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A PRESENTATION ON

THE SOLID STATE PHOTOMULTIPLIER - STATUS OF PHOTON COUNTING BEYOND THE NEAR-INFRARED

TO

THE THIRD INFRARED DETECTOR TECHNOLOGY WORKSHOP
NASA-AMES RESEARCH CENTER
MOFFETT FIELD, CALIFORNIA

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BY

K. M. HAYS, R. A. LaVIOLETTE, M. G. STAPELBROEK, AND M. D. PETROFF

ROCKWELL INTERNATIONAL
SCIENCE CENTER
ANAHEIM, CALIFORNIA

The Solid State Photomultiplier - Status of Photon Counting Beyond the Near-Infrared*

Rockwell International Science Center

Anaheim, CA 92803

Rockwell International's Solid State Photomultiplier (SSPM)[1] is an impurity-band avalanche device which can count individual photons with wavelengths between 0.4 and 28 micrometers.[2] Its response to a photon is a pulse of between 10^4 and 10^5 conduction electrons, making it an important device for use in phenomenology.

The characteristics of the SSPM make it a potentially important device for use in astronomical applications. Contract NAS2-12400 was initiated in June 1986 to conduct modeling and characterization studies of the SSPM to provide a basis for assessing its use in astronomical systems. This paper discusses some SSPM models and results of measurements which characterize the group of SSPMs recently fabricated on this contract.

*K. M. Hays, R. A. LaViolette, M. G. Stapelbroek and M. D. Petroff, Third Infrared Detector Technology Workshop, NASA-Ames Research Center, February 7-9, 1989.

1. M. D. Petroff, M. G. Stapelbroek and W. A. Kleinhans, U. S. Patent Number 4,586,068, Filed Oct. 7, 1983, Granted Apr. 29, 1986.

2. M. D. Petroff, M. G. Stapelbroek and W. A. Kleinhans, Appl. Phys. Lett. **51** (1987) 406.

STRUCTURE OF IMPURITY BAND CONDUCTION IR DETECTORS

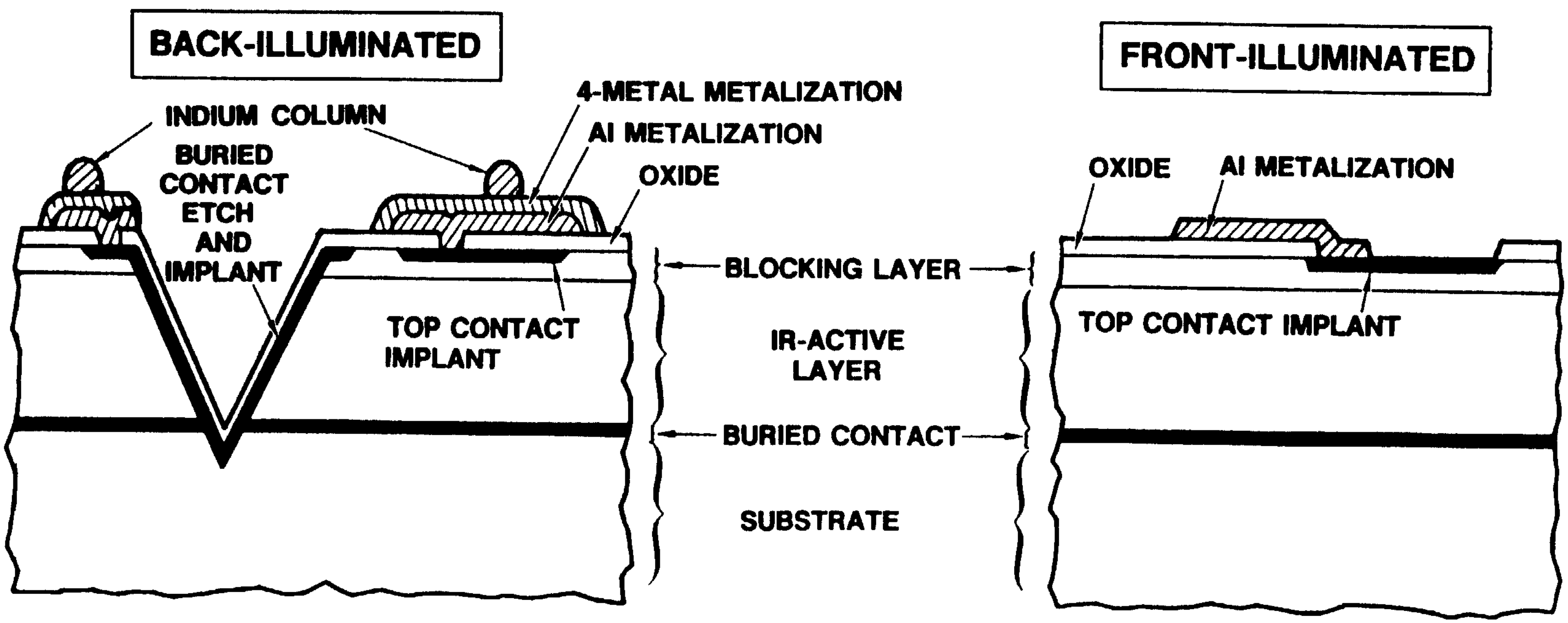
The Solid-State Photomultiplier (SSPM) is the only device known which can continuously count single photons in the 1 to 28 μm wavelength range. The detector is a Si:As impurity band conduction device. SSPMs are fabricated by growing doped and undoped epitaxial layers on silicon substrates and then defining the detectors using established silicon processing techniques.

Area and line arrays of SSPMs, as well as discrete detectors, have been fabricated. Epitaxy for back-illuminated detectors must be grown on intrinsic silicon substrates. Arrays of this type can be connected to multiplexers or other signal processors with indium columns to form hybrids. An etch to the buried contact is required as a common detector biasing lead.

