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**MONOLITHIC INTEGRATION  
OF  
SEMICONDUCTOR AND SUPERCONDUCTOR COMPONENTS**

DARPA/ONR Contract No. N00014-90-C-0226

Honeywell Sensor and System Development Center  
10701 Lyndale Avenue South  
Bloomington, MN 55420

1 January 1992 - 31 March 1992

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## 2.0 PROGRAM SUMMARY

The goal of the program is to develop transistor technology compatible with high transition temperature superconductor technology so that transistor pixel switches can be integrated with  $\text{YBa}_2\text{Cu}_3\text{O}_7$  superconducting microbolometers in the same silicon substrate. A  $4 \times 4$  matrix-addressable superconducting microbolometer array will be delivered at the completion of the program.

The linear arrays of microbolometers produced in the Honeywell funded process run of December 1991 were evaluated under the present contract during January - March 1992. The results, summarized in this report, demonstrate that high -  $T_c$  superconductor microbolometers on silicon microstructures are extremely sensitive infrared detectors.

## 3.0 PROGRAM STATUS

### Task 1.0: Vendor Selection

Mary Weybright, a graduate student in electrical engineering at Stanford University working under the direction of Prof. James D. Plummer, has been engaged as a consultant to model the performance of bipolar transistors at low temperature, in order to determine doping profiles needed for the transistor switches at each pixel.

Monolithic bipolar transistors from a potential vendor, ECI of Santa Clara, CA, have been tested after being subjected to  $700^\circ\text{C}$  for one hour. This heat treatment, which corresponds to that to be used in depositing  $\text{YBaCuO}$  on silicon substrates containing the transistors, did not change the device performance at room temperature.

The monolithic bipolar transistors will be fabricated by Honeywell's MICRO SWITCH Division of Richardson, Texas, and donated to the contract at no cost to the contract. The transistor fabrication task has been deleted from the contract statement of work.

### Task 2.0: First Fabrication Run (completed)

#### Task 2.1: Film Development

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Superconducting films of  $\text{YBa}_2\text{Cu}_3\text{O}_7$  were grown in-situ on 3 - inch silicon wafers coated with amorphous silicon nitride and polycrystalline yttria stabilized zirconia. These films show onset of superconductivity at  $\sim 88\text{ K}$  and zero resistance at  $\sim 65\text{ K}$ . The temperature coefficient of resistance (TCR) was about  $0.15\text{ K}^{-1}$  at the midpoint of the transition ( $\sim 73\text{ K}$ ). The substrates used are ideal for fabrication of microstructures by silicon micromachining techniques. These films were grown using a combination of pure ozone from

Honeywell's ozone distillation system, and ordinary oxygen. The growth temperature for optimum superconducting properties was between 700° C and 735° C. These growth temperatures are believed to be low enough to allow survival of the transistors which will be embedded in the substrate.

**Task 2.2: Mask Design**

The first fabrication run used existing masks from DARPA/ONR Contract #N00014-88-C-0394.

**Task 2.3: Vendor Electronics**

For the first fabrication run, transistors were not embedded in the substrate.

**Task 2.4: Integrated Device**

No working bolometers were produced in the first fabrication run. The YBa<sub>2</sub>Cu<sub>3</sub>O<sub>7</sub> film on the bolometer structures was inadvertently removed by the KOH solution that was used to etch the silicon to thermally isolate the bolometers. In addition, the electrical contact pads did not adhere to the substrate. These problems were solved in a subsequent processing run funded by Honeywell which was completed in December, 1991.

**Task 2.5: Device Evaluation**

Room temperature resistance measurements were performed on the first two wafers of the first fabrication run.

**Task 3.0: Second Fabrication Run**

**Task 3.1: Film Development**

Superconducting films of YBa<sub>2</sub>Cu<sub>3</sub>O<sub>7</sub> have been grown in-situ on 3 - inch silicon wafers coated with amorphous silicon nitride and polycrystalline yttria stabilized zirconia. These films show onset of superconductivity at ~88 K and zero resistance at ~72 K. The temperature coefficient of resistance (TCR) is about 0.30 K<sup>-1</sup> at the midpoint of the transition (~79 K). Thus, these films are superior to the films used in the first fabrication run. A film with this TCR on a thermally isolated microstructure could provide a bolometer with a sensitivity which is high enough

for high performance imaging applications using a staring array. The substrates used are ideal for fabrication of microstructures by silicon micromachining techniques. These films were grown using a combination of pure ozone from Honeywell's ozone distillation system, and ordinary oxygen. The growth temperature for optimum superconducting properties was between 700° C and 735° C. These growth temperatures are believed to be low enough to allow survival of the transistors which will be embedded in the substrate.

Recent work funded by Honeywell has improved the YBa<sub>2</sub>Cu<sub>3</sub>O<sub>7</sub> films to achieve a transition onset temperature of 89 K, transition midpoint temperature of 82.5 K, and zero resistance at 73 K.

Noise measurements are being performed at the University of Minnesota, our subcontractor, on DyBa<sub>2</sub>Cu<sub>3</sub>O<sub>7</sub> films grown at the University of Minnesota on SrTiO<sub>3</sub> and LaAlO<sub>3</sub> single crystal substrates, and on YBa<sub>2</sub>Cu<sub>3</sub>O<sub>7</sub> films grown at Honeywell on silicon substrates with Si<sub>3</sub>N<sub>4</sub>/YSZ buffer layers. The emphasis in the DyBa<sub>2</sub>Cu<sub>3</sub>O<sub>7</sub> film measurements is on understanding the peak in the excess noise spectral density at the foot of the resistive transition. The emphasis in the YBa<sub>2</sub>Cu<sub>3</sub>O<sub>7</sub> film measurements is on understanding the noise near the midpoint of the resistive transition, where a bolometer would be operated.

