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STUDY OF ADVANCED InSb ARRAYS FOR SIRTF

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ABSTRACT

The Santa Barbara Research Center has completed a study leading to the development of advanced Indium Antimonide detector arrays for the Space Infrared Telescope Facility (SIRTF) Focal Plane Array Detector (FPAD) Subsystem of the Infrared Array Camera (IRAC) Band 1. The overall goal of the study was to perform design tradeoff studies, analysis and research to develop a Direct Readout Integrated Circuit to be hybridized to an advanced, high performance InSb detector array that would satisfy the technical requirements for Band 1 as specified in the IRAC Instrument Requirements Document (IRD), IRAC-202. The overall goal of the study was divided into both a near-term goal and a far-term goal. The near-term goal identifies current technology available that approaches, and in some cases meets the program technological goals as specified in IRAC-202. The far-term goal identifies technology development required to completely achieve SIRTF program goals.

Analyses of potential detector materials indicates that InSb presently meets all Band 1 requirements and is considered to be the baseline approach due to technical maturity. The major issue with regard to photovoltaic detectors such as InSb and HgCdTe is to achieve a reduction in detector capacitance. An analysis of Capacitive Transimpedance Amplifiers (CTIAs), Source-Follower per Detector (SFD), and Modified Source-Follower per Detector (MSFD) amplifiers is performed. The baseline approach is the use of a PMOS SFD. An assessment of radiation effects anticipated during the SIRTF mission indicates that orbit-to-orbit performance shifts are negligible, and detector total-dose effects are expected to be negligible for a period of ten years.

INTRODUCTION

The study of Advanced InSb Arrays for SIRTF was performed at the Santa Barbara Research Center, Goleta, California, a wholly-owned subsidiary of GM-Hughes Electronics, for the Harvard-Smithsonian Astrophysical Observatory of Cambridge, Massachusetts. This work is to be utilized by the Smithsonian Astrophysical Observatory (SAO) on its Wide Field and Diffraction Limited Infrared Array Camera (IRAC) Program.

The interim technical goals of the SIRTF IRAC Program are given in Figure 1.

BAND 1 DETECTOR DEVELOPMENT

The selection of Indium Antimonide detectors as the baseline approach for Band 1 of the IRAC was made primarily due to the maturity of InSb technology and the fact that InSb presently meets all SIRTF Band 1 requirements. Mercury Cadmium Telluride (HgCdTe) detector technology could demonstrate performance equivalent to InSb at 10 Kelvins in the future; however, higher quantum efficiencies in the 1 to 5 μm band must be demonstrated and the technology be allowed to mature to be considered for the SIRTF IRAC Band 1 mission. Another alternative to InSb is Gallium doped Silicon (Si:Ga) Impurity Band Conduction (IBC) technology, however, higher quantum efficiencies in the 1 to 5 μm band must also be demonstrated before consideration will be given to this technology. As previously stated, InSb technology presently meets all SIRTF Band 1 requirements and is technically mature.

The major issue that remains with photovoltaic detectors such as InSb and HgCdTe is the reduction of detector capacitance, which is necessary due to circuits in the readout unit cell. Given the fact that Noise Equivalent Power (NEP) increases almost linearly with detector capacitance, and SIRTF mission low-background, long integration time requirements the reduction of detector capacitance is an important goal in the development of SIRTF flight focal plane array detector assemblies.

Several techniques exist that achieve reductions in detector capacitance.

Since the detector gate overlap with the implanted region results in a capacitance that is proportional to that overlap, a reduction in overall detector capacitance can be realized by minimizing the gate overlap or employing gateless detectors, which totally eliminates the gate capacitance contribution. In addition, increasing the depletion width via lower doping and/or a "graded junction" will also serve to decrease capacitance.

Another method of capacitance reduction is the reduction of detector junction size. Figure 2 illustrates the exponential relationship and trade between capacitance and detector size. Obviously, the smaller detectors have lower values of capacitance and therefore, generate lower noise.

