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Preparation and behavior of infrared focal plane linear array using composite ferroelectric film

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Abstract

2×64 focal plane linear array for room temperature infrared imaging detection using composite ferroelectric thin film has been successfully prepared by sol–gel process. Structure and preparation of the linear array detectors are presented. The size of the sensing element of the array is $80\ \mu m \times 80\ \mu m$ with a pitch of $100\ \mu m$. The normalized detectivity of the sensing element is about $1 \times 10^8\ cm\ Hz^{1/2}/W$ which is close to the requirement of practical application.

Keywords: Ferroelectric film; Infrared image; Focal plane array

1. Introduction

Room temperature infrared imaging using focal plane array is getting increasingly interest both in military and in civilian applications. High detectivity and high quality infrared image can be obtained using photon detector array of narrow band gap semiconductor crystals such as $TeCd_{1-x}Hg_x$. However, infrared photon detector has to work under low temperatures. Refrigeration accessories make the imaging device very bulky and expensive. Only high-end military applications can afford to use such photon detector array. Inexpensive and portable infrared imaging devices working under room temperatures are of great needs. There are two major routes to achieve room temperature infrared imaging, bolometer detector array using oxide semiconductor such as VO_x [1] and pyroelectric detector array using ferroelectrics such as (Ba,Sr) TiO_3 (BST) or $Pb(Zr,Ti)O_3$ (PZT) [2]. Adopting the technological achievements of CCD and CMOS video camera of visible light, the infrared bolometer imaging device has got great success and is now already available on the market. However, the device is still expensive and its detectivity is not high enough. Pyroelectric detector array has many advantages, such as broadband detection covering the whole range of near infrared to far infrared, high detectivity, very simple circuitry and very low power consumption, which enable the fabrication of very inexpensive and highly portable infrared imaging device possible.

Both bolometer detection and pyroelectric detection are based on the thermal effect of the infrared radiation. The infrared radiation collected by the imaging device is extremely weak. In order to get the utmost from the infrared radiation, the sensitivity of the detector as well as the thermal effect of the detector should be as high as possible. In the light of the later, the thermal effect of the infrared radiation may be a temperature variation, in the case of bolometer detection, or a temperature variation rate, in the case of a pyroelectric detector. To maximize the temperature variation or temperature variation rate, the thermal mass of the detector and the thermal dissipation from the detector should be as low as possible. To prevent the loss of heat absorbed by the detector and create highest temperature variation or temperature variation rate, the thermal isolation structure of the detector element is of most importance.

Air-gap and air-bridge thermal isolation structures are widely used in the silicon-based infrared imaging devices [3]. A novel thermal isolation structure for the room temperature infrared imaging device has been proposed and patented by us using a porous silica thermal insulation layer

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to prevent the thermal dissipation from the detector [4]. Based on this new thermal structure, a 2×64 linear array of pyroelectric detector using composite ferroelectric film has been successfully fabricated. The structure and fabrication and the behaviors of the linear array will be presented and discussed in this article.

2. Structure and preparation of composite ferroelectric film

Fig. 1 is the schematic structure of the composite ferroelectric film. A porous silica layer in the thickness of 2–3 μm was deployed on a silicon substrate by spin coating using a silica sol precursor. The sol precursor was synthesized from tetraethyl orthosilicate (TEOS) using H_2O and $C_3H_5(OH)_3$ as solvent and NH_4OH as catalyst. A water soluble polymer as porousifier was added to form the porous structure. After heat treated at 500–550 °C, porous silica film can be obtained. The porousity of the film is about 40–60 vol.%, and can be controlled by processing conditions. Fig. 2(a) illustrates the 3D image of atomic force microscopy of the porous structure. The porous structure is quite evident from the figure. The roughness of the surface is about 7.5 nm (RMS), The detail of the processing will be given elsewhere [4].

