Photon Detection with High Gain Avalanche Photodiode Arrays[i]

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Abstract

The detection of light emitted in fast scintillating fibers and Cerenkov radiators used for fiber calorimetry and tracking applications in high energy colliders, requires fast detector arrays with high sensitivity to short wavelength photons. Photomultiplier tubes, the traditional imaging detectors for short wavelength optical radiation, have limited spatial resolution and require expensive anti-magnetic shielding.

We report on short wavelength sensitivity improvement and detection efficiency performance for a novel **p-n** junction planar structure silicon avalanche photodiode (APD) array, operated in Geiger mode. The APD array provides a high sensitivity detector for applications requiring the detection of light spatial distributions with single photon sensitivity.

I. INTRODUCTION

The capability of combining single photon counting with information on the spatial distribution of incoming photons is of great interest for many scientific and commercial applications. High-energy physics and nuclear physics experiments need high sensitivity sensors for the detection of low numbers of photons generated in fast scintillating fiber arrays and Cerenkov radiators emitting in the blue/UV range.

Photomultiplier (PMT) arrays have progressed towards miniaturization and low cost. However, PMTs are susceptible to magnetic fields, the number of pixels is still limited by the electrostatics, signal post-amplification is required, and monolithic integration with readouts is impossible. VLPCs have high gain and single photon sensitivity, but they require cooling to liquid helium temperatures.

The current silicon technology allows the fabrication of optical imaging arrays with high resolution, large number of pixels and at affordable cost. Silicon based APDs are **p-n** junction solid state detectors with high internal gain and have single photon detection capability. Due to short electrical carrier paths and planar structure, APDs have high immunity to magnetic fields.

At RMD Inc., during the last three years, we have developed Geiger mode operated silicon APD arrays processed by planar technology with high sensitivity in the 500 – 700 nm wavelength range. They proved single photon detectivity at room temperature, low crosstalk and less than 250 psec rise time fluctuation [1]. The original APD array structure has been subsequently modified to increase the sensitivity over the 250-500 nm wavelength range.

In this paper we will report on the improvement of the APD quantum efficiency for short wavelength photons and on the measured performance as single photon detectors.

II. GEIGER MODE APD ARRAYS

A. APDs Operated in Geiger Mode

APDs can be used as single-photon detectors when operated at bias voltages exceeding the breakdown voltage (Geiger mode). In Geiger mode the breakdown is initiated by single carriers crossing the high electric field of the **p-n** junction. In cases where the area of the APD or the generation volume of the depleted space charge region of the p-n junction is large, the thermal (dark) generation current results in individual breakdown events and creates dark counts. The Geiger event reset time is in the 10-30 μsec range for passive quenching and limits the Geiger event maximum rate to approximately 30 KHz. Therefore, the dark count rate of the APD has to be minimized, if high repetition rate optical signals are required by the application. Low dark count rates are also required if the signal repetition frequency is low and gating signals are not available to discriminate against the background noise.

Our previous experience with large area APDs operated in Geiger mode showed that even for extremely low generation currents (less than 10 fA/mm^2) the room temperature dark count rate is higher than 10 KHz [2]. Two possible solutions to this problem are to cool the APD or to select discrete devices with extremely low generation current from large fabrication batches. While the first method adds complexity and increases the detector operation costs, the second method becomes impractical for high-yield APD array fabrication.

B. APD Structure

The APD structure design we proposed in 1994 used silicon planar technology to create small generation volume APD arrays. Our goal was to reduce the room temperature dark count rate below 1 kHz while maintaining high

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detection efficiency. APD arrays, with 10 - 30 μm diameter of the avalanche region and depleted region width less than 10μm, have been designed and successfully fabricated. Figure 1 shows the APD pixel structure cross-section. Based on this design, APD arrays with 12 pixels, working in Geiger mode, showed dark count rates ranging from 0.01 – 1 KHz at room temperature [3]. Operation in Geiger mode was accomplished by applying the external bias above the breakdown voltage of the APD through a limiting resistor, with the role to passively quench the avalanche.

