Germanium Detectors for the Far-Infrared

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Abstract

Germanium photoconductors have been used in a variety of infrared astronomical experiments, both airborne and space-based. The bulk of our knowledge of the far-infrared properties of astronomical objects has come from observations made with these detectors. This paper describes the operational theory of these detectors, including amplifier considerations. Examples of recent focal plane array designs, in particular the detectors for the SIRTF MIPS instrument, are shown. Progress in modeling of the non-linear behavior of the detectors is presented. Future directions are discussed, including concepts for large format arrays, modifications for high background operation, and blocked impurity band devices.

I. Introduction

The far-infrared part of the spectrum is crucial for the study of many astrophysically important objects. Luminous infrared galaxies, protostars, and debris disks around stars all have peak emissions at far-infrared wavelengths. Beyond ~40 mm conventional silicon-based detectors do not function, and alternate technologies are required. The two most widely used detectors at these wavelengths have been bolometers and germanium photoconductors. Bolometers are thermal detectors that sense the temperature change caused by the absorption of far-infrared photons. Significant progress has been made in recent years on bolometer technology, and several groups around the world have produced highly sensitive arrays of bolometers. As thermal detectors, however, bolometers are limited by the phonon fluctuations in the device, and state-of-the-art performance requires sub-Kelvin cooling. Consequently, the use of bolometers in space-borne applications has been very limited. For the spectral range 50 to 240 mm, the detector of choice has been the germanium photoconductor. These detectors have been used on all the far-infrared space missions including IRAS, Spacelab-II Infrared Telescope, IRTS, COBE, and ISO (Short Wavelength Spectrometer, Long Wavelength Spectrometer, and ISOPHOT), and they will be used on the future missions SIRTF, IRIS and FIRST. In particular, the survey of IRAS used Ge:Ga photoconductors to produce the most comprehensive look at the far-infrared sky. Figure 1 shows some of the images that were produced by the IRAS mission. IRAS produced these remarkable results utilizing only 16 discrete detectors each in the 60 and 100 mm bands.

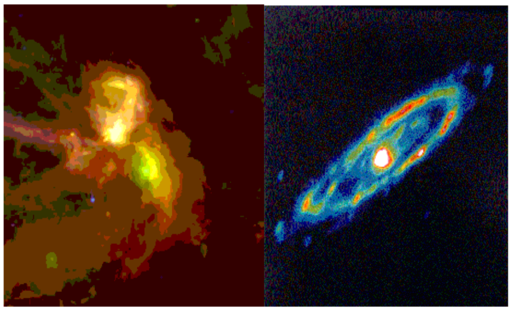

Figure 1. Examples of the legacy of IRAS. (Left) The Rho Ophiuchi star forming region and (Right) M31. In the images the colors blue, green, and red correspond to 12, 60, and 100 µm, respectively.

Figure 1

II. Photoconductor Operation

The intrinsic band gaps of silicon and

germanium are 1.11 and 0.67 eV, respectively, corresponding to long wavelength cutoffs of 1.1 mm and 1.8 mm. Longer wavelength response is possible if the semiconductor is doped with elements that have shallow extrinsic levels. Historically, the most important of these impurities in germanium has been the p-type dopant gallium. Gallium-doped germanium (Ge:Ga) detectors have cutoff a wavelength of approximately 115 mm. The spectral response for the Ge:Ga detectors used in the SIRTF focal plane arrays is shown in Figure 2. The other dopant that has had significant application in infrared astronomy has been antimony. Ge:Sb detectors have a cutoff wavelength of 130 mm.

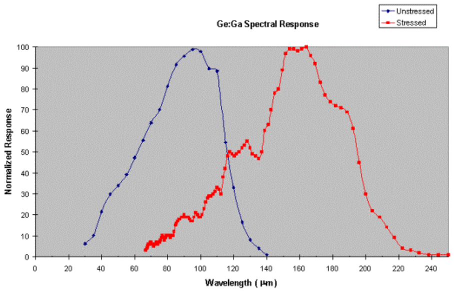

Figure 2. Spectral Response for Stressed and Unstressed Ge:Ga.

