Characterization of silicon avalanche photodiodes for photon correlation measurements. 1: Passive quenching

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We examine the photon correlation and other vital performance characteristics of silicon avalanche photodiodes operated in photon counting or the Geiger mode, and assess their suitability as detectors for photon correlation spectroscopy and laser velocimetry measurements.

I. Nomenclature

APD avalanche photodiode,
α afterpulsing probability, defined in Eq. (1),
$g^2(\tau)$ normalized photon autocorrelation function,
$\bar{n}$ mean number of counts per correlogram sample or delay time,
R APD quenching resistance, in this paper 220 kΩ,
τ correlogram sample or delay time,
V_{BR} APD breakdown voltage,
V_R Voltage applied across APD and series resistances.

II. Introduction

Avalanche photodiodes (APDs) have been available commercially for some years. They are usually manufactured from silicon or germanium, depending on the required spectral sensitivity. Si diodes are usually sensitive from mid-visible through to ~1-μm wavelength. A wealth of literature is available detailing experimental performance results obtained by different researchers using various diodes.[1-6] They have already found application in the telecommunications industry as small, cheap, rugged photon-counting detectors to replace photomultiplier tubes.[7]

APDs may be purchased from RCA, NEC, Hamamatsu and other sources. It is common practice to use them in the so-called Geiger mode, i.e., reverse-bias beyond breakdown to achieve photon-counting operation. In the photon-counting mode, two types of operation are encountered, passive and active quenching. For passive quenching, the APD is placed in series with a ballast resistor and on photodetection the voltage drop across the resistor quenches the breakdown. The APD is allowed to recover from the detection through the natural dead time associated with the time taken to recharge its own capacitance via the ballast resistor. Under active quenching, the presence of a photodetection is recognized as soon as possible after the event and the voltage applied to the APD is modified by surrounding electronics so as to minimize the recovery dead time.

To the authors' knowledge, APDs used in the Geiger mode have, to date, only been used for photon-counting experiments to determine the first-order statistics of light fields, i.e., the moments of the probability density function of photocounts, mean, variance, etc. The purpose of our experiments has been to assess the suitability of these APDs for measurement of higher-order statistical information, i.e., intensity correlations and power spectra. To this end we have examined a selection of RCA silicon APDs in terms of magnitude of dark counts, correlations, afterpulsing effects, quantum efficiency, and stability of counting rate as a function of temperature and operating voltage.

This paper addresses only passive-quenching performance, but it will be seen that devices operated in this mode have potential as replacements for bulkier, more fragile and expensive photomultiplier tubes, and may be useful in lower frequency ($\lesssim$0.5-MHz) photon correlation spectroscopy and laser velocimetry[8] both in the research laboratory and in commercial instrumentation.

III. Characterization Parameters

Detailed assessment and careful selection of photomultipliers used for photon correlation measurements are mandatory for high quality correlogram formation. It is usual to measure many performance parameters of a phototube before use, the pulse-height distribution, dark count, afterpulsing level and correla-

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tions, quantum efficiency, and spurious correlations due to surrounding circuitry effects. Guidelines for the measurement of these parameters in relation to photon-counting and correlation measurements were introduced many years ago,[8] and similar considerations are necessary in selecting and operating APDs. Typical and usually adequate photomultiplier performance parameters are:

pulse height distribution	a well-defined single peak,
dark count	20–100 counts/s,
afterpulsing	≦0.04%, as defined in Eq. (1),
operating voltage	1400–1950 V, device dependent,
quantum efficiency	~7%, wavelength dependent.

IV. Experimental Arrangement

In our experiments we examined only RCA APDs, model C30921S.[9] The electronic arrangement for our passive-quenching measurements is schematically shown in Fig. 1. An EMI model PM28B high voltage supply of ±0.002-V stability was used to supply between −180 and −250 V to the APDs and the resistor network V_R, depending on the operational temperature and dark count required. The pulse output across the 51-Ω resistor caused by photodetection or dark count was amplified ~90 × using three stages of an Ortec 574 amplifier and then via an Ortec 583 discriminator converted to pulses of uniform width and height suitable for photon-counting and correlation equipment, Malvern Instruments photon correlator model K7025. APD output pulse heights were monitored on a storage oscilloscope; correlation functions were processed in a desk-top computer.

