Design and fabrication of a high fill-factor micro-bolometer using double sacrificial layers

Sang-Baek Ju[1], Yoon-Joong Yong, and Sang-Gook Kim
Advanced Display and MEMS Research Center, DEAWOO Electronics, CO., LTD.,
60-8, Kasan-dong, Kumchun-gu, Seoul, KOREA 153-023

ABSTRACT

In the present paper we report a high-fill factor uncooled infrared micro-bolometer array; and, more particularly, a three-level infrared bolometer including an almost 92% fill factor absorber and a separately-designed bridge structure for the electro-thermal isolation of thermal sensor; and a method for the silicon-based fabrication. The present 256×256 bolometer array comprises a CMOS readout circuitry, a bridge level, a pair of posts, and an absorption level. The fabrication of the present bolometer features that it uses double sacrificial layers so as to separate the absorber level from the bridge structure, electrical and thermal path between the absorber and substrate. Also, we chose a titanium thin-film as a bolometer material which is patterned to make a connection between the substrate contact and the post. The absorber level is composed of titanium metal film sandwiched between PECVD deposited silicon dioxide layers to preserve thermal isolation of a bolometer absorber and release the inertial stresses. Additional contact is formed to connect the metal thin-film to the serpentine resistive pattern on the absorbing membrane defined on the top of the second sacrificial layer. From the structural design, we can obtain a good thermal isolation without reducing IR absorbing area.

Keywords: MEMS(micro-electro-mechanical system), infrared, focal plane array, micro-bolometer, sacrificial layers,

1. INTRODUCTION

This report relates to design and fabrication for an infrared micro-bolometric detector; and, more particularly, to a three-level micro-bolometric detection element in each pixel within a two-dimensional IR staring array which provides an increased fill-factor up to about 92% and a good thermal isolation between the bolometric detector and substrate.

Generally, infrared detectors may be classified into two groups: photon detectors and thermal detectors. The former must be cooled to approximately the temperature of liquid nitrogen with the cooling apparatus typically the most expensive component in a cooled IR camera. The latter is thermal detectors, most of which, on the other hand, do not need such an apparatus; they are "uncooled" IR sensors and comparatively inexpensive. Three different types of uncooled FPA's have been developed in recent years: those employing a) *bolometer detectors*, b) *thermopile detectors*, and c) *pyroelectric detectors*.

We have chosen resistive bolometer detectors for use in the present report because their responsivity is much higher than that of thermopile detectors and they are generally easier to fabricate than pyroelectric detectors through the recently developed micro-machining process.

Conventional bolometric IR imaging arrays have used temperature-sensitive resistors as the IR energy-sensitive or active detector elements. Thermal detection mechanism of the bolometer detectors is to measure the change in electrical resistance of a material which is caused by a change in temperature of that material due to absorbed radiant energy. Such resisters based on either metallic or semiconductor films have required suspension above or alongside the semiconductor array signal-sensing circuitry that takes the form of a diode or switchable transistor.

Recently, high-performance micro-bolometric imaging array has been reported for wide applications such as daytime and nighttime, personal and vehicle pilotage, navigation and reconnaissance for military uses and commercial products. However, there traditionally have been some principal issues in the development of such an enhanced bolometric FPA. They are mainly related to the improvement of detector performance, and the readout circuitry that form the eye of the infrared imaging system. Such issues are summarized as follows;

---

[1] Correspondence: Email; sbjoo@tma.dwe.co.kr; Telephone:82-2-818-9856; Fax: 82-2-862-0386

1) Pixel structure for higher fill factor to increase the potion of photon absorption
2) Large percentage of IR absorption in the wavelength band of interest (typically 8-14 microns)
3) High thermal isolation of the detector element to maximize the sensitivity of detector (typically $1 \sim 2 \times 10^{-7}$ W/C)
4) A high temperature coefficient of a measurable parameter (typically resistance in the case of micro-bolometer)
5) A thermal time constant to corresponding to the electronic detector sampling rate (typically 10-20 *msec*)
6) An electronic switch pixel address mechanism (typically a diode, bipolar, field-effect transistor (FET), CMOS switching) and interconnect circuitry within the pixel to access the bolometric detector element and to sample the infrared radiation-induced signal variation
7) Lower Noise effect

This report covers the above issues in the context of the micro-machining structural design for a high performance micro-bolometer. The ideas begin with the analysis of the conventional design of two-level bolometric structure. We have identified the *functional requirements* of each component of the micro-bolometric detection element in each pixel within a two-dimensional IR staring array. In addition, we propose a redesigned prototype through the construction of the associated design parameters sought from the selected *functional requirements* of generally used bolometer. The proposed bolometric structure features that the absorber of IR bolometric detector is located on the top level supported by a pair of legs at lower level. The proposed structural design makes the optical fill-factor increased up to 92% which is possibly improved by enhanced manufacturing technology, and thermal isolation effect maximized by the prevention of the bridge part from heating.

