Detector pixel in dielectric bolometer mode based on ferroelectric thin film capacitors for uncooled infrared image sensor

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A new type of detector pixel circuit operated in a dielectric bolometer mode for infrared image sensor has been developed. The circuit features that change in dielectric constant against temperature is detected through that in capacitance of ferroelectric thin film capacitor such as BST ($\text{Ba}_{1-x}\text{Sr}_x\text{TiO}_3$). Our proposed circuit is a capacitor-capacitor serially connected circuit, where at least one capacitor is composed from a BST ferroelectric thin film. In PSPICE circuit simulations, it is found that when a relative capacitance change in the BST ferroelectric capacitor, which beginning value is 0.10nF, of the detector circuit is 1%, the output level is about 25 mV. After evaluating the assembled above circuit on board with a BST thin film capacitor fabricated on a Si membrane structure, we confirmed that the relationship between the output voltage level and capacitance change in the BST thin film in the assembled circuit agrees well with that in the corresponded simulation results.

Keywords: dielectric bolometer mode, detector pixel, ferroelectric thin film, infrared image sensor

1. Introduction

Recently, Uncooled Focal Plane Arrays (UFPAs) gathers much attention because thermal imaging can be realized easily and show a wide market of great potential [1,2]. Quite recently, UFPAs based on resistive bolometer has been developed and are becoming commercially available [3,4]. But it is known that pyroelectric sensor or dielectric bolometer using ferroelectric material shows higher responsivity than that of the resistive bolometer. So, these kinds of sensors are expected to be applied for the fabrication of UFPAs. Temperature dependence of either polarization or relative permittivity for ferroelectrics can be used for the thermal sensors. The former effect is referred to the traditional pyroelectric (PE) sensor and the latter one is for dielectric bolometer (DB). In DB mode the dielectric constant (ϵ) change against temperature (T) is sensed through the capacitance change in the ferroelectric thin film of relaxor material such as $\text{Ba}_{1-x}\text{Sr}_x\text{TiO}_3$ (barium strontium titanate, BST).

In order to establish UFPAs in dielectric bolometer mode based on ferroelectric thin film capacitors with high sensitivity and high resolution, we have been developing thermal image sensor with isolated structure, BST ferroelectric thin film and processing circuit.

In this paper, we discuss the thermal isolated membrane structure fabricated by Si bulk micromachining process and BST ferroelectric thin films by Pulsed Laser Ablation Deposition (PLD). The supported structure and ferroelectric thin film characteristics were optimized for obtaining a large temperature change in the detector pixel. We also describe the new signal

processing circuit evaluated by PSPICE simulation, and show the experimental results of our measurements by using this sensing circuit for operation in dielectric bolometer mode.

2. Device Structure and Preparation

To promote Super-Eye Image Sensor (SEIS) project, the following technical items are in progress.

- 1) Development of Si-micromachined device structures for the pixel, including thermal insulation design and process techniques for fabricating the structures.
- 2) Development of ferroelectric materials with PLD for use in the dielectric bolometer, where large $d\epsilon/dT$ is required at external temperature.
- 3) Design of circuits and pixels for the dielectric bolometer-type FPAs.
- 4) Development of an integrated process leading to fabricating the UFPAs, in which MOSFETs, thermal-isolated mechanical structure, and the pixels with their control circuits and amplifiers are combined together.

2.1 Membrane Structure of Detector Pixel It is needed to develop thermal-insulated structure for the detector pixel by using simple Si-micromachining process with high reliability in thermal types of infrared sensors. The structure of sensing area usually requires a suspended membrane or bridge structure in order to improve their thermal isolation and obtain a large temperature rise in the detector pixel upon IR irradiation. A cross-sectional view of our detector pixel part is shown in Fig. 1.

Fig. 1. A cross-sectional view of our detector pixel part

After fabricating MOSFET circuit arrays, Si(110) wafer was etched from the back side and the membrane structure with the vertical side wall was fabricated. Then the electrodes and ferroelectric thin film were deposited at low temperature.

Figure 2(a) shows the cross-sectional view of the sensing area, etched at 90°C with TMAH (22wt% tetramethyl ammonium hydroxide) etchant. High aspect ratio was achieved in etched shape using Si(110) wafer. However, p⁺-Si layer could hardly work as an etch-stop layer against the etching solution. Thus the etching was stopped after 3-hours. Figure 2(b) shows the SEM photographs of surface area with 2-points-suspended arms and 4-points-suspended arms, respectively. The precise patterns without strain can be manufactured by means of Si bulk micromachining technology.

