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CIRCUITS FOR EXPLOITING THE TIME RESOLUTION OF AVAILABLE HIGH-QUANTUM-EFFICIENCY HIGH-VOLTAGE SPAD


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Abstract

Avalanche photodiodes known as Single Photon Avalanche Diodes SPADs detect single photons when operated in Geiger-mode, at bias voltage higher than the breakdown level. Silicon SPADs having high quantum detection efficiency (up to 80% at 800 nm wavelength) and sensitive area with a few hundred micron diameter are industrially produced. The main features and the intrinsic performance of recently developed SPAD devices are illustrated and discussed. It is shown that their intrinsic time resolution is better than 100ps rms. These devices are commercially available in compact electronic modules, that require only a low voltage supply and include all the bias and quenching circuitry, but have 200ps rms specified resolution in photon-timing. A new compact active quenching circuit has been specifically designed for extracting at best the time information in the avalanche pulse, with high counting rate and gated operation capability. Experimental results confirm the expected performance and demonstrate that these silicon SPADs offer a combination of detection efficiency and timing resolution of high interest for laser ranging.

1. Introduction: high efficiency SPAD detectors

Silicon avalanche photodiodes working in Geiger-mode, biased at voltage higher than the breakdown level, detect single optical photons. They are therefore called Single-Photon Avalanche Diodes SPADs and, in comparison to photomultiplier tubes (PMT), they provide remarkably higher quantum detection efficiency and mark the photon arrival time with comparable or better resolution [1]. SPADs are gaining wide acceptance in laser ranging applications and have open new perspectives in various other applications of photon-counting and photon-timing measurements. As concerns industrially produced devices, the situation for SPADs is different from that of ordinary avalanche photodiodes (APD), which exploit the avalanche for amplifying linearly the photoinduced current signal. Silicon APDs providing good performance in analog applications are available from various sources, but only a few of these devices can be employed as SPADs with good performance. The group led by R.J.McIntyre at the former RCA Electrooptics laboratories, now EG&G Optoelectronics Canada, has carried out a pioneering role in this field, developing and progressively improving in the last two decades silicon APD devices with high photon detection efficiency, fairly large
sensitive area (150 to 500 micron diameter) and capability of working as SPADs [2]. Since various years the C30902S and C30921S types are specified for photon counting: they have breakdown voltage of about 250V, detection efficiency of about 50% at 633 nm wavelength and it has been verified [3] that they can attain time resolution around 150ps rms (root-mean square).

More recently, a new improved APD has been developed [4] by refining the device structure design and the fabrication technology. This EG&G device, called Slik\textsuperscript{TM}, was originally devised as analog amplifying avalanche photodiode with very low multiplication noise. As outlined in Fig.1, the field profile in the p-n junction has been redesigned [4] for minimizing the value of the effective k ratio (a weighted ratio of the ionization coefficients of holes to that of electrons) for a given thickness of the active volume of the device. In fact, the name Slik stays for "super-low k".

![Diagram of C30902 E/S and SUPER LOW k (SLIK)](image)

Fig.1 Schematic cross section and electric field profile of silicon avalanche photodiodes suitable as SPADs: the new Slik is compared to the C30902S.

Because of the smooth field distribution, the Slik has breakdown voltage $V_B$ remarkably higher than that of the C30902S, about 440V at room temperature. The design approach adopted, however, also leads to improve the operation in Geiger mode, making of the Slik a high performance SPAD.
As illustrated in Fig. 2, the probability that the primary-generated electron-hole pair initiate avalanche is significantly higher [4]. As shown in Fig. 3, the probability of detecting a single photon, that is, the quantum detection efficiency is correspondingly enhanced.

**Fig. 2** Avalanche-triggering probability versus excess bias voltage above the breakdown level for different photodiode structures. The performance of the new Silik is compared to the previous C309025 type.

**Fig. 3** Quantum detection efficiency of the new Silik avalanche photodiode versus photon wavelength, at different excess bias voltage above the breakdown level.
The single-photon detection efficiency of the Slik is significantly better than that of the previous C30902S over most of the spectral range covered with silicon SPAD detectors. A peak efficiency of about 70% is measured at 820nm, consistent with the presence of an anti reflection (AR) coating centered at this wavelength. With a different AR coating and a slightly modified structure, a quantum efficiency in excess of 80% at 500 nm has been verified [4]. As shown in Fig. 3, a photon detection efficiency of about 3% is measured at 1064 nm.

