

Pyroelectric Properties and Applications of Lithium Tantalate Crystals

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Abstract: Lithium tantalate crystals, as a type of pyroelectric material, stand out from many other pyroelectric materials due to the advantages of high Curie temperature, large pyroelectric coefficient, high figure of merits, and environmental friendliness. Due to the pyroelectric effect caused by their spontaneous polarization, lithium tantalate crystals have broad application prospects in wide spectral bandwidth and uncooled pyroelectric detectors. This article reviews the pyroelectric properties of lithium tantalate crystals and evaluates methods for pyroelectric properties, methods for modulating pyroelectric properties, and pyroelectric detectors and their applications. The prospects of lithium tantalate thin films, doped lithium tantalate crystals, and near stoichiometric lithium tantalate crystals as response components for pyroelectric detectors are also discussed.

Keywords: lithium tantalate; pyroelectric; detector applications; near stoichiometric lithium tantalate



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1. Introduction

As an important subclass of piezoelectric materials, pyroelectric materials have attracted increasing attention because of the unique pyroelectric effect caused by spontaneous polarization. The pyroelectric effect, which is the release of charge due to temperature changes in materials, has been well-known as an observable physical phenomenon for centuries, described by Theophrastus in 315 BC. However, it was not until around 1960 that people began to seriously consider the application of pyroelectric technology [1].

Pyroelectric materials have been widely used in infrared detectors of thermal imaging systems, gas detection, non-dispersive infrared gas sensing, and fire alarm equipment, because of their high sensitivity and fast response over a wide spectral bandwidth, good stability over a wide temperature range, and cost-effectiveness compared to photodetection-based systems [2]. Currently, the main materials used to make pyroelectric detectors are lithium tantalate (LiTaO₃, LT) [3], lithium niobate (LiNbO₃, LN) [4], and triglycine sulphate (TGS) [1], and their performance comparison is shown in Table 1. Curie temperature (T_C) is the temperature at which the ferroelectric phase transforms into the paraelectric phase. Pyroelectric properties disappear in the paraelectric phase, and a high T_C is required in most applications. According to Table 1, LN has the highest T_C (1210 °C), but its pyroelectric coefficient is the smallest. TGS has the largest pyroelectric coefficient (350 $\mu\text{C}/\text{m}^2\text{K}$), but its T_C is the smallest, which makes it unsuitable for operation at high temperatures [5]. The LT crystal has a T_C of 605 °C and a pyroelectric coefficient of 190 $\mu\text{C}/\text{m}^2\text{K}$, which is twice that of the LN [4,6,7], and it is the best pyroelectric crystal with comprehensive performance. Therefore, LT crystals that can maintain the ferroelectric phase over a wide range of

temperatures become one of the best materials for making pyroelectric detectors [6]. The optical damage threshold value of the LT crystal is 1500 W/cm^2 , which is nearly 40 times that of the LN crystal, giving LT a higher ability to detect high-power laser radiation than LN [8].

Table 1. Comparison of TGS, LN, and LT performance [1,3,4,9].

	T_c ($^{\circ}\text{C}$)	ϵ_r	$\tan\delta$	p ($\mu\text{C/m}^2 \text{ K}$)	C_v ($\text{J K}^{-1} \text{ cm}^{-1}$)	FOM_D ($10^{-5} \text{ Pa}^{-1/2}$)
TGS	49	40	0.025	350	2.6	4.5
LN	1210	31		96	2.7	
LT	605	47	0.005	190	3.2	4.1

LT has unique acoustic, optoelectronic, piezoelectric, pyroelectric [10], and nonlinear optical characteristics. Especially as a new type of material, Z-cut LT crystals have advantages such as larger pyroelectric coefficient, lower dielectric constant, uniform crystallinity, and lower thermal expansion rate compared to other traditional substrate materials [11]. The small thermal expansion of LT is easily suitable for manufacturing less temperature-dependent microwave devices and is easier to process and fabricate compared to other similar products [10]. Due to its high mechanical stability and very small coefficient of thermal expansion, LT is widely used for the manufacture of uncooled pyroelectric infrared sensors [12,13]. LT is a ferroelectric single-crystal material with spontaneous polarization characteristics. If the temperature inside the crystal increases, the strength of spontaneous polarization will change, causing a change in the amount of surface charge [13]. The change in charge is related to the change in the temperature of the crystal, rather than the temperature itself, so pyroelectric detectors are not thermoelectric detectors, such as thermocouples. Pyroelectric detectors can be used to detect any radiation generated due to a change in the temperature [14].

In summary, LT crystals are important multifunctional crystals with a high T_c and optical damage threshold value, small thermal expansion coefficient, dielectric constant, and excellent spontaneous polarization properties. They are widely used in fields such as surface acoustic wave (SAW) filters, optical communication lasers, and optoelectronics. This article mainly introduces the pyroelectric properties and applications of LT crystals, focusing on explaining the current research status and future research hotspots of LT crystals from the principles and influencing factors of pyroelectric effects, the methods of regulating the pyroelectric properties, pyroelectric detectors, and their applications.

