Thin Film Lithium Tantalate (TFLT™) Pyroelectric Detectors

Vincent Stenger, Michael Shnider and Sri Sriram, SRICO, Inc.

Donald Dooley and Mark Stout, Gentec-EO USA, Inc.

Abstract

Pyroelectric thermal detectors are excellent candidates for detection of broadband radiation. Such detectors utilize permanently poled ferroelectric single crystal lithium tantalate to generate a charge as the crystal heats up by absorbing radiation. The charge, which results in a current output when connected to an external electrical circuit, is directly proportional to the rate of change of temperature of the crystal. The fundamental approach toward enhancing pyroelectric detector response is to form the pyroelectric material into a thin film. An elegant approach for producing bulk quality thin films of pyroelectric materials is by crystal ion slicing. In this paper, we report on the formation of thin film lithium tantalate (TFLT™) pyroelectric detector devices using the ion slicing process. The devices incorporate films less than 9 microns thin and feature apertures as large as 5 mm in diameter. To make functional detectors, ion sliced films were transferred to ceramic carriers in TO-type can test packages. Test results have shown improvement in room temperature detectivity about 20 times higher than the state-of-the-art lithium tantalate pyroelectric detectors.

Keywords: pyroelectric, thin film, lithium tantalate, ion slicing, detector, terahertz

Introduction

Terahertz (THz) radiation occupies the electromagnetic spectrum between far infrared and microwave frequencies. It is a large frequency band spanning from 300 GHz (\(\lambda = 1\) mm) to 10 THz (\(\lambda = 30\) µm). Because of the wavelength range, THz radiation addresses a largely unused application gap between infrared imaging, which is used for line of sight night vision, and radar, which is used for long distance ranging of targets. For homeland security applications, THz rays are ideal, since they can safely penetrate any materials except water and metal. For example, multiple THz imaging units can be set up throughout an airport to continuously monitor passing travelers for suspicious items without the radiation danger normally posed by X-rays. With THz equipment, there is no need for the sophisticated X-ray and metal detector enclosures. By including spectroscopic analysis, dangerous chemicals and drugs can also be detected. As with any radiation detection scheme, there are two types of THz detection: passive and active. Passive implies that THz radiation is picked up from an object that has generated or absorbed and emitted naturally occurring radiation. Although passive THz detectors exist, they are highly complex and bulky, and require extreme levels of cooling. There is also no easy way to establish the radiation spectral content. For most THz applications, room temperature active detection of THz radiation is preferred. That is, THz radiation of known spectral content is directed at the target and one or more observers monitors the return energy using broadband THz detectors. Although broadband THz detection has been reported in numerous literature accounts, there still is no cost effective and compact high resolution THz detection technology that operates at room temperature. Such features are keys to rapid and wide deployment of the technology.

Pyroelectric thermal detectors are excellent candidates for broadband THz detection. Such detectors utilize permanently poled ferroelectric crystals, such as lithium tantalate, which generate a charge as the crystal heats up by absorbing THz radiation. The charge, which results in a current output when connected to an external electrical circuit, is directly proportional to the rate of change of temperature of the crystal. It is therefore important to maximize the temperature change through thermal isolation of the crystal and by using absorbing coatings with low thermal mass to rapidly transfer heat to the crystal. For detection of CW THz radiation, the pyroelectric detector is used in conjunction with a low frequency optical chopper to maximize the detector output. When THz sources are pulsed, the pyroelectric detector can be configured to integrate the pulse and measure its energy.

