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THE DEVELOPMENT OF INFRARED DETECTORS AND MECHANISMS FOR USE IN FUTURE INFRARED SPACE MISSIONS

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Abstract

The environment above earth's atmosphere offers significant advantages in sensitivity and wavelength coverage in infrared astronomy over ground-based observatories. In support of future infrared space missions, technology development efforts were undertaken to develop detectors sensitive to radiation between 2.5 μm and 200 μm. Additionally, work was undertaken to develop mechanisms supporting the imaging and spectroscopy requirements of infrared space missions.

Arsenic-doped-Silicon and Antimony-doped-Silicon Blocked Impurity Band detectors, responsive to radiation between 4 μm and 45 μm, were produced in 128x128 picture element arrays with the low noise, high sensitivity performance needed for space environments. Technology development continued on Gallium-doped-Germanium detectors (for use between 80 μm and 200 μm), but were hampered by contamination during manufacture. Antimony-doped-Indium detectors (for use between 2.5 μm and 5 μm) were developed in a 256x256 pixel format with high responsive quantum efficiency and low dark current. Work began on adapting an existing cryogenic mechanism design for space-based missions; then was redirected towards an all-fixed optical design to improve reliability and lower projected mission costs.

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Introduction

Infrared astronomy from ground-based observatories has produced many discoveries. However, two major difficulties exist in detecting infrared radiation from the ground. First, many incoming wavelengths are absorbed by the earth's atmosphere, and are thus unavailable. Second, the infrared background signal created by the atmosphere is high enough to render faint sources invisible to our detectors. Thus, moving the observatory into space offers the prospect of increased wavelength coverage, and sensitivity improvements of 10 to 100 times that of ground-based systems.

With these capabilities in mind, four areas of discovery have been identified for a space-based infrared astronomy mission:

- The Early Universe
- Ultraluminous Galaxies
- Debris Disks ("Vega phenomena")
- Brown Dwarfs.

High sensitivity, low noise measurements in the wavelength range from 2.5 μm to 200 μm would result in a wealth of new understanding of the infrared universe. In support of obtaining that data, this grant supported the technology development necessary for an infrared Great Observatory in Space.

This report details the activities of NASA grant NAGW-2870, initiated in 1992, and renewed in 1993, and 1994. During this period, the objectives and scope of the project were adjusted as our work progressed, and adapted to external factors.

The grant outlined work in four areas. They are:

I. Silicon Blocked Impurity Band (BIB) Detectors,
II. Germanium Blocked Impurity Band (BIB) Detectors,
III. Antimony Doped Indium Based Detectors,
IV. Cryogenic Mechanisms.

The goals of each area, and the progress made towards meeting those goals follow.

I. Silicon Blocked Impurity Band (BIB) Detectors

Cornell has a long and successful history of developing high performance infrared detectors. Working with the Rockwell International Science Center (RISC), we have developed Si:As Back Illuminated Blocked Impurity Band (BIBIB) detectors, which have been used at the Palomar Observatory and aboard the Kuiper Airborne Observatory. The space-based infrared environment is sufficiently different from the ground-based environment to require additional technology development. The lower background amplitudes and faint target sources will require measurements lasting hundreds of seconds, versus milliseconds for ground-based systems. This data collection methodology and the improved sensitivity needs require detectors with reduced noise characteristics and improved gain features to convert the small photon fluxes into usable signals.

Our goals for grant NAGW-2870 were as follows:

A. Extend the work on the detector materials and optimize the performance in the 4 μm to 28 μm range.

B. Change the array format from 10x50 to 128x128 picture elements on a 75 μm pitch.

C. Develop a low background 128x128 multiplexer for use in space-based applications.

D. Develop a 128x128 Si:Sb BIBIB detector for longer wavelength applications. Test the detector's response to 40 μm.

E. Support a small effort in Si:xx photoconductive arrays.

The success of the first four of these development efforts would make it possible to produce infrared sensitive materials mated with readout devices capable of being used in instruments taking measurements between 5 μm and 40 μm.

A. Extend the work on the detector materials and optimize the performance in the 4 μm to 28 μm range.

In evaluating the operating characteristics of a detector, six parameters are determined.

1. Dark Current
2. Dark Gain Dispersion
3. Read Noise
4. Illuminated Gain Dispersion
5. Responsive Quantum Efficiency
6. Detective Quantum Efficiency

Optimizing a detector entails achieving the best tradeoffs in performance among these characteristics.

