Future infrared detector needs for space astronomy

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## ABSTRACT

The planned set of future NASA space astrophysics missions has been continually undergoing evaluation and analysis, to identify major technology needs and to suggest development programs capable of provid ing this necessary technology. At a recent workshop, a panel of users and technologists worked to assess the state-of-the-art of relevant approaches in the area of direct infrared (IR) detectors. The set of candidate mission concepts was grouped into the categories of low-background and moderate-background systems; development strategies were outlined for each. For low-background systems, detectors with the ultimate in sensitivity arc required, and minimum read noise and dark current are critically important. For moderate-background systems, characteristics such as higher detector operating temperature, large charge storage capacity, and large (or very large) formats arc important. Novel photon counting schemes could greatly enhance the capability of future systems. Since readouts often determine overall performance of IR focal plane systems, continued development was needed. Future development programs need to be well coupled to the expertise within the astronomical community.

## 1. INTRODUCTION

At a recent workshop ("Sensor Systems for Space Astrophysics in the 21st Century," held in Pasadena, California, January 23-2.5, 1991; also known as the "Astrotech 21 Workshop"), a Direct Infrared Detector Panel was assembled to assess those astrophysics sensing requirements in the near to very far IR (1 - 1000 pm) that arc best addressed with direct detectors (as opposed to heterodyne approaches). The panel included experts from the astronomical community, industry, and Government laboratories, Its membership consisted of:

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W. Forrest, University of Rochester
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A set of major and moderate future astrophysics missions has been defined, and it was used as the point of reference in the Workshop.[1] Missions from this set which involve significant IR sensing capabilities include (the dates and requirements represent current planning figures):

| | Spectral Coverage (μm) | Technology Need Date |
|---|---|---|
| Stratospheric Observatory for Infrared Astronomy (SOFIA) | 1-1000 | 1995 |
| Hubble Space Telescope/3rd Generation (HST) | 0.1-10 | 1996 |
| Space Infrared Telescope Facility (SIRTF) | 2-2'00 | 1997 |
| Lunar Transit Telescope (l.'I"I') | 0.1 -2.5 | 1998 |
| Submillimeter Intermediate Mission (SMIM) / FIRST | 100-800 | 1998 |
| Astrometric Interferometer Mission (AIM) | 0.1 -2.5 | 1999 |
| Large Deployable Reflector (LDR) | 30-1000 | 2005-2015 |
| Next-Generatiorl Space Telescope (NGST) | 0.1-10 | 2005-2015 |
| imaging Optical Interferometer (11) | 0.1-10 (20?) | 2005-2015 |
| Submillimeter Interferometer (S1) | 100-800 | 2005"-2015 |

The IR regime is a particularly important wavelength range for future NASA missions. Direct and heterodyne spectroscopy in the IR and submillimeter-wave regimes offers crucial information on composition, by probing the rich region of vibration-rotation spectroscopy in which constituents can be identified by their spectral signatures. However, since the Earth's atmosphere is opaque across much of this regime, and despite sizable investments in military technology, there has been little focused development of sensors for scientific applications in this region prior to the advent of space-based astronomy. IR detector technology is considerably less mature than that for visible wavelengths.

Upon examining this mission set and associated IR sensor requirements, it became clear that significantly different requirements and detector technologies must be addressed. The panel chose to split the IR range into four sections: 1 -5 pm, 5-30 µm, 30-200 pm, and 200-1000 µm, which reflects a natural division among the relevant technologies. The panel also recognized that the mission set could be categorized into systems which provide low backgrounds to the detectors (either by liquid He cooling of the telescope OpLiCs, or through highly dispersive optics), and those missions, with passively cooled optics, which would operate with "moderate" backgrounds. Examples of moderate-background missions include the Lunar Transit Telescope, the Moderate Optical Interferometer, the Next Generation Space Telescope, the Imaging Interferometer, and the low-resolution instruments of the Large Deployable Reflector. For these missions, detector technology needs are in general ones of higher operating temperature (to allow focal planes to operate with the simpler and lower-power closed-cycle coolers), large or very large array formats, and large charge-storage (well) capacity, optimized for levels of perhaps -105-108 (or more) photons/s-pixel. The class of low-background missions include SIRTF and a possible mission in the distant future to observe from beyond the asteroid belt ("Son of SIRTF"). It should be noted that detectors in high-spectral-rcsolrrtion instruments on missions with passively-cooled optics, such as LDR, will also be operating under low-background conditions. For these missions/instruments, the utmost in sensitivity is required, and minimum read noise and dark current arc key parameters. These background levels may be down to (or below) levels of order 1 photon/s-pixel. For ail missions, good quantum efficiency is a requirement. As will bc discussed below, an alternate and powerful approach for low-background sensing is that of photon counting detectors, which could essentially provide a noise-free detection capability.

As a benchmark for assessing IR detector requirements for future missions, a review of recent developments for NASA space applications was compiled.[2] Tables 1 - 4 describe the state-of-the-art, in terms of technologies that have been flown on a NASA mission, those which are under laboratory development or development for a near-term mission, and those which arc being developed for a future mission. Detectors used on the Infrared Astronomical Satellite (IRAS), the Cosmic Background Explorer (COBE), and those baselined for SIRTF arc used as representative examples. The capabilities desired for future missions such as NGST and LDR arc also described in Lhc tables, dramatically illustrating the limitations of curren L technology.

