Semiconductor optical single-photon detectors

Jie Zhang

Abstract—Avalanche Photodiodes (APDs) connected with quenching circuits can be used for single photon detection. This semiconductor photon detector has a better performance than photomultiplier. The principles and applications of APDs are presented. Features, performance of different commercial devices are introduced and compared. Recent research progress based on the improvement of quenching circuits are introduced.

Index Terms—Avalanche photodiode, Geiger mode, single-photon avalanche diode (SPAD)

I. INTRODUCTION

PHOTON counting techniques have been developed over many years by exploiting the performance of photo-multiplier tubes (PMT’s) [1]. In recent years, semiconductor optical detectors, i.e., single photon avalanche diodes (SPAD’s), which operate above the breakdown voltage in Geiger mode connected with quenching circuits have been developed to detect single optical photons. This technique has such wide applications that it has been used in various fields such as: single molecule detection [2], fluorescent spectroscopy [3], optical fiber testing, basic quantum mechanics [4], quantum information and so on. The available detectors based on fast PMT’s can obtain better than 100-ps FWHM resolution, but they have inadequate quantum efficiency [5]. Fig. 1 shows the simple schematic diagram of a PMT’s. With respect to PMT’s, significant improvements have been made for photon detection efficiency, especially in the red and near infrared area.

Fig. 1 Schematic diagram of Photomultiplier Tube

II. SEMICONDUCTOR OPTICAL SINGLE PHOTON DETECTOR: STRUCTURE AND QUENCHING CIRCUITS

A. Structure

A schematic cross section of the fabricated Avalanche Photodiodes is shown in Fig. 2. In order to avoid edge breakdown, a guard-ring surrounding the p+ implantation has been implemented using a p-tub layer inside a deep n-tub available in this fabrication processes. The p+ and n+ implantation will surely make the depletion area narrower than before, therefore got a stronger electric field and then a more accelerated carrier. The active area is defined by means of an optical window opened in the metal light shield only in correspondence with the region where avalanche multiplication occurs.

Fig. 2 The basic structure of an APD, cross section

SPAD’s are essentially p-n junctions operate biased at voltage $V_A$ above breakdown voltage $V_B$. At this bias, the electric field is so high that electron/holes that enter the depletion region undergo a tremendous acceleration. As these accelerated carriers collide with the atoms they can knock electrons from their bonds, creating additional electron/hole pairs and thus additional current. The current rises swiftly (nanoseconds or subnanosecond rise time) to a macroscopic steady level in the milli-ampere range. If the primary carrier is photo-generated, the leading edge of the avalanche pulse marks the arrival time of the detected photon. Fig. 3 shows the I-V curve of a p-n junction. When operate at Geiger mode, avalanche will occur if it is triggered by an incident photon.
Fig. 3 I-V curve of the p-n junction, inserted figure is when bias at a voltage above the breakdown voltage, an incident photon can cause an avalanche.

B. Passive quenching circuits

In order to achieve single photon detection, we need to quench the avalanche by lowering the bias voltage to \( V_B \) or below. Then, the bias voltage is restored to detect another photon. This operation requires that the quenching circuits must sense the leading edge of the avalanche current, generate a standard output pulse that is well synchronized to the avalanche rise, quench the avalanche by lowering the bias to the breakdown voltage, and then restore the photodiode voltage to the operating level. Thus, careful consideration must be given to the design of the external circuits. There are currently two methods in general, which are passive quenching and active quenching, shown in Fig. 4 and Fig. 6 respectively. [6, 7]

Passive quenching, while relatively simple, has a number of drawbacks in its operation. Active quenching, on the other hand, is the preferred method of operation but the design is critical for the efficient operation of an APD in photon counting or Geiger mode.

Fig. 4 Passive quenching circuit

Fig. 5 Retriggering of a SPAD in a passive quenching circuit during the recovery transient after an avalanche pulse, which is the first one displayed on the left side: a, avalanche current \( I_a \); b, diode voltage \( V_D \).

Fig. 4 shows a passive quenching circuit. When an APD is biased above breakdown voltage \( V_B \), an incident photon can trigger an avalanche in the depletion region and the device will start to breakdown. At this situation, the large current that subsequently flows can be quenched by a passive element, the resistors. \( R_1 \) (~200 k\( \Omega \)) is actually a ballast resistor, which can be used to limit the current flowing through the APD. The increase of voltage at node (a) of the APD will drop the voltage across the device to below breakdown. The APD will then start to slowly recharge until the voltage across the device has returned to the original bias voltage. By placing a small sensing resistor \( R_2 \) at node (b), a comparator can be triggered to give a TTL/ECL output signal.

