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Detectors for sub-millimetre continuum astronomy

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ABSTRACT

Sub-mm astronomy has seen an explosive growth in recent years. This has been driven by improvements in detector technology, and in particular the move from single pixel photometric instruments to ones containing arrays of hundreds and even thousands of pixels. Sub-mm detectors are different from those used in astronomy at most other wavelengths in that they are not produced commercially. Instead, research, development and construction is carried out in universities and government laboratories. We are also at an interesting point in that several competing detector technologies are under development and it is not yet clear which will be used in future instruments. I review current instruments as well as the issues facing us in developing the next generation of instruments, operating both on the ground and from space.

1. Introduction

Sub-millimetre astronomy is a rapidly evolving field, driven by continual improvements in technology along with the desire to address fundamental astronomical issues such as the birth of planets, stars, galaxies, and even the universe itself. The most common detectors used for sub-mm photometry are bolometers; the general principle is shown in Fig. 1.

There is no strict definition of the term sub-mm; the upper limit is often taken to be a few mm, the highest wavelengths at which bolometers are generally used. At the low wavelength end, there is no sharp division between sub-mm and infrared astronomy; the division is often put at around 200 μm which is the highest wavelength at which photoconductors (used for almost all infrared astronomy) are useful.

2. Bolometer instruments past and present

The first bolometers were developed (in 1880) for infrared astronomy, and operated at room temperature. Reducing the temperature reduces background blackbody radiation on the detector, and also increases sensitivity since heat capacity reduces with temperature. The foundations for modern cryogenic bolometers were laid in 1961 when F. Low developed a bolometer operating at a temperature of 4 K with doped germanium as the thermometer. With appropriate doping, semiconductors can have extremely large changes of resistance with temperature at cryogenic temperatures, resulting in high sensitivity. Germanium bolometers were not developed with astronomical applications in mind, but rapidly came to the attention of astronomers.

Bolometers have now largely been overtaken by semiconductor photodetectors for infrared astronomy but are the detector of choice for sub-mm photometry. To achieve sufficiently low noise, it is necessary to operate them at ultra-low temperatures (300 mK or below). Achieving and maintaining such temperatures is challenging, and is one area which distinguishes sub-mm instruments from most other areas in astronomy. Another difference from the more common areas of optical and infrared astronomy is that, lacking commercial or military applications, development has largely been carried out in universities and government laboratories, rather than industry.

A bolometer is a broad-band device, responding equally to all wavelengths that are absorbed. In use, therefore, it is necessary to use filters to restrict the radiation reaching the bolometer to the wavelengths of interest. If high resolution spectroscopy is required, coherent systems such as are employed in radio astronomy are suitable at sub-mm wavelengths. These are, however, outside the scope of this review.

An important step in bolometer design was the introduction of the composite bolometer, in which separate materials are used for the absorber and thermistor. First used in the 1970's, this approach allows a large absorbing area with a much lower heat capacity than if the thermistor itself were used as the absorber. Early sub-mm instruments consisted of a single pixel; building up images was thus a slow process.

Arrays appeared in the 1990's; the largest of the early arrays were contained in the SCUBA instrument. With 131 pixels, it enabled maps of the sky to be made up to 10 000 times faster than

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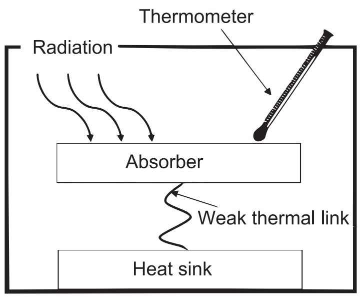

Fig. 1. Schematic of a bolometer. Radiation is absorbed in the absorber. A thermometer detects the resulting increase in temperature. Heat is removed by a weak thermal link to a heat sink.

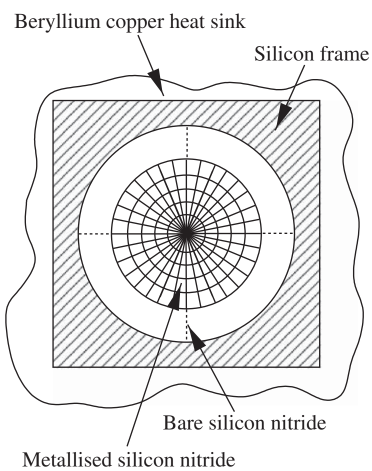

Fig. 2. Layout of a spiderweb bolometer.

before [1]. The absorber in each bolometer was made from sapphire, with the brass wires making the electrical connection to the thermistor forming the weak thermal link. Each bolometer was constructed by hand. The arrays were then made up from individually constructed pixels placed side by side. Such an approach makes building large arrays somewhat impractical.

