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Infrared Receivers For Low Background Astronomy
Incoherent Detectors and Coherent Devices From One Micrometer to One Millimeter
Final Report

June 1979

National Aeronautics and Space Administration

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16. Abstract

The status of incoherent detectors and coherent receivers over the infrared wavelength range from one micrometer to one millimeter is described. General principles of infrared receivers are included, and photon detectors, bolometers, coherent receivers, and important supporting technologies are discussed, with emphasis on their suitability for low background astronomical applications. Broad recommendations are presented and specific opportunities are identified for development of improved devices.

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PREFACE

In response to a request from the Office of Space Sciences, a subpanel of the MOWG for airborne astronomy was formed under the chairmanship of Professor P. L. Richards to report on the status of incoherent detectors and coherent devices over the infrared wavelength range from 1 micrometer to 1 millimeter. Funding was made available by Dr. N. W. Boggess of the Office of Space Sciences. Dr. C. R. McCreight was contract monitor. Dr. L. T. Greenberg served as panel staff member. The following persons participated in the preparation of this report:

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I. SUMMARY AND RECOMMENDATIONS

I-A SUMMARY

The problem of summarizing the state of development of incoherent and coherent infrared receivers for space astronomy is exceedingly complex. It is impossible in a document of this length to explore the topic in any detail. The procedure chosen by the panel has been to discuss the relevant technologies in qualitative terms, to provide current unclassified information on receiver performance, and to list selected references in which each subject can be pursued in more detail.

In its discussion of incoherent detectors, the panel focused on the needs of low background space astronomy. Occasional mention is made in the report, however, of the related needs of high background space observations, such as planetary missions. The discussion of coherent receivers is relevant to both low and high background applications.

The panel feels that the potential for infrared space astronomy will not be fully realized without significant NASA sponsored development of both incoherent and coherent infrared receivers. The problems faced in the administration of such a development program will be at least as complex as those faced by this committee. In some areas small amounts of development money can yield large dividends. In other areas, all of the foreseeable NASA infrared receiver development funds could be spent without producing results that are significant to low background space astronomy. Infrared receiver development is a very sophisticated branch of technology. Past experience has shown that the productivity of a development program depends critically on the capabilities of the personnel involved.

The degree of readiness of the technologies discussed in this report is extremely uneven. As an example, discrete photon detectors for wavelengths shorter than 120 μm are a relatively mature technology of proven usefulness, so optimization and development can be planned in a reasonably orderly manner. Heterodyne mixers for $\lambda \sim 100$ μm, by contrast, are in a very primitive state. They seem possible in principle and would be very useful, but present ideas are clearly inadequate and innovation is required.

In order to illustrate some of the many issues involved in the management of an effective receiver development program, the panel has made recommendations for appropriate NASA activities. The remainder of this section lists six general recommendations followed by a number of specific recommendatons which point out opportunities for receiver development.

The technical information in this report is introduced in Section II GENERAL PRINCIPLES OF INFRARED RECEIVERS and then continues in III PHOTON DETECTORS, IV BOLOMETERS, V COHERENT RECEIVERS, and VI IMPORTANT SUPPORTING TECHNOLOGIES. A glossary of symbols used in the report and a list of suggested reading are included in the APPENDICES.

I-B GENERAL RECOMMENDATIONS

1. As a direct result of the Infrared Astronomical Satellite (IRAS) and the Spacelab 2 Small Helium-Cooled Infrared Telescope Experiment (Spacelab 2 IRT), the problem of low background detection using arrays of discrete photoconductors is being studied intensively. It is imperative that the technical and engineering results of these efforts be utilized to form a sound foundation for the further development which is needed to implement future programs. One way of accomplishing this goal is to fund a

small, highly competent group of engineers and technicians within NASA to study and document the performance of these systems and to continue the development of improved arrays of discrete low background detectors and the associated electronic systems.

2. The Department of Defense (DoD) is continuing to spend very large sums to develop advanced infrared sensors. Much of the technology developed is of interest for NASA space missions. There is need for a technically expert committee with the appropriate security clearance to keep this matter under continuous scrutiny and for NASA to develop cooperative communications with the DoD at whatever level is needed to produce technology transfer.

3. Because of the complexity of the task of properly managing NASA sensor development funds, a mechanism must be found to broaden the input of expert knowledge in the decision-making process. Broadly-based peer review will greatly enhance the effectiveness of NASA sensor development activities.

4. A number of areas are identified in this report in which innovation is very desirable. Innovation should be supported by NASA to provide improved technology for the next generation of space missions. Such innovation need not be excessively costly, but is inherently a disorderly process with a high risk of failure. It depends on the creativity of talented individuals and cannot be effectively directed by a committee. Management techniques which have proved effective in encouraging innovation include sophisticated consideration of unsolicited proposals and continuity of support for groups with a record of high productivity.

5. Infrared sensors are continually evolving, and many new types of sensors will be required for future space missions. There is an enormous gap between laboratory

feasibility studies and full flight-system demonstrations. NASA support for scientific projects which utilize new sensor concepts and hardware can be an effective way to gain valuable experience. Special attention should be given to projects which involve infrared backgrounds which are relevant for space astronomy.

6. Many of the problems encountered in the development of infrared sensors for space astronomy are of a kind which will challenge members of the general scientific community. Many instances exist of solutions to NASA problems being provided at little or no cost to NASA when the technical community has been made aware of NASA needs. This panel favors the widest possible dissemination of technical information about NASA needs and the results of NASA investigations, including post-mission analysis of the engineering performance of NASA-developed systems. Technical reports are useful and should be widely distributed. They should not be considered as substitutes, however, for talks at relevant scientific conferences and publication in the generally available scientific literature.

I-C OPPORTUNITIES FOR SENSOR DEVELOPMENT

1. Discrete Incoherent Detectors

Discrete detectors having very low noise-equivalent power (NEP) are needed over the entire wavelength range from 1 μm to 1 mm to utilize the full capabilities of space telescopes such as the Shuttle Infrared Telescope Facility (SIRTF).

a. Development of photovoltaic (PV) detectors by the DoD should be carefully monitored. Items of special interest are decreased NEP, decreased capacitance, and longer wavelength capability. Promising types should be acquired and tested.

b. Existing ideas for improvements in photoconductive (PC) detectors should be developed with NASA funding. Items of interest are the influence of materials quality, contacting techniques, and geometry on responsivity, NEP, and anomalous effects. New ideas for longer wavelength capability should be explored with small programs.

c. Since many existing photon detectors are amplifier-noise limited at low backgrounds, NASA should support the development of amplifiers with lower noise.

d. Existing ideas for improvements in bolometric detectors should be supported with NASA funding. Items of interest include techniques for assembling arrays of bolometers, materials and fabrication techniques for lower temperature bolometers, and improved amplifiers and space qualified coolers for temperatures below 1 K. There is also need for thermal detectors that are optimized for operation in the temperature range $50 \leq T \leq 150K$ which can be achieved with passive cooling.

2. Integrated Arrays of Incoherent Detectors

Integrated one- and two-dimensional detector arrays are of great potential value for space astronomy. Arrays with high quantum efficiency are required for high background measurements. For low background applications, arrays are required with values of NEP which are comparable to the best discrete detectors. Array development is very costly so careful selection and timing of NASA programs is imperative.

a. Development of PV and PC arrays by the DoD should be carefully monitored. Arrays with favorable properties should be acquired and tested by NASA. An item of special interest is the possible improvement in NEP by reduction of the read-out rate.

b. Integrated arrays for $\lambda \gtrsim 30\ \mu m$ are not likely to be developed by the DoD. Ideas should be explored with small programs so that NASA development can begin when the technology is ripe.

c. Ideas for extending the response of infrared photocathodes to 2 to 3 μm should be explored with a small level of effort.

3. Coherent Receivers

Although most infrared astronomy is now being done with incoherent receivers, the development of heterodyne receivers for $25\ \mu m \lesssim \lambda \lesssim 1000\ \mu m$ with performance which approaches the quantum noise limit is an important goal. Both short term development of existing ideas and long term support for innovation will be required.

a. Present NASA efforts on near-millimeter heterodyne receivers should be maintained.

b. New ideas for broad-band low-noise mixers for $\lambda \gtrsim 25\ \mu m$ should be explored where there is potential for large improvements in performance.

c. Low-noise broad-band IF amplifiers for heterodyne receivers should be developed.

d. New ideas for practical tunable local oscillators for the $10\ \mu m \lesssim \lambda \lesssim 1000\ \mu m$ range should be explored.

4. Supporting Technologies

a. Radiation hardening of state-of-the-art receivers is a continuing problem that will require NASA support at a small level of effort.

b. There is need for improved cold filters, primarily for $\lambda > 20\ \mu m$. Small programs aimed both at short term development of existing ideas and long term support for innovation will be required.

II. GENERAL PRINCIPLES OF INFRARED RECEIVERS

Astronomical observations usually involve the measurement of the flux of radiant energy emitted by distant objects. At infrared wavelengths it is often convenient to visualize this flux of energy as a stream of photons. The uncertainty principle of quantum mechanics places certain restrictions on the simultaneous measurement of both the number of photons (intensity) and phase of the photons (that is, the phase of the electromagnetic field). Any receiver which determines both the intensity and the phase is called a coherent receiver. Coherent receivers (except for up-converters) have inherent spontaneous emission of photons. These additional photons are always present along with the signal to be measured. They introduce a source of noise which limits the performance of the coherent receiver so that it is consistent with the requirements of the uncertainty principle. The noise introduced by this spontaneous emission is roughly equivalent to the noise produced by background noise of a blackbody at temperature $T = hc/\lambda k$. Here λ is the average wavelength of the receiver's response, h is Planck's constant and k is Boltzmann's constant. A receiver which is limited only by this spontaneous emission is called an ideal coherent receiver.

Direct detectors which produce an output voltage or current proportional to the signal power do not measure the phase of the photon's electromagnetic field. Since the phase is not determined by such incoherent measurements, the uncertainty principle places no restriction on the precision of the measurement of the number of photons. Thus, incoherent (direct) detectors can be in principle completely noiseless and can detect the arrival of a single signal photon. Such a direct detector (with unit efficiency) is called an ideal photon counter.

The infrared portion of the electromagnetic spectrum is a crossover region where the eventual choice between coherent and incoherent receivers is dictated by the astronomical requirements such as spectral range, spectral resolution, and spatial resolution. Thus, it can be expected that both coherent and incoherent infrared receivers will be needed to realize the full astronomical potential of the infrared spectral range.

In practice, very nearly ideal incoherent photon counters can be constructed at optical wavelengths. In the infrared, however, incoherent detectors fall at least 2 to 3 orders of magnitude short of counting single photons. Though nearly ideal coherent receivers exist at a few selected wavelengths in the infrared, generally coherent receivers in this region are also far from approaching the ideal limit.

In nearly all astronomical experiments, unwanted (background) photons reach the receiver in addition to the signal. The background level and the scientific requirements of a particular astronomical measurement not only affect the type of receiver which should be employed (i.e., coherent or incoherent), but also the degree of perfection which is required in the receiver system. Most present infrared observations, especially those made from the ground, are made under conditions which have a very high background. While an ideal photon counter could be used under such conditions, it is usually not necessary to measure the arrival of each individual photon. As an example, consider a direct detector used for near-infrared photometry on a large ground based telescope. Under these conditions the background would correspond to $\sim 10^{12}$ photons s^{-1} on the detector. The noise fluctuations in such a background due to the Poisson statistics of photon detection will be $\simeq 10^{6}\eta^{-1/2}$ photons in one second (referred to the detector input). Here η is the quantum efficiency. Thus, any incoherent detector which can detect 10^{6} photons in one second will be limited by background noise. A detector with relatively low responsivity which is amplifier-noise limited at 10^{6} photons s^{-1} but with unit quantum efficiency will perform as well under these conditions as an ideal photon counter. (Responsivity is the ratio of signal to incident power and often has units of amperes per watt.) The above example provides the insight that under background limited conditions it is not the responsivity of the detector which should be optimized, but rather the quantum efficiency. Under low background conditions, such as can be obtained with a cryogenically-cooled space telescope, the fluctuations in the background became so small that, because of the effects of amplifier noise, responsivity often becomes more important than quantum efficiency per se.

Except for devices using photocathodes and electron multiplication, all incoherent infrared detectors presently in use (photoconductors, photovoltaic devices, and bolometers) make use of sophisticated electronic circuitry to measure very weak currents or voltages produced in the device. Though these weak signals are often produced by individual photo events in the detector, fundamental considerations involving the capacitance of the detectors and of solid state electronics preclude the detection of single photons. The sensitivity of such detectors is measured in terms of the noise equivalent power (NEP). The NEP of a detector is defined to be the radiant power, in watts, which must be incident on the detector to produce a signal which is equal to the rms noise of the detector (with its associated electronics) within an electrical bandwidth of one Hz. Thus, the smaller the NEP, the more sensitive the detector. The NEP of a detector is directly related to the minimum number of photons at a particular wavelength which can be detected in one second. For example, an NEP of 10^{-15}W Hz$^{-1/2}$would allow the detection at unity signal/noise ratio of 3.6 x 10^{3} photons in one second at a wavelength of 1 μm or 3.6 x 10^{6} photons in one second at a wavelength of 1 mm.

In addition to the NEP, many other characteristics must be considered in the selection of a receiver for astronomical observations. These characteristics are not usually independent parameters, so receiver performance must be optimized in a complex tradeoff which depends on the application. Several of the important receiver characteristics are listed below along with some general comments which will be expanded in later sections on individual devices:

1. Noise equivalent power (NEP) should be minimized. A lower limit is often set by a radiation background or electronic noise.

2. Noise temperature (T_N) is a sensitivity measure defined only for coherent receivers. T_N should be minimized.

3. Wavelength and bandwidth of operation (λ, $\Delta\lambda$) should be determined by the type of observation (e.g., spectroscopy, photometry) and the spectrum of the astronomical source.

4. Quantum efficiency (η) should be maximized. Under background limited conditions, the NEP is proportional to $\eta^{-1/2}$.

5. Responsivity (S) should be made large so as to minimize the effect of amplifier noise.

6. Speed of response can often be traded for NEP. Faster detectors often have higher NEPs.

7. Linearity of response, or at least reproducibility, is essential to allow quantitative measurements of flux.

8. Suitability for incorporation in arrays is of importance since in many cases the time required to make an observation is inversely proportional to the number of detectors which can be used.

9. Operating characteristics such as detector temperature, power dissipation, sensitivity to energetic nuclear particles, and ruggedness often determine suitability for a given mission.

Many infrared astronomical observations from space platforms will require receivers capable of achieving optimum performance under conditions of extremely low background. In some cases, orbiting infrared observatories will allow background reductions of factors of 10^6 to 10^8 over those commonly encountered on the ground. In order to make maximum observational use of these platforms, detectors in advance of the present state-of-the-art are required.

II-A. SENSOR NEEDS FOR LOW BACKGROUND SPACE ASTRONOMY

A new era of infrared observations of the universe will be opened by measurements made above the atmosphere in the low background conditions which are possible in space. Several presently contemplated or on-going NASA scientific programs in space infrared astronomy are described in the following reports:

1. Report on Space Science 1975,
   National Academy of Science, 1976.
2. Shuttle Infrared Telescope Facility (SIRTF), Interim Report,
   Ames Research Center, April 14, 1978.
3. Infrared Astronomical Satellite (IRAS), Mission Definition Report,
   Goddard Space Flight Center, May 1976.
4. Spacelab 2, Infrared Telescope Design Study, Final Report,
   Smithsonian Astrophysical Observatory, April 1978.
5. Cosmic Background Explorer (COBE), Interim Report,
   Goddard Space Flight Center, February 1, 1977.
6. Submillimeter Space Telescope,
   Jet Propulsion Laboratory, April 10, 1978.

7. Space Telescope Infrared Photometer, Final Report,
Lockheed Missiles and Space Company, March 1976.

8. Infrared Photometer for the Space Telescope, Phase B Definition Study,
Final Report,
Ball Brothers Research Corporation, June 1976.

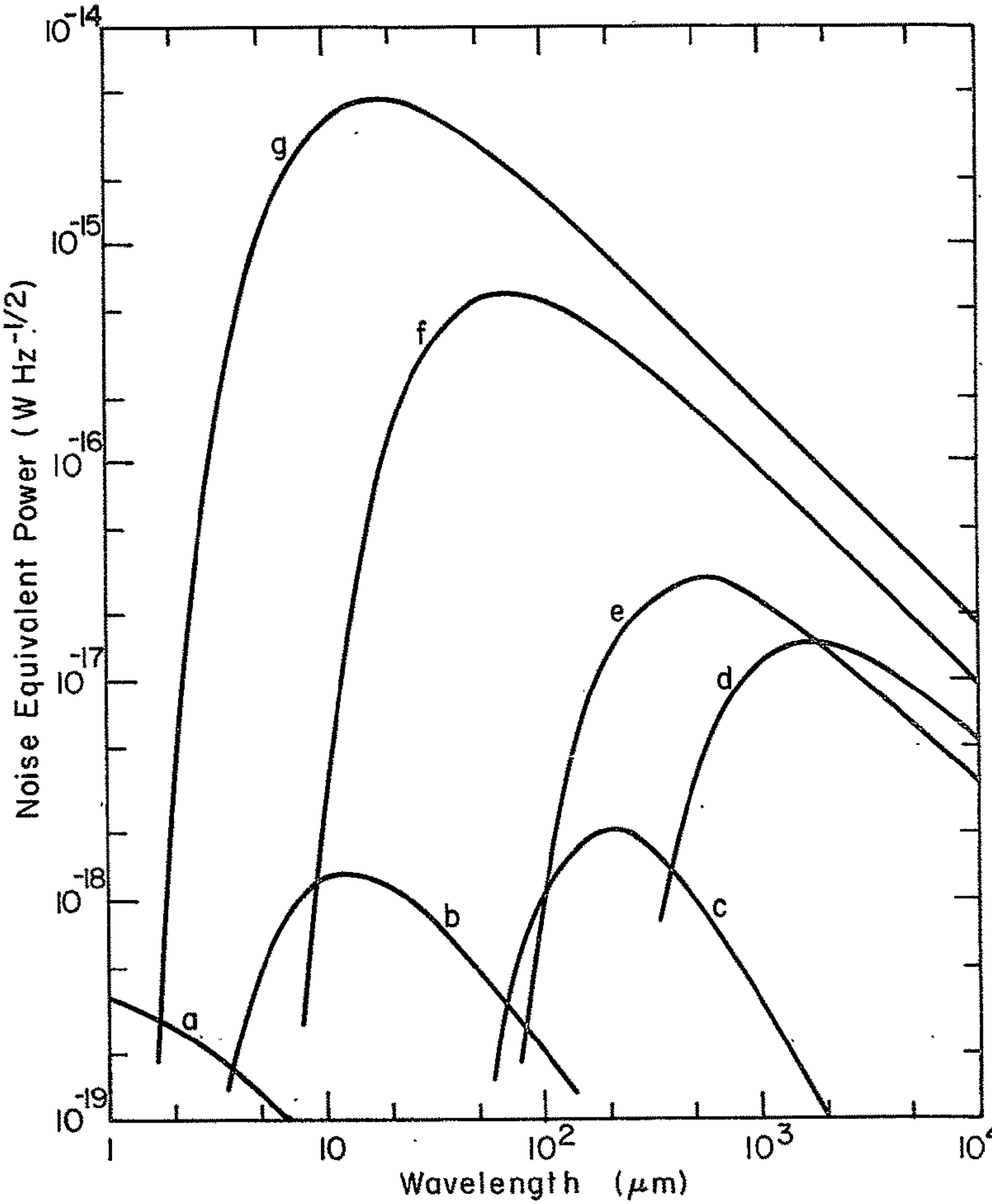
The most pressing need is the development of single element direct detectors and direct-detector arrays which can be background limited on cryogenic telescopes operated in space. Figure 1 shows the irreducible noise of detectors due to various sources of infrared background. The figure is directly applicable to moderately broad-band photometry and polarimetry with diffraction limited apertures and can be scaled in a simple way for other bandwidths or apertures. As the various sections of this report indicate, detectors do not exist for any part of the infrared spectrum which will be limited by the astrophysical background. This is even more strongly the case when detectors are used for narrow-band spectroscopy since the background limited NEP varies directly as the square root of the infrared bandwidth. Improvements in single element detectors would pay off handsomely since the integration time to achieve a given ratio of signal/noise varies as the square of the NEP.

The development of low NEP one- and two-dimensional arrays would also have a substantial impact on space infrared astronomy. As with single detectors, the stress should be on sensitivity (low noise and high quantum efficiency) rather than speed. Photometric mapping is a straightforward example of the potential use of arrays. The observing time required to map a region of the sky with a fixed ratio of signal/noise is reduced by a factor equal to the number of elements in the array, provided that each element of the array has the same NEP as the single detector used for comparison. However this potential gain is rapidly lost if the array elements have significantly larger

Fig.1. The theoretical limits to detector NEP set by several background sources relevant for space missions are illustrated as a function of wavelength λ in curves (a) - (g). These curves were all calculated assuming a spectral bandpass $\Delta\lambda/\lambda = 0.1$, a throughput which accepts 84 percent of the energy from a point source ($A\Omega = 3.7\,\lambda^2$), quantum efficiency for incident photons $\eta = 1$, and optical efficiency, $\epsilon = 1$. For other values of bandpass, efficiency, or throughput, the NEP scales as $\left(\frac{A\Omega}{\epsilon\eta}\ \frac{\Delta\lambda}{\lambda}\right)^{1/2}$. Where more than one source is present, the NEP values should be combined in quadrature. Curves (a) - (g) show limits set by statistical fluctuations in the photon rate from the following sources:

(a) zodiacal scattered light at the ecliptic pole;
(b) zodiacal dust emission at the ecliptic pole;
(c) interstellar dust emission at high galactic latitude;
(d) the 3 K cosmic background radiation;
(e) a 10 K, 10 percent emissive telescope;
(f) a 77 K, 10 percent emissive telescope; and
(g) a 300 K, 10 percent emissive telescope.

