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Comparing leakage currents and dark count rates in Geiger-mode avalanche photodiodes

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This letter presents an experimental study of dark count rates and leakage current in Geiger-mode avalanche photodiodes (GM APD). Experimental results from circular diodes over a range of areas (20–500 μm diam), exhibit leakage current levels orders of magnitude higher than anticipated from dark count rates. Measurements of the area and peripheral components of the leakage current indicate that the majority of the current in reverse bias does not enter the high-field region of the diode, and therefore, does not contribute to the dark count rate. Extraction of the area leakage current term from large-area devices (500 μm) corresponds well with the measured dark count rates on smaller devices (20 μm). Finally, the work indicates how dark count measurements represent 10^{-18} A levels of leakage current detection in GM APDs. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1483119]

Sensors capable of detecting single photons are required for a diversity of fields from astronomy[1] to fluorescence decay[2] and ultraweak biochemiluminescence measurements.[3] For next-generation laboratory and systems on a chip, small geometry single-photon counters that can be integrated with readout circuitry in multipixel arrays are required. The shallow junction, Geiger-mode avalanche photodiode (GM APD) shown in Fig. 1(a) provides single-photon-counting capability with a low-breakdown voltage ($\approx$30 V) and is manufactured using standard complementary metal–oxide–semiconductor (CMOS) substrates and fabrication steps.[4]

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 biased beyond electrical breakdown. The device can remain in this state until a free carrier is generated in the depletion region, becomes accelerated by the electric field, and acquires sufficient energy to result in a self-sustaining breakdown of the diode by the process of impact ionization. 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 generated thermally through Shockley–Read–Hall recombination–generation centers, or by bulk diffusion of minority carriers from the quasineutral region [components 1 and 2 in Fig. 1(a), respectively]. The generation of e/h pairs and thermal bulk diffusion represent a characteristic noise of the detector and sets a limit for the ultimate sensitivity of GM APDs. 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. Typical dark count levels for 20 μm diam circular diodes shown in Fig. 1(a) are between 10 and 2000 counts per second from measurements taken at room temperature.[5]

As the dark count originates from thermally generated e/h pairs and bulk diffusion,[6] it is expected that the dark count rate should be reasonably estimated from the measurement of the reverse bias leakage current prior to breakdown. The calculation is expressed as

$$C_{\mathrm{dark}} \approx \left(\frac{I}{q}\right) P_{\mathrm{ai}}, \tag{1}$$

where C_{dark} is the dark count rate, q is the electron charge, and P_{ai} is the probability that a single charge carrier will initiate a breakdown, which can approach unity for diodes biased 10–15 V above breakdown.[6,7] However, based on dark count measurements performed on a range of devices it is found that the current levels predicted using Eq. (1) are orders of magnitude below the measured leakage current from the same devices. For example, consider a 20 μm active area Geiger-mode diode with a dark count of 1000 s^{-1} at 25 °C and a unity charge carrier initiation probability (P_{ai}), Eq. (1) yields $I_{\mathrm{sim}} \approx 0.16 \times 10^{-15}$ A, which is below typical resolution of current measurement system capabilities. However, measured leakage current values of $I_{\mathrm{meas}} = 233 \times 10^{-15}$ A are recorded at 15 V reverse bias, which are three orders of magnitude higher. The objective of this letter is to investigate the large disparity between the measured dark count rate and the leakage current in GM APDs.

For this letter, shallow junction GM APDs, peripheral area test structures, and gate-controlled diodes, as shown in Figs. 1(a), 1(b), and 1(c), were manufactured in p-type epitaxially grown bulk silicon using a conventional 1.5 μm CMOS process reported previously.[4]

To investigate the physical origins of the leakage current in GM-APD structures, activation energy plots were obtained for both small geometry GM-APD structures (20 μm) and compared with much larger circular guard ring test structures