The thermal generation of carriers within the active junction volume (that gives rise to the primary dark counting rate) is reduced to very low level, a few thousand per second or less at room temperature. After each avalanche pulse, the carrier trapping and delayed release phenomena (that produce afterpulsing effect enhancing the total dark-counting rate) are reduced to rare events (probability of a few percent) occurring within a short time (a few tens of nanoseconds). As shown in Fig.4, this brings down to very low level the intrinsic noise of the detector. The total dark counting rate is only a few 1000 counts per second at room temperature and can be dramatically reduced (down to a few counts/s) by lowering the detector temperature to -40 C, a level that can be easily attained by using a double stage thermoelectric peltier cooler.

Fig. 4 Dark-counting rate at room temperature versus excess bias voltage above the breakdown level for a Slik avalanche photodiode having active area with 250 μm diameter.

In order to facilitate the application and avoid practical drawbacks due to the fairly high breakdown voltage, Slik detectors are commercially available in compact electronic modules (SPCM series) requiring only a 5V voltage supply and including all the necessary front-end circuitry, that is, the high voltage supply and the quenching circuitry, with passive and active quenching versions [4].
2. Timing performance of high efficiency SPADs and limitations due to quenching circuits

Theoretical analysis of the physical phenomena involved in the avalanche build-up and in the propagation over all the active area, supported by computer simulations that take into account the detailed structure of Slik photodiodes, point out that the inherent detector resolution is significantly better than 100 ps rms [1,5-7]. Experimental data supporting the theoretical predictions have been reported, obtained in measurements performed with the Slik device working in a simple passive quenching circuit, deriving a fast output signal directly from the fast avalanche current pulse and processing it with external fast amplifying and timing circuits [8]. With the available SPCM active-quenching module, however, resolution values limited to about 200 ps rms are specified. Other circuits developed in our laboratory for astronomical applications, that primarily required high counting rate capability and compact circuit structure [9], showed equivalent performance in photon timing. We estimated that a significant limitation to the performance had to be ascribed to the design approach adopted in these quenching circuits, aiming to high counting rate rather than high resolution timing [4,9]. In fact, a basic limitation of these circuits can be ascribed to the configuration employed for taking out the avalanche signal and for extracting the time information from it. A schematic diagram of the circuit described in Ref.4 is shown in Fig.5.

![Schematic diagram of the compact active quenching circuit employed in the SPCM modules and described in Ref.4.](image)

When a photon triggers an avalanche, the current flows in the 100KΩ resistor, providing a voltage signal to the threshold discriminator. The photon arrival time is marked by the switching of the discriminator. Since a stray capacitance $C_S$ of a few pF between the node A and ground is unavoidable, the voltage pulse on the discriminator input is actually affected by a low-pass filter with non negligible time constant $R_LC_S$. It has been foreseen in theoretical analysis and verified in experiments that such a filtering has a detrimental influence on the photon-timing accuracy, which can be only in part compensated by employing a very low threshold level in the timing circuit [7,10].
3. New compact active quenching circuit for high-resolution photon-timing

We have specifically developed a compact active quenching circuit for extracting at best the time information in the avalanche pulse, maintaining the capability of gated operation and of working at high counting rate. A schematic diagram of the circuit is shown in Fig. 6. It represents an evolution of the above mentioned design approach [9]; the essential new feature is the addition of circuitry that exploits the very first part of the avalanche current signal for generating a timing signal.

Fig. 6 Simplified diagram of the compact active quenching circuit developed for high resolution photon-timing with SPADs having high breakdown voltage.