Figure 2

The absorption coefficient of an extrinsic photoconductor at wavelength l is given by the product of the photoionization cross section s(l) and the doping concentration of the impurity *n*. In principle, it is desirable to make *n* as high as possible. In practice the concentration is limited by the onset of impurity banding effects that cause a huge increase in the dark current. For Ge:Ga, the relevant values are s(l) = 1 x 10^{-14} cm^{2} and n = 2 x 10^{14} cm^{-3} (Wang et al. 1986), which gives an absorption coefficient of 2 cm^{-1}. An important consequence of this relatively low absorption coefficient is that Ge:Ga detectors must either be physically large, or they must be mounted in integrating cavities. Table 1 gives some of the typical parameters for unstressed Ge:Ga detectors. More detailed discussions of theory and operation of extrinsic photoconductors can be found in the review papers of Bratt (1977) and Sclar (1984) and the book by Rieke (1994).

Table 1. Typical Parameters for Unstressed Ge:Ga Photoconductors

Acceptor Concentration	2 x 10^{14} cm^{-3}
Donor Concentration	< 1 x 10^{11} cm^{-3}
Typical Bias Field	50 mV/mm
Responsivity	7 A/W
Quantum Efficiency	20%
Dark Current	< 200 e^{-}/s
Operating Temperature	1.8 K

An important modification in the long wavelength response of Ge:Ga can be achieved by the application of stress along the appropriate crystal axis. Applying stress along the [100] axis can result in a significant extension of the cutoff wavelength. (Kazanskii, Richards, and Haller 1977). Figure 2 shows the response for the SIRTF stressed detectors, where a pressure of 490 MPa has been applied.

III. Readout Considerations

A key part of any detector system is the amplifier that is connected to the sensing element. IRAS and COBE utilized transimpedance amplifiers (TIA) to convert the photocurrent into an output voltage. The TIA is a feedback amplifier circuit that uses a resistor in the feedback loop. The output voltage is simply given by the product of the photocurrent *i* and the feedback resistor R_f. Although the TIA has many useful characteristics (Wyatt, Baker, and Frodsham 1991), it suffers from thermal noise from the feedback resistor. Consequently, recent photoconductor focal planes such as for ISO and SIRTF have utilized charge integrating amplifiers.

The characteristics of Ge:Ga detectors place special demands on the readout electronics. Most importantly, it is highly desirable for the amplifiers to operate at the same temperature as the detectors. Having the amplifiers at the detector temperature eliminates the complications of thermal and photon isolation that are inherent in heated amplifiers. Unfortunately, most silicon devices do not operate properly at these low temperatures. J-FET and bipolar devices to not function below 50 K, and even MOSFET's fail to operate reliably below the freezeout temperature of ~20 K. Among the problems seen in deep cryogenic silicon MOSFET devices are DC instability, kinks and hysteresis in the response function, loss of transconductance, and increased noise (Glidden et al. 1995). Despite efforts to produce cryogenic circuits using alternate materials such as GaAs and Ge, no useful substitute for silicon has emerged for integrated circuit readouts.

The DC instability is particularly troublesome for Ge:Ga photoconductors. Because the devices operate at very low bias voltages (typically, 50 mV for unstressed detectors and 30 mV for stressed devices), even small changes in the operating points of amplifiers can result in unacceptable bias changes on the detectors.

Fortunately, modifications to the standard MOSFET recipe can yield useful devices for very low temperature operation. A NASA-supported effort has produced a family of readouts, the Raytheon CRC-696, that exhibit excellent performance at 2K and below. The key modifications to the wafer starting material are the use of:

1) A degenerately-doped substrate,

2) A very thin epitaxial layer, and

3) Light doping in the epitaxial layer to insure full depletion at operating temperature.