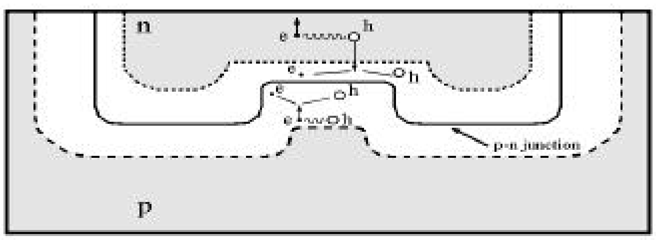

Figure 1. Cross-section of the APD pixel structure. The central n/p junction is protected against premature breakdown by the surrounding guard ring. The breakdown voltage is in the 40 V range. The photon generated electron – hole pairs are collected in the electric field of the p-n junction, biased above its breakdown voltage. The carriers, crossing the p-n junction, are accelerated in the high electric field at the avalanche junction and create secondary electron – hole pairs.

To work as single photon detectors, the detection efficiency (DE) has to be maximized:

$$DE = 1 - \exp(-P_b * QE * n_{ph}) \quad (1)$$

where: P_b is the single carrier breakdown probability, QE is the quantum efficiency, and n_{ph} the average number of photons/pulse [4].

The optimization of the detection probability requires optimization of the quantum efficiency and increasing the breakdown probability. In the next sections we report on the improvement of quantum efficiency at short wavelength and evaluation of the detection efficiency for low number of photons/pulse.

III. APD Quantum Efficiency Enhancement

The detection of short wavelength photons in silicon **p-n** photodiodes has been a long-standing challenge due to the shallow absorption of photons in silicon. Korde reported the use of arsenic doping to enhance the collection of photogenerated carriers, resulting in high-quantum efficiency photodiodes at short wavelength [5].

We used shallow arsenic doping to enhance the electric field at the APD surface and improve the collection of shallow generated carriers. The APD structure is a planar n/p junction with the n type region doped with phosphorous at approximately 1 micron junction depth. Following the phosphorous doping, the batch of silicon wafers was split into three groups: (1) reference wafers without arsenic implantation; (2) arsenic implanted and laser annealed and (3) arsenic implanted and thermally annealed wafers. Groups 2 and 3 were implanted with arsenic ions at 30 KeV through a thin silicon dioxide, designed to minimize the reflection losses at 254 nm.

The efficacy of laser annealing was first evaluated by monitoring the dopant electrical activation. Reference wafers (without APD patterns) were implanted with arsenic, subsequently annealed over 0.3-1.7 J/cm^2 laser pulse energies, and the sheet resistance was measured. As shown in Figure 2, the sheet resistance approaches the expected values corresponding to total dopant activation for laser energy greater than 0.6 J/cm^2.

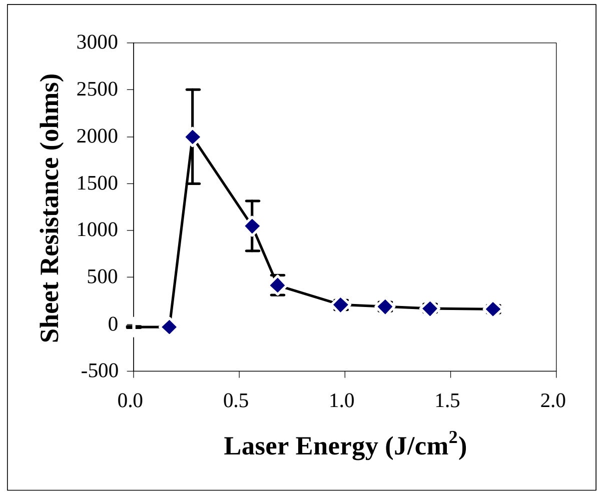

Figure 2. The measured sheet resistance of arsenic implanted reference wafers versus the laser energy/pulse. For energy densities higher than 0.6 J/cm^2 the sheet resistance reaches 180 ohms/square This value agrees well with the value corresponding to the total electrical activation of arsenic atoms in single-crystalline silicon.