To get sensitive and uniform behaviour in the thermistor, it is necessary to have extremely uniform doping. Conventional methods of doping germanium do not provide sufficient uniformity. The method adopted in SCUBA and other modern germanium bolometers is to use the neutron transmutation doping (NTD) process [2]. This makes use of the fact that germanium naturally occurs with several isotopes. One of these isotopes is converted to gallium under neutron bombardment. Since the different isotopes will be uniformly mixed in the initial material, the result is, therefore, an extremely uniform doping.

Modern germanium bolometers still use the NTD process, but employ micromachining techniques to produce composite bolometers. They are produced from a silicon wafer upon which silicon nitride is deposited. The silicon is then etched away to produce thin membranes of bare silicon nitride. These are mechanically strong, and make up both the absorber and its supports. A deposited metal film defines the absorbing area, as well as providing leads to the thermistor; these leads also control the thermal conductance to the absorber. The absorber can be made as a mesh or "spiderweb" shape (Fig. 2). The low resulting cross-section reduces heat capacity as well as exposure to ionizing radiation such as cosmic rays, but a large cross-section is still presented to sub-mm radiation, since the web spacing is much smaller than the wavelength. The bolometers can then either be broken out of the wafer to make up an array of individual detectors [3], or left in the wafer to form a complete array [4].

This approach enables the structure for many bolometers to be built up simultaneously, although the germanium thermistors still have to be placed on the bolometers individually. An alternative is to use doped silicon as the thermistor material. Instead of placing germanium crystals onto bolometers fabricated from silicon wafers, the thermistors can be made by ion implantation of the silicon itself. Such bolometers have had problems with excess noise (i.e., noise in addition to that caused by fundamental and unavoidable physical processes). However, it is now known that by making the ion implanted area thicker, the excess noise can be essentially removed [5].

For both germanium and silicon, it is difficult to multiplex the readout circuitry without introducing an unacceptable level of noise. This puts a clear limit on the total possible number of pixels, particularly since they must operate at very low temperatures, where the heat transmitted through the wires from room temperature, along with the heat generated by the first stage amplifiers, is a serious issue.

Ion implanted silicon bolometer arrays with 256 pixels have been produced using a CMOS multiplexed readout [6]. The large inherent noise in such a readout is partially overcome by using very high (GΩ–TΩ) thermistor resistances to achieve high responsivity. Such detectors are being used at wavelengths between 60 and 210 μm in the PACS instrument on the Herschel Space Observatory [6]. This is a wavelength range over which photoconductors can be used, but making arrays is extremely difficult. Bolometers were therefore chosen, despite requiring an operating temperature of 300 mK as opposed to a few K.

Even without multiplexing, semiconductor bolometers have reached their fundamental noise limits, and a new generation of instruments are being built employing superconducting detectors, often known as transition edge sensor (TES) detectors. These offer lower fundamental noise limits, can be constructed on silicon wafers on the scale of an entire array by thin-film deposition and optical lithography, and can be multiplexed with minimal noise penalty by using superconducting electronics.

A superconductor has a very large change in resistance over a narrow temperature range at the superconducting transition, but the resistance is nearly constant otherwise. To be useful as bolometers, the absorber must therefore be held at a precise temperature. The key to their successful use in astronomy was the realisation that if biased with a constant voltage (rather than current as is traditional with semiconducting bolometers), an automatic feedback mechanism will hold the absorbers on the superconducting transition for a wide range of heat sink temperature and absorbed power [7]. This behaviour is essential to the operation of arrays, since it allows many pixels to operate with a common bias supply despite the fact that each pixel will have slightly different properties.

This solution did not make superconducting detectors immediately useful. As with any detector technology, early detectors did not reach fundamental noise limits due to various sources of excess noise, and it has taken several years to identify and reduce these noise sources. However, we are now at the stage where many new sub-mm instruments are being built with superconducting detectors, with some already in operation (e.g. Ref. [8]). The total number of pixels in these instruments varies from a few hundred to over ten thousand. The focal planes in these instruments are generally made up from a mosaic of several smaller arrays. These arrays vary in size from tens of pixels (e.g. Refs. [8,9]), to over 1000 pixels [10], with each array having an independent multiplexer. Operating temperatures are 300 mK or below.