A Reexamination of Silicon Avalanche Photodiode Gain and Quantum Efficiency

Mickel McClish, Richard Farrell, Kofi Vanderpuye, and Kanai S. Shah

Abstract– **Traditionally the measured gain of an avalanche photodiode (APD) has been considered the product of two parameters: the multiplication process and quantum efficiency (QE), the former being wavelength dependent and the latter being bias independent. We propose a new examination of these related parameters where the APD gain is considered intrinsic, defined as being the amount of electron multiplication each photoelectron undergoes based on the applied bias, and independent of the incident photon wavelength, and the QE being considered intrinsic as a function of only wavelength and bias. This is a more logical, and physically real, perspective of APD behavior. We introduce a technique to measure the intrinsic gain and the intrinsic QE of a deep diffused silicon APD. The mechanisms by which the gain and QE vary as a function of wavelength involve charge collection and light absorption due to the light penetration depth dependency on wavelength. Once the intrinsic gain vs. bias of the APD is measured, it becomes possible to use this measurement as an absolute parameter. With the intrinsic gain known, we show how the intrinsic QE of an APD, for a given wavelength, changes as a function of bias. We also show that when the APD is operated from the low to high gain regime, light at 400 nm to 800 nm experiences an increase in QE, while light at longer wavelengths experiences a reduction in QE. These fundamental, dynamic and operational properties of APDs are critical when considering the wavelength(s) that are of interest for a given application.**

I. Introduction

Semiconductor detectors for nuclear radiation detection have over the past several years experienced an increased popularity due to material and fabrication improvements. This has resulted in semiconductor detectors being applied towards ever growing fields of science ranging from nuclear medicine, x-ray and γ-ray astronomy, nuclear and particle physics, and nuclear safeguarding. In particular among the various detectors, silicon APDs are being implemented, or are being considered, for these applications. Of the many attractive characteristics of silicon APDs is the increased QE over a broad band of photon wavelengths compared to photomultiplier tubes (PMTs). APD QE can be a factor of 2 to 4 greater than a PMT for a given wavelength. Considering the importance of QE for a detection system, it is critical for one to be aware of how, and by what magnitude, QE is affected by changing operating conditions.

One of the factors that determine the QE of a silicon APD at a given wavelength is the penetration depth of the incident light, which is based on its wavelength. Less penetrating, short wavelength light (~ 400 nm) has a 50% penetration depth that is approximately 0.1 μm in silicon. These photons are absorbed on the P-side of a deep diffused APD surface, which allows for charge carrier losses due to recombination with surface states and with the bulk material. These two loss mechanisms reduce the QE. At longer wavelengths, up to approximately 800 nm, where surface state recombination is negligible, bulk recombination still occurs while the charge carriers travel across the drift region into the depletion region. The amount of recombination experienced is dependent on the distance the carriers must travel across the drift region, and this distance is dependent on the wavelength determined penetration depth. As the wavelength increases further, the incident photons can penetrate beyond the P-N junction until finally reaching the room temperature wavelength cutoff at approximately 1100 nm where the photons are no longer absorbed due to having less energy than the silicon band gap energy, 1.12 eV. At this point the QE reduces to near zero (Fig. 1).

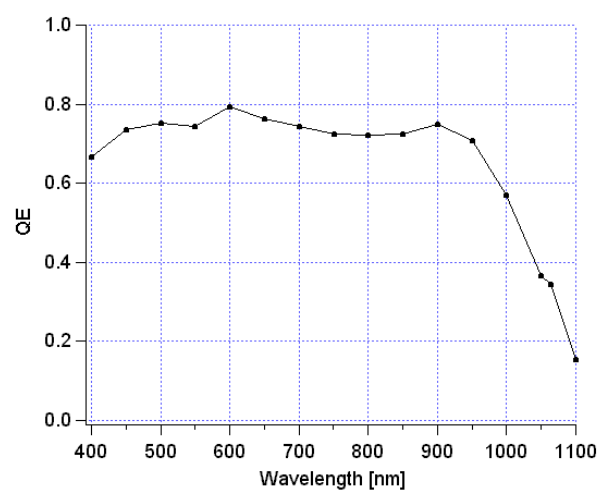

Fig. 1. APD QE vs. wavelength at unity gain.