In most of our experiments it was necessary to cool the APDs to <0°C to reduce the dark count to an acceptable level. The cooling was achieved using two RS Components mini-Peltier devices, model 5847, operated typically at ~0.1 V and 0.7 A. The APDs were thermally isolated from the environment by encapsulation in 3-mm thick polystyrene insulation.

V. Experimental Results

For brevity we present just one set of experimental results obtained from the APD whose dark count was the worst of the batch supplied by the manufacturer, s/n S45415. This diode had a room temperature dark count of 2.1 × 10⁴/s at 5% quantum efficiency and 820 nm (manufacturers data[9]). The figure for the best diode of our batch was 1.2 × 10⁴ counts/s. Our experiments can be summarized in seven brief sections:

A. Pulse-Height Distribution

We examined pulse-height distributions at room temperature. The procedure was to adjust the discriminator threshold level and accumulate counts for 1 min. The amplified peak pulse heights from the APD were ~150 mV with V_R set to ~3 V beyond V_{BR}. The

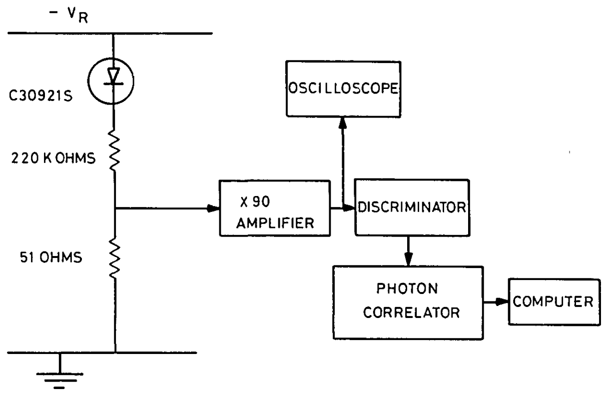

Fig. 1. Circuitry for testing APDs in passive quenching.

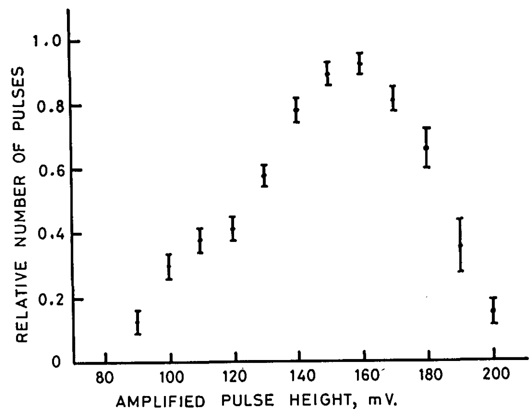

Fig. 2. APD pulse height distribution.

pulse-height distributions were then calculated from the differences in photon counts recorded for adjacent threshold settings. A typical distribution, Fig. 2, shows a well-defined peak as required for clean threshold discrimination. We found that a threshold level of ~100 mV allowed utilization of the majority of photodetections and discriminated against amplifier noise at lower voltages (not shown).

B. Dark-Count Rates

Dark-count rates were measured as (1) a function of temperature for constant APD output pulse height (through control of V_R) and (2) a function of voltage for constant APD temperature. The results for the diode being discussed are presented in Figs. 3 and 4. Figure 3 shows that an acceptable dark-count rate of less than a few hundred counts per second could be achieved by reducing the APD temperature to between −20 and −30°C.

Figure 4 shows how sensitive the dark count is to applied voltage in excess of V_{BR}. The quantum efficiency is also sensitive to this variation and in any real application of APDs to photon counting/correlation a trade-off has to be made between quantum efficiency and dark count for a fixed applied voltage. In practice we used an excess voltage above breakdown of ~3–3.5 V when acquiring correlograms from an APD operated at approximately −20°C.

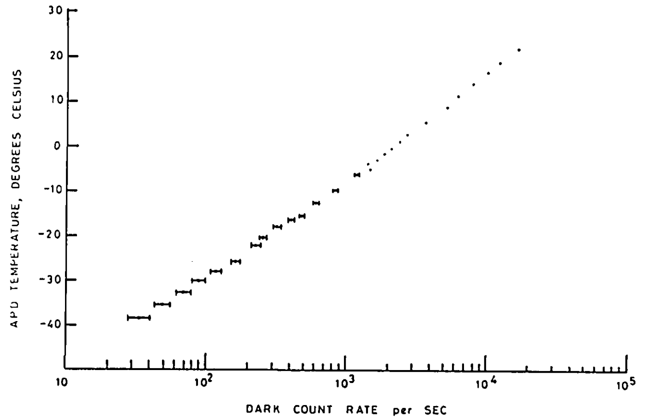

Fig. 3. Variation of APD dark count as a function of temperature.