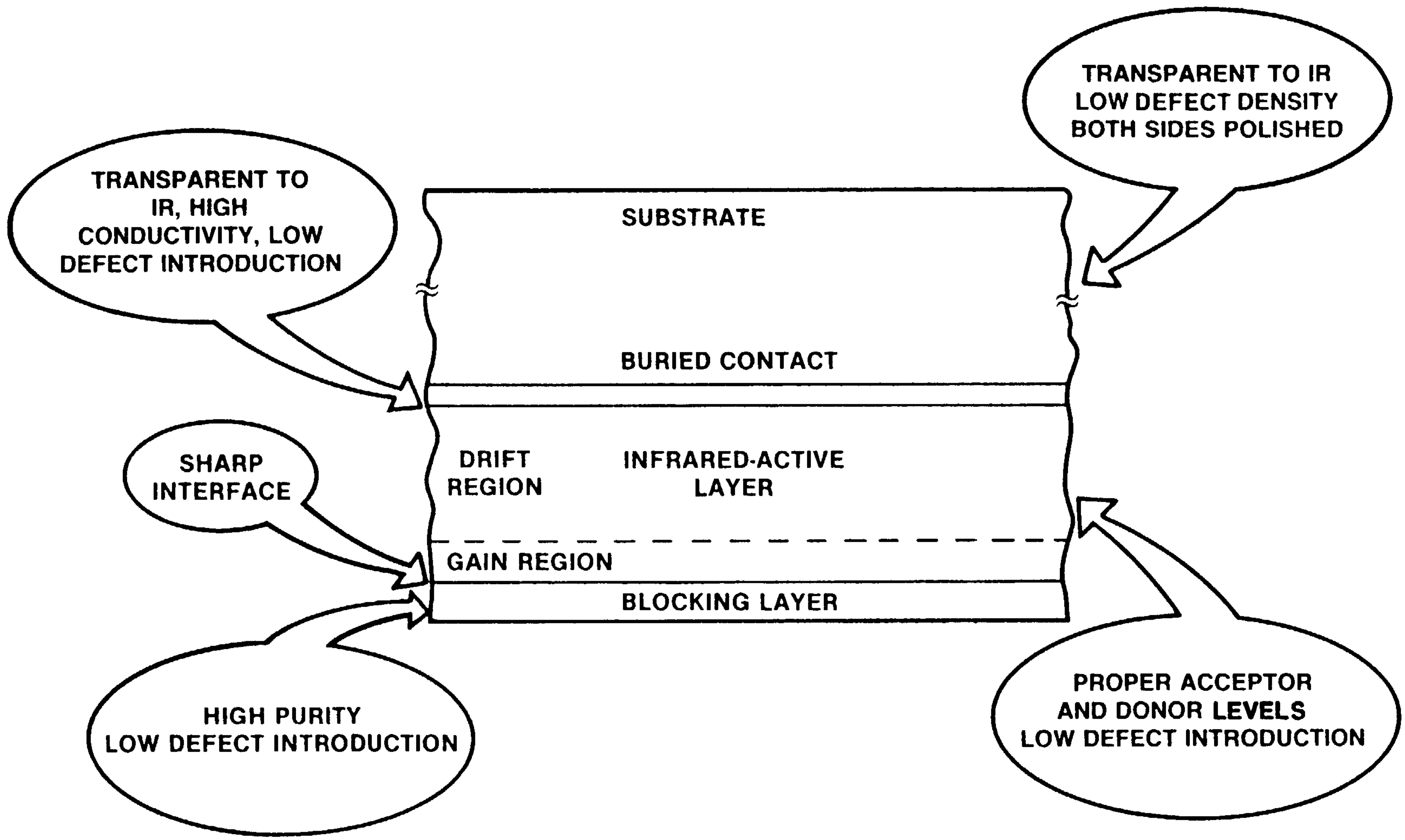
Front illuminated SSPMs have also been fabricated. Heavily-doped substrates can be used for front-illuminated devices to reduce optical crosstalk and to eliminate the need for a transparent buried contact.

STRUCTURE OF IMPURITY BAND CONDUCTION IR DETECTORS

• DEVICE SCHEMATIC CROSS-SECTION (NOT TO SCALE)