In order to reduce the roughness of the porous silica surface and to improve the behaviors of the successively deposited bottom electrode and the ferroelectric layer, a dense silica buffer layer in the thickness of 200 nm was applied on top of the porous layer. The buffer layer was also spin coated using silica gel precursor, however, no polymer porousifier was added. The porousity of the buffer layer is about 5 vol.%. Fig. 2(b) is the 3D surface imaging of the buffer layer on top of the porous layer. The roughness of the surface is about 3.2 nm (RMS), which was much improved in comparison with the porous layer.

A thin platinum (Pt) layer in the thickness of 60 nm with titanium (Ti) as an interfacial layer to improve the adhesion of the Pt and the buffer layer was used as the bottom electrode of the detector and was applied on top of the buffer layer using dc sputtering. The patterning of the bottom Pt electrode will be discussed in the next section. Then

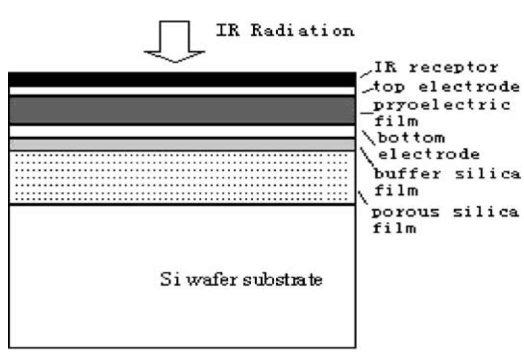
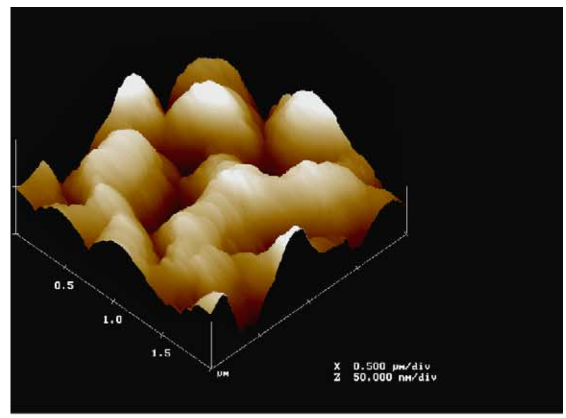
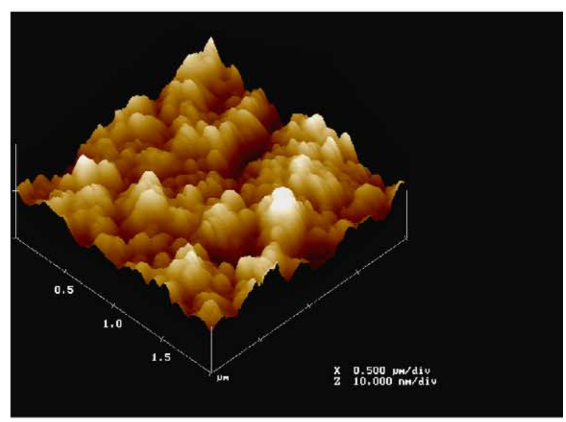


Fig. 1. Schematic structure of composite ferroelectric film.

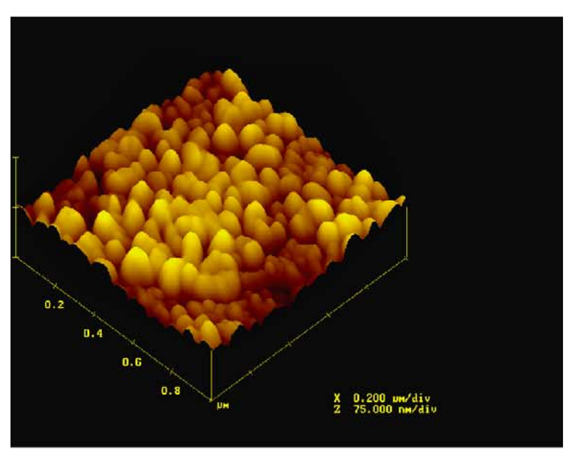
a $PbTiO_3$ (PT) ferroelectric layer in the thickness of 600 nm was deposited by six to eight times of successive spin coating. Using a PT sol precursor of 0.5 mol concentration, the thickness of each spin coated film is about 80–100 nm. After each coating, the film was heat treated at 400 °C in air to remove the solvent and to burn out all the organic species of the sol precursor. After the last coating, the films were annealed at 550–600 °C for 30 min to transform the amor-