These curves were calculated using Poisson statistics because the Bose correction factor is important only at long wavelengths for efficient systems with high background temperatures ($\lambda \gtrsim 10^3$ μm, for a 10 percent efficient system and a 100 percent emissive 300 K source).



10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
Noise Equivalent Power (W Hz$^{-1/2}$)
g
f
e
d
c
b
a
1
10
10^2
10^3
10^4
Wavelength (μm)

NEP than that of the single detector because of the dependence of integration time on the square of the NEP. In low backgrounds the dominant noise in an array (as well as in a single detector) is often the noise in the readout system. Under these conditions improved readout electronics are very desirable. There may sometimes be practical advantages to integrating arrays that can store the signal in the form of a charge for a significant time and then read it out quickly.

Spectroscopy has applications for low noise single element detectors as well as for one- and two-dimensional arrays. Grating spectroscopy, which becomes an attractive technique when the detector noise has been reduced to the point where the dominant noise comes from the fluctuations in the photon rate of the background or of the observed source, requires low noise, one-dimensional and long, narrow two-dimensional arrays. Fourier transform spectroscopy has use for both single element detectors of low NEP and moderate speed as well as arrays for spectroscopic imaging. Observations of spectral lines from small objects with Fabry-Perot interferometers require single element detectors with the highest possible sensitivity. There is a complicated trade-off between these spectroscopic techniques which depends not only on the scientific mission, but also on the properties of available detectors. This trade-off is discussed in the appendices to the April 14, 1978 SIRTF Interim Report.

Heterodyne techniques will find increasing application in high resolution spectroscopy, especially at wavelengths longer than $\sim 10\mu m$. The full utilization of heterodyne techniques will require the development of tunable local oscillators and broad-band mixers. Broad mixer and IF amplifier bandwidths are needed to facilitate line searches and multi-(frequency) channel operation with a single receiver.

Not all space applications require detectors optimized for low backgrounds. For example, backgrounds in planetary astronomy can be very much higher than the astrophysical backgrounds used to calculate curves (a) to (d) in Figure 1. However, planetary probes (and other multi-year space missions) have severely limited cryogenic capabilities. Under these operating conditions, available detectors for wavelengths $\gtrsim 5$ μm are often not photon-noise limited even for the relatively high planetary backgrounds. Thus, considerable benefit could be obtained from improved detectors for long wavelengths which are designed to operate in temperature range $50\ K \lesssim T \lesssim 150\ K$, which can be achieved with passive cooling techniques.

II-B. RECENT HISTORY OF SENSOR DEVELOPMENT

The present state of development of infrared detectors and mixers can be understood only in terms of the impact of DoD applications on the funding of research and development. The development of lead-salt photoconductors (PbS, PbSe, PbTe) began during World War II and continued during the decade following the war. Since that time DoD applications have driven development of photovoltaic detectors, extrinsic (Si:XX, Ge:XX) detectors, and ternary alloy (HgCdTe, PbSnTe, etc.) detectors, for use at wavelengths up to about 30 μm. Part of this development has gone into detectors designed to operate in moderately low infrared backgrounds. Present DoD detector programs are focused around large scale integrated arrays of detectors for wavelengths to approximately 30 μm, and refrigeration systems to cool them. Exploratory research on semiconducting detectors has usually been carried out at university or government laboratories. The development of the more promising detector types has then shifted to industries interested in producing detectors for defense systems. This pattern of development has changed with the interest in large scale detector arrays because of the concentration of array processing technology in industrial hands.

A civilian market for infrared spectroscopic equipment has developed since World War II. This market generally makes use of relatively insensitive room temperature detectors which are of little use for low background space astronomy, though they have some relevance for planetary investigations. Only a limited number of civilian applications (such as thermography) have made use of the more sensitive cooled detectors.

The communications industry and the DoD have both contributed to the development of microwave receivers. The existing Schottky-barrier-diode heterodyne receiver technology at millimeter and submillimeter wavelengths (including low-noise intermediate frequency (IF) amplifiers) is a direct extension of heavily funded development of systems for longer wavelengths.

Development costs for a new class of infrared sensors can be extremely high. Estimates of the total funding involved in the development of ternary intrinsic detectors for the 10 μm region, or for distinctly new arrays, approach \$100M. It is clear that NASA funding of the development of infrared receivers for space astronomy cannot have major impact in technologies which have profited from funding on this scale. In these areas the appropriate NASA activity may be the acquisition and testing of detectors with properties optimized for space astronomy. By way of contrast, there are other areas of infrared detector development which have little or no DoD funding. These areas include extremely sensitive single detectors (including their amplifiers) at all wavelengths, especially photoconductors for $\lambda \gtrsim 30$ μm and bolometers, arrays of detectors for $\lambda \gtrsim 30$ μm, and heterodyne mixers at most infrared wavelengths. In these cases astronomical applications have strongly influenced what development has taken place, and NASA funding can have a major impact in the future. Modest funding of detector development for the IRAS project, for example, has produced significant improvements on a very short time scale.

II-C PAST NASA FUNDING

NASA has sponsored a number of projects which utilize infrared detection. Relatively little development of detectors has been directly sponsored by NASA. More typically NASA funds have been used for instrument development, involving the application of an existing detector in a specific flight or ground-based instrument. Most of the past NASA projects have involved terrestrial or planetary rather than astronomical observations. The detector systems utilized, while frequently involving the same detector materials and principles as those useful in astronomy, have not had to face the problems associated with the low-background, low-temperature environment.

A history of NASA funding of infrared detector development has been compiled in Table I. It includes a reasonably complete listing of the projects which have had as their primary objective the improved performance of infrared detectors. Funding amounts for projects which were related but not directly concerned with the development of detectors are also included (with parentheses). In some instances, infrared detector development was only one of many technological or scientific tasks carried out under NASA-funded programs. The numbers given in these cases are estimates of the relevant fraction of the total program funding. Many infrared astronomy observational programs have been funded, primarily by the Office of Space Science (OSS). A small percentage of this activity concerned improved detector performance. The sum of these detector-related activities represents a remarkable contribution to infrared detector technology for space astronomy, but the level of these activities, which is roughly equivalent to $25K per year, is quite difficult to determine accurately, and has not been included.

It is evident from Table I that the NASA funding which has been directed toward astronomical projects has not been part of a comprehensive, coordinated program. Also,

TABLE I. NASA FUNDING OF INFRARED DETECTOR DEVELOPMENT (in thousands of $)

Supporting Office	Description	Responsible Organization	FY74	75	76	77	78	79
OSS	Development of silicon bolometers	MIT				55	55	
OSS	Development of composite Ge bolometers	GSFC			10	10	10	10
OSS	Infrared Radiometer on the ST (Ge composite bolometers, filters)	Caltech		76				
OSS	Improved photoconductors (Ge:Ga)	NRL		10				
OSS	Development of Ge:Ga photoconductors	Cornell/NRL		14				
OSS	Schottky barrier and Josephson junction development	GISS	65	65	70	70	70	70
OSS	IRAS detector development (Si:As, Si:Sb, Ge:Ga, Ge:Be photoconductors)	Rockwell/SBRC/ARC*			84	191	112	15
OSS	SIRTF detector development (IRCCD array survey, discrete and array evaluations)	Various/ARC*					103	125
OSS	Schottky barrier and Josephson junction production, applications	GISS	(65)	(65)	(60)	(60)	(60)	(60)
OSS	< 2 K cryostat for bolometer cooling	Cornell				(30)	(30)	
OSS	SIRTF: 0.1 K adiabatic demagnetization for bolometer cooling	UCB					(15)	
OSS	Development of heterodyne receivers	GSFC	(75)	(30)	(35)	(60)	(200)	(280)
OAST	1 x 20 element InSb IRCCD	SBRC/LaRC*	(50)	(60)	(65)	(100)	(100)	(125)
OAST	Discrete photoconductors and arrays for 5-200 μm astronomical applications	ARC*					25	200
OAST	Josephson junction devices	JPL	105	88	88	117		

TABLE I. (CONT.)

Supporting Office	Description	Responsible Organization	FY74	75	76	77	78	79
OAST	Improved silicon bolometers	JPL					85	85
OAST	IR arrays for planetary instruments (HgCdTe)	JPL*					150	450
OAST	Development of 15-30 μm photomixer	GSFC						75
OAST	CCD arrays for LANDSAT-mapper (PbSnTe or HgCdTe)	GSFC						(425)
OSTA	Detectors for terrestrial observations	Various	(300)	(300)	(300)	(300)	(300)	(300)
		TOTALS: direct	170	253	252	443	610	1030
		Indirect	(490)	(455)	(460)	(550)	(705)	(1190)

Note: funding levels are approximate.

*Management responsibility

( ) denotes projects indirectly related to astronomical detector development.

in contrast to the support given to terrestrial projects, the agency's funding in this area has been rather modest. Although significant progress has often been made in these small efforts, limited funding has meant that sustained support of investigators over several years has not been common, and full benefits from this work have probably not been realized.

It has been found that limited funding can sometimes produce significant improvements in detector performance in a timely manner. For example, work on Ge:Ga photoconductors during FY75-78, which was stimulated by the needs of the IRAS program, has produced two orders of magnitude sensitivity improvement in sensitivity for a NASA investment of about $230K. Only a small fraction of this amount was sufficient to demonstrate that the improvements were possible. Significant improvements in Si:As and Si:Sb photoconductor performance have also resulted from IRAS. The IRAS program would have been in a far stronger technical position, however, had a well-coordinated detector development effort been carried out in advance. The Space Telescope project provides an example of the penalties paid for the absence of a detector program. When the first generation flight instrument complement was picked, it was concluded that the infrared detector technology was not ready for space. As a result, no infrared instrument was included in this complement.

The principal source of NASA funding for infrared detector development for astronomy has been the Astrophysics Program Office of OSS. The most important funding categories have been 1) on-going improvement of techniques under scientific programs, 2) a limited program initiated in FY77 for support of individual detector and detector-related projects, 3) space project, such as IRAS and SIRTF, detector development programs (developments carried out by the space projects have focused on extrinsic silicon and germanium photoconductor technology, and have tended to address specific detector requirements and operating conditions which are peculiar to the mission), and 4) on-going support at GISS for the development and production of Schottky barrier and Josephson junction heterodyne receivers (a portion of the GSFC heterodyne receiver work has also been supported by a second OSS source, the Planetary Office).

The Office of Aeronautics and Space Technology (OAST), which funds the development of advanced technologies, has recently begun significant support of infrared detector research and development. The OAST has supported the development of monolithic InSb infrared charge-coupled-devices (CCDs) since FY73. During FY78 and FY79, technology programs are being set up at ARC for discrete and integrated arrays, and at GSFC for terrestrial imaging and heterodyne spectroscopy.

Approximately $300K per year has also been spent on infrared detector development by the Office of Space and Terrestrial Application (OSTA). This work has been directed almost exclusively toward high-background applications in wavelength ranges which correspond to atmospheric windows.

II-D. SECURITY CLASSIFICATION

A serious constraint arises in the application of new DoD technology to space astronomy. Massive DoD funding for receiver development occurs when it is anticipated that the receivers will be used in new defense systems. As a result, performance data on new types of receivers, which is of great interest to space astronomy, is often highly classified. At the present time the classification of the performance of large detector arrays is hindering the planning of astronomical systems. In some cases the argument can be made that the astronomical application is sufficiently different from the defense application that NASA use will not prejudice DoD goals. For example, it appears that many defense applications of detector arrays require rapid frame rates. For astronomy, by contrast there are potential advantages to extremely slow rates. In such cases it is at least possible that vendors that have developed new technologies with DoD funding will be permitted to furnish arrays of detectors based on those technologies to NASA for space astronomical missions. It should be recognized, however, that in some cases the astronomical application will be sufficiently close to the DoD application that declassification or even classified NASA use will be restricted.

In this context it should be mentioned that this report has been prepared entirely from unclassified sources.

III. PHOTON DETECTORS

In Section III-A through III-F we discuss the operating principles and performance of detectors that respond to the rate at which photons, not power, are incident upon the active area. By contrast Section IV discusses bolometers, which respond to power, while Section V discusses coherent receivers which respond to the electromagnetic field of the incident radiation.

Several types of photon detectors can be distinguished from one another. In external photodetectors a current proportional to the incident photon rate is produced in the form of free electrons emitted from a photocathode into a vacuum. These detectors are discussed in Section III-A. Subsequent sections, III-B through III-F, discuss internal photodetectors, where the current flow occurs inside the detector material. Section III-G discusses briefly an unconventional type of photon detector known as a quantum-counter.

III-A PHOTOCATHODES

Photocathodes have been employed in a large variety of highly successful astronomical detectors for wavelengths less than 1 μm. Photomultiplier tubes, image intensification tubes, and vidicons are but a few of the devices which make use of the photoemission of electrons from a cathode surface. In large measure these devices have gained their success because each free photoelectron may be accelerated to a high energy by an electric field and detected as a single event. Such detectors have good linearity and, in many cases, closely approach the performance of an ideal photon counter. Large developmental efforts have been devoted to improving the performance of photocathodes both in terms of increasing their quantum efficiency and extending their response into the infrared. By far the most significant improvement has been the development of negative-electron-affinity III-V photocathodes. With these cathodes quantum efficiencies of 20 to 30 percent in the visible and 10 percent near 1 μm have been obtained in practical single photon counting systems.

In present photocathode materials, interfacial potentials of ~ 0.8 eV limit the longest wavelengths of response to ~ 1.0 μm. Other material combinations may be discovered which will allow lower interfacial potentials and hence longer wavelength response. For the near term, however, it seems more likely that other techniques may significantly extend the response of photocathodes. An example of perhaps the most straightforward technique is field assisted photoemission.

In a field assisted photocathode, a very thin metallic layer is placed within the photocathode structure. This layer, which is transparent to electrons due to its extreme thinness, allows an external voltage bias to be applied to the cathode. The voltage produces an internal electric field which enhances the negative-electron-affinity of the cathode. This technique has demonstrated photoresponse out to 1.5 μm in the laboratory. The possibility of response at even longer wavelengths seems to exist, since semiconducting alloys can be tailored to have band gap energies corresponding to nearly any desired near-infrared wavelength. Present work on photocathodes beyond 1 μm deals with the many solid-state-physics problems which remain to be solved.

The wide variety of demonstrated techniques for detecting single photoelectrons would certainly allow any reasonably efficient photoemitter in the infrared to be an unexcelled detector at the very low astronomical backgrounds which can be expected in the 2 to 3 μm spectral region. For example, an IR photocathode combined in an image tube with existing CCD electron detectors would offer an enormous step forward.

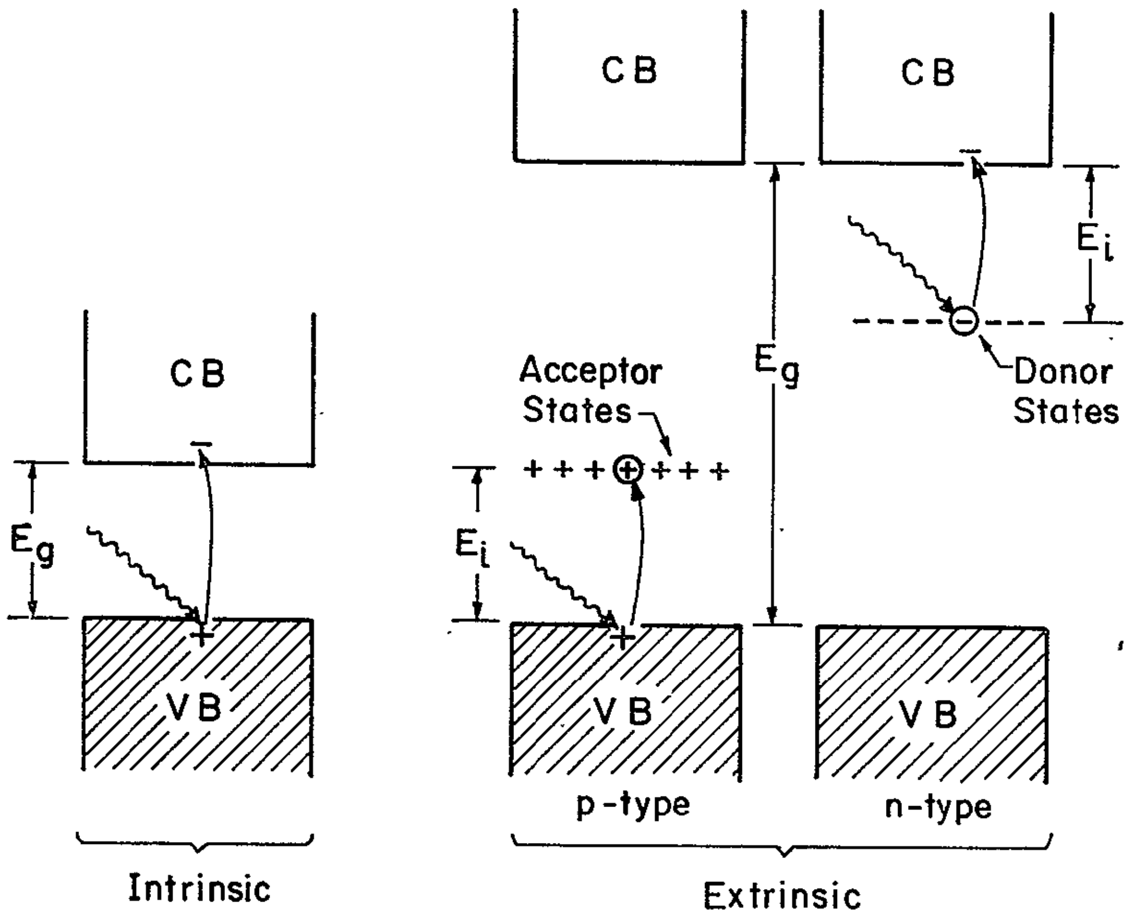
III-B PHOTOVOLTAIC AND PHOTOCONDUCTIVE DETECTORS

Internal photodetectors can be made from either intrinsic or extrinsic semiconductor materials. In the former case, free charge carriers are generated from the bulk semiconducting material itself. In the latter case, they are generated from impurity atoms which are deliberately introduced into the bulk material. Figure 2 compares the electronic energy levels in an intrinsic semiconductor with the corresponding levels in both p- and n-type extrinsic semiconductors. All three materials are shown with the same long-wavelength cutoff.

In an intrinsic semiconductor, absorption of a photon with energy greater than the bandgap simultaneously creates a free hole in the valence band and a free electron in the conduction band. These free carriers are then able to move under the influence of an electric field and thereby produce a current. Thus photoresponse exists shortward of a cutoff wavelength, $\lambda_c = hc/E_g$, where E_g is the semiconductive bandgap. Considerable effort has gone into producing detectors from semiconductors with a wide range of bandgaps. High performance intrinsic detectors for low background conditions are currently available only for the wavelength region $\lambda \lesssim 15\ \mu m$. Intrinsic response longward of 20 μm has, however, been reported in alloy-semiconductors such as HgCdTe. Intrinsic detectors are often preferable to other types of detectors for the wavelength region where they are available.

In a p-type extrinsic material, the absorption of a photon with energy larger than the separation E_i between the valence band and the acceptor states (between the conduction band and the donor states in n-type material) causes the generation of one mobile hole (electron) and an immobile ionized impurity. The cutoff wavelength, $\lambda_c = hc/E_i$, for extrinsic photoconductivity depends upon both the properties of the host

Fig. 2. Electronic energy levels in an intrinsic semiconductor compared with p- and n-type extrinsic materials with the same long wavelength cutoff. The electronic transition which results from the absorption of a photon and the resulting mobile charges are shown in each case. Ionized (neutralized) impurity states are shown circled. They are immobile and do not contribute to current flow. VB is the valence band and CB is the conduction band; E_g is the gap energy and E_i is the impurity ionization energy.


