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Ga:Ge ARRAY DEVELOPMENT

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Abstract

We describe work at the University of Arizona and at Lawrence Berkeley Laboratory on the development of a far infrared array camera for the Multiband Imaging Photometer on SIRTF. The camera design uses stacked linear arrays of Ge:Ga photoconductors to make a full two-dimensional array. Initial results from a 1 x 16 array using a thermally isolated J-FET readout are presented. Dark currents below 300 electrons s^{-1} and readout noises of 60 electrons have been attained. Operation of these types of detectors in an ionizing radiation environment are discussed We present results of radiation testing using both low energy gamma rays and protons. We also describe work on advanced C-MOS cascode readouts that promise lower temperature operation and higher levels of performance than the current J-FET based devices.

I. INTRODUCTION

SIRTF will be the premier infrared facility in the late 1990's and will represent a dramatic increase in the sensitivity attainable in infrared astronomy. An important part of this capability will be a far infrared camera being developed by the Multiband Imaging Photometer for SIRTF (MIPS) team. The basic goal for this camera is to provide diffraction limited imaging between 60-120 μm at a sensitivity limited only by the natural backgrounds. Of equal importance in a real system are the requirements of good stability, ability for precise calibration, and low power dissipation. We describe our development efforts for this camera. This paper is divided into discussions of detector development, J-FET-based readout arrays, and C-MOS readout technology.

With the change in the SIRTF orbit from a 900 km to a 100,000 km high earth orbit baseline, there is now an increased premium for very low power dissipation, resistance to ionizing radiation, and stable photometric performance. The far infrared array development for MIPS has evolved to reflect these changes.

II. DETECTOR DEVELOPMENT

Ionizing radiation effects can greatly complicate the operation of infrared detectors in space. Two general problems have been identified that can make sensitive observations with photoconductors difficult. First, individual particles (primarily high energy protons) generate a large number of hole-electron pairs in the detector. Since all the new systems under development will use integrating amplifiers because of their much higher sensitivity, the result will be a large step in the input voltage of the amplifier until a reset occurs. The Ge:Ga detectors planned for the far infrared camera operate at a relatively low bias voltage (~50 mV), and this voltage step can represent a significant bias change for the detector. Since some photoconductors exhibit long time constant relaxation effects after bias changes (Young and Speed 1985), and we have devoted some effort in characterizing the single hit behavior of the proposed Ge:Ga detector material. The second radiation effect is the change in responsivity after an exposure to ionizing radiation. During the IRAS mission, changes in excess of a factor of 5 were observed after a passage through the South Atlantic Anomaly (IRAS Explanatory Supplement 1988). Since, a SIRTF goal is to do photometry to the 1 to 2% level, it will be important to be able to understand and correct for these changes. In general, it has been observed that these effects are more serious at lower infrared backgrounds, so we have begun a program of radiation characterization at the very low backgrounds appropriate to SIRTF.

The bulk of the radiation testing has been done at Steward Observatory using a 10 mCi Americium^{241} gamma ray source. This isotope primarily produces 60 keV radiation. Because of the low energy of the gamma rays, the radiation is easily shielded and collimated with simple brass fixtures. The test apparatus also includes a photon-tight dewar with an internal infrared source and an integrating J-FET amplifier capable of measuring currents below 1 electron s^{-1}. Backgrounds in the dewar below 10^3 photons cm^{-2} s^{-1} at 100 μm have been observed. With the internal stimulator, changes in responsivity can be observed even at ultra-low background levels, while changes in the dark current can be determined with the stimulator turned off.

Figure 1 shows the radiation induced responsivity change in a Ge:Ga detector made from boule LBL 113 at two different infrared background levels. This material is characteristic of the best currently available Ge:Ga photoconductors. At the high background, the increase in responsivity appears to saturate at a factor of 5-6, while the saturation value for the low background case is twice as high. Additionally, the dose required for a given responsivity increase is significantly lower for the low background case. These two effects are consistent with a self-annealling rate that is dependent on the infrared background flux.

