The Far-Infrared Detector Technology Advancement Partnership - FIDTAP

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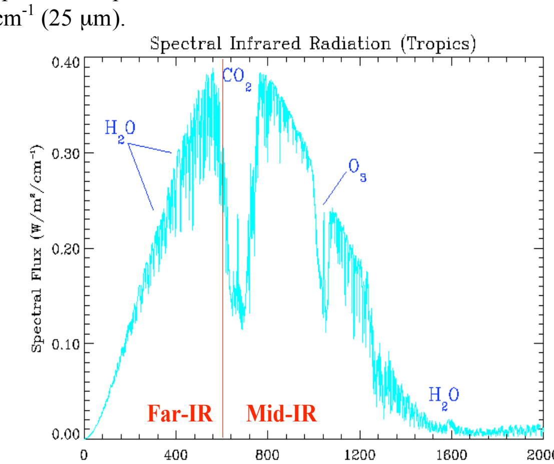
Abstract. Earth's far-infrared (far-IR) spectrum, nominally wavelengths longer than 15 µm, contains approximately half of the outgoing longwave radiation from the planet. The far-IR radiation is modulated by water vapor, the main greenhouse gas, and by thin cirrus clouds in the upper troposphere. Despite its fundamental importance, space based far-IR observations of the Earth and it atmosphere have not been routinely made. Under NASA's Instrument Incubator Program the Far-Infrared Spectroscopy of the Troposphere (FIRST) instrument was developed to demonstrate the technology necessary to make space-based measurement of the far-IR spectrum routine. FIRST demonstrated spectrometer, beamsplitter, and focal plane technologies. The remaining technology required to achieve far-IR measurements in space is detectors with sufficient speed and sensitivity that can be cooled by low temperature (10 Kelvin) cryocoolers that are becoming available for space systems. FIDTAP is a partnership between the NASA Earth Science Technology Office, the NASA Langley Research Center, and DRS Technologies, Inc., to develop prototype detectors necessary to achieve space-based far-IR measurements.

I. INTRODUCTION

The radiation budget of the Earth system was the first quantitative measurement to be made from orbiting satellites. Since the 1960's, radiation budget measurements have consisted of the total (reflected solar plus emitted thermal infrared) radiation and the reflected solar radiation; these are spectrally integrated or broadband measurements with little spectral discrimination. The emitted longwave radiation is obtained by subtraction of the two classic energy flows. These measurements provide the integral constraints on the Earth's climate and energy budget. The response of and feedbacks within the Earth's climate system are determined by the terms of the integral, i.e., the absorption and emission spectra. Since the days of the first radiation budget measurements, they have been refined significantly in terms of their spatial resolution, angular sampling capability, and radiometric calibration. Temporal sampling is improved by placing additional sensors in different orbit planes or by placing radiation budget sensors in geostationary orbit, as has recently been done with the orbiting of the Geostationary Earth Radiation Budget (GERB) instrument on the *Meteosat* satellite. Despite these continuous improvements, radiation sensors are essentially making the same basic measurements as 45 years ago with little additional spectral distinction. Remote sensing of the Earth's energy balance is an eight dimensional sampling problem. The improvements noted above in spatial, angular, and temporal sampling address seven of the eight dimensions. The remaining critical dimension, the spectral dependence of the entire infrared including the far-IR, remains to be measured from space.

The infrared spectrum of the Earth and its atmosphere is now being measured at high accuracy and precision from orbiting satellites. The Atmospheric Infrared Sounder (*AIRS*) and Moderate Resolution Imaging Spectrometer (*MODIS*) instruments on the EOS-Aqua satellite record the infrared spectrum between 4 and 15 µm. The *IASI* instrument under development in Europe and about to be launched is a Michelson interferometer that will similarly record spectra between 4 and 15 µm. The Crosstrack Infrared Sounder (*CrIS*) instrument is a Michelson interferometer that will fly later this decade on the NPOESS series of satellites also covering the 4 to 15 µm spectral region. Similar spectral measurements of the infrared emission from Earth were made by the NASA *IRIS* instruments in 1969 and 1970 and by the Russian *Meteor* spacecraft in the mid-1970's, although at much coarser spatial and spectral resolution. IRIS did measure out to 400 cm^{-1} (25 µm).



Shown above is the calculated longwave spectral flux at the top of the atmosphere in the tropics. Indicated are the major gaseous absorption features that contribute to the spectrum. The distinction between far-IR and mid-infrared is made with the red line, which indicates the longwave cutoff at 15 μm of current and planned sensors. This cutoff at 15 μm of these spectral sensors is primarily due to the physical properties of the detector material used, and not scientific necessity. There are extremely compelling scientific reasons to measure the far-IR beyond 15 μm [1]. Recognizing these, the Far-Infrared Spectroscopy of the Troposphere (FIRST) instrument [2] was developed by NASA's Instrument Incubator Program (IIP). FIRST is a Michelson interferometer with a 0.625 cm^{-1} unapodized spectral resolution. FIRST has significantly advanced technology in high throughput interferometers and in broad spectral bandpass beamsplitters, achieving a throughput of 0.47 cm^2sr and a bandpass of 6 to 100 μm in one beamsplitter and a single focal plane array. The FIRST detectors, however, are off-the-shelf silicon bolometers cooled to 4 Kelvin in a dewar of liquid helium.