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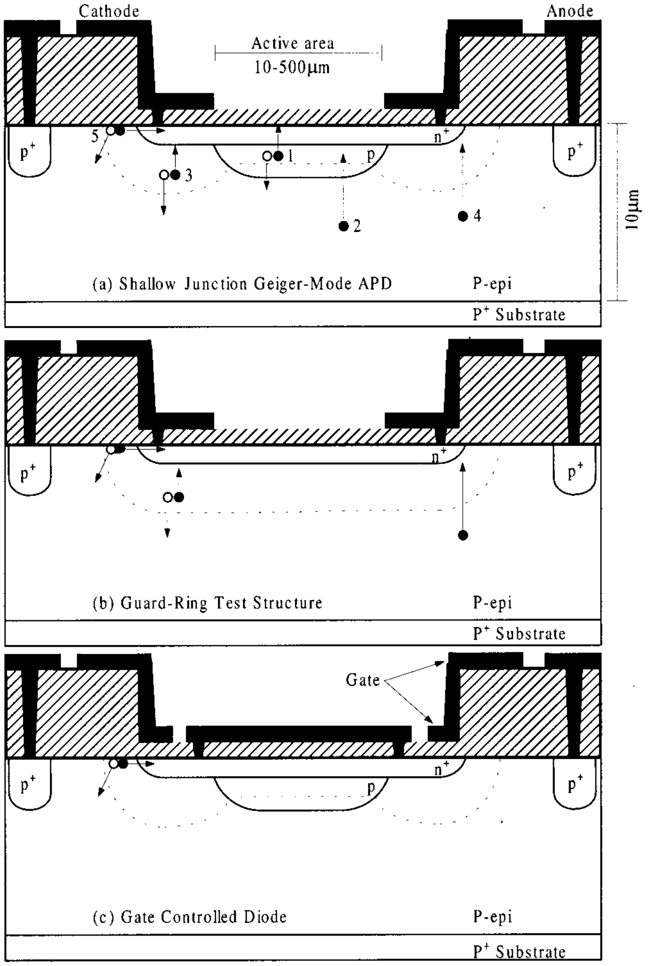

FIG. 1. (a) Shallow junction, virtual guard ring Geiger-mode APD structure used for single-photon detection. (b) Guard ring test structure used to determine the perimeter leakage current term for the shallow junction diodes. (c) Gate-controlled diode to modulate the perimeter surface leakage current.

(500 μm). Comparing both structures was necessary to establish that the reverse bias leakage current measured on small-area (20 μm) diodes has the same origin as that measured on larger-area (500 μm) guard ring test structures. This comparison was necessary as leakage current measurements require large-area structures for accurate peripheral current extraction. Conversely, for dark count measurements, it is necessary to use small-area GM APDs to keep the counting rate low to prevent afterpulsing and diode heating effects from obscuring the measured count rate.[1]

To determine the origin of the leakage current in the test structure, the area and peripheral bulk diffusion terms from the leakage current data were extracted. This was performed using the standard method[8–10] using a variety of test structures, as shown in Fig. 1(b) with diameters between 200 and 500 μm and using combined $C-V$ and $I-V$ analysis. After removing the peripheral bulk diffusion current from the total measured current, the corrected leakage current due to generation in the space-charge region was found to have an activation energy of 0.68 eV. This value of activation energy coincides with the value obtained for the 20 μm GM APDs. It is, therefore, believed that the leakage current measured in the actual structure is largely comprised of leakage current originating from the parasitic diode formed by the n^+ overlap into *p*-epi, which forms the virtual guard ring and also a surface generation component [see components 3, 4, and 5 in Fig. 1(a)]. As these leakage current components do not flow through the high-field region, they do not contribute to the dark count rate.

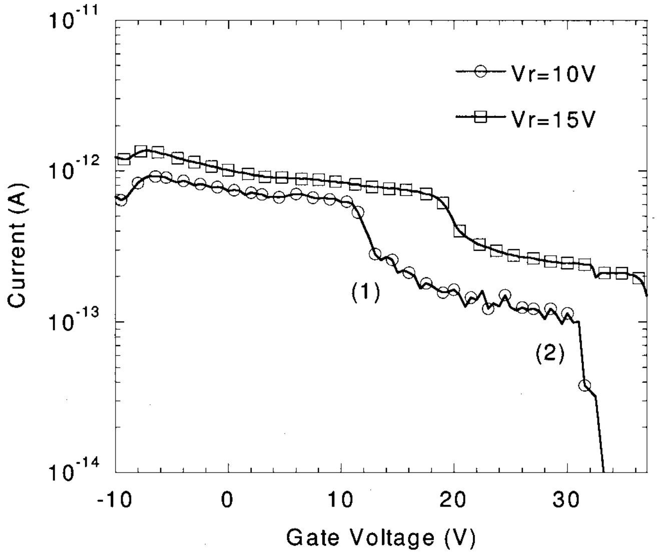

FIG. 2. Leakage current measured in a circular gate-controlled diode with a diameter of 500 μm. Markings (1) and (2) in the 10 V diode measurement give an indication of the silicon inversion under the multilevel oxide structure shown in Fig. 1(c).

