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Computer simulation of temperature field of multilayer pyroelectric thin film IR detector

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Abstract

Multilayer pyroelectric thin film IR detector uses the pyroelectric effect to transform temperature variation to corresponding electrical signal. Large temperature variation rate in pyroelectric film is very important for high response of the pyroelectric thin film IR detector. In this paper, a finite element modeling (FEM) using ANSYS applied to simulate the temperature field of multilayer pyroelectric thin film IR detector. The results show that the porous silica film as a thermal-insulation layer obviously reduced the heat loss due to the conduction of heat from the pyroelectric film to the Si substrate. Temperature variation rate in pyroelectric film with 6 μm porous SiO_2 film is one order of magnitude higher than those without porous silica film. Other factors that influence temperature variation rate in pyroelectric film are also discussed.

Keywords: Pyroelectric thin film IR detector; Finite element modeling; Temperature field; ANSYS; Porous silica film

1. Introduction

Recently, much attention has been paid to multilayer pyroelectric thin film IR detector in many applications such as intruder alarm, sensor for pollution monitoring, gas analysis and hot image detector [1–4]. Acting as uncooled thermal infrared detector, multilayer pyroelectric thin film IR detector has many advantages, such as lower system cost, room-temperature operation, fast and wide spectral response with high sensitivity.

As we all know, dynamic pyroelectric response current of multilayer pyroelectric thin film IR detector can be expressed as:

$$i_{\mathrm{p}} = \eta RA \frac{\mathrm{d}T}{\mathrm{d}t} \quad (1)$$

where η is absorption coefficient of radiation, P the pyroelectric coefficient of pyroelectric thin film, A the detector area, and $\mathrm{d}T/\mathrm{d}t$ the temperature variation rate of pyroelectric film. From Eq. (1), we can see the response current of multilayer pyroelectric thin film IR detectors is in proportion to the temperature variation rate of the pyroelectric film. That is, higher the temperature variation rate in pyroelectric film, higher the response current of multilayer pyroelectric thin film IR detector. So finite element method using ANSYS was performed in order to simulate the temperature field of multilayer pyroelectric thin film IR detector.

2. Fabrication of the multilayer pyroelectric thin film IR detector

Multilayer pyroelectric thin film IR detector was composed of some functional films integrated on Si substrate. The schematic structural and cross-sectional diagram of multilayer pyroelectric thin film IR detector is shown in Fig. 1. The porous silica film acted as thermal-insulation layer, buffer silica film and pyroelectric film (PZT) were spin-coated on Si substrate by sol–gel method. The bottom and top electrodes were fabricated via sputtering, photolithographic and lift-off techniques. The black gold film as absorber of the incident infrared radiation is evaporated on the top electrode.

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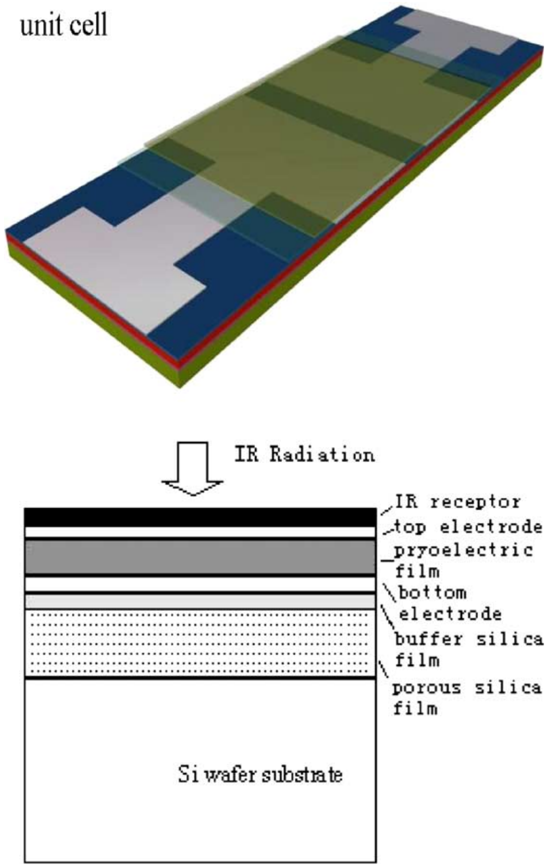

Fig. 1. The schematic structural and cross-sectional diagram of multilayer pyroelectric thin film IR detector.

3. Modeling and simulation

3.1. Finite element model of detector

According to the cross-sectional diagram of the detector shown in Fig. 1, the present finite element model of one unit cell detector was generated in PREP7 module within ANSYS FE program by fellow sequence. Firstly, the geometry model was set up by Plane55 model, which could be used as a plane element or as an axisymmetric ring element with a two-dimensional thermal conduction capability. Secondly, the parameters of various thermal properties of the films given in Table 1 were assigned to corresponding layers. The thermal conductivity of porous silica film was derived from the measurement of ultra-low frequency way [5]. The other thermal properties were assumed to be similar to those of the bulk material values. For modeling, it was assumed that the film properties were isotropic. In order to optimize the design of the detector, some parameters of the films were varied at the simulation stage. Finally, the geometry model was meshed appropriately. The two-dimensional finite element model of detector is shown in Fig. 2.