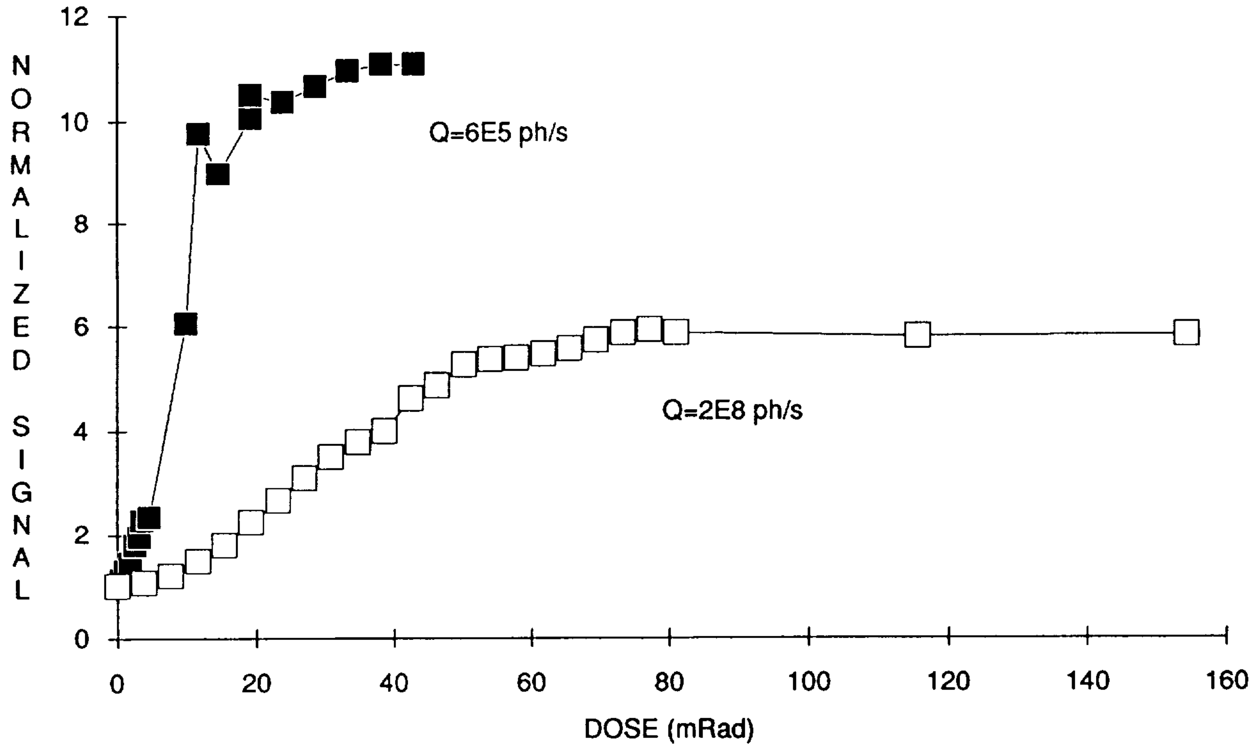

Figure 1. Responsivity change in LBL 113 Ge:Ga detector with gamma ray exposure.

The very low thresholds for significant responsivity changes in Ge:Ga suggests that the normal cosmic ray proton background may be enough to induce troublesome effects in a SIRTF application. To investigate these effects, we have extended the radiation measurements to lower infrared backgrounds (10^3 ph/s) and lower ionizing dose rates ($<10^{-6}$ rad/s). We have found a complicated behavior under these conditions. There appears to be a persistent 2x responsivity increase with a very long time constant and another component that decays with a background dependent rate.

We have also investigated the efficacy of various correction schemes for these radiation effects. The methods we have considered are the bias boost as used in IRAS, thermal anneal, and photon flooding. In general, the thermal anneal technique, where the detector temperature is raised for a few seconds to ~8K appears to be the most effective and rapid method.

Since the ionizing flux for SIRTF will primarily be high energy protons rather than gamma rays, it is important to understand the differences due to proton irradiation. In particular, it is important to define the effects of the much larger energy per interaction for the protons. Initial investigation of proton effects was made in January 1989 at the Crocker Nuclear Laboratory cyclotron at the University of California, Davis. This facility can produce 60 MeV protons at fluxes ranging from a few tens of protons s^{-1} cm^{-2} to many orders of magnitude higher. The bulk of the run was spent simulating a SIRTF-like cosmic ray flux to investigate the gradual increase in responsivity. The cyclotron output was adjusted to 60 MeV energy and an initial flux of approximately one hit per 5 seconds in the 1 mm^3 detector. Figure 2 shows an averaged plot of the Ge:Ga detector current over nearly 12,000 seconds of exposure. Each point represents the median average of three five-second integrations, with time given in seconds after midnight. The initial photocurrent from the detector is approximately 2000 e/s due to the background in the dewar and is typical of the expected SIRTF conditions. The lower envelope of the curve is a measure of the responsivity of the detector, while samples well above the envelope are contaminated by particle hits. The gradual increase in responsivity is evident as dose accumulates. The most dramatic increase, however, only occurs after t=50500 seconds when the proton flux is increased by a factor of 300 over the initial rate. At 52300 s and 52600 s, the detector is thermally annealled dropping the responsivity to nearly the original level. For this run, however, the anneal temperature only reached 5.9K, and the recovery is not complete. The responsivity drifts upward even though the proton exposure was stopped at t=51,000 s. Clearly much additional work is needed to come up with an optimal radiation recovery strategy.