The 1/f noise in YBa<sub>2</sub>Cu<sub>3</sub>O<sub>7</sub> films grown at Honeywell on silicon substrates with Si<sub>3</sub>N<sub>4</sub>/YSZ buffer layers is now low enough that if they were used in a large thermal imaging array of microbolometer pixels 50 µm x 50 µm in size, the 1/f noise voltage would be only about 4 times larger than the Johnson noise voltage, under typical operating conditions.

### **Task 3.2: Mask Design**

The mask design for the transistor fabrication is complete, and these masks have been purchased from the mask vendor. The mask design for the microbolometer fabrication is nearly complete. It is anticipated that these masks will be ordered in time to be delivered in mid-April 1992. In the 4 x 4

arrays, each pixel (including transistor) will occupy an area  $125\text{ }\mu\text{m} \times 200\text{ }\mu\text{m}$ .

**Task 3.3:**    Vendor Electronics

Honeywell's MICRO SWITCH Division has delivered bipolar transistors produced in a pilot run in which their standard fabrication process had been modified for improved low temperature performance according to suggestions by Mary Weybright, our consultant at Stanford University. The transistors were tested at low temperature (down to 77 K) and the results were given to Mary Weybright to determine further process modifications. These process modifications, including heavier doping of the epitaxial silicon layer, are being incorporated into the transistors to be delivered by MICRO SWITCH for microbolometer integration.

**Task 3.4:**    Integrated Device

The process sequence for the next fabrication run, in which microbolometers will be integrated with bipolar transistors, is nearly established.

**Task 3.5:**    Device Evaluation

Devices fabricated in the recent processing run funded by Honeywell have been evaluated. A responsivity of 1300 volts/watt with a dc bias current of only  $1\text{ }\mu\text{A}$  was measured at a substrate temperature of 73 K in a microbolometer occupying a  $125\text{ }\mu\text{m} \times 125\text{ }\mu\text{m}$  area. In thermal imaging applications, pulsed bias currents of about  $100\text{ }\mu\text{A}$  would be used, resulting in a responsivity of 130,000 volts/watt. A 12-element linear array showed responsivity nonuniformity less than 7% over most of the array. The detectivity,  $D^*$ , measured at a frequency of 7 Hz, was  $7.5 \times 10^8\text{ cm Hz}^{1/2}/\text{Watt}$ . The noise was dominated by  $1/f$  noise in the  $\text{Au/YBa}_2\text{Cu}_3\text{O}_7$  contacts. It is expected that this contact noise can be eliminated by straightforward process modifications, resulting in an improvement in the  $D^*$  at 7 Hz by about a factor of 10. In the microbolometers that were tested, there was no significant degradation of the electrical properties of the superconductor during the processing required to fabricate the microbolometers.

#### **Task 4.0: Third Fabrication Run**

Work on this task has not begun.

#### **4.0 ACCOMPLISHMENTS (for 1 January 1992 to 31 March 1992)**

##### **Task 1.0: Vendor Selection**

No work was performed on this task during this period.

##### **Task 2.0: First Fabrication Run**

No work was performed on this task during this period.

##### **Task 3.0: Second Fabrication Run**

##### **Task 3.1: Film Development**

Substantial reductions have been made in the amount of  $1/f$  noise present in the films grown at Honeywell on silicon substrates with  $\text{Si}_3\text{N}_4/\text{YSZ}$  buffer layers. The  $1/f$  noise in these films is now low enough that if they were used in a large thermal imaging array of microbolometer pixels  $50\text{ }\mu\text{m} \times 50\text{ }\mu\text{m}$  in size, the  $1/f$  noise would be only about 4 times larger than the Johnson noise. This assumes typical operating conditions for a large thermal imaging array:  $100\text{ }\mu\text{A}$  bias current and a noise bandwidth covering the frequency interval  $0.1\text{ Hz}$  to  $100\text{ kHz}$ . These films were grown and patterned in the Honeywell - funded process run of December 1991. The noise measurements were performed at the University of Minnesota and at Honeywell.

Measurements of the excess noise in the tail of the resistive transition of  $\text{DyBa}_2\text{Cu}_3\text{O}_7$  films grown at the University of Minnesota on  $\text{LaAlO}_3$  and  $\text{SrTiO}_3$  single crystal substrates has focussed on the magnetic field dependence of the noise. For low fields (less than approximately  $0.5\text{ Tesla}$ ), it is becoming apparent that the excess noise is due to vortex motion. The noise does not appear to be caused by charge trapping and detrapping at grain boundaries. The latter mechanism is often the cause of noise in grain boundary junction SQUIDs. For magnetic fields larger than about  $0.5\text{ Tesla}$ , the noise properties are qualitatively different. This is thought to be due to the density of vortices becoming comparable to the density of grain boundary junctions in the samples.

The resistive transition of the films grown at Honeywell on amorphous  $\text{Si}_3\text{N}_4$  with a polycrystalline YSZ buffer layer have been improved in work funded by Honeywell. A film was grown with superconducting onset temperature of 89 K, a transition midpoint temperature of 82.5 K and zero resistance of 73 K.

