**Borrower:** CON

**Lending String:** *NHM,SSJ,MWR,AD#,FNN

**Patron:** Tallmon, Sheila

**Journal Title:** Millimeter and submillimeter detectors for astronomy ; 25-28 August 2002, Waikoloa, Hawaii, USA /

**Volume:** 4855 **Issue:**
**Month/Year:** June 2003 **Pages:** 19-29

**Article Author:**

**Article Title:** W Duncan, Wayne S. Holland, Michael D. Audley, M. Cliffe, T. Hodson, et al.; SCUBA-2; Developing the Detectors

**Imprint:** Bellingham, Wash. ; SPIE, c2003.

**ILL Number: 67865028**

**Call #:** Per - R12B. .6 v.4855 (also on-line) (SPIE)

**Location:** Storage Per REQUEST item AVAILABLE

**Charge**
**Maxcost:** 20IFM

**Shipping Address:**
ILL/Boulder Labs Library
U.S. Dept. of Commerce
325 BROADWAY - MC5
BOULDER, CO 80305-3328

**Fax:** boulderlabs.ill
**Ariel:** 140.172.211.165
**Odyssey:** 206.107.42.84

# SCUBA-2: Developing the Detectors

W. D. Duncan[a], W. S. Holland[a], M. D. Audley[a], M. Cliffe[a], T. Hodson[a], B. D. Kelly[a], Xiaofeng Gao[a], D. Gostick[a], M. MacIntosh[a], H. McGregor[a], T. Peacocke[a], K. D. Irwin[b], G. Hilton[b], S. Deiker[b], J. Beier[b], C. Reintsema[b], A. J. Walton[c], W. Parkes[c], T. Stevenson[c], A. Gundlach[c], C. Dunare[c], P. A. R. Ade[d],

[a]UK Astronomy Technology Centre, Royal Observatory Edinburgh, Blackford Hill, Edinburgh EH9 3HJ, UK
[b]National Institute for Standards and Technology, 325 Broadway, MS 814.03, Boulder, CO 80303, USA
[c]Scottish Microelectronics Centre, University of Edinburgh, The Kings Buildings, West Mains Road, Edinburgh EH9 3JF, UK
[d]Department of Physics and Astronomy, University of Wales, 5 The Parade, Cardiff, Wales CF24 3YB, UK

## ABSTRACT

SCUBA-2 is a second generation, wide-field submillimeter camera under development for the James Clerk Maxwell Telescope. With over 12,000 pixels, in two arrays, SCUBA-2 will map the submillimeter sky ~1000 times faster than the current SCUBA instrument to the same signal-to-noise. Many areas of astronomy will benefit from such a highly sensitive survey instrument: from studies of galaxy formation and evolution in the early Universe to understanding star and planet formation in our own Galaxy. Due to be operational in 2006, SCUBA-2 will also act as a "pathfinder" for the new generation of submillimeter interferometers (such as ALMA) by performing large-area surveys to an unprecedented depth. The challenge of developing the detectors and multiplexer is discussed in this paper.

**Keywords:** Submillimeter astronomy; large-format superconducting arrays; SQUID; Multiplexer; James Clerk Maxwell Telescope

## 1. INTRODUCTION

In a companion paper[1] the expected scientific impact of SCUBA-2 is discussed and an introduction to the instrument is given. In this paper we provide more detail and the progress to date of the key challenge in constructing SCUBA-2, developing the detectors. The companion paper should be read in conjunction with this one.

## 2. DETECTOR ARCHITECTURE

The chosen architecture for the detectors for the focal planes of SCUBA-2 is close-packed arrays, with a high filling factor, of absorber coupled bolometers. They are intended to fully sample or be close to fully sampling the spatial information content of the focal planes. Any lack of full sampling will taken care of by micro-stepping the arrays relative to the focal plane image.

This architecture will require thousands of pixels and requires a detector technology which may be multiplexed. The detector and mux technology and architecture must also be compatible with the processing and wafers sizes of the semi-conductor industry to allow the fabrication of the thousands of pixels by relatively standard techniques. To this end we have chosen to develop TES bolometers with multiplexed readout implemented with SQUID's[2] for our detector technology. Our detectors and multiplexers are fabricated at the National Institute for Standards and Technology (NIST) and the micro-machining of our detector structures is carried out at the Scottish

[a] Further author information: e-mail: wdd@roe.ac.uk

Microelectronics Centre (SMC). The common Si wafer processing size is 3 inch. The low heat dissipation of the SQUIDs allows them to be at the same temperature as the detectors. Consequently, we have chosen to hybridise a detector wafer to a multiplexer (MUX) wafer with indium bump bonding, as is common practice with IR arrays, and as was used in one of the proposed designs for the SPIRE detectors[3].

## 2.1 Numbers of pixels

The numbers of pixels are set by the requirement to fully sample the field of view of the instrument. The maximum field of view of the telescope is a circle of 11 arcminutes and we are able to select a 7.8 by 7.8 arcminute square from that field and re-image it, albeit with a complicated optical scheme, to a focal plane with a small f-number. To fully sample an image in an aberration free telescope the number of pixels is proportional to the telescope diameter to wavelength ratio squared. For the JCMT this is some 6400 pixels at 850 μm and 25600 at 450 μm in the approximation that the wavelengths are in the ratio 2 to 1. This is 80 by 80 pixels at 850 and 160 by 160 pixels at 450 μm. However, due to the size of the unit cell of the multiplexer circuit we have decided to reduce the number of pixels at 450 μm to that of the 850 μm array. This means that the 450 array has the same physical geometry as the 850 array and the complexity of the detector development is reduced at the expense of having to microstep to fully sample an image at 450 μm.