2. ANALYSIS AND DESIGN OF IR BOLOMETRIC DETECTOR ELEMENT

2.1 Structural design

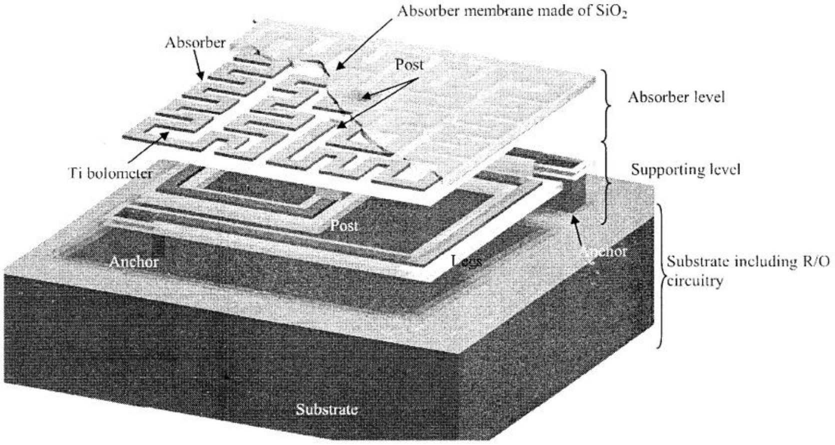


Figure 1 The configuration of a three-level micro-bolometer pixel structure by using surface-micromachining.

Figure 1 shows a perspective view illustrating a three-level bolometer comprising an on-chip integrated circuitry level, a supporting level, and an absorber level. The integrated circuitry array level includes a CMOS array circuitry, connecting terminals and a passivation layer. The CMOS array circuitry serves as switches, turning ON and OFF the bias current or voltage applied to the bolometric element of each pixel, and at the same time, reading out the changes in the current of bolometric detection element. In addition, it also includes vertical and horizontal multiplexers that allow individual addressing of pixels. The passivation layer made of, silicon nitride covers the substrate, which protects and insulates the on-chip integrated circuitry.

The supporting level includes a pair of bridges made of titanium conduction lines sandwiched by upper and lower silicon dioxide layers supporting the global structure of the pixel. Each of the bridges is provided with an anchor portion, a leg portion and an elevated portion, the anchor potion including via hole through which one end of the conduction line is electrically connected to the on-chip integrated circuitry, the leg supporting the elevated portion.

The absorption level is provided with a serpentine bolometer element made of titanium, an absorber made of silicon oxide and an IR absorber coating formed on top of the absorber. The absorber is fabricated by depositing silicon dioxide before and after the formation of the serpentine bolometer element to surround the serpentine bolometer element.

Each of the posts is placed between the absorption level and the support level. Each of the posts includes an electrical conduit made of a metal, e.g., titanium and sandwiched by an insulating material made of, e.g., silicon dioxide. Top end of the electrical conduit is connected to one end of the serpentine bolometric element and bottom end of the electrical conduit is connected to the conduction line on the bridge, in such a way that both ends of the serpentine bolometer element in the absorber level is electrically connected to the connecting terminals of the integrated circuitry array level through the electrical conduit, the conduit lines and the connecting terminals. When exposed to infrared radiation, the resistivity of the serpentine bolometer element changed, causing a current and a voltage to vary, accordingly. The varied current or a voltage is amplified by the integrated circuit, in such a way that the amplified current or voltage is read out by an on-chip or off-chip readout circuitry.

