medical diagnostics predicts a need for integrated photodetectors in the next five years (4). There is a paradigm shift occurring in life science and biotechnology instrumentation fields as bench-top detection platforms based on discrete detector subsystems are miniaturized into SOC platforms. For the true functionality of SOC platforms to be realized, ultra-sensitive photodetectors with integrated electronics which can be fabricated using industry standard CMOS fabrication techniques will be required.

Current optical based measurement systems are typically based on integration of a discrete charge coupled device (CCD) or photomultiplier tube (PMT)/microchannel plate (MCP) with reaction chambers, focusing optics and readout/signal processing electronics. The ubiquitous PMT, while easy to align because of its large active area (>mm) is based on vacuum tube technology, requires several thousand volts to operate, has a quantum efficiency limited by the photocathode material, and is not well suited for integration into SOC platforms. The CCD has extremely high photodetection probabilities, but the long readout times required are not optimal for fluorescent lifetime measurement which is a commonly used measurement technique. Practical solid-state alternatives to the PMT exist in the PerkinElmer SPCM (5). The PerkinElmer detector, while optimized for photon counting in its discrete module form, operates at high internal voltages of several hundred volts and processing conditions used to fabricate the deep reach through junction and low doped absorption regions are not compatible with standard CMOS processes and integrated electronics.

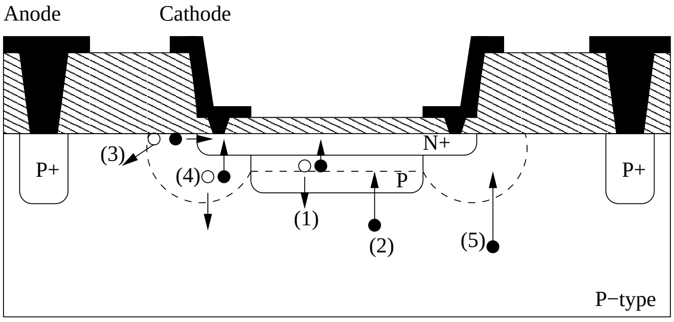

Fig. 1. Graphical representation of the basic GM-APD structure

The shallow junction, Geiger-mode APD (GM-APD) is fabricated with CMOS compatible processing steps and is designed for integration into integrated low light level sensing applications, see Fig. 1. The basic detector structure consists of a p-type substrate with a p-type doping forming the central active area and setting the breakdown voltage of the detector to ≈ 30 volts. The N^+ doping overlaps the active area, forms the diodes cathode, and contact to metal layers. The overlapping guard ring, and the diode it forms with the p-type substrate, prevents edge breakdown of the central active area. A high dose P^+ implant on the detector's periphery is used for top contact to the anode providing a planar device, which allows flip-chip integration. These detectors have shown to be sensitive to *atto* Ampere current levels (6), characterized for DNA microarrays (7) and have been successfully integrated into flip-chip microfluidic cell sorting experiments (8).

The ability to count single photons is a feature of the high electric field that is engineered in the active area of a GM-APD. In Geiger-mode operation, the APD is reverse biased beyond the electrical breakdown voltage. A GM-APD can remain in this state until a free carrier is generated and enters into the depletion region. There it is accelerated by the electric field and acquires sufficient energy to produce a self-sustaining breakdown of the active area by the process of impact ionization. In the absence of light the electrical effect of these mechanisms is termed the dark count rate, and is a measure of the number of false photon counts generated by the detector per second.

For normal device operation it is desired that the free carrier which initiates breakdown is generated by an incident photon. However, electron/hole (e/h) pairs can also be

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generated thermally through Shockley-Read-Hall (SRH) recombination-generation centers, or by bulk diffusion of minority carriers from the quasi-neutral region which are components 1 and 2 in Fig. 1 respectively. Periphery currents in the guard ring, currents 3-5 in Fig. 1, contribute to the measured leakage current but not to the dark count since the breakdown voltage of the guard ring is greater than the breakdown voltage of the central active area. The generation of e/h pairs and thermal bulk diffusion through the active area represent a characteristic noise of the detector and sets a limit for the ultimate sensitivity of GM-APDs. For normal GM-APD operation, a passive quench circuit (9) or faster active quench circuit (10) is used to lower the voltage across the diode after a breakdown event and raise the voltage above the breakdown voltage once the charge in the diode has dissipated. In this manner, a GM-APD cycles between on and off states and is able to register a macroscopic current flow to a single incident photon.