The CRC-696 has 32-channel integrating amplifier with a fully addressable multiplexer. The mask set included a variety of circuit variations for the input stage including the Source Follower per Detector (SFD), Common Source Cascode (CSC), and Capacitive Transimpedance Amplifier (CTIA). The bias stability requirement of Ge:Ga makes the CTIA the readout of choice. The schematic of the CTIA version of the CRC-696 is shown in Figure 3. With a 36 fF feedback capacitor, the CTIA version of the CRC-696 gives a high transconductance of 4 mV/e$^-$, a full well capacity of ~300,000 e$^-$, and a read noise below 50 e$^-$ for the bare multiplexer. Because of the negative feedback, the potential at the input node does not change significantly during an integration.

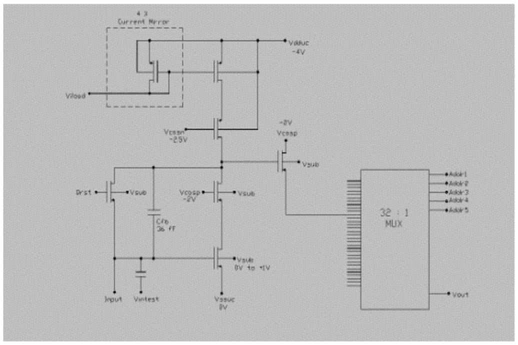

Figure 3. Circuit Diagram for CRC-696 CTIA Multiplexer

Figure 3

IV. SIRTF Far-Infrared Arrays

The Multiband Imaging Photometer for SIRTF (MIPS) has two band that utilize Ge:Ga photoconductors. The 70 mm band has a 32x32 array of unstressed detectors, while the 160 mm band has a 2x20 array of stressed detectors. Both focal plane arrays represent very large extensions of the technology at these wavelengths. These arrays were designed, constructed, and tested at Steward Observatory, the University of Arizona.

The unstressed array is built up of 4x32 modules interconnected by a common backplane. Figure 4 shows the major components of the array. Each 4x32 module consists of four CRC-696 readouts, four photolithographically delineated Ge:Ga detector bars, undoped germanium optical concentrators, a ceramic multiplayer board, a molybdenum frame, and an output flex cable. The detector material was grown at Lawrence Berkeley Laboratory. Details of the construction can be found in Young et al. (1998). The full SIRTF array requires eight 4x32 modules, which are mounted on a molybdenum base. For the MIPS program, three complete 32x32 arrays were produced: flight, flight spare, and engineering. Figure 5 is a photograph of the flight 70 mm array.

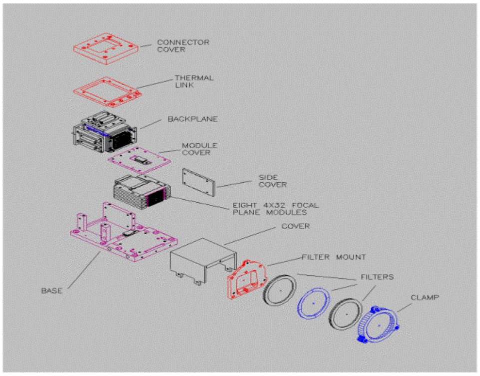

Figure 4. Major components of the MIPS 70 µm Array.

Figure 4

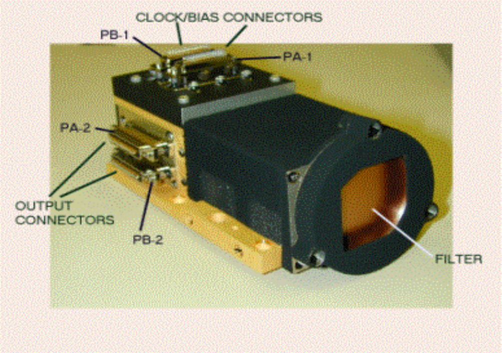

Figure 5. MIPS Flight 70 µm Array

Figure 5

The 2x20 stressed array is shown in Figure 6 (Schnurr et al 1998). The four stressing rigs, each containing a 2x5 array of detectors, are made of Aermet 100, a special high strength steel. In the MIPS design, each detector is individually stressed with a spring arm. This conservative approach was taken to minimize the system impact of a failed detector element. Besides the very high strength, the other useful property of Aermet 100 is its relatively low heat capacity at very low temperatures. The stressing rigs are thermally isolated from the base using thin-walled fiberglass tubes and directly heat sunk to the SIRTF helium bath via a high conductivity copper strap.

