

Photon Counting with Passive Quenched Silicon Avalanche

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Abstract

We investigate the performance of silicon avalanche photodiode (APD) with passive quenching circuit for photon counting in the near-infrared range. The characterizations of an APD cooled at -20°C are described in terms of dark counts, operating temperature and bias-voltage.

Keywords: optoelectronics, optical detector.

1. INTRODUCTION

It is well known that photon counting is the technique of applications in which faint and fast responsibilities of light detection are required. In recent years, significant demonstrations have been widely used in quantum teleportation [1], quantum cryptography [2], optical communication and in sensor applications [3]. For the first telecommunication window, there are commercially available single photon detectors. They are based on silicon (Si) avalanche photodiodes, which have high quantum efficiencies ($\geq 50\%$) and low noise rates.

Several groups have reported the Ge APDs operating in the Geiger mode, i.e., at a voltage higher than the breakdown level, can detect a single photon at $1.3\ \mu\text{m}$ if they are first cooled to 77 K to reduce noise.

However, the single photon efficiency is very low ($\sim 10\text{-}30\%$) and intrinsic noise rate (dark counts rate) ≥ 1000 times higher than Si APD at $0.85\ \mu\text{m}$ [4].

After a brief introduction to the principle of operation of a Geiger mode APD with passive quenching, we then report the performance of a C30902S-DTC Si APD manufactured by EG&G which includes a built-in thermoelectric cooler (TEC) and a thermistor. The experimental results of temperature controller and dark counts as a

function of the temperature and bias voltage are discussed.

2. THEORY

2.1 Principle of operation

The APD is a solid state quantum, optical detector intended for low light level application in the visible and near infrared region. It operates in a reverse bias in either its normal linear mode when the bias voltage, V_R , less than the breakdown voltage, V_{BR} . In this mode the gain is up to 250 or greater, or as a photon counter in Geiger mode when V_R held above the breakdown voltage. Under this condition, a single photoelectron can trigger an avalanche pulse of about 10^8 carriers. In this mode, no amplifiers are necessary and single-photon detection probabilities up to 50% are possible. After the avalanche is triggered, the current keeps flowing until the avalanche is quenched by lowering the bias voltage down to V_{BR} or below. The bias voltage is then restored in order to detect another photon. The APD current can either be turned off passively by limiting the current flowing with a suitable resistor, or actively by lowering the bias voltage after the onset of the avalanche.

2.2 Passive quenching circuit

Passive quenching is simple to implement, requires a minimum of power,

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space and is robust. In this mode, the APD is reverse biased beyond breakdown through a high impedance resistor R_L in Figure 1. To be in the conducting state at V_{BR} two conditions must be met [5]:

1. The avalanche must have been triggered by either a photoelectron or a bulk-generated electron entering the avalanche region of the diode. (holes are inefficient at starting avalanches in silicon) The probability of an avalanche being initiated is discussed above.

2. To continue to be in the conducting state a sufficiently large current, called the latching current, I_{LATCH} , must be passing through the device so that there is always an electron or hole in the avalanche region. Typically in the C30902S-DTC, $I_{LATCH} = 50 \mu A$. For currents $(V_R - V_{BR})/R_L$, much greater than I_{LATCH} , the diode remains conducting. If the current $(V_R - V_{BR})/R_L$, is much less than I_{LATCH} , the diode switches almost immediately to the non-conducting state. If $(V_R - V_{BR})/R_L$, is approximately equal to I_{LATCH} , then the diode will switch at an arbitrary time from the conducting to the non-conducting state depending on when the number of electrons and holes in the avalanche region statistically fluctuates to zero.

When R_L is large, the photodiode is normally nonconducting, and the operating point is at $V_R - I_{ds}R_L$ in the non-conducting state where I_{ds} is the dark surface current. Following an avalanche breakdown, the device recharges to the voltage $V_R - I_{ds}R_L$ with the time constant CR_L where C is the total device capacitance including stray capacitance. Using $C = 1.6 \text{ pF}$ and $R_L = 400k\Omega$, a recharge time constant of 0.64 microseconds is calculated.

