BNL-25757
OG451

AVALANCHE PHOTODIODES FOR ISABELLE DETECTORS

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INTRODUCTION

At ISABELLE some requirements for detecting bursts of photons are not met by standard photomultiplier tubes. The characteristics of immunity to magnetic fields, small size (few mm), low power consumption (~100 mW), insensitivity to optical overloads, and wide dynamic range (~60 dB) are achieved with difficulty, if at all, with PMTs. These are characteristics of the solid state avalanche photodiode (APD), the preferred detector for light-wave communications. Successful field tests with APD detectors stimulated the design of standard optical-fiber communication systems to replace wire carriers by the early 1980's. In other characteristics, i.e., counting rate, pulse-height resolution, effective quantum efficiency, detection efficiency, and reliability, bare APDs are equivalent to standard PMTs. APDs with currently available amplifiers cannot resolve single photoelectrons but they could provide reasonable detection efficiencies and pulse-height resolution for packets of ≳100 photons. Commercially available APDs can cost up to 100 times as much as PMTs per active area, but they are potentially much cheaper.

Six topics are discussed below: (1) detectors for light-wave communication and detectors for particles, (2) avalanche photodiodes, (3) commercially available APDs, (4) dynamic response of PMTs and bare APDs, (5) photon counting with cold APDs, and (6) conclusions and recommendations.

I. DETECTORS FOR LIGHT-WAVE COMMUNICATION AND PARTICLES

Transmitters inject photons into a small (<1-mm) optical fiber. Each burst represents one bit. The detector has three components: APD, bias circuit, and amplifier. In comparison with particle counters these detectors are very efficient at one miss per 10^9 bits. Very high bit rates are achieved with these detectors,[1] as shown in Fig. 1. Diagonal lines indicate the optical power per bit. The upper horizontal band covers detector performing range if nonmultiplying PIN photodiodes are used. The lower band is for detectors that use APDs where ~200 photons per bit support rates up to 10^9 bits per second. The number of photons is constant above 10^7 bits per second. Error rates of 10^{-6} (10^{-3}) would require 140 (70) photons per bit.[1] An ideal detector's efficiency would be limited by quantum noise, the Poisson fluctuations in the number of photons per bit. Twenty-one photons per bit corresponds to one miss expected in 10^9 bits due to quantum noise. Thus, ideal detectors are only 20 dB more sensitive than contemporary detectors.

In many particle detectors short bursts of photons are stimulated by individual particles. The light might be emitted from a

*Supported in part by the U.S. Department of Energy.

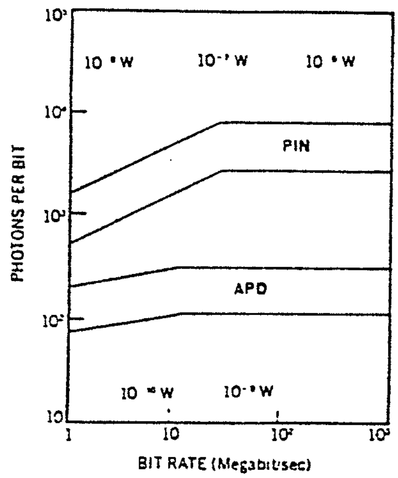

Fig. 1. Sensitivity of detectors used in light-wave communication.[1]

scintillator, by the Cerenkov effect, from an electric discharge, or from a phosphor.

In 1957 Reynolds and Condon[2] reported that an average of 110 photons are emitted from one end of a short 1-mm-diam filament of scintillator when it is exposed to minimum ionizing particles. Hence it is likely that detectors for light-wave communication would respond to typical bursts of scintillation light.

II. AVALANCHE PHOTODIODES

An APD chip is the size of a piece of paper a few mm square. Electrically it is a back-biased diode, as shown in Fig. 2. The internal gain of the diode increases with bias until the diode breaks down.

A limit on the gain-bandwidth product[3] restricts APDs to gains of a few hundred for broad-band use. Quantum efficiencies of 80% are typical. From 100 photons an average pulse of 8×10^3 electrons

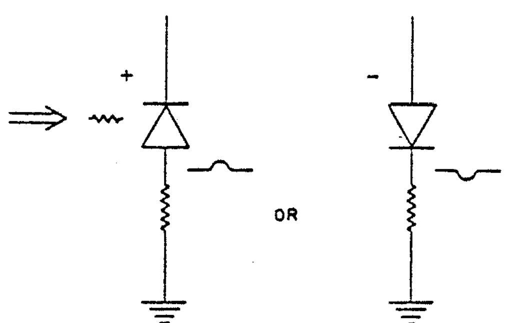

Fig. 2. Photodiode circuit.

is passed into the amplifier. Monolithic amplifiers like those designed for PWCs are least expensive. Thick-film hybrid amplifiers are more sensitive but more expensive.