## 2.2 Focal plane dimensions

To ensure good efficiency in a simple absorber structure the pixels should be approximately a wavelength in size, at minimum. This sets a limit on the final f-number, F#, of the optics which illuminate the detector focal plane. The pixels are F# $\lambda/2$ in size for full sampling of the image. Thus the final f-number must be greater than 2. We have chosen close to 2.76 for our final f-number in order to have good image quality. This makes the pixel area ~ 100 mm by 100 mm. This is still too large for 3 inch wafers so we have chosen to use 4 two side-buttable sub-arrays to populate the focal plane area. The 850 μm sub-arrays are thus 40 by 40 pixels. The focal plane layout is shown in Figure 1 below.

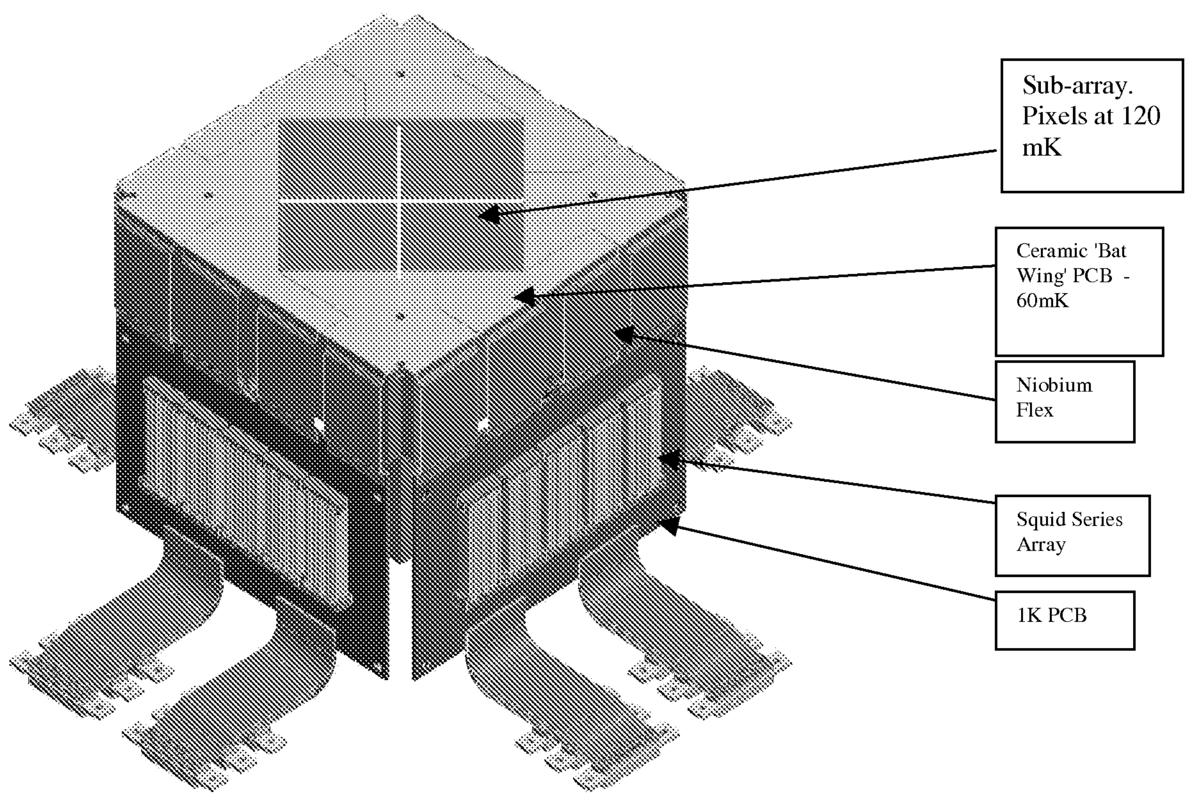
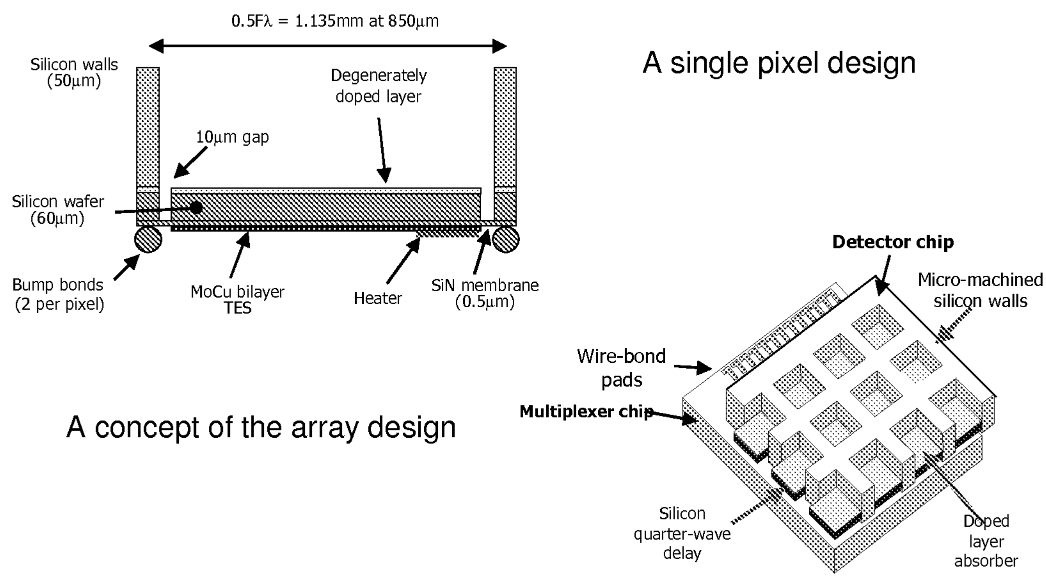



**Figure 1** Focal plane layout for SCUBA-2. Sub arrays are 53 mm on a side.

## 2.3 Absorber coupling

Bolometer technology allows the separation of the absorption and detection function and the possibility of optimizing both functions. In free-space, a very efficient simple absorption structure is formed by separating a 377 ohms per square layer from a highly reflective layer by odd multiples of $\lambda/4$. Thermally connecting the detector to the absorbing layer allows the absorbed power of the layer to be measured.