MATERIALS REQUIREMENTS



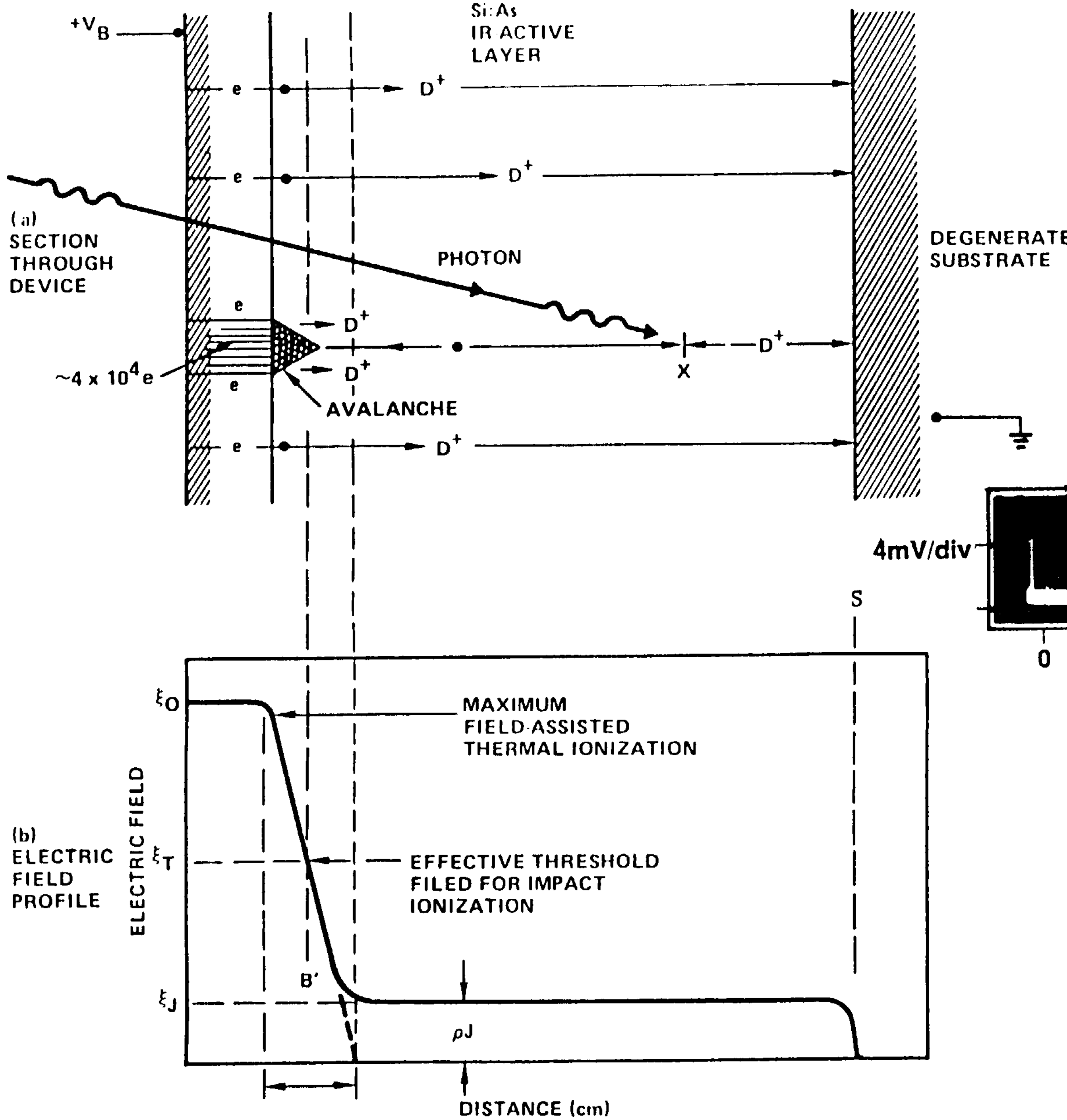
SOLID STATE PHOTOMULTIPLIER OPERATING PRINCIPLE

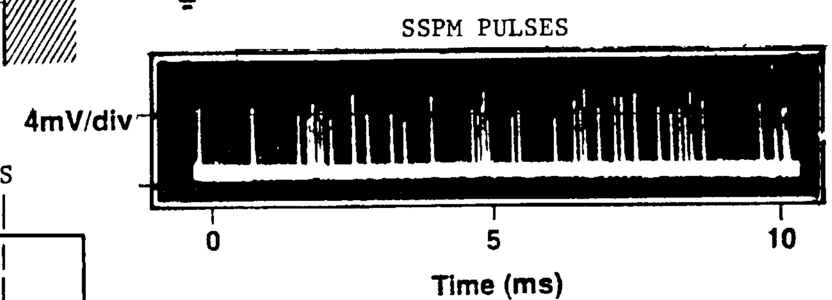
The Solid State Photomultiplier is a unique device in that it can continuously count single photons of wavelengths up to 28 μm. A pulse of about 40,000 electrons is the immediate and direct consequence of the absorption of a single photon.

An electric field profile through the SSPM is shown in (b), with the blocking layer on the left side of the cross-section. The slope of the field in the (depleted) gain region is proportional to the acceptor concentration. The higher fields toward the left end of the gain region produce most of the dc bias current by field-assisted thermal ionization (Poole-Frenkel effect). The dc bias current is responsible for the non-zero field throughout the undepleted part of the IR-active layer.

The detection of a single photon is shown schematically in (a). The photon ionizes a neutral donor in the drift region. The resultant ionized donor charge travels toward the substrate, while the conduction electron moves more quickly toward the gain region. At some point in the gain region the electric field is strong enough for impact ionization to occur. The primary photo-electron then ionizes additional neutral donors which, in turn, ionize other neutral donors, causing an avalanche. The produced pulse is a few nanoseconds wide and contains an average of about 4×10^4 electrons. The ionized donor charges produced in the avalanche move slowly and contribute a low tail to the pulse.

SOLID STATE PHOTOMULTIPLIER OPERATING PRINCIPLE





THEORY OF SSPM PULSE AMPLITUDE DISTRIBUTION

The SSPM pulse amplitude distribution is strikingly narrow, a feature which cannot be predicted with conventional avalanche photodiode (APD) theory.[3] A new phenomenological theory of the SSPM avalanche successfully predicts the shape of the observed pulse amplitude distribution by including the history-dependent effects present in the electron transport.[4] These effects appear as the presence of a finite mean distance ℓ in the threshold distribution.[5] In conventional APDs, the mean distance-to-threshold is so small (i.e. $\ell<0.05\mu m$) that its neglect is justified. For a simplified SSPM model, Monte-Carlo calculations show that $\ell\simeq0.15-0.25\mu m$.[4] Although such distances are only about 5 percent of the SSPM gain region thickness, they are not negligible. The magnitude of the distance is due to the low (relative to the APD) electric field in the SSPM gain region; the variations are strongly correlated with variations in the field. As the accompanying figures show, for the SSPM model employed in Ref. 4, the theory provides pulse-amplitude distributions which are both realistic and dramatically different from the history-independent prediction.

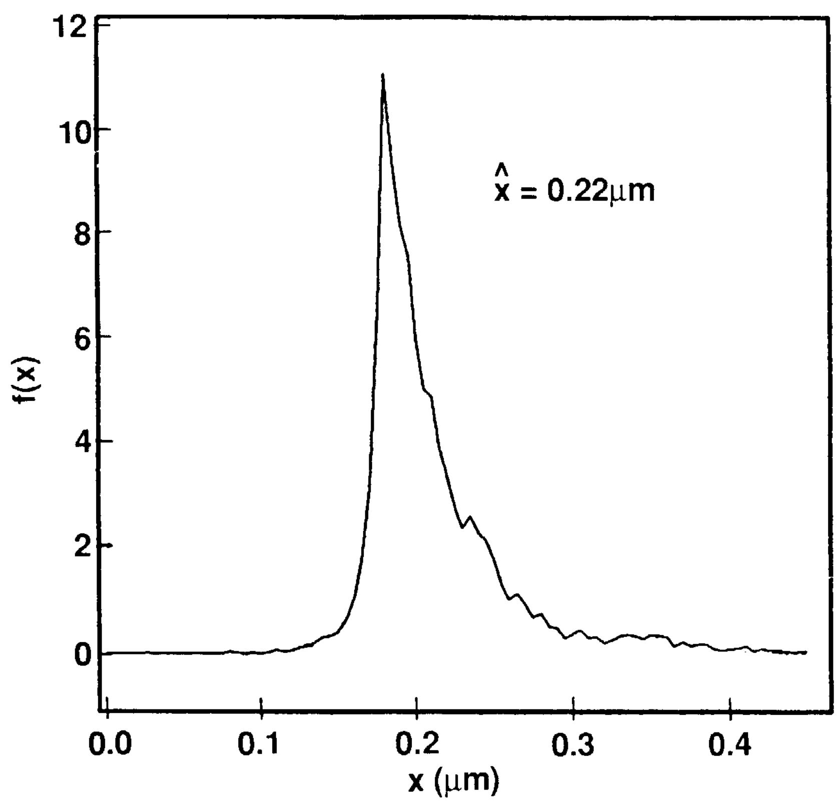
3. G. E. Stillman and C. M. Wolfe, in *Semiconductors and Semimetals*, edited by R. K. Willardson and A. C. Beer, Vol. 12 (Academic Press, NY, 1977) .

