Detectors for sub-millimetre continuum astronomy

Adam L. Woodcraft*[1,2]

[1]SUPA, Institute for Astronomy, Edinburgh University, Blackford Hill, Edinburgh EH9 3HJ, UK
[2]UK Astronomy Technology Centre, Blackford Hill, Edinburgh EH9 3HJ, UK

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.

Keywords: Sub-millimetre, Astronomy, Instrumentation, Bolometer, STJ, KID
PACS: 95.55.Rg, 07.20.Mc, 07.57.-c, 85.25.Pb

Nuclear Instruments and Methods in Physics Research Section A., 604 (1-2):30-33, 2009

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.

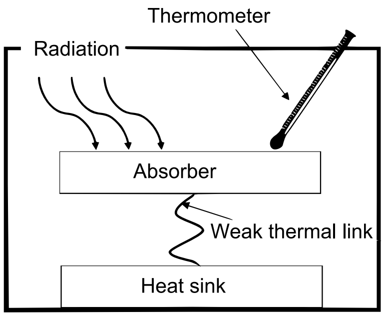

Figure 1: Schematic of a bolometer. Radiation is absorbed in the absorber. A thermometer detects the resulting increase in temperature. Heat is removed by a weak thermal link to a heat sink.

*Web: http://woodcraft.lowtemp.org

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 infra-red 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 infra-red 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 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 process (NTD) [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.

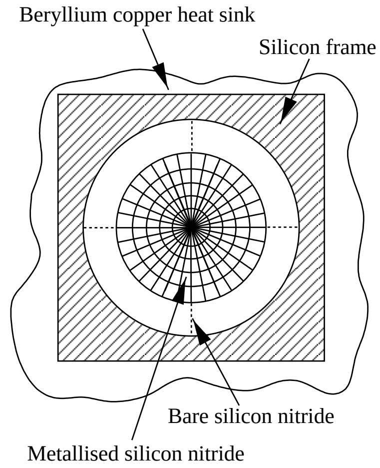

Figure 2: Layout of a spiderweb bolometer.

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 to 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

Table I: A list of facility sub-mm instruments which are currently on the telescope. The status is operational unless otherwise shown. The number of pixels shown for SCUBA-2 is the ultimate number when all arrays are installed.

Telescope	Instrument	Wavelength(s)	Pixels	Technology	Temperature	Status
APEX	LABOCA	870 μm	295	NTD Ge	300 mK	
ASTE	AzTEC	1.1 or 2.1 μm	144	NTD Ge	300 mK	
CSO	SHARC-II	350, 450 or 850 μm	384	Ion implanted Si	300 mK	
CSO	Bolocam	1.1 or 2.1 mm	119	NTD Ge	300 mK	
GBT	MUSTANG	3 mm	64	TES	300 mK	In commissioning
Herschel	PACS	60 - 210 μm	2560	Ion implanted Si	300 mK	Awaiting launch (2009)
Herschel	SPIRE	200 - 670 μm	326	NTD Ge	300 mK	Awaiting launch (2009)
IRAM 30 m	MAMBO-2	1.2 mm	117	NTD Ge	300 mK	
JCMT	SCUBA-2	450 and 850 μm	10240	TES	100 mK	In commissioning

the stage where many new sub-mm instruments are being built with superconducting detectors, with some already in operation (e.g. [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.

The most ambitious instrument, SCUBA-2 [10], will contain eight arrays, each with 1280 pixels. Each array contains 32 columns, each of which has a multiplexer which reads out the 40 pixels in the column. The control lines for the column multiplexers are shared, reducing the wire count from that required for 32 independant multiplexers. The number of connections between the multiplexer and the detector wafer is large, and they are achieved by having the multiplexer and detector wafers bonded together with electrically conducting indium bump bonds, in a similar manner to an infra-red detector array (Fig. 3).

However, TES detectors are not without their problems. Fabrication of the multiplexing circuitry is quite complex, especially for large arrays, and the wire count is still quite large. Increasing array sizes above those currently produced will be difficult. Another problem is that if the absorbed power is sufficient to warm them above the superconducting transition, they saturate and will not operate at all. By comparison, semiconducting bolometers will still operate, with a sensitivity that reduces gracefully as the background power is increased. This is a particular concern for space missions, where it can be hard to accurately predict the background radiation from the telescope, and where nothing can be done if the detectors do saturate.

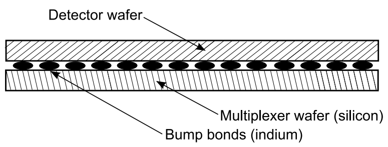

Figure 3: SCUBA-2 detector and multiplexer bonding method.

To give a snapshot of the detector technologies currently operational, Table I lists current sub-mm facility instruments (a facility instrument is one which is available for general use by astronomers). This does not include the considerable number of instruments (and telescopes) dedicated to cosmic microwave background studies. Future ground and space based instruments will require increased pixel counts and even lower noise operation than current instruments. There is therefore considerable research and development being carried out, on various detector technologies.

3 Other technologies and future developments

One technology which is currently receiving a large amount of attention is also based around superconductors, but unlike a TES operates in the fully superconducting state. In a superconductor, electrons pair up into Cooper pairs. If it exceeds the binding energy, the energy from absorbed radiation will break some of these pairs, creating quasiparticles. This is similar to the creation of electron-hole pairs in semiconductors, except that the energy required is considerably smaller ($<$ 1 meV as opposed to 1 eV in silicon).