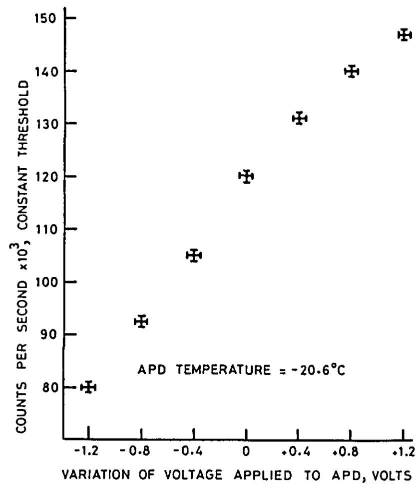

Fig. 5. Variation of APD count rate with applied voltage.

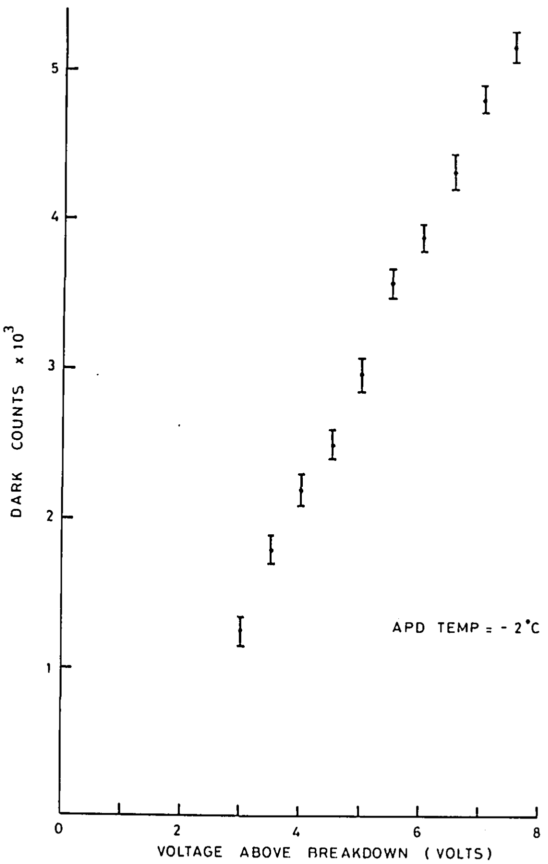

Fig. 4. Variation of APD dark count as a function of voltage in excess of V_{BR}.

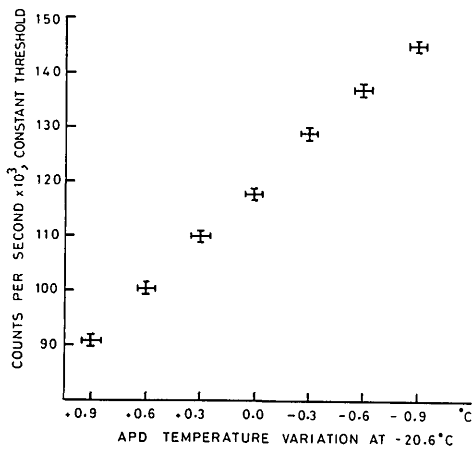

Fig. 6. Variation of APD count rate with temperature.

C. Count-Rate Stability

The count rate is strongly dependent on the voltage above breakdown applied to the APD. Since the breakdown voltage varies rapidly with the device temperature, there is also a strong dependence of count rate with APD temperature change. Figures 5 and 6 plot these variations for the diode under discussion. Such plots indicate the required temperature and voltage stability needed during acquisition of correlograms to ensure correct normalization. It can be seen that a count rate change of ~1.0% occurred for voltage changes of only 0.1 V (Fig. 5) and for temperature changes of 0.04°C (Fig. 6).

The variation of breakdown voltage with temperature was found to be an essentially linear function with gradient 0.75 V/°C. At −25°C the breakdown voltage was approximately −207.5 V for the diode being discussed.