2. Pyroelectric Effect and Its Influencing Factors

2.1. Pyroelectric Effect

The pyroelectric effect is a change in spontaneous polarization caused by a change in temperature in certain polar materials. The working principle of the pyroelectric effect is shown in Figure 1. Pyroelectric materials themselves exhibit spontaneous polarization. The spontaneous polarization is along the polar axis and is generated by electric dipoles of the pyroelectric material itself. When two conductive electrodes are added to the surface of the pyroelectric material, the spontaneous electric field inside the pyroelectric material is changed due to the electrostatic induction, and an equal amount of opposite polarity charges are generated on the two conductive electrodes through the external circuit. When the temperature of the pyroelectric material increases ($dT/dt > 0$), the degree of electric dipole oscillation is enhanced and the spontaneous polarization is weakened, which in turn leads to the migration of electrons in the external circuit, reaching a new electrostatic equilibrium state. When $dT/dt = 0$, the internal electric field caused by spontaneous polarization is in equilibrium with the external induced electric field. When $dT/dt < 0$, spontaneous polarization is enhanced, which again breaks the electrostatic equilibrium and causes electron reverse migration [15,16]. The pyroelectric effect is widely used in pyroelectric infrared detectors, including radiation and non-contact temperature measurement [17],

infrared spectroscopy measurement [18], laser parameter measurement [19], industrial automatic control [20], space technology [21], and infrared videography [22].

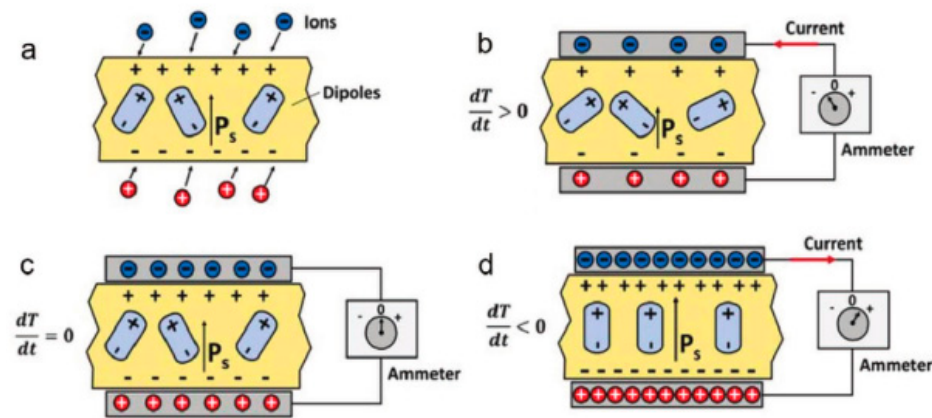


Figure 1. Schematic diagram of the pyroelectric effect [15].

2.2. Pyroelectric Coefficient

The pyroelectric coefficient reflects the responsiveness of dielectric polarization intensity to changes in the temperature of pyroelectric materials. For dielectrics, the displacement D of the dielectric is defined as:

$$D = Q/S = \epsilon E + P \quad (1)$$

in the formula, Q is the pyroelectric charge, S is the electrode surface area, ϵ is the dielectric constant, E is the external electric field, and P is polarization. Under constant stress (σ) and electric field (E), the pyroelectric coefficient is defined as:

$$p = \partial Q / \partial S = (dP/dT)_{\sigma, E} \quad (2)$$

the letters (σ , E) in the subscript represent a constant condition. Assuming that the temperature (T) of the pyroelectric material is uniform and the pyroelectric coefficient is constant, the pyroelectric current (i_p) is:

$$i_p = dQ/dt = pS(dT/dt) \quad (3)$$

where dT/dt refers to the rate of temperature change. It should be noted that Equation (3) is only applicable to the short-circuit situation, and the direction of the polar coordinates should be perpendicular to the electrode surface. According to Equation (3), the pyroelectric current is only proportional to the surface area of the material and is independent of its thickness and volume. The pyroelectric coefficient obtained from Equation (3) is:

$$p = i_p(dT/dt)^{-1}/S \quad (4)$$

Therefore, given the temperature change rate and sample area, the pyroelectric coefficient can be calculated by measuring the pyroelectric current [9,23,24].

2.3. Factors Affecting Pyroelectric Performance

The pyroelectric effect has been widely applied in various fields, such as pyroelectric power generation, pyroelectric imaging, ultraviolet/infrared light detection, temperature sensing, and gas analysis. The following three types of figure of merits, current responsivity, voltage responsivity, and specific detectivity are commonly used to comprehensively evaluate the performance of pyroelectric materials and devices. [1,9,16,25]:

$$FOM_i = p/c = p/(\rho c_p) \quad (5)$$

Equation (5) is the current responsivity, where ρ and c_p are the density and specific heat capacity of the pyroelectric material, respectively. Voltage responsivity is expressed as Equation (6):

$$FOM_V = p / (\rho c_p \epsilon_0 \epsilon_r) \quad (6)$$

where ϵ_0 is the vacuum dielectric constant and ϵ_r is the relative dielectric constant of the pyroelectric material. For pyroelectric detectors, the specific detectivity is an important performance parameter and can be expressed as Equation (7):

$$FOM_D = \frac{p}{\rho c_p \sqrt{\epsilon_0 \epsilon_r \tan \delta}} \quad (7)$$

$\tan \delta$ is the dielectric loss. According to Equation (7), a higher pyroelectric coefficient, lower specific heat capacity, lower relative dielectric constant, and dielectric loss are the preferred conditions for preparing pyroelectric detectors with higher sensitivity.