The crystal thickness and efficient absorption of the radiation and transfer of heat to the crystal govern performance of a pyroelectric detector. The charge, thus the current generated by a pyroelectric detector, increases as the material thickness is reduced. A 10 micron film will have 10 times more response than a 100 micron film based on geometry alone. However, there are other benefits to the thin film as well. In particular, the thermal time response is faster by virtue of reduced thermal sinking through the thin film to the surrounding support structure. In general, both the thinness...
and the aspect ratio of detector aperture to film thickness will determine the performance gain achieved over a comparable sized thicker film detector. High aspect ratio detectors have additional benefit for arrays, where thermal isolation between pixels is especially important. Based on fundamental physical models, thin film pyroelectric detectors exhibit superior detectivity performance relative to quantum devices. Specifically, the models show that pyroelectric detection is superior for room temperature operation in the MWIR and beyond, while quantum detection is best suited for operation at SWIR and shorter wavelengths. This property makes pyroelectric detectors especially suitable for room temperature THz operation.

The most common approach toward enhancing pyroelectric detector response is to form the pyroelectric material into a thin film. Current practice to obtain thin lithium tantalate crystal films relies on chemical mechanical polishing techniques. Due to the limitations of polishing technology, the thinnest lithium tantalate films are in the 25 to 50 micron regime. Further thinning to about 5 microns may be achieved in specific regions of the crystals using advanced ion beam etching techniques. State-of-the-art single element pyroelectric detectors offered by DIAS Infrared GmbH and Gentec-EO specify a room temperature noise equivalent power (NEP) of about 100 pW in a root Hz bandwidth ($10^{-10}$ W/Hz$^{1/2}$). This is comparable to the performance of Golay cells offered by QMC Instruments Ltd., UK. A major drawback to mechanical thinning and ion beam techniques is that the wafer size is typically limited to about 20 mm due to the difficulty of handling the thin crystal.

Instead of resorting to the laborious process of polishing and wafer thinning, SRICO has combined the emerging technologies of wafer bonding and ion slice layer transfer to achieve uniform and thin mono-crystalline lithium tantalate films on device carrier substrates. The thin film lithium tantalate (TFLT™) layers have ranged in size from a few millimeters to 25 mm. In addition to thin film formation, SRICO has developed periodic domain engineered patterns in the thin films for the purpose of suppressing noise sources from the film outside the detector aperture. Domain engineered periodic patterns effectively and reliably de-pole the film. Judicious use of domain engineering may also be applied within the device aperture to suppress standing wave acoustic noise.

Using TFLT™ technology, SRICO has demonstrated record breaking 20 times detector performance improvement relative to state of the art commercial products. Further reductions in thickness are expected to enable room temperature pyroelectric detector response approaching 100 times that of currently commercially available devices. By application of suitable THz absorbers, the new TFLT™ pyroelectric detectors are operable over the entire terahertz spectrum of 100 GHz to 30 THz. Applications of the TFLT™ pyroelectric detector technology include non destructive evaluation and inspection of aerospace materials and structures, imaging and spectroscopy. Deployment of these newly developed detector devices would result in successful implementation of a large number of important defense, industrial, medical, and environmental applications that could benefit from terahertz radiation technologies. Pyroelectric detectors may also be used as a transfer standard in the calibration of other terahertz detectors. A partial list of commercial applications is given in Table 1.

<table>
<thead>
<tr>
<th>Research Applications</th>
<th>Medical &amp; Industrial Applications</th>
<th>Government Applications</th>
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<tr>
<td>Optical Calibration Transfer Standards</td>
<td>IR Detectors for Blood Gas Analyzers</td>
<td>Low Noise Horizon Sensor for Satellite Applications</td>
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<tr>
<td>High Precision Broadband Radiometers</td>
<td>Rugged, Non-Hygrosoppic IR Detectors for FTIR Systems</td>
<td>Calibration System for IR Target Designators</td>
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<td>High Sensitivity, Room Temperature, Broadband THz Power Sensors</td>
<td>THz Image Sensors for Non-Invasive Medical Diagnostics</td>
<td>Quad Detectors for Laser Targeting and Alignment</td>
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<td></td>
<td>Non-Destructive IR or THz Material Testing</td>
<td>Broadband Detectors for THz Measurement, Control or Calibration</td>
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<td></td>
<td>Improved Pulsed Laser Sensors</td>
<td>THz Field Communications Systems</td>
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<td></td>
<td>IR Flame Detectors</td>
<td>Cancer Research and Diagnostics</td>
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TFLT™ Pyroelectric Detector Fabrication

Initially developed for the silicon on insulator (SOI) industry, the smart-cut process may be extended to other materials systems as well. Smart-cut thin film layer transfer of lithium niobate has been widely reported in the literature, with helium ions commonly used in place of, or in combination with hydrogen ions. However, lithium tantalate is the preferred substrate for pyroelectric detectors because it has a higher pyroelectric coefficient than lithium niobate.

