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Study of poling methods for multilayer pyroelectric thin film infrared detectors

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Abstract The multilayer pyroelectric thin film infrared detector arrays were prepared by a metallo-organic compound decomposition method. A DC poling and a pulse poling methods have been investigated to reduce the poling time and improve the poling efficiency of pixels of an uncooled infrared focal plane array. It's found that the efficiency of the DC poling increased by 20% via optimizing the poling conditions. While the efficiency of the pulse poling increased by over 31%. Compared with the DC poling, the pulse poling can improve poling efficiency and reduce the poling time significantly. Furthermore, a stepwise pulse field can reduce the breakdown of thin films during poling.

Keywords Field poling · Pyroelectric thin film · Lead titanate · Uncooled infrared detector

1 Introduction

Ferroelectric domains of lead titanate (PT) thin films prepared by a metallo-organic compound decomposition (MOD) method are randomly oriented, resulting in a zero net polarization. To obtain an optimal pyroelectric effect, a poling process is required. This is an important step for pyroelectric devices [1, 2].

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Ideally, a poled PT thin film contains only monodomain grains; the polarization of each grain is perpendicular to the film plane. In reality this is hardly achieved. First of all, most grains will have an unfavorable crystallographic orientation in polycrystalline films, i.e., the polarization direction can't be perpendicular to the substrate plane. This leads to a reduction of total polarization. During poling, when a sufficient high dc electric field is applied to the film with both surfaces coated with metal electrodes, the domains are oriented in the allowable directions closest to the direction of applied field. When the field is removed, the orientation of domains is partially retained, resulting in the film with favorable properties for pyroelectric application. Here we define poling efficiency for the convenience of further discussion. It is given by

$$\eta = \frac{C_{\mathrm{O}} - C_{\mathrm{P}}}{C_{\mathrm{O}}} \qquad (1)$$

where η is the poling efficiency, C_{O} is the sample capacitance before poling, and C_{P} is the sample capacitance after poling.

A DC poling process, as a widely used conventional method, uses a continuous DC voltage applied on two electrodes of a parallel capacitor made by a ferroelectric film at room temperature or elevated temperatures [3–5]. On the other hand, a pulse poling process uses a pulse voltage [5–8].

In this paper, the two poling methods have been investigated and compared. The poling processes for PT thin films have been optimized. Furthermore, a modified pulse poling process in which the pulse amplitude has been gradually increased was also studied to prevent the breakdown of the thin films during the pulse poling.

2 Experimental and discussion

2.1 Deposition of the thin films

Commercially available oxidized silicon wafers were used as substrates. A sol-gel process was used to prepare porous SiO_2 thermal insulating layer and SiO_2 buffer layer [9]. Then Pt/Ti (100/10 nm) bottom electrode was sputtered. PT ferroelectric thin films were prepared by MOD process and annealed in air at 650°C for 60 min. The final thickness of the films was about 600 nm. For electrical measurements, gold top electrodes (450 nm thick) with an area of 0.02–0.03 mm^2 were sputtered. The preparation process is similar to our previous work [10, 11].

2.2 DC poling

Among several poling methods, DC poling method is widely used, especially for single-element detector. We have built a DC poling system which is composed of a HP4192A impedance analyzer, a computer, a temperature controller and a probe station.

The main poling parameters in DC poling method are electric field, time and temperature. Figure 1(a) shows a typical DC poling profile for PT thin films. First, the sample was heated to a set temperature (poling temperature). At the poling temperature, an applied poling voltage was gradually increased to a certain value (poling electric field). Then the poling electric field was held for a period of time (poling time). Finally, the poling electric field was gradually decreased to zero (between the room temperature and 80°C). Figure 1(b) shows time dependence of the capacitance during poling. The results indicate that the dielectric constant of the thin films strongly depend on poling field and poling temperature, as the electric field changes the orientation of domains in the films and the poling temperature makes domain orientation easy. It can be also found that the dielectric constant decreases after poling. This is understandable as the domain density in PT films was decreased after poling. Therefore the poling results can be evaluated by measuring the capacitance of PT thin films.

The poling time of 15 min was found to be enough to get saturated polarization curves. Poling effect can be enhanced by increasing poling electric field. But the breakdown of the film samples sharply increased when the poling electric field exceeded 250 kV/cm. It is well known that increase of the poling temperature is an effective way to improve poling for ceramic materials. At high temperature, the mobility of domains increases and the domains have a better alignment along the poling field direction. On the other hand, the leakage current increases with temperature. The higher the poling temperature, the lower the breakdown field for PT films. As a result, the optimized poling conditions for the PT films are: to apply a field of 250 kV/cm on a film sample for 15 min at a temperature of 120°C, and the poling efficiency is about 20%.

