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Antenna-coupled microbolometer arrays with aerogel thermal isolation

F.J. González [a,*], C.S. Ashley [b], P.G. Clem [b], G.D. Boreman [a]

[a] School of Optics/CREOL, University of Central Florida, 4000 Central Florida Boulevard, Orlando, FL 32816-2700, USA
[b] Sandia National Laboratories, Albuquerque, NM 87185-1411, USA

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Abstract

Uncooled bolometric detectors used in infrared imaging systems have slow response times (∼10 ms) which makes them impractical for fast-frame-rate applications. Antenna-coupled microbolometer arrays have been shown to have fast response times (∼130 ns) and can be used as picture elements in infrared imaging systems but lack sufficient responsivity. Thermal isolation of antenna-coupled microbolometer arrays will increase its responsivity but will also increase its response time. Thermal isolation can be achieved using silica aerogel as a substrate, and its porosity can be used to modify the thermal conductivity down to values lower than air. In this paper antenna-coupled microbolometer arrays were fabricated on a substrate coated with a thin film of aerogel, noise, response and radiation characteristics were measured and compared to similar devices fabricated on a SiO_2 substrate. The measured signal-to-noise ratio of devices fabricated on aerogel were one order of magnitude higher than devices fabricated on SiO_2 and had time constants around 5 μs.

Keywords: Microbolometer; Infrared focal plane array; Silica aerogel; Antenna-coupled detectors

1. Introduction

High density detector configurations lead to higher image resolution as well as greater system sensitivity [1]. Current uncooled infrared focal plane arrays consist of two-dimensional arrays of micromachined bolometers that have typical pixel areas of 50 μm-by-50 μm. These bolometric detectors have slow response times (10 ms) which makes them impractical for fast-frame-rate applications [2]. The need for fast, sensitive detection in focal plane devices motivates the development of antenna-coupled IR sensors. Antenna-coupled microbolometers have been shown to have very fast response times with time constants as low as 130 ns [3]. Two-dimensional arrays of antenna-coupled microbolometers can be configured into pixels to cover standard FPA pitch spacings of 25–50 μm [4]. These type of detectors share the speed of antenna-coupled detectors and still cover the required pixel area.

The voltage responsivity of a bolometer is given by [3]

* Corresponding author. Tel.: +1-407-823-6843; fax: +1-407-823-6880.
E-mail address: javier@creol.ucf.edu (F.J. González).

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$$\Re_v = \alpha \cdot |Z_{th}| \cdot V_{bias}, \quad (1)$$

where α is the temperature coefficient of resistance of the bolometer, V_{bias} is the dc bias voltage across the device and Z_{th} is the thermal impedance of the device which accounts for all the heat conduction paths out of the bolometer and depends on the modulation frequency of the incoming radiation. An expression for the magnitude of the thermal impedance as a function of frequency can be derived from the expression of the thermal impedance in the Laplace domain found in [3] as

$$|Z_{th}| = \frac{R_{th}}{\sqrt{1 + \omega^2 R_{th}^2 C_{th}^2}}. \quad (2)$$

The thermal response of a bolometer is characterized by its time constant which is given by

$$\tau_{th} = R_{th} \cdot C_{th}, \quad (3)$$

from Eqs. (1)–(3) we can see that an increase in the thermal impedance of the detector would increase the responsivity of the detector, but will also increase its time constant, slowing down the response of the detector and therefore decreasing its bandwidth. The highest thermal impedance would occur when the detector is completely isolated from the environment, therefore the use of high thermal conductivity substrates will make a bolometer faster but will reduce its responsivity.

From the above stated we can see that a trade-off exists between responsivity and speed of the detector; in order to fabricate fast detectors low thermal isolation is required which yields low responsivity, therefore the thermal conductivity of the substrate has to be chosen so that it gives the maximum response for the required frame-rate.

Aerogels are materials that consist of pores and particles that are in the nanometer size range and have exceptional optical, thermal, acoustical and electronic properties [5] which depend on the porosity of the film. Thermal conductivity decreases linearly as porosity of the aerogel film increases, values lower than air have been measured on 70–99% porosity films [6]. Thin aerogel films with up to 98% porosity can be deposited on Si wafers by spin coating or dip coating, and can later be used as substrates for further lithographic processing [5]. In this paper the noise, response, time constant and radiation characteristics of two-dimensional arrays of antenna-coupled microbolometers fabricated on aerogel-coated substrates is studied and compared to similar devices fabricated on $Si–SiO_2$ substrates.