If the detectable leakage current present in a GM APD is mainly comprised of perimeter leakage current, then using a gate-controlled diode structure located at the diode edge should enable a reduction of this leakage current component. A gate-controlled diode structure, as shown in Fig. 1(c), was used to modulate the reverse bias leakage current flowing in the diode structure. As can be seen in Fig. 2, it was possible to reduce the leakage current flowing in the gate-controlled diode test structure to below the detection limit of the $I-V$ measurement systems used in this experiment. The gated diode inversion of the silicon layer underneath the multilevel oxide is clearly seen from the decrease in current at a reverse bias voltage of 10 V, at (1) and (2) in Fig. 2 from the inversion of the surface under the thin and thick oxide regions, respectively. The inversion of the *p*-type silicon results in a decrease in the surface generation component of the total diode leakage current.[11]

Once it was determined through activation energy and gate-controlled diode measurements that the majority of the leakage current in GM APDs is comprised of peripheral leakage current through the n^+ region, an experiment was performed to determine if the dark count of a small geometry detector could be extracted from the leakage current in large-area device structures. As a plot of the leakage current versus reverse bias voltage is flat for the diodes used in this letter, a direct comparison between identical diameter GM APDs and guard ring test structures should give an indication of the dark count to be expected. The difference between the GM-APD [Fig. 1(a)] reverse bias leakage current, and the reverse bias leakage current in an equivalently sized guard ring test structure [Fig. 1(b)] was normalized with area and compared to measured dark count data from 20 μm Geiger-mode diodes fabricated on the same wafer. After normalization, an

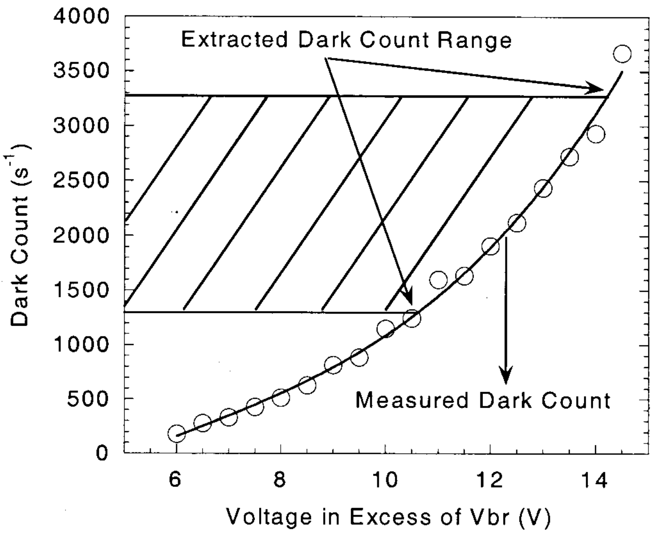

FIG. 3. Extraction of the dark count rate caused by a 3250 electron per second current flux through the active area of a GM APD. Calculated electron flux is multiplied by the electron avalanche initiation probability for the voltage range of operation and shown in the shaded region.

electron flux of 3250 s^{-1} was obtained. The dark count from a 20 μm diode measured at a range of reverse biases in excess of the breakdown voltage is shown in Fig. 3. As the electron avalanche initiation probability increases with excess bias from levels of 0.4 to over 0.9 for this excess bias range,[6] a distribution of the dark count rate that is generated by the extracted current flow through the high-field region of the diode are indicated in Fig. 3 and are in agreement with the measured values.

The leakage current that is measured when performing reverse bias measurements has been shown to depend almost entirely on a perimeter component that can be extracted when using a suitable test structure. The large perimeter component is primarily due to a surface generation component of e/h pairs from surface states at the Si/SiO_2 interface. The peripheral current in a GM APD [Fig. 1(a)] does not flow through the high-field region, and hence, does not contribute to the dark count rate. In fact, the existence of a large perimeter leakage current could be attributed to a poor Si/SiO_2 interface on the perimeter, which might provide intrinsic gettering sites to aid in contaminant gettering from the critical high-field active region of the Geiger-mode APD. A further significant observation from this work is that the measurement of the dark count rate is an indirect method of measuring very low leakage current (10^{-18} A) levels in small-area diodes. Dark count rates in the range of 10–10 000 s^{-1} can be measured quickly, and without difficulty. This corresponds to leakage currents in the range of 10×10^{-19}–10×10^{-16} A. A measurement of these currents clearly would be beyond the scope of commercially available low-current meters.

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