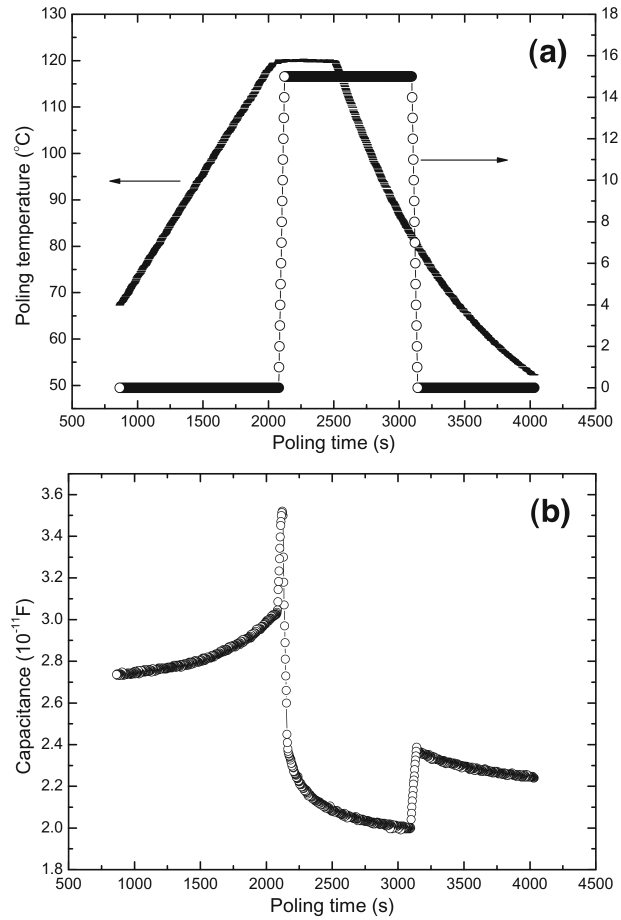

Fig. 1 (**a**) DC poling process. (**b**) Capacitance of a film sample as a function of time during DC poling

2.3 Pulse poling

A quick and simple poling method is required to pole a focal plane array because it deals with a large number of pixels on chip. The pulse poling method has been successfully developed by several groups to pole photoelectric copolymers [6–8] and ferroelectric thin films [5]. This method has advantages of easy operation, short poling time and high poling effect. Thin film is prone to breakdown under a high field by using a conventional DC poling. But for the pulse poling, electric field distribution in the films is more homogeneous due to the release of excess injected charges during the pulse poling, resulting in increasing of the threshold of the breakdown field. Consequently, a pulse field higher than 1 MV/cm can be applied instantaneously on film samples. Figure 2 gives a schematic waveform of a typical pulse electric field. The

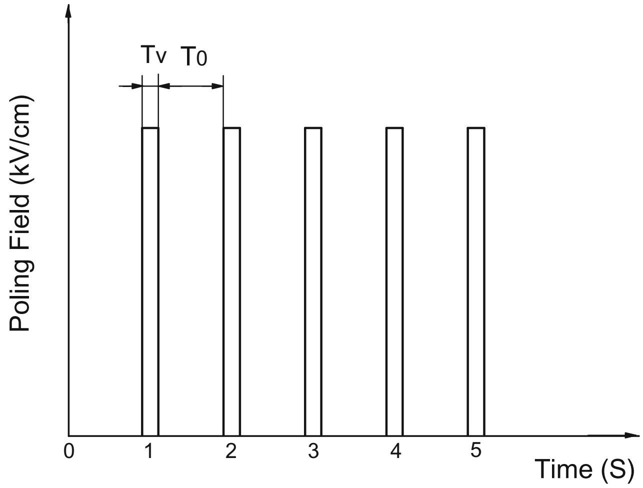

Fig. 2 Schematic waveform of a pulse poling field; T_v is the poling interval and T_0 is the pause (short circuit)

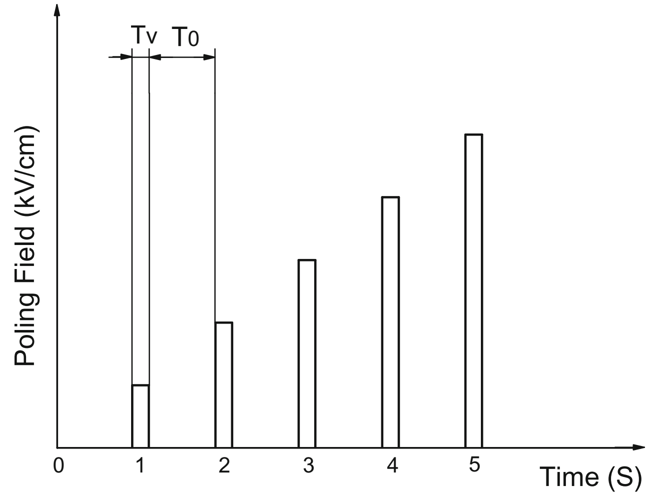

Fig. 4 Schematic waveform of a stepwise poling field; T_v is the poling interval and T_0 is the pause (short circuit)

pulse width is the poling interval. Between two poling intervals, the electric field is zero (short circuit).

