Development of Large Format Far-Infrared Detectors

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Abstract

Several far-infrared (30 to 300 μm) astronomy missions and/or instruments will be proposed for the next decade. Many important astrophysical processes have signatures at these wavelengths: the peak of the spectral energy distributions of protostars and ultra-luminous galaxies falls near 100 μm; there is a wealth of biologically interesting spectral lines to be found in this range, and lines such as the 158 μm line of singly ionized carbon are important for the energy balance of the interstellar medium in our own and in external galaxies.

The promise of a new generation of large format far-infrared detector arrays seems to be attainable, but getting there will require a focused development program with enough resources available to allow exploration of several paths. Development must be encouraged if we are to maximize the scientific return from future far-infrared missions.

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1 Introduction

Whenever humans find a new way of looking at the Universe, a revolution in our understanding of the Universe ensues (*e.g.* Figure 1). Remote sensing using the electromagnetic spectrum is our primary means of exploring the stars and galaxies, and for much of that spectrum, we have well-developed, highly sensitive detectors. However, with perhaps the exception of detectors for the very highest energy gamma rays, far-infrared detectors lag significantly behind all other types, and as a consequence, this wavelength range is comparatively little explored.

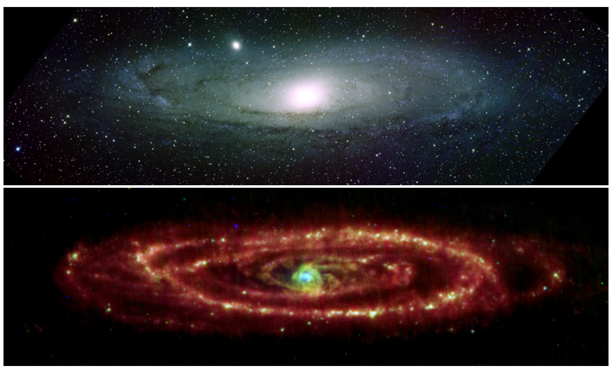

Figure 1: Visible (0.4–0.7 μm) and far-infrared (24–170 μm) views of the Andromeda Galaxy; the far-infrared highlights the areas of active star formation within the spiral arms. Such discrete rings had not been previously anticipated.

In 2002, the Astronomy and Physics Division of NASA's Office of Space Science chartered the Infrared, Submillimeter, and Millimeter Detector Working Group (ISMDWG) to produce a roadmap of detector developments needed to attain the scientific goals of missions defined in the various long-range plans then being assembled. This group surveyed a wide range of technologies covering the 1 μm to 10 mm wavelength range and made specific recommendations for the continued development of these technologies. The past decade, however, has seen comparatively little growth for detectors at wavelengths longer than 5 μm due to funding limitations and focus on other technologies, and therefore, *the recommendations of that report are as valid today as they were in 2002.* (Please see `http://safir.gsfc.nasa.gov/docs/ISMDWG_final.pdf`.)

In this paper, we describe the progress that has been made in spite of that limited funding and outline some of the more promising devices that might be brought to a Technology Readiness Level (TRL) of 6 within the next 10 years. Since there will be several other white papers describing advances at both the shorter and longer wavelength ranges of the ISMDWG report, we restrict this paper to direct photon detectors within the wavelength range of 30 through 300 μm. We follow the relatively standard astronomical terminology of "near-infrared" as being 1 to 5 μm, "mid-infrared" 5 to 30 μm, and "far-infrared" 30 to 300 μm, and therefore our focus is on far-IR detectors, along with some issues that also concern the mid-IR.

1.1 Science motivation

For a number of fundamental reasons, observations in the far-infrared are required to get a complete picture of many astronomical phenomena. The extinction and emission from cool dust, the cosmic expansion, and the wavelengths of important spectral features have combined to make observations at these wavelengths essential to the modern mix of astronomical capabilities. In particular, two of the most exciting areas of current astronomical research, the formation and evolution of galaxies and the formation of stars, depend heavily on observations at these wavelengths.