Fig. 2. SEM photographs of the microstructure in the sensing area

2.2 Temperature Change in Detector Pixel It is important to simulate the temperature increase in sensing area in order to evaluate the magnitude of output signal and design the signal processing circuit. The temperature increase in sensing area of several kinds of structures and materials was simulated by using thermal analysis simulator ANSYS (ANSYS Inc.), as shown in Fig. 3. The whole area of the sensor is irradiated homogeneously. In this figure, the pattern is a membrane with 4-points-suspended arms. Thermal energy diffuses into Si substrate through suspended arms of the membrane. Therefore, it is effective to enhance temperature increase^① by using membrane materials with a small thermal conductivity, and ^② by reducing the number of long and narrow suspensions.

Optimum microstructure based on the thermal simulation was fabricated by Si anisotropic etching, as shown in Fig. 2.

Fig. 3. Simulated thermal distribution on the floating membrane (material of membrane : Si, atmosphere : in air)

A temperature increase in a detector pixel by He-Ne laser illumination (388mW/cm² on a detector pixel) to its surface was measured by a "thermo-micro", which is a microscope with a cooling type of infrared detector, as shown in Fig. 4. A temperature increase of about 1.4°C was observed in the sensing area with 2 suspensions, which was consistent with our thermal simulation results.

Fig. 4. Measured thermal distribution on the floating membrane (material of membrane : Si, atmosphere : in air)

2.3 Characteristics of Ferroelectric Thin Film Ferroelectric BST with perovskite structure possess large temperature coefficient of dielectric constant around their Curie temperature (T_c) and the T_c can be continuously shifted from 0°C to 70°C by controlling the Ba/Sr ratio. In addition, it

exhibits characteristic features of diffuse phase transition, *i.e.*, the ferroelectric phase transition takes place in a relatively wide temperature range near T_c with a very high-and-sharp dielectric peak. The high value in dielectric constant is essentially important in highly integrated small element (say $50\text{ }\mu\text{m}$ square) pyroelectric array sensors and provides good capacitance match to the preamplifiers.

It is also important to develop ferroelectric thin film for use in the dielectric bolometer, where a large $d\epsilon/dT$ is required at room temperature. BST films were fabricated by PLD method as species evaporated by strong laser beam are highly excited and the thin films can be prepared at low temperature, which is needed not to damage the substrate. Crack-free and highly oriented films were successfully prepared on the $\text{Pt/Ti/SiO}_2/\text{Si}(110)$ substrates in different gas ambient. The crystallinity of these films was examined by XRD (X-ray diffraction) analysis. Electrical properties such as leakage characteristics, ferroelectric hysteresis loops, and capacitance-temperature dependence were characterized and analyzed.

Abrupt change in dielectric constant near room temperature was achieved in the BST films, which is expected to be employed in infrared sensor of dielectric mode superior to that of pyroelectric mode. BST thin films were deposited on $\text{Pt/Ti/SiO}_2/\text{Si}(110)$ substrate above 450°C in O_2 gas of pressure about 0.1 Torr . N_2O gas instead of O_2 gas improved the crystallinity of BST thin films because of highly chemical activity due to ultraviolet irradiation of ArF laser. X-ray diffraction pattern of the film has large peaks of (100), (110), and (112) planes. Temperature dependence of dielectric constant of the $\text{Ba}_{1-x}\text{Sr}_x\text{TiO}_3$ thin films shows a sharp change having a peak around room temperature, as shown in Fig. 5.

Fig. 5. Dielectric constant vs. temperature of BST thin films ($T_s=500^\circ\text{C}$, 0.1 Torr)

Peak exists below 25°C in the film of $x=0.5$, and shifts to above 50°C in the film of $x=0.17$. In the film of $x=0.33$, the peak point exists near 27°C and the peak is very sharp. The differential dielectric constant against temperature is the largest in the film of $x=0.33$ among them and is about $100/\text{K}$. This value is equivalent to a pyroelectric coefficient of 1.8×10^{-7}

$\text{C}/\text{cm}^2\text{K}$ in the film of thickness $0.5\text{ }\mu\text{m}$, capacitance area $8 \times 10^{-4}\text{ cm}^2$ and bias field $20\text{ kV}/\text{cm}$, and is almost same as that of LiTaO_3 crystal.