The processes described above considered a static P-N junction. Naturally with photodiodes, the thickness of the drift, depletion, and surrounding undepleted silicon will vary as a function of the applied bias across the P-N junction. It is reasonable then to expect that the QE and gain for a given wavelength, which is determined by the drift and depletion

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region thickness, would also vary as a function of the applied bias (Fig. 2). The difficulty making measurements of an APD's QE as a function of wavelength and bias (gain) is due to the fact that the two parameters, QE and gain, are intimately related. A common way to measure the QE is to perform a

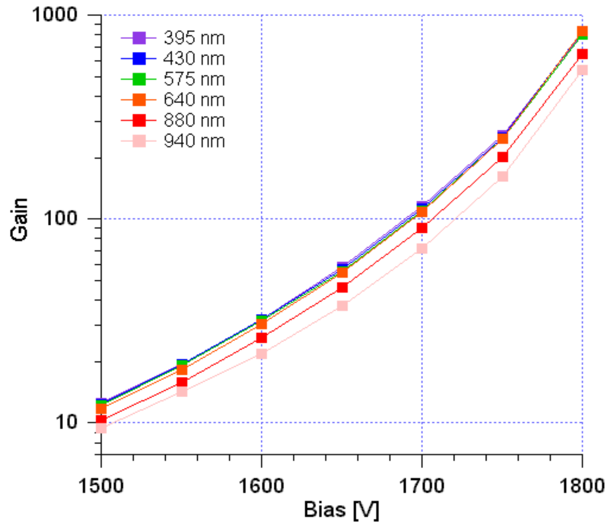

Fig. 2. APD gain vs. bias for various wavelengths.

relative measurement comparing the APD's photocurrent at unity gain to that of a calibrated photodiode. When the gain is unity, one can be assured that changes in photocurrent at various wavelengths are due to changes with the QE. However, when the applied bias is increased, one cannot normally remove the gain contribution to the measured photocurrent to extract the QE because that variable is unknown.

II. Silicon APD Fabrication

Radiation Monitoring Devices, Inc. (RMD) silicon APDs are fabricated with a wide depletion region in order to achieve a high operating gain. This in turn requires a deep P-N junction that is created with deep diffusion. The edges of the detectors are beveled using a planar process. This process has greatly reduced the technical difficulty associated with manual beveling without any compromise in performance [1], [2]. This design involves cutting grooves in the entrance face of an N-type neutron transmutation doped (NTD) silicon wafer. Deep diffusion of the P-type dopants is then performed. Due to the grooves, the dopant profile (and the corresponding P-N junction profile) is curved, which acts as a planar bevel. Large area APDs (areas from 1 mm^2 to 45 cm^2) have been fabricated at RMD using this planar process. This study focused on 8 x 8 mm^2 APDs (Fig. 3).

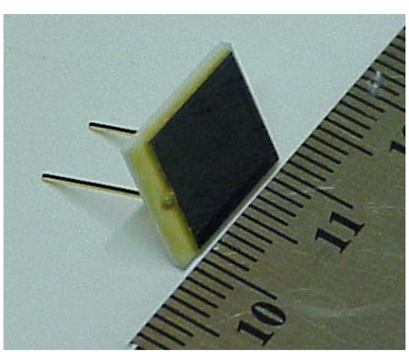

Fig. 3. A photograph of an 8 x 8 mm^2 APD.