The importance of these wavelengths was highlighted over 20 years ago by the Infrared Astronomical Satellite (IRAS), which detected numerous infrared-luminous galaxies in the local universe. IRAS showed that there was a population of IR luminous galaxies that emitted the bulk of their luminosity at far-IR wave-

Table 1: Some Key ISM Diagnostic Lines

Lines	Wavelengths (μm)	Diagnostics
[C II] [O I]	158 63 & 146	PDR Parameters, interstellar radiation field, and density
[N II] [O III]	122 / 205 88 / 52	Line pairs yield gas density
[N II] / [N III]	205 / 57	Hardness of radiation field
[N II]	205	Ionizing Flux
[N II] / [C II]	205 / 158	Fraction of [C II] arising in ionized regions
[N III] / [O III]	57 / 52	Evolution of Abundances

lengths, with a spectrum peaking there. This behavior is not unusual: most of the energy of nearby galaxies undergoing active star formation emerges in the far-infrared part spectrum. Subsequent studies with ISO and Spitzer have only strengthened this picture. The next generation of facilities will have the sensitivity and angular resolution to permit the detailed study of the emission regions in external galaxies.

The transformation of the interstellar medium (ISM) into stars and the subsequent return of the material into the ISM is the fundamental process in the evolution of galaxies. For the study of both the Milky Way and external galaxies, spectroscopy in the far-infrared will be essential in understanding the mechanisms in play. Emission lines from gaseous species reveal the physical and chemical conditions, are the sole tracers of dynamics, and are the primary coolants of the ISM (Table 1).

The most important of the interstellar cooling lines is [C II] at 158 μm. It is the dominant emission line of the interstellar medium, and it plays a key role in the conversion of neutral atomic gas into molecular clouds. Unlike the well-observed 21 cm line of atomic hydrogen, [C II] preferentially selects clouds rather than the more diffuse Warm Neutral Medium. As is the case for the Milky Way, the [C II] line is the brightest line in most star forming galaxies, and can have a luminosity that is 10^{-3} to 10^{-2} of the total far-infrared luminosity. To support a future generation of advanced far-infrared spectrometers, large, sensitive detector arrays will be needed.

One of the outstanding issues in star formation is the exact role of magnetic fields. The fields appear to play a role in supporting some clouds from collapse, but the relative importance of magnetic fields in determining fundamental properties like the timescale of collapse or the initial mass function is the still the subject of much debate. Far-infrared polarimetry is one method of directly assessing the importance of magnetic fields in molecular clouds. At long wavelengths, the scattering efficiency is very low, and the polarized flux is due to dichroic emission from aligned grains. Polarimetry is a challenging observational technique, requiring careful attention to systematic effects. Large array detector systems will enable much more sensitive observations than are possible with current systems.

1.2 State-of-the-art

For mid-infrared wavelengths, arsenic-doped silicon (Si:As) blocked impurity band (BIB) arrays are by far the most mature, and the WISE and JWST/MIRI instruments/missions have pushed these arrays to megapixel levels. (Both are 1024×1024 pixel arrays, but from different vendors.) In comparison, the 128×128 pixel Si:Sb BIB arrays for the Spitzer Space Telescope have advanced only modestly to 256×256 format for the FORCAST instrument on SOFIA, and the Spitzer Ge:Ga photoconductor arrays have 1024 pixels total (32×32) at 70 μm and 40 pixels (2×20) at 160 μm and are still amongst the largest, even though they were built in the 1990s [1, 2].

More recent far-IR arrays are to be found on Herschel/Planck and Akari, but these are no larger than the arrays on Spitzer. On Herschel's PACS instrument, there are two 25×16 Ge:Ga arrays, one stressed for longer wavelength response (to 200 μm), and each is built up from twenty-five 1×16 pixel modules [3].

Akari also has stressed and unstressed Ge:Ga arrays; unstressed arrays include a 20×2 and a 20×3 arrays, while the stressed detectors use 15×3 and 15×2 arrays [4]. Akari also uses two 256×256 Si:As detector arrays for mid-infrared coverage.