Dark count non-linearities

To investigate the dark count in GM-APDs, a range of circular detectors with diameters ranging from 10μm to 750μm were fabricated in commercial p-epitaxial (10μm p-type silicon epitaxy on <100> P^+) and Czochralski (CZ) (525μm <100> p-type) substrates. The dark count was measured at room temperature in a light tight enclosure using an active quench circuit and a variable power supply to bias the GM-APDs from 3 to 14 volts above the breakdown voltage. The measured dark counting rate for 15-50μm diameter circular detectors is shown in Fig. 2 for the CZ substrate detectors. Similar dark count rate trends were also observed for the p-epitaxial substrate detectors however, it was noticed that the dark count increased more rapidly beyond 25μm diameter. The detectors from 10-20μm showed lower dark counts than comparable CZ substrates. The thicker absorption region of the CZ substrate appears to increase the thermal diffusion component of the dark count and thus the CZ devices show a slightly higher dark counting rate than the p-epitaxial substrate devices as shown in Fig. 2.

The dark counting rate of the GM-APDs would be expected to increase with increasing diameter from thermally generated carriers. However, the dark count rate does not increase linearly with increasing detector area as shown in Fig. 3 where the dark count rate per unit area at five and ten volts above the breakdown voltage is plotted for detectors from 10-50μm diameter. A non-linear increase in dark count rate has been attributed to afterpulsing associated with trapping effects due to defects in the silicon (11). It is thought that the gettering mechanism for the removal of defects and impurities is not sufficient to remove the defects outside the active area in larger diameter detectors. This limits useful devices to diameters typically less than 20μm. While the smaller area detectors show promise for integration into future SOC systems, where the small size is of benefit, integration into today's larger optical based measurement systems is quite difficult because of tight optical alignment tolerances needed to couple light into the small diameter detectors.

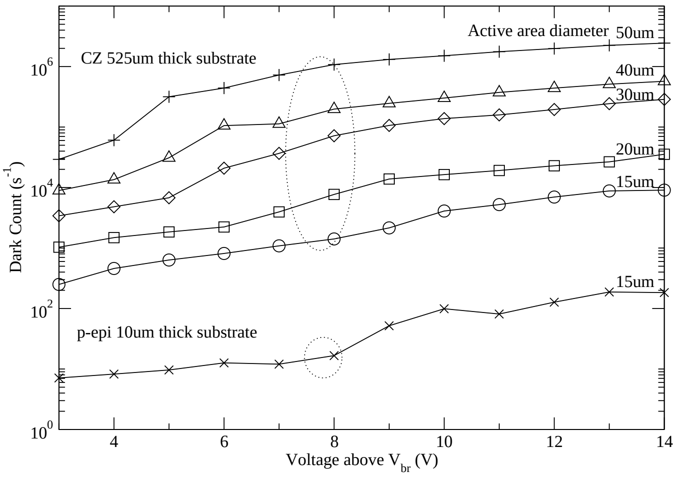


Fig. 2. Measured dark count of 15, 20, 30, 40, and 50 μm diameter circular Geiger-mode diodes measured at biases of 3 to 14 volts above the breakdown voltage using an active quench circuit with a hold off time of 200ns.

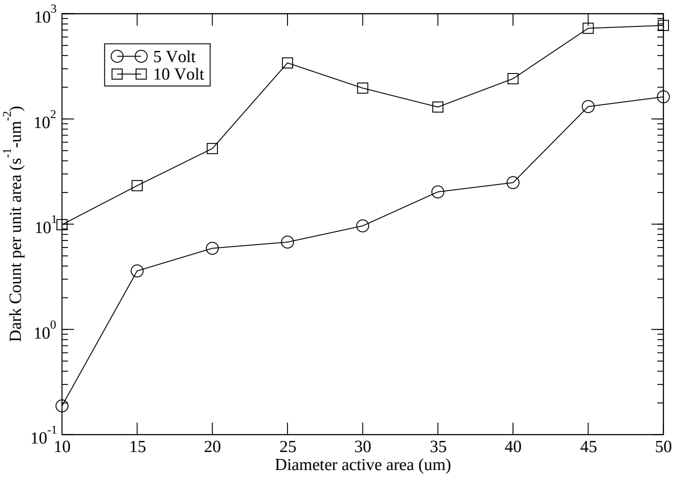
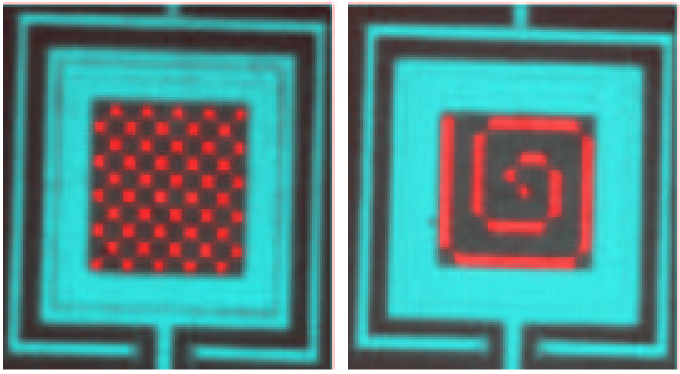


