Characteristics of Surface Micromachined Pyroelectric Infrared Ray Focal Plane Array

Sang-Ouk Ryu, Seong Mok Cho, Kyu-Jeong Choi, Sung-Min Yoon, Nam-Yeal Lee, and Byoung-Gon Yu

Abstract—**We have developed surface micromachined Infrared ray (IR) focal plane array (FPA), in which single SiO_2 layer works as an IR absorbing plate and $Pb(Zr_{0.3}Ti_{0.7})O_3$ thin film served as a thermally sensitive material. There are some advantages of applying SiO_2 layer as an IR absorbing layer. First of all, the SiO_2 has good IR absorbance within 8 ~ 12 μm spectrum range. Measured value showed about 60% absorbance of incident IR spectrum in the range. SiO_2 layer has another important merit when applied to the top of Pt/PZT/Pt stack because it works also as a supporting membrane. Consequently, the IR absorbing layer forms one body with membrane structure, which simplifies the whole MEMS process and gives robustness to the structure.**

Index Terms—**IR absorption, PZT, ferroelctric thin film, pyroelectric, IR focal plane, MEMS process**

I. INTRODUCTION

After Tompsett has made his first proposal for solid state thermal imaging arrays thermal type IR FPA has been investigated for decades. Due to its discrete advantages over cooled type IR detection devices, Uncooled IR imaging devices are under intensive investigation for commercial application. One of the promising market may be driver's vision enhancer (DVE) system [1], which will be realized in the near future if low cost fabrication and large volume production would be possible.

So far the development of uncooled type IR detector has divided into two large categories. One is bolometer type and another is pyroelectric type IR detector. Bolometer type IR detector has been developed for longer period and it has already been commercialized for some applications. The main advantages of bolometer type IR detectors are a compatibility with conventional silicon IC process and no requirement of chopping process when acquiring signal.

However, the bolometer type IR detectors have some drawbacks such as self heating under constant bias, thermal noise, process variation of bolometer materials [2,3]. Pyroelectric type IR detector does require chopping process and the functional materials used in the device are mostly pyroelectric thin films that are not easy to integrate into the conventional silicon process. Despite of all, pyroelectric type detector has many strong points such as an ideal modulation transfer function (MTF), no requirement of thermo-electric cooler to keep constant temperature of detector, fast response, *etc.*

Recently some excellent thermally isolated MEMS design has been carried out regarding pyroelectric type IR detector and FPAs. One of the outstanding results was produced by Raytheon Inc. in 2000, which utilized transparent conducting oxide as top and bottom electrode and the electrode itself works as supporting membrane [4]. To have faster response time against incoming IR radiation it is necessary to have the smallest thermal mass in the MEMS structure. However, when it comes to a large production scale, it maybe extremely difficult to control the quality of QVGA(320x240) FPA and each pixel having MEMS structure like couple of thin layer hung in

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the air as a bridge structure.

In this report, simple SiO_2 layer was chosen as IR absorbing layer. SiO_2 deposited by PECVD is readily available in silicon fab. We designed to let SiO_2 layer have multifunction in the each bridge structured pixels, which means it works not only as an IR absorbing layer but also as a supporting layer and a pixel protection function.

II. THE PROPERTIES OF IR ABSORBING LAYER

1. Black Platinum and Metal Alloy Thin Film as IR Absorbing Layers

Major function of IR absorbing layer is to absorb incoming IR radiation and convert it to thermal energy. Conventionally black platinum is widely used in the IR detection device. The black platinum was deposited on the top layer of IR focal plane using DC magnetron sputter deposition technique. To absorb long wave IR ray effectively, the minimum thickness of black platinum should be more than 500nm. As shown in Fig 1, the thickness of black platinum is directly related to the reflectance and wavelength of incoming IR ray. However, the device with black platinum, especially if it is deposited with such thickness could not efficiently response according to incoming IR energy because of the thermal mass of IR absorbing layer itself. Another important drawback of black platinum absorbing layer is a residual stress release after a sacrificial layer was removed to make bridge structure. Figure 2 shows some of the structural fail after sacrificial layer etching.

