Passive Millimeter-Wave Focal Plane Array

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Abstract

We built and tested a low-cost 8-by-8 millimeter-wave focal plane array using antenna-coupled micro-bolometers. The array consists of slot antennas coupled to nickel bolometers and was fabricated using optical lithography on high-resistivity silicon wafers. The measured noise equivalent temperature difference (NETD) of an individual element was 450 K. Simulation results corresponded with observed device performance. An improved design was then implemented using a square spiral antenna. We discuss the fabrication of this type of array element, include some modeling results, and present the methods and results of our measurements.

Introduction

Antenna-coupled micro-bolometers are potential solutions as elements in focal plane arrays for light-weight, low-cost solutions in millimeter wave imaging. These uncooled detectors can be designed to operate at a wide range of frequencies. The fast time constants, simple fabrication processes, low power requirements, and robustness of these monolithic devices make them an important area of research in millimeter wave imaging.

A bolometer is a material in which a change in temperature is accompanied by a corresponding change in electrical resistance. By passing a bias current through the material, one can measure temperature change by observing a change in bias voltage. The responsivity, $\Re_v$, of a bolometer depends on several parameters:

$$\Re_v = \frac{i_{bias} R \alpha \eta}{G\sqrt{1+\omega^2\tau^2}} \qquad (1)$$

Here i_{bias} is the bias current supplied to the bolometer, R is the resistance of the bolometer, α is the material temperature coefficient of resistance (TCR), η is an optical absorption coefficient, G represents the thermal conductivity of the bolometer's primary means of heat loss, ω is the modulation frequency, and τ is the thermal time constant[1].

Because responsivity is directly proportional to TCR, the choice of bolometric material is important. But the inverse proportionality of thermal conductivity, G, has a greater effect on responsivity because it can range over several orders of magnitude, while the range of TCR in different materials is relatively small.

A smaller thermal time constant, τ, also increases device responsivity. The time constant depends on the physical size of the bolometer: a smaller bolometer has a faster time constant. But as the bolometer gets smaller, its collection area also gets smaller, making it less effective as a sensor.

To increase the collection area of the bolometer without increasing its physical size, one can couple the bolometer to an antenna. If the antenna is designed to resonate at the desired frequency, radiation can be directed into the bolometer and responsivity will increase.

Fabrication

The array consists of 64 Ni micro-bolometers coupled to slot antennas. The array elements were designed for operation at 94 GHz, with an RF bandwidth of 20 GHz, based on a simulation using IE3D. The array elements were spaced λ/2 (1.5 mm) apart. The ground plane of each slot antenna is divided into two electrically isolated sections in order to bias the bolometers.

We used optical lithography to create the array pattern on a high-resistivity (> 8000 Ω cm) Si wafer, and deposited 15 nm of electron-beam-evaporated Cr and 70 nm of thermally-evaporated Au. The slot antenna is 15 μm wide and 574 μm long, and the lines separating the positive and negative sides of the ground plane are 15 μm wide. The bolometers were written with an electron-beam lithography system and deposited by dc sputtering Ni. Nickel was chosen as the bolometric material because it has higher TCR than most other metals, 0.6%[2]. Although we used electron-beam lithography to create the bolometers, the dimensions of the bolometers (2 x 30 μm) allow the use of optical lithography as well. Figure 1 shows an array of elements, and a photo of a single element.

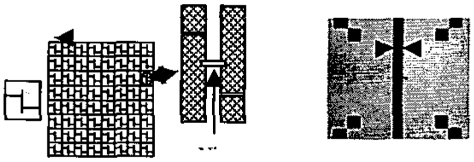
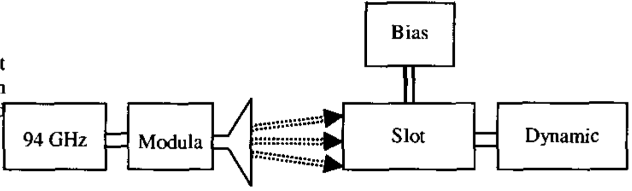


Fig. 1: 8 x 8 slot antenna-coupled microbolometer array.