(a)



(b)



(b)

Fig. 2. 3D atomic force image of (a) porous silica layer, (b) buffer silica layer, and (c) ferroelectric layer.

phous structure to a perovskite crystalline structure. Thus, a composite ferroelectric film for the application of pyroelectric detector and infrared focal plane array obtained.

3. Structure and preparation of infrared focal plane linear array

A 2 × 64 linear detector array has been designed and fabricated as shown in Fig. 3. The upper and lower square dotes are contact pads of the top electrodes of upper linear array and lower linear array. The middle rectangular shapes are the top electrodes of the detectors. The top electrodes of upper array and lower array are separated from each other. There is a small gap between them, which is not clear shown on the figure. The effective area of each detector (the area of top electrode) is 80 μm × 80 μm with a pitch of 100 μm between adjacent detector components. The total length of the array is 6.4 mm. For the sake of comparison, 2 × 32 linear arrays with 160 μm × 160 μm effective area and 200 μm pitch, and 2 × 16 linear array with 320 μm × 320 μm effective area and 400 μm pitch were fabricated on the same silicon wafer substrate. They have the same total length.

For simplicity, the platinum layer of the composite film can be used as a common bottom electrode for all the detector components of a linear array, which makes the design of the array as well as the interconnection of the detectors simple. However, it is advisable that the bottom electrodes of each detector of the linear array should be electrically interconnected but thermally isolated in order to reduce the cross-talks of the adjacent detector components due to the lateral thermal conduction along the platinum layer. It would be better to use individual rectangular electrode to serve as bottom electrode of each detector components. The patterning of platinum layer is rather difficult. Standard lift-off technology of lithograph can be used to pattern the bottom electrode.

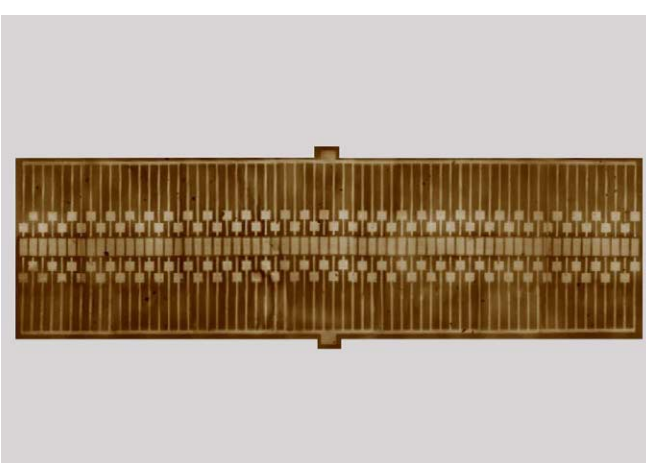


Fig. 3. 2 × 64 linear detector array with 80 μm × 80 μm detector and 100 μm pitch.

Gold (Au) was used as top electrodes and contact pads of the detector array. Normal dc sputtering and lift-off lithograph were used to deposit and pattern the top electrodes. The upper and lower comb-like patterns in Fig. 3 are interconnections of all the top electrodes of the upper and lower arrays, which are used to polarize all the detectors simultaneously. After polarized, the interconnections will be cut off leaving the individual detector components working independently. This is a simple way to polarize the detector components, which avoid polarizing the detector components one by one, however, if any of the detector components broke down during the polarizing process, the polarizing of the whole array would be failed. This imposes high quality and reliability requirements of the ferroelectric film.