III. Method

By knowing the gain as a function of bias, which must be wavelength independent, one could then calculate the QE with the APD operating under high bias. The resulting QE would then be independent of the intrinsic gain. The intrinsic gain can be determined by choosing a specific wavelength, for example 650 nm, to generate a photocurrent whose penetration depth will avoid both surface state and absorption losses. As the photocurrent increases between 0 V and 600 V bias, before gain mechanisms start (unity gain), the calculated drift region shrinks as the depletion region grows between these bias levels. The photocurrent can then be used to determine the percent increase in QE per micrometer decrease in drift region due to bulk recombination effects. Once the QE – drift region thickness relationship is known, it is possible to extrapolate the QE, for 650 nm, into the high-gain regime. This is the intrinsic QE at 650 nm. The intrinsic gain can now be determined by dividing out the intrinsic QE from the gain based on the measured photocurrent. The parameters are related in the following way:

$$M_{photo} = M_{intrinsic} \times QE_{intrinsic} \quad (1)$$

where M_{photo} is the relative gain determined from the measured APD photocurrent, and $M_{intrinsic}$ and $QE_{intrinsic}$ are the intrinsic APD gain and QE, respectively. As discussed earlier, if $M_{intrinsic} = 1$, which is assumed to be the case when the applied bias is < 600 V, then at various wavelengths changes in the photocurrent, and hence M_{photo}, are due exclusively to $QE_{intrinsic}$, i.e., $M_{photo} = QE_{intrinsic}$. Beyond 600 V, if $M_{intrinsic}$ is known, the gain contribution can be removed from M_{photo} allowing $M_{photo} = QE_{intrinsic}$.

A. P-N Junction Modeling

To model how the P-depletion width and the drift region width vary with bias, the doping profile was first measured. Samples of RMD's deep diffused silicon wafers were sent to Solecon Laboratories (Reno, NV). At Solecon's facilities, after careful sample preparations, the resistivity vs. depth was measured using a spreading resistance analysis (SRA) technique [3]. Based on their measured resistivity profile results, the majority carrier concentration — depth profile was then calculated using published carrier mobility values. It was then possible to calculate the doping profile by iteratively solving Poisson's equation using boundary conditions that were consistent with Solecon's SRA results. Finally, from the doping profile, the depletion region width, for a given bias, was iteratively calculated by requiring that the total charge within a specified P and N depletion width be zero. Iterative calculations were performed until a P and N profile was found to satisfy that requirement. The P-depletion width computation was repeated for bias values ranging from unity to high gain (0 V to 1800 V). From the P-depletion width results, the drift region width was calculated by subtracting the P-depletion width from the total junction depth, which is 60 µm and constant (Fig. 4).

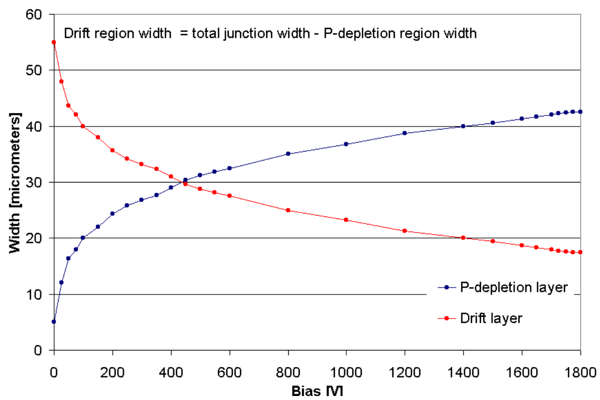

Fig. 4. A plot of the modeled drift layer and P-depletion layer thickness as a function of bias.

B. *Quantum Efficiency at Unity Gain*

The QE of the APD was determined by performing a relative measurement comparing the APD photocurrent to that of a calibrated photodiode with the same light intensity (Fig. 1). The measurement was performed with the APD operated at unity gain (200 V) and at room temperature (23 °C). These data were collected to provide the initial QE at each wavelength from which $QE_{intrinsic}$ as a function of bias could be extrapolated.

