Simulation of Dark Count in Geiger Mode Avalanche Photodiodes

J. C. Jackson, B. Lane, A. Mathewson
National Microelectronics Research Centre,
Lee Maltings, Prospect Row, Cork, Ireland
cjackson@nmrc.ie

A. P. Morrison
Department of Electrical and Electronic Engineering
University College Cork
Cork, Ireland

Abstract

Silicon avalanche photodiodes operated above breakdown, in Geiger mode, can be sensitive enough to allow single photon detection. An inherent limit to GM-APD sensitivity is the noise caused by thermally generated carriers. This noise manifests itself as extraneous counts in the absence of light and is termed the dark count. The presence of the dark count in GM-APD detectors reduces the signal to noise ratio and increases the integration times that are necessary for photon detection. A 1-Dimensional model of the dark count in GM-APD detectors was developed and dark count was found to depend predominantly on carrier generation through Shockley-Read-Hall (SRH) generation centres and secondly on thermal diffusion of minority carriers in the bulk. Simulations performed show that minimisation of the dark count is limited by bulk diffusion of minority carriers. The reduction of process induced damage minimises the dark count and allows theoretically minimum dark counts to be achieved.

Structure

GM-APD detectors are specially designed and fabricated p-n diodes that are operated at biases above the breakdown voltage. Avalanche breakdown of a diode is a statistical process and requires a charge carrier in the depletion region for initiation. A GM-APD can be biased above the breakdown voltage for a finite period of time until an electron or hole enters the depletion region. Depending on the applied bias and the separate ionisation rates of electrons and holes, a probability exists that the incident charge carrier will initiate a self sustaining breakdown. Once a self sustaining avalanche has occurred, quench and reset circuits must be used to reduce the diode bias below the breakdown voltage and allow for the removal of charge within the depletion region. After a suitable hold off time, necessary for the removal of trapped charge, the GM-APD can be biased above breakdown again. In this manner, of breakdown-quench-reset a GM-APD can be used to detect single photons of light. The major limiting factor of device operation is the dark count from thermally generated carriers. To reduce the dark count, commercial detectors rely on large breakdown voltages and complex doping profiles to ensure the junction electric field is kept below the breakdown field. These devices are not compatible with CMOS technology. CMOS compatible shallow junction GM-APD detectors were fabricated as shown in Figure 1.

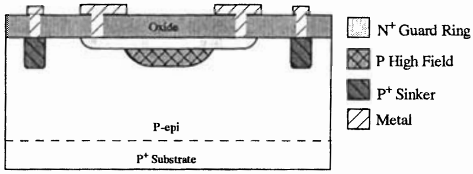

Figure 1: Schematic of shallow junction GM-APD used in this study.

1.1 Dark Count

The room temperature dark-count performance for 10μm and 20μm diameter GM-APD detectors is shown in Figure 2. For these devices, dark counts of less than 100 counts s^{-1} were measured and the dark count scaled with area. The dark count for 50μm diameter devices does not scale with area. The increased dark count can be attributed to defects present in the active area [1]. To determine the theoretical dark count limit for GM-APD operation a device simulator capable of predicting dark counts was necessary.

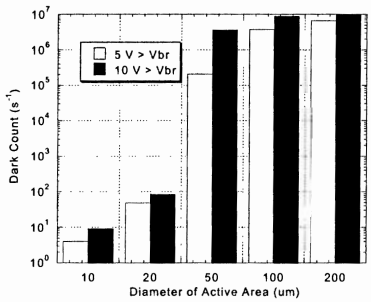

Figure 2: Dark Count for various GM-APD detectors at two different voltages above breakdown voltage.

Commercially available process and device simulators can be used to accurately predict diode breakdown voltage but cannot directly predict the dark count in GM-APD devices. Analytical solutions exist to calculate darkcount and were used to form the basis for the calculation of the minimum theoretical dark count [2]. In this paper a simple 1-D model based upon the local electric field model and commonly accepted impact ionisation coefficients is proposed. This model uses information provided by commercial process and device simulators and extends it to simulating darkcount in GM-APD devices.