To avoid the cross-talk of the adjacent detector components, it is better to cut a grove on the ferroelectric film between two detector components. Lead titanate (PT) and lead zirconate titanate (PZT) can be easily etched by dilute HCl solution. After proper lithograph, dipping the wafer into dilute HCl for only a few seconds is enough to cut a groove on the ferroelectric film. However, the wet etching process is difficult to control and difficult to create a fine and complicate pattern. Dry plasma etching will be better for this purpose. In the present work, no grooves have been cut on the ferroelectric film.

Gold by dc sputtering was used as top electrodes of the detector array. The gold film is a very good infrared reflection medium with very high reflection coefficient. To facilitate the absorption of infrared radiation by the detector components, an infrared absorption layer must be applied on the top electrodes. Gold black is a broad band infrared absorber with high absorption coefficient. In our present work, we failed to use gold black as an absorption medium due to its poor adhesion with the gold electrode and difficulties of patterning. In our present work, conventional Ni–Cr film prepared by vacuum evaporation was used as infrared absorber. The absorption band of the Ni–Cr film very much depends on the thickness of the film. The preparation of the Ni–Cr absorption film of this work has not been optimized. We estimate the absorption efficiency of the film is less then 10%, which strongly degraded the overall performance and detectivity of the detector array prepared in this work.

4. Dielectric and ferroelectric behaviors of the composite film

Fig. 4 is the frequency spectra of dielectric constant and dielectric loss of the composite film taken from the detector component of the linear array. Dielectric constant and dielectric loss of PT composite film are 98 and 0.015 (at 10 kHz) respectively and are fairly stable in the frequency range from 1 kHz to 1 MHz.

Fig. 5 is the current–voltage (I–V) plot of the detector component. The leakage current of the component below 10 V is very small, which testified very good film quality.

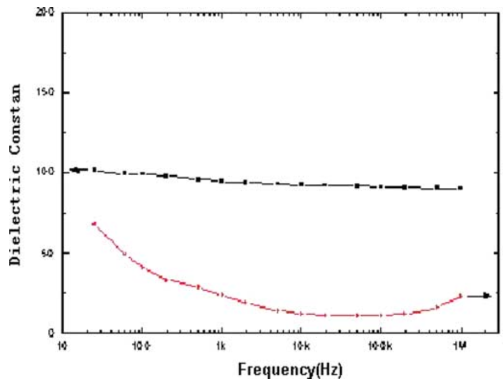


Fig. 4. Frequency spectra of dielectric constant and dielectric loss of PT composite film.

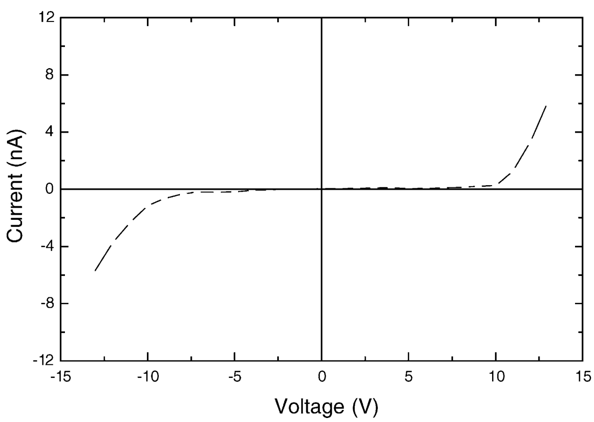


Fig. 5. Current–voltage (*I*–*V*) plot of PT composite film.

The turn-over voltage is about 8–10 V dc. The *I*–*V* curve is roughly symmetrical with positive and negative applied voltage, which means that the interfaces between ferroelectric film and the Pt bottom electrode and the Au top electrode are of ohm contacts.