Schossig et al. [26] thinned LT wafers to 20 μm by lapping and polishing and then locally reduced the thickness to 0.4 μm in the center of the wafers by ion-beam milling technique to reduce crystal damage. The relationships between the dielectric constant, dielectric loss, and pyroelectric coefficient and crystal temperature and thickness were tested. The results showed that the dielectric constant, dielectric loss, and pyroelectric coefficient all increased with the increase in temperature. As shown in Figures 2–4; the dielectric constant and pyroelectric coefficient are not significantly associated with the thickness of the wafer, but the dielectric loss increases with the thickness of the wafer, as shown in Figure 5, which is associated with surface layer damage caused by wafer processing.

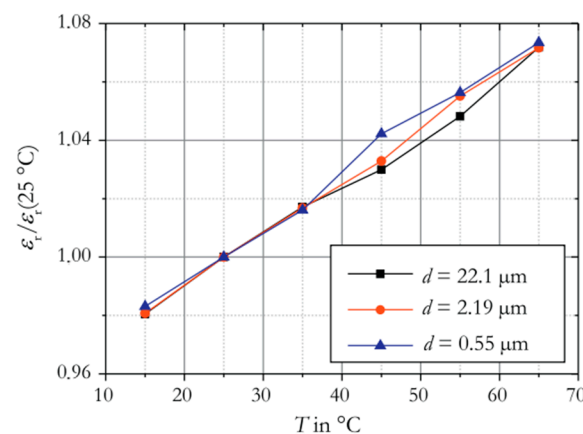


Figure 2. Dielectric constant versus temperature [26].

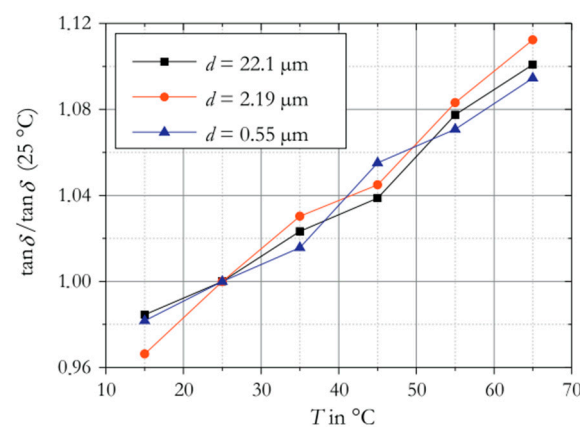


Figure 3. Dielectric loss versus temperature [26].

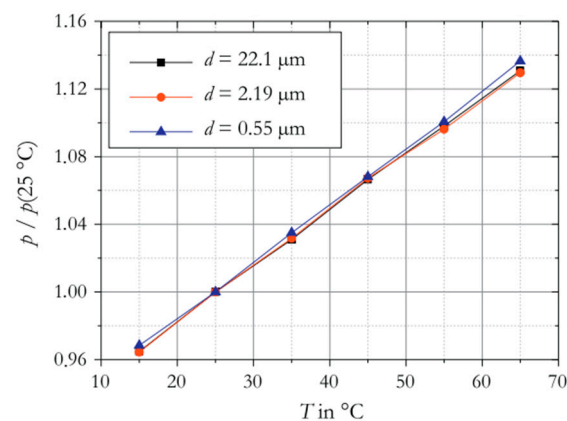


Figure 4. Pyroelectric coefficient versus temperature [26].

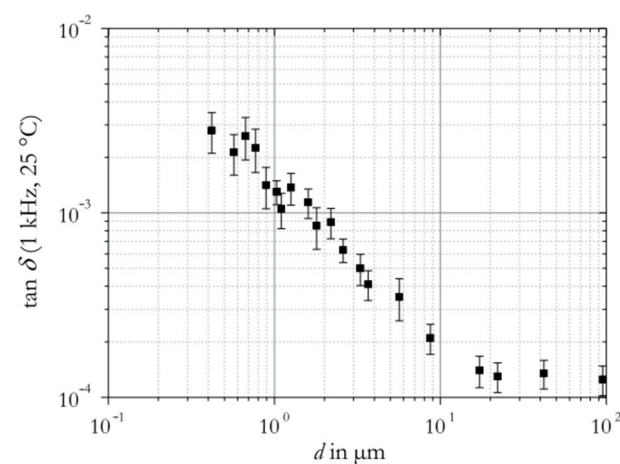


Figure 5. Dielectric loss versus thickness [26].

3. Methods of Modulating Pyroelectric Properties

The pyroelectric properties are related to the material properties and the subsequent processing of the materials. By doping other ions, the material properties can be changed, reducing the defects inside the crystals and improving the pyroelectric properties [6]. The subsequent processing of materials mainly includes reducing the thickness of the wafers and coating the surface with an absorption layer to improve the pyroelectric properties.