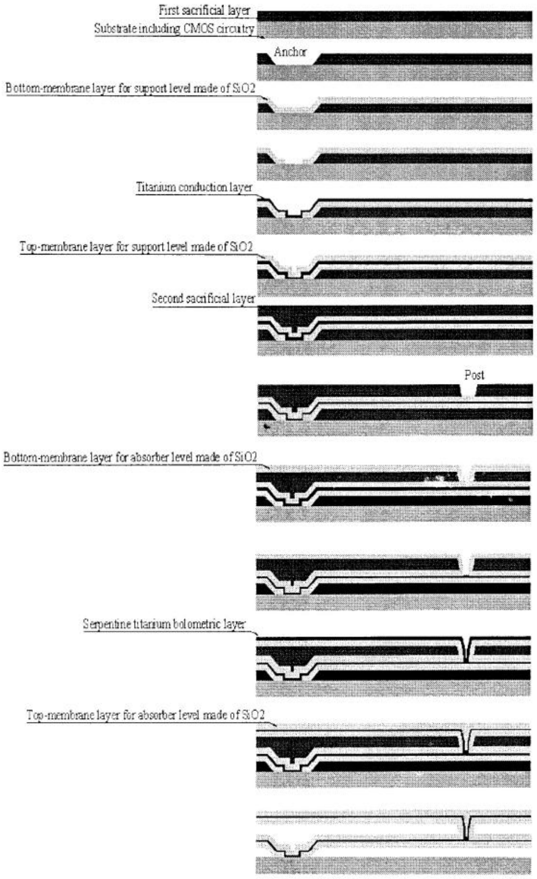
Through the proposed bolometer structure, we achieved a good thermal isolation effect optimizing the dimensions and layouts of each components of the pixel. On the top of the thermal isolation legs the IR absorbing membrane covers almost the entire pixel to achieve a high fill-factor over 92%. Titanium was used as temperature sensing material because it has a relatively high TCR, low noise characteristics, and is compatible with IC processes.

2.2 Fabrication processes

Figure 2 shows the fabrication process steps. First, the sacrificial layer made of polymer-like material is deposited on top of the passivation layer by using the spin coating as shown in Figure 2(a). In a following step as shown in Figure 2(b), the first sacrificial layer is selectively patterned to make a connection between the conduction line of the supporting level and the CMOS readout circuitry at the position of the anchor. Next, a bottom membrane layer of the supporting level made of PECVD silicon dioxide is deposited on top of the first sacrificial layer, which is etched to include a pair of via holes as shown in Figure 2(c) and 2(d). Thereafter, a conductive layer made of a sputtered metal, titanium, is deposited on top of the membrane layer including the via holes, where the via holes are filled with the conductive layer to the connection terminals as shown Figure 2(e). Then, in Figure 2(f), top-membrane layer of the supporting level is deposited and patterned into a pair of bridges.

In a subsequent step, a second sacrificial layer made of a polymer-like material, the same as the first sacrificial layer is deposited on top of the surface comprising the bridges and the first sacrificial layer by using spin coating. After the second sacrificial layer has a flat top surface as shown Figure 2(g), a pair of holes are formed in the layer by using hard mask and a developing method as shown in Figure 2(h). In a following step as shown Figure 2(i), a bottom membrane material made of PECVD silicon dioxide is deposited on top of the second sacrificial layer including the holes, we called, "posts". Next, pair of apertures are formed in the bottom membrane material of absorber level to expose the conduction line of the bridge as shown in Figure 2(j). Thereafter, a bolometric element layer made of sputtered titanium is deposited on top of the first absorption material including the aperture, where the aperture is filled with the bolometer element layer thereby forming a pair of electrical conduits. The bolometric element layer is then patterned into a serpentine element as shown Figure 2(k). Next, the top membrane layer made of PEVVD silicon dioxide is deposited on top of the goggled surface comprising a serpentine-patterned titanium layer and the bottom membrane layer as shown Figure 2(l). In an ensuing step, the absorber layer is diced into an absorber to thereby form an absorption level as shown Figure 2(l). Finally, the first and second sacrificial layers are ashed as shown in Figure 2(m).

In the three-level infrared bolometer of the proposed structure, the bridges are positioned under the absorption level allowing the absorber level to be fully utilized for IR absorption, which will, in turn, increase the optical fill factor up to the maximum.



(a) Deposition of the first sacrificial layer.

(b) Patterning of the first sacrificial layer.

(c) Deposition of bottom membrane layer.

(d) Patterning of membrane layer to expose the connection terminal.

(e) Deposition of conduction layer.

(f) Deposition of top membrane layer.

(g) Deposition of the second sacrificial layer.

(h) Patterning of second sacrificial layer for the construction of post, electrical conduit.