Fig. 6 is the capacitance–voltage (*C*–*V*) plot of the composite film taken from the detector component of the array. The *C*–*V* plot exhibits very typical ferroelectric butterfly shape. The coercive voltage from the maximum capacitance is 10 V, which is corresponding to a coercive force of 17 V/μm. Fig. 7 is the polarization–electric field (*P*–*E*) ferroelectric hysteresis loop of the film also taken from the detector component. A very good square loop was obtained. The coercive force of the film from this loop is 32 kV/mm or 32 V/μm, which is higher than the coercive force taken from the *C*–*V* curve. The difference of the coercive force taken from *C*–*V* curve and *P*–*E* curve is typical for ferroelectric films. The high coercive force and square hysteresis loop of the PT film are characteristics of lead titanate films. From the experimental results, it can be concluded that the ferroelectric behavior of the PT composite film are very good and the films are well prepared.

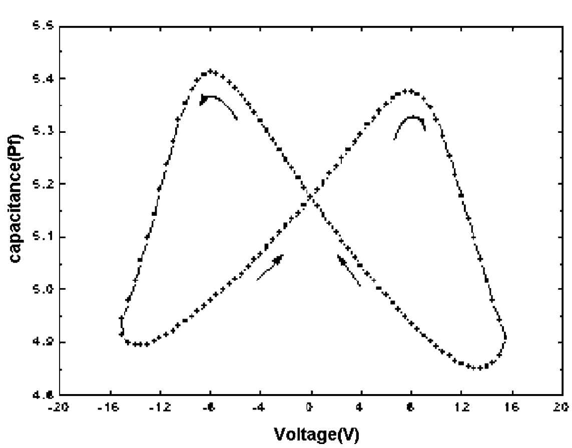


Fig. 6. Capacitance–voltage (*C*–*V*) plot of PT composite film.

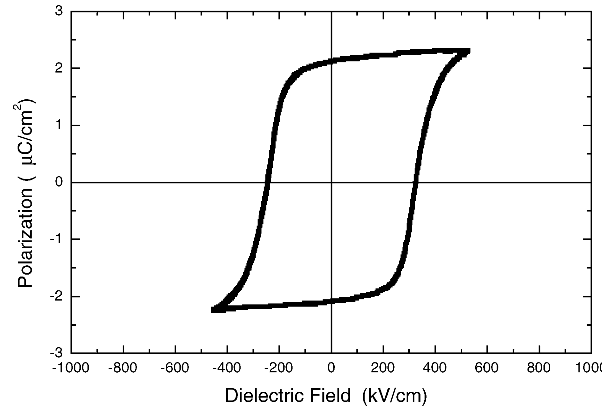


Fig. 7. Ferroelectric hysteresis loop of PT composite film.

5. Pyroelectric detectivity of the composite film detector

Dynamic pyroelectric behaviors of the PT composite film detector were measured by a setup illustrated in Fig. 8. A Black body furnace HFY-100 was used as infrared radiation source. The emissivity of the black body cavity is 0.99.

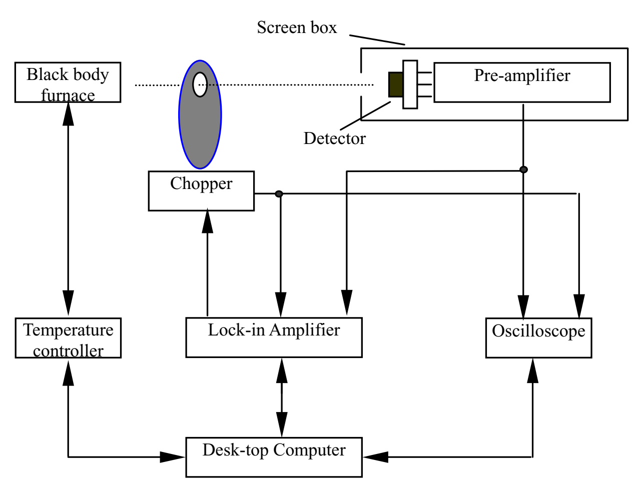


Fig. 8. Measurement setup of dynamic pyroelectric behaviors.