Detectors optimized for astrophysics applications must bc photometrically accurate and stable, capable of operation at slow frame rates, and stable in the natural radiation environments of space. NASA developments should produce not just single elements, but also arrays, of scientifically useful detectors. Low levels of noise and power dissipation arc also required.

Table 1. Near IR (1 -5 µm) Sensor Capabilities for NASA Missions

| Development Status | Flown in Space | Under Laboratory Development | Under Development for Space | Desired for Future Mission |
|---|---|---|---|---|
| Sample Mission<br>Launch Date | COBE<br>1989 | | HST 2nd Gen'n/ NIC<br>-1995 | NGST<br>~2010 |
| Detector | InSb | HgCdTe | HgCdTe | InSb or HgCdTe |
| Array Size | 10 discretes | 256 X 256 | 256 x 256 | 20,000 x 20,000 |
| Array Type | Discrete army | Integrated army | Integrated array | Integrated array |
| Readout Type | JFET TIA | Switched Si MOSFET | Switched Si MOSFET | Low-noise FET |
| Quantum Efficiency(%) | 70-85 (AR coated) | ~65 | ≥65 | ≥80 |
| Spectral Range (µm) | 1-5 | 1 -2.5 | 1 -2.5 | 1-5 |
| NEP (W/√Hz) | ~3 x $10^{-16}$ | 5 x $10^{-18}$ (in 1 s) | 5 x $10^{-18}$ (in 1 s) | 7 x $10^{-20}$ (in 1 s) |
| Read Noise (e-) | | 30 | 30 | ≤1 |
| Integration Time (s) | -1 | 1 000 | 1000 | 1000 |
| Operating Temp (K) | 1.6 | ~60 | ~60 | --M) |
| Radiation Susceptibility | Low | Low | Low | Low |

Table 2. Mid IR (5 -30 pm) Sensor Capabilities for NASA Missions

| 'Development Status | Flown in Space | Under Laboratory Development | Under Development for Space | Desired for Future Mission |
|---|---|---|---|---|
| Sample Mission Launch Date | IRAS 1983 | | SIRTF/IRS & IRAC -2000 | Imag'g Int'r / NGST ~2012/2010 |
| Detector | Si:As & Si:Sb PC | Si:As IBC | Si:As & Si:Sb IBC | Si:x IBC |
| Array Size | 31 discrete detectors | IO X50 | 128 X 128 | 20,000 x 20.000 |
| Array Type | Discrete array | Integrated array | Integrated array | Integrated arrav |
| Readout Type | JFET TIA | Switched Si MOSFET | Switched Si MOSFET | low-noise FET |
| Quantum Efficiency (%) | -10 & 24 | -40 | -40 | ~70 |
| Spectral Range (µm) | 8-15 & 15-30 | 5 - 28 | 5-40 | 3-40 |
| NEP (W/√Hz) | $3 \times 10^{-16}$; $6 \times 10^{-17}$ | $5 \times 10^{-19}$ (in 1 s) | $5 \times 10^{-19}$ (in 1 s) | $\sim 3 \times 10^{-20}$ (in 1 s) |
| Read Noise (c-) | equivalent to -400 | ~50 for $t_i > 1$ s | ~50 for $t_i > 1$ s | ≤1 |
| Integration Time (s) | 0.3 | 100 | 1000 | 10,000 |
| operating Temp (K) | 2.5 | ~4 | 4 | -30- 100 |
| Radiation Susceptibility | High | Low | Low | Low |

Table 3. Far IR (30 -200 µm) Sensor Capabilities for NASA Missions

| Development Status | Flown in Space | Under Laboratory Development | Under Development for Space | Desired for Future Mission |
|---|---|---|---|---|
| Sample Mission Launch Date | IRAS 1983 | | SIRTF/MIPS; IRS ~2000 | LDR ~2008 |
| Detector | Ge:Ga (Bands III and IV) | Ge:Be, Ge:Ga, stressed Ge:Ga PC | Ge:Be, Ge:Ga, stressed Ge:Ga PC | Ge:x IBC |
| Array Size | 31 discrete detectors | 3x32, 3x32, 2x8 | 16 X 32, 32x 32., 2 X 16 | ≥32 x 32 |
| Array Type | Discrete array | Stacked linear modules | Stacked linear modules | Planar integrated arrav |
| Readout Type | JFET TIA | Integrating Si MOSFET | Integrating Si MOSFET | Low-dissipation, low-noise FET |
| Quantum Efficiency (%) | 7 & 5 | ≥10 | ≥10 | >40 |
| Spectral Range (µm) | 40-120 | 40-200 | 40-2,00 | 40-250 |
| NEP (W/√Hz) | $1 \times 10^{-1}$\$6 $\times 10^{-17}$ | $\sim 2 \times 10^{-18}$ (in 1 s) | $\leq 2 \times 10^{-18}$ (in 1 s) | $\leq 2 \times 10^{-19}$ (in 1 s) |
| Rend Noise (c-) | equivalent to -400 | ~40 | 30,40, 40 | ≤50 |
| Integration Time (s) | 0.3 | ~10 | 1000 | -1oo |
| Operating Temp (K) | 2.5 | ~7 | 2.5, 1.9, 1.4 | 2 |
| Radiation Susceptibility | High | High | High | Low |

[The following acronyms and abbreviations were used in Tables 1-4: Near Infrared Camera (NIC), Trans-impedance amplifier (TIA), Infrared Array Camera (IRAC), Infrared Spectrograph (IRS), Multiband Imaging Photometer for SIRTF (MIPS), Noise-equivalent power (NEP), Impurity Band Conduction (IBC), integration time ($t_i$).]