**Task 3.2:**    Mask Design

The mask design for the microbolometer fabrication was nearly completed. It is anticipated that these masks will be ordered in time to be delivered in mid-April 1992. In the  $4 \times 4$  arrays, each pixel (including transistor) occupies an area  $125 \mu\text{m} \times 200 \mu\text{m}$ .

**Task 3.3:**    Vendor Electronics

Fabrication of the monolithic bipolar transistors by Honeywell's MICRO SWITCH Division of Richardson, Texas was begun. These transistors will be donated to the contract at no cost to the contract. The transistor fabrication task has been deleted from the contract statement of work. This first lot of substrates with implanted transistors is expected to be delivered in the second week of April, 1992.

**Task 3.4:**    Integrated Device

The process sequence for the next fabrication run, in which microbolometers will be integrated with bipolar transistors, was nearly completely established.

**Task 3.5:**    Device Evaluation

Devices fabricated in the recent processing run funded by Honeywell were evaluated. A responsivity of 1300 volts/watt with a dc bias current of only  $1 \mu\text{A}$  was measured at a substrate temperature of 73 K in a microbolometer occupying a  $125 \mu\text{m} \times 125 \mu\text{m}$  area. In thermal imaging applications, pulsed bias currents of about  $100 \mu\text{A}$  would be used, resulting in a responsivity of about 130,000 volts/watt. A 12-element linear array showed responsivity nonuniformity less than 7% over most of the array. The detectivity,  $D^*$ , measured at a frequency of 7 Hz, was  $7.5 \times 10^8 \text{ cm Hz}^{1/2}/\text{Watt}$ . The noise was dominated by  $1/f$  noise in the

Au/YBa<sub>2</sub>Cu<sub>3</sub>O<sub>7</sub> contacts. It is expected that this contact noise can be eliminated by straightforward process modifications, resulting in an improvement in the D\* at 7 Hz by about a factor of 10. In the microbolometers that were tested, there was no significant degradation of the electrical properties of the superconductor during the processing required to fabricate the microbolometers.

Honeywell's MICRO SWITCH Division delivered bipolar transistors produced in a pilot run in which their standard fabrication process had been modified for improved low temperature performance according to suggestions by Mary Weybright, our consultant at Stanford University. The transistors were tested at low temperature (down to 77 K) and the results were given to Mary Weybright to determine further process modifications. These process modifications, including heavier doping of the epitaxial silicon layer, are being incorporated into the transistors to be delivered by MICRO SWITCH for microbolometer integration.

#### **Task 4.0: Third Fabrication Run**

Work on this task has not begun.

### **5.0 PROBLEM AREAS/ISSUES**

- Performance of transistors at low temperature must be adequate for good switching performance.
- Transistors must survive the high growth temperature of the YBa<sub>2</sub>Cu<sub>3</sub>O<sub>7</sub> films.
- The electrical resistance of the gold contacts to the YBa<sub>2</sub>Cu<sub>3</sub>O<sub>7</sub> films must be low enough that small area (~10 μm x 10 μm) contacts have a resistance low compared to the bolometer resistance. Small area contacts are necessary for high fill factor in two-dimensional arrays of microbolometers.
- The noise generated in the gold contacts to the YBa<sub>2</sub>Cu<sub>3</sub>O<sub>7</sub> must be low compared to the noise in the YBa<sub>2</sub>Cu<sub>3</sub>O<sub>7</sub> films.

### **6.0 CORRECTIVE ACTION**

- Utilize calculations of transistor performance to optimize low temperature performance.
- Use PtSi ohmic contacts to the transistors.



- Reduce electrical contact resistance and contact noise by depositing gold in-situ by ion beam sputtering immediately after deposition of the  $\text{YBa}_2\text{Cu}_3\text{O}_7$  film. The gold film will then be photolithographically patterned into the desired contact geometry (this work is being funded by Honeywell).

## **7.0 GOALS FOR THE NEXT PERIOD (1 April 1992 to 30 June 1992).**

- Complete the microbolometer mask design for the second fabrication run and obtain the completed masks.
- Complete fabrication of the silicon substrates with embedded transistors for the second fabrication run (transistor fabrication funded by Honeywell).
- Test the process for making small area electrical contacts to the  $\text{YBa}_2\text{Cu}_3\text{O}_7$  films by depositing gold films in-situ by ion beam sputtering (this work to be funded by Honeywell).
- Complete a process run to fabricate 4 x 4 arrays of microbolometers integrated with transistors.
- Evaluate the 4 x 4 arrays of microbolometers integrated with transistors.

## **8.0 PUBLICATIONS**

### **8.1 Papers Published in Refereed Journals**

None

### **8.2 Papers Published in Conference Proceedings**

The following paper will be published in SPIE Conference Proceedings volume 1685, Infrared Detectors and Focal Plane Arrays

B.R. Johnson, T. Ohnstein, H. Marsh, S.B. Dunham and P.W. Kruse, "YBa<sub>2</sub>Cu<sub>3</sub>O<sub>7</sub> Superconducting Microbolometer Linear Arrays."

### **8.3 Presentations**

#### **a. Invited**

B.R. Johnson, "Superconducting Microbolometer Infrared Detector Arrays on Silicon Microstructures," presented at the International Superconductor Applications Convention, San Diego, CA, January 14-16, 1991.

b. Contributed

B.R. Johnson, P.W. Kruse, and S.B. Dunham, "YBa<sub>2</sub>Cu<sub>3</sub>O<sub>7</sub> Films For Infrared Bolometers on Silicon Microstructures," presented at the Materials Research Society Fall Meeting, Boston, MA, December 2-6, 1991.