2. Method

Two-dimensional arrays of dipole-coupled (Fig. 1) and bowtie-coupled (Fig. 2) microbolometers were used in this study. A series configuration was selected to match the input impedance of typical commercial ROIC's which is in the kilo-ohm range [2], and cover a pixel area of 50 μm-by-50 μm. The antenna arrays were patterned using direct-write electron-beam lithography and lift-off. The antenna elements and the dc bias line that serially connects them is made of 100 nm thick evaporated gold. For every antenna element there is a 0.8 μm × 0.5 μm patch of Nb at the feed that acts as the bolometric detector of infrared radiation, the Nb film was dc-sputtered and is 70 nm thick. These detectors were fabricated on 3-in. Si wafers with 200 nm of thermally grown SiO_2 and on 3-in. Si wafers coated with a thin film of silica aerogel.

Silica aerogel thin films were deposited by spin coating onto thermally oxidized silicon wafers using the process used by Clem et al. [6]. The resulting film was 700 nm thick and had a refractive

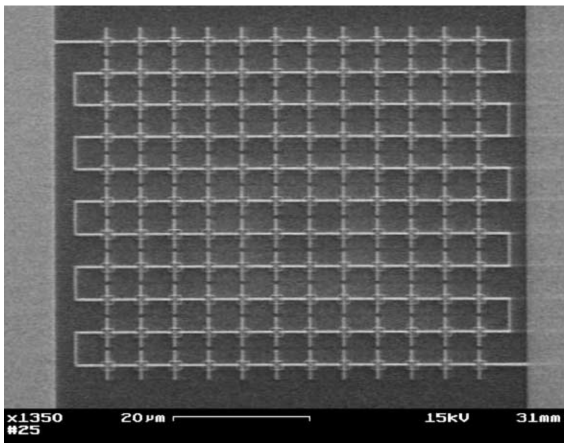

Fig. 1. Scanning electron micrograph of a dipole-coupled array of microbolometers.

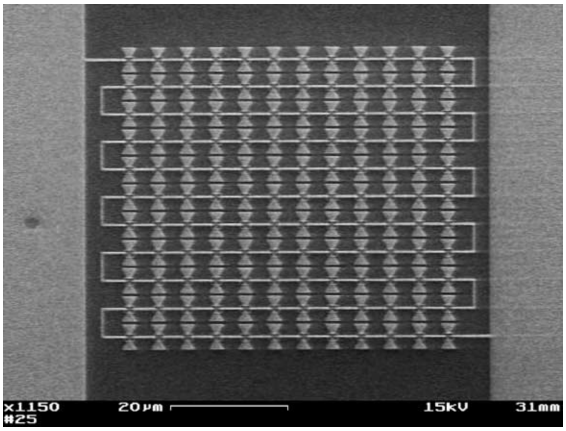

Fig. 2. Scanning electron micrograph of a bowtie-coupled array of microbolometers.

index of 1.06, as measured by 632 nm ellipsometry, which indicates that the silica aerogel film had a porosity of 85% [5]. Silica Aerogels of this porosity have a thermal conductivity of around 15 mW/(m K) which is lower than air (26 mW/(m K)) and much lower than SiO_2 (1200 mW/(m K)) [6].

The processed wafers were diced into 1 cm^2 chips and bonded into specially made chip carriers. Testing of the devices was done using a CO_2-laser at 10.6 μm focused by an $F/8$ optical train which had an almost diffraction-limited spot with a $1/e^2$ radius of 200 μm and an irradiance of 25 W/cm^2 at the focus. The polarization was linear and was rotated using a half-wave plate, all the measurements were made at the optimum polarization where the maximum response was obtained. Measurement of noise, response, angular and time constant characteristics was made using the same procedure explained in [4].

The two-dimensional arrays of microbolometers presented an average dc resistance of 3 ± 0.3 kΩ and all of the measurements were made with a bias voltage of 300 mV.

3. Results

The response of the antenna arrays as a function of the modulation frequency of the laser beam was measured using an acousto-optic modulator. The frequency response of the antenna arrays did not depend on the type of antenna measured but on the substrate the antennas were fabricated on. Antennas fabricated on aerogel presented time constants around 5 μs while antennas fabricated on SiO_2 showed time constants around 130 ns. Fig. 3 shows a typical frequency response measurement on an antenna array fabricated on a SiO_2 substrate and on an aerogel substrate. The antennas on aerogel have a time constant around 40 times slower than antennas on SiO_2 which is within a factor of 2 of the ratio of their thermal conductivities [6].