3.1. Reduced Thickness

Since the voltage responsivity and detectivity of the detector are inversely proportional to the thickness of the pyroelectric infrared sensing element [8], and the thickness of the response element also affects the signal-to-noise ratio of the detector, the use of a thin response element of a specific thickness allows the pyroelectric detector to achieve a high signal-to-noise ratio [27]. The basic method for improving the response of pyroelectric detectors is to thin the thickness of the pyroelectric materials [28]. Currently, there are two methods used to reduce the thickness. One is mechanical thinning, where wafers are thinned through mechanical polishing or ion-slicing technology; the other is to prepare LT thin films, where LT wafers are prepared by magnetron sputtering, the sol-gel technique, and other methods. The method of preparing thin films can make the films thinner, but often the prepared films are polycrystalline, as shown in Figure 6. Annealing is required to produce thermal stresses that degrade the film performance, such as a significant decrease in the pyroelectric coefficient. Although the thickness of the wafers prepared via mechanical thinning will be higher and their various parameters will be better, surface mechanical damage will also have some impact on dielectric loss, as shown in Figure 7.

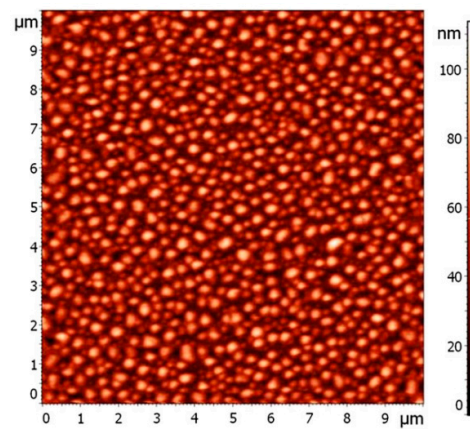


Figure 6. AFM image of LT films prepared using the sol-gel method [29].

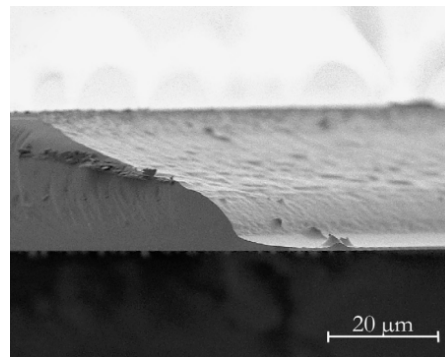


Figure 7. SEM image of LT wafer prepared using chemical-mechanical polishing and ion beam milling techniques [26].

3.1.1. Mechanical Thinning

Crystal ion slicing is a simple method for preparing large pyroelectric material thin films. Stenger et al. [28] used ion slicing technology to make LT films with thicknesses less than 9 μm , packaged them in a standard TO can for testing, and made a pyroelectric device with center aperture openings with 5 mm diameters. The test results showed that its performance at room temperature is six times higher in responsivity and three times higher in detectivity than that of a 50 μm LT thin film pyroelectric detector. Liang et al. [8] thinned the LT wafers to 50 μm via chemical-mechanical polishing, and the thinned and polished wafers had less surface damage, uniform surface charge release, and the pyroelectric coefficient slightly improved to 203 $\mu\text{C}/\text{m}^2 \text{ K}$. At a thickness of 150 μm , the pyroelectric coefficient was only 151 $\mu\text{C}/\text{m}^2 \text{ K}$.

Thinning the wafer thickness using the mechanical polishing method can reach 15–20 μm , while the wafer thickness can reach 2–5 μm using ion beam etching [13,27], and highly selective reactive ion beam etching of LT and photoresist [12], which is important for reducing the thickness of the sensitive elements of single-element pyroelectric infrared detectors, narrowing the distance between the two neighboring sensitive elements of linear sensor arrays, and improving the responsiveness of infrared detectors. Figure 8 shows ion-beam-etched LT chips with different layouts.

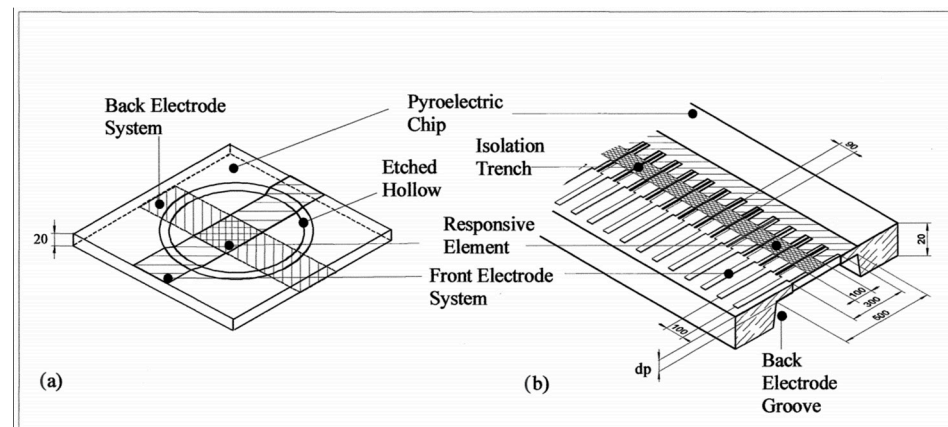


Figure 8. LT chips with different layouts. (a) Ion-beam-etched single-element detector chip (b) Ion-beam-etched linear array [30].