When Cooper pairs are broken, the DC resistance will remain zero, but the AC surface impedance will change. If the superconductor is built into a resonant circuit, the change in impedance will cause a change in resonant frequency, which can be detected. This principle is used in the kinetic inductance device, or KID. A big advantage of such a detector is that many devices with slightly different frequencies can be connected to a single HEMT (high electron mobility transistor) amplifier, which in turn connects to a room temperature readout system. Therefore only a single coaxial cable to room temperature is required to read out hundreds of detectors, as opposed to the many wires for a TES multiplexer. In addition, fabrication of these devices is much more straightforward than the superconducting electronics in a TES multiplexer. An instrument with KID detectors has already been operated on a ground-based sub-mm telescope to demonstrate the concept; a full camera is expected to be deployed in 2010 [11].

As with TES detectors, ultra low temperature operation is required, though for different reasons. KIDs need to be operated well below their superconducting transition temperature, and the highest transition temperature of the materials which have suitable properties to form KIDs is approximately 1 K, driving operating temperatures below 300 mK.

Alternative technologies abound. One example is superconducting tunnel junction (STJ) devices. Like KIDs, they operate via pair breaking of Cooper pairs. The detection mechanism relies on a "tunnel junction" through which quasiparticles can travel, but Cooper pairs cannot. The operation is therefore like a semiconductor photoconductor, except for the smaller energy gap. A major limitation is that there is currently no practical way of multiplexing such devices.

Another area which is being developed is the use of antenna-coupled detectors. Rather than having the radiation fall directly on the absorber of the detector, planar antennae are formed on a silicon wafer by lithography; these are coupled to planar waveguides, which then transmit the radiation to the detectors. These can take advantage of development carried out for coherent sub-mm systems. One advantage of such a scheme is that filtering can be carried out in the waveguides rather than by placing optical filters in front of the detector. Furthermore, several filters can be used so that the radiation from a single antenna can feed a group of detectors, each one detecting a different wavelength range.

The technologies described here also have applications for detecting X and gamma radiation, where instead of responding to the radiation flux, the detectors respond to the absorption of individual photons. Since each photon is measured separately, it is possible to determine the energy, and thus wavelength, of each photon. This has great appeal for X-ray astronomy and other applications, where the high energy resolution and detection efficiency compared with competing technologies justifies the complication of cooling the detectors to temperatures well below 100 mK. This is fortunate, since the result is that much of the development work can be shared between the sub-mm and X-ray communities, and also expands the range of potential applications for such detectors outside astronomy. Some detectors even operate at optical and infrared wavelengths, where they can measure the heating due to absorption of a single photon.

Returning to sub-mm astronomy, the next few years promise to be extremely interesting, with many new instruments coming on-line. In terms of development, it is not yet clear which technologies will dominate for the next generation of instruments. One major goal at present is to develop detectors for a space telescope with a cold (5 K) primary mirror. To take advantage of the low thermal background from such a mirror, detectors will have to be considerably more sensitive than those in any current instrument. Producing such detectors will be a big challenge, but one that many groups have enthusiastically accepted, with TES detectors, KIDs, CMOS multiplexed semiconducting bolometers and many other technologies being contemplated.

---

[1] W. S. Holland et al., SCUBA: a common-user submillimetre camera operating on the James Clerk Maxwell Telescope, Mon. Not. R. Astr. Soc. 303 (1999) 659–672.

[2] E. E. Haller, Physics and design of advanced IR bolometers and photoconductors, Infrared Phys. 25 (1/2) (1985) 257–266.

[3] J. M. Lamarre et al., The high frequency instrument of Planck: Design and performances, Astro. Lett. Commun. 37 (2000) 161–170.

[4] J. J. Bock, J. Glenn, S. M. Grannan, K. D. Irwin, A. E. Lange, H. G. LeDuc, A. Turner, Silicon nitride micromesh bolometers for SPIRE, Proc. SPIE 3357 (1998) 297–304.

[5] D. McCammon et al., 1/f noise in doped semiconductor thermistors, Low Temperature Detectors 605 (2002) 91–94.

[6] V. Revéret, et al., HERSCHEL-PACS bolometer arrays for submillimeter ground-based telescopes, J. Low Temp. Phys. 151 (2008) 32–39.

[7] K. D. Irwin, An application of electrothermal feedback for high resolution cryogenic particle detection, Appl. Phys. Lett. 66 (15) (1995) 1998–2000.

[8] J. Mehl, et al., TES bolometer array for the APEX-SZ camera, J. Low Temp. Phys. 151 (2008) 697–702.

[9] M. Niemack, et al., A kilopixel array of TES bolometers for ACT: Development, testing, and first light, J. Low Temp. Phys. 151 (2008) 690–696.

[10] A. L. Woodcraft, et al., Electrical and optical measurements on the first SCUBA-2 prototype 1280 pixel submillimeter superconducting bolometer array, Rev. Sci. Inst. 78 (2007) 024502–1–024502–7.

[11] J. Schlaerth, et al., A millimeter and submillimeter kinetic inductance detector camera, J. Low Temp. Phys. 151 (2008) 684–689.