CB
CB
CB
Eg
Acceptor States
Donor States
Ei
Eg
Ei
VB
VB
VB
p-type
n-type
Intrinsic
Extrinsic

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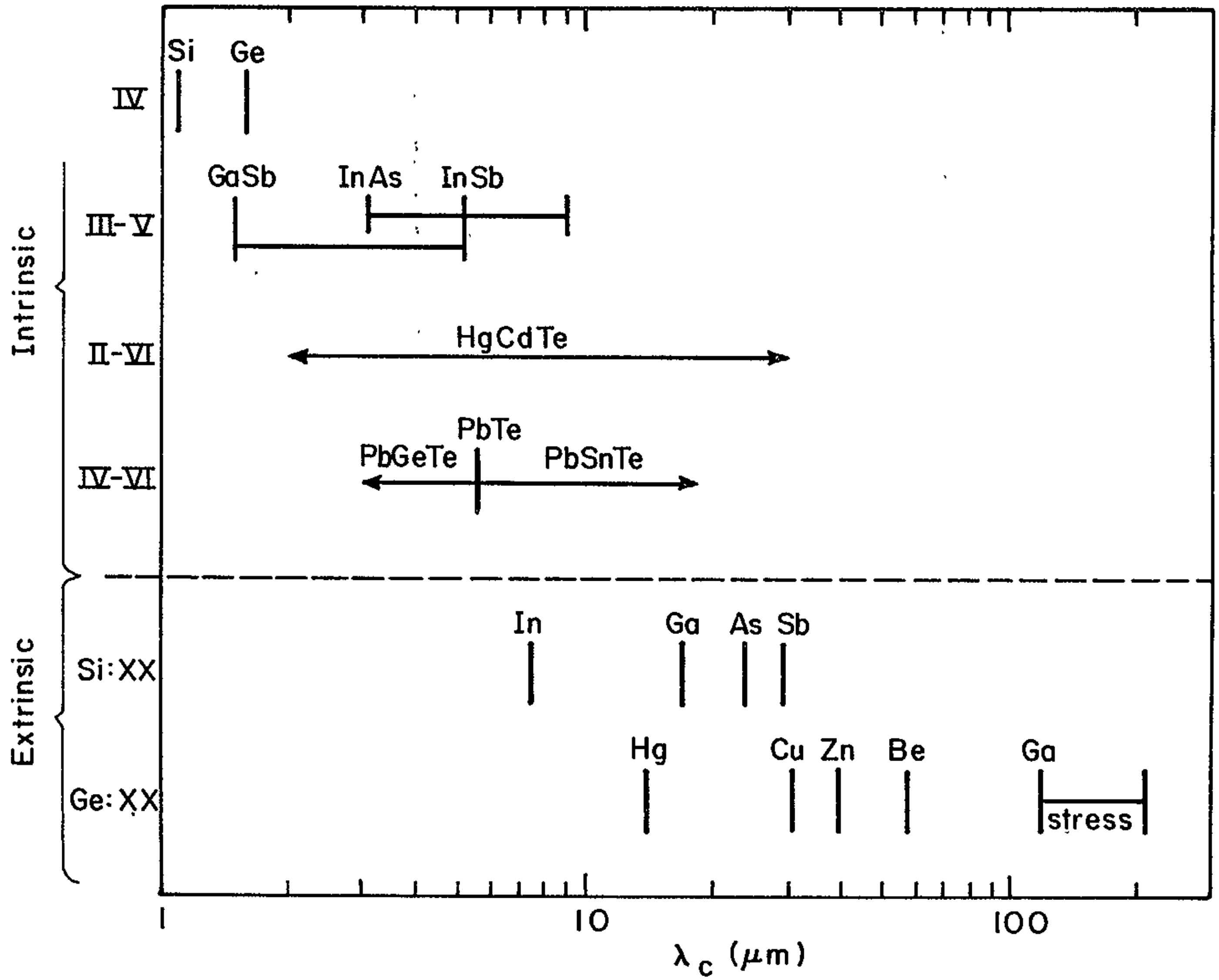
semiconductor and of the particular dopant. Of special interest are extrinsic detectors in silicon and germanium denoted generically Si:XX and Ge:XX (where XX represents any of a number of dopants). These are clearly the best available photon detectors for $15\ \mu m < \lambda < 210\ \mu m$.

Figure 3 shows the long wavelength cutoffs for a variety of intrinsic and extrinsic detectors that are reasonably well developed. Some characteristics of these detectors are discussed further in Section III-C, D, and E.

Several properties of intrinsic detectors make them preferable to extrinsic detectors. At high concentrations the impurity states in extrinsic semiconductors overlap in real space and form energy bands. These and other effects severely limit the doping levels that can be used. As a result, the typical absorption lengths are the order of millimeters in extrinsic materials as compared with micrometers in intrinsic materials. The thinness of intrinsic detectors greatly reduces their susceptibility to optical crosstalk from internal reflections when used in arrays and to the effects of energetic nuclear particles. Another practical advantage of intrinsic detectors is their operating temperature. For the same long wavelength spectral cutoff, the operating temperature required to avoid adverse effects from thermal generation of carriers is not as low for intrinsic as it is for extrinsic detectors. The advantage is compounded by the ability of the fabricator of many intrinsic detectors to adjust the energy gap so that the range of sensitivity corresponds to the spectral region of interest. Finally, a number of curious anomalous effects have been observed in many extrinsic silicon and germanium detectors which so far have not been encountered in most intrinsic detectors.

Internal photodetectors can be operated in two basic modes: photoconductive and photovoltaic. In photoconductive detectors, the free carriers migrate under an external-

Fig. 3. Illustration of the long wavelength cutoff λ_c of various intrinsic and extrinsic photon detectors. Horizontal lines are used in cases where a range of values of λ_c can be obtained by alloying or by the application of a uniaxial stress. An arrow indicates that further extension of the range is possible.



Intrinsic
Extrinsic
IV
Si
Ge
III-V
GaSb
InAs
InSb
II-VI
HgCdTe
IV-VI
PbGeTe
PbTe
PbSnTe
Si:XX
In
Ga
As
Sb
Ge:XX
Hg
Cu
Zn
Be
Ga
stress
1
10
100
λ c (μm)

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ly applied electric field. Such detectors can be made of either extrinsic or intrinsic materials. In a PV detector (also referred to as a photodiode), there is a separation of the two types of carrier under the influence of an internal electric field (sometimes assisted by an external field). Such detectors are always made from intrinsic semiconductors. The internal field may be due to the presence, for example, of a p-n junction, a heterojunction, a metal-insulator-semiconductor (MIS) structure, or a Schottky (metal-semiconductor) barrier. If the PV detector is operated in the rarely used open-circuited configuration, then the separation of charge produces a voltage across the detector contacts. This effect gives the photovoltaic device its generic name. Usually, however, a photodiode is operated in an essentially short circuited configuration and the current produced by the process of charge separation is measured.

The amount of charge transferred per incident photon determines the responsivity of either type of detector. The difference between the two types of charge collection mechanisms, however, has important consequences. In an idealized photoconductor, every free carrier generated in the volume of the device is capable of producing a current. The amount of charge transferred depends upon the carrier lifetime and mobility, the applied electric field, and the detector size. A quantity known as the photoconductive gain, with the usual symbol G, is defined to be the ratio of the transferred charge to the charge on a single electron. In the simple case, this is equal to the ratio of the carrier lifetime to the carrier transit time across the detector. Observed values range from less than 10^{-3} to greater than 10^{4}. Gains greater than 1 require, in addition to long lifetime, what are known as "ohmic contacts". Such contacts allow the free passage of carriers from one electrode into the semiconductor to replenish those carriers removed at the other electrode. Making noiseless ohmic contacts is a substantial part of the art of PC detector fabrication. In terms of G, the current responsivity (S) can be written

$$S = G \eta \frac{e \lambda}{hc} ,$$

where the responsive quantum efficiency η is equal to the number of free carriers (or carrier pairs) generated divided by the number of photons incident upon the active area of the detector. For the sake of conciseness, careful distinctions between various types of quantum efficiency are not made in this report. Issues involved are discussed in the Glossary.

In a PV device, one unit of charge is transferred per electron-hole pair generated within the small active region near the junction. Thus, the equation for the responsivity of a PV detector is similar to that for a PC detector, except that $G = 1$ and η is now the fraction of incident photons that produce carriers that are collected. Typical values of η are > 0.6 for both types of intrinsic detectors. Extrinsic detectors often have values of $\eta < 0.3$.

The control of η in a PV detector is better understood than the control of $G\eta$ in a PC detector. Therefore, PV detectors offer practical advantages in photometric accuracy and in uniformity as array elements. Furthermore, photodiodes typically have much higher impedances than intrinsic photoconductors and do not require bias. Thus, photodiodes offer lower power dissipation and easier coupling to multiplexers, both vitally important characteristics for the feasibility of very large arrays. Strong DoD interest in arrays has therefore focused much of the intrinsic detector development effort on PV devices.

Extrinsic silicon and germanium PC detectors are frequently used for low background applications, particularly for wavelengths longer than 10 μm. The relatively advanced CCD and related MOS technologies in silicon have spurred an intensive effort aimed towards the development of arrays of PC detectors with the associated processing electronics incorporated into monolithic structures.

1. Noise in PV and PC Detectors

The fundamental source of noise in the photodetection process is the statistical fluctuation in the number of incident photons (signal plus background) which is commonly referred to as photon noise. This fluctuation in the arrival rate of photons produces a fluctuation in the rate of generation of free carriers which appears as noise in the detector output current. Due to the determinacy of the charge collection mechanism in PV detectors, there is no additional fluctuation resulting from this process. In photoconductive detectors, however, additional fluctuations which are equal in magnitude but uncorrelated, are caused by the statistics of carrier recombination. Thus, in photon-noise-limited operation, PV detectors are more sensitive by a factor of $2^{1/2}$ than PC detectors. As the background level is reduced, other sources of noise become important and this advantage disappears. Even at high background, some photoconductors such as HgCdTe can be operated under conditions where space charge effects (related to the phenomenon known as sweepout) suppress the recombination noise. Thus, these PC detectors have the same photon noise limited sensitivity as PV detectors.

A commonly used figure of merit is the noise equivalent power (NEP) previously defined (in Section II) as the signal power required to produce a ratio signal/noise equal to 1, where the noise (rms)is measured in a 1 Hz bandwidth. (Another widely used figure of merit, the D-star (D^*) is not used in this report but is defined in the Glossary.) The NEP of a photon detector cannot be less than the limit set by the fluctuations in the background radiation,

$$NEP \geq \frac{hc}{\lambda} (2\dot{N})^{1/2} ,$$

where $\dot{N}$ is the number of background plus signal photons incident upon the detector per second. The difference between the NEP calculated using Poisson statistics as assumed above and that calculated using the exact Bose-Einstein statistics is usually negligible in the wavelength region where photon detectors are available. The NEP of a real detection system is given by the ratio of the rms current-noise i_n to the responsivity, i.e.,

$$NEP = \frac{i_n}{S} = \frac{\left(i_{n,d}^2 + i_{n,a}^2 \right)^{1/2}}{S} ,$$

where $i_{n,d}$ is the current noise of the detector and $i_{n,a}$ is the noise of the associated amplifier. Amplifier noise contributions are discussed in Section VI-A.

Let us first consider the sources of noise particular to PV detectors. A photodiode with zero bias voltage and no photon background can have only Johnson noise since it must be in thermal equilibrium. Excess low frequency noise (commonly referred to as 1/f noise) often appears when a bias is applied. For this reason, photodiodes are usually operated at zero bias, although, theoretically they are more sensitive with reverse bias. The NEP of an unbiased PV detector at temperature T and illuminated by $\dot{N}$ photons per second is

$$NEP_{PV} = \frac{hc}{\eta e \lambda} \left(2e^2 \eta \dot{N} + \frac{4kT}{R_o} + i_{n,a}^2\right)^{1/2} ,$$

where the first term in parentheses is the shot noise in the photocurrent (photon-noise), the second term is the Johnson noise of the diode resistance at zero bias (R_o), and the third term is the amplifier noise. At high backgrounds, where the second and third terms are negligible, the NEP of a PV detector is $\eta^{-1/2}$ times larger than the NEP of an ideal photon detector. Since η is typically greater than 0.6, PV detectors are nearly ideal high background detectors for those wavelengths where they are available.

The usefulness of a PV detector in low background (small $\dot{N}$) improves with increasing values of R_o. Since PV detectors are thin planar devices, R_o is usually inversely proportional to detector area. A common figure of merit is the R_oA product. This important parameter depends upon the particular device structure (e.g. p-n junction, Schottky-barrier junction) and also upon a number of semiconductor properties including band structure, minority-carrier lifetimes and mobilities, acceptor and donor densities, surface generation rates and defect densities. The R_oA product is also strongly dependent upon E_g/T. Thus the required operating temperature decreases with increasing λ_c. For the better developed PV detectors, values of R_oA at low temperatures are often large enough that Johnson noise is negligible compared with amplifier noise.

As discussed in Section VI-A, the effective amplifier noise term becomes larger if the detector capacitance (C) is comparable to or larger than the amplifier input capacitance. Thus, for the lowest NEP, one is restricted to small area detectors. (An important parameter is the detector capacitance-to-area ratio (C/A) which depends on several material properties including the dielectric constant, bandgap and carrier concentration.) A particularly severe case is the PbSnTe PV detector which has very high junction capacitance ($\sim 1\mu F/cm^2$). In an effort to reduce the deleterious effect of this high capacitance, geometrical enhancement techniques have been developed to yield ratios of optical area to electrical area greater than 30.

Let us now consider the case of PC detectors. The NEP of a PC detector (including again its amplifier) may be written

$$NEP_{PC} = \frac{hc}{G\eta e\lambda}\left(4G^2e^2\eta\dot{N} + i_{n,e}^2 + i_{n,a}^2\right)^{1/2}$$

where the excess noise term ($i_{n,e}$) and the gain (G) are frequency, illumination, bias, and temperature dependent. As discussed in an earlier paragraph, the photon noise limited NEP (first term in the parentheses dominant), is $2^{1/2}$ times higher than for a PV detector with the same value of η. Neglecting the excess noise term, we see that at high backgrounds the only figure of merit is η while at low backgrounds the product G should be maximized. In intrinsic PC detectors, η is usually $\gtrsim$ 0.5 as is the case with PV detectors. However, in extrinsic detectors, a much lower absorption coefficient may yield substantially lower values of η. To increase the absorption efficiency, extrinsic detectors are sometimes mounted in chambers with reflective walls called integrating cavities.

The high capacitance of PV detectors is the chief limitation to their ultimate low background sensitivity. This suggests that PC detectors with their low capacitance might eventually be more sensitive, particularly since $G\eta > 1$ is in principle possible.

An unconventional, but revealing, way to summarize the status of development of photon detectors is to plot the minimum photon rate that can be detected in a 1 Hz bandwidth (NE$\dot{N}$) as a function of $\dot{N}$. Available data are shown in Figure 4.

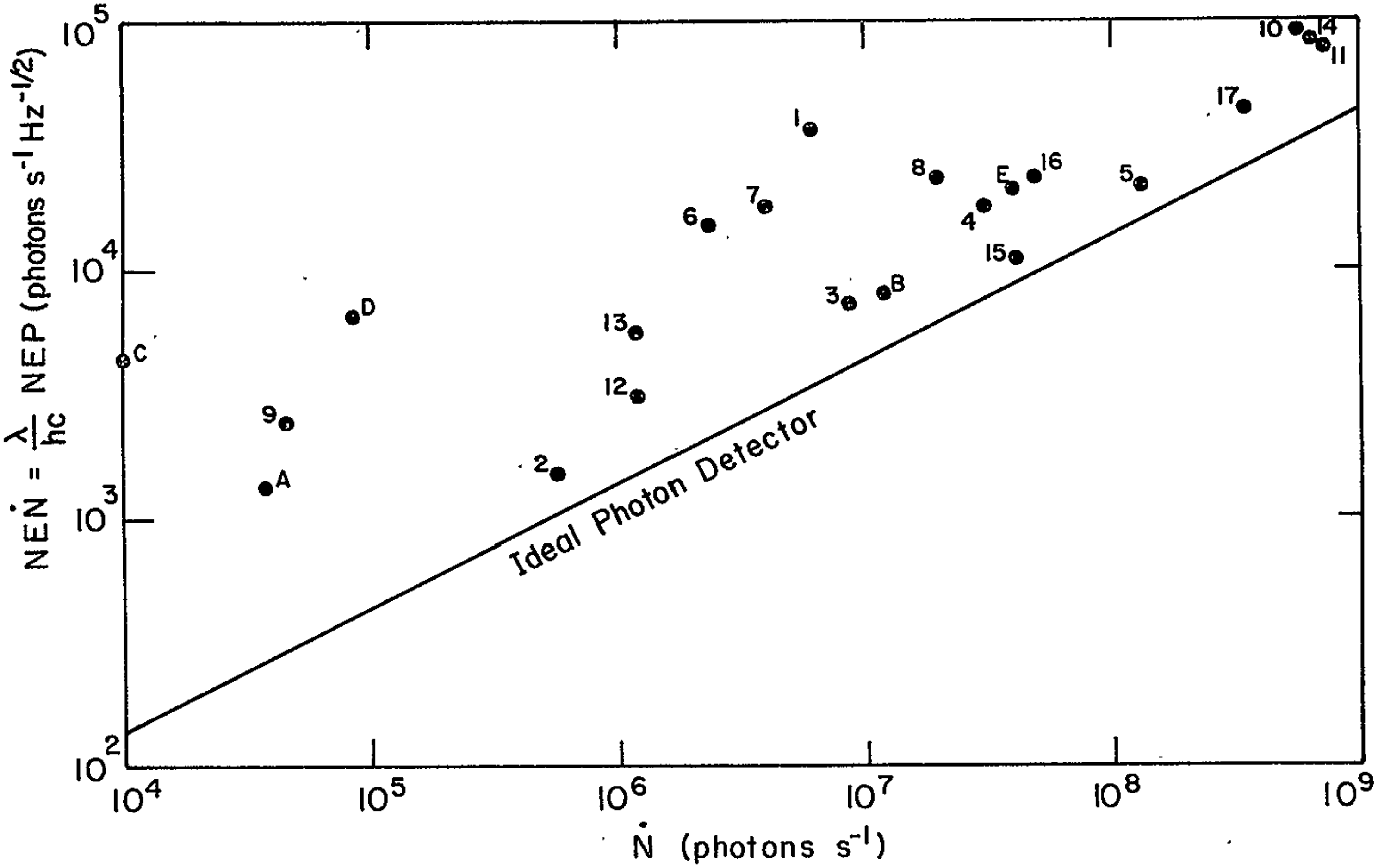
III-C INTRINSIC PV AND PC DETECTORS

Infrared detectors have been fabricated from a wide variety of intrinsic semiconductor materials. The first detectors were made from elemental semiconductors such as Ge and Si, and simple compound-semiconductors such as PbS, PbSe, InAs, and InSb. Interest in longer wavelength response than is available in these simple materials, and the desirability of tailorable spectral response, has led to the exploration of a number of

Fig. 4. The measured noise equivalent photon flux (NE$\dot{N}$, photons s^{-1} $Hz^{-1/2}$) for a number of low background detector tests is plotted as a function of the photon flux ($\dot{N}$, photons s^{-1}) incident upon each detector. The sloping line represents the performance of an ideal ($\eta = 1$) photon detector obeying Poisson statistics. Because NE$\dot{N}$ is defined for a unit bandwidth the ideal limit is NE$\dot{N}$ = $(2\dot{N})^{1/2}$. The points that are plotted came from a variety of sources and in many cases do not represent optimal performance for a particular detector or detector type. The key to the points has the form: detector type, test wavelength (not necessarily wavelength of peak performance), detector temperature, comment (if any). The points are:

1. PbS (PC), 3μm, 150 K
2. InSb (PV), 2μm, 4 K
3. InSb (PV), 5 μm, 65 K (flashed)
4. InSb (CID), 4.2 μm, 77 K
5. InSb (CID), 4.2 μm, 77 K
6. PbSnTe (PV), 10 μm, 30 K
7. InAsSb (PV), 4.3 μm, 80 K
8. GaInSb (PV), 4 μm, 80 K
9. HgCdTe (PC, trapping mode),3 μm, 5 K
10. HgCdTe (PV), 4 μm, 100 K
11. HgCdTe (CCD), 4.3 μm, 77 K
12. Si:As, 15 μm, 2.5 K, (typical IRAS)
13. Si:Sb, 15 μm, 2.5 K, (typical IRAS)
14. Ge:Cu, 10 μm, 4.2 K
15. Ge:Ga, 94 μm, 3 K, cavity
16. Ge:Ga, 94 μm, 3 K, no cavity
17. Ge:Ga, 150 μm, 2 K, stressed

A. InSb, 2.2 μm, 4 K, (from Table II)
B. Si:Ga, 11 μm, 2.5 K, (from Table II)
C. Si:As, 22 μm, 2.5 K, (from Table II)
D. Si:Sb, 24 μm, 2.5 K, (from Table II)
E. Ge:Ga, 61 μm, 2.5 K, (from Table II)



$N\dot{E}N = \frac{\lambda}{hc}$ NEP (photons s^{-1} Hz$^{-1/2}$)
$\dot{N}$ (photons s^{-1})
Ideal Photon Detector
10^2
10^3
10^4
10^5
10^6
10^7
10^8
10^9
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
A
B
C
D
E

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ternary and occasionally quaternary alloy-semiconductor systems. Currently the most advanced alloy systems for infrared detection are GaInSb, InAsSb, PbSnTe, and HgCdTe.

The first available intrinsic detectors were generally operated in the PC mode. These, however, have been largely superceded by photovoltaic detectors. This trend is true for both high-performance single detectors and array elements.

1. Group IV Semiconductors

The well known semiconductors Ge and Si exhibit intrinsic absorption in the near infrared region shortward of 1.6 μm and 1.1 μm, respectively. Silicon photodiodes exhibit high quantum efficiency and are amplifier noise limited in nearly all cases. For moderately high backgrounds, where the detectors are photon-noise limited, their high quantum efficiency makes them better than photomultipliers. Avalanche photodiodes in silicon are reasonably well developed and can reduce the amplifier noise limit somewhat. Recent advances in Ge purification have allowed high quality Ge photodiodes to be made.

Charge-coupled-device (CCD) and charge-injection-device (CID) imagers are well developed in intrinsic silicon. Extremely low-noise CCD arrays with long integration times have been developed by NASA for use on the Space Telescope.

2. Group III-V Semiconductors

Visible and infrared photodetectors have been made of many combinations of Al, Ga, and In with P, As, and Sb. The chief infrared materials have been InAs and InSb, with the alloys GaInSb and InAsSb now under heavy development.

Astronomers have been using InSb PV devices for ground based observations for several years with continually improving sensitivity. R_0A values greater than $10^7 \Omega cm^2$ at 77 K have been reported. A technique called "flashing" that uses brief illumination of a cold detector with strong near-IR radiation has achieved values higher than 10^9 Ωcm^2. Cooling to 5K, without flashing, has yielded R_0A products greater than 10^{10} Ωcm^2 which easily challenge the best amplifiers. Upon cooling below 30 K some InSb detectors show a gradual falloff in responsivity with increasing wavelength. It is possible that this loss could be avoided in a different device geometry. InSb photodiodes have typical capacitances of ~ 50 nF cm^{-2} which are comparable to other III-V and II-VI devices. Techniques used to reduce the much higher capacitance of IV-VI diodes could probably be used in III-V and II-VI detectors, and would provide a useful gain in sensitivity.