1.3 General Considerations

For large format ($\gg$ 10,000 total pixels) detectors to be viable, two components are required: a detector layer where the incoming photons are converted into electrons and are constrained to a discernible 2-D location, and a multiplexed cryogenic readout circuit to measure the charge or current associated with those locations. But of equal, and sometimes greater, significance is the method of packaging these two components. Some means of mating them, cooling them, and mechanically supporting them are required if we are to wrap a scientifically useful instrument around them. (*Note: more details of the detector and readout architectures discussed in this paper, including the terminology used, may be found in George Rieke's Annual Review of Astronomy and Astrophysics paper [5].*)

In the following sections, we outline some of the technologies that we believe show the greatest promise of enabling large format far-infrared arrays within the coming decade. It is not meant to be exhaustive or exclusive; but rather, to illustrate some of the potential developments if the field of far-infrared detectors are given a focused funding opportunity.

2 Detectors

2.1 Si:Sb BIB Detector Arrays

Si:As BIB detectors are highly successful mid-IR astronomical detectors that approach theoretical performance for wavelengths from $\sim$ 5 μm up to a cut-off wavelength near 28 μm. Substitution of antimony for arsenic doping has resulted in a BIB detector with the cut-off extended to approximately 40 μm. This Si:Sb BIB detector variant, while successfully deployed in the Spitzer Space Telescope and the SOFIA FORCAST instrument, has not yet achieved the excellent QE performance of its Si:As sibling. The performance deficiency of Si:Sb (as much as 50%) is understood as a consequence of the comparative imperfection of the base Si:Sb material and layer structure versus Si:As.

Methods being investigated for improvement of Si:As detectors can be expected to largely remove the performance deficit for Si:Sb detectors as well. These methods include the use of highly purified source chemicals for the basic doped silicon detector layer growth via chemical vapor deposition (CVD) and the modification of the detector layer growth process to facilitate substrate removal and application of the common detector-array backside electrical contact after front-side pixel processing has been completed. These changes result in a fully depleted (fully active) detector with little or no absorption of incident light before it reaches the active layer. Implementation of these new approaches would allow the development of improved Si:Sb arrays in the current 1024×1024-pixel format available for Si:As detectors.

2.2 Development of Germanium-based BIB Detectors

As mentioned above, silicon-based BIB detectors doped with arsenic and antimony have are the materials of choice for astronomical detectors at wavelengths from 5 µm to 40 µm. Several attempts have been made to provide a similar direct detector technology for operation in the far-IR by switching from silicon to a semiconductor material that would provide a shallower impurity band [6, 7]. Both germanium-based and gallium arsenide-based systems have been attempted, with greater success achieved in germanium. Figure 2 shows the response of one such prototype device.

2.2.1 CVD growth of Ge BIB Detectors

The main difficulty with producing long-wavelength BIB detectors is the extreme degree of dopant control needed. The "blocking layer" of the device needs to be of exceptional overall purity (probably less than 1×10^{12} active dopant atoms per cm^3), while the "infrared active layer" must be precisely and heavily doped with only one type (p-type or n-type) species. In the past, epitaxial crystal growth techniques failed to meet these requirements. However, it may now be possible to overcome the main difficulties of previous attempts. The same techniques discussed above for improvement of Si:Sb detectors can be applied to the growth and processing of high quality germanium-based BIB detectors layers. Furthermore, the current silicon BIB detector processing facilities, which are customized to avoid contamination of ultra pure BIB detector material during processing, can, with care, be utilized to fabricate Ge BIB detector arrays from improved Ge BIB detector layers.