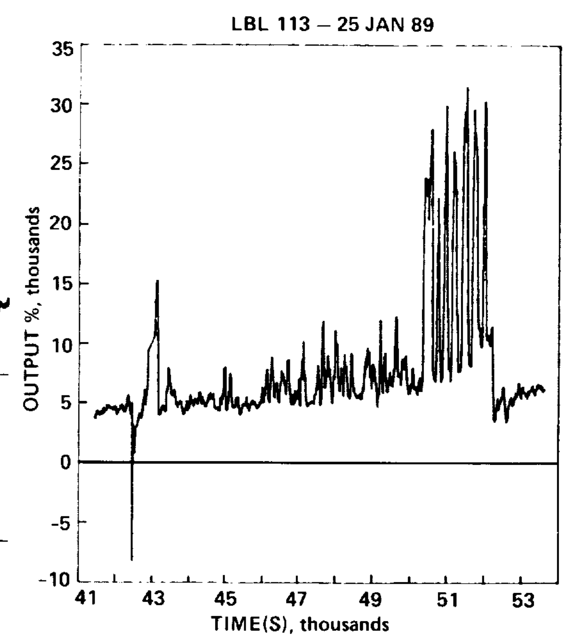

Figure 2. Photocurrent from Ge:Ga detector with low infrared background and proton irradiation. Points are median averages of three 5-second integrations. Thermal anneal cycles were initiated at 52300 and 52600 s.

To summarize these radiation tests, the change in responsivity due to the cosmic ray background is slow and predictable. Precise photometry should be possible with a careful calibration strategy involving regular use of an internal reference source. The single hit effects for this detector do not appear to be serious. LBL 113 recovers from single particle hits rapidly and does not seem to have significant long time constants. Moreover, the charge collection efficiency at the low bias voltages typical for these detectors is less than 10% for both gamma ray and proton events.

III. J-FET DEMONSTRATION ARRAY

The design for the demonstration linear array must satisfy a number of conflicting requirements. First, the design must isolate the J-FET integrators both thermally and optically from the Ge:Ga detectors. Since the electronics must operate at a temperature of 50 K while the detectors must operate below 2 K, a large temperature gradient must be supported by the mount. At the same time, the support must have a very low thermal conductivity to minimize the power dissipation in the unit. It is also desirable, however, to have the first stage electronics as close as possible to the detectors to minimize spurious pickup and microphonics. Finally, the design must be stackable into a two-dimensional configuration with a high filling factor.

Figure 3 shows the basic configuration of the demonstration linear array. The 16-channel J-FET integrator integrated circuit from Burr Brown/Infrared Laboratories and an RCA CD4067 multiplexer are mounted on a metallized sapphire substrate using flip-chip techniques. This substrate is physically suspended and thermally isolated by thinwall 125 μm diameter polyimide tubes. These tubes also provide the electrical connection to the J-FETs since they are metallized with 200 A of chromium and 2000 A of gold. The Ge:Ga detectors are also thermally isolated from the J-FET module using an additional set of polyimide conductors. We have found that even though the frame for the J-FET modules is nominally operating at 2K, this extra degree of isolation is important for minimizing thermal interference. The aluminum frame and the detectors are thermally sunk to the 2K heat station. To insure against photon leaks from the "hot" J-FET electronics, we have made liberal use of indium gaskets and black Stycast epoxy in the joints.

We have found the polyimide support system to have the desired combination of ruggedness and low thermal conductivity. Previous versions of the module used glass fibers or glass sheets for the suspension system. Although the glass fibers potentially have a lower thermal conductivity, the polyimide support is superior due to its much greater resistance to breakage.

We have demonstrated functional operation of several of these arrays, and the latest tests show that the design meets the basic noise and dark current needs of a SIRTF far-infrared imager. Table 1 summarizes some of the module characteristics. The low dark current demonstrates the success of the thermal and optical isolation. It is important to note that these performance figures are for fully multiplexed operation with a computerized data acquisition system and any contribution due to digital noise is included in the total noise. This array would be background noise limited in less than 10 seconds of integration if used in the SIRTF diffraction limited imager.