(i) Deposition of membrane layer for absorber level

(j) Etching of post

(k) Deposition of bolometric titanium layer

(l) Deposition of membrane layer

(m) Removal of the first and second sacrificial layers

Figure **2** Process flow of the three-level micro-bolometer FPA

3. THERMO-ELECTRIC CHARACTERISTICS OF A METALLIC MICRO-BOLOMETER

Self-heating

Generally, the thermal differential equation of the absorber is given by

$$C\frac{d(\Delta T)}{dt}+G\Delta T=P \tag{1}$$

where C is thermal capacitance of the absorber, G is thermal conductance of the absorber, and P is the applied power to the bolometer. In case of metallic bolometer, the P comprises P_o and ΔP_e, the infrared power P_o absorbed by the detector element and the applied electrical power increment dissipated in the detector resistance, respectively. Generally, let P_e be expressed as $P_e=i^2R(T)$ since the resistance, R is a function of temperature and i is the applied bias current to the detector. Therefore, we can obtain the modified differential equation of (1) as follows:

$$C\frac{d(\Delta T)}{dt}+G\Delta T=P_o+P_e \tag{2}$$

Let $R=R_0(1+\alpha\Delta T)$ be a varied resistance by the thermal change. Substituting the expression of R and arranging the last term of equation (2), we obtain

$$P_e=i^2R(T)=i^2R_0(1+\alpha\Delta T) \tag{3}$$

Substituting (3) into (2), we can obtain the governing differential equation of the system considering the metallic bolometer self –heating as follows:

$$C\frac{d(\Delta T)}{dt}+(G-\alpha i^2R)\Delta T=P_t(t)=P_o+i^2R_0 \tag{4}$$

Suppose $P_t(t)=p_o$ is a step function at t=0 such that $P_t(t)=0$ for t < 0. The solution to equation (4) is then

$$\Delta T=\frac{p_0}{G-\alpha i^2R}\left(1-e^{-(t/\tau_e)}\right),\ t\geq 0 \tag{5}$$

By the inspection of equation (5), we find that the time response is exponential with the electrical thermal time constant of

$$\tau_e=\frac{C}{G-\alpha i^2R} \tag{6}$$

Let τ_e called as a *thermo-electrical time constant*, which is a dominant factor in the exponential change of the metallic resistive bolometer having a positive temperature coefficient of resistance, and we will show it through several electrical experiments in section 5.