λ RANGE (μm)	DETECTOR MATERIAL	DETECTOR FORMAT - PIXEL FOV (ARCSEC) WF/DL	READOUT NOISE	DETECTOR QUANTUM EFFICIENCY $\eta/G\eta$	DETECTOR RESPONSIVITY	DETECTOR DARK CURRENT	WELL CAPACITY (e^-)	POWER (MW) 1 frame/sec	READOUT
1.4-5.3	InSb (Si:In) (HgCdTe)	128 x 128 2.35/0.59	$\leq 10e^{-*}$	0.6/0.6	2.4 A/W @ 5μm	$\leq 10e^{-1}$/sec per pixel	$>5x10^5$	≤ 12	Direct Readout Random Access Non-Destructable
5.3-14	Si:Ga (Si:As)	64 x 64 4.7/1.17	$\leq 100e^-$	0.3/0.15	2.2 A/W @ 18μm	$\leq 10e^-$/sec per pixel	$>5x10^5$	≤ 3	" "
14-30	Si:Sb (Si:As)	64 x 64 4.7/1.17	$\leq 100e^-$	0.3/0.15	3.4 A/W @ 30μm	$\leq 10e^-$/sec per pixel	$>5x10^5$	≤ 3	" "

* Design goal, present projected performance ~ 60-80e^-

Figure 1. IRAC array interim performance goals

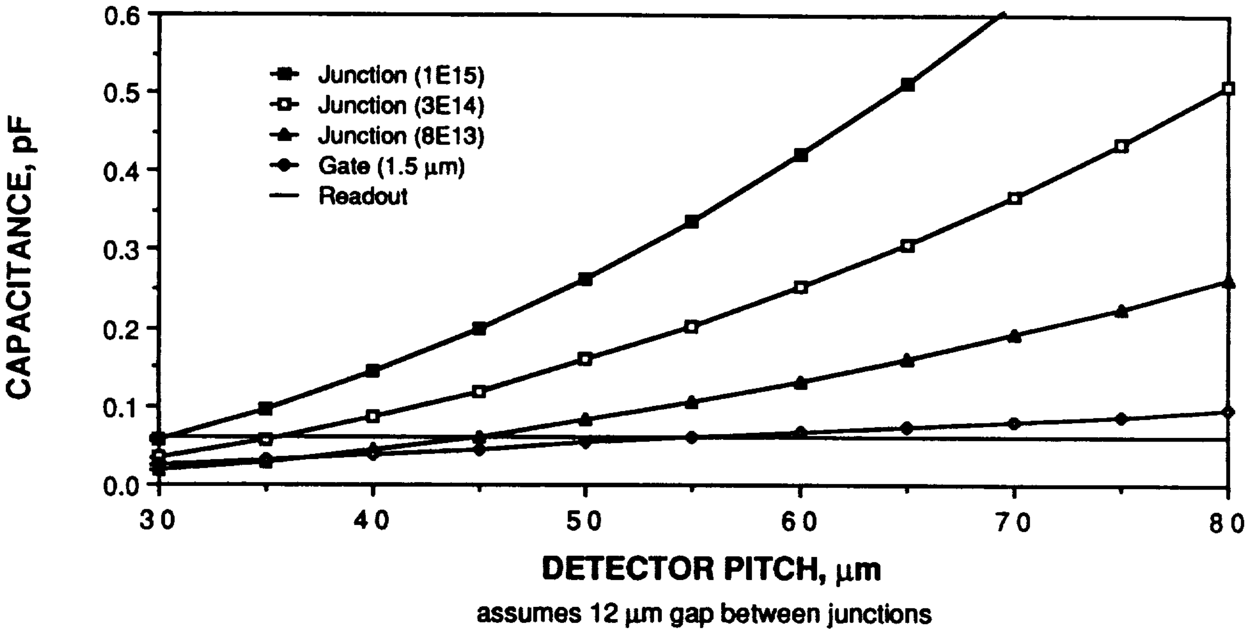


Figure 2. Capacitance as a function of detector size for InSb detectors

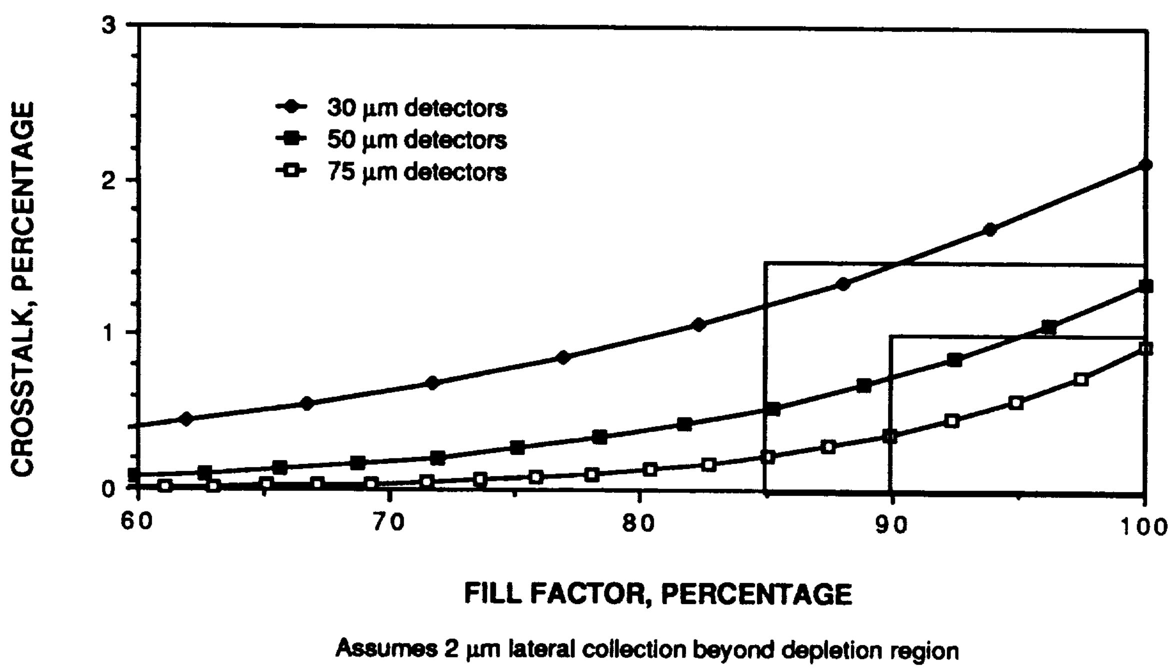


Figure 3. Trade between crosstalk and optical fill factor

The reduction of detector junction size as a capacitance reduction technique must also consider the effect on fill factor and crosstalk. As shown in Figure 3 the tradeoff between crosstalk and fill factor indicates that crosstalk increases with an increase in fill factor. The larger area diodes can experience higher percentages of fill factor (up to 100%) and still have values of crosstalk equal to or less than 1%. As diode area decreases values of crosstalk increase for constant percentages of fill factor. At 100% fill factor a 30 μm x 30 μm diode exhibits 2% crosstalk. The tradeoff between detector capacitance and fill factor must be optimized with consideration given mission performance. In addition, a decrease in the size of the optical image of the focal plane will be experienced when a reduction is made in detector junction area, and must also be considered when evaluating this trade.

READOUT INTEGRATED CIRCUIT DEVELOPMENT