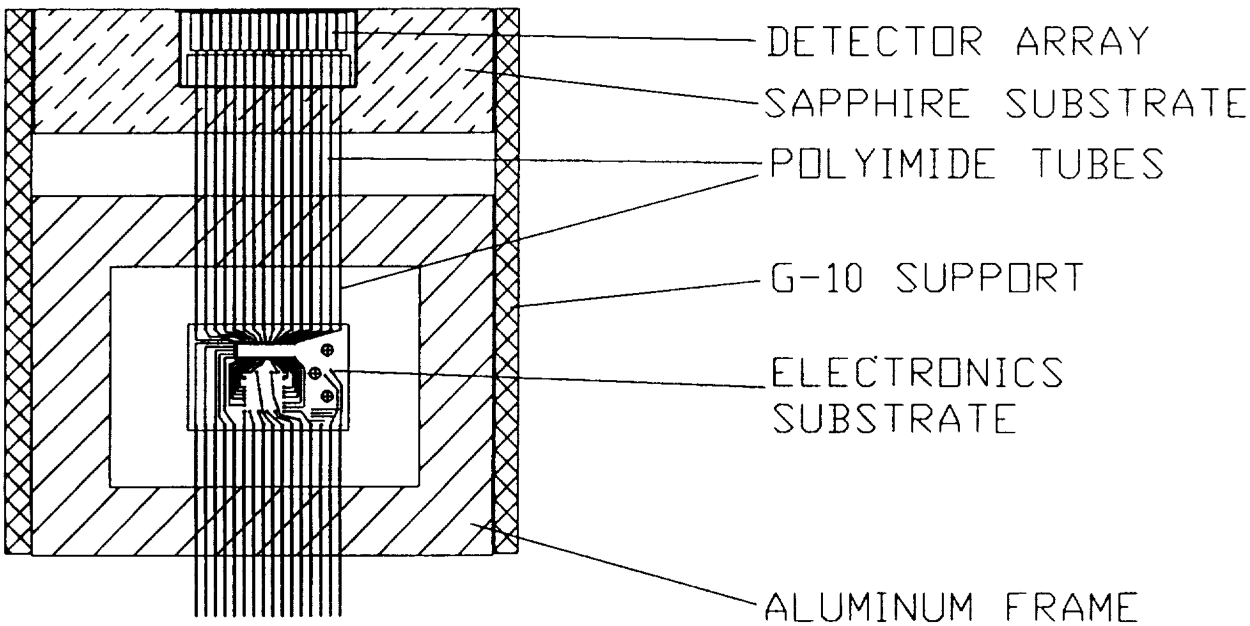

Figure 3. Demonstration Array Sub-module Top View

Table 1. Demonstration Array Module Characteristics

Detector Material	Ge:Ga
Number of Channels	16
Detector Active Area	500 μm x 500 μm
Detector Style	Transverse contact
Module Thickness	0.5 mm
Ambient Operating Temperature	2.0 K
J-FET Operating Temperature	50 K
Power Dissipation	0.5 mW/module
Detector Responsivity	5 A/W
Dark Current	<300 e^-/s @ 50 mV bias
Read Noise	<60 e^- for 32 s integration, 0 bias

With the current array design, the detector filling factor is lower than desired. Using the 500x500 μm detector size with 750 micron pixel spacing, the net filling factor is only 44%. To improve on this situation, we are investigating a number of optical concentration methods. One promising technology involves the anisotropic etching of silicon (Kaminsky 1987). We have experimented with an etch of pyrocatechol and ethylene diamine (P-ED). The etch rate for the 111 orientation is at least one hundred times greater than for the 100 orientation. By using appropriate masks aligned to the crystal orientation in 100 wafers, we have produced arrays of pyramid-shaped solid cones that could act as solid concentrators. We are doing analysis to determine whether the opening angle (which is fixed by the crystal planes in silicon) is appropriate for this application.

IV. C-MOS READOUT DEVELOPMENT

Although the basic requirements of a SIRTF far infrared camera could be met with stacked J-FET based modules, we have been exploring possible enhancements both in the size of the array and performance of the readout. Significant advances in the noise performance of C-MOS analog circuits have been made in the past few years. In particular, the noise now seen for a new 1.25 μm process is only 200 nV $Hz^{-1/2}$ at 1 Hz (1000 square μm gate area). This noise level is about a factor of five better than devices made with the older 3 μm technology, and with this level of performance, C-MOS readouts can be competitive with J-FETs.

C-MOS circuit technology has a number of additional advantages over J-FET technology. C-MOS fabrication has a density advantage of J-FET designs. For the SIRTF imager application, for example, it is possible to produce at least a 32-channel readout with multiplexer using very relaxed design rules. In fact, additional circuitry to do simple signal processing such as baseline correction can be incorporated directly on the integrated circuit. Finally, CMOS circuits can operate at lower temperatures than their J-FET counterparts. For a far infrared camera, the thermal and photon isolation of the amplifier from the detectors is a significant complication. By running the readout at lower temperatures, this problems diminishes greatly.