Schottky-barrier detectors, CCDs, and CIDs have all been demonstrated in InSb, which is the best studied and one of the best behaved compound-semiconductor materials. The InSb CID is used in one of the most successful of the present intrinsic detector arrays. Background noise limited operation at 77 K with η ~ 0.5 has been demonstrated at moderate (~ 3 x 10^{12} photons $cm^{-2}s^{-1}$) background levels. Substantial improvement has been demonstrated for individual CID elements operating at lower temperatures.

The alloy systems GaInSb and InAsSb can be varied to yield devices with λ_c values covering the range 1.6 to 9 μm. R_0A values greater than $10^6 \Omega cm^2$ at 80 K have been reported for diodes with λ_c ~ 4.3 μm in both systems. Self-filtering devices have been demonstrated with a short wavelength cut-on produced by a different composition alloy in a backside illuminated structure.

3. Group IV-VI Semiconductors

PbS and PbSe PC detectors for the 1 to 5 μm region have been available for many years, but their performance at low backgrounds has been surpassed by PV detectors such as InSb. The main IV-VI detector material of present interest is PbSnTe, although detectors have been made in several other IV-VI ternary alloys e.g., PbSnSe, PbSSe, PbGeTe. Detectors have been fabricated with response beyond 20 μm although the main effort has been in detectors for 8 to 14 μm. For this region, PV detectors with very high values of R_oA at low temperature are now available. These are generally amplifier noise limited because of the high junction capacitance of PbSnTe diodes. The high thermal expansion of PbSnTe presents a problem for interconnection of large diode arrays with Si multiplexer chips.

4. Group II-VI Semiconductors

One of the most versatile infrared detector materials is HgCdTe. By varying the alloy composition, detectors with λ_c values from 2 to 30 μm have been fabricated. High performance PC detectors for intermediate backgrounds have been available for several years and there is at present an intense development effort in PV devices. High values of R_oA ($>10^6 \Omega cm^2$), have been attained in detectors with $\lambda_c < 5$ μm. It is expected that high values of R_oA will be available in longer wavelength compositions at low temperatures within a few years.

At the present time HgCdTe PC detectors are not under heavy development. Below a transition temperature which depends upon composition, HgCdTe PC detectors change from the normal PC mode of operation to what is known as "trapping mode", where very large values of G ($> 10^4$) are observed. The "trapping mode" mechanism is not presently understood but is characterized by a strong dependence of responsivity and spectral response upon background illumination, and by spatial non-uniformity. While very high sensitivities have been obtained due to the large gain, effective use of "trapping mode" devices may be difficult until these properties are understood and controlled.

CCDs and CIDs are under development in HgCdTe as well as more conventional hybridization of PV detectors with Si CCD multiplexers.

III-D EXTRINSIC PHOTOCONDUCTIVITY IN Si AND Ge

Impurity photoconductivity in Si and Ge has been studied extensively for 25 years. Most of the recent development effort has gone into Si rather than Ge for several reasons including the mature MOS and CCD technologies in Si, the possibility of smaller detectors because of stronger absorption in Si, and relatively small DoD interest in the region $\lambda > 30\ \mu m$ where Ge:XX must be used.

The long wavelength limit λ_c to the response of an extrinsic photoconductor depends strongly on both the host material and the dopant, and also weakly on temperature. For a given host-dopant combination there is usually a maximum in the photon absorption coefficient at a wavelength which is typically 0.6 to 0.95 times λ_c. The detailed shape of a detector's spectral response function depends upon a number of fabrication parameters, such as doping concentration, detector thickness, and contact geometry, as well as the fundamental variation of the absorption coefficient with wavelength. The spectral response can be further modified by the use of anti-reflection coatings, back-surface reflectors, and integrating cavities. Optimization of the performance is a complex process which is made more difficult by the presence of the poorly understood anomalous effects discussed below. Typically an extrinsic detector will have quantum efficiency greater than half its peak value over a wavelength range from λ_c/x to λ_c, where x varies from 2 to 6.

Photoconductivity has been studied in extrinsic silicon and germanium with a wide variety of impurities. The choice of dopant is influenced by a number of factors besides the cutoff wavelength λ_c and the absorption cross-section. These factors include ease of uniform doping at a controllable level without introducing undersirable impurities and compatibility with other processing steps. Because of these diverse requirements the best dopant for a discrete detector may not, for example, be best for a monolithic array. Values of λ_c for some of the more fully developed dopants in both silicon and germanium appear in Figure 3.

Doped germanium detectors have been developed to cover a wide wavelength region, but currently those detectors with $\lambda_c < 30$ μm, such as Ge:Au, Ge:Hg and Ge:Cd, have been supplanted by Si:XX detectors. However, Ge:Cu ($\lambda_c = 31$ μm) still remains important for use as a photomixer for heterodyne receivers. The shallow impurity levels in Ge produced, for example, by Zn, Be and Ga make it possible to cover the region from 30 to 120 μm. By subjecting Ge:Ga to uniaxial stress, the long wavelength cutoff can be further extended to 210 μm. Ge:Zn was one of the first extrinsic detectors developed and could probably be improved by more recently developed processing techniques. For Ge:Ga there is a long history of development culminating in the detectors developed for the IRAS and Spacelab 2 IRT experiments. Development of Ge:Be is relatively recent and has been too slow for use on these missions.

Because of the small doping permitted in Ge:Ga, several millimeters of optical pathlength is needed to produce adequate absorption, especially near 30 μm. Integrating cavities are especially useful under these conditions. Germanium also has an inherent lattice absorption between 30 and 40 μm which competes with the impurity absorption. A fully developed Ge:Be or Ge:Zn detector should offer an improvement over Ge:Ga in this interval.

The high doping levels used in extrinsic silicon detectors makes the absorption length for photons relatively short ($\lesssim$ 1 mm). The small detector dimensions and low atomic number of Si should make these detectors less sensitive to energetic nuclear particles than Ge:XX detectors with their larger volume and atomic number.

1. Responsivity

The well developed extrinsic photoconductors have current responsivities in the range from 1 to 35 AW^{-1} for silicon or short wavelength germanium detectors and 5 to 24 AW^{-1} for Ge:Ga, with associated $G\eta$ products in the range from 0.05 to 2.7. It is difficult to determine G and η independently from experimental measurements. Typical peak values for η in well developed materials are 0.1 to 0.4. Values as high as 1.0 have been reported while many of the less developed systems have values as low as 0.01. The photoconductive gain, G, can have values greater than 1. Extrinsic detectors, however, often exhibit peculiar effects if G is greater than about 0.5, which can make it difficult to realize the potential decrease in NEP arising from high G.

2. Anomalous Effects

At high bias and low background levels extrinsic photoconductors may exhibit a number of peculiar effects. Many of these effects are thought to be related to properties of the semiconductor-contact interface, but full explanations are not available. The lack of reproducibility of these effects, even in nearly identical detectors, has hampered systematic understanding or empirical control. Among these anomalies are the "memory effects", in which the amplitude of the response to a small signal may depend upon the light level falling on the detector in the preceding few seconds. As the bias and therefore the photoconductive gain are decreased, the importance of these memory effects, and other long time constant (10 to 30 s) anomalies, decreases. With present Si:As and Si:Sb detectors one can expect to sacrifice about a factor of 2 in responsivity in order to reduce the memory effects significantly.

Another effect observed when $G \gtrsim 0.5$ is characterized by a lower value of G for modulated signals than for steady-state signals. Several terms have been used in the literature to refer to this phenomenon: dielectric relaxation, carrier sweepout, space-charge effect, and gain-saturation. A theory exists but detailed agreement with experimental data is not very good.

Spatial non-uniformity of both spectral and overall response has also been observed in some detectors with partially illuminated surfaces under conditions of low background and high bias.

At low illumination levels many extrinsic detectors produce spontaneous current spikes. These are typically very fast pulses (usually limited by the preamplifier electronics to $\sim 10^{-3}$ seconds) which are larger than the detector noise by a factor of 2 to 10^3. Typical spiking frequencies are 0.1 to 10 per second. The occurrence of spikes depends on the detector temperature, the background, and the previous illumination of the detector. The spiking characteristics vary from one manufacturer to another and even from one batch of detectors to another from a single vendor. Electronic supression techniques and/or the equivalent software processing which have been developed to remove the fast pulses resulting from interactions with nuclear particles will also remove these spontaneous spikes from the detector signal. Except in the cases of very frequent spiking ($>10s^{-1}$) or long spikes ($>5 \times 10^{-3}$ s) the signal can be recovered with only a minor penalty in noise.

3. Ultimate Sensitivity

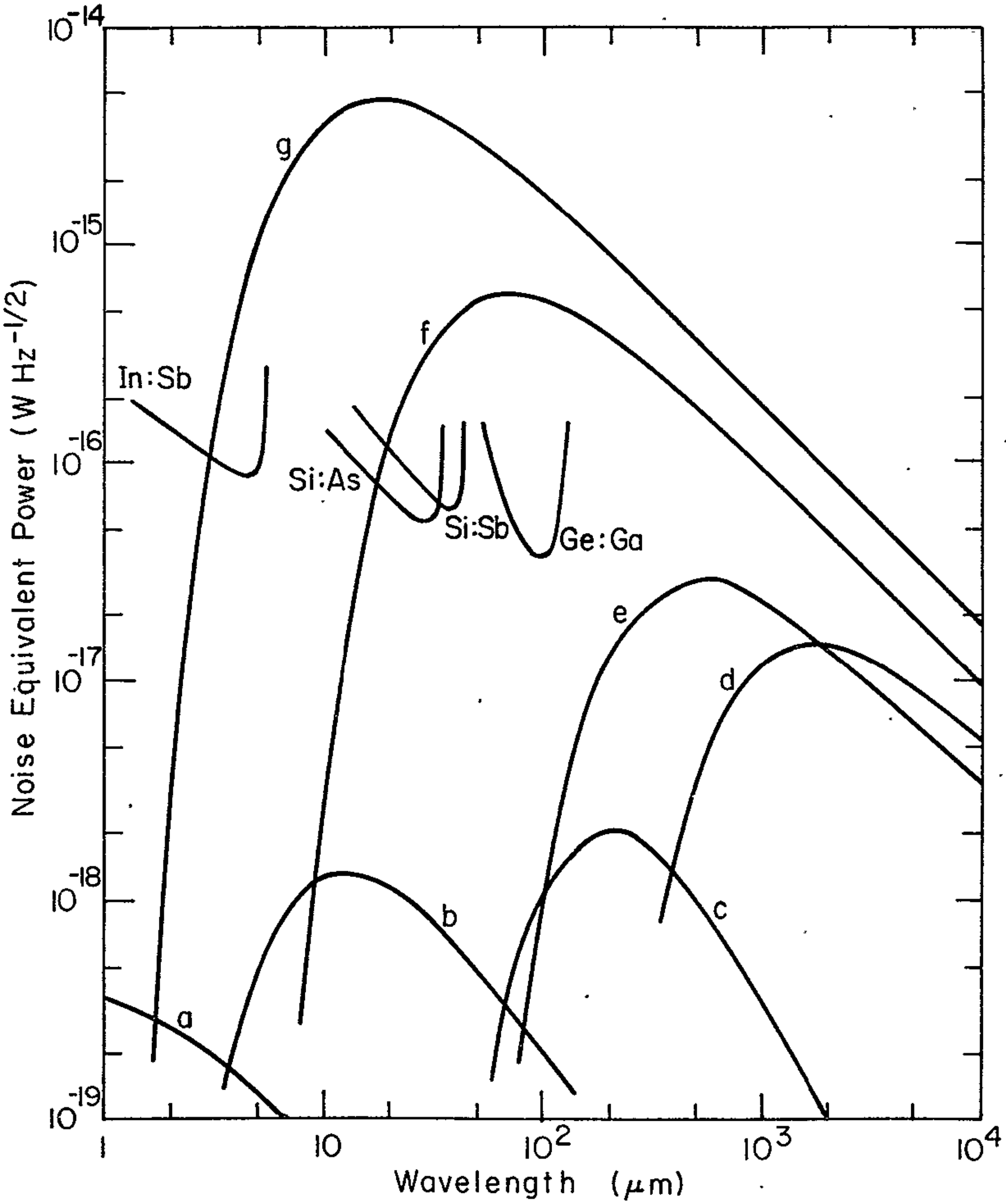
The lowest NEP values reported for extrinsic detectors are about 3 to 10 x 10^{-17} $WHz^{-1/2}$, and are amplifier noise limited. These values were achieved by operating the detectors at high bias. As noted earlier, this increases both the importance of memory effects and the spontaneous spiking problems. Neither of these would seriously affect low level photometry, but both would trouble scanning instruments such as IRAS and rapid scan spectroscopic systems. Figure 5 and Table II summarize current results on the performance of detectors developed and/or considered for IRAS or for the Spacelab 2 IRT.

III-E PHOTON DETECTORS BEYOND 120μm

1. Germanium

The long wavelength limit of photon detectors currently used in astronomy is set by the ionization energy (E_i) of the common shallow acceptors in Ge. This acceptor ionization energy, which corresponds to 120 μm in Ge:Ga, can be reduced by the application of a uniaxial stress along the (100) crystallographic direction. A photoconductive detector has been constructed using this technique which has a long wavelength cutoff at 210 μm, NEP $\approx 6 \times 10^{-17}$ $WHz^{-1/2}$, and a $G\eta$ product (in a cavity)

Fig. 5. The current (Oct. 1978) measured low-background NEPs of detectors that will be flown on the IRAS and Spacelab 2 IRT missions in 1981-82, compared with astrophysical background limits taken from Figure 1. Because of the larger throughput and bandwidth used in the IRAS and Spacelab 2 IRT missions, the background limitations anticipated are closer to the detector performance than the limiting NEP curves here. The plot illustrates, however, the detector improvement required before the full benefit of diffraction limited space missions can be obtained.



Noise Equivalent Power (W Hz$^{-1/2}$)
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
g
f
In:Sb
Si:As
Si:Sb
Ge:Ga
e
d
c
b
a
1
10
10^2
10^3
10^4
Wavelength (μm)

XBL792-5842

TABLE II.

PERFORMANCE OF SAMPLE DETECTORS CONSIDERED FOR USE ON IRAS AND SPACELAB 2 IRT.

	λ_c (μm)	λ_{test} (μm)	$G\eta$	$\dot{N}$ (photons s^{-1})	NE$\dot{N}$ (photons $s^{-1}Hz^{-1/2}$)	NEP (W $Hz^{-1/2}$)
InSb	5	2.2	.39	3.9×10^4	1.3×10^3	1.2×10^{-16}
Si:Ga	18	11	.41	1.2×10^7	7.8×10^3	1.4×10^{-16}
Si:As	24	22	.19	1.0×10^4	4.4×10^3	4.0×10^{-17}
Si:Sb	30	24	.13	6.6×10^4	6.6×10^3	5.5×10^{-17}
Ge:Ga	120	61	.17	4.0×10^7	2.2×10^4	7.0×10^{-17}

of 0.3. Although the use of a mechanically stressed semiconductor as a detector is an unconventional technique, it appears to be sufficiently well controlled for applications in space astronomy. The benefits which are obtained by extending photoconductive technology to longer wavelengths are indicated by the fact that the NEP of this detector is about 2 orders of magnitude lower than for a bolometer at the same operating temperature of 2 K, and about one order of magnitude lower than the best bolometer made at any temperature. Unfortunately the stress technique cannot be extended to longer wavelengths in Ge.

2. III-V Semiconductors

In some compound semiconductors, such as GaAs and InSb, impurity ionization energies are smaller than in Ge so extrinsic photoconductivity at longer wavelengths is possible. Photoconductivity in GaAs has been extensively investigated. A rather smeared out photoconductive onset edge has been observed which extends beyond 300 μm. The performance of this device in high backgrounds, such as those encountered in planetary astronomy, is relatively good, but its low background performance is not competitive with bolometric detectors. The poor sensitivity in low background, and that observed in other extrinsic III-V photoconductors is probably due to residual impurities. Preparation of these compounds with adequate purity is likely to require a major effort.

In the lowest carrier concentration InSb available, impurity state overlap and strong impurity band effects are seen. Long wavelength detectors and mixers have been developed from InSb which are often called hot electron bolometers. The mobility in n-type InSb increases with increasing electron temperature. The resistance of the sample thus reflects the heating of the electron plasma by absorbed photons. This type of detector operates efficiently at frequencies in the neighborhood of the electron plasma frequency which is generally around $\lambda \sim 1$ mm. The best detector performance obtained thus far is not competitive with modern composite bolometers. The performance as a mixer is discussed in Section V.

III-F ARRAYS

1. Advantages of Arrays

In many instruments an array of detectors has potential advantages in integration time or signal/noise ratio over a single detector element. When the system is arranged so that parallel sampling of the scene is accomplished by the n array elements, an observation with a fixed signal/noise ratio can be made in n^{-1} the time required by a single detector. Alternatively, for a given integration time, an array with parallel sampling could provide a $n^{1/2}$ improvement in signal/noise ratio. These improvement factors apply for the ideal case where the scientific mission requires at least n data elements, where the sensitivity of each array element is equal to that of the discrete detector, and where no additional noise sources are introduced by the array. Furthermore, parallel sampling discriminates against non-stationary types of noise which can strongly affect sequentially sampled systems.

Most of the infrared detector development programs currently sponsored by the DoD are aimed towards combining large numbers of detectors (in either one- or two-dimensional arrays) with suitable signal processing electronics. Such a combination is sometimes referred to as an "integrated array". Besides the general sensitivity improvements with arrays listed above, many types of integrated array promise additional practical advantages. They allow time averaging of infrared signals at the detector, rather than after amplification. They also have the ability to do on-chip multiplexing, which means that each detector element no longer requires an individual set of hand-wired electrical leads. Furthermore, on-chip power dissipation is often vanishingly small since a single output amplifier can be used. For large arrays, costs may be lower since automated photolithographic production techniques are used. These techniques also allow smaller detectors and higher focal-plane filling-factors than are possible with discrete detectors.

Many different types of integrated detector arrays are being developed. A majority of these approaches use charge coupled devices (CCDs) to collect photo-generated charge from the individual detector elements and transport this charge to an output amplifier. A CCD is a metal-insulator-semiconductor (MIS) structure in which potential wells, capable of accumulating, storing, and transferring charge, can be created beneath the metal electrodes. In an integrated array using a CCD, the photocurrents generated in the individual detector elements are collected in the form of charge in such potential wells. All types of photodetectors (extrinsic PC, intrinsic PC and intrinsic PV) can be used. The details of how the detector photocurrent is converted into CCD charge packets, however, differ for each case. At the end of an accumulation period, voltage is applied to an adjacent electrode, and the charge packet is transferred laterally into a newly-created adjacent potential well. Charge packets from all array elements are shifted through the device in this manner to an output amplifier where the stream of charge packets produces proportional output voltages. (For a two-dimensional array a second transfer process in the perpendicular direction can be used.) This time-dependent voltage is then amplified and conveyed out of the cryogenic environment. Detailed aspects of CCD operation include the electrode clocking pattern, which typically includes multiple phases and sequential overlapping clock voltage pulses for efficient charge transfer, and the various schemes for injection of charge into the transfer section.

Another approach to integrated detector arrays using an MIS structure is the charge injection device (CID). In contrast to arrays with CCD readout, detector elements in a two-dimensional CID array are individually addressable (random access) by row and column. Readout is accomplished by injecting the charge contained in the selected potential well into the substrate and sensing the substrate current. Further multiplexing electronics may be integrated with the basic CID in a hybrid structure.

The basic sources of detector noise in array elements are the same as for discrete detectors. Performance of a given element may, however, be significantly worse due to the detailed requirements of array fabrication. Besides the noise of the detectors themselves, there is also the effective amplifier noise of the array electronics. For an array using a CCD, the CCD-related noise sources can be divided into three parts arising 1) from the process of injecting the detector photocurrent into the CCD, 2) from the process of charge transfer along the CCD, and 3) from the readout of charge by the output amplifier.

The most highly developed CCD imagers are intrinsic Si devices for visible light. In this case the charge is generated directly in the wells of the CCD. In these visible CCD arrays, charge-transfer and readout noise have been reduced to very low levels. In the analogous infrared-sensitive charge coupled devices, the so-called IRCCDs, the performance achieved so far is much worse, and is unlikely to approach that of visible Si devices in the near future. When infrared photon detectors of various types are coupled to Si CCDs, the dominant noise source is often the injection process, and is much larger than any noise source in visible CCD imagers. The currently available integrated infrared arrays have fairly high readout noise and may also have short charge storage times, yielding NEPs that are substantially worse than those of present discrete detectors. As readout noise and storage time improve, monolithic detector arrays may have a major impact upon low background infrared observations. The sensitivity of charge integrating detectors is discussed in detail in Section VI-A5.

The DoD is providing substantial (> $10M per year) funding for integrated array development. Mosaic focal plane arrays composed of large numbers of multi-element chips are planned. Since these arrays are potential components in future surveillance systems, much of the performance data, and in some cases the actual hardware, are currently classified.