Between 1986 and 1990, Cornell and RISC developed 10x50 infrared arrays for low background operation. The Si:As devices consisted of an IR sensitive detector material bonded to a readout multiplexer. Read noises under 50 electrons and dark currents less than 20 e^-/sec were obtained. While impressive, both of these attributes are still too large to be usable in a space-based observatory.

In order to obtain the best results in terms of responsive quantum efficiency, three factors in the detector material were adjusted, the infrared active layer (IRAL) doping level, the infrared active layer thickness, and the blocking layer thickness. Both experimental and analytical means were employed to achieve the highest responsivity. As detailed in the Quarterly Progress Report, July 1 through September 30, 1993, our work determined that the best combination is:

IRAL Doping:	0.85×10^{18} atoms/cm^3
IRAL Thickness:	18 µm
Blocking Layer Thickness:	3.7 µm

Using these factors, a responsive quantum efficiency of 0.33 was obtained. By early 1994, the design utilized antireflection coatings. Quarterly Progress Report, April 1 through June 30, 1994, records that the responsive quantum efficiency increased to 0.45. The improvement of other performance characteristics is covered in subsequent sections.

During Cornell's testing, we noticed the occurrence of latent images, a persistence of a signal after the illuminating source has been removed. More than 10 frame resets were required to remove the unwanted persistence, which became more pronounced at lower temperatures. if uncorrected, the long delays between successive measurements required to erase the latent images would result in an observing efficiency too low for the mission to achieve its goals. Fortunately, we discovered that a boost to the detector bias, followed by four frames of settling, all at high frame rates, reduced the latent image effects to below a 1% response, considered acceptable for our applications. Details are found in the JPL SIRTF IRS Bimonthly Progress Report, December 1994 - January, 1995.

B. & C. Change the array format from 10x50 to 128x128 picture elements on a 75 µm pitch. Develop a low background 128x128 multiplexer for use in space-based applications.

The advantages of more picture elements (pixels) at a finer pitch in a detector are in terms of resolution. In imaging applications, finer source details can be discerned with smaller pixels. In spectroscopy, narrower wavelength ranges can be separated by using finer pitch pixels, effectively separating radiation at closely spaced wavelengths. Thus, efforts were undertaken to provide designs for both Si:As and Si:Sb devices. Details of the design & layout are provided in the Quarterly Progress Report for period April 1 through June 30, 1992.

The completion of the first layout of a 128x128 multiplexer introduced the low background design needed for space-based applications. Until then, the arrays contained a relatively large effective unit cell capacitance C_{eff}, capable of accumulating the large charge associated with high background fluxes. The reduced C_{eff} improves sensitivity to the low-flux sources, and reduces the read noise.

Once the first array of this design was tested, a number of shortcomings became evident. First, as reported in Rockwell International Monthly Progress Report 4, February, 1993, excessive dark current was observed. This was subsequently determined to have two components, a small IR sensitive materials portion, and a "mux glow" portion; where the clock generator circuitry created an electron flux in the nearby unit cells. Cornell also observed that a design feature which keeps a pixel in reset for two column periods had the effect of adding a static offset to the measured signal. The noise associated with this offset added to the detector's read noise. The reasons for this feature are found in Rockwell International Monthly Progress Report 5, March, 1993. There were a large number of "bad" pixels, open- or short-circuits, which compromised the cosmetics of the array. Each of these problems was subsequently addressed and corrected.

In order to reduce the excessive mux glow dark current, the clock generator and output driver circuits were separated from the multiplexer, and placed on a satellite chip. When this chip was physically separated from the array, the mux glow component of the dark current was eliminated. Details of this are found in Quarterly Progress Report, April 1 through June 30, 1994. The measured dark current fell from thousands of e^-/sec to around 4 e^-/sec at a detector bias of 2 volts, and 11 e^-/sec at a 2.5 volt bias.

Improved process control and more experience fabricating and bonding detectors and multiplexers improved the cosmetics greatly. Arrays can now be made with a few to a few tens of "bad" pixels (as opposed to hundreds or thousands), a value acceptable for most applications.