3.1.2. Preparation of Thin Films

D'amico et al. [23] used the radiofrequency reactive sputtering method to prepare LT thin films on stainless steel and molybdenum substrates using single-crystal LT as the target material. The experiments showed that the dielectric properties of the thin films prepared using this method were close to that of LT single crystals, with a relative dielectric constant of 41.0 and a dielectric loss of 0.022. However, its optimal pyroelectric coefficient was 4.3 times smaller than that of single-crystal LT, which was only $63 \mu\text{C}/\text{m}^2 \text{ K}$. The possible reasons for the decrease in pyroelectric coefficient are the lack and inhomogeneous distribution of Li and the existence of grain boundaries in polycrystalline films. Ye et al. [31] prepared preferred c-axis-oriented LT polycrystalline films using the sol-gel method, and Ti-doped LT films were prepared by replacing 35% of Ta with Ti atoms in the LT precursor solution. By comparing the performance of the two films, it was found that the Ti-doped LT films had a lower T_C of 330°C , but a larger pyroelectric coefficient of $150 \pm 20 \mu\text{C}/\text{m}^2 \text{ K}$ at room temperature. However, both of them had poorer properties compared to LT single crystals, which may be due to the larger porosity of the films. Nougaret et al. [7] prepared LT thin films on RuO_2 and Ru/RuO_2 bottom electrodes via radio-frequency magnetron sputtering with a lithium-enriched target. With Al as the top electrode, a microthermal sensor was fabricated, and the best pyroelectric coefficient obtained was $40 \mu\text{C}/\text{m}^2 \text{ K}$.

In summary, the preparation of thin films results in lower thickness but reduced pyroelectric coefficient and weakened performance. The mechanically thinned LT wafers have an increased pyroelectric coefficient and better performance, which has an important impact on optimizing the layout of pyroelectric detectors and improving their responsiveness.

3.2. Addition of the Absorption Layer

The spectrally flat response of pyroelectric detectors is only limited by the material characteristics of the absorption layer covering the receiving area of the detector. However, LT materials are translucent to visible and infrared radiation, so one or more coatings are required to enhance absorption. The gold-black coating is considered an ideal absorption material, which appears black in the visible and infrared regions and has an absorption of radiation close to 1 [11]; however, the process of deposition on the pyroelectric substrate is complex. Zhao et al. [32] used the electrospray method to deposit carbon black coating on the pyroelectric detector and found that the absorption rate of the carbon black coating was more than 94% in the wavelength range of $2.5\text{--}25 \mu\text{m}$, which was conducive to improving the performance of the pyroelectric detector, as shown in Figure 9.

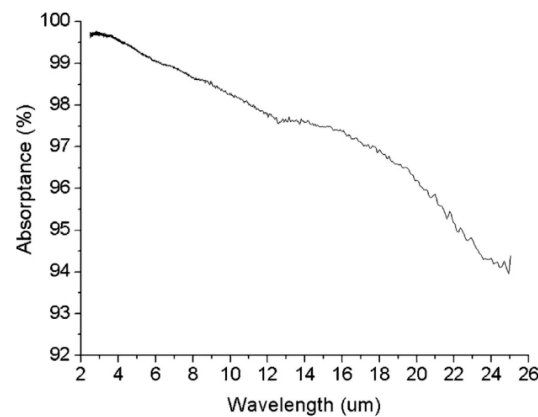


Figure 9. Absorbance of carbon-black-coated pyroelectric detectors in the wavelength range of 2.5–25 μm [32].

The responsivity of the detector depends on the absorption coefficient of the response element. The absorption coefficient of the response element composed of metal front electrode/LT/metal back electrode is about 0.6 at wavelengths from 2 to 20 μm . It can be increased to >0.95 by applying a special absorption layer. The application of a black absorption coating increases the responsivity of the detector by 1.5 times. The maximum value of the measured specific detectivity at 10 Hz is $1.8 \times 10^9 \text{ cm Hz}^{1/2} \text{ W}^{-1}$. Figure 10 shows the increase factor of the spectral response rate of pyroelectric detectors with different black coatings (The increase factor I_f is defined as the ratio of the voltage response of a pyroelectric detector with a certain thickness of black coating to that without black coating) [32]. Sun et al. [33] prepared an amorphous carbon film with a high absorption rate on a 100 μm thick LT film via magnetron sputtering and inductively coupled plasma etching, and made a pyroelectric infrared detector. It was found that the absorptivity was 0.8 after 5 min of etching at a wavelength of 2.5–6 μm , which was 27 times higher than the performance of detectors without this absorption layer.

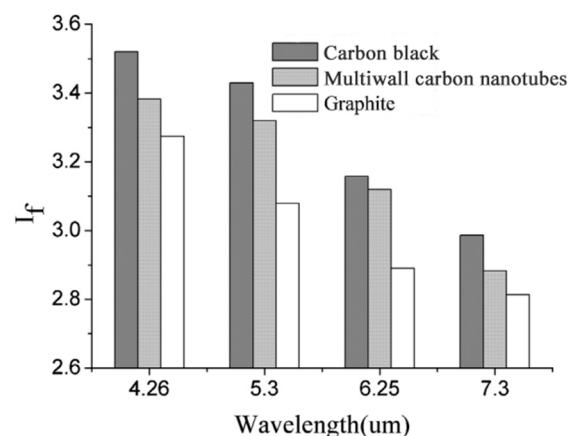


Figure 10. Increase factors of pyroelectric detectors with different black coatings at different wavelengths [32].

Therefore, it is important to maximize the temperature change through thermal isolation of the crystal and the use of low thermal diffusivity absorbing coatings to rapidly transfer heat to the crystal. To detect continuous wave radiation, pyroelectric detectors are used in conjunction with low-frequency light choppers to maximize detector output [28].