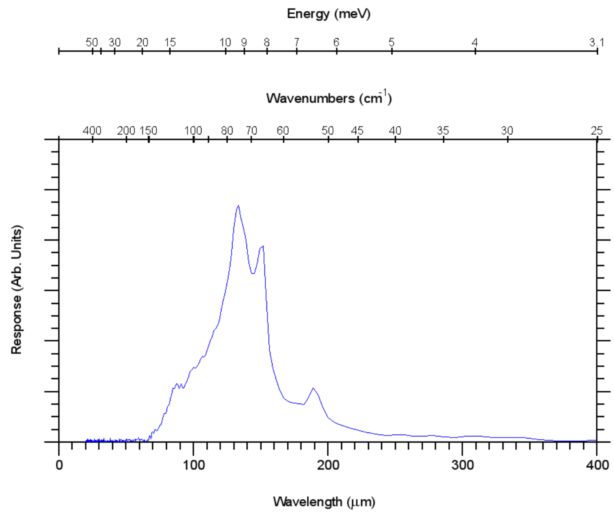

Figure 2: An ion-implanted boron-doped Ge BIB detector. This device demonstrates low responsivity (since the IR-absorbing layer is formed by a shallow ion implant), but clearly shows an extended wavelength response compared to the 120 µm long wavelength cutoff of unstressed Ge:Ga. (Plot from data in [8].)

2.2.2 The Ion Implant Passivated Ge BIB

There is a real possibility that the required purities will be unattainable with CVD growth techniques. However, such purity is possible using bulk germanium crystal growth techniques (less than 1×10^{10} cm^{-3} is possible!), but then it remains essentially impossible to produce a layered BIB structure via that bulk growth. There is a *lesson* from bulk crystal growth that might carry over to fabricating Ge BIB detectors, however.

Ge crystal growers have known for some time that residual aluminum contamination in the Ge starting material can yield an undesirably high level of electrically active acceptors. It has been found, however, that a small amount of oxygen, introduced into the growth ambient, serves to neutralize the electrical activity of the aluminum [9]. The aluminum is not removed during this process, rather it is passivated through chemical bonding with the oxygen, which localizes the electronic hole state that would otherwise be available to the Ge valence band. The result is a crystal with extremely high electrical purity, suitable for the most demanding applications such as diode-based gamma ray detectors, etc.

The "passivation BIB" (P-BIB) concept relies on oxygen passivation as well, but in a limited and directed fashion. Starting with a Ge crystal that has been intentionally aluminum-doped at modest levels, one could prepare an optically polished wafer of this material and ion-implant oxygen into the surface region at a reasonably high level. The wafer is then annealed, which repairs the implant damage, but more importantly, diffuses the oxygen slightly, allowing it to bond with the Al dopant atoms. Passivation of the Al acceptors by oxygen would cause the formation of (energetically favorable) Al-O chemical bonds and create a neutral ("undoped") layer in the crystal that would behave exactly like ultra-pure Ge. Such a process will create the perfect BIB structure by forming a very effective blocking layer in direct contact with a highly-doped IR absorbing region, in this case, aluminum-doped Ge. Since aluminum in germanium is a shallow acceptor comparable to boron or gallium, any resulting detectors made via this process should demonstrate a similar long wavelength cutoff to a boron-doped or gallium-doped Ge BIB, *i.e.*, 200 µm or more.

2.3 GaAs-based quantum well detectors

An entirely different approach draws on existing, mature GaAs-based quantum well infrared photodetector (QWIP) technology that has been successful at shorter wavelengths. The Quantum Well Intra-Subband Photodetector (QWISP) concept has been proposed which extends the useful detection wavelength range of quantum well infrared detectors into the far-