4. R. A. LaViolette and M. G. Stapelbroek, J. Appl. Phys. **65** (1989) 830-6.

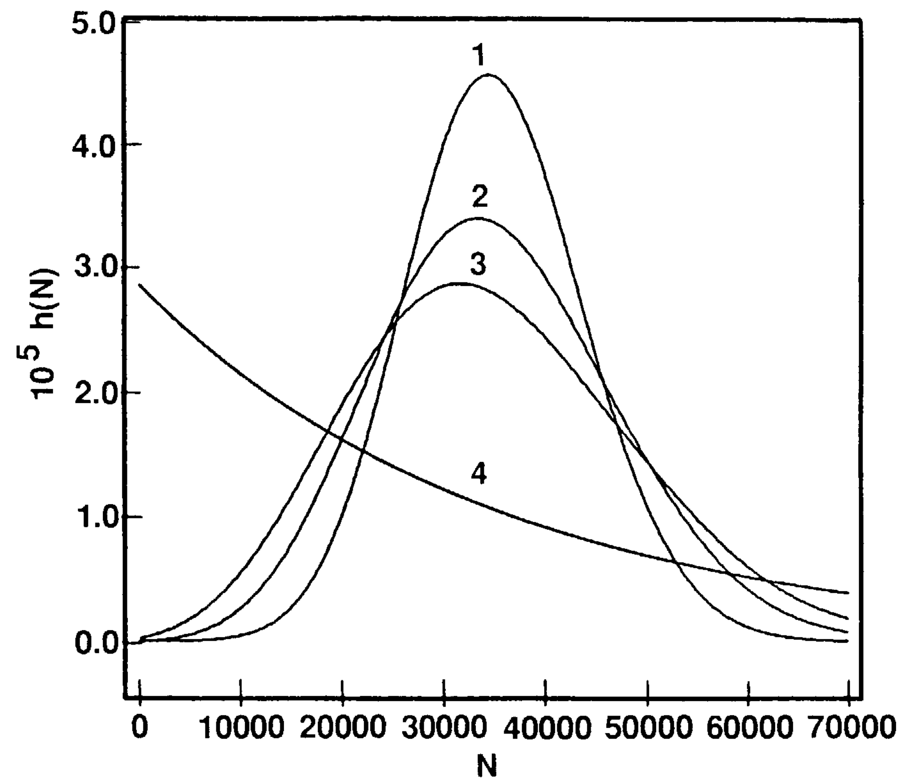
5. The threshold distribution is the distribution of distances between the birth of an electron via impact ionization and its subsequent achievement of the threshold energy required for impact ionization.

THEORY OF SSPM PULSE AMPLITUDE DISTRIBUTION

THRESHOLD-DISTANCE DISTRIBUTION



PULSE-AMPLITUDE DISTRIBUTION



1: $\hat{x} = 0.22\,\mu m$ 2: $\hat{x} = 0.19\mu m$ 3: $\hat{x} = 0.17\mu m$ 4: $\hat{x} < 0.05\mu m$

SSPM PROVIDES HIGH QUANTUM EFFICIENCY FROM 0.4 TO 28 MICROMETERS

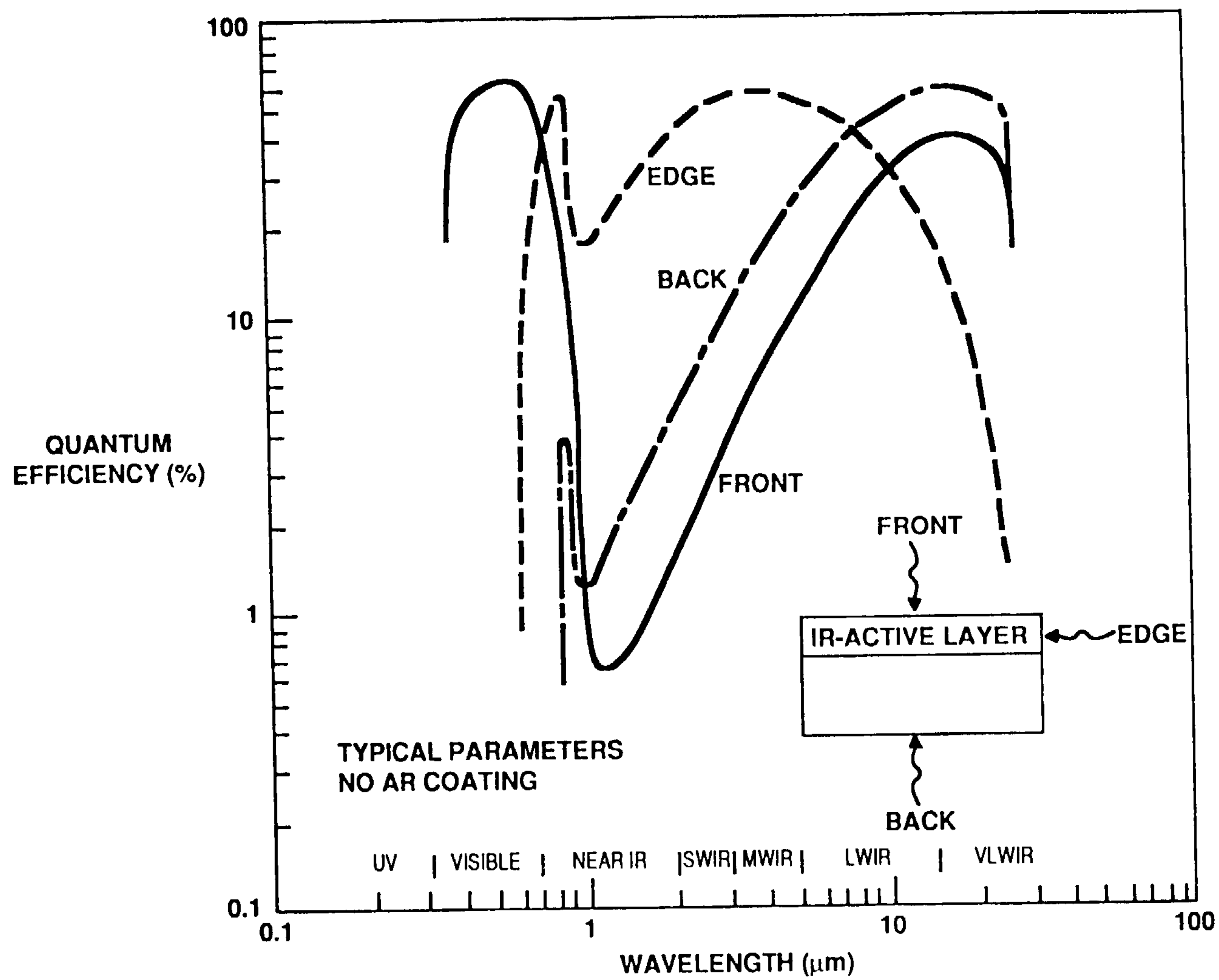
The photon-counting quantum efficiency of an SSPM is affected by illuminating different faces of the device. The quantum efficiency changes because of differences in optical path lengths and the absorption coefficients of various layers.