3.3. Near Stoichiometric Lithium Tantalate Crystals

The current commercially applied LT crystals are Congruent Lithium Tantalate (CLT) crystals with a Li:Ta ratio of 48.5:51.5. Due to the substoichiometry of Li ions, there are numerous defects, including Li vacancy defects and Ta inversion defects [34]. Near stoichiometric lithium tantalate (NSLT) crystals with a Li:Ta ratio close to 50:50 have a more perfect lattice structure due to the good stoichiometry of Li content, which results in higher T_C and better performance compared to CLT crystals [35,36]. Schossig et al. [26] found that the relative dielectric constant of stoichiometric lithium tantalate (SLT) crystals is lower than that of CLT. However, SLT crystals have lower pyroelectric coefficients, higher dielectric losses, and specific heat capacity, and their specific detectivity is smaller, making them unsuitable for use as pyroelectric detectors. However, by studying the acoustic, thermal, and mechanical properties of NSLT crystals, our group found that there is an inflection point for both acoustic and thermal properties, and they do not perform best when they are closest to the stoichiometric ratio [37]. As shown in Figure 11, the thermal conductivity of NSLT crystals reaches a maximum value of 4.6 W/(m·K) when the Li content in the crystals ranges from 49.64 to 49.75% [38]. Based on this, it can be expected that there may be an optimum point in the pyroelectric performance of NSLT crystals as well.

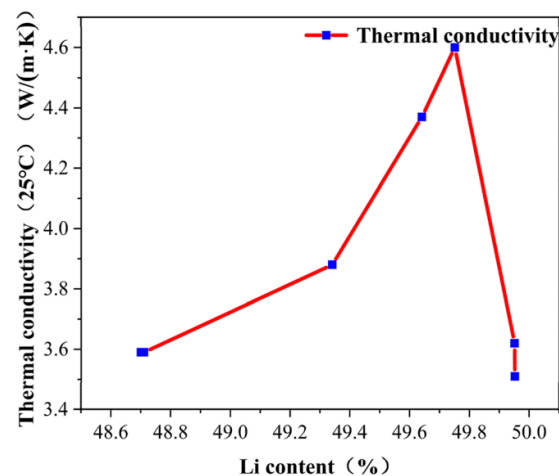


Figure 11. Thermal conductivity of NSLT wafers with different Li contents [38].

Proper doping can improve the thermal properties of LT crystals, resulting in an increase in the T_C of the crystals and an increase in the operating temperature range. Tang et al. [6] studied Mg-doped LT crystals and found that there is also an optimum point in their pyroelectric properties. When the doping concentration is below 4 mol%, their pyroelectric coefficients are significantly lower than when they are undoped. When the doping concentration is 4 mol%, the pyroelectric coefficient significantly increases. When the doping concentration is higher than 4 mol%, the pyroelectric coefficient decreases again. When doped with 5 mol%, the voltage responsivity increased tenfold and the specific detectivity increased 20 times. The position of impurities in the lattice is determined by the shift of the fundamental optical absorption edge of the ultraviolet spectrum. Doping replaces defects, and the substitution of Mg^{2+} for Li^+ and Ta^{5+} alters the spontaneous polarization and affects the pyroelectric coefficient in different ways.

4. Pyroelectric Detectors and Their Applications

4.1. Pyroelectric Detectors

A typical structure of a pyroelectric detector is that the top layer is an absorption layer, which may be black gold coating, carbon black coating, etc. Pyroelectric material is used in the central layer between the two metal electrodes, and the reflective layer is below, all of which are on the substrate material. Its working principle is to use a pyroelectric crystal with a large pyroelectric coefficient, and when the crystal surface is subjected to

incident radiation, heat is generated on the crystal surface, thereby releasing electric charges. When connected to an external circuit, the generated charges will output a current that is proportional to the rate of temperature change in the crystal [28]. Pyroelectric detectors are categorized as single-element detectors, two-dimensional arrays, and linear arrays. A typical schematic diagram of a single-element pyroelectric detector is shown in Figure 12.

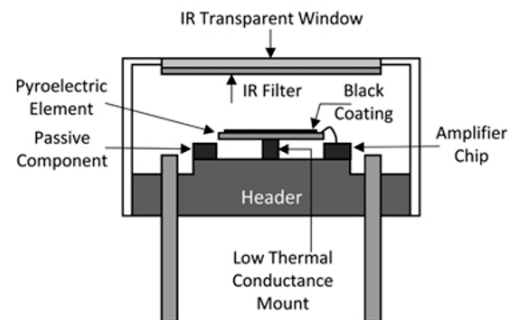


Figure 12. Schematic diagram of the pyroelectric detector [39].

A single-element detector consists of a pyroelectric chip and a preamplifier. These components are fixed and bonded to a PCB or thick film substrate. Depending on the use of the detector and the size of the chip, this setup is installed in a package with an infrared emission window. Typical window materials for detectors are small band filters (gas analysis), bandpass filters (8–14 μm), and spectral broadband windows (spectral measurement, high-temperature measurement) [40]. Figure 13 is a schematic diagram of a single-element detector.