It should be recognized that array requirements for astronomical applications often differ significantly from requirements for DoD applications which have guided infrared array developments to date. Detection of faint infrared astronomical objects will require long integration times, perhaps in the seconds-to-minutes range, as opposed to the millisecond and shorter integration times typically used in defense systems. The astronomical application does not require sophisticated on-chip processing functions. An astronomical array should be "calibratable," since scientific measurements, being photometric in nature, must not only detect an object but also indicate its absolute brightness. Versatile space telescopes will require liquid-helium cooling, so low detector operating temperatures will be available for detectors at any wavelength. Current monolithic arrays have pixel sizes of approximately 0.1 x 0.1 mm. For some astronomical applications a larger pixel size may be desirable. This will probably be accompanied by some increase in NEP. Larger pixel sizes appear necessary at longer wavelengths if the use of several pixels to cover a diffraction limited image is to be avoided.

Perhaps one area of difference in emphasis between DoD and NASA requirements is the NASA need for extremely low values of NEP for low background astronomy. Since the NEPs of discrete detectors are improving, it is difficult to predict when (or whether) the performance of integrated arrays will surpass the performance of arrays of discrete detectors in such applications.

In general, although progress in some areas has been quite rapid, a large amount of work on materials, processing, and characterization remains to be done before the promise of integrated detector arrays will be fully realized. At present, for example, the estimated NEP at low background of the best integrated extrinsic Si arrays (using a 0.1 sec integration time) is at least a factor of 10 larger than the NEP of a state-of-the-art extrinsic Si discrete detector. Therefore, an integrated array operated under the most favorable conditions would require $\gtrsim 10^2$ times more detectors to break even with a discrete array using the same integration time.

Because of the great expense involved in array developments and the relative immaturity of the technology in some areas, it does not seem appropriate for NASA to undertake a large-scale array development program intended for low background astronomy in the near future. The on-going DoD programs in both monolithic and hybrid arrays should, however, be actively monitored, and where possible, sample arrays should be obtained for evaluation under astronomical conditions. There may be cases where NASA can capitalize on the DoD investment by modifying existing designs to suit astronomical needs. Ultimately, integrated detector arrays with low NEP and long integration times are desired for astronomical applications, both in the range ($\lambda < 24\ \mu m$) where substantial DoD funding has been available, and at longer wavelengths, where it appears integrated array development costs will have to be borne by NASA.

2. Status of Development

Three general types of infrared arrays utilizing CCDs are now under development. In the monolithic-extrinsic design a doped Si substrate provides the infrared-sensitive medium, and charge transfer is carried out in a lightly-doped Si CCD layer at or near the surface. In the monolithic-intrinsic array an intrinsic semiconductor substrate, such as InSb, is used for detection, charge transfer and readout. The hybrid array uses separate substrates for detection and charge transfer. Indium "bumps" are commonly used in hybrid arrays to electrically and mechanically interface the detector substrate to a Si CCD multiplexer. Within each general class, a large number of specific design approaches have been pursued. A recent NASA report, listed in the suggested reading, gives more detailed information on some specific array developments.

The most highly developed type of infrared detector array is the monolithic-extrinsic array. The operation of 32 x 32 test chips of Si:Ga and Si:In has been successfully demonstrated. A 12 chip Si:XX mosaic focal plane is currently being evaluated. Work on Si:As arrays for lower backgrounds is also in progress. A reasonable amount of high-background laboratory characterization of the Si:Ga and Si:In arrays has been carried out, although not much is known about monolithic-extrinsic array performance in low background and at liquid helium temperatures. Data on Si:In arrays indicate that sensitivities are considerably poorer than those acchieved by discrete detectors. Responsivities substantially below those of single detectors have been reported. Fast interface state noise, which arises in the charge transfer process, dominates at low background, with typical values an order of magnitude or more above those achieved by intrinsic Si CCDs.

Developmental efforts towards monolithic-intrinsic IRCCDs have largely concentrated on InSb and HgCdTe. Prototype 1 x 20 InSb IRCCDs have recently been produced, but their electrical and optical characteristics have not been fully established. Intrinsic HgCdTe arrays are under development, but successful charge transfer in this material is just now proving possible. Intrinsic arrays are also being developed in sandwiched multilayer form where related semiconductor alloy layers perform different functions, e.g., infrared detection in InAsSb and charge transfer in InGaSb. Although the promise of low NEP exists for IRCCDs, substantial problems remain. The technology for these intrinsic materials is far less advanced than that for silicon, and the high surface state densities are producing leakage currents as large as 10^5 times that achieved by extrinsic silicon CCD arrays. It appears that roughly 5 to perhaps 10 years of development will be required before high-performance intrinsic CCDs become available.

A number of detector materials (InSb, InAsSb, PbSnTe, HgCdTe) are being developed in hybrid arrays where the well-developed silicon CCD technology is exploited. Each detector cell requires an individual micro-connection to the adjacent multiplexer terminal, and the hybrid design must accommodate the differential thermal contraction of the detector and multiplexer materials. Reasonable progress has been made in indium-bonding techniques, and a 98 percent interconnect yield on a 32 x 32 InAsSb array has been reported. Interface circuitry problems are more acute in the hybrid approach, and difficulties with gate-threshold nonuniformities have been encountered. Hybrid arrays are at an intermediate state of development between monolithic intrinsic and monolithic extrinsic arrays.

As discussed earlier CID represents a second general type of integrated array. Most CID development has been done on InSb, with some work on extrinsic Si CIDs. Excellent performance at moderate background has been demonstrated in an InSb CID at 77 K. Preliminary tests suggest that substantial improvement should be possible with lower operating temperatures.

III-G QUANTUM-COUNTERS

The idea behind infrared quantum-counting (and the parametric up-conversion technique discussed in Section V-F) is that of converting the wavelength of the infrared signal into a spectral region where good detectors exist. Initially the concept was to convert infrared into visible radiation, thereby allowing the use of photomultipliers, image tubes, and film detectors. The concept can be broadened to allow for conversion from one infrared wavelength to another. This might prove advantageous since detector array technology is likely to become available for some infrared wavelengths, but not others. Parametric up-conversion is a coherent process while quantum-counting is incoherent. At present neither technique is competitive with PV, PC, or bolometric detection. In principle, if formidable materials problems can be solved, up-conversion and quantum-counting could yield ideal receivers.

The concept of a quantum-counter is to use a multilevel atomic, molecular, or solid-state system which has been pumped into a long-lived excited state as a medium to absorb infrared radiation. An infrared photon either ionizes the system so that the emitted electron can be detected or causes the emission of an energetic photon which can be detected with a photon counter. The detection process is incoherent and therefore has no limit on the number of modes that can be detected. The quantum-counting process, in principle, introduces no additional noise beyond the photon-noise of the infrared signal and background (with the appropriate quantum efficiency), since there is no counter output without an infrared input photon.

Not much has been done with such detectors since the early work using the level structure of trivalent rare earth ions in various host lattices. Difficulties have been encountered in finding systems which have long-lived pumped levels with strong IR absorption, which are also transparent to the output fluorescence. Values of NEP = 3×10^{-9} W $Hz^{-1/2}$ obtained for signal $\lambda = 2\ \mu m$ are far from being competitive with direct detection.

A recently proposed idea is the use of the Rydberg states of alkali atoms pumped by tunable dye lasers and ionized by a combination of the infrared input signal and a static electric field. Values of NEP $\lesssim 10^{-16}$ W $Hz^{-1/2}$ have been predicted.

IV. BOLOMETERS

Bolometers are devices which respond to heating produced by absorbed radiation. Bolometric detectors have three essential parts: an absorbing surface, a thermometer, and a thermal link to a heat sink. The design of these elements depends on the wavelength range over which the bolometer is to be operated, the size of absorbing element required, the background infrared power, and the temperature of the heat sink. Bolometers have had extensive use because of their response throughout the infrared spectrum and their high absorptive efficiency (typically from 0.5 to 1). Since maximum sensitivity is achieved at very low operating temperatures, this discussion treats only bolometers operated at 2 K and below. For applications with severe cooling constraints, such as deep space probes, properly optimized higher temperature (50 to 100 K) bolometric detectors might be significantly better than existing detectors.

Small liquid-helium-temperature bolometers with doped semiconductor thermometers have been important for high background observations at infrared wavelengths $\lesssim$ 100 μm. These generally make use of the absorption in the thermometric material. (A thin layer of black absorbing paint is sometimes used to reduce the large reflectivity of the semiconductor.) The most important current applications of bolometers are at submillimeter wavelengths where no sensitive photon detectors exist. At submillimeter wavelengths the most efficient bolometers are composite structures, using a metal film absorbing element on the reverse side of a thin transparent dielectric substrate which is in contact with a small thermometric element. A commonly used example is a sapphire or diamond substrate with a bismuth or a nickel-chromium-alloy film (thermometers are discussed below). There is an optimum surface resistance of the absorbing film for a given dielectric substrate. For example, on a sapphire substrate with index of refraction equal to 3, a film with surface resistance 200 ohms per square gives a frequency-independent absorptivity of 50 percent.

In low background environments, the fundamental limit to bolometer sensitivity is given by thermodynamic fluctuations in the heat exchanged with the low temperature reservoir. This energy fluctuation leads to a lower limit on the noise equivalent power of a bolometer, NEP = $(4kT^2\mathcal{G})^{1/2}$. Here T is the operating temperature, $\mathcal{G}$ is the thermal conductance between the bolometer and the heat sink, and k is Boltzmann's constant. An important operational parameter which is usually set by the experiment is the thermal time constant $\tau = \mathcal{C}/\mathcal{G}$, where $\mathcal{C}$ is the bolometer heat capacity. If the heat capacity of the bolometer is dominated by dielectric substances, as will often be the case for temperatures 0.3 K $\lesssim$ T $\lesssim$ 100 K, the heat capacity will be proportional to T^3. It follows that the sensitivity of a low temperature bolometer can be expressed as

$$\text{NEP} = FT^{5/2}\tau^{-1/2} .$$

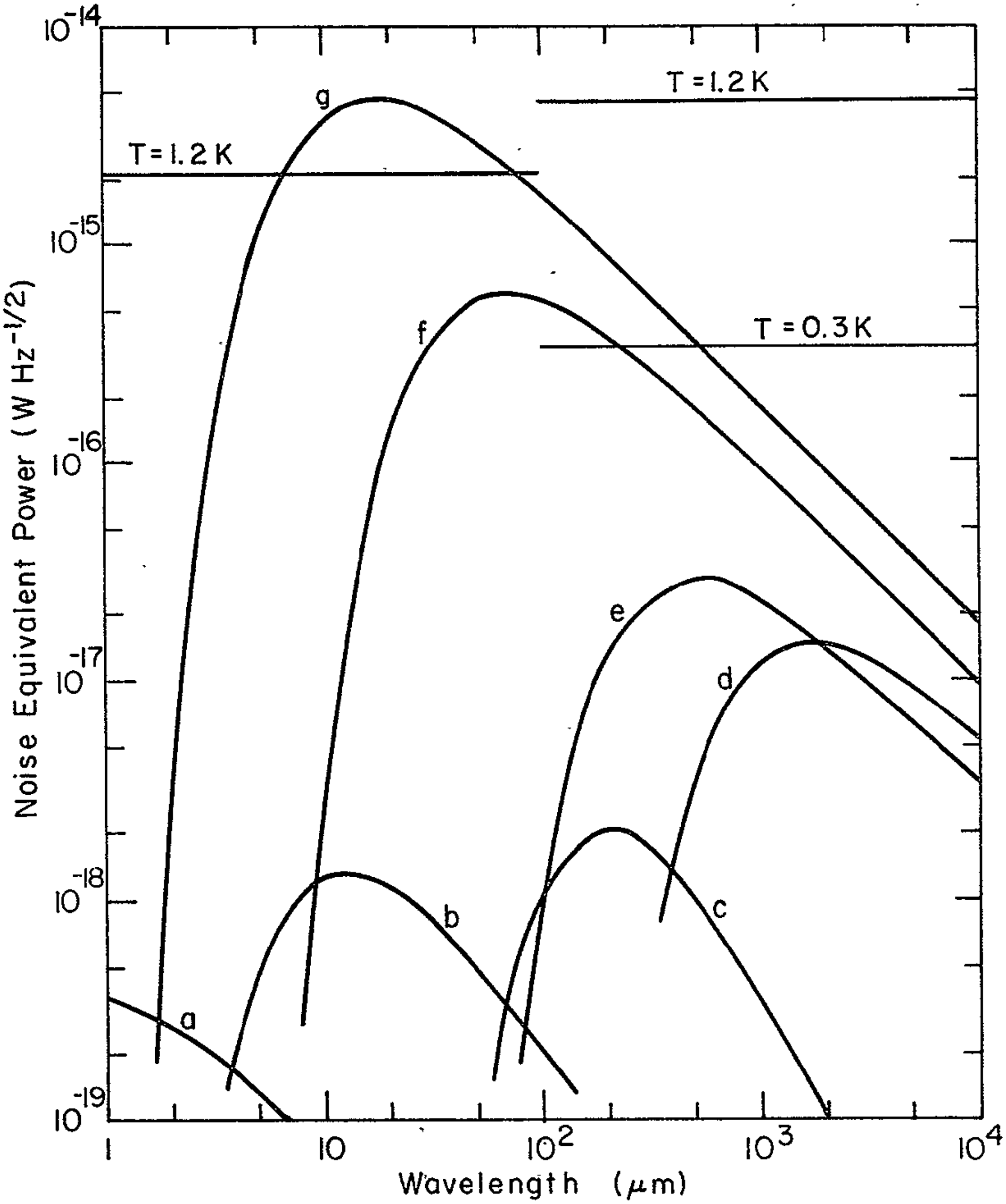
Values for the parameter F in the liquid-^{4}He temperature range are approximately 1 x 10^{-16} W $Hz^{-1/2}$ $K^{-5/2}s^{+1/2}$ for small short-wavelength doped-Ge bolometers and 3 x 10^{-16} W $Hz^{-1/2}$ $K^{-5/2}s^{+1/2}$ for large submillimeter-wavelength composite bolometers. These values are within a factor of 2 of the theoretically expected value $(4k\mathcal{C}/T^3)^{1/2}$. A Si integrated circuit version of the composite bolometer is projected to have F ~ 1 x 10^{-16} W $Hz^{-1/2}$ $K^{-5/2}s^{+1/2}$. Once F is determined for a given bolometer structure, the NEP expression above can be used to extrapolate the bolometer performance in low background to other values of T and τ. In practice, τ is adjusted by proper selection of the bolometer thermal conductance $\mathcal{G}$.

An ideal thermometric element for a bolometer should be able to measure the instantaneous temperature of the absorbing element without contributing any fluctuations of its own. The most commonly used (and only commercially available) thermometric element is a Ge chip heavily doped with Ga. At low infrared background, optimum operation is obtained with very small values of bias current. Under these conditions it has been possible to construct thermometers which make a negligible contribution to the noise of bolometers operated at low audio frequencies in both the liquid-^{4}He and -^{3}He temperature ranges. Current-dependent 1/f-noise in the thermometer places a limit on the lowest frequency at which bolometers can be operated efficiently. At present this limit is 5 to 10 Hz for Ge:Ga thermometers suitable for low background bolometers. Superconducting thermometers are a possible alternative to semiconducting thermometers and have demonstrated good laboratory performance to below 1 Hz. However, superconducting thermometers are more complicated to use than semiconducting thermometers because of the need to stabilize their operating temperatures and provide low-noise amplifiers which match their low impedance. It therefore remains desirable to reduce low frequency noise in semiconducting thermometers for applications benefiting from modulation frequencies below 10 Hz.

Figure 6 shows the performance achieved in negligible background with state-of-the-art bolometers at temperatures of 1.2 K and 0.3 K. Limits to detector NEP from several astrophysical background sources and from cold and warm telescopes are also shown for comparison.

In applications where the radiant background is not negligible, limits to bolometer performance are set by the incident infrared background power. Depending upon a number of system and bolometer parameters, this limitation can arise in either of two ways: the statistical fluctuations in the rate of energy deposition by background photons, and the average temperature rise above the bath temperature caused by the absorption of background power. The effects of photon fluctuations are fundamental and

Fig. 6. Representative NEPs of state-of-the-art bolometers operated in negligible background at temperatures of 1.2 K and 0.3 K compared with the various background limits from Figure 1. A time constant of 10 ms is used in all cases. For other time constants the NEP scales as $\tau^{-1/2}$. The bolometers chosen for this illustration are a conventional Ge bolometer for wavelengths less than 100 μm, and a composite bolometer (Ge thermometer on a sapphire substrate) for wavelengths greater than 100 μm. The break at 100 μm corresponds roughly to practice, but does not represent a sharp cut-off for either device.



T = 1.2 K
T = 1.2 K
T = 0.3 K
g
f
e
d
c
b
a
Noise Equivalent Power (W Hz$^{-1/2}$)
Wavelength (μm)
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
1
10
10^2
10^3
10^4

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unavoidable. To avoid the latter effect, the thermal conductance $\mathscr{G}$ must be made large enough to keep the temperature rise small. This, in turn, sets a lower limit to the thermodynamic noise contribution $(4kT^2\mathscr{G})^{1/2}$, which can be achieved. For arbitrary spectral filtering and background source temperature, there is a bolometer operating temperature below which the photon fluctuation noise always dominates. For bolometers operated at 1.2 K or below, the photon fluctuation limits from the astrophysical sources illustrated in Figure 6 is more restrictive than the sensitivity limits set by background power loading.

The optimization of a bolometer for high background applications is a complicated problem which cannot be treated in detail here. Since low heat capacity is not critical in high background bolometers, it is generally easier to fabricate an optimized bolometer for a high background than for a low background application. However, optimum performance at high background requires operation at higher bias power levels, which can increase problems with current noise in the thermometric element.

In the discussion of the fundamental limits to low background bolometer performance, it was shown that the achievable bolometer sensitivity varies extremely rapidly with operating temperature. The time required for a low background measurement varies as the fifth power of the operating temperature. For example, a bolometer operated at 0.2 K could obtain data in 5 minutes which would require a year of integration with a bolometer operated at 2 K. Though this extrapolation may be somewhat optimistic in that the metallic elements of any bolometer will dominate the heat capacity at sufficiently low temperature and cause the NEP to vary only as $T^{3/2}$, it nevertheless is a matter of great importance for the development of low background satellite systems that refrigerators be developed which can operate bolometric detectors at temperatures below the liquid-^{4}He temperature range. A number of such refrigerators have been developed for other purposes, and with a suitable development effort it should be possible to adapt such techniques to the space environment. It should also be noted that there are potential problems associated with bolometer operation at lower temperatures which need experimental investigation.

The best present bolometers are fabricated by hand, with the result that there are relatively limited sources and low yield of good quality detectors. For applications benefiting from arrays of more than a few detectors, development of more automated production techniques of high quality bolometers would be an important step.

The broad spectral response of bolometers places a strong demand upon spectral filters for rejection of unwanted radiation. For submillimeter photometry there is particular need for development of band pass filters which will operate at low temperatures and provide sharp band definition, high in-band efficiency, and strong out-of-band rejection.

One additional problem, which bolometer users have not had to face in low-altitude applications, is the rejection of unwanted signals and increased noise arising from energy deposited by charged particles and gamma rays. Single events can produce pulses of substantial signal-to-noise ratio in bolometers operated at and below liquid-^{4}He temperatures. Though some work has been done, experience is needed with pulse discrimination and/or suppression techniques that are applicable to bolometers.

V. COHERENT RECEIVERS

Two classes of receivers are used for infrared signals. The incoherent receivers discussed thus far in this report use infrared square-law detectors in which the output signal is proportional to the input power. This class includes photon detectors in which the energy of a photon is converted into the current of an electron in the output, bolometric detectors which are directly sensitive to the input power, and classical diode detectors or rectifiers which produce a dc current proportional to the square of the infrared voltage.

The second major class of infrared receiver uses a coherent mixing process to amplify the signal or to convert it to a frequency at which amplification and detection are more convenient. Heterodyne down-converters, parametric amplifiers and up-converters belong in this category. In coherent receivers the signal electric field is mixed with a pump or local oscillator (LO) field. Only that incoming signal mode which coincides with the pump or local oscillator mode contributes coherently to the output. In practice, therefore, these devices receive only a single mode, whatever nonlinear element or coupling scheme is used. In nearly all astronomical systems the output of the linear coherent device is subsequently detected (rectified) to yield a dc receiver output.

In many infrared astronomical experiments a choice must be made between the use of an optical spectrometer (such as a grating or a Fabry-Perot interferometer) followed by a square-law detector, or the use of a heterodyne down-converter followed by radio frequency filters and detectors. Short wavelengths and wide bandwidths generally favor the optical spectrometers, whereas long wavelengths and narrow bandwidths favor the heterodyne technique. The tradeoff between these approaches is discussed in detail in Appendix A.

V-A. FIGURES OF MERIT FOR COHERENT RECEIVERS

Although the figures of merit for coherent receivers are different from those used for square-law receivers (direct detectors), some analogies are possible. In an astronomical application in which the output is eventually rectified, the concept of an NEP can be used to describe the performance of a coherent receiver system. As is the case with background limited direct detectors, the minimum detectable power depends upon both the infrared bandwidth B and the post-detection bandwidth. When $kT_N \gg hc/\lambda$, the NEP is often expressed in terms of an equivalent noise temperature T_N, i.e.,

$$NEP = kT_N B^{1/2}$$

We thus think of the receiver noise as if it were Johnson noise from a matched input resistor at the physical temperature T_N. Although the NEP improves with decreasing B, measurement efficiency is lost if B is reduced to less than the band spread of the signal of astronomical interest.