Back-illuminated SSPMs make high-efficiency photon detectors in the infrared wavelength ranges, out to 28 μm. Photons that pass once through the active region of the SSPM without being absorbed are reflected at the front surface of the detector by an aluminum layer, so that the active thickness of the device is effectively doubled. Back-illumination is also the best approach for building hybrid focal plane arrays.

Front-illuminated SSPMs make high-efficiency photon counters in the visible and infrared wavelengths. The quantum efficiency in the visible range is extremely high, due to the generation of electron-hole pairs in the blocking layer and the subsequent impact-ionization of neutral donors in the IR-active layer by holes moving toward the substrate.

Finally, edge-illumination offers a significant advantage over front- or back-illumination in the near-to-mid IR wavelength ranges. With edge-illumination, the optical path length is no longer limited by the thickness of the IR-layer epitaxy, so that the probability of detecting these IR wavelengths, with their long attenuation lengths, can be greatly increased.

SSPM PROVIDES HIGH QUANTUM EFFICIENCY FROM 0.4 TO 28 MICROMETERS

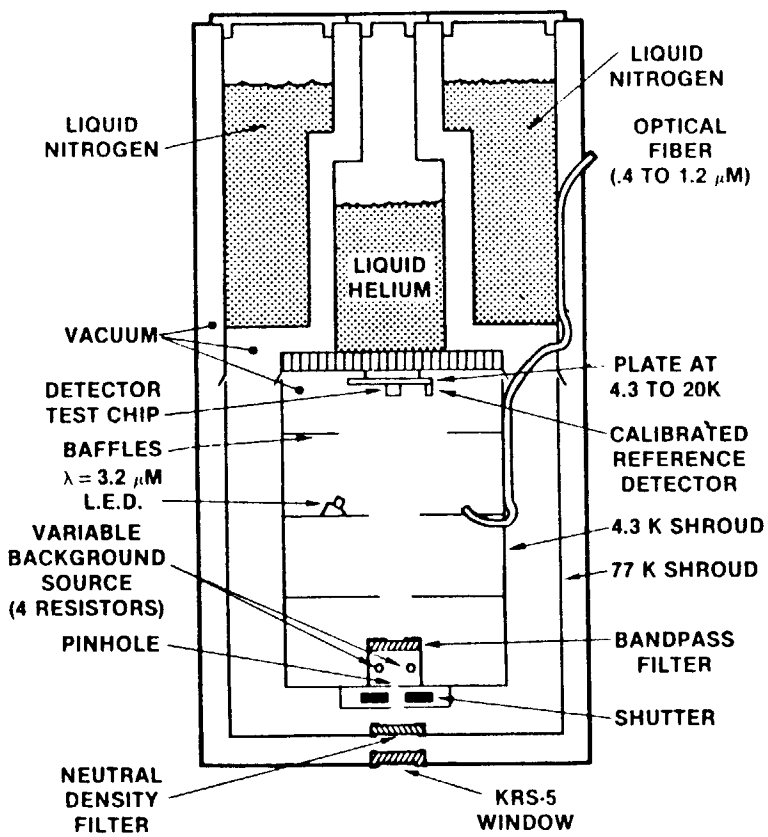


DETECTORS ARE TESTED IN VERSATILE CRYOGENIC DEWARS

SSPMs are characterized in custom-built low background test dewars. The extremely high sensitivity of these detectors requires that the flux be at or below 1×10^6 photons/cm^2-s for accurate dark pulse rate measurements. Flux levels can be measured using an integral calibrated arsenic-doped extrinsic photoconductor mounted in close proximity to the detector cold stage. The temperature of the cold stage can be regulated between 4.3 and 20K.

The dewar contains a 3.2μm LED which can be used continuously or pulsed for intervals shorter than 1 microsecond. Other available illumination sources include pinhole shutter and hot resistor sources which are filtered by an interchangeable bandpass filter. Finally, a plastic optical fiber which transmits visible light and IR up to about 1.0μm wavelength is included for flood illumination studies of spectral response in the short wavelength range.

DETECTORS ARE TESTED IN VERSATILE CRYOGENIC DEWARS



- BACKGROUNDS TO $< 10^6$ PHOTONS/CM^2-s
- PULSED 3.2μm LIGHT AT $>$ 1MHz
- CONTINUOUS VARIATION THROUGH VISIBLE SPECTRUM VIA OPTICAL FIBER
- UNIFORM FLOOD ILLUMINATION VIA FIBER, PINHOLE OR RESISTORS
- FILTERS EASILY INTERCHANGED
- TEMPERATURES RANGE FROM 4.3-20K
- INTEGRAL CALIBRATED DETECTOR

QUANTUM EFFICIENCY OF SSPMs FABRICATED FOR NASA-AMES

A fabrication lot of SSPMs was fabricated for NASA-Ames under contract NAS2-12400. One epitaxy set of wafers contained devices which showed quantum efficiencies of over 60 percent at $\lambda = 20\ \mu m$.