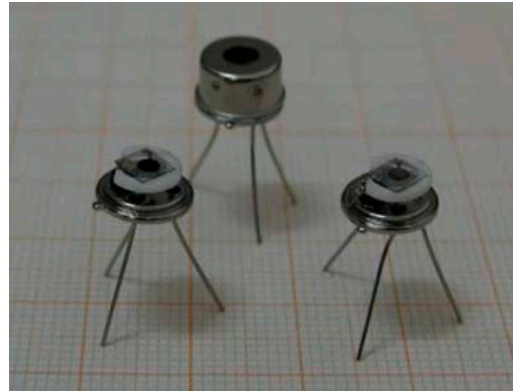


Figure 13. Single-element detector [41].

For applications that do not require high spatial resolution, two-dimensional arrays based on available readout circuits have been developed. Figure 14 is a schematic diagram of a two-dimensional array. The concept of an intelligent infrared safety system is proposed through a pyroelectric detector, compensation elements, and a simple optical system. It can be used for neuroimaging systems and measurement infrared cameras [27]. In the case of two-dimensional arrays, hybrid fabrication and micro-machining technologies are currently widely used. The hybrid method is based on a mesh of ceramic wafers that are polished to a reduced thickness and connected to the readout chip. The goal of micro-machining technology is to fabricate pyroelectric pixels directly on the readout chip in the post-processing line [42].

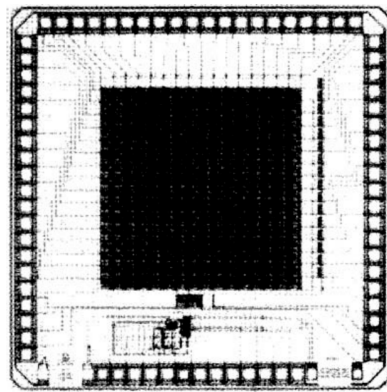


Figure 14. Two-dimensional array with 16×16 pixels [43].

The linear array is a hybrid component, a schematic diagram of the reticulated linear array detector as shown in Figure 15. A single response element is electrically connected to the input structure of a readout circuit through a key bridge. The size of the response element is determined by the overlap area of the front and back electrodes. The time-modulated incident radiation flux is absorbed by the responsive element and causes a temperature change in the pyroelectric material. The ion beam etching and optical functional layer on the response element can significantly improve the thermal and spatial resolution of the detector [44]. Figure 16 is a schematic diagram of a linear array sensor with discrete JFET chips.

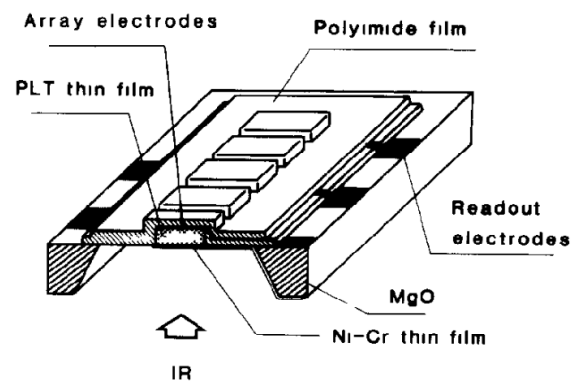


Figure 15. A schematic diagram of the reticulated linear Infrared sensors [45].

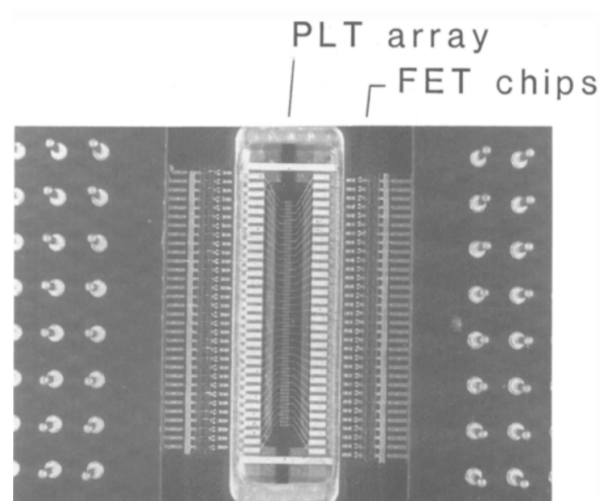


Figure 16. The linear array sensor with discrete JFET chips [45].

4.2. Application of Pyroelectric Detectors

The pyroelectric detectors are excellent candidates for broadband radiation detection [28]. The main application fields of pyroelectric detectors include safety technology (motion switches), gas analysis, pyroelectric measurements, and spectroscopy [27].

Wang et al. [46] manufactured terahertz detectors using LT crystals and LT thin films and found that the detector manufactured with LT crystals had a lower minimum noise equivalent power of 6.8×10^{-9} W at an operating frequency of 30 Hz. Luo et al. [47] utilized the ion slicing technique to obtain a 770 nm thick LT crystal film, which was then bonded to a thermally isolated SiO₂ substrate to produce a pyroelectric infrared detector with high specific detectivity. It can respond quickly and has a maximum specific detectivity of 2.49×10^8 cm Hz^{1/2} W⁻¹ at 300 Hz, which is better than the pyroelectric device made of LT bulk material. Zeng et al. [48] bonded LT wafers onto Si-based thick substrates using the surface-activated bonding technology. A 12 µm thick, 4-inch Si-based LT wafer was obtained using the mechanical rotating grinding process to make a pyroelectric infrared detector with dual-element detection units, which has a higher detectivity of up to 8.34×10^7 cm Hz^{1/2} W⁻¹ at 583.8 Hz and a response time of 1.989 ms. The use of Si wafers as a substrate also makes them integrable with other devices, providing a wafer-level fabrication method for making higher-performance pyroelectric detectors.