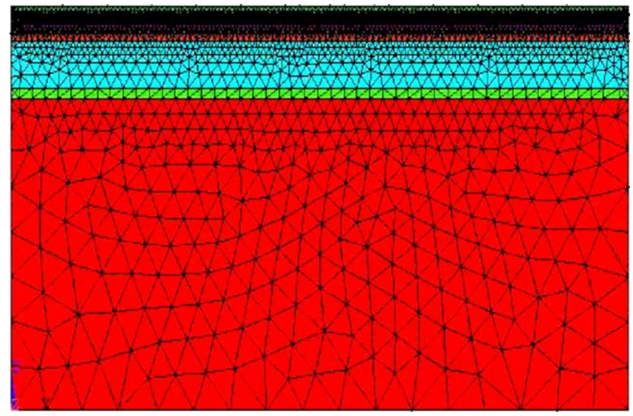

Fig. 2. The two-dimensional finite element model of multilayer pyroelectric thin film IR detector.

3.2. Boundary conditions

According to Eq. (2), the incident radiation power P to the detector is:

$$P = \alpha \frac{\sigma(\varepsilon T^4 - \varepsilon_0 T_0^4)A}{\pi L^2} \tag{2}$$

where α is the modulation factor of chopper, σ the Boltzmann's constant, ε the emissivity of black body, ε_0 the emissivity of chopper, T the temperature of black body, T_0 the ambient temperature (293 K), A the aperture of the diaphragm, and L the distance from the black body to the detector [6]. So, the incident radiation power to the detector by our setup is about 1.228E−12 W μm^{-2}.

Because the detector is usually packed in vacuum, isothermal conditions are applied to the backside of the silicon substrate as boundary conditions.

Table 1
Parameters used in simulation

Material	Thermal conductivity (W m^{-1} K^{-1})	Specific heat (J g^{-1} K^{-1})	Density (g cm^{-3})	Thickness (μm)
Si	145	0.708	2.33	50–400
Porous silica film	0.02	0.78	1.32	0–50
Buffer silica film	1.4	0.70	2.25	0.5
Bottom electrode	71.4	0.133	21.45	0.15
PZT film	2.1	0.36	7.975	1
Top electrode	31.5	0.127	19.3	0.10
Black gold film	2	0.13	0.345	0.5

4. Results and discussion

The transient temperature field in multilayer pyroelectric thin film IR detector upon exposure to 1 s IR irradiation was simulated. Fig. 3 shows the temperature variation rate (d*T*/d*t*) in pyroelectric film with different thickness of porous silica film. As can be seen, the value of d*T*/d*t* in pyroelectric film varies from 1E−08 to 1 s. There is a rapid increase during 1E−08 to 2.5E−07 s. After the maximum peak, the value of d*T*/d*t* in pyroelectric film begins to decrease. In the detector without porous silica as thermal insulator layer, the value of d*T*/d*t* in pyroelectric film sharply decreases and it almost reaches the minimum value at 1E−05 s. It is because the mass of heat flow dissipates at Si substrate with high thermal conductivity. The thickness of porous silica film greatly influences the value of d*T*/d*t* in pyroelectric film. It is obvious that a thicker porous silica film can increase the value of d*T*/d*t* in pyroelectric film in a longer time slice. Compared with thin film detector without porous silica film, the value of d*T*/d*t* in pyroelectric film with 10 μm porous film is much higher during 1E−06 to 0.01 s.

Fig. 4 shows the value of d*T*/d*t* in porous silica film, it can be seen that with thicker porous silica film, the value of d*T*/d*t* in porous silica film decreases and its maximum peak's time moves rightward. This is because, as thickness of porous silica film increases, more heat flow is contribute to increase the value of d*T*/d*t* in pyroelectric film in a longer time slice.

The thermal conductivity of porous silica film could be adjusted by its porosity. So, the influence of thermal conductivity of porous silica film was investigated. Fig. 5 shows that with the decreasing of thermal conductivity of porous silica film, the value of d*T*/d*t* in pyroelectric film greatly improved during 1E−06 to 0.1 s.

It can be seen from Fig. 6 that when the thickness of Si substrate decreases, the value of d*T*/d*t* in pyroelectric film increases during 0.01–1 s. The value of d*T*/d*t* in pyroelectric film with 50 μm Si substrate is seven times that of pyroelec-

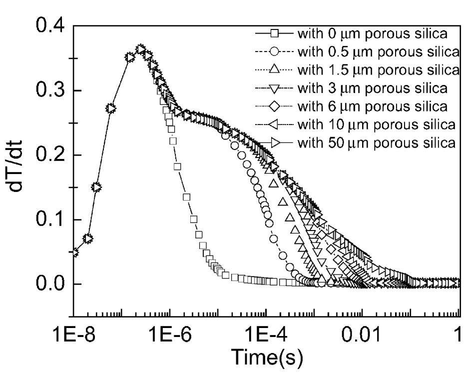

Fig. 3. Temperature variation rate in pyroelectric film as function of time with different thickness of porous silica film.