The present future mission set includes a number of moderate-background projects, Near-term development needs arc clustered at the shorter IR wavelengths ($\lambda < 30$ µm), and the primary drivers there arc expanded format, low read noise, and elevated operating temperature. The panel's recommendations represent a comprehensive approach toward developing technologies capable of meeting both near-term and long-term needs of the mission set. The technology areas identified by the panel as most urgently in need of development arc shown in Table 5. Each of these is discussed in turn in the remainder of this paper.

Note that the findings of the panel represents a set of recommendations to NASA; the resulting development program(s) will be determined after consideration of many factors. including availability of funding and relative mission priorities. Furthermore, the recommendations presented below respond to the request that the planning go beyond the SIRTF era. Progress on SIRTF technology efforts is summarized elsewhere in [his volume.

'I'able 4, Very Far IR (200 -1000 μm) Sensor Capabilities for NASA Missions

| Development Status | Flown in Space | Under Laboratory Development | Under Development for Space | Desired for Future Mission |
|---|---|---|---|---|
| Sample Mission<br>Launch Date | COBE<br>1989 | | SIRTF/MIPS (?)<br>-2000 | LDR<br>-?008 |
| Detector | Si bolometer | Ge & Si bolometers | Ge or Si bolometer | Ge or Si bolometer |
| Array Size | 1 x 4, 1 x 2 | up to 8x8 | 2X2 | 32X 32 |
| Array Type | Discrete bolometers | Discrete bolometers | Discrete bolometers | Integrated array |
| Readout Type | JFET | JFET | JFET or MOSFET | Low-noise mux |
| Quantum Efficiency (Ye) | 50 | -50 | ≥4 0 | ≥50 |
| Spectral Range (μm) | 120-1 000+ | 200-1000 | 200-700 | 200-1000 |
| NEP (W/√Hz) | $5 \times 10^{-15}$ | $\leq 3 \times 10^{-17}$ (electrical) | $\leq 5 \times 10^{-17}$ | $\leq 1 \times 10^{-16}$ |
| Chopping frequency (Hz) | 4.5, 32, 45 | 5 | 5 | TBD |
| Operating Temp (K) | 1.6 | 0.1 | 0.1 | 0.1, 0.3 |
| Radiation Susceptibility | Low | Low | Low | Low |

Table 5. Direct IR Detector Technology Areas Recommended for Development

| Technology Area | Desired Characteristics | Missions Impacted |
|---|---|---|
| ~argc-Format IR Arrays | Larger array formats in all wavelength ranges | All |
| Photon-Counting Detectors | Noise-free detection across entire IR wavelength range for low-background missions/instrum ents | AIM, NGST, LDR |
| Higher-Temperature 10 μm Detectors | Background-limited performance to210 μm operating at ≥65 K | LTT, NGST |
| Ge IBC Detectors | High-sensitivity arrays with planar readouts for far-IR applications | SMIM, LDR, SMMI |
| Improved Si:Sb IBC Detectors | Large-area arrays with high sensitivity, for wavelengths to 40 μm | LDR, Son of SIRTF |
| Modified SIRTF/HST Technology | Operation with higher background and at higher temperatures | All |
| Readout Electronics | Lower read noise in all wavelength ranges, and LHc operating temperatures for far IR | All |

## 2. LARGE-FORMAT ARRAYS

### 2.1. I'ethnology assessment

'1'able 6 summarizes status and approaches for the development of the very large arrays called for in the mission set. The present state-of-[hc-arL is set by near-IR hybrid arrays, for which 2S6 x 256 formats have been demonstrated and array formats in the range 512 x 512 to 1024 x 1024 arc under development. (This excludes conventional Schottky barrier technology, which, because of low quantum efficiency, was judged not to have direct applicability to future astrophysics missions. However, recent breakthroughs in similar device architectures, such as the heterojunction internal photoemission (HIP) detector, may render such technologies viable in the future.) At longer wave.lengths, demonstrated format sizes arc smaller, and future requirements arc also less demanding. The panel agreed that within industry, for wavelengths < 30 μm, there was a significant and sustained technological thrust toward larger IR array formats. It was recommended that NASA monitor this work closely, but its funding in tbc near future should be modest, to provide leverage in carefully-selected areas. At the level of 1000 x 1000 pixels, or perhaps onc step larger, industrial developments may stop. At this point, if the agency were serious about additional advances, it would have be prepared to fully sponsor them.

'1'here was great skepticism among the panel that high-sensitivity IR army formats would exceed a few thousand on a side in the near future, even for wavelengths between about 1 and 20 μm. Today's most advanced IR arrays arc hybrid devices with iridium-bump interconnects, and this architecture is expected to remain state-of-tbc-art for a number of years. One expects physical limits (i.e., both a minimum practical iridium column size and a maximum practical size for high-quality detector substrates) to constrain format sizes in hybrid arrays.