The following paper was presented at the DARPA Second Annual High Temperature Superconductors Workshop, Sheraton Tara Hotel and Resort, Danvers, MA, October 3-5, 1990.

B.R. Johnson, C-J Han, T. Ohnstein, B.E. Cole and P.W. Kruse, "Monolithic Integration of Semiconductor and Superconductor Components."

The following paper was presented at the DARPA Third Annual High Temperature Superconductors Workshop, Hyatt Bellevue Hotel, Bellevue, Washington, September 30 - October 2, 1991.

B.R. Johnson, T. Ohnstein, P.W. Kruse and S. B. Dunham, "YBa<sub>2</sub>Cu<sub>3</sub>O<sub>7</sub> Films for Infrared Bolometers on Silicon Microstructures."

The following papers will be presented at the JPL Innovative Long Wavelength Detector Workshop, Pasadena, April 7-9, 1992.

P.W. Kruse, "Fundamental Limits of Infrared Detectors and Arrays."

B.R. Johnson, T.R. Ohnstein and P.W. Kruse, "High T<sub>c</sub> Superconducting Microbolometer Linear Arrays."

The following paper will be presented at the American Ceramic Society meeting in Minneapolis April 13-17, 1992.

B.R. Johnson, P.W. Kruse, T. Ohnstein, C.J. Han and R. Higashi, "High T<sub>c</sub> Superconductor Infrared Bolometers on Silicon Microstructures."

The following paper will be presented at the SPIE OE/Aerospace Sensing meeting in Orlando April 20-24, 1992.

B.R. Johnson, T.R. Ohnstein, H. Marsh, S.B. Dunham and P.W. Kruse, "YBa<sub>2</sub>Cu<sub>3</sub>O<sub>7</sub> Superconducting Microbolometer Linear Arrays."

The following paper will be presented at the Applied Superconductivity Conference in Chicago August 24-28, 1992.

B.R. Johnson, T.R. Ohnstein, C.J. Han, R. Higashi, P.W. Kruse, A. Wood, H. Marsh and S.B. Dunham, "High T<sub>c</sub>

**Superconducting Microbolometer Arrays Fabricated by Silicon  
Micromachining."**

**9.0 FINANCIAL**

|    |                                                            |           |
|----|------------------------------------------------------------|-----------|
| A. | Funding Authorized                                         | \$559,122 |
| B. | Funds Expended or Committed<br>(Week ending 29 March 1992) | \$508,939 |
| C. | Additional Funds Required to Complete<br>Contract          | \$93,233  |

# YBa<sub>2</sub>Cu<sub>3</sub>O<sub>7</sub> superconducting microbolometer linear arrays\*

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## ABSTRACT

Single pixels and linear arrays of microbolometers employing the high-T<sub>c</sub> superconductor YBa<sub>2</sub>Cu<sub>3</sub>O<sub>7</sub> have been fabricated by silicon micromachining techniques. The substrates are 3-in. diameter silicon wafers upon which buffer layers of Si<sub>3</sub>N<sub>4</sub> and yttria-stabilized zirconia (YSZ) have been deposited. The YBa<sub>2</sub>Cu<sub>3</sub>O<sub>7</sub> was deposited by ion beam sputtering upon the yttria-stabilized zirconia (YSZ), then photolithographically patterned into serpentine 4 μm wide. Anisotropic etching in KOH removed the silicon underlying each pixel, thereby providing the necessary thermal isolation. When operated at 70°K with 1 μA dc bias, the D\* is 7.5x10<sup>8</sup> cm Hz<sup>1/2</sup>/Watt with a thermal response time of 24 msec.

## 1. INTRODUCTION

Following the discovery of high-T<sub>c</sub> superconductors, investigations began into their use in transition edge bolometers<sup>(1-8)</sup>. One of the most promising applications of such bolometers is in arrays for thermal imaging systems.<sup>(9-11)</sup> Such systems today employ linear arrays of cryogenic photon detectors such as Hg<sub>0.8</sub>Cd<sub>0.2</sub>Te. Known as FLIR's (Forward Looking InfraRed), these systems employ a moving mirror to scan the infrared image of a scene over a linear array of photon detectors. The output of the detectors is amplified, multiplexed, and displayed on a video screen at 30 frames per second.

In order to develop a thermal imaging system of similar performance based upon thermal detectors rather than photon, the following requirements must be met:

- The detectors must respond to the wavelength region of interest, usually 8-12 μm for terrestrial viewing;
- The detectors must be capable of being fabricated in linear arrays;
- The responsivity must be high;
- The electrical noise over the system bandwidth must be low;
- The response time must be no greater than about 30 msec.

The YBa<sub>2</sub>Cu<sub>3</sub>O<sub>7</sub> array development described below is directed toward meeting these requirements.

## 2. THEORY

The figure of merit which describes the performance of infrared imaging arrays is the NETD (Noise Equivalent Temperature Difference). It is the difference in temperature of two large objects in the scene being viewed, each having an emissivity of unity, which generates a signal-to-noise ratio difference of unity when imaged on an array. The NETD is expressed in degrees centigrade (deg C) and is given by

$$\text{NETD} = \frac{(4F^2 + 1)V_N}{A_D \tau_o R(T_s)(\Delta P / \Delta T_s)_{\lambda_1 - \lambda_2}} ; \quad (1)$$

where F is the numerical aperture of the lens used to image the scene upon the array, V<sub>N</sub> is the noise voltage within the system bandwidth, A<sub>D</sub> is the area of one pixel, τ<sub>o</sub> is the transmittance of the lens, R(T<sub>s</sub>) is the responsivity of a pixel to radiation from a black body at temperature T<sub>s</sub>, and (ΔP/ΔT<sub>s</sub>)<sub>λ<sub>1</sub>-λ<sub>2</sub></sub> is the change in radiant power per unit area emitted by a black body at temperature T<sub>s</sub> with respect to a change in T<sub>s</sub> measured over the spectral interval between λ<sub>1</sub> and λ<sub>2</sub>. The value of (ΔP/ΔT<sub>s</sub>)<sub>λ<sub>1</sub>-λ<sub>2</sub></sub> for 300°K ambient temperature over the 8 μm - 12 μm spectral interval is 2.62 x 10<sup>-4</sup> W/deg K.