The TFLT™ process begins with a 3-inch bulk wafer of lithium tantalate. Depending on the application, a domain pattern may be formed in the wafer prior to the TFLT™ process. An full wafer ion implant is performed to create a highly stressed implant layer at a depth determined by the implant energy. This depth defines the film thickness and is typically between 5 and 10 microns. The implanted wafer is then temporarily bonded face down to a handle substrate for further processing. Either selective wet etching or a high temperature step is used to separate or “slice” the seed wafer along the ion implant plane, leaving a thin portion of the seed wafer still attached to the handle wafer. Polishing is used to smooth the slice surface and annealing is performed to remove any residual implant stress. The bulk quality TFLT™ film may be further processed for the specific application or transferred directly to a device carrier.

Device carriers are typically comprised of 0.5 mm thick ceramic or quartz discs with center aperture openings of from 2 to 5 mm diameter. In other cases, the carrier was a silicon wafer, either with or without an open window. After transferring the TFLT™ film, metal coatings and wire leads are applied to the top and to the bottom. If the TFLT™ layer is domain patterned over the entire film, an additional poling step may be performed to activate the aperture region. The thinness of the ion sliced films enables in situ poling of devices to activate pyroelectric response only within the desired aperture. Noise contributions normally present outside the aperture are nullified by the periodic domain pattern. An illustration of the domain engineered TFLT™ pyroelectric detector is shown in Figure 2. The carbon nanotube layer ensures efficient detection at wavelengths from visible into the THz regime. The entire assembly is packaged in a standard TO can for testing.
Like any other pyroelectric material, lithium tantalate films cannot absorb the entire incident THz radiation. This will be especially true for thin film lithium tantalate. As in other technologies, an additional absorbing layer enhances radiation capture and conversion. In addition to standard gold-black coatings,\textsuperscript{10} there have been promising reports of carbon nanotubes (CNT) for this application.\textsuperscript{11} These carbon materials provide large broadband absorption while maintaining thermal conductivity and low heat capacity. These thermal properties promote faster thermal response, which is critical for highly sensitive pyroelectric detection. Recent reports indicate multi-walled nanotubes may be even better for this application. Carbon nanotubes are commercially available in powder form, and can be applied using spray-on techniques. One recent development has resulted in columnar growth of nanotubes to about 7 mm height using a CVD process.\textsuperscript{12} More recently, Lehman, et al. has reported on vertically aligned CNT growth on lithium tantalate.\textsuperscript{13} With a suitable radiation absorbing layer, about two orders of magnitude improvement is expected for the thin film detector over currently available commercial pyroelectric detectors.

In addition to suppressing noise sources outside the detector aperture, domain engineering is being explored for suppression of acoustic noise within the device open aperture. The approach starts with experimental determination of resonant modes in a fabricated device. The magnitude of aperture acoustic noise will depend on the level of clamping achieved in the device.\textsuperscript{14} Theoretically, perfectly clamped films will exhibit essentially zero standing wave induced noise. Modeling of the device is performed to determine the domain pattern that results in the minimum standing acoustic wave noise. The operating frequency response of the device and associated electronics are taken into account during optimization. Typically, the lowest frequency vibration signal component is suppressed. The trade-off for acoustic suppression within the detector aperture is reduced responsivity, and is used when a window or vacuum sealing is not possible.