Table 6. Large-Format Arrays Technology Assessment

| State-of-the-Art Technology | Key Components & Desired Level | Promising Technologies | Pros | Cons | Type of Mission |
|---|---|---|---|---|---|
| 1 - 5 µm HgCdTe & InSb $(256)^2$ & ~$(512)^2$ | $2(1000)^2$ arrays for <20 µm | Hybrid (In bump) arrays with Si MOS readouts | Si maturity | Onset of freezeout | Moderate-Back-ground (MB) |
| 5 - 30 µm Si:x IBC $(128)^2$ & $(256)^2$ | | Monolithic arrays | No thermal mismatch | Processing maturity | |
| | | Non-Si readouts | Some radiation hardness | Maturity | |
| 30 - 120 µm Ge:x Photo-conductor (PC) 3x32 | ≥30 µm Ge:x arrays | Stacked Si MOS, cascode or source-follower circuits | Si maturity, SIRTF heritage | Requires very low operating temperature | Low-Back-ground (LB), MB, SMIM |
| | | Planar Si readouts for Ge IBC | Packaging simplicity | Requires very low operating temperature | |
| 120 - 200 µm Stressed Ge:Ga PC 5x5 | Array-compatible bolometer concepts | Superconducting concepts (tunnel junction, kinetic inductance, transition edge, etc.) | SQUID amplifier advancements | Still at idea stage | LB, MB, SMIM |
| ≥200 µm Bolometers 8x8 | | Si bolometer arrays | AXAF heritage | FET coupling | |

The recommended approaches toward large formats include continued development of hybrid arrays, exploration of monolithic approaches (e.g., HgCdTe-on-GaAs-on -S-i monolithic structures or other novel approaches incorporating bandgap-engineered structures) which should avoid the thermal mismatch and interconnect problems, and pursuit of readouts in GaAs or other alternatives to Si. It was also noted that onc might design a telescope system to include a faceted mirror which would divide the beam into parts, as is being done for the second generation HST Wide-Field and Planetary Camera (WFPC-2). Each of these parts might be directed to a hybrid -1000 x 1000 array, or a small mosaic of such arrays, to achieve a composite format of many thousand on a side. However, this approach introduces significant optical -system complexity.

For wavelengths beyond 30 µm, the stacked Si MOS approach presently under development for SIRTF was endorsed for future requirements. Both cascode (which provides gain) and simple source-follower circuits should be pursued. When germanium impurity band conduction (IBC) technology reaches a state of maturity so that planar arrays arc feasible, an appropriate planar readout technology would have to be supported. For both approaches, the arrays and their readouts must be optimized for operation at low (<2 or 3 K) temperature and low (down to 10's of mV) biases.

To achieve bolometer arrays with formats larger than the present state-of-the-art (on the order of 10 x 10), a dual approach of supporting innovative array-compatible superconducting concept(s), and continuing development of Si-based bolometer readout [as is presently being pursued on the calorimeter for the Advanced X-Ray Astrophysics Facility (AXAF)] was recommended. Recently, a number of low-transition temperature (low-T$_c$) superconducting bolometer concepts have been identified, and advances in superconducting readouts based on SQUIDs make arrays of this type much more attractive. These include (a) using the superconducting transition edge as a very accurate, essentially noise-free thermometer, (b) measuring the kinetic inductance of electrons in a superconducting film, and (c) using the critical current of a Josephson junction as a bolometer. Detector/ readout work to support the concept judged to be most promising should be pursued. In addition, the development of techniques to more efficiently bring out leads, for coupling to preamplifiers, and for multiplexing semiconductor (Si and Ge) bolometer arrays must continue.

## 2.2. Development plan

Many of the pressing needs for very large format arrays come before the turn of the century, so this challenge must be faced soon, A sustained, parallel activity is recommended, so that a range of promising approaches can be explored. With significant projects now underway in industry to push for arrays with dimensions at least as large as TV format (roughly 500 x 500 pixels), [he recommended strategy is to monitor and invest only modestly, if it appears that commercial technologies can be adapted to space astrophysics needs. It is expected that industrial interests will fade after ~1000 x 1000 pixel formats have been achieved, and advances beyond that point would likely be NASA's responsibility.

NASA should continue to sponsor work on Si-based hybrid IR array configurations, but also include investigations of concepts which are potentially superior in the far term. These include monolithic and non-Si (e.g., GaAs) hybrid arrays, An evolutionary approach should be followed, with demonstration arrays built (and thoroughly characterized) in successively larger sizes. A developmental increment of at most a factor of two in linear dimension is recommended for the largest format arrays, and probably also for the (smaller) NASA-unique long-wavelength arrays of both photon detectors and bolometers.

For wavelengths beyond 30 μm, where NASA's detector array requirements are unique, significant progress is needed in both Ge:x photon detectors and bolometers. Also, this is the region where the general state of technological development is lower, and where novel ideas or approaches arc especial] y needed. The panel judged that progress w ill be limited by ideas (rather than funding) in this regime, and comparatively small initial efforts are recommended. Parallel approaches toward developing long-wave readout technologies are needed. Work from the SIRTF program on stacked S i MOS readouts should be continued. When Ge:x IBC detectors appear to be sufficiently mature, work on a companion army-con, npatible readout technology must start (or have been underway, at a low level).