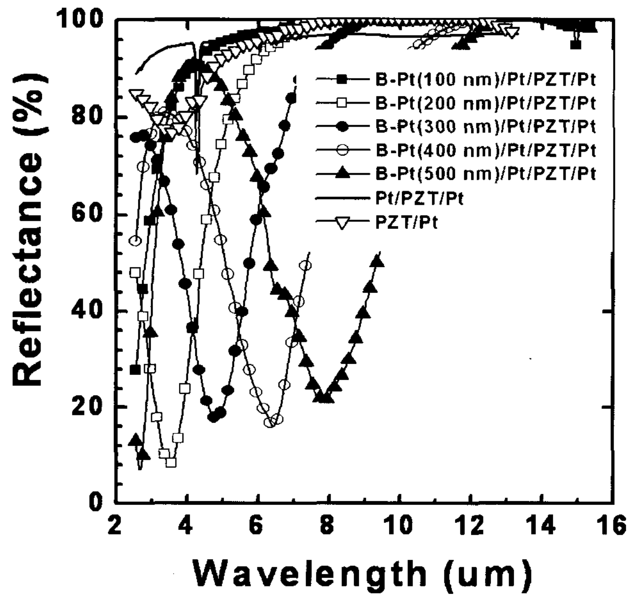


Fig. 1. Characteristics of black platinum IR absorbing layer as a function of wave length

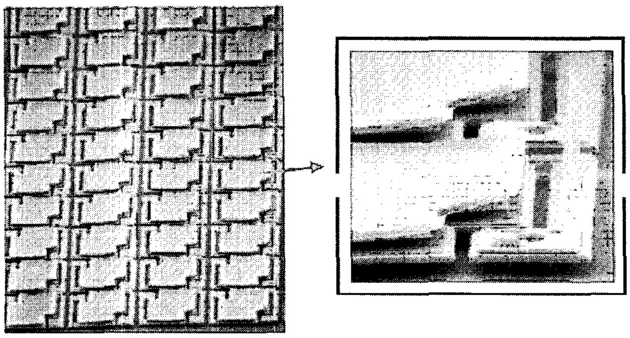


Fig. 2. Example of structural fail due to a residual stress of thick black platinum layer

To avoid thermal mass problems and process complexity discussed above thin metal layer has been studied for more sensitive detectors. Especially nickel and alloy of nickel-chromium films with thickness of about 10-20 nm are particularly appropriate for use as absorber [5]. Recently ferroelectric-conducting oxide thin film structure having resonant cavities with an absorbing bridge element is also intensively researched to further reduce heat capacity of bridge structure [6].

2. SiO_2 Thin Film as an IR Absorbing Layer

For use of SiO_2 film as an IR absorbing layer, basic characteristics were firstly investigated. There are three fundamental vibration bands for the SiO_2 structure in the wavenumber range of 450-1200 cm^{-1}. The first vibration band of SiO_2 is the asymmetric stretching mode observed in the wavenumber range of 1050-1100 cm^{-1}. The second vibration band of SiO_2 is the symmetric stretching or bending mode observed in the wavenumber range of 790-810 cm^{-1} and the third vibration band of SiO_2 is the symmetric oxygen stretching or bending-rock mode observed in the wavenumber range 440-470 cm^{-1} [7,8]. Due to those vibration bands, as shown in Fig. 3, there are abrupt changes of refractive index and extinction coefficient in the wavenumber of IR region, which implies radiation absorption peak in the 8 - 12 μm region.

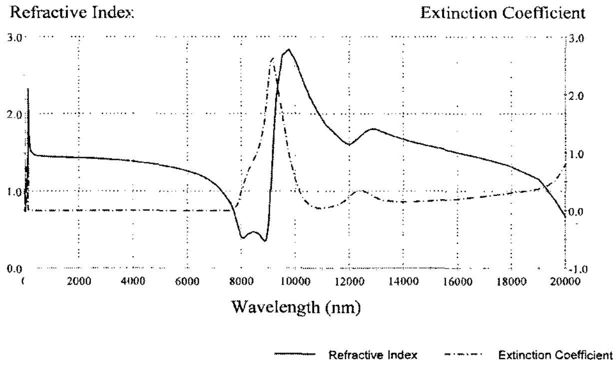
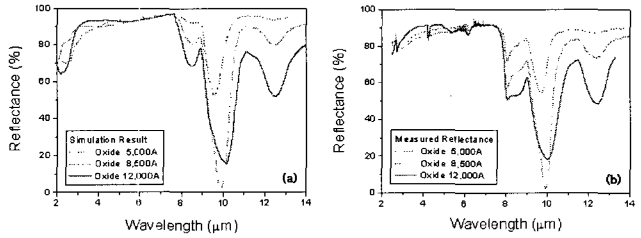