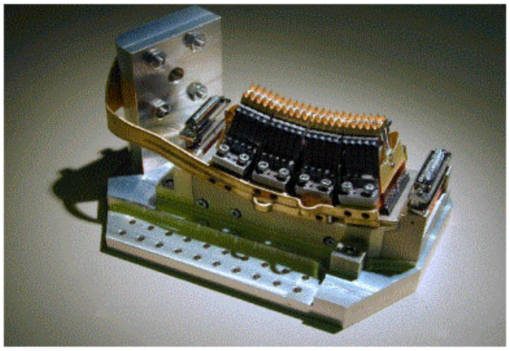

Figure 6. MIPS 160 µm Stressed Ge:Ga Array

Figure 6

This arrangement eliminates the interaction with heat sources in the instrument while at the same time allows occasional thermal annealing of the detectors using resistive heating elements built into the stress rig mount. For space applications, thermal annealing is a particularly effective method of restoring normal responsivity to a detector that has been exposed to ionizing radiation. The MIPS stress rig does this thermal anneal with a time averaged power dissipation of less than 1 mW and a return to operation in less than 120 s.

V. Addressing Non-Ideal Behavior

Photoconductors exhibit a variety of background-dependent long time constant effects. These effects are illustrated in Figure 7 which shows the response of a Ge:Ga detector to a step change in illumination. The detector shows a prompt response which is followed by a drop in photocurrent (the “hook”) and finally a slow increase to an equilibrium level (due to dielectric relaxation). Note that under the very low backgrounds for a space observatory, the dielectric relaxation timeconstant can be measured in hours. These non-ideal detector responses have posed significant problems in the calibration of photoconductor data, especially since the photocurrent as a function of time can depend on the illumination history in a complicated manner.

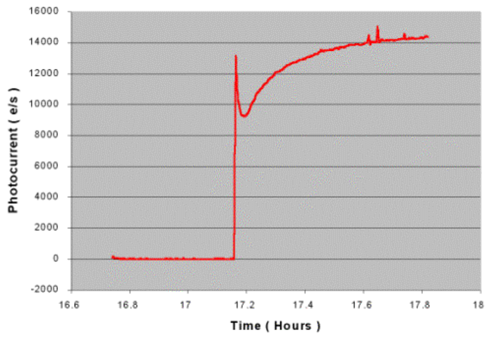

Figure 7. Ge:Ga Response to Step Illumination Change.

Figure 7

The MIPS instrument addresses the calibration issue by combining a number of observing strategies. First, the response of the detector to the change in illumination (the fast response), is much more consistent than the subsequent long term behavior. MIPS uses a scanning mirror in the instrument to modulate the infrared signal on relatively short time scales. The modulated fast signal, although it is of lower amplitude than the equilibrium signal, is much more usable photometrically, and the resultant signal to noise ratio is typically an order of magnitude better. The second operational refinement is the frequent use of internal stimulators to track any response changes in the detectors. Typically, the internal stimulators are flashed every few minutes, and provide a running relative calibration for the array. Laboratory testing of the MIPS 70 mm array using internal stimulators has verified the value of these observational approaches. Point source photometric repeatability relative to internal stimulators of better than 2% has been achieved under realistic SIRTF backgrounds. Finally, significant progress has been made in understanding the cause of this non-linear behavior. Detailed modeling of the charges and fields within the detector by Nancy Haegel (Fairfield University) has demonstrated that much of the behavior is due to effects at the electrical contacts. Figure 8 shows an example of a simulation of Ge:Ga photoconductor response to a step illumination change. Using these insights should help in the optimum operation and design of future devices.