The second thrust of the Advanced InSb Array Study for SIRTF was to evaluate SIRTF mission signal processing requirements versus readout integrated circuit device performance, and define the technology(ies) that would meet SIRTF IRAC specified performance goals.

The first step in determining an appropriate readout circuit for SIRTF is a thorough understanding of the performance requirements. Important performance requirements included noise, power dissipation, pixel sizes, integration time and background. By far the most demanding requirement for the SIRTF focal plane is the low-noise floor of <10 electrons. A summary of the SIRTF Band 1 specification is shown in Figure 4.

Requirement	Specification
Wavelength	2 to 5 μm
Array Size	128 × 128 nominal
Pixel Size	50 to 100 μm
Fill Factor	>90%
Readout Modes	Nondestructive, random access
Pixel Operability	≥98% array, ≥98.5% central 32 × 64
Signal/Noise	BLIP, 10 e^-
Integration Time	≤1000 sec
Background (Average)	10 photons/pixel/sec
Latent Image	Discharge in ≤1 sec
Uniformity	±5% of responsivity
Charged Particle Events	Complete recovery in ≤10 ms
Power Dissipation	≤5 mW
Pixel Access Time	≤75 μs
Array Read Time	≤300 ms

Figure 4. Band 1 specification

Based upon the SIRTF requirements, the possible number of candidate readout circuits was narrowed to two candidates; the source follower per detector (SFD), and the capacitive transimpedance amplifier (CTIA). A noise analysis was performed for both circuits as well as power dissipation and a basic point design.

The SFD circuit is being considered for this program because of its simplicity and low power dissipation. Simplicity of design enables a 128^2 or 256^2 array to be fabricated with high yield. Low power dissipation not only increases focal plane lifetime during a space flight but also reduces the possibility of IR emission from the readout chip itself.

