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Ultraviolet fast-response photoelectric effects in $LiTaO_3$ single crystal

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Abstract
The photoelectric effects of $LiTaO_3$ (LTO) single crystals are experimentally studied with two kinds of LTO wafers, 10° tilted and untilted, at room temperature. A transient open-circuit photoelectrical response of 143 ps rise time is observed in the 10° tilted LTO when a 266 nm pulsed laser with a duration of 25 ps is irradiated directly onto the LTO surface. The untilted LTO with interdigitated electrodes of 10 μm finger width and 10 μm interspacing exhibits a linear dependence on the applied bias and power density of incident light, a response peak at about 235 nm and a sharp cutoff at about 270 nm. The noise current is only 61 pA at 20 V bias under the illumination of sunlight outdoors at midday. The experimental results suggest the promising application of the LTO single crystal in UV detection, in particular, as a solar-blind fast-response photodetector.

AQ2 (Some figures in this article are in colour only in the electronic version)

1. Introduction

Ultraviolet (UV) photodetectors have been widely studied for their potential applications, including environmental detection, security communication, fire forecast, as well as military services [1–3]. In particular, solar-blind detection with high discrimination against solar rays and infrared light is ideal for detection in the background of sunlight. Up to now, great efforts have been made on various wide bandgap materials, such as III–V nitrides [4–7], c-BN [8], zinc oxide [9], diamond [10] and so on. However, most solar-blind photodetectors require a complex and expensive fabrication process.

Lithium tantalite ($LiTaO_3$, LTO) is one of the most important photorefractive materials, and it exhibits various interesting properties, such as piezoelectric, ferroelectric, acousto-optic, electro-optic and nonlinear optical properties [11–14]. Some results demonstrate that LTO single crystal has high electro-optic and nonlinear optical constants, making it suitable to be widely used in many fields including passive infrared sensors, terahertz generators and detectors, surface acoustic wave generators, cell phones, as well as electro-optic beam deflectors [15–18]. The LTO single crystal, as one of the perovskite-type oxide materials, has a wide bandgap of about 4.6 eV, corresponding to a bandgap excitation of ∼270 nm wavelength [19]. This means LTO may be a candidate for solar-blind detection. However, as far as we know, UV-sensitive photoelectric effect based on LTO single crystal has not yet been reported. Our previous works have reported UV-sensitive fast-response photoelectric effects in $SrTiO_3$ and $LaAlO_3$ single crystals [20–22], as well as the high-performance $SrTiO_3$ and $LiNbO_3$ visible-blind photodetectors [23, 24]. In this paper, we report the UV-sensitive fast-response photoelectric effects in the LTO single crystal and prove the possible application of the LTO single crystal in solar-blind detection.

2. Experimental procedure

The LTO single crystal wafers used in this study were as-supplied LTO (0 0 1) single crystal wafers with a purity of

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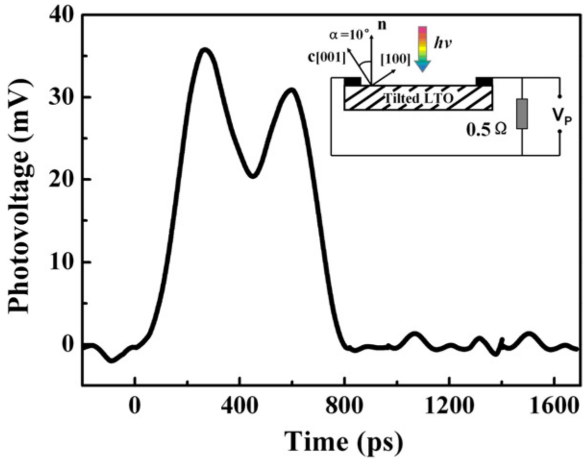

Figure 1. A typical transient open-circuit photovoltage of the 10° tilted LTO when a 266 nm laser pulse with 25 ps duration is irradiated directly onto the LTO surface, and measured by a 2.5 GHz bandwidth sampling oscilloscope. The inset shows the schematic of the measurement circuit.