The figures show photon counting quantum efficiencies gathered as a function of bias voltage and operating temperature. The quantum efficiencies were calculated using:

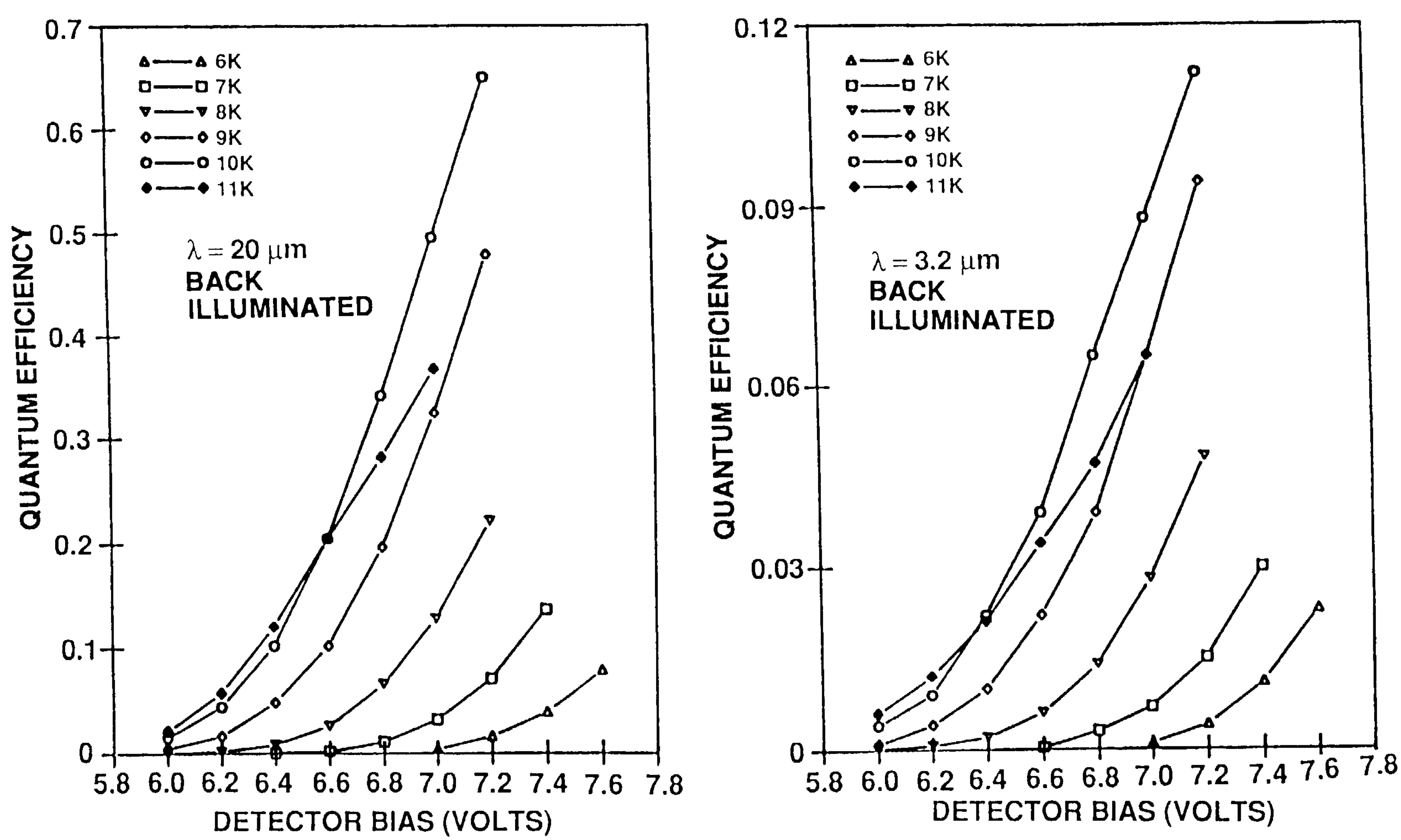
$$\eta = \frac{\nu_{illum} - \nu_{dark}}{\Phi A_{det}}$$

where ν was the average number of SSPM pulses counted per second and $A_{det} = 150 \times 150\ \mu m^2$ was the detector surface area. The incident flux density, Φ, was on the order of 10^8 photons/cm^2-s at both wavelengths.

The improvements in η with higher bias voltages and temperatures were due, in part, to increases in the drift region's electric field. Field-assisted thermal ionization near the high-field end of the gain region causes the bias current to increase at higher temperatures, resulting in a higher drift-region field.

At 11K, the maximum quantum efficiencies were lower than those measured at 10K. This was due to the high ν_{dark}, which was strongly temperature dependent. The recommended operating temperature for these SSPMs was 10K.

QUANTUM EFFICIENCY OF SSPMs FABRICATED FOR NASA-AMES



BIAS CURRENT OF SSPMs FABRICATED FOR NASA-AMES

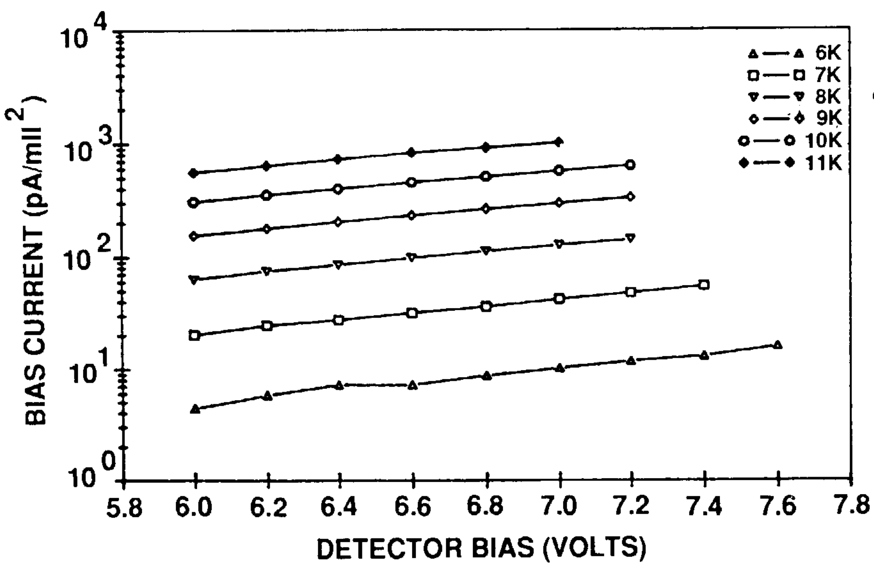
The bias currents of the SSPMs whose quantum efficiencies appeared on the previous chart were measured as a function of temperature and bias voltage. It is important to characterize and minimize bias current for applications in which SSPM output current is integrated on a capacitor and periodically read out.