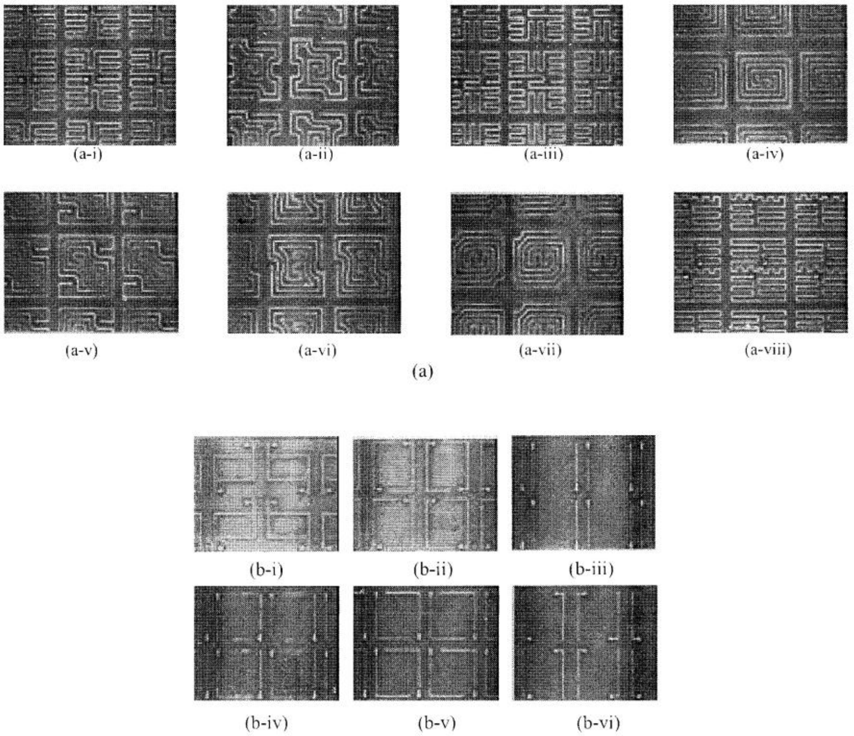
4. DESIGN AND FABRICATION OF THE PROPOSED STRUCTURE

We have chosen silicon dioxide thin-film as a membrane layer that should support the fabricated structure and minimize the heat conduction between the bolometric absorber and a substrate. Silicon dioxide is a suitable material since it has very low heat-conductivity that is about eight times as low as silicon nitride, well-known as a membrane material, and, if well handled, maintains the stiffness enough to support the surface-micro-machining structure. What is better is that we are able to deposit the film in the low temperature process under 200°C, which is a strong point in CMOS-based fabrication since CMOS layer comprising the metal lines is easily attacked by the high-temperature process. However, silicon dioxide film has some defects as a membrane material. One of the most hard-to-handle problems is the aging effect; the deformation with time is inspected in the surface-micro-machining structure made of silicon dioxide membrane. It may frequently lead to fatal structural failures, such as warpage, curl, and delamination in the multi-layer thin-film plate or cantilever structure.

We have experienced the phenomena; the maximum deflection of the cantilevered legs of about 50 μm long and 0.5 μm thick is not less than 8 μm for 20days and 50 $\mu m\times 50\ \mu m$ squared absorber is deformed into severely warping shape. We have solved this problem by the annealing method, which easily gave the structural stabilization without any layout modification; the maximum deflection of the cantilever, we inspected, was to be less than about 0.8 μm.

The configuration design is another point for the robust and stable structure of the proposed bolometer, which covers, particularly, the determination of the post location of the bolometric absorber, the serpentine patterns of titanium sandwiched with silicon dioxide films, and the configuration of the leg part comprising a pair of anchors and cantilevers. The structural simulation tools have been recently developed for these purposes. However, the uses of them are restricted within some limitations; first, the mechanics of the relationship between the stresses and the deformation is clarified in each of the thin films, and the interactive relation, between the layers, and second, the repeatability in fabrication process is achieved. It is very difficult to prospect the expected configuration with the changes of the structural design in the multi-layered thin-film micro-machining process. It is because all of the layers used in the proposed surface-micro-machining process have experienced the various temperature processes, the stress unbalancing in the direction of thickness or length, and tensile or compressive effects from upper or lower layers.

In the present structural design, we have used the symmetry of structure in the direction of thickness for the mitigation of stress unbalancing between the layers, which is adapted to the sandwiched membrane made of silicon dioxide layer. In addition, we have used various test models as shown in Figure 3(a), so as to determine of the location of posts and the serpentine pattern of titanium layer in the absorber part, since they has been inspected to have a great effect on the deformation of absorber part. Figure 3(b) shows the various test patterns of leg part considering the anchor design and the figures of cantilevers.


(a-i) (a-ii) (a-iii) (a-iv)

(a-v) (a-vi) (a-vii) (a-viii)

(a)

(b-i) (b-ii) (b-iii)

(b-iv) (b-v) (b-vi)

Figure 3 Various test patterns for the design of the three-level bolometer (a) Absorber design patterns (b) Cantilever design patterns.

The Figure 4 shows a SEM picture of the conventional two-level structure, which was constructed by using the same materials of membrane and bolometer layer and the same scales of the main parts such as leg thickness, width, and pixel size, as the proposed bolometer pixel. It is evaluated by several electrothermal experiments in section 5, compared to the proposed three-level bolometer pixel. Through the tests of the above structural models in Figure 3, we have achieved an optimized electro-thermal model as shown in Figure 5. The result shows that the center of the absorber is a preferable position as the location of the posts. The serpentine pattern as shown in Figure 3(a-i) is the best, and the leg design is modified as shown in Figure 5(a), the feature of which structure is to connect the ends of both of bridges so as to reduce the curl effect of the cantilever-type bridges shown in Figure 3(b). Figure 5(b) shows a top-view of the proposed three-level, where no bridges and no anchors are inspected; we can easily find form the picture that the fill factor is increased compared to the bolometer shown in Figure 4.