Fig. 3. Optical characteristics of SiO_2 in the IR region



(a) simulated by Maclead 1.0 package

(b) acquired by FTIR analysis in the SiO_2(top layer)/Pt/Pb($Zr_{0.3}Ti_{0.7}$)O_3/Pt/Ti/SiO_2/Si structure

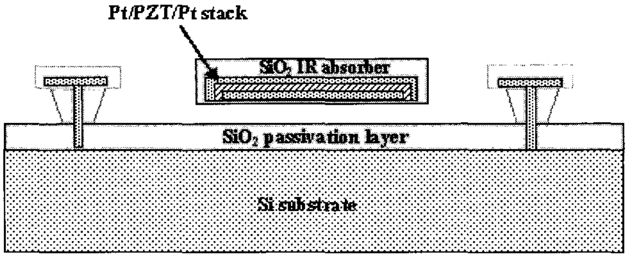
Fig. 4. IR radiation absorbing characteristics of SiO_2 film in the IR region

For use of SiO_2 as an IR absorbing layer, simulational and experimental approaches were also performed. Since FPA of each pixel has a ferroelectic thin film material put between top and bottom electrode we have simulated IR absorbing characteristics of the SiO_2(top layer)/Pt/Pb($Zr_{0.3}Ti_{0.7}$)O_3/Pt/Ti/SiO_2/Si structure. Simulation tool we have used is Macleod 1.0 optical simulation package. For experimental approach SiO_2 layer was deposited on the Pt/Pb($Zr_{0.3}Ti_{0.7}$)O3/Pt/Ti/SiO_2/Si structure by means of PECVD. The thickness of SiO_2 layer was intentionally varied from 500 - 1200 nm. Figure 4 shows the results acquired after simulational and experimental approaches.

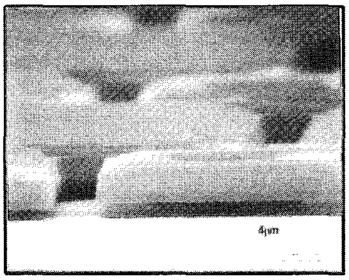
As shown in Fig. 4, both simulational and experimental approaches exhibited similar results. The film showed strong absorption peak at around 10 μm wavelength because of asymmetric stretching mode of SiO_2. The thickness dependence of IR absorbing characteristics is also observed. Because platinum film used as top electrode has thickness of 150 nm the incoming IR radiation is mostly reflected on the upper platinum layer. Therefore the thickness of SiO_2 is solely contributed to the one-quarter wavelength (λ/4) resonance of IR radiation.

III. FABRICATION PROCESS AND EVALUATION OF MONOLITHIC FOCAL PLANES

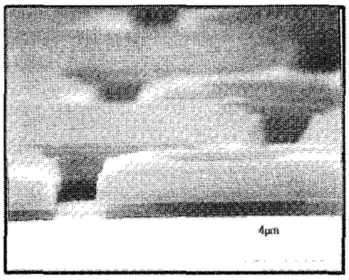
As we have discussed in the introduction chapter, thermally isolated bridge structure is very important to realize fast response and reliable IR detectors. Three main issues to design thermal isolation structure are smallest possible heat capacity, low thermal conductance and robustness. Thermal isolation structure is directly related to thermal time constant (= C/G), which determines response time of the device against incoming IR radiation. In this report we adapted SiO_2 layer as structural material. The advantages of applying SiO_2 as a membrane material were already mentioned in the previous chapter.



(a) cross sectional diagram of IR focal plane



(b) close up image of bridge anchor

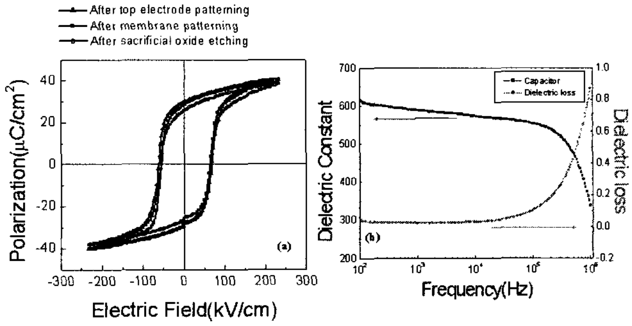


(c) diagonal view of 64x64 IR FPA

Fig. 5. Schematic diagram of MEMS structure and SEM images of thermal isolation bridge structure