However, there are several advantages to the CTIA circuit. The circuit designer can choose to enhance either the sensitivity or the bucket capacity by the adjusting the size of the feedback capacitor. In addition, the CTIA inherently has better linearity than the SFD (although this may not be of paramount importance to astronomy) and the detector bias remains constant at all times. For other applications, the CTIA may be the circuit of choice, but for SIRTF the SFD appears to have an advantage.

As a part of the SIRTF study, readout excess noise was investigated. Transients induced by clock transitions on the array were found to not have an effect on noise. However, a FET that is switched off/on has excess noise due to the switching itself. The noise is increased to as much as 3 times the unswitched noise. This effect needs to be addressed in future readout designs to help achieve SIRTF noise goals.

Another direction for future readouts in astronomy applications is to use PMOS rather than NMOS FETs for all critical transistors. At the relatively low data rates of most astronomy readouts, 1/f noise dominates, and 1/f noise of NMOS FETs is typically 3 times that for comparable PMOS FETs. During the SIRTF study, measurements of 1/f noise as a function of temperature were performed. One result, shown in Figure 5, is that the 1/f noise of some PMOS FETs increases around 10 Kelvins. The presence and magnitude of this effect depends on the readout processing but the cause is not understood.

RADIATION EFFECTS

Radiation effects on the detector have been studied to determine what degradation in the data, if any, could be expected during a SIRTF mission.

The dominant ionizing radiation is high energy protons. Figure 6 shows the number of events over the proton energy spectrum for different detector areas (Figure 6a) and different detector thickness (Figure 6b). For InSb the number of events is nearly proportional to the detector area but there is little change with thickness. For a 50 by 50 μm detector, the expected number of proton events is 1 per second within the South Atlantic Anomaly (SAA) and 1 every 7 hrs. outside the SAA. For a high orbit only the lower rate is applicable. Gamma events are an order of magnitude less frequent: 1 every 2 days.