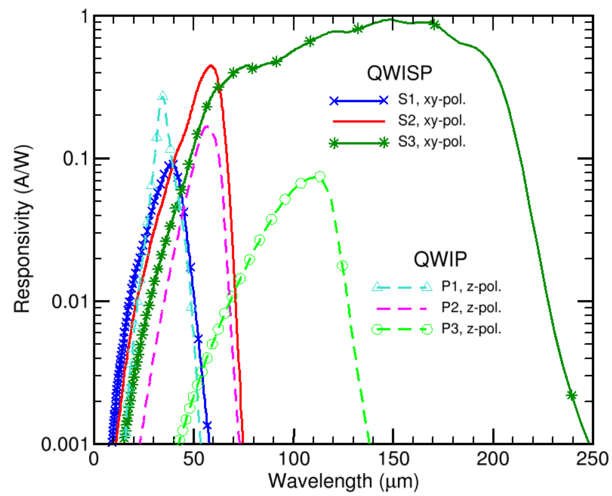

Figure 3: Calculated responsivities for three different structures of far-IR QWIPs (P1, P2, P3) and a set of QWISPs (S1, S2, S3). Note that the QWISP results are for *normal-incidence* radiation, while the QWIP results are for *side-incidence* radiation. The QWIP results should be multiplied by an additional grating coupling efficiency factor (< 1). Plot from [10].

IR [10]. The QWISP uses a GaAs-based structure similar to the QWIP, but with some doping and barrier height differences. This accomplishes two things: it extends detection to longer wavelengths and provides enhanced normal incidence response. (QWIPs work only in non-normal incidence; for focal plane array applications, the QWIPs are coupled to normal incidence light via optical gratings.) Theoretical studies show that QWISP performance improves as the detection wavelength increases past 60 µm, while QWIP performance becomes better as the detection wavelength decreases to below 60 µm. Figure 3 shows the theoretical responsivity of QWISPs as compared to QWIPs. Much like Ge and GaAs BIB detectors, QWISPs are relatively thin structures that lend themselves to forming large arrays and would potentially have similar radiation hardness properties.

The QWISP is a relatively new idea identified thus far only in theoretical studies. However, experimental evidence exists of far-IR intra-subband absorption in modulation doped quantum wells [11]. The QWISP shows great promise, but the usefulness of this technology will only be determined with experimental studies of the feasibility of far-IR detection based on this concept.

3 Readouts

3.1 Readouts for BIB Detectors

The simplest readout unit-cell design is the source follower per detector (SFD), which uses the capacitance at the gate of a source-follower MOSFET to integrate the detector photocurrent. The simplicity of the SFD design is attractive in terms of fabrication, minimal use of electronics real estate, and ease of operation. It also provides the lowest noise signal, and therefore has become the preferred architecture for low-background near- and mid-infrared arrays; the WISE and MIRI Si:As and the Spitzer and SOFIA Si:Sb arrays are SFD designs. It is likely that far-infrared BIB arrays could also use these devices, with some allowances to reduce readout glow by putting the output amplifiers on a second circuit located close by, but not coincident with, the array.

There are deep-cryogenic readouts already available that may be usable for the demonstration of initial large-format Ge-based BIB detector arrays. For example, 128×128 format readouts are residuals from readout development and production cycles leading to the Si:As and Si:Sb FPAs for Spitzer and WIRE instruments. There are also silicon readout foundry processes that can be used to produce readouts suitable for fabrication of future large-format readouts for Ge BIB detector arrays. Both of the current Si:As FPA suppliers have silicon foundry processes that deliver deep cryogenic readouts in 1024×1024 format for Si:As FPAs. In some cases these readouts have been tested for correct functionality and low noise down to ~ 2 K. However, low read noise is much more difficult to assure for deep cryogenic readouts than is functionality. It is generally the case that functionality can be assured by circuit design; however, low noise is greatly influenced by the particular materials and processes utilized in the silicon foundry process.

For this reason, achieving and maintaining a deep cryogenic readout capability is still more Art than Science. Deep-cryogenic performance is achieved by selecting foundry processes likely to remain available for the foreseeable future and ones compatible with circuit designs that have been found to yield good functionality and low-noise operation at deep-cryogenic temperatures. Unfortunately, minor changes to foundry processes (installing new processing equipment and material sources) can have unforeseen negative consequences for deep-cryogenic performance, without affecting the room-temperature diagnostics that the foundry uses to control the process. The only recourse is to exercise the selected foundry process frequently enough to detect deep-cryogenic performance changes and either adapt designs to compensate or move to alternative foundry processes for deep-cryogenic circuits.

