

## A High Fill-Factor Infrared Bolometer Using Micromachined Multilevel Electrothermal Structures

Hyung-Kew Lee, Jun-Bo Yoon, Euisik Yoon, Sang-Baek Ju, Yoon-Joong Yong, Wook Lee, and Sang-Gook Kim

**Abstract**—A high fill-factor uncooled infrared (IR) bolometer has been fabricated by using thin-film titanium resistors sandwiched in a surface-micromachined silicon oxinitride membrane ( $50\ \mu\text{m} \times 50\ \mu\text{m}$ ). This bolometer is realized in multilevel electrothermal structures with a fill-factor over 92%. From the multilevel structure, thermal isolation can be independently optimized without sacrificing IR absorbing area. Initial measurements show a thermal time constant of 12 ms, a responsivity of 1600 V/W, and a detectivity ( $D^*$ ) of  $5 \times 10^8\ \text{cm}\sqrt{\text{Hz}}/\text{W}$ .

**Index Terms**—Bolometer, electrothermal detection, fill-factor, IR sensor, micromachine.

### I. INTRODUCTION

There is a growing interest in infrared (IR) imaging systems for a wide range of applications from military night vision systems to automotive and consumer electronics. Detection mechanism of infrared can be classified into two groups: photon detection and thermal detection. In the evolution of modern infrared detection systems, photon detectors have played a major role due to their fast response time and high detectivity [1]. However, photon detectors are expensive for general commercial applications because cryogenic cooling is required to suppress the thermal noise from the detecting material which is typically low-bandgap semiconductor. Recently, thermal detectors have been widely used for uncooled thermal imaging systems due to their low cost. Enabled by using micromachining technology, good thermal isolation structures can be easily formed for uncooled IR focal plane arrays (FPA's), providing a sensitivity high enough for portable military applications as well as low cost commercial applications.

Three types of thermal detectors have been reported in recent years: resistive bolometers [2]–[5], thermopile detectors [6]–[7], and pyroelectric detectors [8]. Micromachined membrane structures are applied to achieve good thermal isolation for resistive and thermopile detectors while hybrid bulk die attachment through thermally-isolating mesa structures is employed for pyroelectric detectors. In this work we have chosen a bolometer approach because it is relatively easy to achieve a good responsivity and good thermal isolation compared to thermopile detectors and is generally easier to monolithically integrate the structure with readout circuitry compared to pyroelectric detectors.

Bolometers are thermistor-based detectors that measure temperature change in a thermally-isolated membrane heated by infrared radiation absorbed on the surface. Micromachined membrane structure should provide not only good thermal isolation from the substrate but also a high fill-factor and good integrated circuit (IC) process compatibility. It is generally easier to achieve a higher fill-factor in

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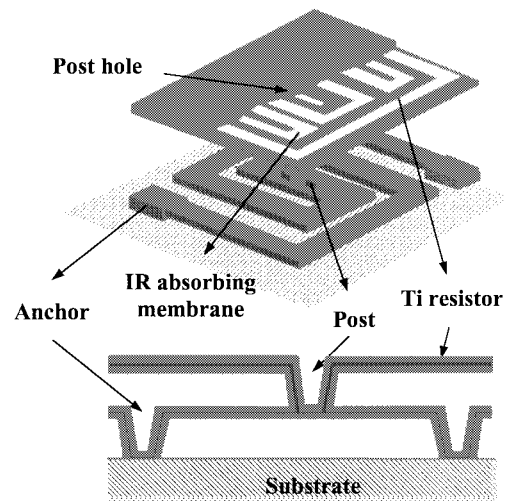


Fig. 1. Proposed high fill-factor bolometer pixel using surface-micromachined multilevel membrane structures.

array structures by using surface micromachining [2]–[4] than bulk micromachining technology [5]–[6]. Typically, IR absorbing areas are formed by a micromachined membrane suspended by two or four arms in the same plane over etched pits on the substrate. The longer the length of the suspended arms becomes in order to achieve good thermal isolation, the smaller the membrane size in the fixed pixel pitch is, resulting in a lower fill-factor. None of previous works has achieved a fill-factor higher than 60% in the pixel pitch smaller than  $50\ \mu\text{m}$ . In this paper we report a high fill-factor bolometer realized using multilevel electrothermal structures.