D. Quantum Efficiency

This parameter was measured with the APD operated at −10°C and excess voltage above breakdown of 3 V, the threshold being set with respect to the pulse height distribution as described previously. The light source was a greatly expanded He–Ne laser beam of 632.8-nm wavelength attenuated by calibrated neutral density filters. Great care was taken to eliminate the effects of stray and reflected radiation via baffling. The measured quantum efficiency was 7.5% ± 1%, in good agreement with the manufacturers data sheet, and comparable to many photomultiplier tubes used for photon counting. At excess voltages beyond 3 V and with additional cooling to compensate for increased noise level and maintain dynamic range, the quantum efficiency can be increased to a value significantly exceeding 7.5%.

E. Dead Time

The dead time of an APD used in the passive-quenching mode depends both on the APD capacitance and on the value of its ballast resistor. From the data sheet and circuit shown in Fig. 1 we expected a dead time of a few microseconds (~1.6-pF capacitance of the APD, 220-kΩ series resistance). From experimental measurements in the manner described by Gulari and Chu[10] using the photon-counting probability density function (pdf) acquired on our photon correlator operated in the pdf mode, we determined the mean dead time to be 1.79 ± 0.07 μs, using twenty pdf results averaged.

F. Normalized Factorial Moments of a Poisson Source

A pdf was accumulated in the photon correlator using a light source having Poisson photon statistics and with a count rate of 4.53 counts per sample time. A total of 2×10^5 samples were taken. A comparison of the measured normalized factorial moments $n^{(r)}$ (Refs. 11 and 12) of the source and the values expected theoretically due to the finite nature of the measurement[11,13] is as follows:

	Theoretical	Measured
$n^{(1)}$	1.0000	1.0000
$n^{(2)}$	1.0000 ± 0.0007	0.99997
$n^{(3)}$	1.0000 ± 0.0022	0.99950
$n^{(4)}$	1.0000 ± 0.0048	0.99822
$n^{(5)}$	1.0000 ± 0.0094	0.99585

These values were computed using corrections for the dead time to second order[12] and using the experimentally determined dead time as discussed above.

G. Correlation Functions and Afterpulsing Effects

We examined the photon autocorrelation properties of the APDs using an attenuated and stabilized dc white light source, the APDs being cooled to approximately −15°C. Correlation functions were acquired for differing count rates and sample or delay times τ. The perfect intensity autocorrelation function from this source would be a constant value throughout all delay times to within the experimental error.

Figure 7 shows three sets of correlation functions obtained at different count rates. Each set shows the correlation function over different time scales obtained by varying the delay time. It can be seen clearly that only in conditions of the delay time being less than or similar to the APD dead time is significant distortion of the correlogram present at the first few delay times, taking a value less than that measured at longer delay times. For delay times rather greater than the APD dead time, only the first delay time is distorted significantly.

The afterpulsing probability α is defined as the probability of detecting a pulse correlated with the photodetection during a later time interval. α can be measured from the excess of a delay channel above the