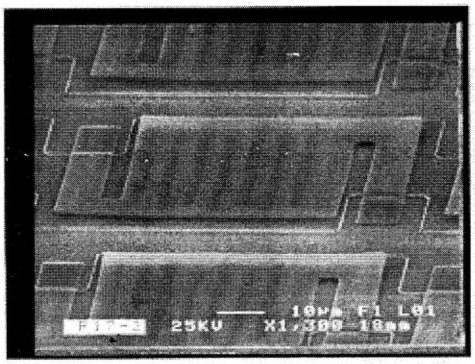
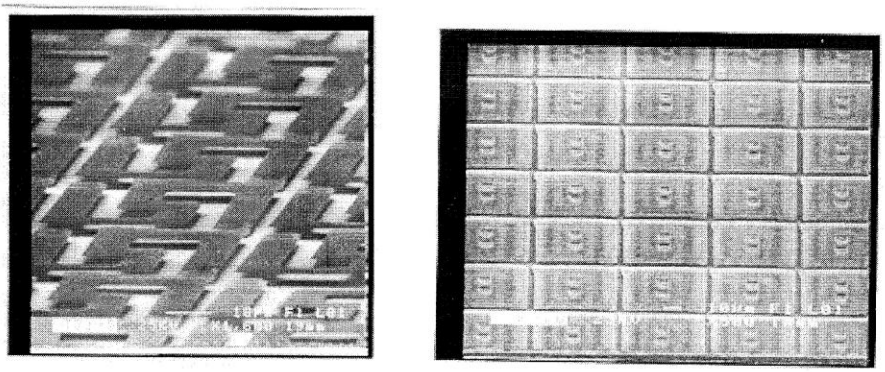


Figure 4 A SEM picture of the conventional two-level titanium bolometer by using silicon dioxide membrane.



(a)

(b)

Figure 5 SEM pictures of the proposed three-level structure. (a) Leg portion, (b) Absorber array.

5. ELECTROTHERMAL PERFORMANCE OF THE PROPOSED BOLOMETER

Figure 6 shows the resistance change of 50nm-thick titanium resistors corresponding to the change of temperature using the hot plate of a probe station, which indicate that the resistive changes of the sputtering titanium thin-film are linear with temperature changes in the range of bolometer operational environment. The value of TCR measured in the test is 0.26%/K.

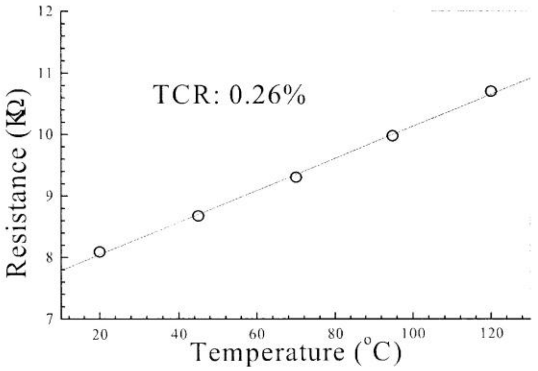


Figure 6 TCR measurement of 50nm-thick titanium film.

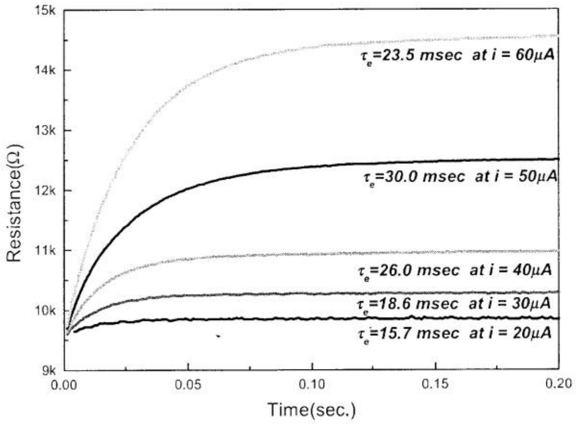


Figure 7 Thermal time constants measured by using various bias currents.

Based on the method in Reference 1, thermal conductance, G measured in vacuum at the pressure of $2mTorr$ is 1.28×10^{-7} W/K, which is relativley a rational value comapared to the commercialized products. As shown in Figure 7, transient resistance changes have been plotted varying the bias current values from 20μA to 60μA, in which we extracted the *thermo-*

electrical time constants corresponding to each of the bias currents. The results show that the *thermo-electrical time* [2]*constant* increases proportional to the quantities of the bias currents, which is consistent to the results expected in the equation (6). Thus, in the metallic bolometric detector, the transient changes of the resistance exponentially increase in terms of the *thermo-electrical time constant* τ_e of the equation (6), not the thermal time constant τ .