An optimal gain boosts the sum of the dark current noise and the quantum noise until they equal the amplifier noise. Higher gain does not improve the signal-to-noise ratio.

The photocurrent is composed of electron-hole pairs created by the incident photons. Subsequently the photocarriers initiate an avalanche of electron-hole pairs by impact ionization in the high-field region of the back-biased p-n junction. The shower quickly propagates through the junction. The ratio of the final current to the initial photocurrent is the gain.

The average gain can be obtained from solutions to the coupled differential equation[4] for the density of carriers along the axis of the APD:

$$dJ_n/dx = -\alpha(x)J_n - \beta(x)J_p - g(x) = -dJ_p/dx \qquad (1)$$

where negative (electron), J_n, and positive (hole), J_p, currents are driven by ionization coefficients, $\alpha(x)$ and $\beta(x)$. They are functions of electric field strength, which varies rapidly with x. The distribution of injected photocarriers is given by g(x). Average gain depends on the shape and strength of the electric field.

The average gain[4] can be uniform over six decades of input photocurrents. Frequency response of APDs reaches 10^9 Hz, as shown in Fig. 1.

Fluctuations in the avalanche contribute noise to the final current. The excess noise factor,[4] F(M), depends on the average gain, M.

$$F(M) = \langle m^2 \rangle / \langle m \rangle^2 \qquad (2)$$

where the instantaneous gain is m and

$$M = \langle m \rangle \quad . \qquad (3)$$

In an ideal amplifier like the electron multiplier of a PMT with a high-gain first stage,

$$M = m \qquad (4)$$

and

$$F = 1 \qquad (5)$$

would apply.

The width[4] of the gain probability distribution is

$$\sigma M/M \approx (F/\varphi)^{\frac{1}{2}} \qquad (6)$$

where φ is the average number of photocarriers injected into the diode, and F is the excess noise factor from Eq. (2).

The excess noise factor[4] is about 5 for APDs. Hence bursts of an average of 100 photons cause an average of 80 photocarriers, and the output pulses contain $(8\pm2)\times10^3$ electrons. Now the amplifier must be sensitive to $\sim6\times10^3$ electrons for each original burst of 100 photons to be detected.

III. REACH-THROUGH APDs

An APD marketed by RCA[4] has a good performance and ultraviolet quantum efficiency. The construction of the diode is shown in Fig. 3. Photons enter from the left through the thin p-layer, which is connected to the positive side of the external circuit. In the next wide layer (~100 μm) of I-type semiconductor the photons are absorbed. Then the photogenerated carriers are multiplied in the thin p-n junction. Some electric field extends back from the p-n junction through the I-layer to the p-layer as shown. This "reach-through" field assures that all carriers are collected by drift velocities approaching saturation. High frequency response and mean gains independent of where the photon is absorbed are achieved by this architecture. The mean gain is shown in Fig. 3.

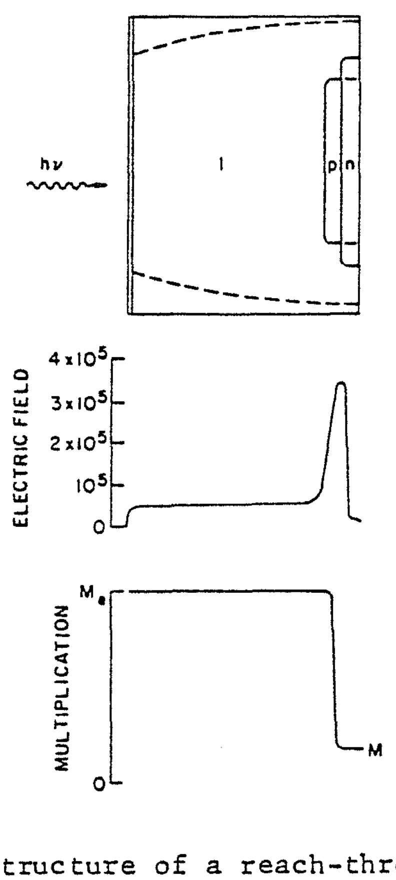

Fig. 3. Structure of a reach-through APD.[4]