Bolometer arrays require coordinated development of the absorber/dlcrmome.tcr detector clement and the readout or preamplifier. Promising approaches for both should be supported. There arc presently a number of very interesting superconducting bolometer concepts which appear to bc suited to array construction; the most promising of these should be supported. When promising superconducting detector elements have been demonstrated, one should then couple them to SQUID readouts for an integrated array demonstration. Additionally, some further advancements in Si or Ge semiconductor bolometer array technology appear to be feasible. This would build directly on the advances made on the SIRTF and AXAF projects. As with the other technology subareas, a downselection must be made after a few years, so that resources and talent can be concentrated on the most promising technologies.

# 3. PHOTON COUNTING DETECTORS

## 3.1. Technology assessment

For future missions requiring very low read noise, and most especially for systems operating at the shorter IR wavelengths, an effective strategy is to develop photon-counting detector technology (see Table 7). This approach could provide essentiallynoiseless detection of individual photons, with inherently digital readout. The Si:As Solid-State Photomultiplier (SSPM) is an emerging technology, capable of photon counting, but its peak response is at much longer wavelengths than desired for deep observations in the 3 μm "window", where background radiation reaches a minimum. The panel recommended that phoLon-sensitive devices for the 1-5 μm range, with the necessary electronic readouts, bc developed. A promising approach is to explore various bandgap-engineered device concepts, which in theory could have wide spectral coverage. A parallel approach is to improve the ability of existing Si:As SSPM device technology to detect <5 μm photons. Another approach, particularly for the near term, is to pursue detectors which have high inherent gain. In this case, a detector gain (of perhaps $10^2$- $10^3$) would allow one [o read out the detector with normal analog electronics, eliminating pulse height discriminators, counting circuits, etc. This route would have the advantage of simplicity, particularly for large arrays.

For wavelengths between about 5 and 28 pm, the development of Si:As SSPM detectors should continue, with support focused on optimizing performance and demonstrating a workable readout concept. With continued advances in Si:Sb IBC devices, it was recommended that an SSPM version of this detector, which would provide spectral coverage out to 35-40 pm, should be pursued. In a similar way, it was also suggested that a Ge:Ga version might eventually be investigated, if and when if a mature basic Ge:Ga IBC technology is proven.

Table 7. Photon-Counting Detectors - Technology Assessment

| State-of-the-Art Technology | Key Components & Desired Level | Promising Technologies | Pros | Cons | Type of |
|---|---|---|---|---|---|
| 1 - 5 µm (non-optimized) Si:As SSPM QE~1% | 1 - 5 µm photon counters & readouts | Small-bandgap superlattices (III-V, II-VI) | Possibly higher operating temp-erature and lower leakage | Unproven « _ » 1 " | - - + |
| | | Improved Si:As SSPM for 1 - 5 µm | Demonstrated at longer wavelengths | Unproven | |
| 8 - 28 µm Si:As SSPM QE -30% T ≤ 8 K | 5-30 pm photon counters & readouts | Si:As or Si:x SSPM and hybrid readout | Detectors demonstrated | Readout still immature | LB |
| >30 µm (none) | >30 µm photon counters & readouts | Ge:Ga SSPM (presuming success in Ge:Ga IBC technology) | Wider spectral coverage | Ge IBC not yet mature | LB |

## 3.2. Development plan

Recalling that high-resolution instruments will provide low backgrounds to detectors even on moderate-background telescope systems, development efforts for photon counters should begin right away. As with the previous area, a number of parallel development efforts are recommended, each of which was judged to be moderate in scope. Except for the matter of a readout for the SSPM (which is funding-limited), projects irr this area were judged to be idea-limited.

The program for <5 pm should support initial efforts in small-bandgap superlattice devices, where somewhat speculative but potential] y superior approaches were disc ussed. In parallel, work on a short- wavelength-optimized S SPM is recommended. For >5 µm sensing needs, the SSPM is clearly the recommended approach. Continued development of the Si:As SSPM is clearly appropriate, and an Si:Sb version of the SSPM would also be useful. In time, development of a Ge:Ga SSPM might be considered. The recommended approach would involve concentration on the performance of the unit cell detector, and then a very small array, and then incrementally larger arrays.

# 4. HIGHER-TEMPERATURE 10 µm ARRAYS

## 4.1. Technology assessment

The moderate-background missions (e.g., LTT, II, and NGST) include the requirement for coverage extending into the thermal infrared with large format arrays. The initial requirements also discussed detector temperatures in the range 70- 100 K, the temperatures onc could expect to reach in a pmsivcly-cooled systcm. The panel assumed that the basic design drivers for these missions were simplicity and low power consumption, and that the plan included the usc of relatively simple closed-cycle coolers to augment this passive cooling.

Presently, HgCdTe detectors arc available which arc optimized for moderate and higher backgrounds and operating temperatures in about the 60 - 90 K range (1'able 8). High- performance Si:As IBC detectors are also available, but these require cooling to about 12 K or lower. None of the emerging bandgap-engineered technologies, including multi quantum well (QW) detectors (GaAs/GaAlAs), HIP approaches (SiGe/Si and GaAs/AlGaAs), and narrow-bandgap type-II superlattice architectures has yet shown sufficiently low leakage current at liquid nitrogen temperatures, but this limitation is not predicted to be fundamental, and may yet be overcome.