### II. PIXEL STRUCTURE AND FABRICATION

Fig. 1 shows the multilevel electrothermal isolation structure of the proposed bolometer [9]. The first level forms the suspended arms which mechanically support the top IR absorbing area by connecting it to the substrate via anchors. Good thermal isolation can be achieved from optimizing the dimension and layout of the arms between anchor and post. On the top of the thermal isolation arms the IR absorbing membrane covers almost the entire pixel to achieve a high fill-factor over 92% in the  $50\ \mu\text{m} \times 50\ \mu\text{m}$  membrane. In the previous approaches [2]–[5], the IR absorbing membranes and the thermal isolation arms are formed and connected in the same level. Therefore, there is a trade-off between good thermal isolation and high fill-factor. The long arms for better thermal isolation results in the reduction of the IR absorbing membrane size. On the contrary, in our structure thermal isolation can be independently optimized without sacrificing IR absorbing area to achieve a high fill-factor. Titanium was used as temperature sensing material because it has a relatively high temperature coefficient of resistance (TCR), low noise characteristics, and is compatible with IC processes. A serpentine titanium resistor is sandwiched in the plasma enhanced chemical vapor deposition (PECVD) oxinitride membrane and is connected to the substrate anchor through the post.

Fig. 2 shows the fabrication process steps. First, the amorphous silicon sacrificial layer ( $1\ \mu\text{m}$ ) is defined on the silicon substrate which includes on-chip CMOS readout circuitry and passivation layers. A PECVD silicon oxinitride film (250 nm) is deposited and patterned in order to form thermal isolation arms. Sputtered titanium

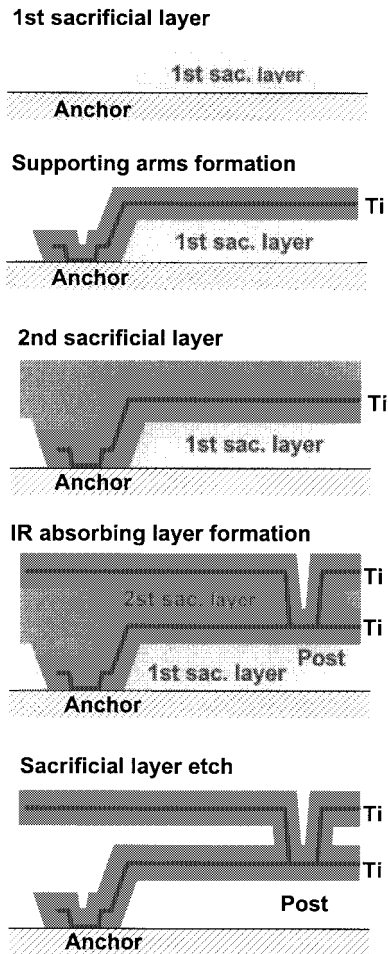


Fig. 2. Fabrication process flow of the multilevel electrothermal bolometer structure.

thin-film (50 nm) is patterned to make a connection between the substrate contact (anchor) and the post. Actually, titanium metal film is sandwiched between silicon oxinitride layers to prevent oxidation and release the stress. Additional contacts (posts) are formed to connect the titanium film to the resistor sensor on the absorbing membrane. After the second sacrificial layer (1.5  $\mu\text{m}$ ) is defined, the absorbing membrane with the titanium resistor sensor is formed using the same material and process as the arms. The titanium resistor sensor is formed in a serpentine pattern. Finally, the sacrificial layer is removed by isotropic dry etching ( $\text{XeF}_2$ ) process. The silicon oxinitride membrane is optimized to give low residual stress. Fig. 3 shows the fabricated test structures. It shows a high fill-factor array can be implemented in multilevel electrothermal structures. The membrane size is  $50\ \mu\text{m} \times 50\ \mu\text{m}$ . Currently, the on-chip CMOS readout circuits are being integrated with a  $256 \times 256$  bolometer array; the results will be published elsewhere.