Because coherent receivers respond to incoming signals with a specific phase relationship to the LO or pump, there is an uncertainty of $\pm$ 1 photon in the receiver over a time B^{-1}. For a system with an infrared bandwidth B this corresponds to an unavoidable quantum noise limit to the NEP of $\frac{hc}{\lambda} B^{1/2}$. Quantum noise limited operation can be expressed in terms of an equivalent noise temperature $T_N \sim hc/\lambda k$, or ~ 15 K for λ = 1 mm, and ~ 1,500 K for λ = 10 μm. At near-millimeter wavelengths the sky temperature for ground based telescopes is considerably larger than $hc/\lambda k$, so ideal (quantum noise limited) receivers are not required. Ambient temperature space telescopes, however, can easily have effective emission temperatures $\lesssim$ 15 K, so that quantum noise limited receivers can be used to advantage at all infrared wavelengths. For infrared wavelengths $\lambda < 100$ μm where thermal noise makes a negligible contribution to receiver noise, the NEP of a coherent receiver can be expressed in terms of a system quantum efficiency η_S,

$$\mathrm{NEP} = \frac{hc}{\lambda\eta_S} B^{1/2}$$

A numerical factor of 2 is sometimes seen in this expression depending on the type of mixing element being used.

Receiver developers sometimes define a minimum detectable power or NEP in units of WHz^{-1} (rather than $\mathrm{WHz}^{-1/2}$), which is equal to the above NEP with B = 1 Hz. Although this parameter is relevant to certain heterodyne applications such as communications and radar, it does not directly represent the performance of an astronomical system. The more useful procedure is to specify an NEP in units of $\mathrm{WHz}^{-1/2}$ by including the actual bandwidth required by the measurement, or to specify the noise temperature (or the system quantum efficiency).

V-B HETERODYNE RECEIVERS

The heterodyne down-converter is the most generally useful coherent infrared receiver. Any of the square-law detectors described previously in this report can be operated as mixers for heterodyne receivers. In practice, however, the speed of detector response must be adequate to provide a useful receiver bandwidth B. In the heterodyne application the output of a relatively strong infrared LO is incident upon the square law device in addition to the smaller signal of interest. Thus, in addition to the rectified dc output, the mixer output has ac components at the differences frequency $|\nu_S - \nu_{LO}|$ and, in some cases, at harmonics and higher combination frequencies. In a heterodyne receiver the output is coupled to an intermediate frequency (IF) amplifier which is sensitive only to a relatively narrow difference-frequency-bandwidth from ν_{IF} to $\nu_{IF} \pm B_{IF}/2$. Because relative frequencies are preserved in the down-conversion process, such receivers generally use intermediate frequency filters rather than infrared filters to define the wavelength band being observed. The output of a heterodyne receiver used to measure lines which are narrow compared with B_{IF} is subdivided by means of an array of radio frequency filters, followed by individual square-law detectors. The number of filter channels equals the number of infrared spectral elements observed simultaneously.

Infrared frequencies in the lower sideband, $\nu_{LO} - \nu_{IF} + B_{IF}/2$ to $\nu_{LO} - \nu_{IF} - B_{IF}/2$, and in the upper sideband, $\nu_{LO} + \nu_{IF} - B_{IF/2}$ to $\nu_{LO} + \nu_{IF} + B_{IF}/2$, appear superimposed in the output of usual types of infrared mixers. In broad-band radiometric experiments both the upper and the lower sidebands provide useful information. For spectroscopy, the line of interest usually appears only in one sideband. Since antenna and mixer noise from both sidebands is down-converted, the useful figure of merit for spectroscopy is usually a single-sideband noise temperature, which is twice the double-sideband (DSB) value used to characterize a receiver for broad-band radiometry.

The mixer parameter which is analagous to the responsivity of a detector is the conversion efficiency (conversion loss $L)^{-1}$. Conversion efficiency is the ratio of the intermediate frequency power coupled out to the IF amplifier divided by the available signal power. Because the conversion efficiency of most heterodyne mixers is substantially less than unity, the noise in the IF amplifier becomes an important issue. The noise in a near-millimeter heterodyne receiver system is often expressed in the form of a receiver noise temperature T_N by referring all noise sources to the receiver input. Thus

$$T_N = T_M + LT_{IF} ,$$

where T_M and T_{IF} are the mixer and IF amplifier noise-temperatures respectively.

The development of monochromatic infrared laser oscillators has made possible the extension of heterodyne techniques to wavelengths $\lambda \ll 1$ mm. Most of the research in this area has been dedicated to developing receivers for coherent narrow-band sources such as are used in infrared radar and communication systems. In astrophysics, infrared heterodyne receivers have proved useful for high resolution spectroscopy and spatial interferometry, primarily near $\lambda = 10\ \mu m$. In principle, the technique promises quantum limited detection in narrow bandwidths, throughout the infrared. Depending upon the application, coherent receiver performance for $\lambda \lesssim 10\ \mu m$ can suffer, however, by comparison with direct detection receivers as discussed in Appendix A.

V-C ANTENNA COUPLING AND OPTICAL COUPLING

It is convenient to make a distinction between optically coupled and antenna coupled devices. Both types of devices can be used in either incoherent or coherent receivers. In optically coupled devices, the infrared signal is imaged directly on the device surface whose dimensions are comparable to, or large compared with one wavelength. There are no inherent throughput limitations to this type of coupling. When an optically coupled device is used in a coherent receiver, the requirement, discussed earlier, for overlap with the pump or LO field applies, and the throughput is restricted to the single mode value of λ^2. Antenna coupled (or waveguide coupled) devices, by contrast, are small compared to one wavelength and respond to the infrared current or voltage which appears at the output terminals of an antenna. In such devices the antenna theorem limits the throughput to a single electromagnetic mode (diffraction limited beam) with one polarization, even for incoherent receivers.

Optically coupled photon detectors or bolometric detectors can thus be either single or multi-mode receivers. Small diodes, or small antenna coupled bolometric detectors, on the other hand, are limited to single mode operation. The coupling efficiencies of antenna coupled devices are usually discussed in terms of antenna and device impedances. These are closely analagous to the reflection and absorption coefficients used in the discussion of the coupling (or quantum) efficiencies of optically coupled devices.

All antenna coupled devices for submillimeter wavelengths share a serious coupling problem. Waveguide techniques which provide efficient coupling to microwave diodes over a wide range of impedances become prohibitively difficult for $\lambda \ll 1$ mm. Matching to low impedance diodes is especially troublesome. It is probable that some kind of quasi-optical coupling, possibly with components fabricated by optical lithography will be important in the future. Many structures have been suggested, a few of which have been explored experimentally. Despite considerable recent progress, the efficiencies achieved are generally poor by microwave standards. Uncertainties in the performance of matching structures greatly complicate the evaluation of high frequency diodes.

V-D DIODE MIXERS FOR NEAR-MILLIMETER WAVES

Coherent receiver technology at near-millimeter wavelengths comes primarily from extending microwave diode heterodyne mixer technology to shorter wavelengths. Because the quantum noise limit to mixer noise temperature in this wavelength range is low compared with the noise temperature of available IF amplifiers, it is important to maximize conversion efficiency. The ideal nonlinear element for this purpose is a switch which can be driven between high and low resistance states within the LO. In principle such a device can have a double sideband conversion efficiency approaching $L^{-1} = 1$.

1. Schottky Barrier Diodes

The GaAs Schottky barrier diode is the most commonly used mixer from microwave to submillimeter wavelengths. In order to minimize both noise and series resistance, the barrier is usually produced on a thin epitaxial layer of lightly doped GaAs grown on a heavily doped (low resistance) GaAs substrate. Thermally activated conduction produces an exponential I-V curve of the form $I=I_0[\exp(eV/kT)-1]$ The curvature parameter e/kT which equals 40 V^{-1} at 300 K can be increased, and mixer noise reduced, by cooling the device below 300 K.

The equivalent circuit of a Schottky diode at near-millimeter wavelengths is quite complicated. Some of the major issues can be understood, however, in terms of a simplified model which considers the junction to be a nonlinear resistor shunted by a capacitance C, both in series with a linear series (or spreading) resistance R_S. Since the junction capacitance must discharge through R_S twice each cycle, there is an important cutoff frequency $(2\pi R_S C)^{-1}$ which limits high frequency operation. This frequency has been extended to ~ 1 THz (λ ~ 300 μm) by using diodes with micrometer dimensions to reduce C, and by using a very thin epitaxial layer and a heavily doped substrate to reduce R_S. A variety of parasitic loss effects involving skin effects and the plasma frequency in the semiconductor should become important when $\lambda \ll 1$ mm.

Cut-off wavelengths as short as 30 μm have been reported in submicrometer size Schottky diodes with uniform heavy doping. The heavy doping reduces the thickness of the Schottky barrier until tunneling currents are dominant, and increases the plasma frequency.

The Schottky barrier diode is a very successful device which has been optimized carefully for wavelengths longer than 1 mm. Careful work at near-millimeter wavelengths is now beginning. The device has some inherent limitations, however, which should be mentioned. The amount of LO power (P_{LO}) required to drive a diode mixer depends on the curvature of the I-V curve or, more precisely, on the bias power required to drive the junction between the high and low impedance states. A Schottky diode mixer operated at 300 K requires $P_{LO} \gtrsim 10^{-3}$W. Such high power levels are difficult to produce at arbitrary submillimeter wavelengths. Another problem is that the noise in presently available Schottky diode mixers does not continue to decrease as the temperature is reduced to the liquid-He range. The thermally activated current decreases with temperature until the essentially linear tunneling current becomes important.

Considerable improvement in Schottky diode performance has been made recently by using the techniques of molecular beam epitaxy to optimize the doping profile. When doped sufficiently the substrate undergoes a Mott transition to a metallic state. A Schottky barrier device with a steep doping profile can thus combine a thick depletion layer (with low capacitance and small tunneling current) with a small spreading resistance. A DSB mixer noise temperature of 104 K was obtained at 81 GHz from such a Mott-diode mixer operated at 18K. The LO power required was reduced to 1/6 that required by 300 K Schottky-diode mixer. Although this development is very promising, it is not yet clear whether the conventional Schottky diode mixer will approach the quantum noise limit at near-millimeter wavelengths.

2. Superconducting Mixers

Mixing at millimeter wavelengths has been explored in a variety of superconducting tunneling devices. The effective nonlinearities of all of the superconducting mixers are very large compared with those of the conventional Schottky diode. The required LO power is therefore reduced by a factor $> 10^5$. The problem of how to supply LO power is greatly alleviated, but with a corresponding reduction in the saturation level of the device. In most cases, however, the dynamic range is large enough for astronomical purposes.

In one class of device the nonlinearity used arises from the peaks in the density of states of the superconductor at the edge of the superconducting energy gap. If tunneling is between a superconductor and a normal conductor, there is a sharp onset of (quasiparticle) tunnel current when the bias voltage exceeds the half-energy-gap voltage. When the tunneling is between two superconductors, the onset of quasiparticle tunnelling is at the full gap voltage, which for example is 2.6 mV for Pb. Such devices can be given the general name of quasiparticle diodes.

The first of the quasiparticle diodes to be developed was a Schottky barrier device made from superconducting Pb on GaAs. This "super-Schottky" has an essentially exponential I-V curve down to 1 K where $e/kT = 11{,}600\ V^{-1}$. At a wavelength of 3 cm it gave the lowest mixer noise temperature (DSB $T_M = 3$ K) ever reported. The DSB conversion efficiency was 0.40. Because of its inherently low cutoff frequency, however, the GaAs super-Schottky diode appears to be limited to operation at wavelengths considerably longer than 1 mm. Super-Schottky diodes have also been made on very thin Si membranes. Shorter cutoff wavelengths are expected, but have not yet been demonstrated.

Quasiparticle mixers have also been made from superconductor-insulator-superconductor (SIS) tunnel junctions of the type used for Josephson effect devices. The nonlinearity in the I-V curve of this device is even sharper than for the super-Schottky diode. Laboratory results for Pb alloy junctions at 36 and 115 GHz gave DSB $T_M \leq 7$ K and $\leq$ 40 K, respectively. The former result is only four times the quantum noise. The respective conversion efficiencies were 0.32 and 0.20. Receivers are now being constructed for use on radio telescopes at wavelengths from 2.5 to 3.8 mm (80 to 120 GHz). This type of junction has several promising features. It is an evaporated film device and is thus compatible with integrated circuit technology. The series spreading resistance is zero so there is no "cut-off" frequency in the usual sense. Intensive development of the type of junction required is being funded because of the interest in Josephson effect digital computers.

The very low mixer noise temperatures of present quasiparticle mixers suggest that they could approach quantum noise limited operation at submillimeter wave lengths. Correspondingly good system performance cannot be realized, however, without IF amplifier noise temperature $\lesssim$ 1 K. This represents a substantial improvement over the best available broad-band devices (cooled GaAs field effect transistor (FET) amplifiers have $T_{IF} \sim 15$ K, paramps ~ 12 K, masers ~ 6 K).

If the coupling problem can be solved adequately, there may be important applications of quasiparticle diodes as direct detectors. The NEP = $5 \times 10^{-16} WHz^{-1/2}$ reported in a super-Schottky diode at 1 K suggests that the SIS quasiparticle diodes with their shorter cut-off wavelengths may prove to be competitive detectors of single mode, broad band near-millimeter radiation.

A second class of superconducting device is based on the Josephson effect. It makes use of the nonlinear properties of the electron pair current in SIS tunnel junctions and related devices such as Nb point contacts. Josephson devices can be operated in a reactive mode as any of several kinds of parametric amplifier or in a resistive mode as either of two kinds of mixer. The parametric amplifiers, however, show noise saturation phenomena which have thus far prevented useful low noise operation. The ac Josephson oscillations can in principle be used as an internal LO for a heterodyne mixer. Their line width, however, is too wide for effective use in astronomical line receivers. The heterodyne mixer with external LO is the most promising Josephson effect device for submillimeter astronomy. To operate in this mode, a Josephson junction must have negligible capacitance at the gap wavelength (~300 μm in Pb or Nb). Consequently, operation has been limited thus far to relatively unstable point contact junctions. Compared with the quasiparticle mixers this device has relatively large DSB noise (10 to 20 times the ambient temperature) and high DSB conversion efficiency 0.6 to 2.8. The IF amplifier problem is therefore much less serious than with quasiparticle mixers. Very good laboratory results have been obtained from the Josephson effect mixer with external LO at a variety of millimeter and submillimeter wavelengths. A receiver is now being constructed for use on a radio telescope at $\lambda = 2.5$ mm.

3. Status of Infrared Diodes

Molecular line astronomy has provided most of the motivation for the development of low noise mixer receivers for wavelengths near one millimeter. Adequate funding has not been available to optimize the diodes discussed above for submillimeter wavelengths. Since this is a relatively complicated, and therefore expensive task, difficult choices will eventually have to be made. However, despite significant recent progress, moderate investments of NASA funds could lead to further advances at submillimeter wavelengths with existing types of diodes.

It is likely that new diodes will have to be invented in order to approach quantum noise limited operation in the 100 μm region. Problems with heating in submicrometer size structures and the lack of intense LO sources seem to favor highly nonlinear mixers. Present high frequency devices such as metal-oxide-metal (MOM) diodes have relatively weak nonlinearities. Systematic investigations of mixing in tunnel structures suggest that it is desirable to increase the device nonlinearity until photon assisted tunneling effects become important at the operating wavelength. The superconducting devices, for example, are optimum in this sense at wavelengths close to the energy gap wavelength $\lambda \sim 300\ \mu m$, room temperature Schottky devices at $\lambda \sim 40\ \mu m$, and MOM diodes at $\lambda \sim 1\ \mu m$.

4. Hot Electron Mixer

In the absence of low noise, broad bandwidth diode mixers at submillimeter wavelengths, very useful performance has been obtained for $\lambda > 300\ \mu m$ by operating the liquid-helium-temperature InSb hot-electron-bolometer discussed in Section III D as a waveguide-coupled heterodyne mixer. The relative simplicity of this device has allowed it to be rather well optimized at a variety of wavelengths. The available bandwidth, however, is severely limited by electron relaxation times to $B \lesssim 2$ MHz. At such low frequencies, relatively low IF amplifier noise temperatures $T_{IF} \simeq 4$ K are available, so receiver noise temperatures are very good. The limited bandwidth has not proved too serious for molecular line spectroscopy in cases where line frequencies are precisely known in advance. When wide frequency bands must be searched, however, the receiver figure of merit varies as $T_N^{-1}B^{1/2}$, so wider band, higher noise Schottky-diode receivers give comparable performance.

V-E PV AND PC MIXERS

Most of the sensitive coherent receiver development for $\lambda \lesssim 100\ \mu m$ has focused on optically coupled PV and PC mixers. The optimization of infrared devices for heterodyne mixer applications is quite different than for the same devices used as incoherent detectors. A heterodyne mixer operates in the strong field of a local oscillator, that is, in a high radiation background. The emphasis in mixer design is on high quantum efficiency, high speed so as to obtain a large bandwidth B, and good performance at high power so as to permit the application of enough LO power to obtain good conversion efficiency.

The performance of a mixer with a photon detector as the nonlinear element can be described in a general way. The oscillating IF current at the output of the mixer is

$$I_{IF} = \frac{G \eta e \lambda}{hc} \left(2P_{LO} P_{SIG} \right)^{1/2} ,$$

where P_{LO} and P_{SIG} are the local oscillator power and signal power incident on the mixer and G is the photoconductive gain (G = 1 for PV detectors).

The receiver NEP can be written

$$NEP = \left[\frac{\alpha hc}{\lambda \eta} + \frac{2kT_{IF}}{R_{IF} P_{LO}} \left(\frac{hc}{G \eta e \lambda} \right)^2 \right] B^{1/2}$$

The first term in the square bracket arises from the irreducible shot noise of the local-oscillator-induced photocurrent. The parameter α in the shot-noise term is equal to 1 for photodiodes, and ranges between 1 and 2 in photoconductors because of the additional noise from the lack of correlation between charge generation and recombination in PC devices. The second term arises from noise in the IF amplifier which is characterized by a noise temperature, T_{IF}, and an equivalent input resistance, R_{IF}.

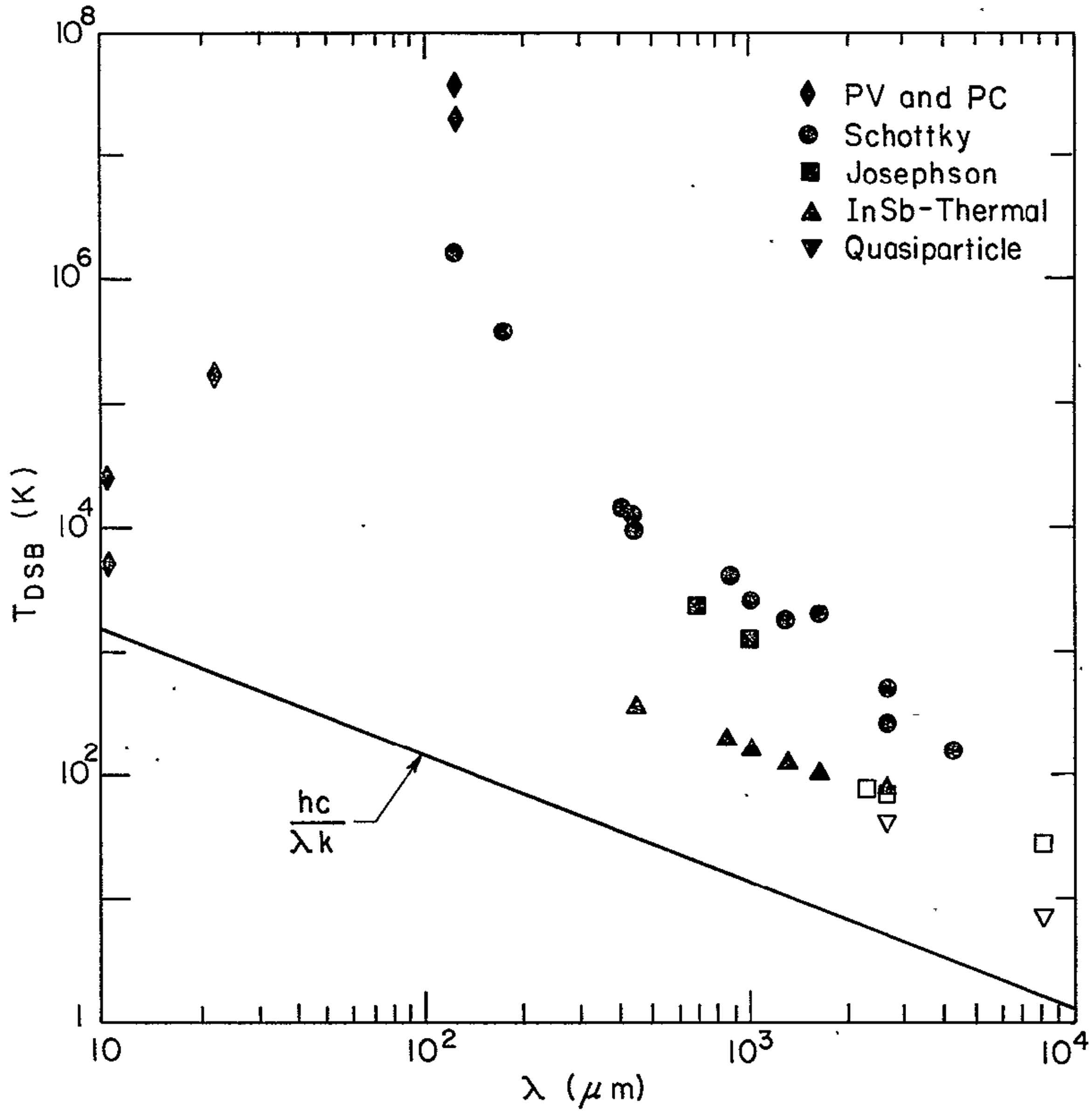
This expression shows directly the requirement for quantum limited performance, namely that the second term in the bracket be smaller than the first. The necessary conditions are a combination of large LO power, low noise IF amplifiers, and high gain mixers. The overriding factor affecting ultimate performance is the quantum efficiency. Good measuring efficiency also requires the system bandwidth be as wide as the frequency range of interest. Currently available PV and PC mixers have difficulty meeting this condition for many experiments of interest.