The prime development opportunity identified was that of adapting the heavily-funded 10 µm HgCdTe technology base for somewhat lower temperatures. HgCdTe detectors (1 O pm) arc now thermally limited at temperatures of 90-100 K; higher sensitivity could be achieved by cooling to 30 -40 K. At this temperature, one would anticipate coupling a background-limited HgCdTe detector to a relatively efficient and reliable cooler technology (e.g., two-stage Stirling-cycle cooler). Also, 'l'able 8. Higher-1'emperature 10pm Arrays - Technology Assessment

| State-of-the-Art Technology | Key Components & Desired Level | Promising Technologies | Pros | Cons | Type of Mission |
|---|---|---|---|---|---|
| '1 - 10 μm HgCdTe PV<br>QE - 80%<br>T = 40 - 60 K | L-Ow-leakage intrinsic or intrinsic-like arrays<br>QE - 50%<br>T = 70 - 100 K | 10pm PV HgCdTe | Large technology base | Unproven below 50 K | MB |
| | | Small-bandgap type-II superlattice detectors | Tailorable cutoff | Early stages of development | |
| | | Quantum well, HIP detectors | Tailorable cutoff | Non-normal incidence. low QE | |

small-bandgap superlattice technology may well provide good solutions in this area. The technology of III-V strained superlattices is relatively new, but it could in principle produce devices which arc lower in leakage and which operate at a higher temperature than HgCdTe detectors with comparable spectral coverage and sensitivity. QW and HIP devices could also be refined and optimized for astrophysical requirements in this area. They offer the advantages of tailorable spectral response, but in present form have limited quantum efficiency, QW detectors arc also awkward to incorporate in systems, since they require non-normal incidence of light.

### 4.2. Development plan

Support of a number of parallel research and development projects is rccommcndcd in this area. The kcy approaches recommended for initial support [adaptation of HgCdTe detectors for -30 kelvin (or higher) operation, and development of the small bandgap superlattice] build upon present activities. Because of this, the judgment was that initial progress would be limited by funding, rather than by ideas.

## 5. L ONG-WAVE IBC DETECTORS

### 5.1. Technology assessment

Ge IBC detector technology was recognized to potentially offer a number of significant advantages for space astronomical applications (Table 9). As with Si:As IBC detectors, Ge IBC devices have very thin optica[ly-active layers, and hence diminished radiation susceptibility. One expects that large-format, low-crosstalk arrays can be built from these devices, and that their response will be more linear and well-behaved than that of bulk photoconductors. Presently, Ge IBC detectors have progressed past proving basic feasibility, and have demonstrated quantum efficiencies approaching those of bulk Ge:x photoconductive detectors. Ge IBC detectors require temperatures around 1.5 K, to suppress dark current for SIRTF-t ypc applications. The limiting factor in this activity is Ge processing technology, which must in part be relearned and in part be developed for the first time. NASA-sponsored efforts arc now focusing on producing a backside-illumirmted Ge:Ga structure with epitaxial layers for both blocking and IR absorption. A parallel development has produced boron ion-implanted Ge IBC structures. While achieved Ge:B IBC quantum efficiencies arc well below a percent, the devices have been fabricated with only a very thin (-1000 A) IR active layer.

Similarly, continued development of Si:Sb IBC detectors is recommended. This technology draws on the relatively well-established Si:As IBC technology base, and should offer the advantages which have been proven in Si:As. Si:Sb IBC detectors and arrays arc important for SIRTF, and for future missions, since it would provide a bridge between 28 and roughly 40 μm, where Ge:x detectors suffer from poor response due to lattice absorption.

### 5.2. Development plan

The panel strongly endorsed continued development of Ge IBC detectors. They could be applicable to a wide range of future missions, and their simple structure and radiation hardness could allow major engineering simplifications in focal planes. Work should continue to focus on Ge cpi-layer and ion-implantation technology. In the panel's opinion, it is very important to maintain support for multiple approaches in this area. The panel fcit that progress will be idea-lirnitcd, at least in the near-term. Continuation of development is also strongly recommended for Si:Sb IBC detector arrays. As the characteristics of the

Table 9. Lang-wave IBC Detectors - l'ethnology Assessment

| State-of-the-Art Technology | Key Components & Desired Level | Promising Technologies | Pros | Cons | Type of Mission |
|---|---|---|---|---|---|
| 40 - 200 μm Ge:Ga "bulk" IBCs and early epi IBCs QE - few % T < 1.5 K | Ge:x IBC arrays with QE -30% | Epitaxial-layer Ge:Ga IBC detectors | Linear response, radiation hard, array compatible, low crosstalk, simple structure | Processing problems “ | LB, MB, SMIM |
| | | Ge:B ion-implanted IBC detectors | Same as above Low leakage | Low QE? | |
| 10 - 36 μm Si:Sb IBC discrete devices, Cutoff -36 μm | Si:Sb IBC arrays with QE ≥ 30% | Epitaxial-layer Si:Sb IBC detectors | Si:As IBC heritage, advantages of IBC structure (see above) | Arrays not yet proven | LB, MB |

first epi-produced detectors and unit cell structures arc understood, progressive steps to small- and mocieratc-scale arrays should be taken.

## 6. READOUT ELECTRONICS

A separate panel considered readout electronics needs and approaches.[3] The following comments from the Direct Detector Panel represent a subset of the overall needs. These remarks are focused on particular needs of the direct detector area.

### 6.1. Technology assessment

In the readout area, general requirements for direct detectors include the need for low-noise devices, circuits resistant to the radiation effects encountered in space, low power dissipation (to simplify cooling requirements), and large well capacity for systems operating with significant background levels. An assessment of the readout electronics problem is presented in Table 10.