### III. RESULTS

The TCR of 50 nm-thick titanium resistors has been measured as 0.26%/K over the temperature range between 20 and 120  $^\circ\text{C}$ . Thermal conductance of the multilevel membrane structure has been measured as  $4.3 \times 10^{-5}$  W/K in air and as  $6.3 \times 10^{-7}$  W/K in vacuum (2 mTorr), respectively. These numbers have good agreement with those calculated from the simple linear electrothermal conduction models of the structure. Transient resistance change has been monitored when the step current is applied. From this curve the thermal time constant

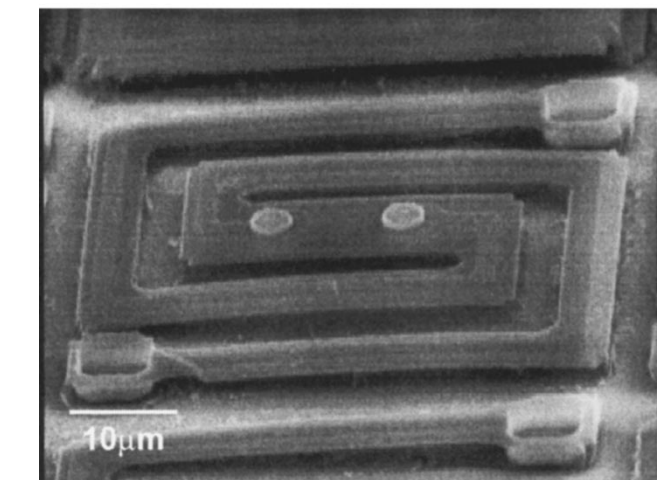
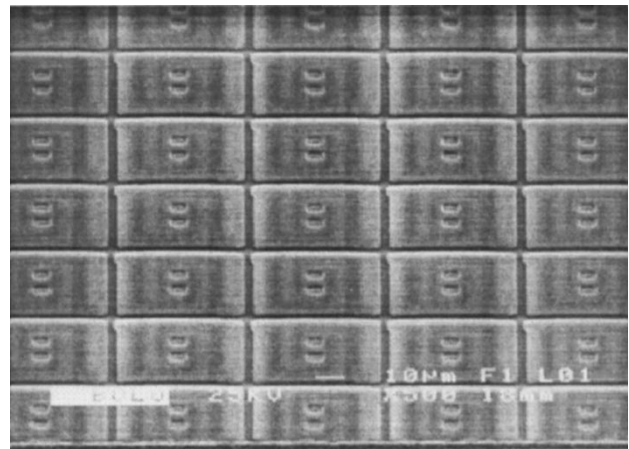


Fig. 3. SEM pictures of the fabricated test pixels.

of the pixel structure has been measured as 12.7 ms. Fig. 4 shows the output detector response when a chopper modulates a continuous IR source. Initial measurements show a maximum responsivity of 1600 V/W in vacuum without amplification when the constant current source of 70  $\mu\text{A}$  is applied to the resistor. We have not used any infrared black to improve absorption. The absorbance of the current absorbing membrane has been estimated about 60% from the measured data.

We have measured the current noise spectral density of the bolometer (5 k $\Omega$ ) in the range of 1–100 Hz using the HP3563A dynamic signal analyzer and a low noise transimpedance amplifier. Fig. 5 shows noise spectral densities of the bolometer measured at 300 $^\circ\text{K}$  with varying current bias. It shows thermal and  $1/f$  noise spectra. The typical power spectral density of  $1/f$  noise is represented by  $s_{i,f} = K I^2 / f^\alpha$ , where  $K$  is a constant,  $f$  is frequency, and  $\alpha$  is a power of  $f$  that is nearly 1. The thermal noise of the bolometer is in good agreement with an expected value (1.8 pA/ $\sqrt{\text{Hz}}$ ). The constants of  $1/f$  noise in the bolometer,  $K$  and  $\alpha$ , are measured as  $1 \times 10^{-14}$  and 0.9, respectively. The  $1/f$  noise in the titanium bolometer is very low compared to that in semiconductor materials [10].