Fig. 3. Dark count per unit area measured on 10-50μm circular Geiger mode APDs. Dark count does not scale linearly with increasing area.

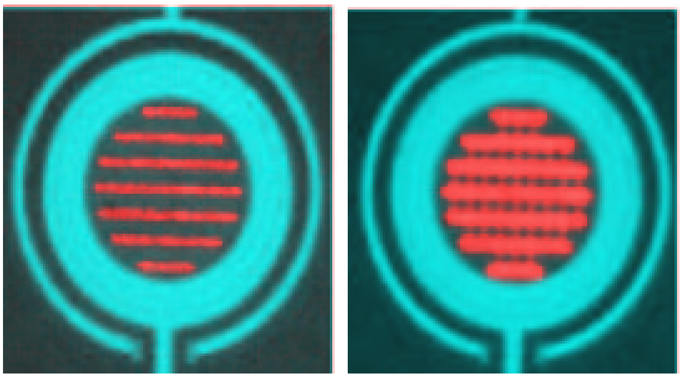
Novel Detectors

Since the gettering mechanism appears to be efficient in small diameter devices to produce low dark count detectors it was thought that many smaller area detectors operating in parallel would perform the function of a much larger area detector with a dark count rate per unit area that would compare favorably with a small area GM-APD (12).

To demonstrate the viability of this concept a range of devices was fabricated with different active area geometry. Since it was suspected that defects not removed from the active area by gettering contribute to higher levels of dark counts in large detectors, detectors were fabricated with separate active areas as well as with several connected active areas. A range of standard GM-APD detectors, described above, as well as novel detectors were fabricated. Wafer level emission camera images of several detector structures were obtained operating above breakdown as shown in Fig. 4. The light emission from reverse biased pn junctions is a well known phenomenom that limits the minimum pixel spacing of GM-APD arrays (13), (7). By operating the devices in parallel the light emission is not of concern for discrete devices and allows multiplying active areas to be viewed.



(Structure 1) (Structure 2)



(Structure 3) (Structure 4)

Fig. 4. Novel GM-APDs operating in Geiger-mode and viewed with an emission microscope.

The emission images from a selection of fabricated structures in Fig. 4 shows a range of devices with varying implementations of parallel active areas, but all with 100μm overall diameters or widths. In Fig. 4, Structure 1 is a device with full spacing around the active area to allow for maximum gettering while Structures 2 and 3 show devices with less gettering space and Structure 4 shows a device with a minimal of gettering space surrounding the active areas.

To determine the effect of the gettering zones on the GM-APD dark count performance, structures 1-4 of Fig. 4 were measured along with 15μm test GM-APDs from a single wafer. The dark count per unit area of the novel shapes is shown in Fig. 5 along with the baseline set by the 15μm circular GM-APD. As can be seen in Fig. 5, Structure 1, which has the largest amount of space surrounding each individual pixel for gettering closely approximates the 15μm detector in its dark count per unit area. As the amount of gettering room surrounding the active area decreases, as in Structures 2-4, the dark count per active area is shown to increase.