The response of the antenna arrays to 10.6 μm radiation was measured, the maximum signal was obtained for the polarization parallel to the antenna axis. The bowtie-coupled antenna arrays on SiO_2 gave a maximum response of 7.3 ± 0.03 μV, the same type of antennas fabricated on aerogel gave a maximum response of 142 ± 2 μV, a 20× increase in response. The same measurements where made on dipole-coupled antenna arrays, resulting in a maximum signal of 3 ± 0.7 μV for devices on a SiO_2 substrate and 100 ± 12 μV for the ones on aerogel, showing a 30× increase in response. From Eq. (1) we can see that for an equal change in the thermal impedance of both type of arrays a similar increase in response should be obtained, however since we are working with antenna-coupled detectors a change in the permittivity of the substrate from 4.7 for SiO_2 to 1.1 for high-porosity silica aerogel [5] will change the electrical size of the antenna which would affect its radiation characteristics. Fig. 4 shows the

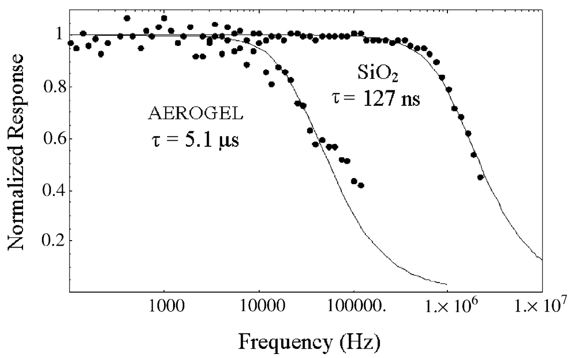

Fig. 3. Frequency response measurement of devices fabricated on SiO_2 substrates and on aerogel.

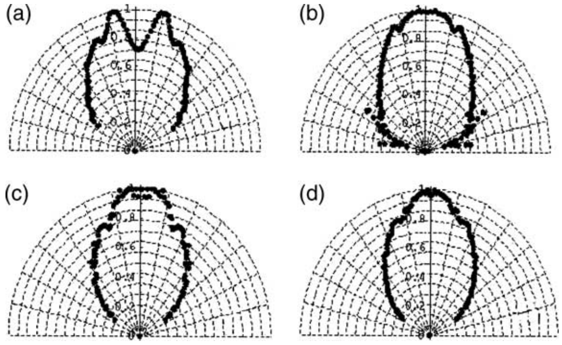

Fig. 4. Radiation patterns for dipole-coupled microbolometer arrays on (a) SiO_2, (b) aerogel and bowtie-coupled arrays on (c) SiO_2 and on (d) aerogel.

measured radiation patterns of both type of antenna arrays on SiO_2 and on aerogel. The radiation characteristics of the dipole-coupled arrays was more affected by the change in substrate compared to the bowtie-coupled array. This is due to the fact that bowtie antennas are broadband structures and a change in its electrical size does not significantly change its radiation characteristics [7].

Infrared detectors usually have large background noise pedestals, therefore figures of merit involving the signal-to-noise ratio (SNR) of the detectors are key to evaluate detector performance [1]. D^* is a figure of merit that permits comparison of detectors of the same type but having different areas, it is widely used for infrared detectors and is defined as the SNR in a 1 Hz bandwidth per unit incident radiant power per square root of detector area [1]. Fig. 5 shows the noise versus frequency

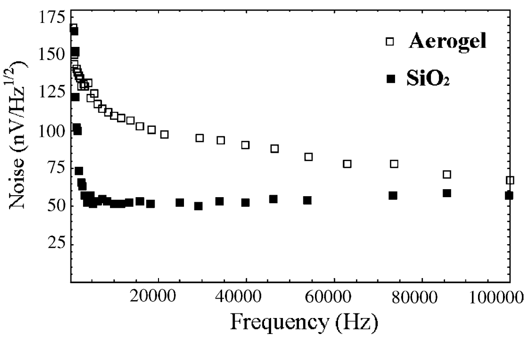

Fig. 5. Noise frequency spectrum for devices fabricated on SiO_2 and on aerogel.

characteristics of detectors on SiO_2 and aerogel substrates. The noise level of detectors on aerogel is higher and does not decrease as much with frequency as detectors on SiO_2. For a chopping frequency of 2500 Hz the noise level of detectors on aerogel is two times higher than for detectors on SiO_2, which means that the increase in response of 20 and 30 times due to the aerogel substrate will translate into a 10 and 15 times increase in D^*. The noise increase observed in detectors on aerogel can be atributed to lower quality contacts due to the roughness of highly porous material added to higher thermal fluctuations observed in metal films deposited on low thermal conductivity substrates [8].

4. Conclusions

The use of silica aerogel as a substrate for antenna-coupled microbolometer arrays resulted in a gain in responsivity and a noise increase that gave a one order of magnitude overall increase in SNR as compared to the same type of devices fabricated on SiO_2 substrates.

For antenna-coupled detectors the change in the dielectric permittivity of the substrate also resulted in a change in the radiation characteristics of the antennas which were more significant in the case of resonant antennas than with broadband antennas. In order to maximize the response of resonant antennas fabricated on aerogel a design modification that would account for the change in the electrical size of the antenna has to be made.

One of the interesting characteristics of silica aerogels is that its thermal conductivity can be controlled by varying its porosity, therefore it can be used as a substrate for antenna-coupled microbolometer arrays to maximize the responsivity of the detector for a specific frame-rate.

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