\* Supported in part by Defense Advanced Research Projects Agency with Office of Naval Research as the contracting agency.

To obtain a low NETD, which is desirable, one needs small F/no., highly transparent optics, large pixel area, high pixel responsivity and low noise. The expression for the responsivity of a bolometer is

$$R(T_s) = \frac{I_b \alpha R_e \eta}{G(1 + \omega^2 \tau^2)^{1/2}} \quad (2)$$

Here  $I_b$  is the bias current,  $R_e$  is the pixel resistance,  $\eta$  is the optical absorptance of the pixel,  $G$  is the thermal conductance between the sensitive area of the pixel and the thermally heat sunk substrate,  $\omega$  is the angular modulation frequency of the radiation falling on the pixel,  $\alpha$  is the temperature coefficient of resistance (TCR) of the pixel, given by

$$\alpha = \frac{1}{R_e} \frac{dR_e}{dT} ; \quad (3)$$

and  $\tau$  is the thermal response time of the pixel, given by

$$\tau = \frac{C}{G} \quad (4)$$

where  $C$  is the heat capacity of the pixel.

A figure of merit describing the signal-to-noise ratio of a pixel is the detectivity  $D^*(T_s)$ , given by

$$D^* = \frac{R(T_s)(A_p B)^{1/2}}{V_N} ; \quad (5)$$

where  $V_N$  is the electrical noise within the bandwidth  $B$ .

In order for the bolometer to have a high responsivity, so that the NETD will be low and the  $D^*$  will be high, it is necessary to have a high TCR and a highly thermally isolated pixel. A high TCR is the reason for operating at the transition edge of a superconductor. The TCR of  $YBa_2Cu_3O_7$  near the superconducting transition temperature is roughly 100 times higher than that of semiconductors and 1000 times higher than that of metals.

The requirement for excellent thermal isolation dictates the structure of the pixel. That used here consists of a  $Si_3N_4$  membrane upon which is deposited YSZ, then  $YBa_2Cu_3O_7$ . Infrared radiation falling on the pixel causes a minute rise in temperature. The heat is conducted away through the  $Si_3N_4$  to the surrounding Si. The thermal decay time  $\tau$ , which is required to be no greater than about 30 msec to be TV frame rate compatible, thus gives rise to a need for a very small pixel heat capacity.

### 3. ARRAY FABRICATION

Fabrication of the single pixels and linear arrays begins with 3 in. diameter Si wafers which have been coated with a layer of  $Si_3N_4$  3000 Å thick. The wafers are loaded into an ion beam sputtering system capable of depositing both YSZ and  $YBa_2Cu_3O_7$ . A rotating target assembly is employed to first deposit a layer of YSZ 600 Å thick, then a layer of  $YBa_2Cu_3O_7$  2000 Å thick at 735°C using ozone and oxygen. The  $YBa_2Cu_3O_7$  is deposited by sputtering from 8 inch targets of  $Y_2O_3$ ,  $BaO_2$ , and Cu in a timed sequence in order to control the film stoichiometry. The entire sequence is repeated once every 8 seconds.

A small amount of Ag is co-sputtered with the Cu in order to increase the critical current and reduce the noise in the  $YBa_2Cu_3O_7$  films. The resulting films are c-axis oriented. A final layer of YSZ 300 Å thick is deposited on top of the  $YBa_2Cu_3O_7$  to passivate the superconductor against damage in subsequent processing steps. The  $YBa_2Cu_3O_7$  is then patterned into serpentine 4 μm wide by standard photolithography and ion milling. Silicon nitride 7500 Å thick is then deposited to provide further passivation and to provide structural strength for the thermally isolated microstructures. The

YBa<sub>2</sub>Cu<sub>3</sub>O<sub>7</sub> on the electrical contact pads is exposed by plasma etching and ion milling, and gold is sputter deposited to make electrical contact to the superconductor. The final step is a KOH anisotropic etch which removes the Si underneath the Si<sub>3</sub>N<sub>4</sub>. Figure 1 is a photomicrograph of a microbolometer made in this manner. The thermally isolated area is approximately 85  $\mu\text{m}$  x 115  $\mu\text{m}$  with an average thickness of 1.2  $\mu\text{m}$ . The overall pixel area is 125  $\mu\text{m}$  x 125  $\mu\text{m}$ .

#### 4. PERFORMANCE

Figure 2 illustrates the resistance as a function of temperature for seven thermally isolated pixels and one thermally heat sunk pixel from one linear array. Six of the seven thermally isolated pixels have nearly identical resistance vs. temperature characteristics. It is not known why one of the thermally isolated pixels has an anomalous resistance. The thermally isolated pixels are heated by background radiation from the inner walls of the cryostat vacuum can, resulting in a lower apparent superconducting transition than the heat sunk pixel. The pixel resistance does not go to zero below the transition edge due to resistance at the Au/YBa<sub>2</sub>Cu<sub>3</sub>O<sub>7</sub> contacts.