C. *Intrinsic Quantum Efficiency and Gain at 650 nm*

A measurement at room temperature (23 °C) of the APD photocurrent at 650 nm vs. bias was performed and the data were then used to calculate M_{photo}. Many photocurrent datum points were taken between 0 V to 600 V because it is within this bias range that the model described in section *A* shows the P-layer depletion thickness, and hence the drift region thickness, changing at the greatest rate compared to the model

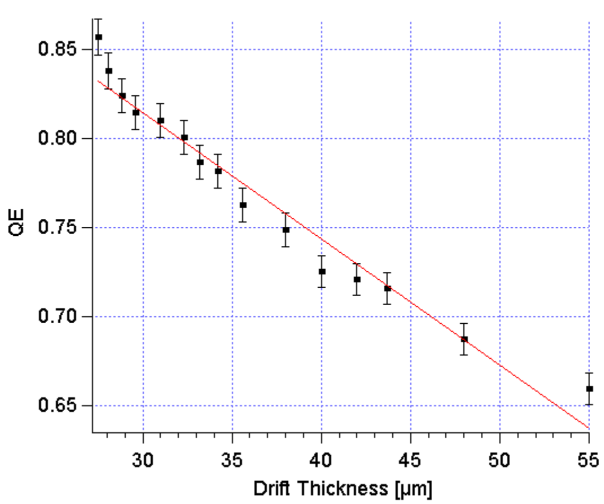

Fig. 5. A plot showing QE at 650 nm vs. drift region thickness.

results beyond 600 V. Similarly, many datum points were also taken in the high gain region due to the APD's large gain rate of change in that operating regime.

Based on the photocurrent measured between 0 V to 600 V, and the QE measured at 650 nm from section *B*, QE as a function of drift region thickness can be plotted with a linear fit. The result of the fit shows how the QE changes per micrometer change of drift region thickness as a result of bulk recombination (Fig. 5). Based on the fit results, the QE changes by approximately 0.7% per micrometer. This relationship enables the extrapolation of the QE at 650 nm from unity gain to the high gain regime—this is $QE_{intrinsic}$ at 650 nm.

With $QE_{intrinsic}$ known at 650 nm, it is now possible to calculate $M_{intrinsic}$ using equation 1. Due to the absence of gain mechanisms between 0 V and 600 V, $M_{intrinsic} = 1$. Beyond 600

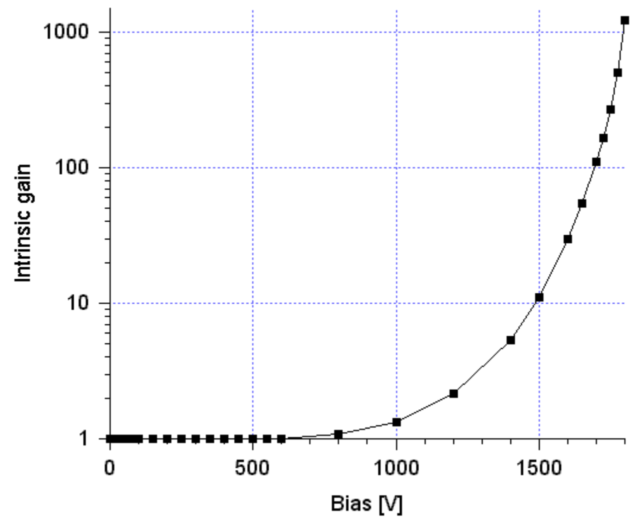

Fig. 6. A plot of intrinsic gain vs. applied bias. The gain, now intrinsic, is wavelength independent.

V, dividing both sides of equation 1 with $QE_{intrinsic}$ calculates $M_{intrinsic}$, which as a result, is wavelength independent and can now be used to calculate $QE_{intrinsic}$ at other wavelengths (Fig. 6).

D. *Intrinsic Quantum Efficiency*

In order to calculate $QE_{intrinsic}$ as a function of bias for a given wavelength, M_{photo} must first be measured for that wavelength as a function of bias. This is the same technique used to measure M_{photo} at 650 nm. Once M_{photo} as a function of bias is calculated for a given wavelength, $M_{intrinsic}$ is then used to calculate $QE_{intrinsic}$ as a function of bias using equation 1. This was performed from 400 nm to 1100 nm in 100 nm increments, with the exception of 600 nm. The 650 nm data set was used instead. The results are shown in figure 7.