**TFLT™ Device Performance**

TFLT™ devices were produced on closed aperture silicon carriers and on 2 mm and 5 mm open aperture sapphire and ceramic carriers. Responsivity tests were performed using a range of spectral power density radiation sources, including short pulsed ND:YLF laser, chopped He-Ne laser, and chopped blackbody emitter.

**TFLT™ attached to metalized silicon**

A total of six assembled detector chips were prepared. Some chips were then assembled into a TO-5 package as shown in Figure 3a. Testing was carried out by solder installing the device in the Spectrum Detector Mach 5 probe PCB shown in Figure 3b. The photoelectric response of the device to a Nd:YLF pulsed near-infrared laser is shown in Figure 4. The voltage responses for a 25 micron film reference device and the TFLT™ device were 800 V/J and 6.12 kV/J, respectively. Correcting for detector areas, the results indicated about a 3x improvement for the ion sliced device relative to the state of the art 25 micron film device. This result proved that the silicon mounted films have a performance advantage even without backside window formation in the silicon substrate.

![Figure 3. TFLT™ on silicon detector device (a) mounted in TO-5 package, (b) enclosure for testing packaged chips](image-url)
Figure 4. Voltage response of the lithium tantalate-on-silicon detector device to a Nd:YLF laser pulse

TFLT™ on Ceramic

Examples of ceramic mounted TFLT™ films at various stages of assembly are shown in Figure 5. The ceramic open window aperture was 2 mm. A chopped He-Ne laser was used to test the devices. Room temperature test results for three device samples are given in Table 2. From the data in Table 2, it can be seen that the devices exhibited consistent performance across multiple devices. Some devices were hybrid packaged with an integrated TIA circuit to determine noise limited performance. Hybrid packaged devices exhibited noise equivalent power of less than 200 pW/√Hz at a voltage responsivity of more than 0.8 MV/W. Typical D* values were greater than $2 \times 10^9$ cm√Hz/W for these 2 mm aperture devices. TFLT™ films were also transferred to sapphire in a manner similar to that used for ceramic carriers. Room temperature performance for sapphire mounted devices was comparable to that measured for ceramic carriers.

(a)        (b)             (c)

Figure 5. Sliced TFLT™ films on ceramic carriers in various stages of assembly, (a) after backside and front side deposition, (b) after packaging in TO can, (c) after spray-on CNT THz absorber

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Sample 1</th>
<th>Sample 2</th>
<th>Sample 3</th>
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<td>572</td>
<td>µW</td>
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<td>Current Responsivity ($R_i$)</td>
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<tr>
<td>Capacitance ($C_d$)</td>
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<td>217</td>
<td>211</td>
<td>pF</td>
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</table>
Large Aperture Devices

A process was developed for handling and assembly of larger TFLT™ films. Figure 6 shows one of the TFLT™ on 5-mm aperture sapphire carrier structures prior to electrode metallization.

![Figure 6: Image of TFLT™ film on 5-mm aperture sapphire, before electrode metallization.](image)

Metallization and packaging steps were performed as the next step to form complete devices. Metal Cr front and Cr-Au backside electrodes were deposited by shadow masked e-beam thermal evaporation. After metallization, the detector device structure was packaged into a TO-8 can for testing. An example of a fully packaged device is shown in Figure 7.

![Figure 7: TO-packaged 5-mm aperture TFLT™ pyroelectric detector](image)