3.2 Readouts for Photoconductor Arrays

For low bias voltage photoconductors, the SFD circuit suffers from the inherent drawback that the integrated charge at the MOSFET gate debiases the detector and thereby severely degrades the detector linearity, and possibly the measurable detector photocurrent. A capacitive transimpedance amplifier (CTIA) design offers an effective solution and one that has been successfully used in Spitzer [12].

The CTIA readout utilizes a high gain amplifier with a capacitor in the feedback loop. During the integration time, when the reset switches are open, the photocurrent from the detector accumulates as an integrated charge on the feedback capacitor. By virtue of the negative feedback, the capacitor also pins the detector's input node to a constant voltage, thereby keeping the detector bias constant, regardless of the integrated signal. Other design features can be added such as auto-zero to improve the uniformity across the array, a sample-and-hold circuit to improve the sampling efficiency, and multiple feedback capacitors to allow operation under different background levels. The downside to CTIA is the circuit complexity and that the circuit has to be on all the time, increasing power consumption.

Recently, a 32×32, 2-side buttable CTIA readout has been fabricated (SB349, see Figure 4) [13], and is capable of operating at deep cryogenic temperatures (< 4.2 K). By butting four such readouts together, this design will allow construction of a mosaiced 64×64 array—a suitably large format that can be used for future astronomical instruments. Initial tests have shown that this readout has $> 99\%$ operability and $> 97\%$ uniformity across the array but has excess read noise compared to its one-dimensional predecessors, *e.g.*, the Spitzer-MIPS arrays [12].

To fully exploit the inherent potential of future large-aperture space telescopes, such as SAFIR (Single Aperture Far-Infrared Observatory) [14] and its subsequent design concept CALISTO (Cryogenic Aperture Large Infrared Space Telescope Observatory) [15], array sizes of $\geq 128 \times 128$ are needed. We believe the current 32×32 technology can be expanded to 2-side buttable 64×64 devices, if not a fully monolithic 128×128 readout.

Despite the progress made in the past ten years, readout fabrication for deep cryogenic applications remains the most challenging and most urgent technology development for far-IR photoconductor FPAs. In particular, further study of MOSFET behavior at temperatures below 10 K is needed in order to allow refinement of cryo-CMOS process and eliminate anomalies commonly seen at these temperatures.

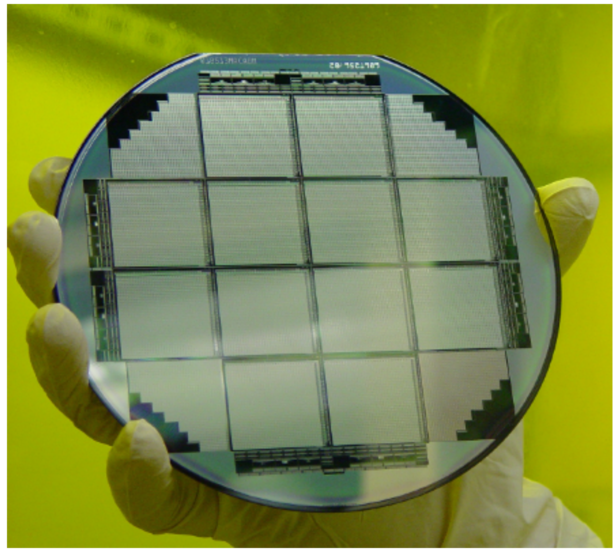

Figure 4: A processed wafer containing twelve 32×32 pixel far-IR compatible readout multiplexers.