Liang et al. [49] realized pulsed neutron detection using LT crystals. LT crystals are heated by incident radiation to produce pyroelectric signals so that the neutron flux as a function of time can be calculated and pulsed neutron detection can be realized. The use of LT crystals to fabricate the detector makes the detector small in size and simple in circuit structure because of the large neutron reaction cross-section of Li, which does not require an additional neutron converter.

Zhang et al. [50] combined metamaterial perfect absorber Au/SiO₂/Au with the LT thin film obtained by ion slicing technology to obtain an infrared sensor with wavelength selection function. The sensor has a maximum absorbance of 97.8% at 4.04 µm, a maximum voltage responsivity of 1.7×10^4 V/W at 8.3 Hz, a maximum detection rate of 1.7×10^8 cm Hz^{1/2}/W, and a response time of 5.8 ms at 80.3 Hz. It is independent of the angle of radiation incidence and polarization, and its wavelength-selective function has stability, which provides a possibility for the application of LT thin-film pyroelectric detectors in wide-range infrared devices. Pyroelectric detectors coated with absorption layers have higher absorbance. Figure 17 shows the normalized spectral voltage response of CB coated pyroelectric detectors.

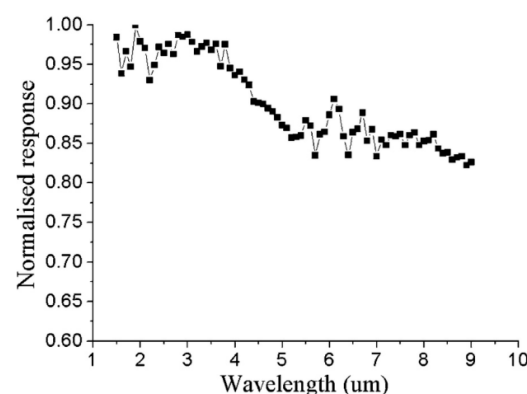


Figure 17. The normalized spectral voltage response of a CB-coated pyroelectric detector [32].

Zhou et al. [51] designed a CO₂ gas detection system based on non-dispersive infrared technology, which is a dual-channel pyroelectric infrared detector based on the LT crystal. The temperature and humidity compensation algorithm obtained by the least squares method was used to reduce the error, making the measurement accuracy reach $\pm 0.9\%$ of full scale. Mitmit et al. [52] fabricated a selective gas sensor using LT pyroelectric detectors

and multilayer bandpass filters. The bandpass filter was a 7-layer Ge/Al₂O₃ bandpass filter with a maximum transmittance of 84.5%, centered at 3250 nm and with a bandwidth of 450 nm, which enabled the detection of ethanol concentrations. Its LT pyroelectric detector has a voltage responsivity of 4.32 V/W and a specific detectivity of 1.5×10^{-6} W Hz^{-1/2} at a chopping frequency of 12 Hz. It has a poor response due to the lack of thermal isolation and low absorption, but it is easy to fabricate and proves its functionality as a gas sensor at room temperature.

5. Summary and Outlook

LT crystals, as a very promising pyroelectric material, have a large pyroelectric coefficient of 190 $\mu\text{C}/\text{m}^2 \text{ K}$ and a high Curie temperature of 605 °C, which gives them a wide operating range and means they can be used to fabricate uncooled pyroelectric detectors. The large pyroelectric coefficient, low specific heat capacity, dielectric constant, and dielectric loss are the preferred conditions for making high-performance pyroelectric detectors. In addition to the influencing factors of the material itself, the performance of the pyroelectric detectors can be improved by reducing the thickness of the wafer and increasing the absorption layer. Pyroelectric detectors based on LT crystals have a wide range of applications and can be used to detect terahertz waves and achieve pulse neutron detection and gas detection, all of which have good responses. Appropriate doping can also improve the pyroelectric performance of LT crystals.

Based on the potential applications and existing problems of LT crystals in pyroelectricity, it is recommended that research in the following aspects be strengthened: (1) Research on the pyroelectric performance of NSLT crystals, that is, to explore the relationship between the Li content and the mechanism of the pyroelectric performance of NSLT crystals, and to find the optimal Li content to make NSLT crystals with the best pyroelectric performance. (2) Ion-doped LT crystal pyroelectric performance study, i.e., optimizing doped ions to explore the pyroelectric performance and mechanisms of doped LT crystals. (3) Research on the preparation and performance of LT crystal thin films, because the performance of pyroelectric detectors is inversely proportional to the thickness of their sensing elements. Although the film thickness may be very low, most of the prepared films are polycrystalline, resulting in a decrease in their pyroelectric performance. Therefore, while improving the preparation method for polycrystalline thin films, it is necessary to also explore the preparation of single-crystal thin films. (4) Research on the improvement of intelligent mechanical processing technology. Improving the mechanical thinning process and developing intelligent thinning technology can effectively reduce the wafer damage caused by mechanical thinning and enhance pyroelectric performance.

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