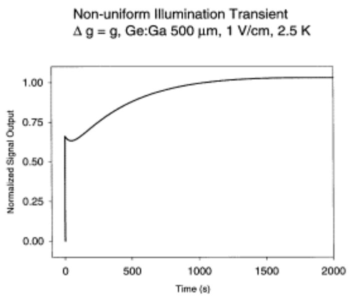

Figure 8. Model of Ge:Ga Response to Step Photon Change, Including Non-uniform Contact Illumination (N.Haegel)

Figure 8

A second type of non-ideal behavior occurs when the detector is exposed to ionizing radiation. Under low backgrounds, the infrared responsivity can increase nearly an order of magnitude with only a 100 mRad dose of radiation. This increase in responsivity is particularly troublesome since its recovery time is background dependent, and it is often accompanied by additional noise. There are a number of ways to restore the pre-irradiation conditions. Among the methods are bias boost, where the bias voltage is increased to the breakdown level for a short time (typically minutes), photon flooding, where the detector is illuminated with a very high flux of *infrared* photons, and thermal anneal, where the detector is heated to a level where the dark current becomes high enough to drive the detector into saturation. For Ge:Ga a temperature of 8 K for ~10 s is sufficient to restore the pre-irradiation conditions using thermal anneal. The MIPS arrays utilize the thermal anneal method as the primary remediation, and bias boost is used as a backup strategy.

VI. Other Developments

The state of the art in germanium far infrared detectors continues to advance, and in this section we sample some recent work.

a) FIFI-LS and PACS

The Field Imaging Far-Infrared Line Spectrometer (FIFI-LS) is a First-Light instrument for SOFIA that is being constructed at the Max Planck Institut für Extraterrestrische Physik under the direction of Albrecht Poglitsch. It is an innovative integral field spectrometer that produces a 5x5 pixel image with 16 spectral resolution elements per pixel in each of two bands. To accomplish this, the instrument has two 16x25 Ge:Ga arrays, unstressed for the 45-110 mm range and stressed for the 110 to 210 mm range. As with the MIPS arrays, construction is modular, although for the FIFI-LS arrays, the basic building block is a 1x16 linear module with readouts. For the stressed arrays, a common spring arm simultaneously stresses an entire stack of 16 detector elements. Figure 9 shows one of the 1x16 stressed array modules and a CAD model of the full array.

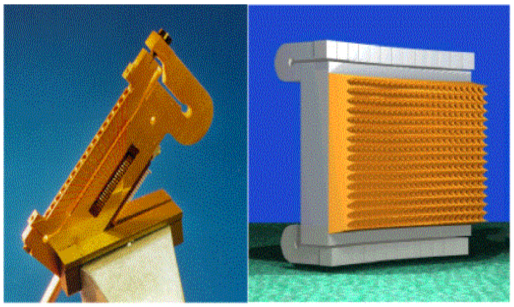

Figure 9. (left) FIFI-LS Stressed Array Module. (right) CAD Model of Full FIFI-LS Stressed Detector Array (A. Poglitsch)

Figure 9

The Photoconductor Array Camera & Spectrometer (PACS) is one of the three science instruments for ESA's FIRST Mission. Like FIFI-LS, PACS employs two 16 x 25 pixels Ge:Ga photoconductor arrays (one stressed, one unstressed). The instrument has a number of modes including imaging photometry, Fabry-Perot imaging, and imaging line spectroscopy in the 60 to 210 mm wavelength band.

b) High Background Readout Development

The CRC-696 readout has excellent performance for SIRTF, but it has inadequate well capacity for a high background application such as SOFIA. To support the Airborne InfraRed Echelle Spectrometer (AIRES) for SOFIA as well as the development of future large format far infrared arrays for imaging, Ed Erickson (NASA Ames) and the author, in collaboration with Raytheon have developed a successor to the CRC-696. The SBRC-190 readout features 32-channels of CTIA amplifiers. The newer part, however, has eight selectable feedback capacitors, yielding full well capacities ranging between 1 x 10^5 e^- to in excess of 2 x 10^7 e^-. In addition, the SBRC-190 includes an auto-zero circuit on the input stage that corrects for any threshold variations in the devices. With low bias voltage Ge:Ga detectors, eliminating the requirement of excellent threshold voltage matching greatly increases the yield of usable readouts.