4 Structures

4.1 Detector-Readout Integration

For large-format Ge-based or GaAs BIB detectors the issue will arise of managing the relative thermal expansion differentials between the Ge or GaAs detector array and a silicon readout intimately attached to it via indium bump interconnects at each pixel location. Experience in solving this problem for large-format HgCdTe-on-silicon FPAs can be brought to bear on this problem. The general approach is to force the silicon readout to comply in its expansion characteristics to the detector material. This is accomplished by first thinning the readout substrate to reduce the shear forces necessary to

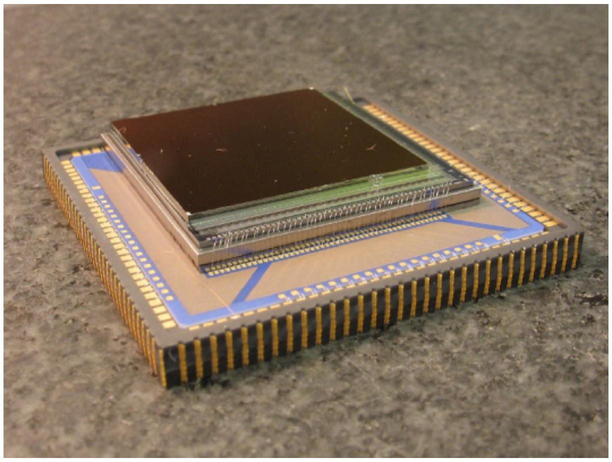

Figure 5: The first standard-hybrid Ge:Sb FPA hybridized to an 32×32 pixel CTIA readout and fully packaged in a 124-pin leadless chip carrier. A composite layer underneath the readout forces the thermal contraction of silicon to match that of germanium.

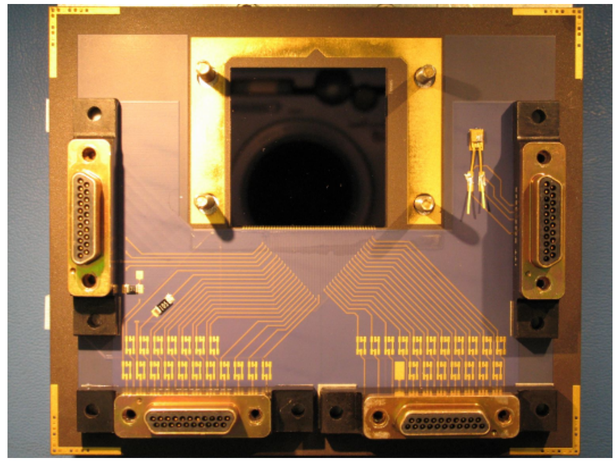

Figure 6: The first fully assembled layered-hybrid Ge:Sb FPA with SB349 readout. Shown is the readout side; the detector is located on the other side of the fanout board.

stretch or compress it, and then underlaying the thin readout with a thick material (or composite) that is matched to the thermal expansion characteristics of the detector array.

An example of this type has been demonstrated as part of the 32×32 Ge:Sb/CTIA focal plane array development [16]. A photograph of the full functional hybrid arrays is shown in Figure 5. However, test results have indicated that this architecture is not generally suitable for far-IR arrays, at least of the CTIA variety, primarily because glow from the readout is sensed by the detector, degrading its performance. For BIB/SFD arrays, which are much lower power, this arrangement may prove adequate, especially if the output drivers can be moved to a "satellite" chip.

A second hybridization architecture is the layered hybrid, where the detector and the readout are separated by an intervening substrate [17]. The goal is to block the readout glow from reaching the detector, provide more efficient heat dissipation, improve temperature uniformity across the array, and mitigate the thermal mismatch between the detector and the readout. In addition, the substrate serves as a fanout board, with multi-layer printed traces and noise suppression capability, providing a simple and robust way to connect the FPA to the external electronics with no additional packaging requirement. Figure 6 shows the fully assembled FPA using the layered-hybrid architecture.

This approach seems very promising and initial tests show that most obstacles have been overcome. This FPA, however, is still under test and will need further development to bring the technology to an acceptable level of maturity.

5 Maintaining the Technology Capability

As was amply noted in the 2002 ISMDWG report, the development and maintenance of sensor capabilities in the far-infrared are purely the province of NASA and/or the astronomical community. There is simply no other customer base. Historically, much of the effort that led to the successful development of high-performance mid-IR focal plane arrays for

Spitzer leveraged significant DoD investment in detector readout technology during the 1980s and early 1990s. Subsequent developments for the upcoming WISE and JWST/MIRI instruments have shown that key US industrial base for these devices is now quite tenuous, and has become increasingly vulnerable with NASA's decided turn away from investment in fundamental technology development programs in favor of other priorities.