Table 10. Readout Electronics - Technology Assessment

| State-of-the-Art Technology | Key Components & Desired Level | Promising Technologies | Pros | Cons | Type of Mission |
|---|---|---|---|---|---|
| **For T > 20 K** Si MOS discrete FETs ~4 $e^-$ read noise | Si FETs 1 $e^-$ read noise | Si MOS | Si maturity | Onset of freezeout | MB, SMIM |
| | Stable-bias circuits | MOS TIA & other innovative concepts | Si maturity | Power dissipation? | LB, MB, SMIM |
| **For T < 20 K** Si MOS array -50 $e^-$ read noise | Si FETs 1 $e^-$ read noise @ 4 K | Si MOS | Si maturity, SIRTF heritage | Onset of freezeout | LB |
| | Non-Si FETs 1 $e^-$ read noise | GaAs, Ge, InSb, etc. | Superior predicted low-T properties | Immature technologies | Post-SIRTF, LB |
| **For Bolometers** Si JFETs Noise ≈ few nV/√Hz @ 40 K No mux | Bolometer readout & mux | Isolated Si, GaAs, superconducting devices, etc. | Optimized performance possible | Immature technologies | LB, MB, SMIM, LDR |
| **Photon Counting** **None** | Photon counter readout & mux | Si MOS, GaAs & other innovative concepts | Digital data chain, low power | Immature technologies | LB |

The future mission set includes a number of projects which call for 1 e⁻ rms read noise levels. Data on a Si cascode FET circuit (~4 e⁻ input-referred read noise) have recently been obtained. This would indicate that the 1 e⁻ goal may be within reach, since this device has not yet been optimized. However, this device presently requires operation above the Si freezeout temperature of about 20 K. For large arrays, read noise of about 30 e⁻ has been achieved on the 256 x 256 NIC HgCdTe (2,5 μm cutoff) hybrid arrays, at 60 K. For extrinsic silicon arrays and temperatures in the 4- 10 K range, read noises at and below the 100 e⁻ level (for> 1 s integration times) have been measured. The best non-Si low temperature readouts appear to be those in GaAs, which are capable of read noise in this same range, in discrete devices or small arrays. Selected Si junction field-effect transistors (JFETs) presently provide relatively good performance, but require operation at elevated temperatures (40 K or above) to run reliably.

To meet the 1 e⁻ goal for readout electronics, the panel recommended continued work with Si metal-oxide-semiconductor (MOS) technology, based on good progress to date, and the high state of sophistication of silicon processing. One branch of Si MOS technology development is for elevated-background applications, where operation at temperatures above freezeout is quite acceptable, and where read noise would not need to be especially low. Another branch would be for low-background applications, where low-noise, low-dark current would be sought with Si MOSFET readouts at temperatures down to the 1.5-4 K range. To meet the stable, low bias requirements of long-wavelength IR detectors such as Ge:Ga IBCs, it was suggested that feedback circuits such as the capacitive-feedback trans-impedance amplifier (CTIA) held promise. Recent data at higher temperatures indicate that these readouts could be successfully operated at reduced (e.g., 100 nW/channel) power levels. Long-wavelength readout circuits would typically not have to have many channels, since the desired array formats are smaller. To supplement these approaches, and to reduce the influence of carrier freezeout, innovative FET development ideas in alternate semiconductor materials such as GaAs, Ge, InSb, or others should be supported for longer term requirements.

Advances in bolometer development are presently limited by readout technology. The pressing requirements are for a low-noise FET which operates at or near the bolometer temperature, and for a credible bolometer multiplexing scheme. To meet these needs, it was suggested that novel concepts in Si (e.g., small FET structures produced on thermally- and electrically-isolating oxide layers) and other semiconductors be explored. Also, superconducting readouts may be particularly well-suited for applications "with bolometers.

Development of photon counting detectors with significant internal gain would relieve the need for very low-noise readout circuitry. To take full advantage of these detectors, which give an output pulse for each photon detected, the readout circuit should be able to operate as a digital counter. This avoids analog readout and the significant power levels associated with analog-digital conversion. The design of compact unit cells to couple to photon counting detectors, and of circuitry for multiplexing of arrays, has not been very well explored. The panel recommended that, in conjunction with work on photon-sensitive detectors, development of the associated readouts be vigorously pursued.

The panel concluded that for astronomical applications sophisticated on-chip data processing was not a requirement, It is expected that investigators will continue to want the maximum amount of flexibility to analyze and correct their data for unanticipated effects encountered in space. Only modest amounts of data compression might be required.

## 6.2. Development plan

Given the long string of astrophysics missions, and the central importance of readout electronics to overall detector/array performance, the panel recommended a long-term, steadily supported program to explore and develop a number of important technologies. Since moderate-background missions tend to dominate in the near-term, the strategy should be to emphasize approaches which satisfy these requirements. However, the program must also provide for support of longer-range needs as well, since these will require concerted effort over longer time scales to be successful, and development of the two classes of electronics will tend to support each other.