Room temperature current responsivity for the device shown in Figure 7 was measured to be 4.62 μA/W, which was similar to that measured for 2 mm aperture devices. Noise performance for 5 mm TFLT™ devices was determined by measuring low frequency zero stability of the amplified device output when mounted in a Gentec-EO TPR-D-65 probe head. A mounted 5 mm TFLT™ detector device is shown in Figure 8. The probe head incorporated a transimpedance amplifier (TIA). A cover plate was used to shield the device from ambient wind currents and acoustic waves. For comparison, zero stability measurements were also taken for a standard 5 mm aperture 50 micron film lithium tantalate detector device. The measurements are shown in Figure 9. From Figure 9, it can be seen that the TFLT™ device exhibited almost two times the zero drift of the reference device. However, the responsivity of the TFLT™ device was measured to be more than six times higher than for the reference device. The detectivity of the TFLT™ device when mounted in the TPR-D-65 probe head was thus more than three times that of the standard 50 micron thick film device. The intrinsic detectivity of the device cannot be extracted from this measurement because the noise performance was limited by electronic (TIA) noise. However, test results for hybrid packaged devices have confirmed the approximately 10x improvement for 5 mm aperture TFLT™ devices over state of the art 25 micron devices. Hybrid packaged devices integrate low noise JFET electronics to achieve D* closer to the theoretical maximum for the pyroelectric film.
The response uniformity of the 5 mm device was measured by scanning a 632 nm radiation source beam across the aperture and measuring the voltage response. The beam diameter was about 0.6 mm. The result of the uniformity measurement is shown in Figure 10. It is believed that interference effects are responsible for the periodic undulation in the spatial response. Interference fringes were visible to the naked eye prior to metal electrode coatings. These fringes are the result of finite thickness non-uniformity along the radius of the film. This non-uniformity is inherent in the wet etch ion slicing process, as the center of the film will tend to be etched less than the edges. Two fringes at 632 nm correspond to a thickness non-uniformity of about 2500 Angstroms in lithium tantalate, or less than 3% of the 9 micron film thickness. It is anticipated that application of carbon nanotube or other absorber coatings would eliminate these interference effects and ensure response uniformity at all wavelengths.
Domain Engineered TFLT™ Device

The poling process was tuned to produce a 35 μm period and 50% duty cycle domain pattern in lithium tantalate. The TFLT™ process was used to form a 9 micron thin and 3 mm size domain patterned films on sapphire carriers. After top and bottom metallization, the carrier mounted films were TO packaged and tested. An example packaged device is shown in Figure 11. The device of Figure 11 was specifically designed to have one portion of the active area as domain patterned, and another portion unpatterned. This represented the ideal control and test case. A focused visible laser beam was used to independently probe the response in the patterned and unpatterned portions of the detector. It was anticipated that the patterned region of the device would exhibit highly suppressed response relative to the unpatterned region.

Figure 11. Packaged domain patterned LT thin film pyroelectric device. Note that only a portion of the aperture is periodically patterned.

The test results for the detector of Figure 11 are shown in Figure 12. A helium neon (He-Ne) laser chopped at 125 Hz was used as the signal source. The un-patterned region of the device yielded a current responsivity of 4 μA/W, which was typical of devices fabricated from previous un-patterned and sliced 9 micron LT films. From Figure 12b, the patterned portion of the device was found to exhibit highly suppressed response relative to the un-patterned region. Any signal present in Figure 12b may be attributed to finite thermal isolation from the un-patterned portion and to finite laser spot size. The data indicated conclusively that periodic domain patterning does result in high pyroelectric suppression. It is anticipated from these results that domain patterning would be just as effective at suppression of piezoelectric and other noise sources.

Figure 12. Pyroelectric test results for the (a) unpatterned vs. (b) patterned portions of the pyroelectric
Conclusion

The TFLT™ process has been used to form pyroelectric devices with open apertures of from 2 to 5 mm diameter. Experiments have demonstrated up to 20 times improvement in performance of the ion sliced TFLT™ pyroelectric devices over state of the art commercially available lithium tantalate film pyroelectric detector devices. The performance proves the viability of the TFLT™ process for production of bulk quality ultra thin film lithium tantalate pyroelectric detectors. Product development currently is focused on improving yield and manufacturing cost. Other product development includes further thinning of the TFLT™ films to achieve even higher room temperature detectivity. VACNT films are being explored to achieve efficient operation over the entire THz band. Efforts are also being directed at implementing detector arrays using a wafer scale TFLT™ film process.

Acknowledgements

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