In order to take the FIRST measurements to space, new detectors are needed that do not require passive cooling in a dewar of liquid helium. For a long-term (3-5 year) mission, the quantity of liquid helium required would likely be prohibitive. We note that NASA is investing in the development of low temperature cryocoolers operating at temperatures between 6 and 12 Kelvin. Our goal then, is to develop and characterize detectors sensitive in the far-IR that operate efficiently at temperatures achievable by the cryocoolers now under development. With new low temperature cryocoolers and the FIRST far-IR interferometer technology, sensitive detectors at these temperatures are the remaining technology needed to realize space-based far-IR spectral measurements over the required wavelength range.

II. DETECTOR REQUIREMENTS

The FIRST concept is to merge operational sounding capability into an instrument with the stability and sensitivity for earth radiation budget applications. Because of the potential to contribute to atmospheric water vapor sounding, we required an instrument capable of global coverage on a daily basis. The FIRST instrument developed under IIP is a high throughput (0.47 cm^2sr) interferometer covering the 6-100 μm spectral range in a single focal plane with a single broad bandpass beamsplitter is designed to achieve this goal, assuming a 900 km orbit, a +/- 45 degree cross-track scanning mode, and the capability to record 100 interferograms on a 10 x 10 array every 1.2 seconds (i.e., 10 km pixels). The validation flight of the FIRST instrument has confirmed the throughput and spectral response goals are achieved [2]. The requirements on the detectors are then:

- broad spectral response 10 to greater than 70 μm
- several kilohertz sampling frequency
- operational temperatures above liquid helium temperatures, nominally in the range of 10 Kelvin to be compatible with emerging cryocooler technology

III. FIDTAP TECHNICAL APPROACH

We are going to develop prototype far-infrared detectors appropriate for the Far-Infrared Spectroscopy of the Troposphere (FIRST) instrument requirements. Our present approach is to extend the operating wavelength of doped silicon Blocked Impurity Band (BIB) detectors. Extrinsic silicon Blocked Impurity Band (BIB) detectors are attractive because they have demonstrated high quantum efficiency, excellent operability, and excellent uniformity out to wavelengths as long as about 40 μm. The primary materials for BIB detectors are arsenic-doped silicon (Si:As) which responds as far as 30 μm and antimony-doped silicon (Si:Sb) which responds to about 40 μm.

Our concept is to provide a substantial extension to the wavelength response for Si:Sb BIB detectors (currently ~40 μm cut-off). The technical approach is to increase antimony doping concentration. The scientific basis underlying this approach is well understood: At conventional donor doping in N-type BIB detectors (typically 10^{17} to 10^{18} dopant atoms per cubic centimeter) the electrons orbiting two (2) nearby neutral donor atoms substituted in silicon lattice sites are close enough to rapidly interact with each other quantum mechanically. When one is removed the other can rapidly tunnel across to fill its place. If an electric field is present to provide motivation, this positive vacancy moves from donor atom to donor atom in the direction of the field, until it exits the device. In semiconductor terminology, it can be said that a new valence band (an impurity conduction band) is formed just below the silicon conduction band, and that donor holes (D+ charges) flow in this band.

The energy gap between the impurity conduction band and the silicon conduction band varies with the average distance between dopant atoms, i. e. inversely with the doping concentration. This effect arises from the Fermi statistics of interacting identical particles. Two donor atoms close enough to interact will form a system of two energy levels, one state higher in energy (closer to the conduction band edge) and one lower than the original energy level of an isolated donor atom. The difference in energy between the two energy levels will be greater if the atoms are close together (strongly interact) than if they are further apart (weakly interact). Three interacting atoms will form a system with three different levels, and so on. So, as doping increases, the set of isolated donor electron states transitions into a band of energy states with its top edge ever closer to bottom edge of the silicon conduction band. The near-random placement of donor atoms in the silicon lattice during silicon doping results in further spreading of the impurity band and narrowing of the impurity band gap.

We summarize the principles underlying our approach as follows: The present, modest long-wavelength extension observed for BIB detectors is a direct result of the phenomenon of impurity banding employed in the operating principle of these detectors. As the doping concentration (taking *n*-type doping for concreteness) increases two effects combine to lower the energy needed to liberate an electron from a neutral donor and create and create a mobile carrier pair (the electron and the ionized donor charge or D^+ charge). First, the impurity band formed from the ground states of the neutral impurities broadens, decreasing the impurity bandgap. Second, the mobility edge, *i.e.* the point in energy above which an electron has a wave function that is delocalized so that the electron is mobile, moves down in energy with concentration. This principle should allow the detector to respond out to 70 microns or longer.

IV. THE PARTNERSHIP

The Far-Infrared Detector Technology Advancement Partnership (FIDTAP) is a joint effort involving the NASA Earth-Sun System Technology Office (ESTO), the NASA Langley Research Center, and DRS Technologies, Inc., located in Cypress, CA. DRS has developed infrared detectors for numerous NASA astronomy and earth science programs over the years.

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