**Figure 2** Pixel geometry and array structure.



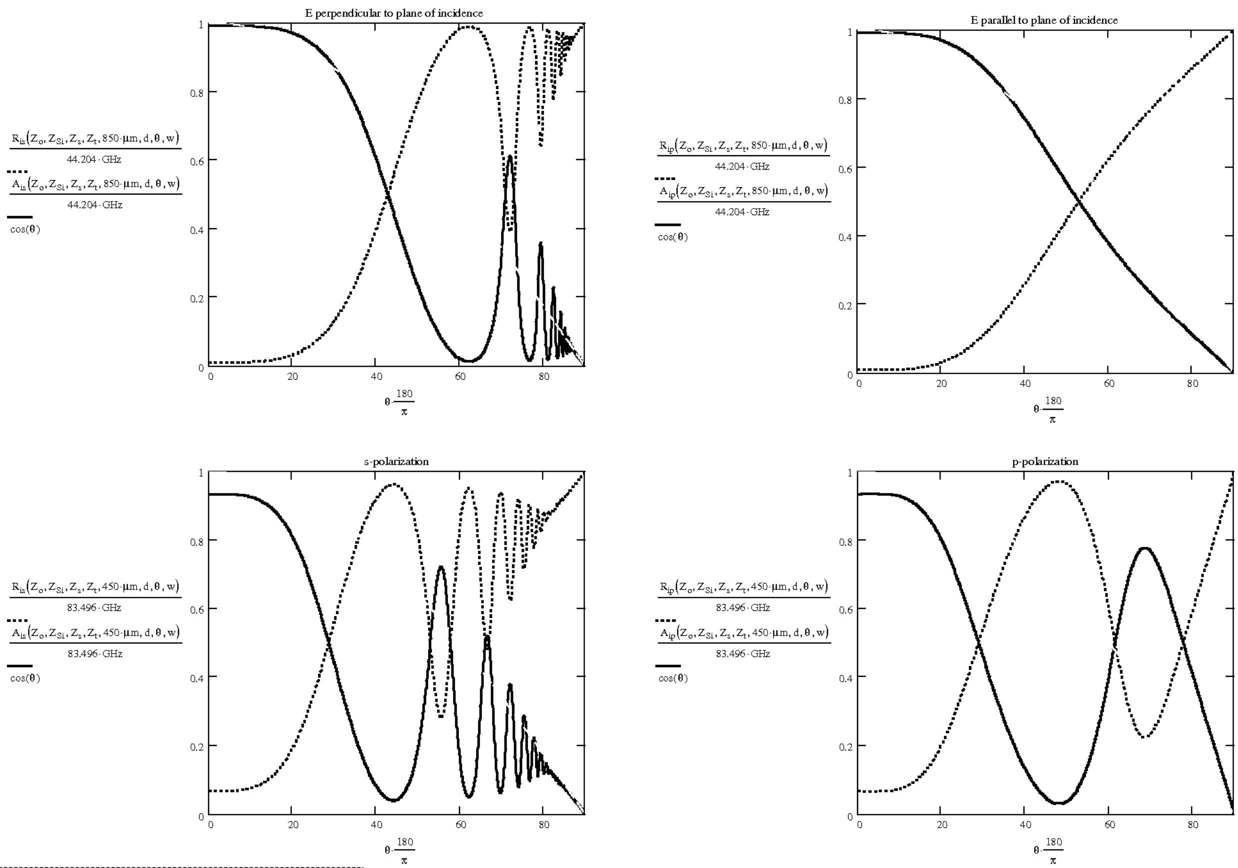

Application of this principle to far-IR bolometers has generally lead to the physical separation of the reflecting layer or backshort from the pixel due to the extra heat capacity involved in the metallic layer and the dielectric which would separate the two layers. However, by operating at a sufficiently low temperature (<< 300 mK), the problems of excess heat capacity may be removed, at least for the high background situation at the JCMT. This leaves us with the simple pixel structure shown in cross-section in Figure 2. The TES covers the whole of the back of the structure and acts as the back short.

The 400 ohms per square is achieved by ion implantation of the front of the wafer using degenerate doping with phosphorus ions. We have generated a dose versus surface impedance curve, using optical methods at 1.5 K to characterise the doping[4]. The thickness of the Si spacer is 62 μm for a quarter wave at 850 μm and 33 μm at 450 μm. We can also use three quarters of a wave delay (~100 μm) at 450 to avoid the Si layer being too thin to process reliably.

The resonant structure will limit the bandwidth of efficient absorption and we also need to understand the performance at the range of angles of incidence of the light from the optics. A transmission-line model, which assumes that the layers are infinite in lateral size, averaged over the filter bandpasses of 35 GHz and 65 GHz at 850 and 450 μm respectively, gives the response with angle and polarisation shown in Figure 3. The 850 μm results are for a quarter wave delay and the 450 for three quarters of a wavelength delay. The arrays are illuminated at angles up to 20 degrees off axis, dependent on their position in the focal plane. In both cases the response is very good out to these angles.