The τ_e is also derived from the bandwidth of the output voltage as a function of the modulation frequency of an infrared chopper, which, in Figure 8, is tested using the bias current of 20μA in the range of chopper frequency from 2Hz to 25Hz. As shown in the figure, the result shows that the obtained values of output signal are in accordance with the theoretical values. The estimated value of τ_e in the test is 15.8 *msec*, which is almost the same value as the result extracted from the experiment of Figure 7

Figure 9 shows the responsivities corresponding to each of the varied bias currents, in which the responsivity is proportional to the values of bias currents. As shown in the figure, the responsivity of the proposed bolometric detector is about 9000V/W with the bias current of 70μA. But, the two-level bolometer pixel shown in Figure 4 gave the heat conductance of 4.7E-7W/K and the responsivity of 1700 V/W, respectively, which shows that the proposed structure is superior to the two-level conventional model. In addition, we measured the current noise spectral density of a thin film titanium resistor using dynamic signal analyzer and a low noise transimpedence amplifier[2]. The value of rms noise voltage is 4.04μV, and assuming 64kHz bandwidth and 1mA bias current, a detectivity D* of 2.4E+9 $cm\sqrt{Hz}/W$ can be achieved.

6. SUMMARY AND CONCLUSION

We have developed a three-level IR bolometer array using the double sacrificial layers, which structural design makes the optical fill-factor of the IR bolometric detector increase up to 92%, and, also, the thermal isolation minimized. Through several tests, the performance of the proposed detector shows that this multi-level bolometer pixel newly designed and fabricated by using the double sacrificial layers performs well as an ideal electrothermal structure for effective collection of IR radiation, further scaling of the pixel size and for the development of highly integrated FPA.

ACKNOWLEDGEMENTS

This work has been carried out as a G7 National Project in KOREA and with the collaboration and assistance of colleagues of all three authors and J. Lee.

REFERENCES

1. Pontus Eriksson, Jan Y. Asdersson, and Goran Stemme, Thermal characterization of surface-micromachining silicon nitride membranes for thermal infrared detector, Journal of microelectromechanical systems, Vol. **6**, No. 1, 1997
2. H.-W. Lee, J.-B. Yoon, E. Yoon, S.-B. Ju, Y.-J. Yong, W. Lee and S.-G. Kim, A high fill-factor using multi-level electrothermal structures, IEDM Tech. Digest, 1999

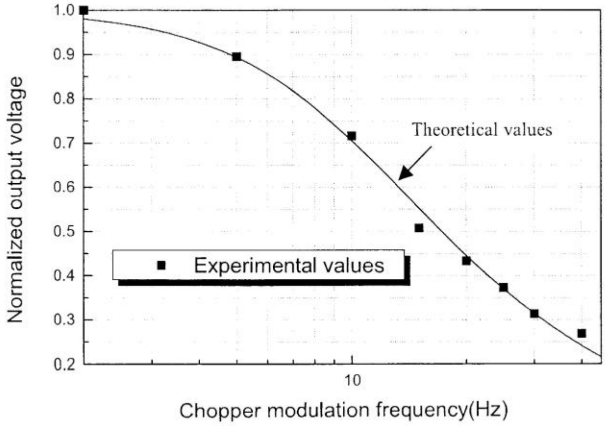


Figure 8 Normalized detector responsivities as a function of chopper modulation frequency.

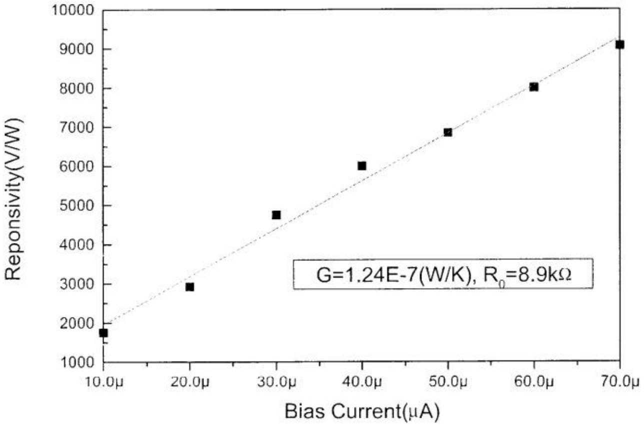


Figure 9 Responsivity changes as a function of the varied bias current.