The current pick-up stage has a variable impedance input. In the quiescent state the impedance is low, so that the SPAD terminal is connected to a low impedance load. When the SPAD is triggered, the onset of the avalanche current pulse flows into this low impedance input. A waveform with the fast risetime of the avalanche current (about one ns or less) is therefore supplied by the current pick-up stage to a timing circuit, which can thus exploit at best the detector performance. As soon as the avalanche current exceeds 1mA the variable impedance is switched to a high value, so that the current is diverted to the load resistor $R_L$. It thus develops a voltage signal at the input of the threshold discriminator, which controls the quenching and reset circuitry. Fast ECL comparator and monostables are employed for minimizing the delay between the onset of the avalanche and the application of the quenching pulse to the SPAD. The quenching and reset switches are implemented by using fast DMOS FET transistors (Siliconix SST215), which can be employed with a maximum excess bias voltage of about 25V. ECL to TTL level converters provide the proper driving signal to these switches and generate a standard TTL output pulses. An external TTL gate-off signal acts on the quenching switch through an OR circuit. Gate-off pulses with duration ranging from 10ns to minutes can be employed.
A mixed passive-active quenching scheme is adopted in the circuit [10]. A fairly high passive load ($R_L+R_S$) provides a prompt passive quenching or at least a quasi-quenching, reducing the avalanche current to very low value. With a short delay (typically 10 ns), quenching is confirmed by the active loop formed by the discriminator, the monostable and the quenching switch. The active loop drives the voltage well below (by about $4V$) of the nominal breakdown voltage $V_B$, avoiding reignition due to nonuniformity of $V_B$ over the APD active area [4]. The mixed passive-active quenching is advantageous for minimizing the avalanche charge and the related afterpulsing effect due to carrier trapping [10]. Furthermore, this approach turns out to be in practice almost mandatory for minimizing the power dissipation of SPADs with high breakdown voltage $V_B$ working at high excess bias voltage. In these devices the power dissipation attains various Watts and, without an effective limitation of the pulse charge, it would lead to excessive heating of the detector at high pulse repetition rate. The various phases in the operation cycle can be identified in the voltage waveform at the SPAD terminals, as shown in Fig.7. After the passive quenching phase (A) the quenching switch is activated (B); the SPAD is then held below the breakdown voltage during the hold-off time (C); finally, the reset switch is activated (D) and makes the SPAD ready again to detect another incoming photon. The capability of working at remarkably high counting rate is illustrated by Fig.8. The fast quenching and reset circuitry enables to work with an overall deadtime for counting below 40 ns, corresponding to a counting rate exceeding 25 Mcounts/s.

![Fig.7 Voltage waveform at the terminals of a SPAD working in the circuit of Fig.6. The various phases in the quenching-holdoff-reset cycle are pointed out in the figure.](image)

The resolution in single photon timing of the Slik working in the new active quenching circuit was tested in a conventional time-correlated single-photon counting setup. A gain switched laser diode emitting pulses with pulse duration 20 ps full-width at half maximum (FWHM) at 820 nm wavelength was employed. The detector was operated at room temperature, biased 20 V above the breakdown voltage.
Fig. 8 Output voltage waveform of the circuit in Fig. 6, showing that the deadtime is shorter than 40 ns (horizontal scale 10 ns/div; vertical scale 0.5 V/div).

Fig. 9 Time resolution of the Slik detector as a function of the threshold level of the timing discriminator. The detector is biased 20 V above the breakdown voltage.

Fig. 9 shows how the time resolution of the Slik detector depends on the threshold level of the timing discriminator. A minimum value of about 220 ps FWHM (~ 100 ps rms) was measured with a threshold of 8 mV, corresponding to an avalanche current level of 160 μA. These results are in agreement with the data reported by Li and Davis: in tests performed employing laser pulses at 584 nm wavelength and a Slik at 20 V excess bias voltage, cooled at -45 C and
operating with a simple passive quenching circuit, they obtained 168 ps FWHM time resolution at low repetition rate of the avalanche pulses [8].

4. Conclusion

In conclusion, we have demonstrated that the intrinsic performance of the new Silk silicon avalanche photodiodes can be fully exploited working with suitably designed compact quenching circuits. It is thus possible and practical to work in laser ranging applications with a single-photon detector that, over a wide spectral range extending up to 1064nm, offers an unprecedented combination of the highest available quantum detection efficiency and a very good time resolution. Among the available single-photon semiconductor detectors, this resolution is inferior only to that of the ultrafast SPADs, having structure optimized for timing at the cost of remarkably lower quantum efficiency [1].

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References