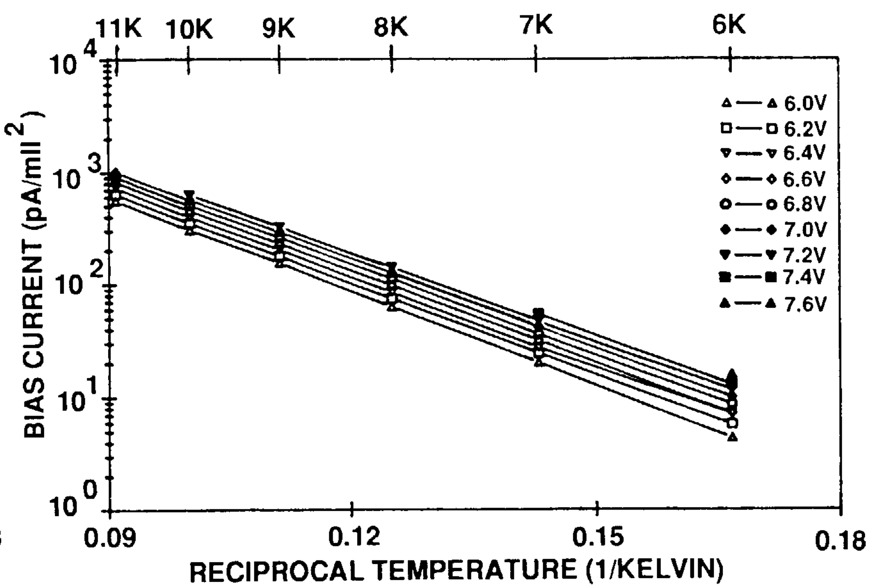
The bias currents were approximately given by:

$$I_{\mathrm{bias}}(V_{\mathrm{bias}}, T) = C_1 A_{\mathrm{det}} e^{(C_2 V + C_3 / T)}$$

where A_{det} is the SSPM's area and C_1, C_2, and C_3 are constants which depend on the doping levels used in a particular device. The effect of field-assisted thermal ionization and the doping levels can cause changes in the detector's electric field profiles at different biases. This can result in a departure from the exponential dependence at lower bias voltages.

BIAS CURRENT OF SSPMs FABRICATED FOR NASA-AMES





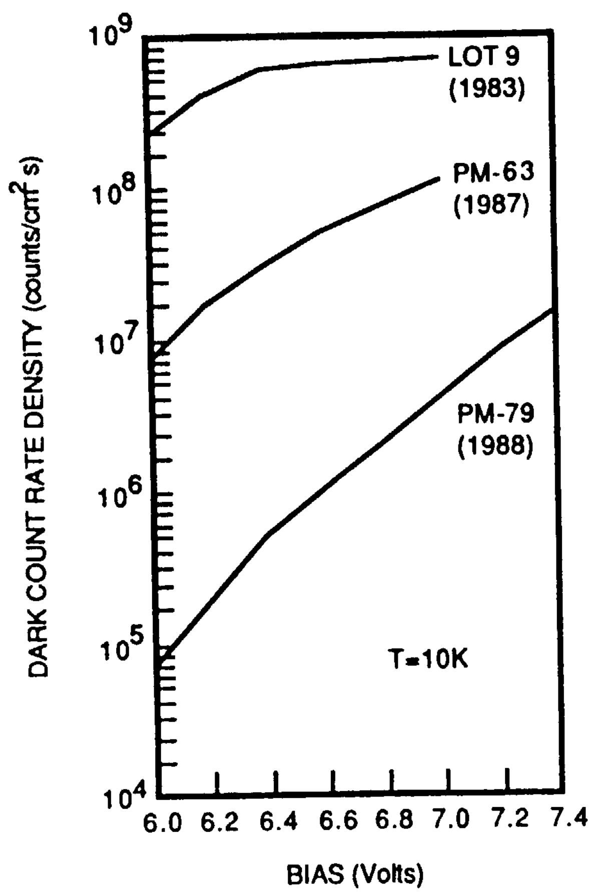
UNSURPASSED RESULTS OBTAINED FROM RECENT DEVICES

Efforts to produce SSPMs with lower dark count rates and higher operating temperatures have been successful. Since their invention, SSPM dark count rates at 10K have been reduced by almost two orders of magnitude. The success was due, in part, to improvements in epitaxy control and characterization. Lot PM-79 was produced under contract NAS2-12400 with NASA-Ames for Dr. C. McCreight. At their operating temperature, devices from lot PM-79 have higher quantum efficiencies and lower dark count rates than any previously produced SSPMs.

Further improvements in materials control are expected to result in further improvements in SSPM performance. The goal is a level of understanding and control sufficient to design SSPMs with gain, gain dispersion, dark count rates and operating temperatures matched to the needs of specific applications.

UNSURPASSED RESULTS OBTAINED FROM RECENT DEVICES

DARK COUNT RATE VERSUS BIAS
FOR THREE SSPM LOTS



- DARK NOISE IS PROPORTIONAL TO THE SQUARE ROOT OF THE NUMBER OF DARK COUNTS
- THE PHOTON COUNTING QUANTUM EFFICIENCY OF AN SSPM IS MAXIMUM AT HIGH BIAS
- THE BEST GROUP OF SSPMs FROM LOT PM–79 HAS A LOWER DARK COUNT RATE AT ITS OPERATING BIAS THAN ANY PREVIOUSLY PRODUCED DEVICE GROUP