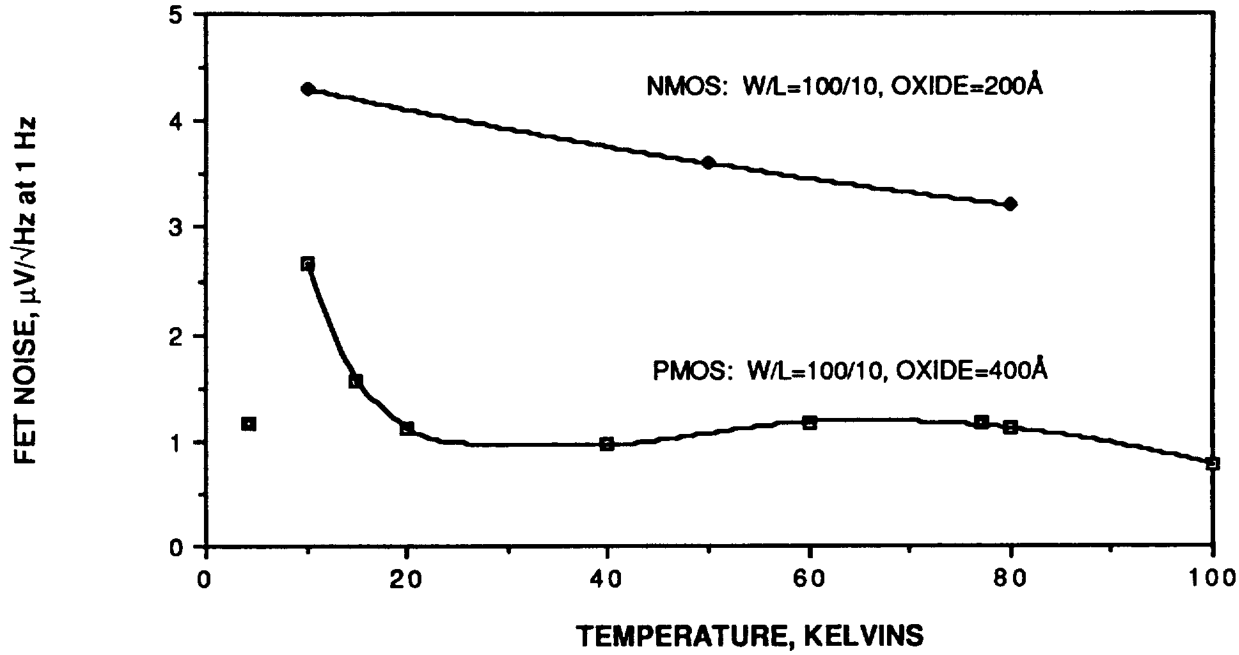


Figure 5. 1/f noise versus temperature for an NMOS and PMOS FET

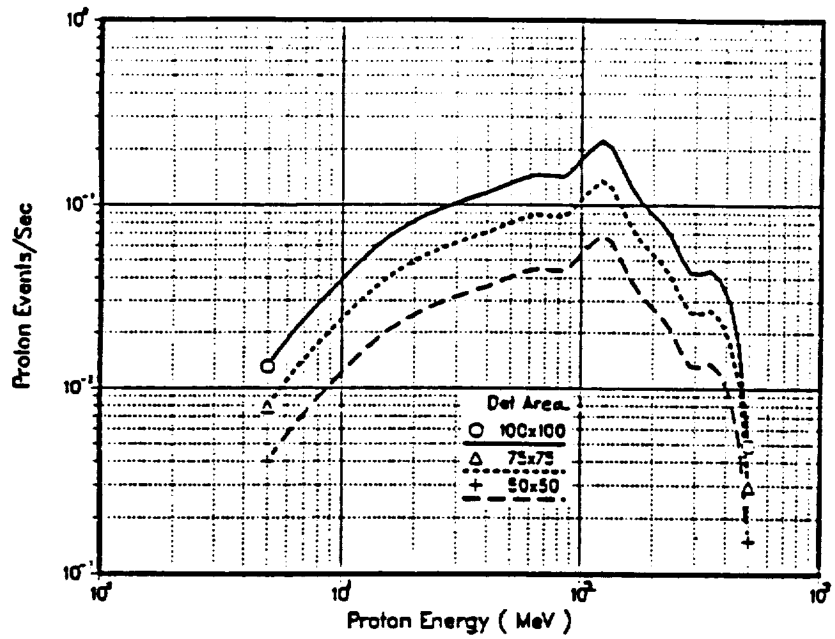
The pulse amplitude for each proton event is determined by the proton energy, as shown in Figure 7. The amplitude depends less on detector area (Figure 7a) than on thickness (Figure 7b). The amplitudes are large enough that they can be easily discriminated from the infrared signal.

Total dose requirements for SIRTF are not severe for either InSb detector material or silicon MOSFET readouts. Even for a low orbit that includes transiting the SAA, the total dose is just 750 rad(Si) per year. SBRC InSb detector arrays have been irradiated with up to 10^4 rad(Si) without any degradation in quantum efficiency or leakage current. Recently another detector surface passivation has been developed and tested out to 6 x 10^5 rad(Si) without degradation.

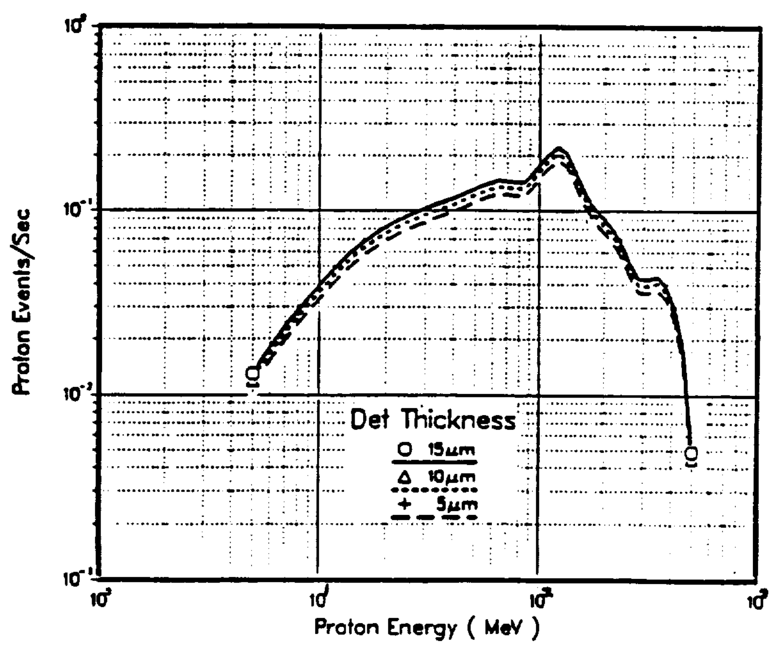
Typical CMOS devices with 200 to 300 Å oxides exhibit a 0.1 volt shift in threshold after irradiation with 10^4 rad(Si). Readout circuits can easily accept this much shift without performance degradation.