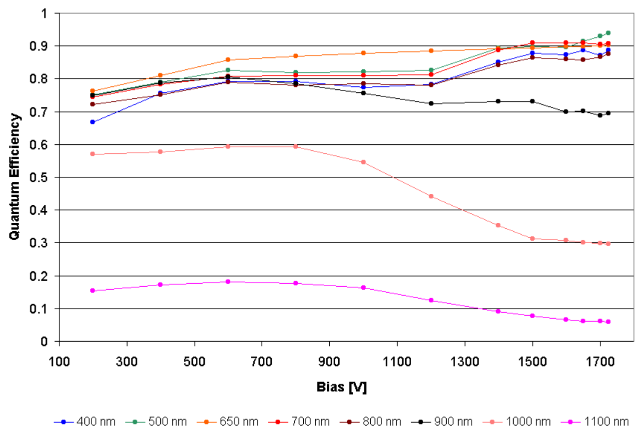

Fig. 7. A plot of intrinsic QE vs. bias for various wavelengths.

IV. Result Summary and Discussion

The final results shown in figure 7 indicate the bulk recombination charge carrier loss mechanism, how its effect varies with a changing P-N junction as a result of biasing, and how the net result impacts APD QE. For shorter wavelength light that is relatively less penetrating (0.1 µm), such as 400 nm, some charge carrier loss will occur due to surface effects regardless of bias. Longer wavelength light that is relatively more penetrating (50 µm), such as 1000 nm, will experience charge multiplication loss due to absorption beyond the P-N junction, however, it will not experience much bulk recombination as it is largely absorbed beyond the drift region. As expected, $QE_{intrinsic}$ increased with bias for short wavelength light due to a decreased amount of charge loss from bulk recombination, while $QE_{intrinsic}$ for longer wavelength light decreased with bias because of the photo generated holes, now the majority carrier in the N-type material, undergo much less multiplication compared to photoelectrons. At unity gain, holes and electrons contribute equally to the APD photocurrent. The behavior of $QE_{intrinsic}$ as a function of bias changes between 800 nm and 900 nm. It is within this wavelength region where the penetration depth (10 µm) is deep enough where neither the bulk recombination losses in the drift region, nor losses from absorption beyond the P-N junction, are significant enough to positively or negatively impact $QE_{intrinsic}$.

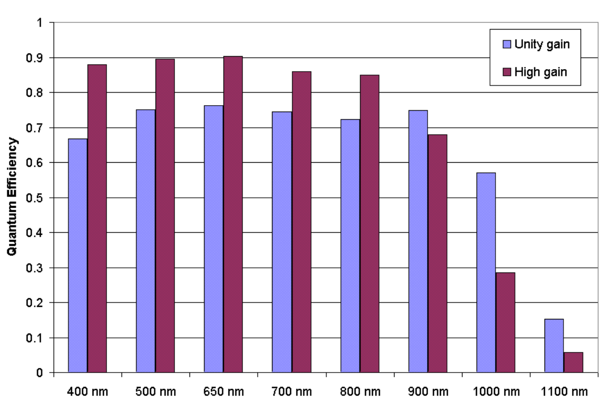

Fig. 8. A plot comparing the unity and high gain quantum efficiency of each wavelength.

These detectors are clearly well suited for those applications where short wavelength (400 nm to 800 nm) light detection is needed. However, the QE at near infrared (near-IR) wavelengths degrades. The QE is normally relatively low in the near-IR region due to absorption losses and is degraded further as the gain is increased.

End users of silicon APDs should be knowledgeable of the P-N junction dynamics and how they strongly influence important APD properties such as QE. Figure 8 shows, side-by-side, the changes between unity and high $QE_{intrinsic}$ for each wavelength.

References

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[2] K. S. Shah, R. Farrell, R. Grazioso, and L. Cirignano, "Large Area APDs and Monolithic APD Arrays," *IEEE Trans. Nuc. Sci*., vol 48, no. 6, page 2352, 2001.

[3] Solecon Laboratories web site: www.solecon.com