SSPM HAS UNPRECEDENTED SENSITIVITY AND SPEED

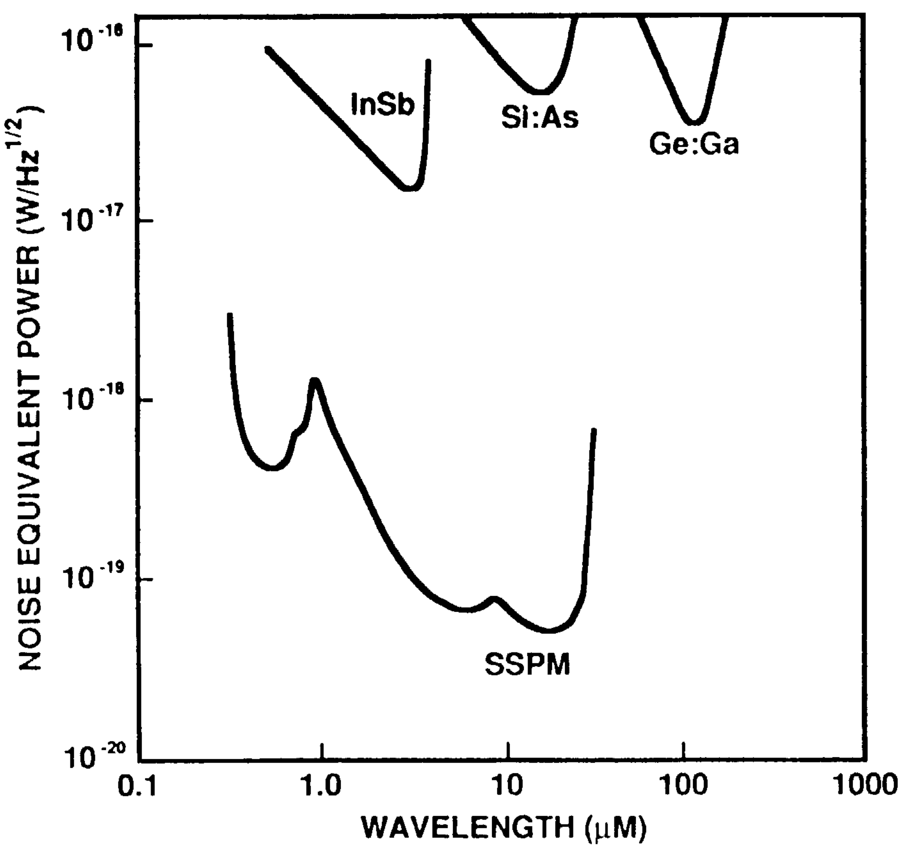
Due to its high gain, low gain dispersion and high speed, the SSPM does not require an ultra-low noise amplifier in order to resolve pulses due to single photons. As a result, SSPM performance is not limited by amplifier noise, even at extremely low flux levels. When it is used as a photon counter at low flux densities, the noise is given by:

$$\sigma_{\mathrm{n}} = (n_{\mathrm{dark}}+n_{\mathrm{signal}})^{1/2}$$

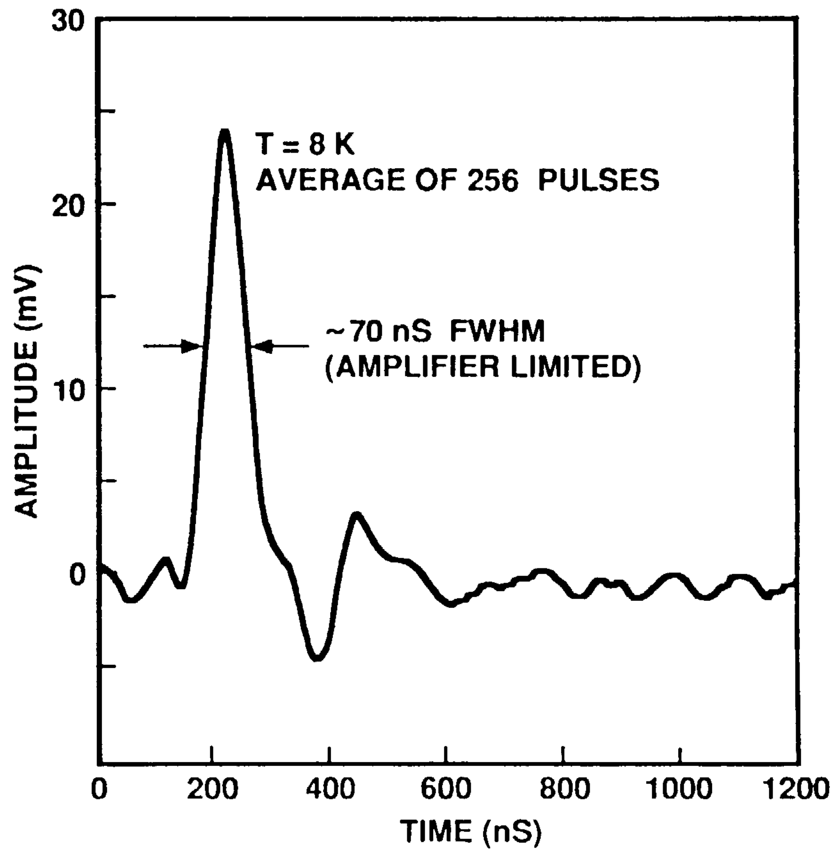
where σ_{n} is the uncertainty in the number of counts, and n_{dark} and n_{signal} are the numbers of dark and signal counts, respectively. If the best illumination approach (e.g. front, back, or edge-illumination) is used at each wavelength, the low dark count rate and sensitivity of the SSPM result in a noise equivalent power that is orders of magnitude better than what is typically obtained from other common infrared detectors.

SSPM HAS UNPRECEDENTED SENSITIVITY AND SPEED

SENSITIVITY



SPEED



SUMMARY

- ROCKWELL'S SOLID-STATE PHOTOMULTIPLIER OUTPUTS A FAST PULSE OF ELECTRONS IN RESPONSE TO THE ABSORPTION OF A SINGLE 0.4-28 μm PHOTON
- MATHEMATICAL MODELS TO BETTER PARAMETERIZE THE SSPM AVALANCHE GAIN MECHANISM IN TERMS OF MATERIALS CHARACTERISTICS ARE CURRENTLY BEING DEVELOPED AND REFINED
- DRAMATIC IMPROVEMENTS IN PERFORMANCE HAVE RECENTLY BEEN REALIZED
- FURTHER OPTIMIZATION OF THE DEVICES IS BEING FUNDED BY NASA-AMES* AND OTHER AGENCIES