To confirm that this sort of performance would apply when the finite size of the pixel and the presence of the support structure was taken into account detailed modeling was undertaken using Ansoft's HFSS[5]. This confirmed that absorption in the region of 85% could be expected and with less sensitivity to off-axis angles than indicated above. The results are presented in some detail in an upcoming paper[4].

**Figure 3** Off-axis response averaged over filter bandwidth




## 2.4 Pixel support structure

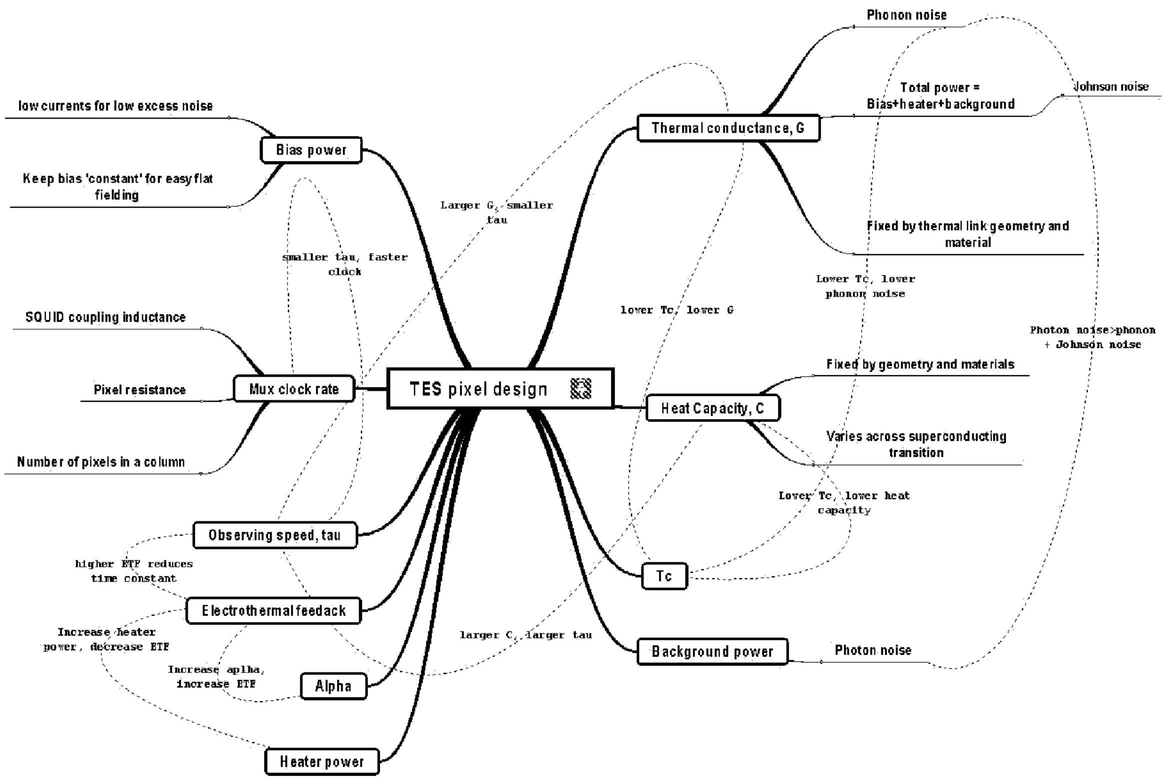
The TES on the base of the pixel senses the change in temperature of the pixel as the power incident on it changes. The mechanical support of the pixel and the thermal isolation of the pixel is achieved by the silicon nitride membrane shown in Figure 2. This is only 10 μm wide and together with the 50 μm wide support walls allows a high filling factor. Slots are micro-machined in the silicon nitride membrane to control its thermal conductivity.

## 2.5 Design of TES pixels

The thermal and electrical design of the pixel and its coupling circuit is essential to meet the performance targets of SCUBA-2. The design process is complex and iterative (see Figure 4 for some of the interrelationships) but the design is dominated by a few key parameters set by the science requirements:

- **Background power**
  Controls the saturation power of the pixel. The background power varies with the water vapour content of the atmosphere and the airmass of the observation.
  The background power also determines the minimum level of photon noise. The science goal is for the sensitivity to be limited by the photon noise under all observing conditions. We will aim for a design in which all the fundamental noise limits (phonon, Johnson) are much less than the photon noise to allow some headroom in the noise margin in case our pixels suffer from excess noise. This tends to drive down the operating temperature.