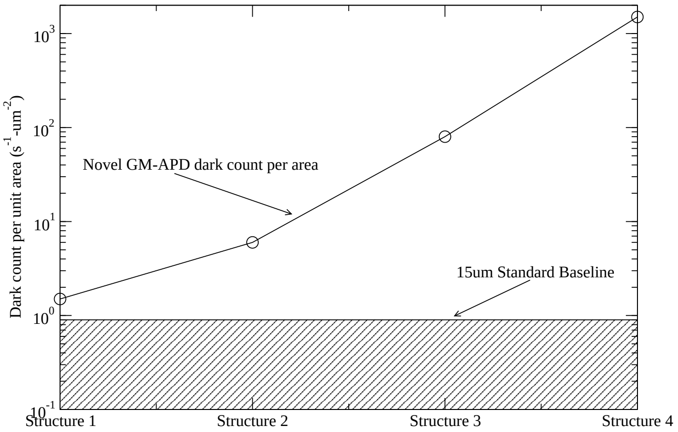


Fig. 5. Graph of the measured dark count per unit area for Structure 1-4 and a 15 μm circular diameter Geiger-mode APD. The dark count of Structure 1 which has the largest gettering area has the lowest dark count possible per unit area.

The proposed GM-APD structure would appear to provide a method by which to produce detectors with dark counts that scale linearly with area as well as arbitrarily sized detector structures that can be tailored in shape and size to fit a specific application. One drawback of this approach is that the detectors quantum efficiency will suffer from the loss of detection area caused by the dead space between active areas. To study the possible effects of this a photon detection probability experiment using a halogen light source, a calibrated reference detector and various 10nm wide narrow bandpass filters with center wavelengths from 400nm to 700nm was carried out. A 20μm GM-APD fabricated on p-type epitaxy was operated between 3 and 10 volts above the breakdown voltage using an active quench circuit operating with a 125ns hold off time. The measured photon detection probability measured at 10 volts above the breakdown voltage is shown in Fig. 6. A total photon detection probability of 43% was obtained which is considered excellent since no anti-reflection coating was used on these test samples.

Room temperature operation of the new structures was not possible as the detector's dark count, while increasing linearly with area, would require cooling, where an order of magnitude decrease in dark count is obtained for every 20 degree drop in temperature (7), for satisfactory operation. The effect of the dead space between the parallel detectors can be extracted by calculating the packing density of the shape filled and extracting from the 20μm photon detection probability to the estimated structure. Structure 1 has a

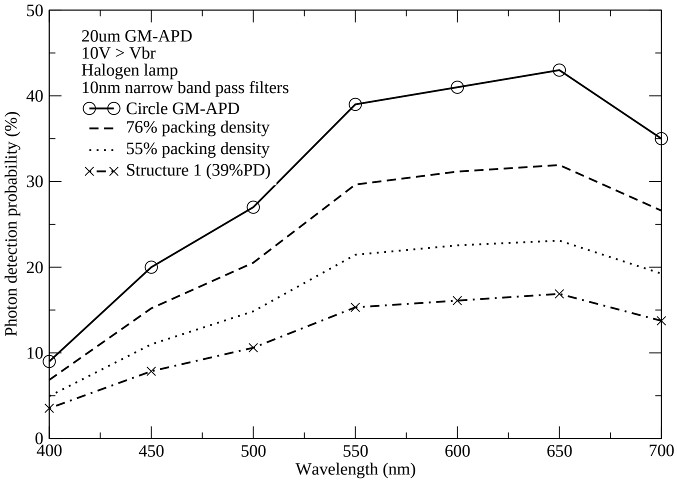


Fig. 6. Photon detection probability measured for a 20μm GM-APD and compared with extracted curves for various active area packing densities.

packing density of 39% which would theoretically reduce the photon detection probability to 15% of the maximum shown in Fig. 6. For most discrete applications a fiber coupled to the detector is desired and thus a circular active area is needed.

Conclusion

In conclusion a CMOS compatible, low voltage (30 volt breakdown), shallow junction, Geiger-mode APD detector suitable for future integration into integrated system-on-a-chip platforms has been demonstrated. The non-linearity of GM-APD dark count with increasing circular diameter has been shown. A novel GM-APD structure using the parallel implementation of many smaller near ideal active areas was proposed to allow arbitrary shape and size detectors to be fabricated. Fabricated test structures had measured dark count rates that scale linearly with active area and the removal of gettering dead space between pixels was shown to increase the dark count per unit area. The measured photon detection probability of a 20μm diameter detector was shown to have a maximum peak at 650nm of 43% and it has been proposed that packing density can be optimized to prevent signal loss. With proper cooling and packaging, these detectors are ideally suited for integration into many current single photon detection platforms and provide and ideal method for downscalling to SOC level.

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