Arguably, the success of Spitzer has undermined future mid-IR and far-IR missions by creating an impression that readout technology is highly mature and readily available, making continued development efforts harder to justify in the view of NASA Program Mangers facing tight budgets. In fact, industrial capability dipped significantly following Spitzer, as evidenced by the 7-year investment required for the JWST/MIRI detector development to reach a comparable performance level, and by the significant reduction in sensitivity in the WISE mid-IR focal plane, compared to Spitzer. The gains won back through MIRI's development will certainly be lost if no sustaining investment is made in advancing readout technology, putting at risk the maturation of Si:Sb BIB systems, which represent the closest thing to "low hanging fruit" in extending mid-IR technology further into the far-IR with sensitivity to 40 μm.

Extension of the specialized deep-cryogenic electronics that enable mid-IR astronomy is crucial to the far-IR, where even lower operating temperatures are required. Existing SFD readout architectures may be good to about 40 μm with appropriate detector materials, but extension to longer wavelengths means adapting to lower-bias detectors requiring a constant-bias linear input stage such as a CTIA. These circuits have been implemented in modest formats, but lack the maturity and performance track record of SFD devices. Continued investment is required to bring readouts for larger-format far-IR arrays to sensitivities achieved in the mid-IR.

NASA's ROSES program provides a mechanism for funding low-TRL detector and readout development, but the typical size of a ROSES grant is insufficient to support low-volume commercial VLSI circuit development with the unique process modifications required for operation at deep-cryogenic temperatures. Very few large firms are willing to provide subsidies from IRAD funding as NASA curtails its own technology development budget, and smaller firms are unable to participate due to high costs. As noted in the ISMDWG report, funding for more complex mid-TRL development is outside the reach of a ROSES grant, and no other funding mechanism exists to bridge the gap so that new technologies can become serious candidates for application in flight missions.

Simply assuming that detector technology will be available when needed will lead to disappointments (and potentially unsuccessful missions). Continued neglect of basic technology development in this area will hinder competed and strategic mission opportunities, and exciting science discoveries will therefore be lost. These new sensor technologies must be moved from promising ideas to established, high-TRL tools for astrophysics.

6 Recommendations

Interest in the far-infrared region of the spectrum is unique to the astronomy community. But despite the difficulties, far-infrared studies are absolutely essential in understanding basic phenomena such as star formation and the formation and evolution of galaxies. A number of promising technologies are within reach to enable these studies if a strong and focused development program is available; these technologies include those discussed in this paper such as the Ge and GaAs BIB detectors and their associated deep-cryogenic readout technologies. Despite the sparse development effort to date in this area, some progress has been made, and a number of worthy new ideas have been generated. When compared to the much more established technologies in the silicon industry from which Si BIB detectors have benefited, we are still in the earliest stages of development. We can expect that a modest investment in these technologies now will have a comparatively large payoff in the future.

Indeed, in these resource-constrained times, an investment in far-infrared detector technologies is perhaps the most cost effective use of funding. The expenditure of a few million dollars here will result in several orders of magnitude improvement in observing speed due the higher sensitivity and larger area coverage of these detectors. A notable example of this is the progression from IRAS to ISO to Spitzer. All were cold telescopes of roughly the same size, and the great increases in capability came principally from the bigger and better detector arrays and the instrumentation they enabled. We can expect dramatically larger gains for SOFIA and proposed missions like CALISTO, where the telescopes are indeed much larger, if there is a will to develop the technology in advance of the missions. We therefore urge that a mission-agnostic, competition-based funding program be established to push far-infrared detector development, roughly akin to the philosophy that NASA used for developing the near- and mid-infrared detectors for JWST, which was done well in advance of the formal mission, and even the instrument, Phase A concept studies.

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