**Figure 4** Pixel design interrelationships.



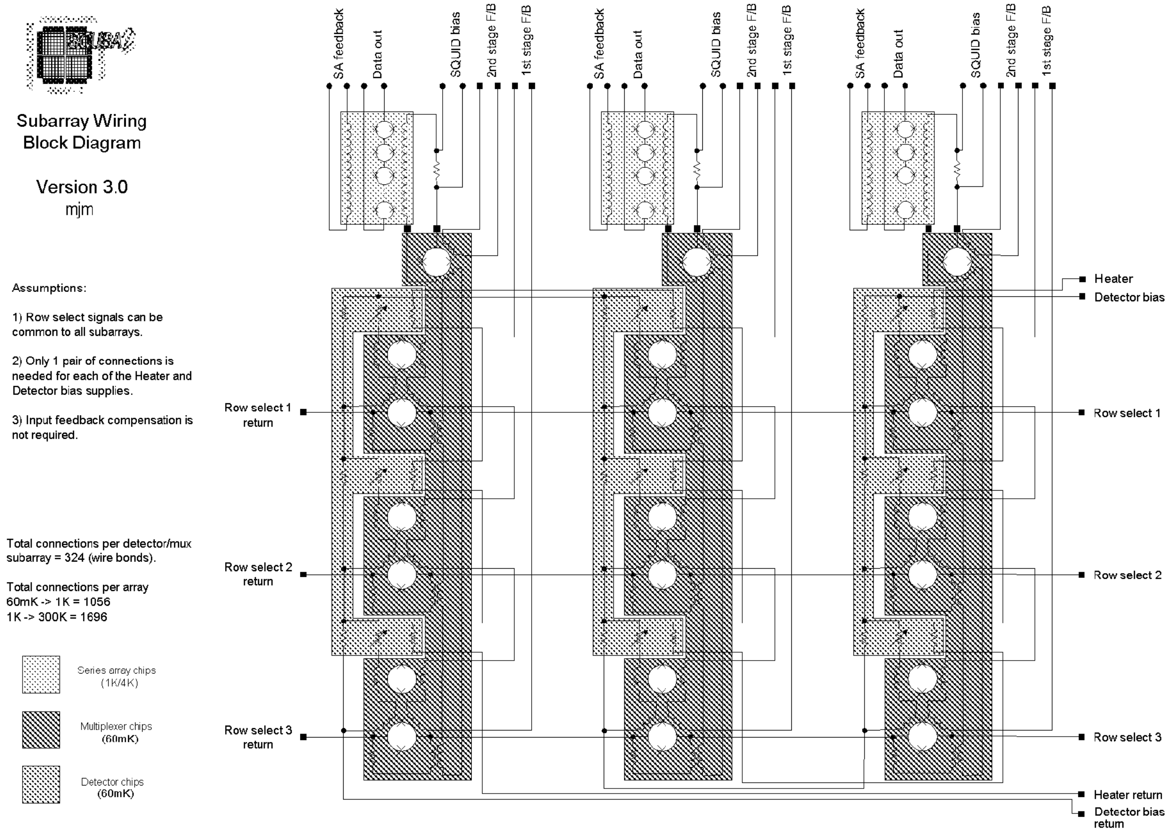

- **Observing speed**
  To capture images in a ground based situation such as the JCMT on Mauna Kea the observing strategies have to cope with the fact that the astronomical signals are buried in the high terrestrial background signal from the atmosphere and telescope. The atmospheric signal is dominated by the emission from water vapor. Water vapor is ill-mixed; hence the background signal is prone to wind driven low frequency spatial and temporal fluctuations which often dominate other noise sources. To overcome this limitation we must take complete observations (fully sampled fields) in times short compared with the atmospheric fluctuations and any '1/f' type fluctuations in the detectors or electronics. For SCUBA-2 on the JCMT this means that the effective time constant of the detectors must be shorter than 2 msecs. The atmospheric fluctuation also give rise to source amplitude and position variations (tip-tilt seeing effects).
- **Crosstalk**
  In order to produce images where the dynamic range in the image is set by the telescope point spread function (PSF) it is necessary to control pixel to pixel crosstalk. There is a limit set by this requirement of < 0.3 % for non-nearest neighbors. Meeting this requirement has necessitated the use of two SQUIDs per pixel in a balanced pair. One of these SQUIDS is unbiased and acts to cancel crosstalk in unaddressed pixels as the SQUID bias and feedback is switched from row to row. This has been shown to work very well[6], but does increase the area required under each pixel for the multiplexer circuitry. This prevents us from achieving the 25600 pixels required at 450 μm for full sampling. The circuit employed is shown in Figure 5.

These science driven requirements set limits on the G, C and Tc of the pixel and the SQUID layout for the multiplexer chip. The design is further constrained by practical considerations and the inherent properties of the TES and readout:

- **Constant power**
  TES devices are close to constant power over the range of the transition from the normal to the superconducting state. We have to design the power handling of a pixel to cope with the fact that we might underestimate the background power falling on the pixel (the SCUBA-2 system does not exist yet so the background levels are estimates). If this happens, then the pixel could be forced into the normal state and the arrays would not work at all. This could be corrected by building new arrays or putting in a (cold) neutral density filter in the cryostat to

reduce the background power. Neither of these is desirable so we design in a margin on the power handling level of a pixel.

**Figure 5:** SCUBA-2 Detector and Readout circuits




- **Data rates and multiplexer electronics complexity.**
  We have set a lower limit to the time constant of 1 msec in order to keep the multiplexer clock rate slow (we will use time division multiplexing) so that the data rate is easy to cope with and we can use multi-channel digital feedback cards[8] to keep the amount of room temperature electronics small. The clock rate will be 200 - 500 kHz. The clock rate is set by the TES speed, feedback stability requirements set by the L and R of the detector bias circuit and the number of rows or columns to be multiplexed[7]. With the value of the heat capacity, C, of a pixel largely set by the chosen pixel geometry and the G constrained by the power handling of the TES and the phonon noise we find that the pixels are too fast due to electrothermal feedback to allow our target clock rate. To reduce the feedback and increase the effective time constant, we employ a heater on each pixel.
- **Flat fielding**
  In order to flat field the images in simple stare mode we would require flat field accuracy of parts in $10^6$ to $10^7$ for long observations (up to 1 hour). Achieving these sort of stability levels is likely to be very difficult and we expect to use stare mode only for very bright sources. For differential schemes such as chopping the accuracy is required is parts in $10^4$ to $10^5$. The responsivity of a TES is a nearly linear function of the bias current. This function will not be identical for every pixel, so as the bias power changes to compensate for the background power from the atmosphere changing (electro-thermal feedback), there would be undesirable changes in relative response (the flat field). This leads to the use of pixel heaters on a slow servo to keep the operating point and hence the flat field of the array close to constant.
- **Pixel heaters**
  The pixel heaters are used to provide thermal power to help bias the pixels. The use of heater power reduces the level of electrical bias power needed which lowers the level of ETF and slows the pixel down. Lower electrical bias power seems to help reduce excess noise[9] and the heaters are useful in helping to calibrate pixel responsivity and speed.