The estimated detectivity can be calculated from

$$D^* = R_V \sqrt{BW \cdot A} / V_n$$

where

$R_V$  responsivity;  
 $A$  detector area;

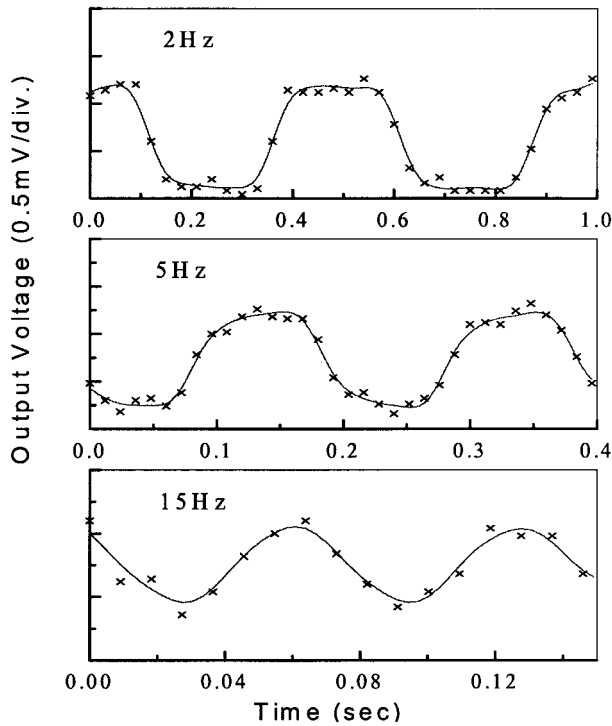


Fig. 4. Detector response modulated by an optical chopper for various chopper frequencies.

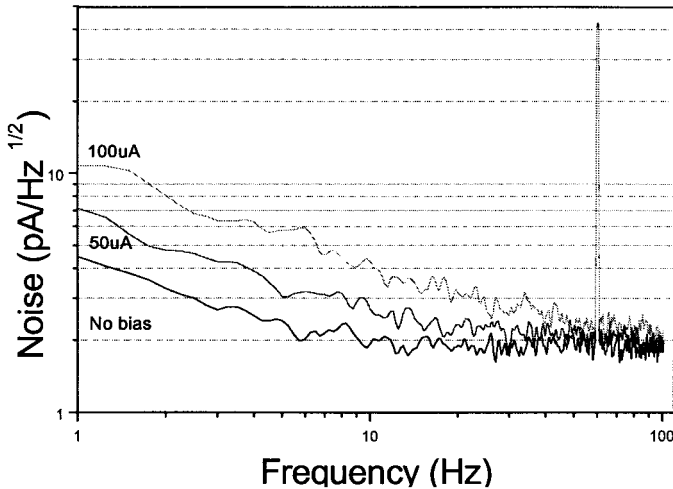


Fig. 5. Noise spectral density of a Ti resistor.

$V_n$  rms noise voltage;  
 $BW$  amplifier bandwidth.

As the bias current increases, the detectivity linearly increases when only thermal noise is considered. But as the amplifier bandwidth decreases,  $1/f$  noise contribution becomes significant. In the system point of view small bandwidth and large bias current are desirable for better performance. Assuming 64 kHz bandwidth and 70  $\mu$ A bias current, a detectivity ( $D^*$ ) of  $5 \times 10^8$   $\text{cm}\sqrt{\text{Hz}}/\text{W}$  is achieved. The characteristic parameters of the bolometer are summarized in Table I.

IV. CONCLUSIONS

We have developed a high fill-factor IR bolometer using multilevel electrothermal structures. With this structure we can obtain a fill-factor of 92% which may not be obtainable from conventional

TABLE I  
 TYPICAL DETECTOR DIMENSIONS AND MEASURED PERFORMANCE PARAMETERS AT ROOM TEMPERATURE

Parameter	Value
Pixel size ( $\mu\text{m} \times \mu\text{m}$ )	$50 \times 50$
Resistance ( $\text{k}\Omega$ )	5
DC Infrared Responsivity (V/W)	1600
Response time (ms)	12.7
Detectivity ( $D^*$ ) ( $\text{cm}\sqrt{\text{Hz}}/\text{W}$ )	$5 \times 10^8$
Fill-factor (%)	92
Thermal conductance (W/K) in vacuum	$6.3 \times 10^{-7}$

structures. The fabrication process is fully compatible with standard silicon IC processes. Measurements show a thermal time constant of 12 ms, a responsivity of 1600 V/W, and a detectivity ( $D^*$ ) of  $5 \times 10^8$   $\text{cm}\sqrt{\text{Hz}}/\text{W}$  in a  $50 \mu\text{m} \times 50 \mu\text{m}$  micromachined membrane structure. This high fill-factor, multilevel bolometer pixel is an ideal electrothermal structure for effective collection of IR radiation and is suitable for further scaling of the pixel size in high density IR FPA's.

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