CONCLUSIONS

Most SIRTF IRAC requirements have been demonstrated on test devices. In particular, InSb detector dark current and radiation hardness measurements meet SIRTF goals.

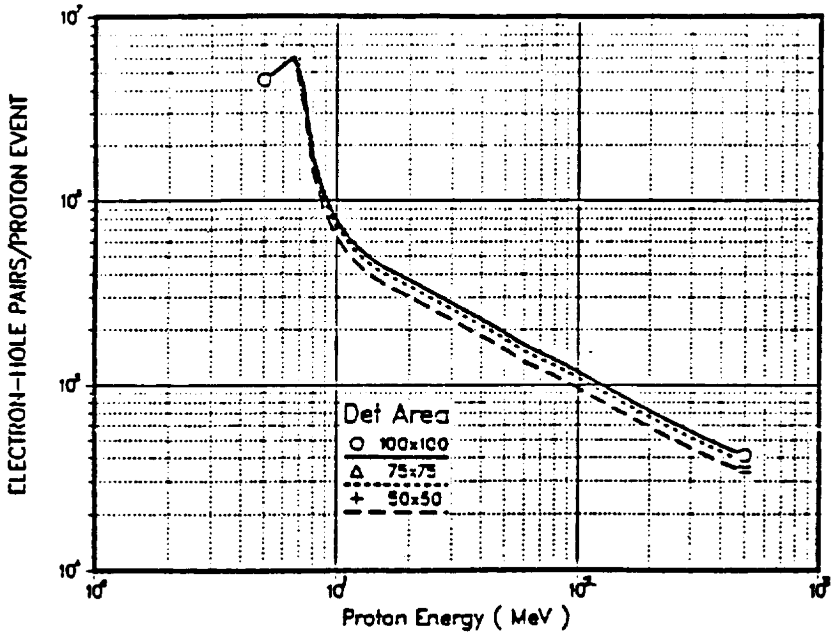


a. Proton events for 15 μm thick detectors of different areas

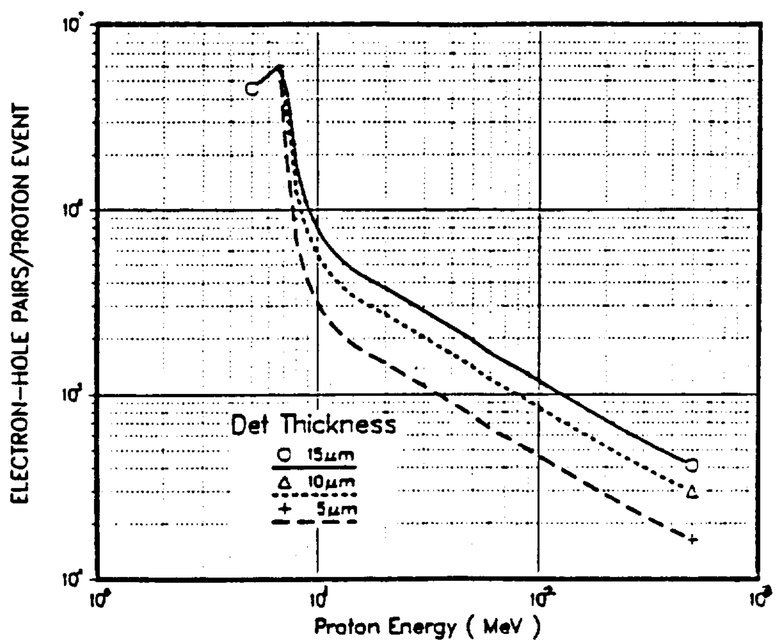


b. Proton events for (100 μm)^2 detectors of different thicknesses

Figure 6. Proton event rate in the SAA for InSb detectors as a function of proton energy



a. Pulse amplitudes for 15 μm thick detectors with different areas



b. Pulse amplitudes for (100 μm)^2 detectors of different thicknesses

Figure 7. Pulse amplitude per proton event as a function of proton energy

One major issue, excess noise, still needs to be addressed to insure optimum performance of the flight instrument. The noise goal can be approached from two sides: reduce detector capacitance and improve readout noise. Noise associated with FET switching needs to be addressed in future SIRTF research and development. Many of the capacitance reduction techniques discussed above will be investigated this year. The excess 10 Kelvin PMOS noise will be examined both analytically and experimentally to determine its origin. A PMOS 256^2 readout will also be developed this year to demonstrate the performance and producibility of this type of array.

ACKNOWLEDGMENTS

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