A pulse poling system in this study is composed of a computer, a HP4192A impedance analyzer, a D/A converter, a temperature controller and a probe station. The frequency, duty ratio and pulse number can be set by the computer. In addition, the amplitude and width of each pulse can also be adjusted.

The samples were first pulsed poled at different temperatures. It's found that unlike the DC poling, the pulse poling process couldn't benefit from heating the samples. On the contrary, heating had a tendency to worsen the poling performance. Hence the samples were pulsed poled at room temperature in our experiments. An electric field with about 100 pluses and different amplitudes were applied to the samples. The results show that the optimized poling condition is the frequency of 1 Hz, the time of 50 ms and the amplitude of 40 V (667 kV/cm). The poling time is only about one tenth of the time for the DC poling and the poling efficiency increased by about 31%. Figure 3 shows C–V curves for the poled and unpoled thin films, respectively. The butterfly loop for the poled sample exhibits lower permittivity and is shifted by the internal bias field. In addition, both the butterfly loops aren't close. Generally, we believe that measurement field causes the remnant polarization, which makes the loop unclosed.

The film samples were also poled by a pulse field with stepwise amplitude in which the pulse amplitude was increased gradually. Figure 4 shows a schematic waveform of the stepwise poling technique. In such a poling, a field with 40 consecutive pulses was applied to the sample. The amplitude of the first pulse was 1 V and the amplitude of the last pulse was 40 V. The amplitude difference between two pulses was 1 V. Above pulse poling was repeated until the polarization reached saturation. When the pulse field was gradually applied to the films, more domains were

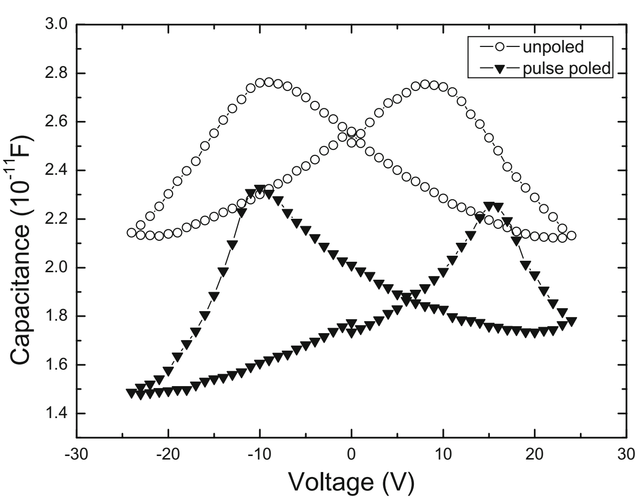

Fig. 3 C–V curves for an unpoled and a pulse poled samples, respectively

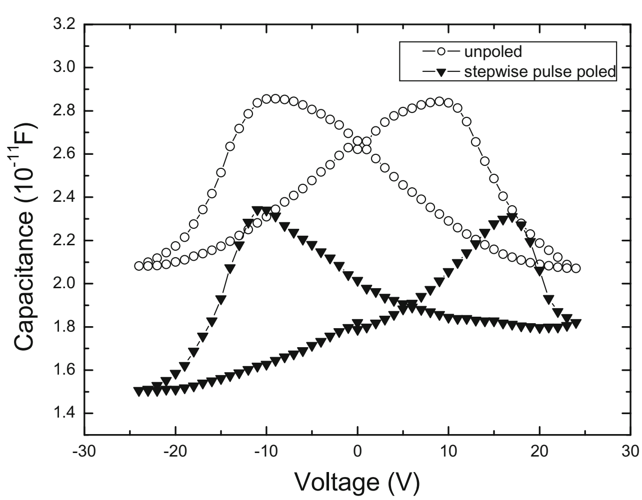

Fig. 5 C–V curves for an unpoled and a stepwise pulse poled samples, respectively

oriented toward the direction of the poling field, and the polarization increased steadily. It is one of the advantages that this technique decreases the risk of the electric breakdown significantly. In addition, the injected charges are limited since the charges are already present in polarized PT thin films. Therefore, a current induced by the injected charges is also limited and the probability for a thermal breakdown is reduced. Figure 5 shows C–V curves for the stepwise pulse poled and unpoled thin films, respectively.

3 Conclusions

Two poling methods have been studied for multilayer $PbTiO_3$ pyroelectric thin film infrared detector arrays. The efficiency of DC poling reaches 20% by optimizing poling condition, and the optimized parameters are poling time of 15 min, electric field of 250 kV/cm and temperature of 120°C.

The pulse poling method can improve poling efficiency and reduce poling time. The optimized poling condition is the frequency of 1 Hz, the time of 50 ms, the amplitude of 40 V (667 kV/cm), and the pulse number is 100. The poling time is only about one tenth of the time for a DC poling and the poling efficiency increased by about 31%. In addition, the way of gradually increasing pulse electric field amplitude would reduce the probability of both electric and thermal breakdown.

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