Quantum efficiencies are optimized by appropriate antireflection coating of the entrance. Highly absorbed ultraviolet light requires a thin p-layer at the entrance.[4]

McIntyre's theoretical model[6] for the reach-through APD depends on one measurable parameter of silicon,

$$k = \beta(E)/\alpha(E) \qquad (7)$$

where ionization coefficients $\alpha(E)$ and $\beta(E)$ of Eq. (1) depend on field strength, E. Gain probability distributions depend on k and on the average number of photons per pulse at input. The excess noise factor defined by Eq. (2) depends on mean gain and k.

In 1972 Conradi[7] measured the distribution of gains and the excess noise factor shown in Figs. 4 and 5 for reach-through APDs. Excellent experimental confirmation of the model over many decades was achieved with no adjustable parameters.

In 1978 the Electro Optics Department of the Solid State Division of RCA Limited undertook a feasibility study on the use

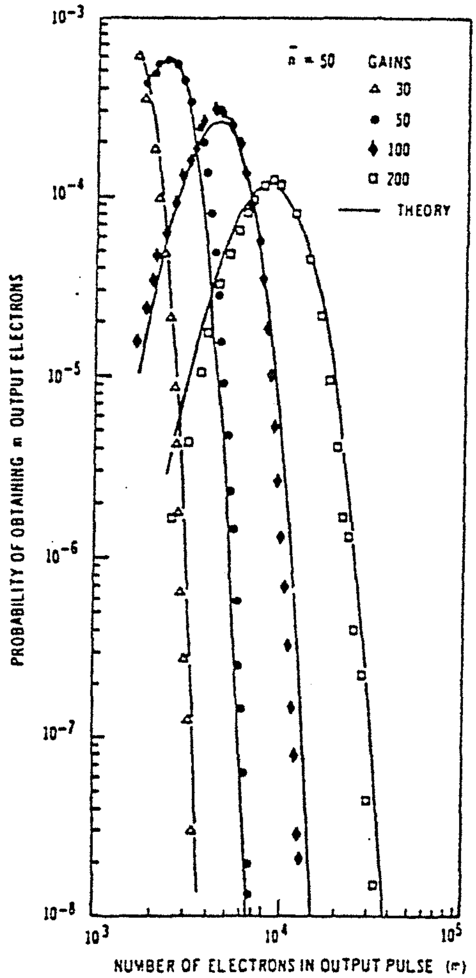

Fig. 4. Experimental and theoretical gain distributions for an average number, $\bar{n}$, of 50 photoelectrons.[7]