Two other performance improvement features were addressed in the new array design. As described in Rockwell International Monthly Progress Report 11, September, 1993, a transistor was added to the unit cell design on arrays designed for moderate (ground-based) backgrounds to isolate the detector element from the charge collection capacitor. This effort to keep large photon fluxes from debiasing the detector resulted in arrays being manufactured with an extremely linear response. Up to 6.5 million electrons were accumulated on a device with a well depth of 8 million electrons without loss of sensitivity. Quarterly Progress Report, April 1 through June 30, 1994 reports the data. Finally, the feasibility of fabricating a unit cell with a switchable integration capacitance was explored. Arrays of this type could be evaluated in earth-based and space-based applications, improving the pool of available detectors. Reported in Rockwell International Monthly Progress Report 2, November, 1994; no arrays were built according to this design under this grant.

To assess array sensitivity to radiation doses (such as solar flares), two devices were subjected to nearly monochromatic proton beams of about 50 MeV, with a total dose of about 200 rad-Si. Both dark and illuminated images were recorded to determine how the arrays recover from single and multiple radiation hits.

Dark current performance was found to be the parameter most degraded by radiation. The tests showed that between 8% and 10% of the pixels on a low background array with a satellite chip exhibited excessive dark current after a 140 rad-Si dosage. This is about 4 times the acceptable limit for space-based applications. Follow-up studies are planned.

D. Develop a 128x128 Si:Sb BIBIB detector for longer wavelength applications. Test the detector's response to 40 μm.

Pertinent spectroscopic information on 3 of the 4 major areas of discovery, The Early Universe, Ultraluminous Galaxies, and Debris Disks, exists in the wavelength range from 25 μm to 40 μm. The responsivity of Arsenic-doped-Silicon is too low at wavelengths much beyond 25 μm for practical use. Antimony-doped-Silicon retains its responsivity beyond 40 μm, and was chosen as an infrared detector material. The RISC proceeded to fabricate devices. The first Si:Sb array, SbM-1, contained numerous defects. Hundred of "bad" pixels, whole nonresponsive rows, and dark currents of 10^4 e^-/sec were observed. More detail on this is found in Rockwell International Monthly Progress Report 5, March, 1993. Again process control, manufacturing experience and the use of a satellite chip turned the tide.

Array SbL-7 showed only 10 "bad" pixels, a 100-fold improvement over previously fabricated arrays. However, the dark current was still high, approaching 10^6 e^-/sec at biases above 2.5 volts, part of which was attributable to mux glow. This is reported more fully in Quarterly Progress Report, October 1 through December 31, 1993.

By using the satellite chip design, correcting the two column reset, and including a buffered contact layer to prevent breakdown at biases above 2 volts, we achieved an improved responsive quantum efficiency and decreased dark current. The array SbL3-2 demonstrated dark current as low as 34 e^-/sec at a bias of 1.5 volts. The responsive quantum efficiency was 0.17 at 10.4 μm, and 0.37 at 18 μm without the use of antireflection coatings. The dark current remains a strong function of bias voltage above 1.5 volts, with a current of about 700 e^-/sec at V_{bias}= 2.0 volts, and a current above 10^4 e^-/sec at V_{bias}=2.5 volts. When the array was cooled from 4.6 °K to 2.8 °K, (a temperature closer to those predicted for space-based applications), the measured dark current fell to 24 e^-/sec at a bias of 2.25 volts, and 111 e^-/sec at a bias of 2.5 volts. Full details of the experiments are recorded in the SbL3-2 Logfiles.

Future work on these detectors will focus on multiplexer-based anomalies such as an observed signal droop on sample-up-the-ramp integrations, and sensitivity to ionizing radiation.

E. Si:xx Photoconductive Arrays

Another technology capable of detecting infrared radiation is silicon-based photoconductive arrays. In the event of serious difficulties with BIBIB devices, photoconductive arrays could be adapted to our applications. Towards this end Cornell supported a small effort with Dr. Tom Roellig of NASA Ames Research Center.

Dr. Roellig evaluated a 256x256 arsenic-doped-silicon impurity band conduction (IBC) detectors, provided by Hughes Technology Center. The devices had a 30 μm pixel pitch, and a 20 μm thick infrared active layer doped to an As concentration of about 5×10^{17} cm^{-3}. Dr. Roellig's work is summarized in *Evaluation of a 256x256 Si:As IBC Detector Array for Astronomy*, "Infrared Astronomy with Arrays', p. 327-328, Kluwer Academic Publishers, 1994.

These IBC arrays performed comparably to the BIBIB devices. The photoconductive arrays had dark currents less than 20 e^-/sec at 5.5 °K and -1 volt applied bias. The read noise was less than 100 electrons; and the detective quantum efficiency evaluated to 0.20, roughly independent of bias voltage. A similar device, a 58x62 pixel array was also investigated with essentially the same results, published as *58x62 Si:As IBC Detector Arrays on PMOS Multiplexers for Astronomy*, Proceedings, S.P.I.E., Volume 1946, 1993. The device was successfully integrated into an infrared camera for observations from ground-based telescopes.