Figure 3 illustrates the TCR of one thermally isolated pixel from the same array as a function of temperature. The peak value of about 0.34/deg K occurs at about 72°K. Although the TCR of YBa<sub>2</sub>Cu<sub>3</sub>O<sub>7</sub> films on lattice-matched substrates is nearly ten times higher, it is difficult to obtain steep transitions for films on polycrystalline YSZ over amorphous Si<sub>3</sub>N<sub>4</sub>. Furthermore, a very steep edge reduces the dynamic range of the system and makes temperature stabilization at the midpoint more difficult.

Figure 4 illustrates the responsivity as a function of temperature, comparing it to  $\alpha R_e$  as a function of temperature. The radiation source was a 1000°K black body illuminating the sample through a 1 Hz chopper and a sapphire window. The maximum responsivity of 62,000 V/W measured at 16  $\mu\text{A}$  bias is found at 70°K. There is significant self-heating of the pixel when a dc bias current of 16  $\mu\text{A}$  is used. This enhances the peak height, makes the peak narrower, and shifts it to lower temperature relative to the peak in responsivity at low bias current. For example, the peak in responsivity with 1  $\mu\text{A}$  dc bias is 1,300 V/W, at a temperature of 73°K.

Noise measurements on the pixels show a 1/f power law dependence from 50 Hz to 1000 Hz, for a dc bias current of 100  $\mu\text{A}$  with a small amount of gas in the cryostat to enhance the thermal conductance and reduce the amount of self-heating of the pixel. The noise voltage is proportional to bias current, as expected for resistance fluctuations. Two-probe and four-probe noise measurements on test structures on the same wafer reveal most of the excess noise to be associated with the Au/YBa<sub>2</sub>Cu<sub>3</sub>O<sub>7</sub> contacts.

Frequency response measurements reveal a thermal response time (3db on rolloff) of 24 msec for small bias current (1  $\mu\text{A}$ ). With larger bias current, self-heating causes a longer time constant. The measured  $D^*$  for a 1  $\mu\text{A}$  dc bias current at a frequency of 7 Hz (the 3db rolloff frequency) is  $7.5 \times 10^8 \text{ cm Hz}^{1/2}/\text{Watt}$ . It should be mentioned that the noise bandwidth in a large thermal imaging array can be of order 100 kHz. Thus, the noise per unit bandwidth at 7 Hz where 1/f noise dominates, is much larger than the average noise per unit bandwidth of a typical thermal imager.

#### 5. DISCUSSION

While not yet exhibiting performance equivalent to Hg<sub>0.8</sub>Cd<sub>0.2</sub>Te arrays, these results are nevertheless very promising. Many areas of improvement are possible.

- The NETD is limited by 1/f power law noise from the contacts. Contacts with lower resistance (and presumably, lower noise) can be fabricated by in-situ deposition of Au on the YBa<sub>2</sub>Cu<sub>3</sub>O<sub>7</sub>. This should reduce the total noise voltage by a factor of 10. Reductions in the YBa<sub>2</sub>Cu<sub>3</sub>O<sub>7</sub> noise are also possible.
- The optical absorption is low. By employing free space impedance matching absorbers (190 ohms/square) and anti-reflection coatings, the absorption can be raised by a factor of 2.
- Joulean heating limits the responsivity. Under low duty cycle pulsed bias the peak responsivity will increase by at least 10 times.

For a thermal imaging system with 125  $\mu\text{m}$  pixels, 0.1 Hz to 100 KHz noise bandwidth, using 100  $\mu\text{A}$  pulsed bias current, F/1.0 optics, imaging in the 8  $\mu\text{m}$  to 12  $\mu\text{m}$  wavelength band, the present pixels would give a NETD of 17 mK. If the above improvements are made, the NETD for an array of these 125  $\mu\text{m}$  pixels could be reduced to 1 mK.

The performance of such an array would be fully competitive with not only  $\text{Hg}_{0.8}\text{Cd}_{0.2}\text{Te}$  linear arrays but also  $\text{Hg}_{0.8}\text{Cd}_{0.2}\text{Te}$  staring arrays. Fabricated by Si processing, the production cost should be much less than  $\text{Hg}_{0.8}\text{Cd}_{0.2}\text{Te}$ .