1.2 Simulation & Results

A calibrated process simulation was used to obtain doping profiles within the GM-APD detector. The model requires the local electric field, minority carrier concentration and SRH generation rate data. Defects are introduced by modifying the Shockley-Read-Hall generation lifetime or through the inclusion of multiple defect levels in the device simulator. Poisson's equation was modified to account for added charge and the local electric field was then solved. The local electron and hole impact ionisation rates were calculated using data from van Overstraeten and De Man [3]. Electron and hole breakdown initiation probabilities were calculated by solving the differential equations presented by Oldham *et al.* [4]. These are shown in Figure 3 for various voltages above the breakdown voltage.

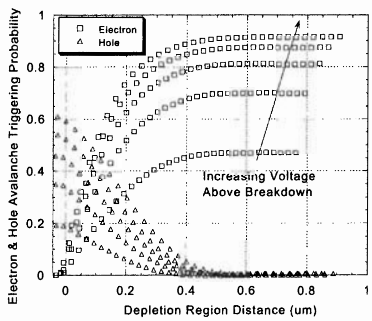

Figure 3: The position dependent electron and hole avalanche triggering probability.

The avalanche initiation probabilities were then combined with the minority carrier densities from the device simulator to yield dark count contributions for each region of the device as shown in Figure 4.

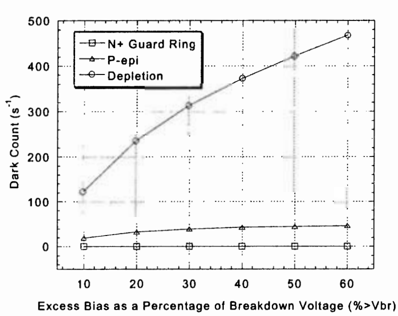

Figure 4: Major contributions to dark count density in a GM-APD detector.

The local generation rate data was used with the local avalanche initiation data obtained from Figure 3 to calculate the contributions of carriers generated in the depletion region. The addition of defects has been incorporated in the device simulator and compared with measured GM-APD dark count performance in Figures 5. A simulation incorporating zero defects has been shown as well, in Figure 5, which predicts the theoretical dark count limit based on a defect free depletion region.

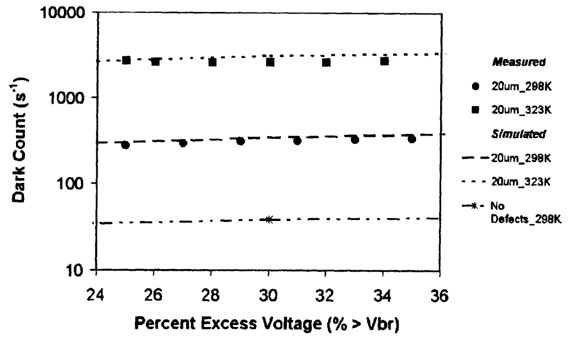

Figure 5: Measured and simulated dark count for a 20μm diameter GM-APD versus percent excess voltage at 298K and 323K A defect free detector with SRH generation removed is shown to predict the theoretical minimum dark count.

Conclusions

In summary a 1-D model based on the local electric field model has been developed to accurately predict dark count performance of GM-APD detectors. The inclusion of defects and trapping centres was accounted for within the model. It was shown that Shockley-Read-Hall generation and minority carrier bulk diffusion contribute to the dark count present in GM-APD detectors. This technique provides a simple and accurate method for predicting real and ideal GM-APD performance.

References

[1] A. Zanchi, F. Zappa, M. Ghioni, A. Giudice, A. P. Morrison and V. S. Sinnis. "Probe detectors for mapping manufacturing defects", *Proceedings of 3rd International Caracas Conference on Devices, Circuits and Systems* (ICCDCS2000).

[2] W. J. Kindt and H. W. van Jeijl, "Modeling and fabrication of Geiger mode avalanche photodiodes", *IEEE Transactions on Nuclear Science*, vol. 45, no. 3, 715-719, 1998

[3] R. Van Overstraeten and H. De Man, "Measurement of the ionization rates in diffused silicon p-n junctions", *Solid-State Electronics*, vol. 13, 583-608, 1970

[4] W. G. Oldham, R. S. Samuelson and P. Antognetti, "Triggering phenomena in avalanche diodes", *IEEE Transactions on Electron Devices*, vol. 19, no. 9, September 1972