- **Power dissipation in the Mux chip**
  Measurements on the 1 by 32 SCUBA-2 mux development chip indicate that the power dissipation of the 40 by 40 mux chip required for a sub array will be 2.5μW with the SQUIDs voltage biased . To lower the power dissipation on the detector chip we will also place the TES bias resistors on the mux chip. The power dissipation in this resistor will be 10 times the electrical bias power in the TES.
- **1/f in the electronics**
  The room temperature electronics, 2nd stage SQUIDS and series arrays will have some 1/f noise. We intend to add an extra row of 1st stage SQUIDS, not connected to pixels, to our mux chips and read this once per cycle. Subtraction of this signal from the others will reduce the level of 1/f noise (see Figure 5 for test results).

We give the key target specifications for the SCUBA-2 pixels in Table 1.

**Table 1:** Key specifications for SCUBA-2 pixels

| | **Target specifications for SCUBA-2 pixels** | | | |
|---|---|---|---|---|
| | **850μm** | **450μm** | **Units** | **Notes** |
| **Background power** | 7<br>19 | 92<br>150 | pW (minimum)<br>pW (maximum) | Prediction from model |
| **Design pixel power level** | 30<br>0.2 | 200<br>1.3 | pW per pixel<br>μW per focal plane | |
| **Target Tc** | 100 - 120 | 200 | mK | |
| **Target G** | ~1700 | ~5000 | pW/K | |
| **Likely C** | 6.5 | 11 | pJ/K | Dominated by TES |
| **Bias power** | 5 to 10 | 5 to 10 | pW | To reduce ETF |
| **Minimum photon noise level** | 6.5 | 33 | $10^{-17}$ W/$\sqrt{Hz}$ | |
| **Phonon and Johnson Noise** | 1 | 9 | $10^{-17}$ W/$\sqrt{Hz}$ | |
| **Mux chip power dissipation** | 3 to 4 | 3 to 4 | μW per focal plane | Depends on bias power level used |
| **Time constant target** | 1- 2 | 1 -2 | msecs | |
| **Distant pixel to pixel cross talk** | <0.3 | <0.3 | % | |

## 3. PROCESS DEVELOPMENT

At the time of writing, the project team is involved in achieving mastery of all the process steps necessary to construct the arrays. The main processes required to manufacture our detectors are:

1 Ion implantation of surface of detector wafer to achieve 400 ohm sq
2 Wafer bonding of waffle wafer to ion implanted wafer to Si support grid wafer.
3 Grinding and polishing of bonded wafer to achieve nλ/4 detector thickness
4 Low stress silicon nitride film deposition on detector wafer
5 Deposition of TES, heater and bond pad metals on bottom of detector wafer (Mo, Cu, Heater, normal metal) banks, passivation layer)
6 Deposition of SQUID mux structure and wire bond pads on Mux wafer plus passivation layer
7 Partial etch through of slots in silicon nitride support membrane to achieve required G.

8 Application of Niobium layer with a AuPd overlayer to facilitate soldering of Mux chip to array chip holder fingers (high purity copper piece with machined fingers to alleviate the thermal stresses which occur on cooling).
9 Partial RI etching of waffle (partial etching allows the detector chip to be vacuum chucked during the bump bonding process).
10 Application of indium bumps and bonding of the two wafers.
11 Deep RI etching to completely reveal Si grid and suspend pixels on silicon nitride wafer.

Process steps 1 through 4 have been successfully developed and demonstrated at the SMC. Steps 6 and 7 have been demonstrated at NIST and step 8 has been done on test wafers which have been soldered to copper test pieces and cycled to 77 K several times at high cooling rates (up to 10 K per minute). Step 9 has been demonstrated all the way through to a silicon nitride stop layer. Step 10 is our least developed process and we are intending to use the services of an industrial company with many years of successful chip hybridization with indium bump bonding. Step 11 is forced on us by the need to vacuum chuck the wafers during the hybridization step - the silicon nitride support membranes cannot support vacuum forces. We have to limit the access of the etching plasma to the underside of the wafer during this step to prevent etching of the indium bumps and the underbump metals.

## 4. TEST RESULTS

In this section we illustrate some of the achievements of the development program to date.

### 4.1 Pixel development

Figure 5 shows measurement of the transition of a SCUBA-2 850 μm test pixel. The pixel has a Tc of ~ 110 mK. The TES covers the whole of the pixel and has the lateral dimensions of Figure 1 but does not have an absorbing structure. The thermal conductance of the 10 μm wide membrane on another pixel, with partially etched through slots in the silicon nitride membrane, is shown in Figure 6. This test pixel came very close to the requirements of the SCUBA-2 pixel both in terms of G and Tc.