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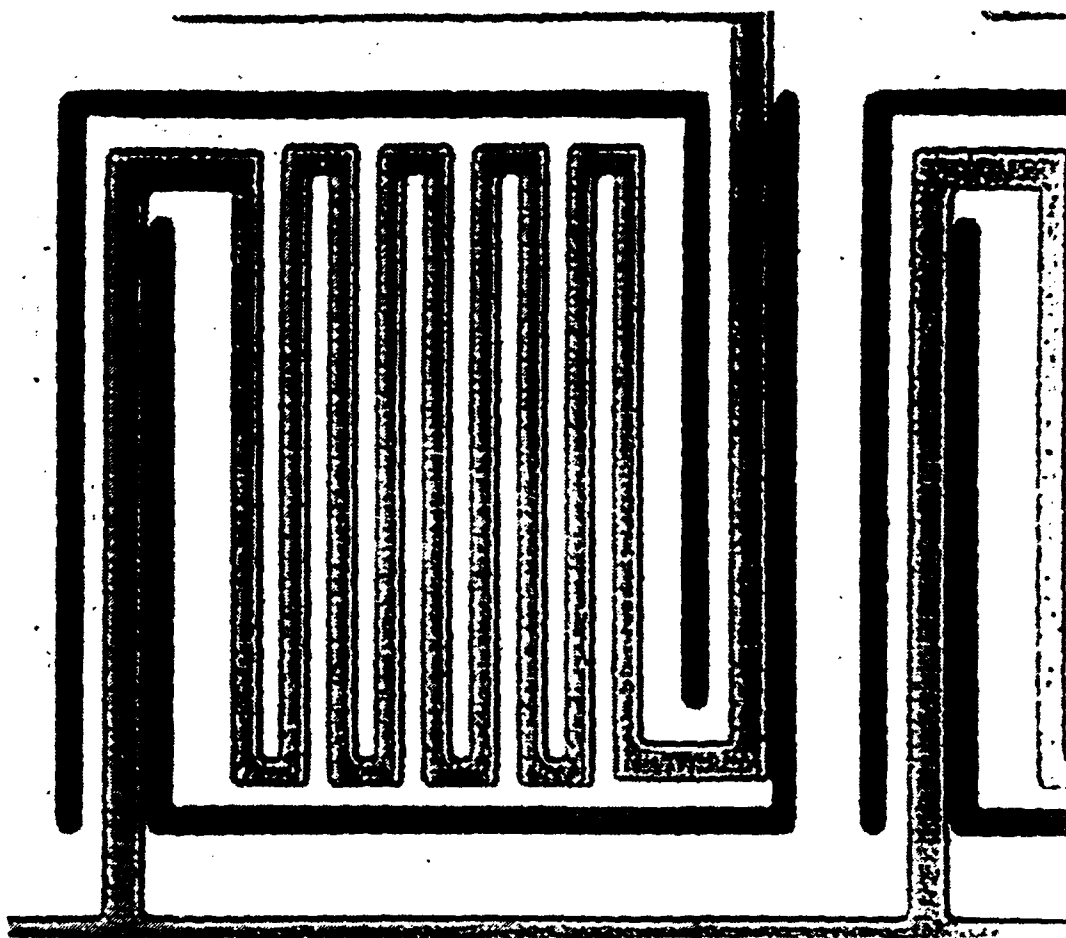


Figure 1. One Pixel of a YBaCuO Superconducting Microbolometer Array



File RvTUnitCov.ana 3/16/92, Die B7, Wafer 2-15  
 1  $\mu$ A Current, Window covered,  $p < 1$  mTorr  
 Note: Pixel #13 is heat sunk

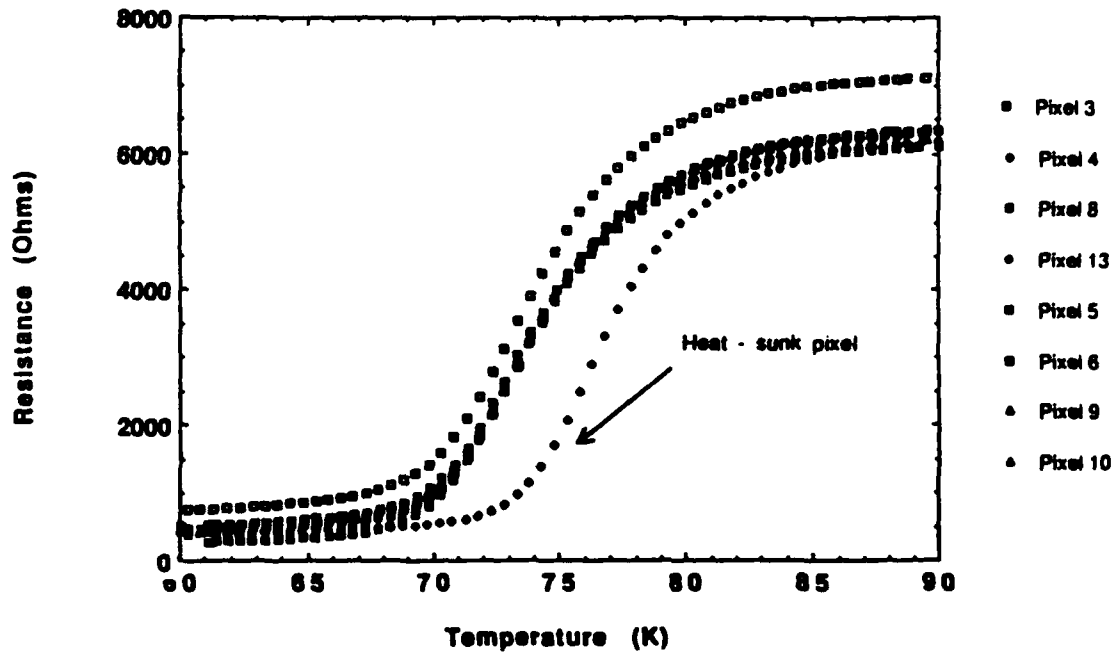


Figure 2. Resistance Vs. Temperature for Several Pixels

File B7031uA.ana 3/16/92  
 Pixel #3, Die B7, Wafer 2-15  
 Window covered, 1  $\mu$ A Current,  $P < 1$  mTorr