Testing and Measurements

We measured the response of individual elements to 94 GHz radiation from a Gunn oscillator. Our test setup is shown in figure 2. The radiation from the Gunn diode is modulated at the video frequency and launched into free space through a horn antenna. Our array element is illuminated through the Si substrate and connected to a chip carrier by aluminum bond wires. The bolometer is given a dc bias of 100 mV, and the signal is sent through a series of filters and amplifiers. By modulating the 94 GHz signal at a lower frequency we observe the signal in the frequency domain on a signal analyzer.



This measurement setup gave us the ability to easily measure the attenuation of different materials at 94 GHz. We placed each sample in the path between the horn antenna and our array element and compared the measured signal to the unobstructed signal. Our results are summarized in table 1.

Table 1: Attenuation of various materials at 94 GHz	
Cotton fabric	2.4 dB
5/8" dry wall	3.2 dB
Padded cardboard shipping envelope	5.2 dB
320-grain sandpaper	5.3 dB
Anti-static cardboard shipping envelope	10.1 dB
Leather	12 dB
120-grain sandpaper	20 dB
Lead-lined x-ray-proof film pouch	20.9 dB
Proceedings of SPIE, Volume 4719 (412 pages)	37.7 dB
Aluminum foil	68 dB
Noise floor	70.4 dB

The measured response of a single array element was 1.18 μV at 30 Hz, with 68 nW of flux onto the device and a noise level of 330 $\mathrm{pV}/\sqrt{\mathrm{Hz}}$. We were interested in the noise equivalent power (NEP) and noise equivalent temperature difference (NETD) of the sensors, which are calculated as follows:

$$\mathrm{NEP}=\frac{\phi_e}{v_{sig}/v_n} \tag{2}$$

$$\mathrm{NETD}=\frac{\mathrm{NEP}\sqrt{b}}{ekB} \tag{3}$$

where φ_e is the radiant flux (in Watts), v_{sig} is the detected signal voltage (in Volts), v_n is the noise voltage (in Volts/√Hz), b is the video bandwidth (30 Hz), e represents antenna coupling efficiency which we estimate as 0.6, k is Boltzmann's constant, and B is the RF bandwidth of the antenna (28 GHz). From these measurements we calculated a noise equivalent power (NEP) of 19 pW/√Hz and a noise equivalent temperature difference (NETD) of 450 K.

To improve detector performance and decrease NETD, we designed a new array element (fig. 3). The square spiral antenna was used instead of the slot antenna because of its superior thermal characteristics and bandwidth. The extended RF bandwidth of the square spiral antenna will result in a significant drop in NETD.

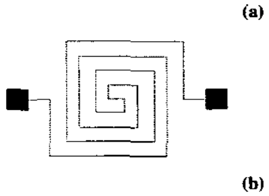


Fig. 3: A square spiral antenna designed to resonate at 94

3. Present activities and plans

It is important to isolate the bolometer thermally so that as much heat as possible stays in the bolometer. In the case of the slot antenna, the large ground plane acts as a heat sink and reduces the sensitivity of the bolometer. The square spiral uses significantly less metal, so that thermal losses are predominantly to the substrate.

To reduce substrate losses, we attempted to fabricate the bolometers on a membrane of Si_3N_4. The Si wafer is coated with a 3-μm layer of SiO_2 and a 400-nm layer of Si_3N_4, and the membrane is formed after the antenna fabrication process by etching holes in the Si_3N_4 layer with CF_4 plasma and then isotropically etching the SiO_2 layer with HF. After the antenna and bolometer have been fabricated, a 200-nm layer of thermally-evaporated chromium is deposited to protect the device from subsequent etch processes. This chromium layer is finally removed in a wet etch process after the membrane has been formed. By operating the detectors under vacuum, we expected to see significant device performance enhancement due to the improved thermal isolation of the membrane.

Conclusions

Antenna-coupled microbolometers represent a low-cost solution for millimeter-wave imaging applications. We fabricated an 8-by-8 array of antenna-coupled bolometers using optical lithography and measured the performance of individual array elements. The NETD of the slot antenna-coupled bolometers was 450 K. We attempted to refine our array element design by increasing the RF bandwidth of the antenna and improving the thermal isolation of the bolometer to its surroundings. The fabrication process is still under development. Simulation results helped explain the performance of the devices and have given direction for future work.

References

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[2] D. R. Lide, *CRC Handbook of Chemistry and Physics*, 84th Edition, CRC Press, 2003.