Both PV and PC devices have been used as mixers in heterodyne receivers. Extrinsic photoconductors used for incoherent detectors generally have long charge carrier relaxation times $\sim 10^{-7}$ s. In order to increase their bandwidth for use in heterodyne receivers, they can be heavily doped with compensating impurities which, however, reduces the photoconductive gain. Among the extrinsic materials that have seen use in heterodyne mixers are Ge:Au, Ge:Hg, Ge:Cu, Ge:Ga and Si:As. Besides the normal photoconductivity extending in wavelength to $\lambda_c = hc/E_i$, negative-donor-ion-state (D^-) photoconductivity in extrinsic silicon may prove useful in the 100 to 500 μm range.

Nearly quantum-noise limited performance and bandwidths of 2×10^9 Hz are currently obtainable for wavelengths $<$ 12 μm at 77 K using HgCdTe photodiodes. HgCdTe devices have been used to wavelengths as long as 18μm by operating at liquid-helium temperatures, but with reduced electrical bandwidths.

A summary of present heterodyne receiver performance is given in Figure 7. No good heterodyne receivers exist at present in the wavelength band from 24 to 300 μm.

Fig. 7. Recently reported values of double-sideband heterodyne receiver noise-temperature (solid symbols) and mixer noise-temperature (open symbols). The broad-band diode receivers are about two orders of magnitude above the quantum noise limit in the near-millimeter range. The fractional bandwidth of these receivers can be as large as $B\lambda/c \sim 0.1$. The lower noise temperatures of the hot electron mixers are partially compensated by their small fractional bandwidths ($B\lambda/c \sim 10^{-5}$). The absence of good mixers for $\lambda \sim 100$ μm is apparent. Quantum noise limited PV and PC mixers can be made for $\lambda \lesssim 10$ μm wherever sufficient LO power is available. The fractional bandwidths of these mixers are $< 10^{-4}$.



PV and PC
Schottky
Josephson
InSb-Thermal
Quasiparticle
hc/λk
T_{DSB} (K)
λ (μm)

XBL 791-5524

V-F PARAMETRIC UP-CONVERTERS

An infrared up-converter is a coherent device which is analogous in some ways to an optically coupled heterodyne down-converter. The infrared signal frequency ν_S is mixed with a pump frequency ν_p from an intense laser source in a medium with a non-linear index of refraction. The pump and signal waves generate a polarization wave at the sum (output) frequency $\nu_O = \nu_S + \nu_p$. The attractiveness of upconversion (discussed earlier in the context of quantum counters) is the possibility of the availability of better detectors for ν_O than for ν_S. If the pump-, signal-, and sum-frequency waves can be made to satisfy the phase matching condition which arises from momentum conservation in the dielectric, the amplitude of the sum frequency wave will increase with the distance through the dielectric until all photons at ν_S have been converted to photons at ν_O. The conversion efficiency, defined as the ratio of the number of photons at ν_O to that at ν_S depends in practice on the pump power, the non-linear polarizability of the dielectric, and the length of dielectric over which a phase match can be maintained.

In principle, the up-conversion process is noise free since there can be no sum-frequency photon unless there is a signal (or background) photon present. Up-conversion can be a broad-band process but because of dispersion in the dielectric the phase matching condition can only be satisfied in practice over a narrow wavelength band. The major difficulty in up-conversion is in finding materials that have small absorption at all three wavelengths, large non-linear polarizability, appropriate dispersion and/or birefringence, and sufficient material homogeneity to permit phase matching over long interaction lengths. Present up-converters have conversion efficiencies of $\sim 10^{-6}$ for signal $\lambda = 10.6\ \mu m$, and $\sim 10^{-3}$ for $\lambda \sim 3\ \mu m$, and most have suffered from an excess noise source that is not fully understood. The resulting NEPs are not competitive with those of incoherent PV and PC receivers.

Imaging with up-conversion is possible since the phase matching conditions impose a one-to-one correspondence between the direction of propagation of the signal-frequency and sum-frequency waves. Thus, up-conversion is not strictly a single mode process but does preserve the uniqueness of individual modes.

VI. IMPORTANT SUPPORTING TECHNOLOGIES

VI-A AMPLIFIER NOISE LIMITATIONS OF PV AND PC DETECTORS

Most high performance PV and PC detectors have resistances on the order of 10^{10} to $10^{13}\,\Omega$ when operated under low background conditions. These high impedances require the use of high load resistances and cold preamplifiers. The better types of detectors are limited in low infrared background by the equivalent current noise of the amplifier referred to its input, $i_{n,a}$, which has dimensions A $Hz^{-1/2}$. Under these conditions the NEP of a PV or PC detector can be written

$$NEP = \frac{i_{n,a}}{S} = \frac{hc}{e\lambda}\,\frac{i_{n,a}}{G\eta} ,$$

where G = 1 for a PV detector. Gains in sensitivity can come only from decreasing $i_{n,a}$ or increasing the $G\eta$ product.

The equivalent current noise of a preamplifier (voltage follower or trans-impedance) employing a load resistor R_L at temperature T_L and a field effect transistor (JFET or MOSFET) is

$$i_{n,a} = \left(\frac{4kT_L}{R_L} + i^2_{n,F} + \left(\frac{v_{n,F}}{Z}\right)^2\right)^{1/2} .$$

In this equation $i_{n,F}$ is the gate current noise of the FET, $v_{n,F}$ is the series voltage noise of the FET (at the low frequencies of usual interest $v^2_{n,F}$ varies approximately as 1/f), and Z is the parallel impedance of the detector, FET, load resistor, and stray capacitance. In addition, there may be an excess current noise contribution from the load resistor. With the very high values of detector and load resistance that are commonly used, the impedance Z is capacitive above a characteristic frequency which is typically $\lesssim$ 1 Hz. The minimum capacitance possible is that of the FET alone. If the capacitance of the detector is larger than that of the FET, then the contribution to $i_{n,a}$ due to $v_{n,F}$ becomes relatively larger and the limiting NEP is thereby degraded. This effect is of particular importance for PV detectors since their capacitance can be many picofarads. Thus, it is often important to use an FET having low voltage noise with PV detectors.

1. JFETs

Since the voltage noise of a good JFET is typically 10^{-2} that of a MOSFET, JFETs are generally preferred over MOSFETs for use with PV detectors and most bolometers. The voltage noise and, especially, the current noise of a JFET decrease as it is cooled below room temperature. However, currently available Si JFETs do not operate below about ~ 80 K. Amplifiers have been built with FETs at higher temperatures than the detectors and load resistors. However, detectors for wavelengths $\lambda \gtrsim 20\ \mu m$ must be shielded from the thermal radiation of the preamplifier while maintaining electrical performance. With large numbers of detectors, this approach of warm (~ 80 K) amplifiers with cold ($\lesssim$ 10 K) detectors becomes cumbersome. The JFETs with the lowest voltage noise tend to have large input capacitance ($\gtrsim$ 10 pF) and non-negligible current noise (typically 10^{-17} to $10^{-16} AHz^{-1/2}$). Development of better JFETs, particularly ones with lower operating temperature, current noise, and input capacitance would substantially improve the sensitivities achievable at low background of both PC and PV detectors.

2. MOSFETS

Long wavelength extrinsic PC detectors usually operate below 10 K, and have capacitances which are typically less than 1 pF. It has become customary to use MOSFETs with these detectors since they typically have low input capacitance (~ 3 pF) negligible current noise, and operate at low temperatures. Their voltage noise, which has a 1/f power spectrum, is much larger than for a JFET. Typical $v_{n,F}$ for a good quality MOSFET is 300 nV $Hz^{-1/2}$ at 5 Hz.

Commercially available MOSFETs display a variety of properties below ~ 15 K which are loosely grouped together and sometimes called the "open substrate phenomena." These include a marked drift in their dc operating point (typical drifts amount to ~ 500 μV over a period of several hours), increased 1/f noise at low frequencies (0.1 to 1 Hz), and very long recovery times (5 to 20 minutes) for turn-on transients and saturating noise spikes. Current investigations suggest that these effects are related to carrier freeze-out in the silicon substrate.

3. Load Resistors

Some problems encountered with many existing load resistors are that their voltage and temperature coefficients-of-resistance are large enough that these non-idealities can be sources of excess noise and calibration errors. These resistors often change in value by a factor 2 or more over normal variations in low temperature operating conditions. Selected components do not have such large coefficients, but the yield is often small. More sensitive detectors in the future will require resistors with higher values of resistance and, in some cases, lower shunt capacitance than are currently available.

4. Frequency Response of Preamplifiers

With the exception of rapid scan Fourier transform spectroscopy, most astronomical signals are in the frequency range from 0 to 10 Hz. However, the availability of a wider bandwidth allows a clean separation of infrared signals from both spontaneous detector spikes and spikes induced by energetic nuclear particles. The separation and the subsequent blanking of these spikes is important if one is to achieve the maximum sensitivity from a detector operated on a space platform. Use of a trans-impedance amplifier (TIA) does not improve the ratio of signal/noise at a given frequency, but does extend the frequency response over that obtainable with a simple voltage amplifier. The frequency response of a TIA is usually determined by the RC time constant of the load resistor. Large bandwidths thus require load resistors with small shunt capacitance.

5. Charge Sensitive Amplifiers with Accumulation Mode Detectors

Rather than sensing the detector current continuously, it is possible to accumulate the photo-generated charge during an integration period τ_{int} and then read out the charge quickly with a charge sensitive amplifier. This method is in wide use with advanced detector arrays because of the possibility of multiplexing many detectors sequentially with a single amplifier. The NEP of such a combination of a detector with a charge sensitive amplifier is

$$NEP = \frac{hc}{G\eta e\lambda} \left(\frac{2}{\tau_{int}} \right)^{1/2} Q_{rms} \quad ,$$

where Q_{rms} is the uncertainty in the amount of charge that is read out. We have assumed 100 percent readout efficiency. For example, at 10 μm with $Q_{rms} = 10^3$ electrons, $\tau_{int} = 1$ s, and $G\eta = 1$, the NEP is 2.8×10^{-17} W $Hz^{-1/2}$.

At high backgrounds where Q_{rms} is (hopefully) determined by the statistics of the photocurrent, the NEP obtained is the same as with a continuous-current-sensing amplifier. We are concerned here with the low illumination limit, where Q_{rms} is the result only of noise in the readout electronics. In this case, charge integration can be more or less sensitive than continuous current sensing using the same components and a modulation frequency of τ_{int}^{-1}. In principle, if R_L/T_L is sufficiently large that Johnson noise is not important, the accumulation mode is of advantage only if the unavoidable, low frequency, FET noise "power"-spectral-density ($v_{n,F}^2$) varies more rapidly than 1/f. In practice, however, there are likely to be advantages to accumulation mode detectors even if this criterion is not met, if integration times longer than several seconds can be used.

Values of Q_{rms} so far obtained with infrared detectors are typically 1000 electrons. However, values as low as ~ 25 electrons have been achieved in visible Si CCD devices. Attainment of such low values of Q_{rms} and values of $\tau_{int} > 1$ s would yield substantial improvements in infrared sensitivity. Large values of τ_{int} require not only low photon background and low leakage, but also sufficient charge storage capacity in order to have the desired dynamic range.

VI-B CHARGED PARTICLE INDUCED NOISE IN INFRARED DETECTORS

A charged particle passing through an infrared detector loses an amount of energy E which depends upon the pathlength within the detector, the chemical composition of the detector, and the particle's energy and type. A fraction of the energy deposited in a semiconductor produces electron-hole pairs. Experimentally, for a large number of semiconductors, the energy loss per pair created is about 3.5 times the bandgap energy. Thus, a particle which loses energy E in a PV or PC detector creates ~ $E/3.5E_g$ pairs. These pairs produce a current pulse which is roughly equivalent to an incident photon pulse of $E/3.5\eta E_g$ photons. For intrinsic detectors $E_g = hc/\lambda_c$, while for extrinsic detectors it is E_g/E_i times larger. Thus, the equivalent photon input is ~ $E\lambda_c/3.5\eta hc$ for intrinsic detectors and ~ $(E\lambda_c/3.5\eta hc) \times (E_i/E_g)$ for extrinsics. However, the energy loss E in extrinsic detectors is much larger than in intrinsic detectors because the path length required for good quantum efficiency is many times larger. As a result, intrinsic detectors should be less vulnerable to charged-particle-induced noise than extrinsic detectors. Considerations similar to those above for charged particles apply to gamma-rays that interact with infrared detectors.

All the energy lost in a bolometer raises its temperature, and thus, the equivalent photon input (for an operating wavelength λ) is $E\lambda/hc$. Bolometers are usually intermediate in thickness between intrinsic and extrinsic detectors. Since they are used at long wavelengths, have large cross-sectional areas, and have slow response times, the sensitivity of bolometers may be substantially limited in space environments by particle and/or gamma-ray events.

While the basic considerations discussed here may be useful as guidelines, it is very important that the vulnerability of all types of infrared detectors proposed for low-background space experiments be studied experimentally, and that shielding and circumvention techniques be more fully developed.

1. Shielding Techniques

In near-Earth orbit, energetic charged particles arise from several sources: the trapped-particle (Van Allen) belts, the primary cosmic rays, and occasionally, particles from solar flare events. Moderate amounts of shielding (a few $g \cdot cm^{-2}$) will stop most of the trapped electrons (and their bremsstrahlung) and the lower energy ($\lesssim$ 50 MeV) protons. In dense parts of the radiation belts (e.g., in the region of the South Atlantic Anomaly), however, this amount of shielding will permit substantial pulse rates and more elaborate shielding may be required. Virtually none of the high energy particles in primary cosmic rays or high energy trapped protons will be stopped by practical shielding.

Space missions with durations of one year are expected to be too short for charged particles to produce significant permanent degradation in present infrared detectors, if they are used with appropriate shielding.

2. Circumvention Techniques

Many circumvention schemes have been developed to reduce the effect of charged-particle-induced noise. These schemes can be implemented through hardware or software, but always use the rapid rise time of a charged particle event to trigger a blanking mechanism. This blanking can range from simply gating off the data stream for a preset time, to linearly fitting a straight line to the pre- and post-event outputs. In the case of IRAS, the detector output is clamped at its pre-pulse value for a time which depends on the magnitude of the pulse.

VI-C SPECTRAL FILTERS

Improved filters for the 20 to 1000 μm band are badly needed both for photometry and to serve as order sorting filters for spectroscopic work. For wavelengths shorter than 20 μm, high efficiency multilayer dielectric filters are available commercially. These filters can be cooled many times without serious degradation. Dielectric filters for the 20 to 30 μm band exist but generally have poor efficiencies. In addition the materials used in the filters change their optical properties upon cooling, further reducing their efficiencies at low temperatures. There are also problems with delamination.

Crystal resonance bands are used for filtering in the 20 to 200 μm region. Band selection can be accomplished by using the crystals either in reflection, in transmission or by scattering. Although there are a large number of candidate crystals for this purpose, many of them are difficult to use because they are hygroscopic, fragile and/or soft, or because they have weak resonances leading to only slow variations of optical properties with wavelength.

Interference filters made with metal meshes at room temperatures have been used extensively at submillimeter wavelengths. Techniques are being developed to permit cooling of such filters without degradation of their properties. It also seems possible to build high efficiency mesh filters for wavelengths shorter than those where mesh filters are in current use.

VI-D RECEIVER COOLING

Most high performance infrared detectors must be cooled to temperatures $\lesssim$10 K. Some but not all of the short wavelength PV detectors are exceptions to this rule. Even though InSb PV detectors operate well up to ~ 70 K, the very best performance is achieved at liquid-helium temperatures. Most infrared systems developed for defense purposes employ closed cycle refrigerators to achieve the required temperatures. On the other hand, planned NASA programs use stored cryogenic liquids for cooling. The IRAS telescope for example, is to be cooled by superfluid helium for a mission duration of about a year.

More advanced programs may use bolometers or other detectors requiring cooling below the region ($T \gtrsim 1$ K) accessible with liquid-^{4}He. Several schemes have been identified for achieving these low temperatures in the space environment. Temperatures $\gtrsim 0.3$ K can be reached with pumped liquid-^{3}He refrigerators similar to those which have been used at balloon and aircraft altitudes. Other low temperature laboratory techniques such as adiabatic demagnetization and dilution refrigeration could be adapted to produce temperatures $\lesssim 0.01$ K. These approaches should be studied with the goal of developing simple, reliable schemes.

The best heterodyne receivers require cooling to temperatures $\lesssim 10$ K. Schottky-diode mixers and some types of IF amplifiers (masers and most paramps) place a large load ($\gtrsim 10$ mW) on the cooling system. Superconducting mixers and FET amplifiers by comparison have much less power dissipation.

VI-E SPECIAL REQUIREMENTS FOR HETERODYNE RECEIVERS

1. IF Amplifiers

Intermediate frequency amplifier noise contributes significantly to the noise in all near-millimeter receiver systems and in receivers at shorter wavelengths that are starved for LO power. Improvements in IF amplifier technology will clearly have to accompany mixer improvements if lower noise systems are to be available in the future.

Typical conversion efficiencies for near millimeter mixers are $0.1 < L^{-1} < 0.2$ (the larger values obtained with the Josephson mixer are exceptional). Since LT_{IF} enters the expression for receiver noise temperature, it follows that values of $T_{IF} \lesssim 2$ K are required for a receiver to approach quantum noise limited operation at $\lambda = 1$ mm and 20 K at $\lambda = 100$ μm. Such values are difficult to obtain with the broad-band ($B_{IF} > 10^8$Hz) amplifier technology available today. The problem is compounded by the prediction that conversion efficiency will decrease as the quantum noise limit is approached in tunnel junction mixers.

Most IF amplifiers in current use operate in the low GHz frequency range. This choice allows $B_{IF} \gtrsim 10^8$ Hz, even with resonant impedance matching. Significant separation between the signal and LO frequencies is desirable for strongly pumped mixers, such as conventional Schottky diodes, and PC mixers, so as to avoid noise from the pump source. This is not an important issue for the superconducting mixers with their small P_{LO} requirement.

Cooled GaAs FET amplifiers are very attractive for space astronomy applications because of their simplicity and low power dissipation. Noise temperatures as low as 15 K have been achieved. Parametric amplifiers with $T_{IF} \sim 12$ K and masers with $T_{IF} \sim 6$ K are more complicated devices with larger power dissipation.

Besides the need for broad-band low-noise amplifiers, there is a related need for compact, multi-channel IF-filter banks. Efficient heterodyne spectroscopy with space telescopes requires broad-band filter banks with lower power consumption, bulk, and weight than those currently used on the ground. Acousto-optic techniques are one promising method of achieving these goals.

2. Local Oscillators

The available sources of LO power limit the application of heterodyne techniques to infrared astronomy at many wavelengths. At near-millimeter wavelengths the severity of the problem depends on the type of mixer being used. Schottky-barrier diodes require $P_{LO} \sim 10^{-3}$ W which is available at most submillimeter wavelengths only from backward wave oscillators such as the O-type Carcinotron. Although these oscillators make reasonably satisfactory LO sources for Schottky-diode mixers for $\lambda \gtrsim 450\ \mu m$ (670 GHz), they are bulky, expensive, and require large, well regulated power supplies. This backward-wave-oscillator technology is about 25 years old. There has been little development of related oscillators during this period. The LO power requirement of the superconducting mixers is sufficiently small (10^{-8} to 10^{-9}W) that it can be obtained by harmonic generation from klystron or other millimeter wave oscillators over the expected operating wavelength range of the devices.

Mixers for $\lambda < 300\ \mu m$ generally require large amounts of LO power. Molecular discharge lasers and CO_2 pumped molecular lasers are the only practical sources of continuous-wave LO power for a wide range of infrared wavelengths. Although several effects can be used to tune these laser LOs over narrow wavelength ranges, they are essentially fixed-wavelength sources.Although many lines are available, most heterodyne receiver developments have taken place at the wavelengths of a few well known lasers: $\sim 10\ \mu m$ (CO_2), 118 μm (H_20), 337 μm (CN^-), etc. Heterodyne spectroscopy is now limited to frequency ranges of a few GHz on either side of the laser frequency. Continuously tunable infrared diode lasers are becoming available for $\lambda \lesssim 20\ \mu m$. The shorter the wavelength, the better the state of development. The amounts of infrared power available from such LO sources is generally so small that receivers are IF amplifier noise limited at NEPs which are significantly above the quantum noise limit.