To explore the applicability of these new technologies to high performance infrared focal plane arrays, this program has funded the fabrication of test circuits at Amber Engineering. Four input circuits were considered to cover a range of possibilities. Because of the flexibility of C-MOS fabrication processing, all four test circuits were placed on a single die. The test circuits consisted of p- and n-channel versions of the source follower and common source cascode amplifier. The use of the common cascode circuit for infrared array readouts is discussed in more detail in the accompanying paper by Woolaway and Young (1989). The most important difference between the cascode and source follower configurations is that the cascode provides a factor of 20-30 gain. Although the cascode should theoretically have no noise advantage over the source follower, the extra gain makes it significantly easier from a systems standpoint to meet the noise potential of the MOSFETs. Table 2 gives some of the measured performance values for the test circuits at a temperature of 77K. Even though the input capacitance is relatively large, the noise level for the cascode circuits is excellent. We have also carried the testing to lower temperatures. For the p-channel cascode, the noise performance holds down to 30K, below which there is a gradual increase in low frequency noise. At the lowest temperature measured (2 K) the circuit continues to function but with a readout noise of 30 e-.

Table 2. Performance of AE133-2A Test Circuits

Circuit	Voltage Gain	Input Capacitance (pF)	RMS Noise ($e^{-}\ Hz^{-1/2}$)
n-channel Cascode	27.6	0.68	7
p-channel Cascode	26.9	0.66	8
p-channel Follower	0.84	0.43	38
n-channel Follower	0.75	0.44	*

Temperature = 77K
Power Dissipation = 114 μW
* Not measured due to excessive leakage current in input test diode.

The excellent performance of the common source cascode circuits gave us the confidence to go ahead with the fabrication of a 32-channel readout based on these circuit concepts. If the performance of these parts attains the predicted levels, the task of fabricating full far-infrared arrays will be greatly simplified. The integrated circuit is being fabricated using a 2 μm design rule p-channel process. P-channel is used for its superior low temperature operation. In addition to the cascode input stages, the circuit includes an AC-coupled driver stage and a serial multiplexer. The purpose of the AC-coupling is to remove any offset voltages in the input stage and results in an improved dynamic range for the circuit. The multiplexer is a shift register-transmission gate configuration that features break-before-make operation. Table 3 gives some of the predicted characteristics of the circuit.

One of the more challenging constraints on the design was the desire to minimize the power dissipation in the circuit. Minimizing the power dissipation is especially important in the SIRTF high orbit context since parasitic and aperture heat loads are very low. We were able to meet the power dissipation goals by maintaining only a minimal continuous current in the input cascode stage. The subsequent driver and logic stages are operated in the switched mode, drawing current only when a given channel is being read out. With this power management strategy, the total power dissipation for a 32 x 32 array would be only 5 mW.

Table 3. Design Characteristics of 1x32 Readout

Input configuration	p-channel common-source cascode
Reset accuracy	limited by kTC
Multiplexing	serial shift register
	break before make
Sample rate	up to 32 x 10 Hz
Output circuit	current-mode
Input stage gain	15-20
Maximum input excursion	20 mV
Full well capacity	1.2 x 10^6 electrons
Power dissipation	156 μW
Input capacitance	9 pF
Read noise	50 e^-, 0.01-100 Hz
Operating Temperature	<30 K

The expected performance of this readout should demonstrate the usefulness of custom circuits for infrared astronomical applications and extends the application of MOS readouts to high input capacitance applications. The benefits of low noise, low power dissipation and higher levels of integration should enable us to more fully exploit the power of SIRTF with a large format far-infrared camera.

Acknowledgements

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References

IRAS Explanatory Supplement, 1988 C.A. Beichman, G. Neugebauer, H.J. Habing, P.E.Clegg, and T.J. Chester, editors. NASA RP-1190.

Kaminsky, G. 1987 "Micromachining of Silicon Mechanical Structures" in ***Science and Technology of Microfabrication***, ed. R.E. Howard, E.L. Hu, S. Namba, and S. Pang, (Pittsburgh: Materials Research Society) p. 111.

Woolaway, J.T., and Young, E.T. 1989 "Common Source Cascode Amplifiers for Integrating IR-FPA Applications" this volume.

Young, E.T. and Speed, D. 1985, ***Proceedings NASA Infrared Detector Workshop, Ames Research Center***, NASA Technical Memorandum.