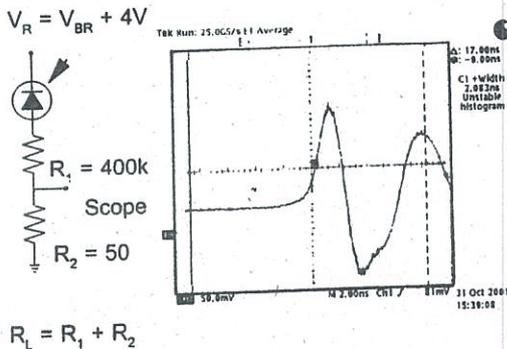


Figure 1. Passively quenched APD in the photon-counting mode and real-time trace pulse shape.

2.3 Photon counting

The APD can be triggered not only by photons, but also by carriers generated due to thermal, tunneling and trapping processes inside the semiconductor. These processes cause a self-triggering rate of the detector which is called dark counting rate, R . Thus counting all the pulses can lead to overestimating the light intensity at the detector.

In photon counting measurements, the signal is produced by the photoelectron counted by the detector while the noise is contributed to the statistical fluctuation. The minimum detectable optical power P_m can be expressed:

$$P_m = \frac{h\nu}{\eta} \left(\frac{R}{T} \right)^{1/2} = \frac{NEP}{(2T)^{1/2}} \quad (1)$$

Where NEP is the detector noise-equivalent power, T is the measurement time, η is the photon detection efficiency of the detector, and $h\nu$ is the photon energy.

When APDs is operated with a passive quenching circuit, and the count rate is low ($< 250 \text{ kHz}$), the dead-time correction count rate, n_s , can be estimated from [3]

$$n_s = \frac{n_c}{1 - n_c \tau} \quad (2)$$

Where n_c is the observed count rate, and τ is the dead time.

2.4 APD temperature dependence

An APD is a device similar to a rectifier diode, except its output current contains a term which is dependent on the incident light intensity on its surface in the operating wavelength range. The APD output current is given by

$$I_{APD} = -I_d + I_s \left(e^{\frac{qV}{kT}} - 1 \right) \quad (3)$$

where I_{APD} is the APD output current, I_d is the detected photo-current, I_s is the saturation dark current, q is the electron charge, V is the

device bias voltage (negative for reverse bias), k is Boltzmann's constant, and T is the temperature. The second term of equation (3) represents the APD dark current and the first term, I_d , represents the photo-current, given by

$$I_d = \mathfrak{R} \cdot P \quad (4)$$

where \mathfrak{R} is the APD responsivity, and P is the incident optical power. The APD responsivity, \mathfrak{R} (A/W), is obtain from

$$\mathfrak{R} = \eta G \cdot \frac{q}{hc} \cdot \lambda \quad (5)$$

where η is the wavelength dependent quantum efficiency, G is the APD internal gain, h is Planck's constant, c is the speed of light, and λ is the wavelength of the incident light. At a constant bias voltage, the APD operating temperature affects its output current. The APD gain, and therefore its responsivity, is a strong function of the device temperature. On the other hand, the APD dark current, as well as the dark current noise, is also dependent on the APD temperature.

2.5 APD temperature controller

The EG&G APD C30902S-DTC is supplied with a built-in TEC cooler to control the detector temperature. The temperature status of the APD is sensed by the thermistor, R_T , which is located as close as possible to the APD in order to ensure a minimal temperature gradient between the two devices. For this particular thermistor, the relation between its resistance (Ω) and the temperature (K) given by

$$T = \left\{ \frac{\ln \left(\frac{R_T}{5.1 \times 10^3 \Omega} \right)}{3200} + \frac{1}{298} \right\}^{-1} \quad (6)$$

The bridge is supplied by the zener diode, D , with a zener voltage V_Z .

The temperature monitor voltage reading, V_{TM} , is given in term of the zener voltage as

$$V_{TM} = \frac{R_S}{R_S + R_T} V_Z \quad (7)$$

Where R_S is bridge balance resistance.