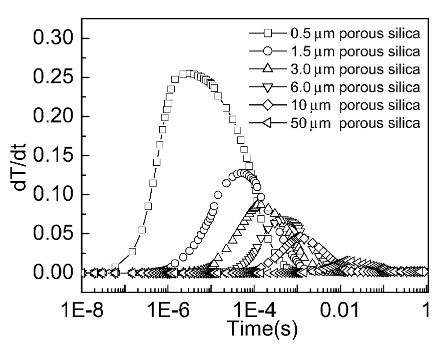

Fig. 4. Temperature variation rate in different thickness of porous silica as function of time.

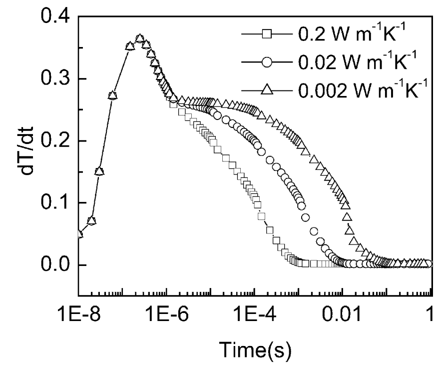

Fig. 5. Temperature variation rate in pyroelectric film as function of time with different thermal conductivity of porous silica film.

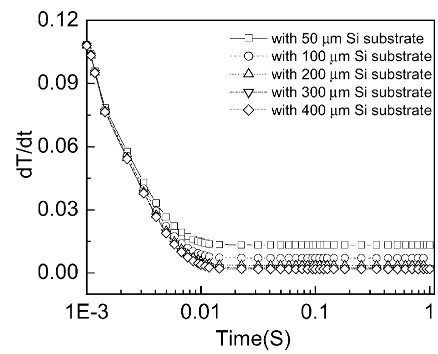

Fig. 6. Temperature variation rate in pyroelectric film as function of time with different thickness of Si substrate.

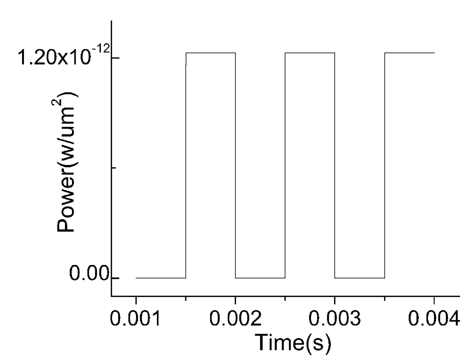

Fig. 7. Waveform of the modulated IR radiation generated by a chopper.

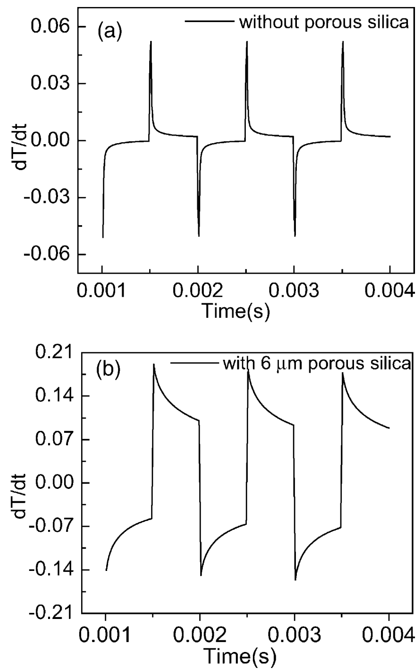

Fig. 8. Temperature variation rate as function of time in pyroelectric film without porous silica film (a) and with 6 μm porous silica film (b) upon exposure to IR irradiation at chopping periodic time 0.001 s.

tric film with 400 μm Si substrate. So in the designing of IR detector, the thickness of Si substrate should be as thin as possible.

The transient temperature field in multilayer pyroelectric thin film IR detector upon exposure to IR irradiation at chopping periodic time 0.001 s was simulated. The effect of porous silica film as thermal-isolation layer was also investigated. Fig. 7 shows waveform of the modulated IR radiation generated by a chopper.

From Fig. 8, it can be seen that exposing IR detector with and without porous silica film to the same chopped IR irradiation, the response value of d*T*/d*t* in pyroelectric film with 6 μm porous silica film is one order of magnitude higher than those without porous silica film.

5. Conclusion

By using a finite element method, temperature field of multilayer pyroelectric thin film detector was simulated. The simulation results proved that the porous silica film obviously reduced the heat loss due to the conduction of heat from the pyroelectric film to the Si substrate. The simulation results also showed that when the thickness of substrate decreases, the response value of d*T*/d*t* in pyroelectric film would be improved, and it was the same to the current response of pyroelectric thin film IR detector. So, a proper match of thickness and thermal conductivity of porous silica film and choosing the thickness of Si substrate would gain greatest benefits in improving the properties of multilayer pyroelectric thin film IR detector.

Acknowledgements

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