Prior to laser annealing, we evaluated the Al ablation threshold on dummy samples and found to be higher than 1.2 J/cm^2. After arsenic implantation on group 2 wafers, the APD planar surface junction of the guard ring was protected with 1 micron Al sacrificial layers. Holes were etched through the Al layer to expose only the arsenic implanted area to laser pulses. The wafers were annealed with 20 nsec, 254 nm excimer laser pulses at Resonetics Inc. (Nashua, NH) over 0.5-1.2 J/cm^2 energy range. Groups 1 and 3 received a thermal annealing at 800°C for 40 min. After annealing, all three groups were processed to receive the top electrode metallization layer, diced, packaged and tested. Both annealing procedures (laser and thermal) resulted in working APDs. No breakdown voltage degradation was detected for laser-annealed APD structures, showing that the Al layer has efficiently protected the APD planar (surface) junction against the laser pulses.

Measuring the quantum efficiency at 254 nm with a Hg vapor lamp and 20 nm bandwidth interference filters tested the efficacy of arsenic doping. Large area windowless APDs (180 μm diameter) were used for QE measurements. It is known that planar photodiodes collect the photo-generated carriers around the planar junction perimeter. Care was taken to suppress the lateral collection using a blocking aperture in intimate contact with the APD surface. Table 1 shows the measured quantum efficiency on laser and thermally annealed APDs in comparison with the reference devices (no arsenic doping). The quantum efficiency of laser-annealed APDs shows marginal improvement, while the thermal annealing devices have the highest quantum efficiency.

Table 1. Measured QE of the reference APDs (without arsenic doping) and enhanced sensitivity APDs at 254 nm. The arsenic doping process doubled the quantum efficiency at 254 nm and resulted in 75% QE at 437 nm.

APD process type	**QE (%) (254 nm)**
No arsenic doping (reference)	17
Arsenic doping, laser annealing	24
Arsenic doping, thermal annealing	59

Doping profile calculations and quantum efficiency modeling with PC-1D [6] predicted 50-60% quantum efficiency at 100 cm/sec surface recombination velocity and 254 nm. The low UV sensitivity for laser annealed devices may be due to incomplete annealing of surface defects or to contamination of the APD surface with ablated Al.

IV. PERFORMANCE EVALUATION

A. Breakdown Voltage

APD arrays, with arsenic layers annealed by laser and thermal treatment, were tested for avalanche multiplication in the passively quenched Geiger mode. The measured breakdown voltage uniformity was better than 0.2 volt / array at a breakdown voltage of 40 volt. The devices showed no degradation of the maximum signal amplitude and peak width as compared to the devices without arsenic doping. Typical pulse amplitude spectra are shown in Figure 3. The Geiger avalanche was quenched using 100 KΩ limiting series resistors (passive quenching) and the corresponding gain was in the 10^8-10^9 range.

B. Detection Efficiency Measurements

The detection efficiency of enhanced QE APDs was tested with pulsed LEDs emitting at 470 nm peak wavelength. Lenses were used to spread out the light spot to approximately 14 mm diameter. Light uniformity was tested prior to the detection efficiency measurements. The LED was pulsed for 50 msec and the light spot was imaged with a Photometrix cooled CCD camera (flat field correction was used to factor in the camera non-uniformity). The light spot uniformity was better than 3% over 10 mm diameter apertures.

For the detection efficiency measurement, the LED was biased with approximately 100 nsec current pulses at 1 kHz repetition frequency. The number of photons/pulse was adjusted by modifying the LED driver pulse width. The photon density was calibrated using a Hamamatsu Si photodiode with 6 mm diameter of the sensitive area. The detection efficiency dependence on bias is shown in Figure 4 for a low number of photons/pulse incident on the avalanche region. The detection efficiency increases monotonically with the number of photons/pulse and reaches 98% at 12 photons/pulse.