3. EXPERIMENTAL SETUP AND RESULTS

The simple setup of our APD module for photon counting is illustrated in Fig 2. The avalanche photodiode was placed in the closed black box to ensure that there is no any light reaching the APD. The output signal from the APD without amplification (Figure 1) has an amplitude ~ 100 mV and duration < 5 ns FWHM. The dead time in the detector $\sim 1 \mu$ s is in reasonable agreement with calculation. This signal is discriminated by an comparator (Analog Device, AD96687). Dark counting rate and after pulse can be effectively reduced by this pulse shape discriminator (PSD). The pulse stretcher circuit (PS) is used so that the maximum APD output fit the minimum digital counter limit. The output detected signal from the PS is then applied to the digital counter (Leybold, 54745). In our experiments we incorporate a non paralyzable electronic dead time that ignores those counts that arrive within a short time (250-1000 ns) after every pulse. We find that most afterpulses occur within a few microseconds of an initial pulse, so the electronic dead time serves to eliminate some of the afterpulses from the count rates that we measure. Since the APD responsivity is a strong function of its voltage bias and temperature. The low ripple (0.025%) high voltage bias controller was designed follow Ref. 6 which can be adjusted manually to apply a constant voltage to APD.

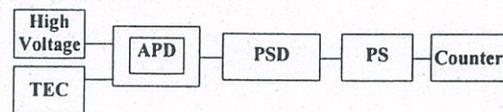


Figure 2. The experimental

The proportional integral temperature controller circuit from Ref. 8 was adopted to cool the detector to a fixed set point from the ambient temperature. With the precision resistors $R_S = 34.8 \text{ k}\Omega \pm 50 \text{ ppm}$, the APD temperature was set to -20°C from the initial room temperature of 20°C .

The temperature measurement is obtained by converting the temperature monitor voltage to a thermistor resistance according to equation (7), and then this is further converted into temperature according to equation (6). Figure

3. shows the temperature variation of the APD with the thermoelectric cooler controller. The steady-state temperature is -20 ± 0.1 °C with the settling time approximately 3 s.

Figure 4. shows the measured dark counting rate as a function of voltage beyond breakdown and operated at -20 °C to keep the dark count rate low.

We observed that the breakdown voltage of our detector is about 193 Volt and the dark counts rate is exponentially increased approximated by

$$y = 0.4513x^2 - 0.4847x - 0.0072,$$

where y is the dark counts rate (kHz) and x is the excess bias (Volt).

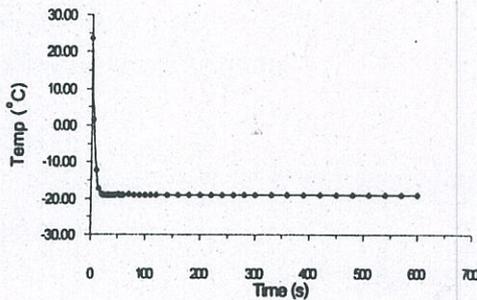


Figure 3. APD temperature variation.

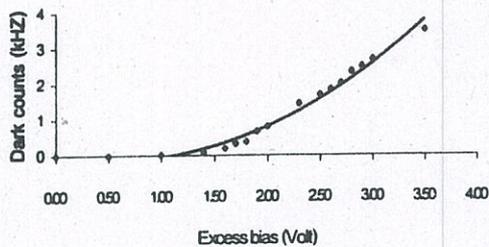


Figure 4. Dark counts versus excess bias (threshold 193V) @ -20 °C.

4. CONCLUSION

In this paper, we have carried out measurements on commercially silicon APD to implement it as single-photon counting in the first telecommunication window. The experimental results show that the simple but robust passive quenching circuit incorporated

with the high voltage controller, and proportional integral thermoelectric cooler are well suit to reduce the dark count rate and afterpulse at the low count rate. The APD module are potential for applications requiring high efficiency and high counting rate capability as, for instance, quantum cryptography, single molecule detection, fluorescent decays, etc. The active quenching circuit or the gated mode technique is preferable to use in the high counts rate for reducing the dead time and increasing the counting rate.

5. ACKNOWLEDGEMENTS

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