The panel recommended support for improvement of silicon MOS readout technologies, for applications both below and above the ~20 K freezeout temperature. For low-background, low-temperature applications, additional development of both the geometry and composition of the unit cell transistors, and the circuits in which these are used, is needed. In parallel, Si MOS circuits should also be pursued for the elms of higher-temperature moderate-background applications, which generally come sooner in the mission set, The design of these Si devices would likely be different than that of the low-temperature versions, since they do not need to operate in such extreme environments or to such challenging performance levels. Falling largely, but not exclusively, under the Si electronics category is the need for circuits which provide 10W, stable bias to detectors. These requirements could ultimately be folded into readout development projects after the basic unit cell performance is demonstrated.

Support should also be given to the recommended non-silicon readout concepts. NASA should monitor the efforts in GaAs and Ge and other materials systems presently underway in industry and universities, and where appropriate, set up projects which leverage this work. One should start with small exploratory efforts, which could be scaled up as feasibility is successfully demonstrated.

To meet the need for improved bolometer readouts, efforts should initially focus on achieving lower noise ($\leq$1 nV/$\sqrt{Hz}$) with minimum power dissipation. The operating temperature of these readout electronic.s must be lowered from the -100 K presently needed for best Si JFET performance. These high temperatures presently drive cryogenic designs, and require that FETs be totally shielded from Lhe view of the highly-sensitive far-IR bolometers. This program should initially support at a modest level a number of promising approaches from the various Si and non-Si semiconductor options.

Support is recommended for exploring concepts for readouts and multiplexers for photon counting detectors. Solutions to the various functions can potentially be implemented in various materials. Initially, support should be given to a number of innovative approaches; later, the most promising ones should be funded for the development of larger array-scale structures.

In all readout areas, the viability of the selected concepts should be demonstrated at the individual device level first. Only after careful and thorough demonstration of performance on this scale, or possibly up to the level of small (e.g., <20 elements) arrays, demonstration models of progressively larger arrays should be built and tested. In the course of development, as larger and larger structures are built and tested, readouts must be coupled to detector arrays and evaluated as complete focal planes.

## 7. ADAPTING SIRTF AND HST TECHNOLOGY BASE

In many cases, the technology options discussed above have their roots in the IRAS, SIRTF, and second-generation HST technology development programs. These were highlighted in Tables 1-4. Future missions must effectively utilize both the state of device technology and the body of operational expertise which have been built up for direct IR detectors in astronomical applications. A range of technologies is now approaching a comparatively advanced state of development, particularly for very low background applications. There is a need to reevaluate and reoptimize these technologies for future missions, which typically involve backgrounds which are orders of magnitude higher, and/or higher detector operating temperatures. Note, however, that moderate-background missions will likely include high-resolution spectroscopic instruments, which will operate at very low backgrounds, comparable to those of SIRTF. These instruments will directly benefit from the SIRTF technological heritage.

The panel recommended that a study and test program be set up to reevaluate and reoptimize this technology. The costs of recharacterizing and reoptimizing SIRTF / NIC technology would only be moderate, and NASA would be able to preserve and exploit its sophisticated technological heritage in this area. One should first pursue those aspects of the SIRTF / NIC technologies which are most applicable to the near-term, moderate-background missions. It is also important to start early on longer-term projects, to assure that techniques are not lost, and to begin efforts to meet very challenging future requirements. In this recommendation area, one should utilize the existing characterization facilities and expert personnel to the greatest possible extent. It would also be reasonable to support grounci-based, bailoon-borne, and airborne astronomical demonstrations as a means of characterizing SIRTF **and** HST detector technology under higher background conditions.

## 8. OTHER ISSUES

Discussions within the panel also touched on other general development issues, It was noted that the long-wavelength IR detector development community is small, and that progress is paced by the expertise and availability of a few key individuals. Additionally, there appeared to be room for improvements in the long-wavelength base technology. While important advances have been made on a number of fronts, limited resources have meant that some aspects of the technology have not received recent attention. An example is in the area of Ge:x detector material, where the best available boule of Ge:Ga, one now being reserved for possible use in SIRTF flight detectors, was produced *24 years ago*. An element of future support in this area should be support for critical individuals and institutions.

Throughout the infrared, but especially for wavelengths beyond 30 μm, there is a need for novel ideas and approaches. In some cases, bulk semiconductor technologies may be reaching limits. Emerging technologies, such as those in the general area of bandgap-engineered layered structures and superconducting (both low-$T_c$ and high-$T_c$) de.vices, hold promise as a means of meeting the stringent requirements of the future mission set.

Progress in developing IR detector technology is often limited by one's ability to accurately characterize the latest devices. This applies both at the device level (where, for example, novel equipment and approaches are needed to characterize Ge IBC cpi layers) and at the integrated detector or detector array level. A very important means of proving the technology, and of uncovering subtle effects that may remain hidden in the laboratory, is through ground-based, balloon-based, and airborne observing. An example is the discovery of "ghost images" in earlier InSb arrays, which were only discovered when they were being used in an observational program. Support for all of these aspects -- improved device and focal plane characterization tools, and support for demonstration testing on telescopes -- is recommended.

## 9. SUMMARY

In developing recommendations for future direct IR detector technology development for astrophysics missions, a wide range of technological options was considered. The panel judge.d that the problems of very large array formats, and of very low-noise readout electronics, were the most challenging. The recommendations of the panel include a desirable mix of technologies which are evolving from IRAS, SIRTF, and second-generation HST, and "also novel, more speculative technologies which may pay large dividends in the long run. While there arc some aspects of the necessary NASA developments which will benefit from other government or industrial programs, these. arc very limited.

## 10. ACKNOWLEDGMENT

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