With the successful operation of silicon BIBIBs, the need for development work on photoconductive arrays was alleviated. Under this grant, Dr. Roellig continued to assist us with the development of blocked-impurity-band devices.

II. Germanium Blocked Impurity Band (BIB) Detectors

Gallium-doped-Germanium (Ge:Ga) detectors are sensitive to infrared radiation at relatively long wavelengths (80 - 200 μm). Modest-sized (6x6) BIB detectors have been fabricated and evaluated. These early devices suffered from unstable dark currents, low responsive quantum efficiency at short wavelengths (around 40 μm), and long time constants. The work sponsored by grant NAGW-2870 was in support of a larger NASA technology development program dealing with the materials and processing aspects of fabricating Ge:Ga BIB detectors.
In 1992, Ge:Ga arrays from material lot #6 were examined. Quarterly Progress Report No. 1, January 1 through March 31, 1992, contains the complete details of the examination. The peak responsivity was 50 A/W. Good responsivity was maintained at wavelengths approaching 40 μm. However, the detective quantum efficiency was disappointingly small; the dark current was considered too large; and the system exhibited excessive noise.

When detectors from lot 6B were tested (as reported in Quarterly Progress Report No. 2, April 1 through June 30, 1993), a responsivity less than 0.1 A/W ensued. This effect was traced to highly resistive ion implanted electrodes. There was also evidence of contaminating donor atoms during implantation. These contaminating atoms were determined to be oxygen.

Subsequent testing in 1993 on a 6x6 Ge:Ga BIB resulted in a peak responsive quantum efficiency of 0.15 and a dark current less than 40 e^-/sec per square millimeter of the array. However, the persistent contamination by donors at the blocking-absorbing layer interface lowered the detective quantum efficiency to the 0.03 range. This is reported more fully in the Annual Progress Report for NASA Grant NAGW-2870, January 1, 1993 - December 31, 1993.

In an attempt to resolve the contamination issue, two production process steps were proposed. First, a controlled HCl etch of the material was to be attempted as a means of removing the contaminating atoms. Second, using a single reactor to grow both the blocking and absorbing layers was proposed as a way to reduce the risk of introducing contaminating atoms. Unfortunately, persistent difficulties with obtaining funding through the principal NASA technology development grant during 1994 prevented the evaluation of these concepts.

III. In:Sb Based Detectors

In the wavelengths between 2.5 µm and 5 µm, detectors made of antimony-doped-indium are useful. Santa Barbara Research Corporation (SBRC) and the University of Rochester developed and evaluated several devices.

Early attempts to produce 256x256 multiplexers for indium antimonide detectors met with limited success (see Monthly Progress Report No. 22, January 1 through January 31, 1992). As the device temperature was lowered, the signal noise increased. Also, the dark current of the CRC 463 multiplexer was not stable or repeatable. With the advent of the array designated FPA 48, things got better. Quarterly Progress Report No. 1, April 1 through June 30, 1992, reports that the device manufacturing used a new passivation technique which reduced the latent images seen earlier. Measurements at 29 °K showed a read noise of 12 electrons and a responsive quantum efficiency greater than 0.80 for the antireflection coated array. Dark currents of 12 e^-/sec and higher were attributed to multiplexer glow.

Cryo CMOS technology from Hughes Technology Center was incorporated in the In:Sb hybrid FPA 84. This device had a read noise of 17 e^- at 25 °K, and 28 e^- at 6 °K. The responsive quantum efficiency was 0.65 on the non-antireflection coated array. However, latent images were observed, due to not using the passivation technique in their production. Low level signal nonuniformity was observed on FPA 84 as excess charge.

When the temperature was lowered from 11.9 °K to 6 °K, the excess charge increased from 70 e^- to 600 e^-. When the flux was increased from 7×10^3 to 15×10^3, e^-/sec/pixel, the excess charge increased from 250 e^- to 600 e^-. When the gate voltage was changed from -2.0 to -1.7 volts, the excess charge increased from 400 e^- to 600 e^-. Finally, when the clamp-to-sample time was changed from 5 µsec to 10 µsec, the excess charge increased from about 100 e^- to 250 e^-.