APPENDIX A. A COMPARISON OF HETERODYNE WITH DIRECT DETECTION RECEIVERS

1. Spectroscopy

The elements of an astronomical heterodyne spectrometer are shown in Figure 8(a). Under ideal circumstances, when the noise of the heterodyne receiver is dominated by shot noise from the local oscillator, the quantum-noise-limited minimum-detectable-power incident on the optical mixer per unit post detection bandwidth is

$$\mathrm{NEP} = \frac{hc}{\eta\lambda} B^{1/2},$$

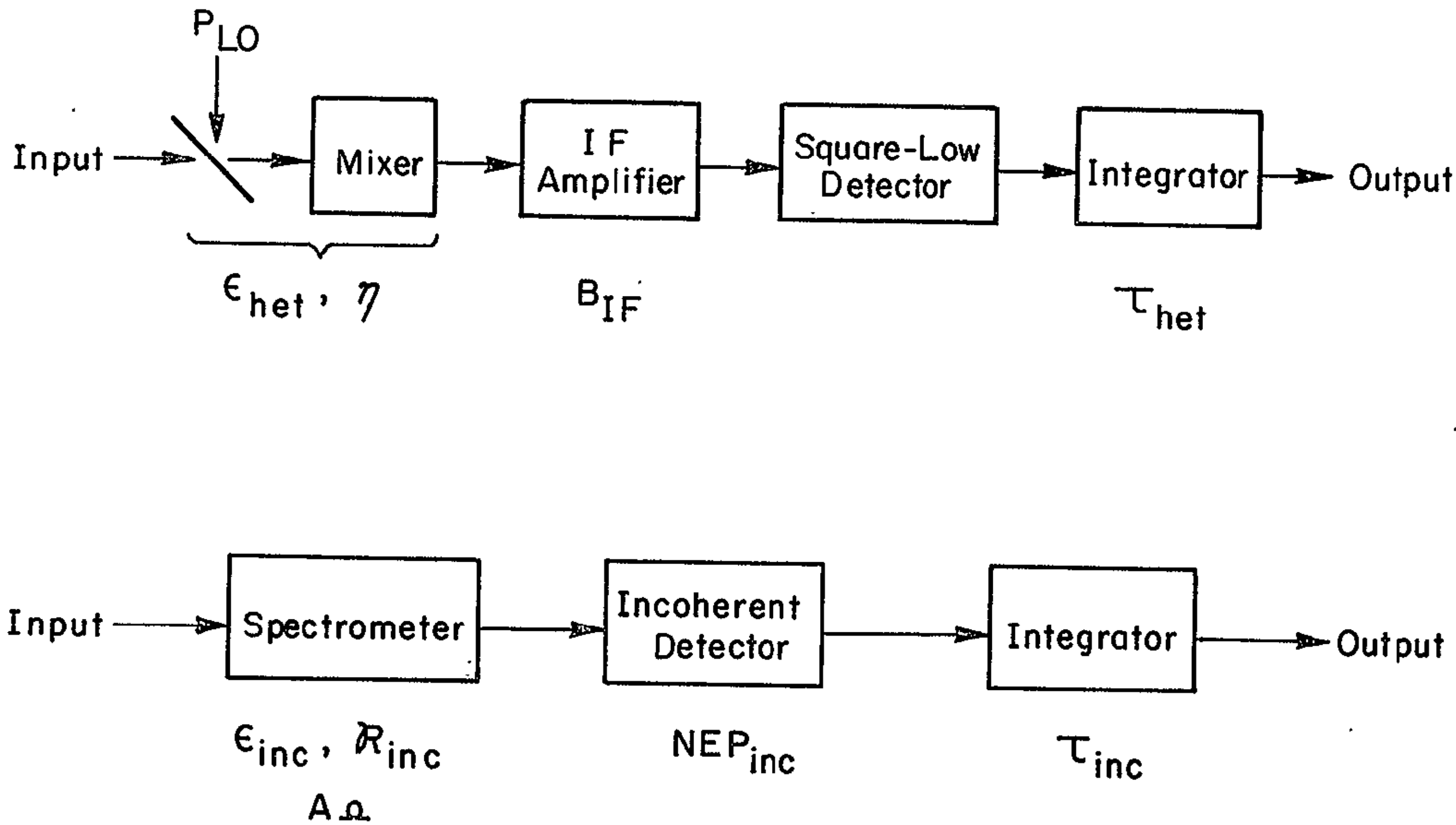
where η is the quantum efficiency of the mixer and $B = 2B_{IF}$. The signal power from a source of spectral radiance L_λ (W m^{-2} sr^{-1} μm^{-1}) incident on the mixer is

$$P_{SIG} = \epsilon_{het} L_\lambda \lambda^2 \Delta\lambda \quad ,$$

where $\Delta\lambda = \lambda^2 B/c$. Here ϵ_{het} is the optical efficiency of the system which includes reflection losses, wavefront distortion, chopping losses, etc., and also accounts for the sensitivity of a heterodyne receiver to only one polarization. Unless an array of mixers is used, the throughput of the receiver is limited to the single mode value of λ^2 by the coherent mixing process. The integration time required to obtain a given ratio signal/noise, (S/N), is in general,

$$\frac{1}{2} (S/N)^2 \left(\frac{\mathrm{NEP}}{P_{SIG}}\right)^2 \quad ,$$

Fig. 8 Functional diagrams of a heterodyne receiver (a) and an incoherent receiver (b). In the latter case, the box labeled spectrometer could, for example, be infrared filters, a prism or grating spectrometer, a Fabry-Perot interferometer, or a Fourier transform spectrometer. Important properties affecting system performance are shown below the relevant elements. The effect of IF amplifier noise in the heterodyne receiver has been absorbed into η. The quantum efficiency of the incoherent detector has been absorbed into NEP_{inc}.


P_LO
Input
Mixer
I F
Amplifier
Square-Low
Detector
Integrator
Output
ε_het , η
B_IF
τ_het
Input
Spectrometer
Incoherent
Detector
Integrator
Output
ε_inc , R_inc
AΩ
NEP_inc
τ_inc

XBL793-6028

which for this heterodyne receiver example becomes

$$\tau_{het} = \frac{1}{2} (S/N)^2 \frac{h^2 c^3}{\epsilon_{het}^2 \eta^2 L_\lambda^2} \frac{\mathscr{R}}{\lambda^9} \quad ,$$

where the resolving power $\mathscr{R} = \frac{\lambda}{\Delta\lambda} = c/\lambda B$. The very rapid dependence of the integration time, τ_{het}, on wavelength in this expression is an important feature of heterodyne spectrometers.

The integration time, τ_{inc}, required to achieve a given signal to noise ratio with the generalized incoherent spectrometer, shown in Figure 8(b), is

$$\tau_{inc} = \frac{1}{2} \left(\frac{(S/N \quad NEP_{inc}}{\epsilon_{inc} L_\lambda \quad A\Omega} \right)^2 \frac{\mathscr{R}^2}{\lambda} \quad .$$

Here NEP_{inc} is the NEP of the detector employed in the incoherent spetrometer, ϵ_{inc} is the spectrometer efficiency, $A\Omega$ is the spectrometer throughput, and $\mathscr{R}$ is the resolving power.

A useful comparison of the two techniques is to calculate the ratio of the integration times to achieve the same S/N for equal resolving power. This yields

$$\frac{\tau_{het}}{\tau_{inc}} = \left(\frac{\epsilon_{inc}}{\epsilon_{het}} \frac{hc}{\eta \, NEP_{inc}} \frac{A\Omega}{\lambda^3} \right)^2 \frac{c}{\lambda\mathscr{R}}$$

where $c/\lambda\mathscr{R}$ is equal to the bandwidth B. As long as there is no limit imposed by the solid angle subtended by the source, this ratio is only limited by practical constraints on the throughput of the incoherent spectrometer. An interesting case (which favors the heterodyne system somewhat) is to assume that we are viewing a point source, for which the effective $A\Omega = \lambda^2$. The ratio of the integration times then becomes

$$\frac{\tau_{het}}{\tau_{inc}} = \left(\frac{\epsilon_{inc}}{\epsilon_{het}} \frac{hc}{\eta \, NEP_{inc} \, \lambda}\right)^2 \frac{c}{\lambda \mathscr{R}}$$

Typical heterodyne receivers have $\epsilon_{het} \sim 0.1$ with mixer quantum efficiencies ~ 0.5. An astrophysically interesting resolving power might be $\mathscr{R} \sim 10^5$ to resolve a typical Doppler broadened line. A Fabry-Perot or Michelson interferometer, or an echelle spectrometer, with comparable resolution could reasonably have $\epsilon_{inc} \simeq \epsilon_{het}$. For a incoherent detector with an NEP of 10^{-16} W $Hz^{-1/2}$, the crossing point for the two techniques occurs at $\lambda \sim 23\ \mu m$ (and at $\lambda \sim 11\ \mu m$ for a resolving power of 10^6). If the detector NEP is 10^{-17}W $Hz^{1/2}$ the crossing point is at $\lambda \sim 110\ \mu m$ for $\mathscr{R} = 10^5$ and $\lambda \sim 50\ \mu m$ for $\mathscr{R} = 10^6$. High resolution and long wavelengths favor the heterodyne receiver. Furthermore, resolving powers much greater than 10^5 are difficult to achieve efficiently with incoherent techniques. Thus, it is likely that for those scientific problems where such high resolving powers are necessary, heterodyne spectrometers will be attractive over a wide wavelength range.

A technique that is used with both heterodyne receivers and spectrometers is to employ multiple outputs so as to scan many resolution elements simultaneously. The time needed to search for a line (in frequency) or to measure its profile is then reduced by the number of channels. The relative ease of making multiple filter banks following the IF amplifiers is an asset for heterodyne spectrometry and highlights the need for broad band mixers and IF amplifiers.

2. Radiometry

Both coherent and incoherent techniques are used to measure the brightness of a source with a broad spectrum. In this case the cross-over between the two techniques is at wavelengths near 1 mm, where the noise in available heterodyne receivers is considerably above the quantum limit. The infrared bandwidth B of the heterodyne receiver is generally limited by the IF amplifier to a value which is significantly less than that of an incoherent radiometer. The equations derived above to compare the times required for the two types of instrument to perform a spectroscopy experiment can be used for radiometry, if we distinguish between the resolving powers used and include a factor f which is the ratio of the noise in the coherent receiver to the idealized quantum noise, i.e.,

$$\frac{\tau_{het}}{\tau_{inc}} = \left(\frac{\epsilon_{inc}\, f\, hc\, A\Omega}{\epsilon_{het}\, NEP_{inc}\, \lambda^2} \right)^2 \frac{c\, \mathscr{R}_{het}}{\lambda^3 \mathscr{R}^2_{inc}}$$

If we assume a point source so that $A\Omega = \lambda^2$ for both receivers, then

$$\frac{\tau_{het}}{\tau_{inc}} = \left(\frac{\epsilon_{inc}\, fh}{\epsilon_{het}\, NEP_{inc}} \right)^2 \frac{c^3\, \mathscr{R}_{het}}{\lambda^3 \mathscr{R}^2_{inc}}$$

Parameters for a presently available GaAs Schottky diode mixer receiver at $\lambda \sim 1$ mm are $f/\epsilon_{het} = 70$ and $\mathscr{R}_{het} = 150$ (B = 2 GHz). A good composite bolometer at T = 0.3 K will have $NEP_{inc} \simeq 10^{-15} WHz^{-1/2}$ with $\epsilon_{inc} \simeq 0.3$ and $\mathscr{R}_{inc} = 3$. The latter system is close to being background limited on a 300 K telescope. These numerical values give $\tau_{het} \simeq 90\ \tau_{inc}$.

The limiting sensitivity for both systems at $\lambda = 1$ mm is determined by fluctuations in the 3 K cosmic background. If ideal receivers of both kinds were available with the resolving powers given above then $\tau_{het} = \mathscr{R}_{het}\, \tau_{inc}/\mathscr{R}_{inc} \simeq 50\ \tau_{inc}$. Thus, ideal coherent detectors are not competitive with ideal incoherent detectors as radiometers for $\lambda \sim 1$ mm, unless their IF bandwidth can be increased.

APPENDIX B. GLOSSARY OF SYMBOLS AND ACRONYMS

A	Detector area
$A\Omega$	Throughput
B	Predetection (infrared) bandwidth of a heterodyne receiver
B_{IF}	IF bandwidth of heterodyne receiver
$\mathcal{C}$	Bolometer heat capacity
C	Capacitance of detector or amplifier
c	Speed of light
CB	Conduction band of a semiconductor
CCD	Charge coupled device
CID	Charge injection device
D*	D-Star; $D^* = A^{1/2}\ NEP^{-1}$ (cm $Hz^{1/2}$ W^{-1})
DSB	Double sideband
E_g	Semiconducting bandgap; also superconducting bandgap
E_i	Impurity ionization energy
F	Quality factor for bolometers (W $K^{-5/2}$ s)
f	Ratio of coherent receiver noise to quantum noise
FET	Field effect transistor; see JFET, MOSFET
$\mathcal{G}$	Thermal conductance between bolometer and heat sink
G	Photoconductive gain
Ge:XX	Extrinsic germanium; XX can be chemical symbol for specific dopant e.g., Ge:Ga
h	Planck's constant

I-V	Current - voltage
I_{IF}	IF current of heterodyne mixer
IF	Intermediate frequency
IR	Infrared
IRCCD	Infrared sensitive charge coupled device
i_n	Current noise; total current noise (A $Hz^{-1/2}$)
$i_{n,a}$	Amplifier contribution to i_n
$i_{n,d}$	Detector contribution to i_n
$i_{n,F}$	Gate current - noise of an FET
JFET	Junction field effect transistor; c.f. MOSFET
k	Boltzmann's constant
L	Conversion efficiency of heterodyne receiver
L_λ	Spectral radiance of a source of infrared radiation (W m^{-2} sr^{-1} μm^{-1})
LO	Local oscillator
MIS	Metal insulator semiconductor
MOM	Metal oxide metal
MOS	Metal oxide semiconductor
MOSFET	Metal-oxide-semiconductor field effect transistor; c.f., JFET
n	Number of detectors in an array
$\dot{N}$	Rate of photons incident on detector (photons s^{-1})
NE$\dot{N}$	Rate of photons incident on a detector that is required to produce a signal-to-rms-noise ratio of unity in the detector's output; the noise is measured in a 1 Hz bandwidth (photons s^{-1} $Hz^{-1/2}$).
NEP	Value of monochromatic power incident on a detector that is required to produce a signal-to-rms-noise ratio of unity in the detector's output; the noise is measured in a 1 Hz bandwidth (W $Hz^{-1/2}$). In other documents monochromatic NEPs often appear with a subscript λ. An alternate

convention is to specify the bandwidth whereby the units of NEP become watts. Depending upon usage the value for the incident power may be either the steady state value or the rms value of a modulated signal.

NEP_{het}	NEP of a heterodyne receiver or spectrometer
NEP_{inc}	NEP of an incoherent receiver or spectrometer
NEP_{PC}	NEP of a photoconductive detector
NEP_{PV}	NEP of a photovoltaic detector
P_{LO}	Local oscillator power of a coherent receiver
P_{SIG}	Signal power
PC	Photoconductive
PV	Photovoltaic
Q_{rms}	Root-mean-square readout noise of a charge sensitive amplifier.
$\mathcal{R}$	Resolving power of a spectrometer, may have subscript indicating incoherent or heterodyne.
R	Resistance
R_{IF}	Equivalent noise resistance of an IF amplifier
R_L	Load resistance of current amplifier for PV or PC detector
R_S	Spreading resistance of a diode mixer
R_o	Zero-bias impedance of a PV detector
S	Responsivity of PV or PC detector (A W^{-1})
SIS	Superconductor insulator superconductor
S/N	Signal to noise ratio
Si:XX	Extrinsic silicon; XX can be chemical symbol for specific dopant e.g. Si:As
T	Temperature
T_A	Ambient temperature
T_{IF}	Noise temperature of IF amplifier

T_M	Mixer noise temperature
T_N	Noise temperature; also specifically receiver noise temperature
V	Voltage
$v_{n,F}$	Series voltage-noise of an FET
VB	Valence band of a semiconductor
Z	Amplifier input impedance
α	Generation - recombination noise parameter
ϵ_{het}	Efficiency of heterodyne receiver or spectrometer
ϵ_{inc}	Efficiency of incoherent receiver or spectrometer
η	Quantum efficiency; two different types of quantum efficiency exist. The responsive quantum efficiency (RQE) compares the observed responsivity of a detector to that which would occur if every incident photon contributed equally, i.e., $S = G\,\eta\,\frac{e\lambda}{hc}$. The detective quantum efficiency (DQE) compares the detector noise with that which would occur if there were only ideal photon noise, i.e., $NEP_{PC} = (4\dot{N}/\eta)^{1/2}$. Both RQE and DQE can be defined for coherent receivers as well as for incoherent receivers.
λ	Wavelength
$\Delta\lambda$	Wavelength bandwidth
λ_c	Cutoff wavelength; longest wavelength of response
ν	Infrared frequency
$\Delta\nu$	Infrared bandwidth, $\Delta\nu = B$
ν_{IF}	IF frequency of heterodyne receiver
ν_O	Output frequency of upconverter

ν_P	Pump frequency of upconverter
ν_S	Signal frequency of upconverter
τ_{het}	Integration time of heterodyne receiver or spectrometer
τ_{inc}	Integration time of incoherent receiver or spectrometer
ARC	Ames Research Center
COBE	Cosmic Background Explorer
DoD	Department of Defense
GISS	Goddard Institute for Space Studies
GSFC	Goddard Space Flight Center
IRAS	Infrared Astronomical Satellite
JPL	Jet Propulsion Laboratory
LaRC	Langley Research Center
MIT	Massachussetts Institute of Technology
NRL	Naval Research Laboratory
OAST	Office of Aeronautics and Space Technology
OSS	Office of Space Science
OSTA	Office of Space and Terrestrial Applications
Rockwell	Rockwell International Corporation
SBRC	Santa Barbara Research Center, Subsidiary of Hughes Aircraft Corporation
Spacelab 2 IRT	Spacelab 2 Small, Helium-Cooled Telescope Experiment
SIRTF	Shuttle Infrared Telescope Facility
UCB	University of California, Berkeley

APPENDIX C. SUGGESTED READING

The literature on infrared detectors is very large. It is not feasible to attempt even a representative sample. A few review articles are listed below that supply more thorough discussions of many of the issues raised in this report, and also extensive references to the published literature. Unfortunately the best detector results often appear only in unpublished contract reports many of which are classified.

Books of general interest include:

1. Willardson, R. K., and Beer, A. C., eds. Infrared Detectors I, Vol. 5 in Semiconductors and Semimetals, (New York: Academic Press, 1970), and Infrared Detectors II, Vol. 12 in the same series (1977).

2. Keyes, R. J., ed., Optical and Infrared Detectors, (New York: Springer Verlag, 1977).

3. Hudson, R. D., Jr., and Hudson, J. W., eds., Infrared Detectors, (Halsted Press: Stroudsburg, PA, 1975). (reprint collection)

4. Arams, F. R., ed., Infrared-to-Millimeter Wavelength Detectors, (Artech House: Dedham, MA, 1973). (reprint collection)

5. Wolfe, W. L., ed., Handbook of Military Infrared Technology, (U. S. Government Printing Office, 1965).

6. Proceedings of the Meetings of the IRIS Specialty Group on Infrared Detectors, annual. Classified Secret prior to 1976, since then published in two volumes, one of which is unclassified. Distribution controlled. Request copies from Office of Naval Research, Branch Office Chicago, 536 S. Clark St., Chicago, IL, 60605.

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Emmons, R. B., Hawkins, S. R., and Cuff, K. F., "Infrared Detectors: An Overview," Opt. Eng. 14, 21-30 (1975).

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Kruse, P. W., "The Photon Detection Process," general reference 2, pp. 5-69.

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Submillimeter Space Telescope, Jet Propulsion Laboratory, April 10, 1978.

COBE, Cosmic Background Explorer, Interim Report, Goddard Space Flight Center, February 1, 1977.

IRAS, Report of the Joint Scientific Mission Definition Team for an Infrared Astronomical Satellite, Goddard Space Flight Center, May, 1976.

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Spicer, W. E., "Negative Affinity 3-5 Photocathodes: Their Physics and Technology," Appl. Phys., 12, 115-130 (1977).

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Longo, J. T., Cheung, D. T., Andrews, A. M., Wang, C. C., and Tracy, J. M., "Infrared Focal Planes in Intrinsic Semiconductors," IEEE Trans. Electron Devices, ED-25, 213-232 (1978).

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Bratt, P. R., "Impurity Germanium and Silicon Infrared Detectors," general reference 1, vol. II, pp. 39-142.

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Haller, E. E. Hueschen, M. R., and Richards, P. L., "Ge:Ga Photoconductors in Low Infrared Backgrounds," Appl. Phys. Lett., 34, 494-496 (1979).

Putley, E. H., "InSb Submillimeter Photoconductive Detectors," general reference 1, Vol. II, pp. 143-168.

Stillman, G. E., Wolfe, C. M., and Dimmock, J. O., "Far-Infrared Photoconductivity in High Purity GaAs," general reference 1, Vol. II, pp. 169-290.

IIIF

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Nelson, R. D., "Infrared Solid State Imaging Arrays," Proc. Soc. Photo-Optic. Instrum. Eng., 124, 91-101 (1977).

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Linke, R. A., Schneider, M. V., and Cho, A. Y. "Cryogenic Millimeter Wave Receiver Using Molecular Beam Epitaxy-Diodes," IEEE Trans. Microwave Theory Tech., MIT-26, 935-938 (1978).

Richards, P. L., Shen, T. M., Harris, R. E., and Lloyd, F. L., "Quasiparticle Heterodyne Mixing in SIS Tunnel Junctions, "Appl. Phys. Lett., 34, 345-347 (1979).

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See general reference 1, Vol. I, chapters 8, 9, and 10.

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Boyd, R. W., "Infrared Upconversion for Astronomy," Opt. Eng., 16, 563-568 (1977).

The following recent NASA technical reports contain detailed information on specific detector types:

Detection of Long Wavelength Infrared at Moderate Temperatures, NASA-CR-151,559, April, 1977.

Characterization of IRAS Doped Silicon Detectors, NASA-CR-151,941, December, 1976.

Further Characterization of IRAS Doped Silicon Detectors, NASA-CR-152,014, June 1977.

Development of Doped-Germanium Photoconductors for Astronomical Observations at Wavelengths from 30 to 120 Micrometers, NASA-CR-152,046, November 30, 1977.

Continued Development of Doped-Germanium Photoconductors for Astronomical Observations at Wavelengths from 30 to 120 Micrometers, NASA-CR-152,125, April 24, 1978.