**Figure 6:** R, T curve for a SCUBA-2 test pixel

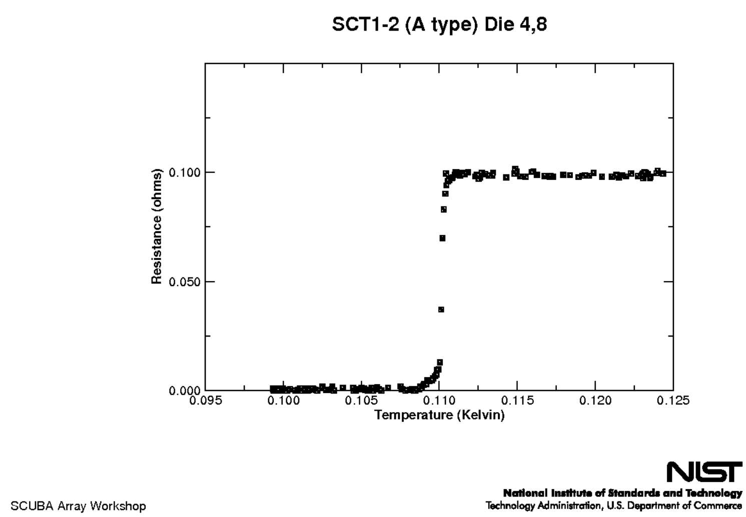
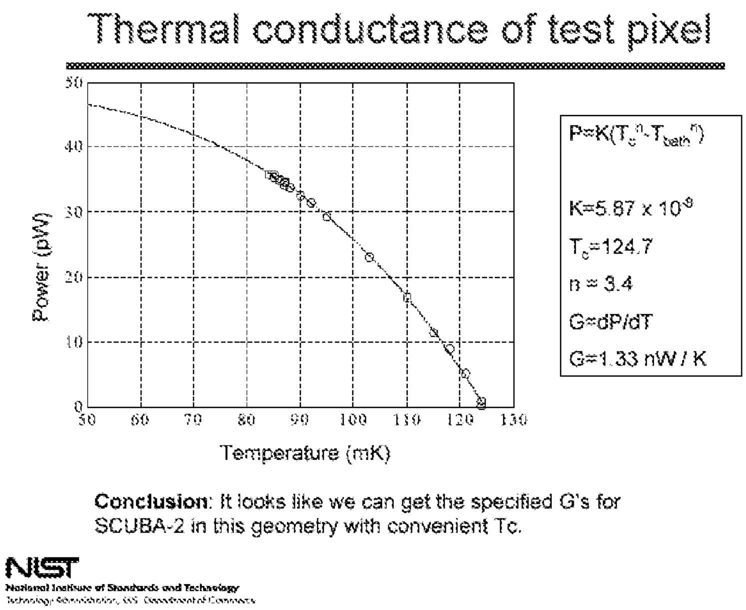


**Figure 7:** Measurement of G for a test pixel




## 4.2 Multiplexer results

The major details of the test results on the 1 by 32 MUX test chip with balanced SQUID inputs are given in paper[4]. However, using one of the SQUIDs in the column as a dark SQUID and subtracting its o/p is shown in Figure 7. This technique removes a great deal of the low frequency noise and pushes the 1/f knee out to lower frequencies.

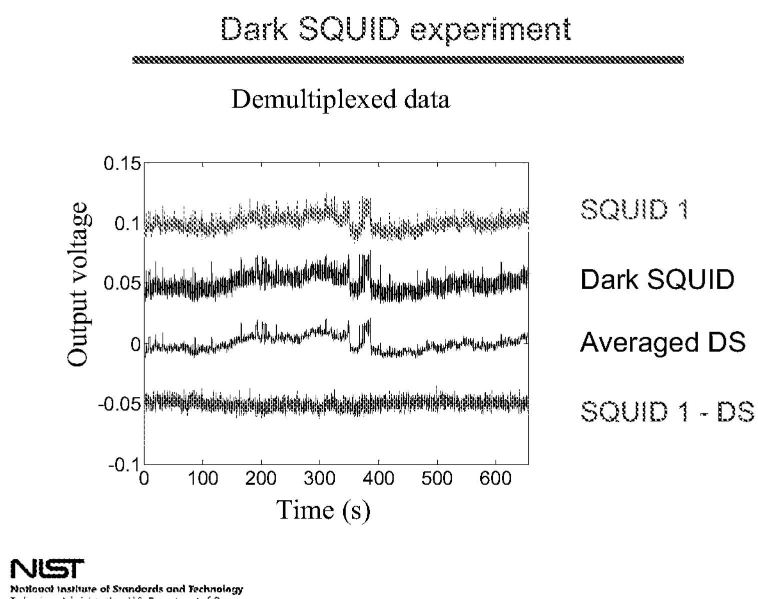



**Figure 8:** Dark SQUID results

### 4.3 Deep reactive ion etching of the detector structures

We show some micrographs of the SCUBA-2 array structures to illustrate the control of the Deep RIE process for the SCUBA-2 arrays.

**Figure 9:** SEM section of 1mm waffle pattern, etched, The walls are 50 μm thick.

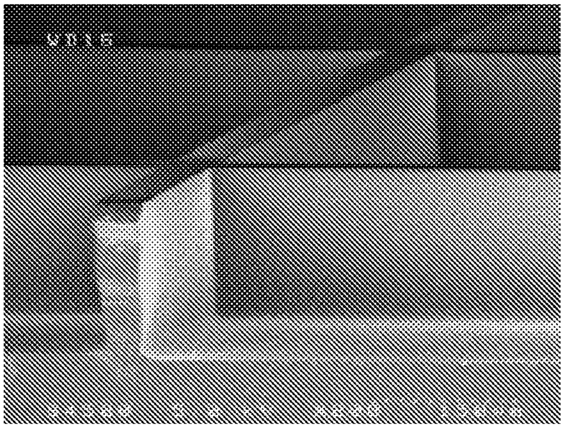


**Figure 10:** is in reflected light, of a patterned bonded pair etched right through to the nitride membrane with supported silicon detector 'bricks'. The black square is a missing brick. The wafer bonding was done without aligning the upper, grid, wafer to the lower detector wafer.