But the drawback is: the recharge period is so long that at this period, the APD is less sensitive to photons. Since the recharge time or the dead time can be in the order of 1 or 2 \( \mu s \), the overall maximum counting rate is limited to about 200,000 per second. Another drawback of using this passive quench arrangement is the dead time of the detector itself is not constant or well defined. This can pose a number of problems in certain applications. The noise of the detector, referred to as the dark count is also affected by the passive quenching arrangement. The initial current that is allowed to flow before being quenched will dissipate a large amount of energy in the device. It will result in an increase in temperature of the device, which will obviously bring in a bigger dark count rate. A further drawback is an effect called afterpulsing, which will have a considerable effect on the dark count rate. During an avalanche, some electrons and holes get trapped in the depletion region, only to be released later to cause a further avalanche. This again is a major result of the large current flowing by the passive quenching circuit. If the current can be limited quickly, then less electrons and holes would fill those traps, which will result in less afterpulsing and therefore fewer dark counts. Fig. 5 shows the retriggering of a SPAD in PQC during the recovery transient after an avalanche pulse, from which we can find that the photon that arrives during the first recovery is almost certainly lost. This shows the limitation of APD in passive quenching circuits and these limitations of passive quenching arrangement will make it unsuitable for wide applications.

C. Improved active quenching circuits

In order to overcome these drawbacks mentioned above,
active quenching circuits are developed and used. Be different from the passive quenching circuits, when an incident photon comes in and the device gets break down, an active quenching circuit will quickly sense and reduce the bias voltage down across the APD. After a certain hold off time, \( \tau_d \), the voltage will be subsequently restored. Fig. 6 shows an improved active quenching circuit. It is essentially a mix of active and passive quench circuits. By using a capacitor at the inverting input of the comparator, the hold off time is then controlled and therefore this design is presented for low voltage breakdown APDs (20-45V) that avoids the disadvantages of high voltage active quench circuits and their associated complexity.

After the APD has detected a photon, the voltage will be quickly sensed by the comparator, due to the large resistor, \( R_1 \). The comparator will turn on the fast FETs which in turn drop the voltage at the APD node (a) and bring the device below breakdown. The device is held below breakdown for a hold-off time determined by the time constant in discharging the variable capacitor VC. The device then quickly resets through \( R_2 \) before being ready to detect further photons. This circuit and design has proved very reliable with numerous different APD designs and is capable of detecting well in excess of 10x10^6 counts per second for long periods. One of the main advantages of the design is the placement of the input of the comparator before the ballast resistor, \( R_1 \). This ensures that only a small amount of current is necessary to generate the voltage needed to trigger the fast comparator. Some of the benefits of this are reduced power dissipation, lower dark counts and less afterpulsing.

![Fig. 6 Geiger mode active quenching circuit](image)

### III. COMMERCIAL DEVICES: PARAMETERS & PERFORMANCES

<table>
<thead>
<tr>
<th>Features of different commercial devices</th>
<th>( \eta )</th>
<th>FWHM (ps)</th>
<th>MCR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thick Si SPAD’s</td>
<td>&gt; 50% @ 540–850 nm</td>
<td>350–150</td>
<td>10 Meps</td>
</tr>
<tr>
<td>Thin Si SPAD’s</td>
<td>45% @ 500 nm</td>
<td>20</td>
<td>40 Meps</td>
</tr>
<tr>
<td>Germanium SPAD’s</td>
<td>&gt; 15% @ 1300 nm</td>
<td>85</td>
<td>11 Meps</td>
</tr>
<tr>
<td>InGaAsP SPAD’s</td>
<td>&gt;10% @ 1550 nm</td>
<td>250</td>
<td>3 Meps</td>
</tr>
</tbody>
</table>

Nowadays, along with the considerable progress achieved in design and fabrication techniques, SPAD’s devices have been extensively developed and are commercially available. Performances of these devices are dependant on parameters listed below:

- Breakdown voltage \( (V_B) \)
- Photon detection efficiency \( (\eta) \)
- Multiplication factor (Gain)
- Time resolution
- Dark-count rate, and
- Maximum counting rate (MCR).

Table I lists some important parameters of different SPAD devices. Almost all devices show a nice performance in the red and near IR spectral range.

### IV. CONCLUSION

Geiger Mode SPAD’s, together with a quenching circuit can be used as single photon detectors and has higher performance with respect to PMT’s, particular in the visible and near IR spectral range. This photon counting techniques provide the ultimate sensitivity and accuracy in measurements of weak and/or fast optical signals and has been commercially available for a wider use.

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### REFERENCES