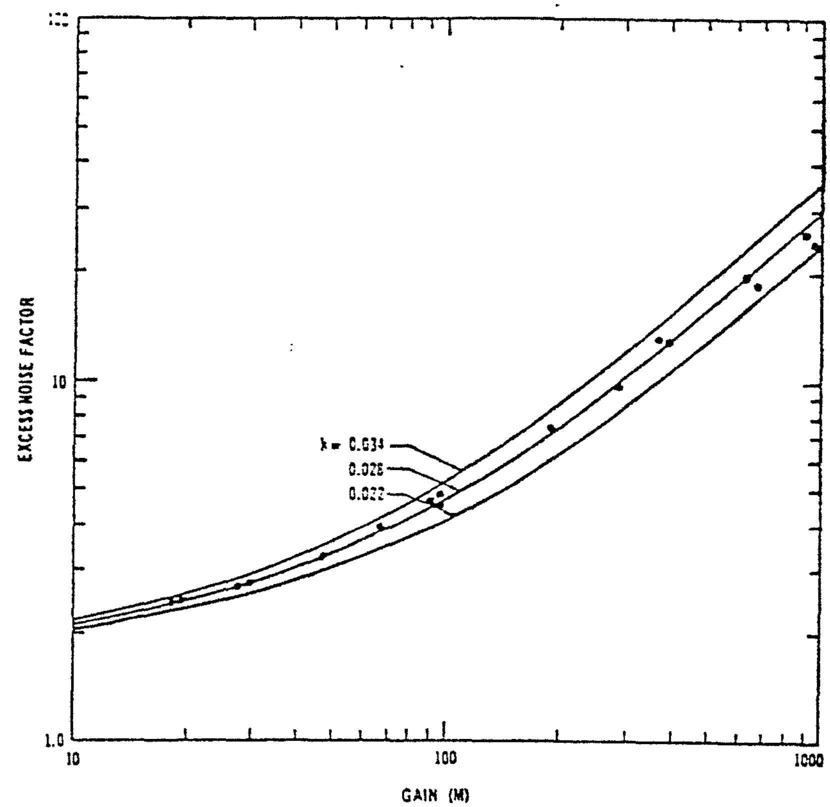

Fig. 5. Excess noise factor versus gain.[7]

of APDs with scintillators for the omega group in the BNL Physics Department. In July 1978 RCA reported an improvement in the quantum efficiency of APDs brought about by changing the antireflective coating from 900 nm to 450 nm (see Table 1). To improve the quantum efficiency further, RCA will manufacture a batch of APDs with thinner entrance layers.

Table 1

Quantum Efficiencies for RCA Reach-Through APDs Antireflection Coated at 900 nm and at 450 nm

	Wavelength (nm)				
	500	436	365	313	254
Four devices coated at 900 nm					
Mean	0.40	0.33	0.078	-	-
Standard deviation	0.055	0.017	0.003	-	-
Four devices coated at 450 nm					
Mean	0.77	0.63	0.092	0.04	0.03
Standard deviation	0.072	0.023	0.007	-	-

RCA has provided three APDs AR coated at 450 nm to which pieces of NE102 scintillator 2x3x6 mm^3 have been attached. These will be evaluated. If they work, several low-noise amplifiers will be used to explore the performance of the first APD counters.

IV. DYNAMIC CHARACTERISTICS OF APDs AND PMTs

At present bare APDs can be expected to perform effectively as well as PMTs if the photons can be focused on the smaller apertures of APDs. Rise times and counting rates are comparable. The numbers of photons needed to achieve a desired efficiency are similar.[6]

Pulse-height resolutions are comparable. For a contemporary PMT with high-gain first stage[5] the resolution is given by

$$(\sigma P/P)^2 = N_e^{-1} \quad , \tag{8}$$

$$(\sigma P/P)^2 = (\eta_p N_\gamma)^{-1} \tag{9}$$

where the number of electrons, N_e, is given by the product of the quantum efficiency, $\eta \approx 0.15$, and the number of photons, N_γ.

For an APD the resolution[4] is approximately

$$(\sigma P/P)^2 \approx F(M)/N_e \tag{10}$$

$$(\sigma P/P)^2 \approx F(M)/\eta_a N_\gamma \tag{11}$$

where the excess noise factor, F(M), is a function of the gain, M, as shown in Fig. 5. Here the APD quantum efficiency, $\eta_a \approx 0.85$. Hence the distribution of gains in bare APDs which causes $F > 1$ effectively reduces the quantum efficiency

$$\eta_a' = \eta_a/F \approx \eta_p \tag{12}$$

so that resolutions of PMTs and bare APDs given by Eqs. (9) and (11) are comparable.

However, APDs need quiet amplifiers. From the data in Fig. 1 we conclude that there are amplifiers which use ~200 photons per bit to support counting rates of 10^9 per second with inefficiencies $<10^{-9}$. Perhaps these or similar amplifiers can be used for particle detectors.

V. COLD APDs FOR COUNTING PHOTONS

In 1970 Webb and McIntyre[8] described the performance of an APD at 77°K. The dark current was a few electrons per second. When the APD was reverse-biased above breakdown by ~50 V, large pulses were triggered by single photons. The single-photon detection efficiency was better than 10% in the near infrared, and the dark count rate was a few per second. In 1973 McIntyre[9] derived expressions for the avalanche initiation probability of APDs above the breakdown voltage. The breakdown pulse of a photodiode rises in <1 ns to ~50 V and thus eliminates the need for a preamplifier and provides a precise leading edge for accurate time definition. Today's APD technology permits one to expect single-photon efficiencies >50%.[10]

Unfortunately, the first attempt to bias cooled 1978 reach-through APDs beyond breakdown failed because of high dark counting rates. The cause of the new background is being investigated. The cause is not believed to be fundamental or unavoidable because the 1970 diodes[8] functioned in the photon counting mode.