Figure 5 shows brief diagram of MEMS structure to accomplish thermal isolation structure. After passivation of readout IC sacrificial layer was deposited on the passivation layer. Selection of sacrificial layer was made based on etch gas and tools. In this process we have chosen a SiO_2 membrane and an amorphous silicon as sacrificial layer therefore, the highest etch selectivity maybe achieved by means of XeF_2 gas etch system. Because pyroelectric/ferroelectric thin film in the device is extremely vulnerable in the strong acid such as hydrofluoric acid, it is not appropriate applying oxide material as sacrificial layer. Selectivity between amorphous/poly silicon and ferroelectric materials in the XeF_2 gas is very high so that even after several cycles of etch process in the XeF_2 chamber the hysterisis characteristics of ferroelectric thin film does not change at all. After applying sacrificial layer thin layer of about 50 nm SiO_2 was deposited to prevent possible silicon -metal electrode reaction during high temperature crystallization process of ferroelectric film. Contact hole to readout IC pad was then opened (in the present process the readout IC was not actually embedded in the silicon wafer). About 150 nm thick platinum electrode(bottom electrode), 400 nm thick PZT thin film and 150 nm thick platinum electrode(top electrode) were sequentially deposited and patterned. About 1000 nm thick SiO_2 layer was deposited by PECVD and patterned on the top of the Pt/PZT/Pt stack. Finally the sacrificial layer was etched to form thermal isolation structure. Figure 5 also shows scanning electron microscopic images of completed IR focal plane arrays (64x64 size). The air gap between top surface of passivation layer and bottom surface of bridge is about 0.8 μm. No significant bending or distortion was observed after final etch process.

The ferroelectric PZT thin film was deposited by means of sol-gel spin coating. The PZT compositional ration of Zr/Ti was selected based on calculated figure of merit, which showed most appropriate for the application to IR detector at Zr/Ti = 30/70 [9]. To check the process reliability the ferroelectric characteristics of the functional material i.e., $Pb(Zr_{0.3}Ti_{0.7})O_3$ thin fim were examined after each process step. Figure 6 presents polarization-voltage hysterisis behavior of $Pb(Zr_{0.3}Ti_{0.7})O_3$ thin fim after some major process steps and typical dielectric response as a function of frequency. There were slight reduction of remanent polarization charge values after sacrificial layer etch, however, well-defined ferroelectric hysterisis behavior was observed throughout the process. The slight reduction of remanent polarization after final etch process is not caused by process damage but by stress relieving of each layers in the bridge structure.



(a) ferroelectric hysterisis behavior measured after some of major process steps

(b) dielectric properties as a function of frequency

Fig. 6. Typical characteristics of ferroelectric $Pb(Zr_{0.3}Ti_{0.7})O_3$ thin fim

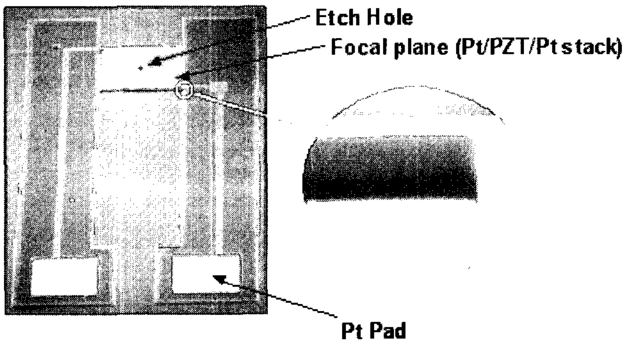
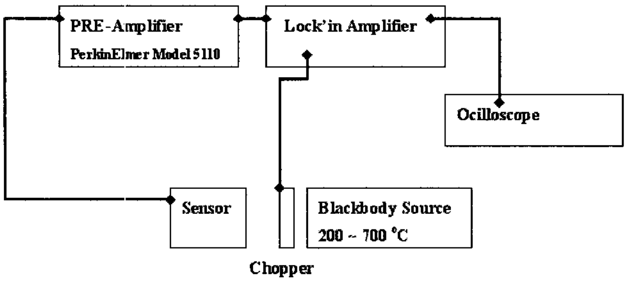