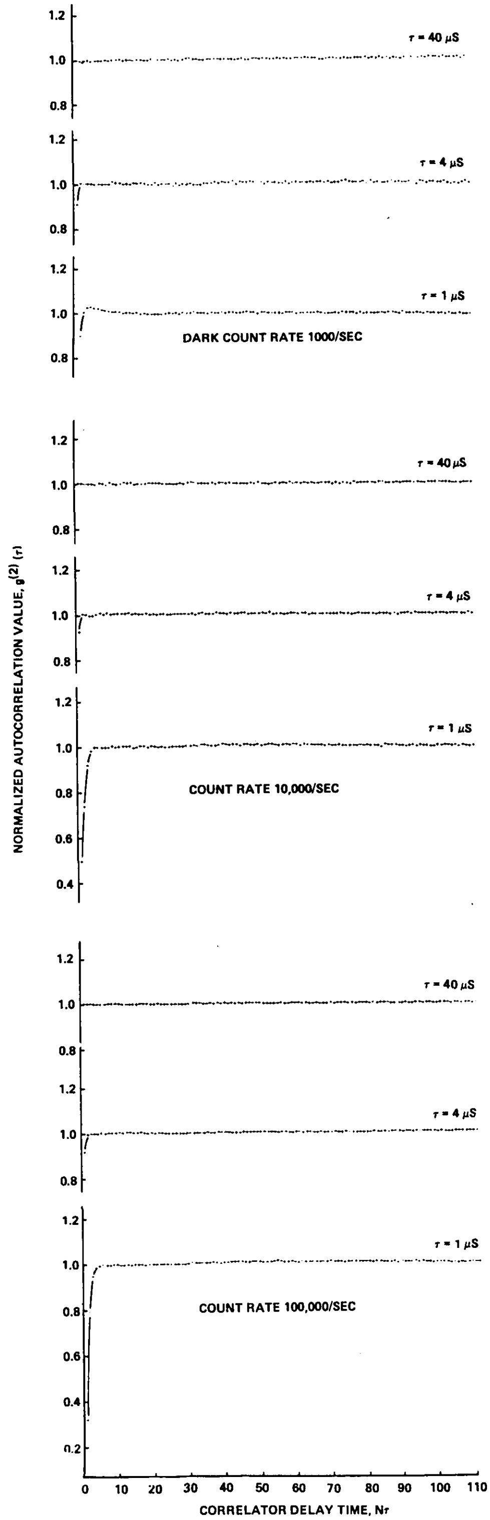

Fig. 7. Correlograms from an APD: (1) top three traces at dark-count rate; (2) middle three traces at 10^4 counts/s; (3) lower three traces at 10^5 counts/s showing dead time and afterpulsing effects.

normalized long-delay-time correlation value, using the equation (Ref. 8, pp. 168–173)

$$\alpha = (g^2(\tau) - 1) \cdot \bar{n}. \tag{1}$$

This yielded a maximum value for α of 0.006% ± 0.001% in the fifth delay channel with a sample time of 1 μs. This was typical of our batch of APDs. In Fig. 7 the afterpulsing effect is most noticeable in the first few delay times of the third trace from the top, because the measurement was conducted at low count rate. At normal count rates (Fig. 7, lower six traces) the afterpulsing effect on the intensity autocorrelation function is negligible. The afterpulsing values that we have measured compare very favorably with the effects that are typical from photon-counting photomultiplier tubes, often >0.04% and thus unusable for high quality photon correlation measurements.

VI. Discussion and Conclusions

It would appear from our measurements on a set of RCA APDs that when cooled to between −20 and −30°C and operated at ~3 V beyond breakdown voltage, these devices offer a passive-quenching performance that is similar and in some respects better than some photon-counting photomultiplier tubes of considerably greater size and cost. The performance is adequate for a restricted range of photon correlation measurements. The restriction on the range of measurements stems from the APD dead time, which at present limits the upper frequency of intensity fluctuations to ~0.5 MHz with minimal distortion in the first delay time of the correlogram. Early indications are that development of active-quenching circuitry will extend the range of operation of these APDs to ≦30-ns dead time (i.e., being useful up to maximum signal frequencies of a few tens of megahertz) and will be considered in a forthcoming paper.[14] Limitations due to dark count are minimized by cooling. In typical PCS and LDV applications with signal count rates above 4×10^4 counts/s cooling to 0°C may be adequate as this limits dark counts to $\sim 2 \times 10^3$/s and only slightly lengthens the experiment duration for a given correlogram accuracy.

The practical deployment of these APDs in photon correlation systems will depend mainly on the ability to control their temperature within exacting tolerances and the cost of supplying the necessary cooling. If these problems can be overcome, there are a wide range of new application areas: multiobservation-angle photon correlation spectroscopy and simultaneous multispatial-position low-frequency laser Doppler velocimetry (approximately meters per second velocities for typical laser beam geometries) to suggest but two. Furthermore, new miniature rugged industrial control systems may become possible allowing measurements in awkward environments.

In practice, it will be necessary to stop frosting of the APD entrance aperture due to sub-zero °C operation, unless an integral optical fiber lead is used to guide light to the detector. Furthermore, if temperature drift is likely during a long correlogram accumulation, as is often the case in photon correlation spectroscopy, the corresponding count rate drift must be minimized by acquiring and averaging a contiguous sequence of short, independently normalized correlograms, as is common practice in our laboratories.[15]

Finally we note the development of superlattice APDs[16] and hope that they may in the future provide improved noise performance at temperatures closer to room temperature.

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