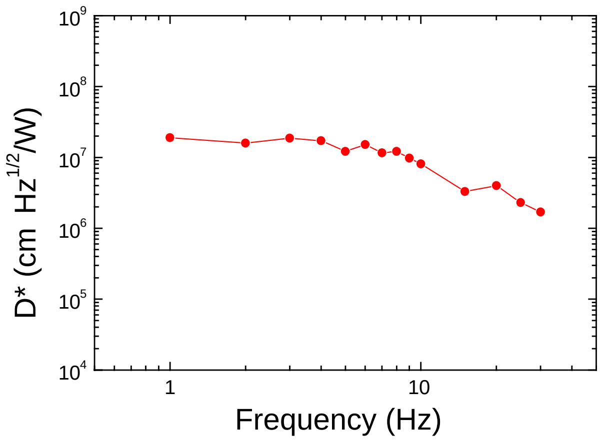


Fig. 9. Normalized pyroelectric detectivity D^* of ferroelectric composite film detector.

The temperature of the furnace was kept at 500 K with 0.1 K resolution. A temperature controller is used to control and maintain the temperature of the furnace. The aperture of the furnace was 10 mm in diameter. The distance between the sample and the furnace was 15 cm. Thus the infrared radiation received by the detector can be calculated. An EG&G 194 chopper was used in the measuring system to create a periodical radiation stimulus, so that the dynamic pyroelectric signal can be measured by a lock-in amplifier. The frequency range of the chopper is 1–3000 Hz, the frequency stability is better than ±0.01%. An EG&G 5302 Lock-in amplifier is used for the measurement of the pyroelectric signal of the composite film detector. The frequency range of the lock-in amplifier is 1 MHz–1 MHz with a measuring range of 1 μV–1 V. The input noise is better than 25 nV/Hz$^{1/2}$ and the common mode rejection is higher than 40 db (50/60 Hz). In the measurement, the bandwidth of the lock-in amplifier was set to 2 Hz. A pre-amplifier using a FET working under common source mode is attached directly adjacent to the detector under test to transform the high impedance of the detector to low impedance in order to match the input impedance of the lock-in amplifier. In order to minimize the system noise, the detector under test and the pre-amplifier were all well shielded and well grounded. The chopping wave form and the pyroelectric signal wave form were monitored by an oscilloscope. The system was controlled by a desk-top computer.

Using the measuring system described above, normalized pyroelectric detectivity D^* can be calculated using the following relation [5]:

$$D^* = \frac{V_S}{PV_N}(A_D\,\Delta f)^{1/2} \quad (1)$$

where V_S is pyroelectric signal voltage measured by the lock-in amplifier when the infrared radiation is on, V_N the system noise voltage when the infrared radiation is off. Δf is the effective band width of the measuring system, A_D the effective area of the detector and P the infrared radiation power received by the detector which can be calculated from the temperature of the black body and the distance between the sample and the black body. Fig. 9 is the frequency dependence of the normalized detectivity D^* of the PT composite film detector measured from the linear array. At frequency of 1 Hz, $D^* = 2.37 \times 10^7$ cm Hz$^{1/2}$/W has been achieved, which is close to the minimum requirement of a room temperature infrared focal plane detector array. Considering the infrared absorption efficiency of our sample is quite low, there will be much room to improve the performance of the detector array further.

6. Conclusion

Composite ferroelectric film has been proved to be suitable for the fabrication of infrared focal plane array. The porous silica layer is very effective to serve as a thermal insulation layer of the pyroelectric film. The pyroelectric detection performance of the composite film structure is similar to that of the microbridge air-gap structure and is close to the minimum requirement of practical application. The processing of the composite film is well compatible to the normal silicon technology and is much simple compared to the process of air-gap microbridge structure, while the composite film as a solid monolithic structure is more robust compared to the air-gap microbridge structure. There is still much room to improve the overall performance of the detector array further.

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