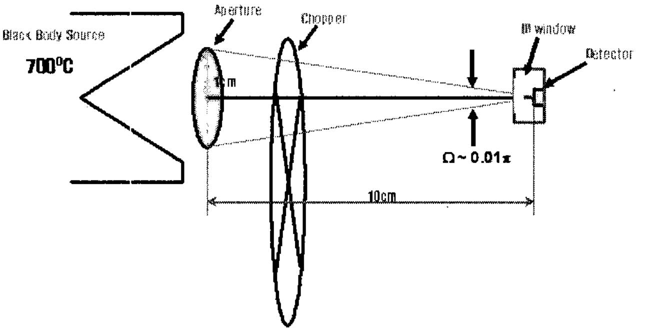
Fig. 7. Specially designed single focal plane to evaluate response characteristics against incoming IR ray

For the evaluation of fabricated FPA, specially designed single focal plane having electrode pad for wire bonding was fabricated and presented in Fig. 7. Area of the focal plane is 100 x 100 μm^2. Firstly, pyroelectric coefficient of the PZT film in the FPA was measured by using HP4156A current meter in the temperature range from 20 ~ 80 °C. Calculated pyroelectric coefficient was about 0.04 $\mu C/cm^2K$. To evaluate direct response against IR radiation the single focal plane in Fig 7 was packaged in a TO5-vacuum housing. The IR transmission filter attached on top of the package is 6.5 μm-cut window made of polysilicon. The finished package was place on the evaluation circuit described in Fig. 8.

Blackbody temperature was varied from 250 ~ 700 °C. Preamplifier gain and lock'in amplifier gain were set to 500dB and 20 dB, respectively. Band width was filtered in the range of 0.03 ~ 3 Hz. Chopping frequency was set to 1Hz.



(a) circuit system



(b) detector and blackbody arrangement

Fig. 8. Schematic diagram of evaluation system

Figure 9 exhibits voltage response of IR detector at 1 Hz chopping frequency as a function of blackbody temperature. Ocillation of voltage was clearly observed in accordance with chopping frequency. In the figure, some phase shift of ocillation frequency was observed as the blackbody temperature is increased. At this moment, it is not clear the phenomena was caused by some problem during data acquisition or thermal time constant of the detector itself because we could not vary chopping frequency of the evaluation system. Measured responsive voltage (rms) and noise spectral density at 700 oC balckbody was 40 ~ 42 mV and 0.2 ~ 0.25 mV/Hz$^{1/2}$, respectively. If we confine IR wave length between 8 ~ 12 μm and assume modulation frequency of incoming IR has square wave the calculated radiation power arriving at detector itself becomes 2.5 x 10^{-3} W/cm^2. Therefore, calcualted detectivity becomes about ~ 10^7 cmHz$^{1/2}$/W according to detectivity(D*) = S/{n x I x (area)$^{1/2}$} where, S is a responsive voltage, n is a noise spectural density and I is a radiation power at detector.

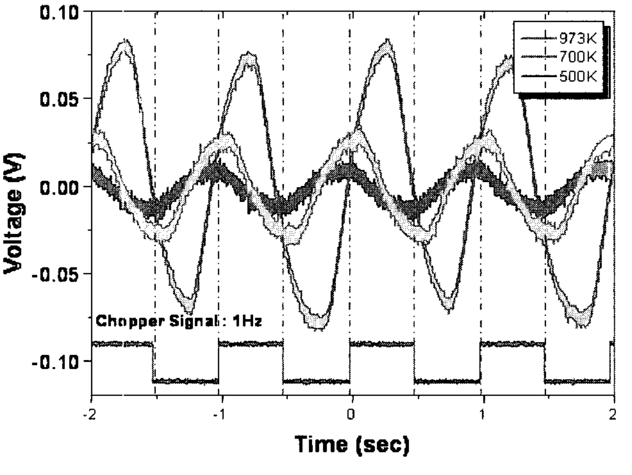


Fig. 9. Voltage response of IR detector at 1 Hz chopping frequency as a function of blackbody temperature

IV. CONCLUSIONS

We successfully fabricated IR FPA utilizing SiO_2 IR absorbing material. Newly designed IR focal plane by applying SiO_2 as an IR absorbing layer exhibit many advantages. The overall structure was simplified due to multifunctional SiO_2 layer, i.e., it works not only as IR absorbing layer but also as supporting membrane. The IR detector showed clear response against IR radiation and the measured detectivity was about ~ 10^7 cmHz$^{1/2}$/W.

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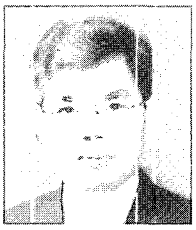

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