A multiplexer-based dark current anomaly with FPA 84 was observed. At 6 °K, the top half of the array had a dark current under 1 e^-/sec; while the bottom half dark current was measured at less than 0.2 e^-/sec. The dark current was not dependent upon the bias voltage. Details of these experiments are recorded in Quarterly Progress Report No. 3, July 1 through September 30, 1992.

The range of flatband was investigated on FPA 84 during the same period. This is the voltage range which controls the gateless-passivation array. Dark current as a function of V_{gate} was used to determine the range of flatband. At 6 °K, the flatband was slightly less than 1 volt. At 12 °K, the flatband was slightly greater than 1 volt wide. At 27 °K, the range of flatband was 0.5 volts wide. In the lower dark current region of the array, the flatband was at least 0.5 volts wider at all measured temperatures.

A 256x256 In:Sb array from SBRC was installed in a camera and operated at the 2.3 m WIRO telescope. This array demonstrated a responsive quantum efficiency greater than 0.80, and a read noise as low as 12 e^- when using sample-up-the-ramp techniques.

Under the direction of the Technical Monitor at JPL, transfer of ownership of the work on In:Sb based detectors to the Smithsonian Astrophysical Observatory was effected at this point. Further development activities were not covered under the NAGW-2870 grant.

IV. Cryogenic Mechanisms

Cryogenic mechanisms are used in infrared detecting systems where the detectors are required to be cooled to a few degrees Kelvin. These mechanisms typically provide the wavelength filtering, and positioning needs of a system, providing arc second positioning accuracy with power dissipations of 0.5 mW or less. Mechanisms meeting these requirements have been built; however, for space-based missions, they are typically too large, have not been vibration tested, and possess excessive thermal drift.

Work began on identifying and studying the elementary issues inherent in a spectrograph design. These issues would be explored through the construction and iteration of an optical bench where concepts could be tested and verified. The concept that seemed to be best was to use 4 detectors (Si:As, Si:Sb, and 2 Ge:Ga) to detect infrared radiation in the 5 μm to 200 μm range at high resolution, and reconstruct low resolution spectra from the high resolution data (described in the Annual Progress Report for NASA Grant NAGW-2870, January 1, 1993 - December 31, 1993). A design consisting of one mechanism for each of the optical benches was conceived, similar to one developed by Ball Aerospace for use in a ground-based instrument, SpectroCam-10. This design met the operational goals for low and high precision positioning. A draft plan to develop a second working model was created by Cornell and Ball Aerospace.

It was at this time that the loss of the Mars Observer resulted in a new impetus to simplify designs as a means of improving their reliability. Before the plan could be presented, a new directive from the NASA Administrator concerning future missions, rendered it impractical.

Actions taken to address the directive included the reluctant abandonment of spectroscopy beyond 40 μm, and developing a new concept for an all-fixed spectrograph to reduce the size, risk, and cost of the instrument. Two low resolution and two high resolution optical benches would cover infrared radiation between 7 μm and about 45 μm.

The result of these efforts are found in two System Engineering Reports by Ball Aerospace:

2830-93.056 *"All Fixed Instrument Concept for IRS"*

2830-93.057 *"Attempt to Design a Low Resolution Spectrograph From 7 to 25 Microns Using a Pair of Prisms"*

Consideration of spectrometers without moving parts shifted our focus from mechanisms to optical materials and system layout. Cornell and Ball Aerospace coordinated their efforts to develop a spectrometer which met the science goals for low and high resolution spectroscopy without requiring actuators. Subsequent work on the new instrument design is summarized in the following Ball Aerospace System Engineering Reports.

2830-94.058 *"Factor of 3 Wavelength Range With High Resolution on a 128x128 Array"*

2830-94.059 *"Feasibility of a High Resolution Camera for 256x256 Arrays"*

2830-94.060 *"All Fixed Spectrograph Layouts"*

2830-94.061 *"Central Processing Unit (CPU) Block Diagram"*

2830-94.062 *"First Order Optics Layout"*

Summary

Between 1992 and 1994, much of the research and ideas about infrared detectors was converted into working devices and processes. As problems became apparent, they were analyzed and corrected, leading to our current level of high performance, low noise infrared detector arrays covering wavelengths between 2.5 and 200 µm. Mechanisms capable of operating in cryogenic environments aboard space-based instruments have also been designed, based on similar models in use now. Future infrared astronomical missions, both space-based and ground-based will employ the knowledge and techniques developed by NASA grant NAGW-2870.

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