c) Germanium Blocked Impurity Band Detectors

As mentioned earlier, conventional photoconductors suffer from a number of shortcomings including non-linear response, large radiation cross sections, and the need for stressing to get response beyond the normal cutoff. To a large extent, these shortcomings have been eliminated below 40 mm with the use of the Blocked Impurity Band (BIB) structure in silicon detectors. The concept of the BIB detector is illustrated in the band diagram in Figure 10. The bulk photoconductor is replaced with a thin infrared absorbing layer that is much more heavily doped than a conventional photoconductor. Such a high doping would normally cause an unacceptably high dark current due to impurity banding. This band conduction is blocked, however, by the addition of a layer of undoped germanium. The key to success in Ge BIB detectors will be the quality of the blocking layer, specifically the level of minority acceptors. Several attempts to produce Ge BIB detectors have been made in recent years. Figure 11 shows results that were achieved by Dan Watson (University of Rochester). The devices showed BIB behavior in the extended long wavelength response as well as improved transient response. The detectors, however, were limited by the attainable purity of the blocking layer as well as the lack of a suitable passivation layer for germanium. Recently, both Watson and Eugene Haller and Jeff Beeman (E.O. Lawrence Berkeley National Laboratory) are beginning new efforts to apply more modern techniques to produce Ge BIB detectors.

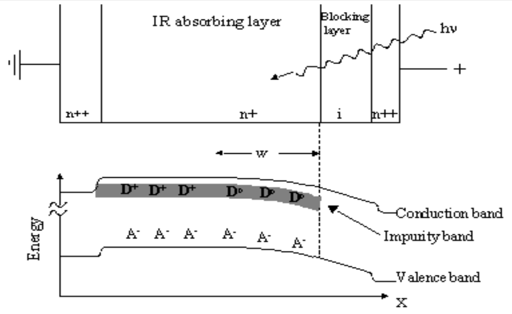

Figure 10. Schematic and Band Diagram for n-Type Blocked Impurity Band Detector (E. Haller and J.Beeman)

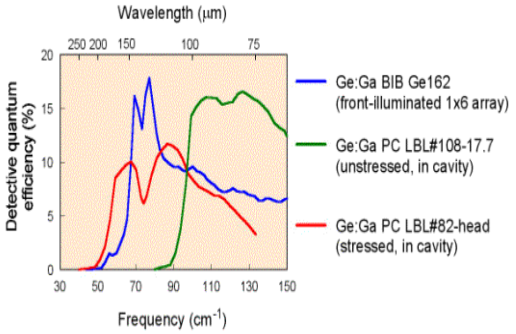

Figure 11. Comparison of Ge BIB and Conventional Photoconductors (D. Watson)

Figure 10

Figure 11

The Berkeley approach is to grow the blocking layer using Liquid Phase Epitaxy (LPE) as illustrated in Figure 12. The germanium is dissolved in a solvent, in this case ultra high purity lead. They have found that using the best source of Pb commercially available produces n-type Ge layers of 5 x 10^{14} donor atoms per cm^3 and a compensating p-type impurity concentration as low as 3 x $10^{11} cm^{-3}$. This level of purity is adequate for producing good quality IR active layers and suggests that with additional lead purification, adequate blocking layers can be grown.

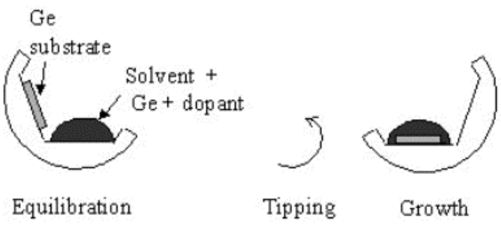

Figure 12. Liquid Phase Epitaxy Growth
(E.E. Haller and J. Beeman)

Figure 12

VII. Summary

Germanium far infrared detectors have been the detector of choice for low background astronomy between 50 and 240 mm. Large format arrays have been produced for flight on SIRTF, and germanium photoconductors will be used for instruments on SOFIA and FIRST. Ge:Ga shows non-linear behavior under very low backgrounds, but operational adjustments can yield photometric repeatability to better than 2%. Potential advances in the technology include extension to high background airborne applications and the production of useful Ge BIB detectors.

Acknowledgements

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