Dielectric constant of the BST film, which is about 450 at 25°C , changes by nearly 1 to $10\%/K$ in ambient temperature. The maximum change is as large as about $100/K$, and more than about $10\%/K$ relative change in the dielectric constant or the corresponding capacitance has been induced. This means more than about $10\%/K$ relative change in the dielectric constant or the corresponded capacitance has occurred.

3. Analysis of Infrared Response

3.1 Circuit Design The circuits have been designed for newly fabricated dielectric bolometer pixels. The principle of our proposed circuit is based on an intrinsic characteristic of BST ferroelectric material. A main operation principle in the dielectric bolometer-type detector is as follows, 1) when temperature of ferroelectric material in the detector pixel is increased, its dielectric constant changes and therefore its capacitance becomes changed, 2) the change in the capacitance is detected as voltage change, which is amplified through some operational amplifiers.

As for capacitor sensors, several types of basic circuits such as capacitor-capacitor bridge, resistor-capacitor bridge, and those without reference circuit part have been considered. These basic pixel circuits have been simulated including X-Y addressing switch MOSFET's by using PSPICE. Figure 6 shows one example of the detector pixel circuits for simulations; capacitor-capacitor serially connected circuit for a detector pixel.

Fig. 6. One example of detector pixel circuits for PSPICE simulations

Layout patterns have been designed for the above basic pixel circuits and resultant 4×4 focal plane arrays. Especially the pixel structure shown in Fig. 6 is a simple configuration, and then is very effective in reducing their pixel size and then increasing the pixel density. In our first stage the control circuit such as X-Y selector or the operational amplifiers are not monolithically integrated. First of all, it is needed to confirm the operation in the basic pixel circuit and the possibility of two-dimensional operations. The ferroelectric capacitor size is about

150 μm square, and the cell size is between about 250 μm square to 500 μm square, where our minimum interconnection design rule is 10 μm line and 15 μm space.

3.2 Simulation Results By considering the substrate resistance and implantation dose, the MOSFET characteristics were evaluated. From major results in the FET characteristics, the measured data have been used for PSPICE parameters. The proposed circuits have their own merits and demerits such as output voltage, the number of components and cell size. Figure 7 shows the simulation results of the detector pixel circuit, as shown in Fig. 6. In PSPICE circuit simulations, it is found that when a relative capacitance change in the capacitor of about 0.1nF is 1%, the output level is as large as 25mV, which is large enough to be input into commercially available operational amplifiers.

Fig. 7. Simulated output of the detector pixel circuit, as shown in Fig. 6, with different $\Delta C/C$

4. Experimental Results of Infrared Response

The pixel arrays, its control circuit and operational amplifiers have been developed by combining both MOSFET process and the micromachined process. In our first stage, however, n-MOSFET process is used because the FET is confirmed to be reproduced through several times of process flow. Thereafter FPAs, its control circuits and operational amplifiers can be monolithically integrated.

Figure 8 shows the output voltage waveform in the detector pixel circuit fabricated as mentioned above. The fabricated membrane consists of Pt/BST(500nm)/Pt(160nm)/SiO₂(1 μm)/Si multilayer, shows size of 500 $\mu\text{m} \times 500 \mu\text{m}$, and is supported by 2 arms. As a result of on board evaluation of the assembled circuit with a source-follower output, it is found that when a relative capacitance change of the pixel is about 3%, the output level is about 40mV. It is considered that the circuit has enough output signal level for input of conventional operational amplifier. It is confirmed that the relationship between the output voltage and capacitance change in the BST film in the assembled circuit agrees well with that in the corresponded simulation results.

Fig. 8. Output voltage waveform in the detector pixel circuit

5. Conclusions

Infrared detector pixel operated in dielectric bolometer mode based on ferroelectric thin film capacitors has been developed for uncooled infrared image sensor. The thermal isolated structure was optimized defining the anisotropic etching in Si bulk micromachining process, and the temperature change can be increased. The change of dielectric constant and dielectric peak position are dependent on the Ba/Sr ratio in BST thin film corresponding to ferroelectric thin film characteristics. The proposed circuit, capacitor-capacitor serially connected circuit, where at least one capacitor is composed from a BST ferroelectric thin film was evaluated by PSPICE simulation. When a relative capacitance change in the BST ferroelectric capacitor of the detector circuit is 1%, the output level was about 25mV. After evaluating the assembled above circuit on board with a BST thin film capacitor fabricated on a Si membrane structure, it is confirmed that the relationship between the output level and capacitance change in the BST thin film in the assembled circuit agrees well with that in the corresponded simulation results.

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