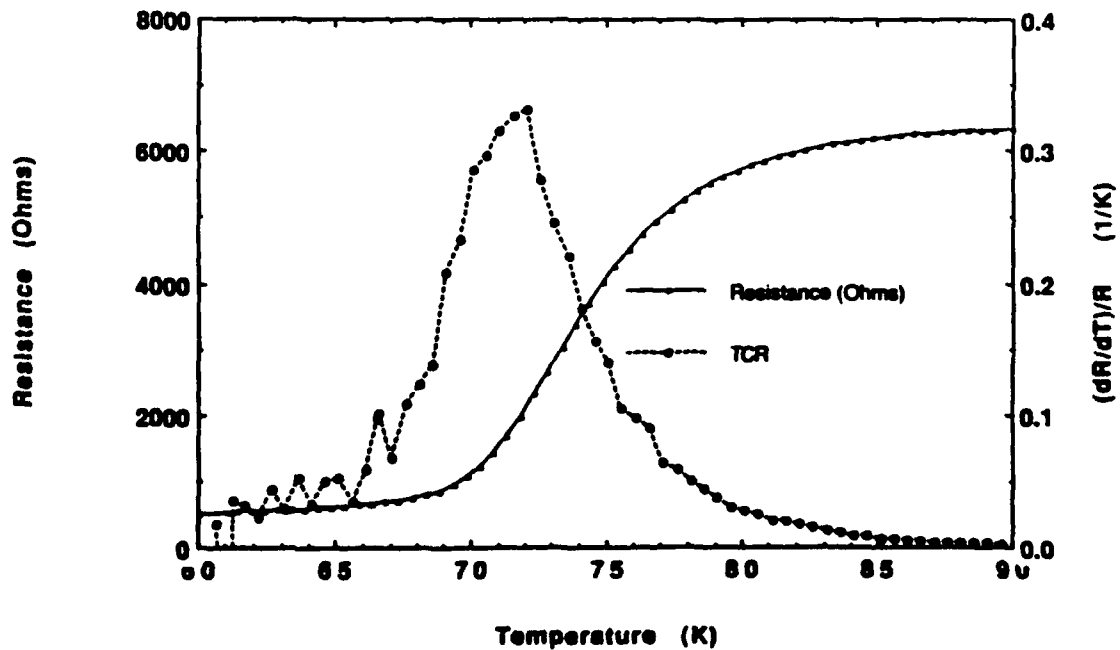


Figure 3. Resistance and TCR vs. Temperature

File B70316uArsp&dRdT.gra 3/17/92  
Pixel #3, Die B7, wafer 2-15  
16  $\mu$ A Bias, Chopper 1.04 Hz  
Note: At Responsivity peak, IR peak to peak  
signal is 40% of bias voltage!

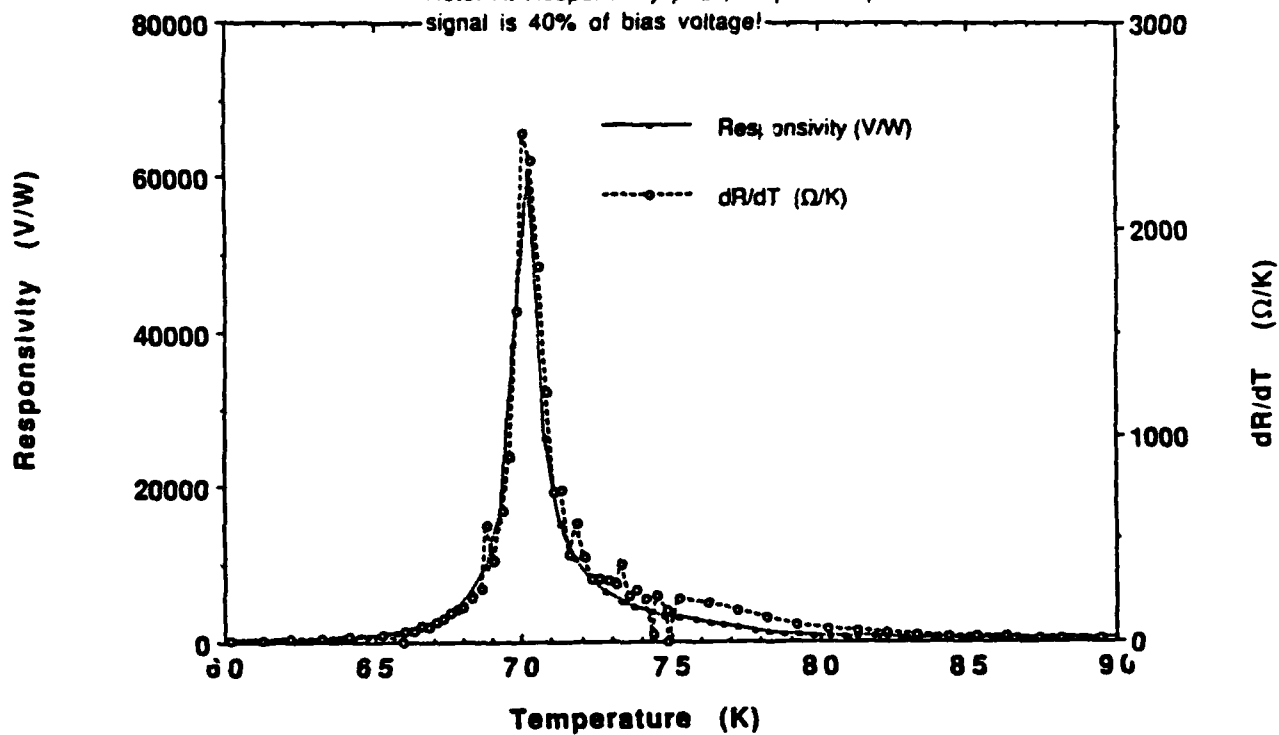


Figure 4. Responsivity and dR/dT vs. Temperature at 16  $\mu$ A Bias

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