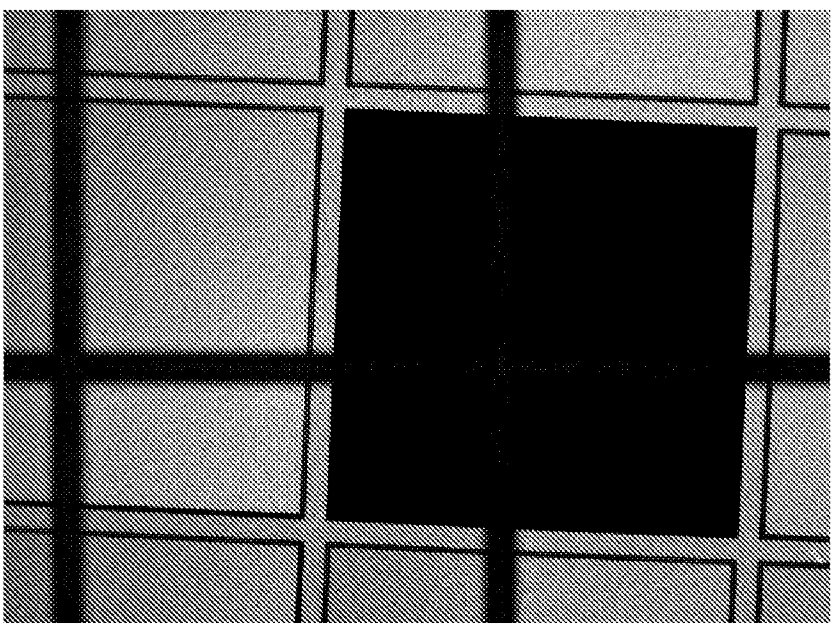
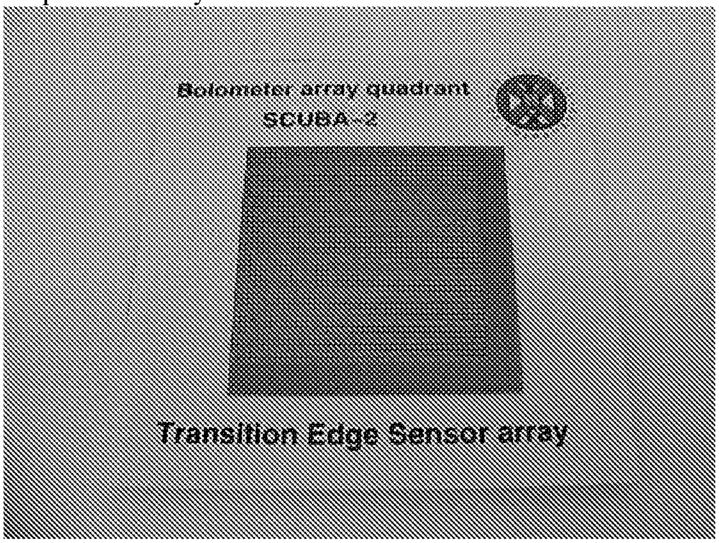


**Figure 11:** This shows the deep etch of a full sized sub array support grid and gives an good impression of a completed subarray.




## 5. SUMMARY

The project team is well on the way to developing and controlling all the key technologies ready to make a SCUBA-2 prototype sub-array towards the end of 2003. As mentioned in the companion paper in this volume, results from SCUBA-2, combined with results at other wavelengths and facilities, is sure to make great improvements in our understanding of the far-ir Universe.

## 6. ACKNOWLEDGEMENTS

More information on SCUBA-2 can be found at: http://www.roe.ac.uk/atc/projects/scuba_two

The SCUBA-2 Project is a collaboration between the UK Astronomy Technology Centre at the Royal Observatory Edinburgh, the National Institute of Standards and Technology (Boulder), the Scottish Microelectronics Centre of the University of Edinburgh, the University of Wales (Cardiff), and the Joint Astronomy Centre (Hawaii). It is supported by funds from the Particle Physics and Astronomy Research Council and the JCMT Development Fund.

## 7. REFERENCES

1. Holland W. S., Duncan W. D., Irwin K. D.,. Walton A. J, Ade P. A. R., Robson E. I. 'SCUBA-2: a large format submillimetre camera on the James Clerk Maxwell Telescope', This volume.
2. K. D. Irwin, " An application of electrothermal feedback for high resolution cryogenic particle detection", Appl. Phys. Lett. 66, pp. 1998-2000, 1995
3. Griffin, L. G. Vigroux, and B. M. Swinyard, "SPIRE: a bolometer instrument for FIRST", *Proc. SPIE Vol. 3357*, pp. 404-413, Advanced Technology MMW, Radio, and Terahertz Telescopes, Thomas G. Phillips; Ed. 1998.
4. Audley, D, et al., 'Electromagnetic design and verification of SCUBA-2 pixels absorption efficiency' In preparation.
5. High Frequency Structure Solver (HFSS), Ansoft Corporation, Four Station Square, Suite 200, Pittsburgh, PA 15219
6. Beyer J, et al ' Performance of 32 Channel Time-Division SQUID Multiplexer for Cryogenics Detector Arrays. Submitted August 6th 2002 to Applied Superconductivity
7. Irwin, K. D. 'SQUID multiplexers for transisition-edge sensors', Physica C, vol. 369, pp. 203-210, 2002
8. S. Nam et al, 'Electronics for Arrays of Transition Edge Sensors using Digital Signal Processing', Submitted August 6th 2002 to Applied Superconductivity
9. Lindeman, M. A., Chervenak J. A., Figueroa-Feliciano E., Finkbeiner, F. M., Galeazzi M.,Li M. J., Stahle C. K. 'TES physics: probing the phase transition', TES Workshop at NIST Boulder, 2002.