Many microseconds are required for the circuit to recover. A self-quenching structure might be possible,[9,10] or an external quenching circuit[9] could be employed to limit the recovery time.

VI. CONCLUSIONS AND RECOMMENDATIONS

APDs with their supporting bias circuits and amplifiers are mature components in light-wave communication. Personick[11] observed that a quieter APD needs no amplifier and that a quieter amplifier needs no APD.

New detectors for ISABELLE should be faster, smaller, more reliable, and cheaper than existing detectors. APDs are as fast as PMTs, small (~5 mm), and reliable. Immunity to magnetic fields and low power consumption (~100 mW) allows them to occupy little space in magnets. Acceptance of the detector is improved, and less of the magnetic field volume is wasted. The large dynamic range of APDs would be useful in calorimeters and in dE/dx counters. Their insensitivity to overloads would be useful in counters placed close to the beam pipes.

Since bare APDs and PMTs have the same effective quantum efficiency, their dynamic behaviors are comparable. To exploit this comparable resolution and efficiency, however, low-noise amplifiers must be found. They have been found for light-wave communication. Inexpensive APD and amplifier units would have many uses in particle detectors at ISABELLE.

The cold APD (77°K) would detect half of incident photons and would define times to better than 500 psec without a preamplifier. It would have all the virtues of APDs except for linear response and room temperature operation. Low heat loads might allow thermoelectric cooling[10] to be used. Cold APDs detecting Cerenkov light rings or Cerenkov light for time-of-flight measurement could extend the range of particle identification at ISABELLE.

Recommendation One

The development of cold APD photon counters should be continued.

The APD's immunity to magnetic fields, low power consumption, low dark currents, and small size are characteristics required for scintillator layered calorimeters used in magnetic fields. However, APDs are much smaller than the area of the wave-shifter bars that are normally coupled to PMTs. The cross section of a smaller second wave-shifter bar mounted on the end of the first wave-shifter bar is matched to the area of an APD, as shown in Fig. 6. This was suggested in 1970 by Keil.[12] The loss[13] of two-thirds of the photons in the wave shift doubles the width of the pulse-height spectrum obtained from APDs.

Recommendation Two

The use of wave-shift bars to focus light onto an APD should be tested.

Readout of scintillating fibers in a fine-grained hodoscope by APDs is most analogous to APD development for light-wave communication.

Recommendation Three

A prototype hodoscope should be built and tested as soon as fibers and APDs are avilable.

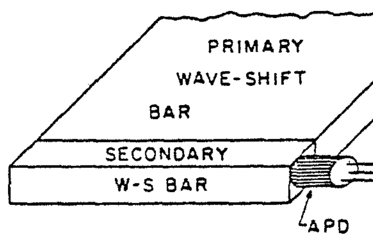

Fig. 6. Secondary wave-shifter bar for optical coupling of APDs to larger primary wave-shift bars.

Acknowledgments: It is a pleasure to acknowledge many helpful conversations with Drs. Robert Palmer, Mark Sakitt, Joshua Alspector, and Pavel Rehak of the omega group and with Veljko Radeka of the BNL Instrumentation Division. The encouragement and support of Dr. Palmer have made this research possible.

REFERENCES

1. S.D. Personick, Bell System Tech. J. 52, 875 (1973); T. Li, Bell Lab. Rec. 53, 333 (Sept. 1975).
2. G.T. Reynold and P.E. Condon, Rev. Sci. Instrum. 28, 1098 (1957).
3. H. Melchoir, J. Lumin. 7, 390 (1973).

4. P.P. Webb, R.J. McIntyre, and J. Conradi, RCA Rev. 35, 234 (1974).
5. G.A. Morton, H.M. Smith, Jr., and H.R. Kroll, IEEE Trans. Nucl. Sci. NS-16, 92 (1969).
6. R.J. McIntyre, IEEE Trans. Electron Devices ED-19, 703 (1972).
7. J. Conradi, IEEE Trans. Electron Devices ED-19, 713 (1972).
8. P.P. Webb and R.J. McIntyre, Bull. Am. Phys. Soc. 15, 813 (1970).
9. R.J. McIntyre, IEEE Trans. Electron Devices ED-20, 637 (1973).
10. R.J. McIntyre, Private communication.
11. S.D. Personick, Private communication.
12. G. Keil, Nucl. Instrum. Methods 89, 111 (1970).
13. S.D. Smith, Private communication.