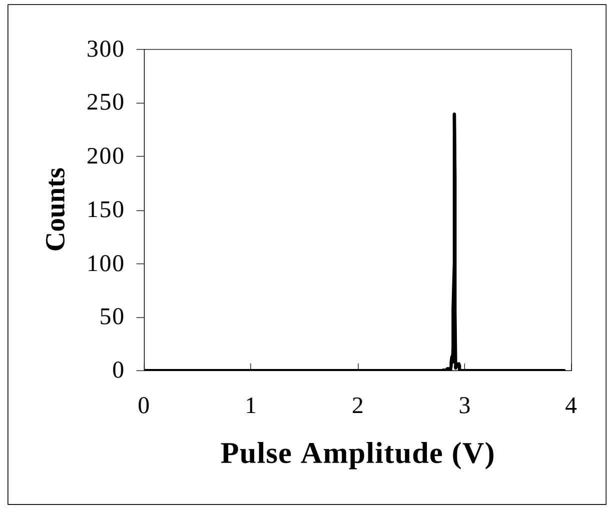

Figure 3. Pulse height amplitude spectra of 30 μm diameter APDs, biased at 3 volts above the breakdown voltage. The avalanche is passively quenched with 100 KΩ limiting resistors. Assuming the avalanche is triggered by single carriers, the multiplied charge corresponds to a charge gain of 5 x 10^8. The narrow peak width demonstrates uniform avalanche multiplication across the APD sensitive area. As opposed to PMTs, no baseline pulses are registered. This allows setting the threshold level high enough to suppress the noise pickup.

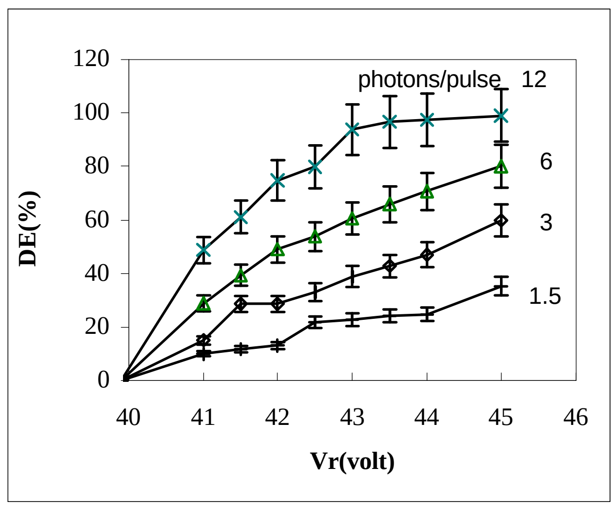

Figure 4. Measured detection efficiency of APDs versus bias, for a low number of photons/pulse, incident on the avalanche region (room temperature). A pulsed LED, with peak emission at 470 nm, was used for measurements.

APD pixels with different sensitive areas were tested for dark count rate and the results are shown in Table 2. The low dark count rate of these APDs allows operation at high detection efficiency even at room temperature. As shown in Table 2, the dark count rate is nonlinear with the pixel area.

Table 2. Measured APD dark count rates at room temperature for different APD sizes. The APDs were biased at 3 V above the breakdown voltage.

APD Pixel Size (μm)	**10**	**20**	**30**
Count Rate (Hz)	0.8	34	192

We assumed that this non-linearity is due to the decrease in the avalanche effective area as the space charge region laterally expands inwards (see Figure 1: the space charge region boundary in the **p** type region). We calculated the electric field profile along the avalanche junction and found that the high electric field region diameter shrinks by approximately 6 µm, thus decreasing the effective avalanche area. Avalanche gain calculations or optical beam scanning of the APD sensitive area could yield more accurate evaluation of the effective size of the avalanche region and correctly predict the dependence of the dark count rate on the geometrical area of the avalanche region.

Dark currents, measured on APD pixels at low bias corresponding to unity gain, were in the 100 pA range and showed no dependence on the avalanche area. The bulk current through the avalanche region, estimated from dark count rate and detection efficiency measurements, was found to be in the fA range and demonstrated that the dark currents are dominated by the surface generation of non-multiplied currents.

V. Summary and Future Developments

A novel solid state APD array for the detection of low number of optical over extended spectral range has been developed. The prototype is comprised of 12 pixel APDs with active area diameter ranging from 10 to 30 microns. The APD array works in Geiger mode, exhibits gains higher than 10^8 , and low dark count rate at room temperature. The devices have high detection efficiency for single photons.

We are currently investigating p-n junction APD arrays with pixel integrated isolation. In parallel, we are developing improved active quenching circuit designs with the goal of implementing pixel level circuitry to quench the Geiger avalanche within less than 100 nsec.

These APD arrays may provide a detector with high sensitivity to UV for applications requiring single photon sensitivity like high-energy physics, free space optical communications, LADAR and LIDAR, adaptive optics and medical imaging.

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VII. References

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