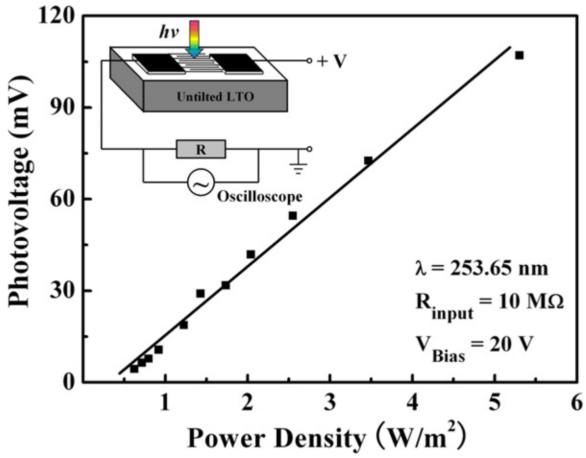

Figure 2. Photovoltage of the 10° tilted LTO with 10 μm width interdigitated electrodes as a function of the power density of Hg lamp at 20 V bias. The top inset shows the schematic of the measurement circuit.

99.99% and mirror single polished. The geometry size of all the wafers was 5 mm × 10 mm with a thickness of 0.5 mm. In order to investigate the photoelectric effect of the LTO single crystal and test the application in UV detection, two kinds of LTO wafers, 10° tilted and untilted, were used in our experiments. To prevent the influence of external bias, we chose the 10° tilted LTO wafer to study the photoelectric effect and to measure the open-circuit photovoltage. As shown in the inset of figure 1, the (0 0 1) plane of the LTO wafer is tilted 10° with respect to the surface. The tilting of the *c*-axis was further confirmed by an x-ray diffraction measurement with the θ–2θ scan. Two indium electrodes were painted on the surface of the 10° tilted LTO wafer and separated by 1 mm. Thus, the efficient area was $1 \times 5\,\mathrm{mm}^2$. The electrodes were always kept in the dark during the experiment to prevent the influence of electrical contacts. A fourth harmonic of an actively–passively mode-locked Nd : YAG laser (266 nm, 25 ps and 12.7 $\mu\mathrm{J\,mm^{-2}}$) was chosen as the light source and the energy on the effective area of the LTO wafer was 63.5 μJ/pulse. The photovoltaic signals were recorded by a 2.5 GHz bandwidth sampling oscilloscope (Tektronix TDS7254B).

The untilted LTO wafers were used to study its application in UV detections. An Au layer with 100 nm thickness was deposited on the polished surface of the LTO wafers by electron-gun evaporation. Conventional UV lithography and the etching technique were used to fabricate the interdigitated electrodes. The structure of the interdigitated electrodes is shown in the inset of figure 2. The finger width and the interspacing of the electrodes were of the same size of 10 μm. The effective area of the device was $2 \times 2\,\mathrm{mm}^2$. A dc voltage source was taken as the supplied bias, and the LTO wafer was in series with a sampling resistance R. A monochromatic Hg lamp (253.65 nm, 0.53 $\mathrm{mW\,cm^{-2}}$) and the Nd : YAG pulsed laser mentioned above were employed as light sources. The photocurrent is calculated by $I_P = V_P/R$, where V_P is the voltage across the sampling resistance R.

The spectral responsivity measurement of the LTO wafer was carried out using a monochromator with a standard lock-in amplifier. A 30 W D_2 lamp was used as the light source. The photocurrent under sunlight was measured using a Keithley Model 2182 nanovoltmeter. The powers of Hg and D_2 lamps were calibrated by a UV-enhanced Si photodetector.

3. Results and discussion

Figure 1 shows a typical transient open-circuit photovoltaic signal when a 266 nm laser pulse is irradiated directly onto the surface of the 10° tilted LTO. To reduce the RC influence in the measurement circuit, we connected a 0.5 Ω resistance in parallel with the LTO wafer. The schematic of the measurement circuit is shown in the inset of figure 1. The peak photovoltage V_P and photovoltaic sensitivity are 35.8 mV and 563.8 $\mathrm{mV\,mJ^{-1}}$ and the peak photocurrent I_P and photocurrent sensitivity are 71.6 mA and 1127.6 $\mathrm{mA\,mJ^{-1}}$, respectively. The rise time (10–90%) is 143 ps and the full width at half maximum (FWHM) is 535 ps. The experimental results indicate that the photoelectric effect in the LTO single crystal is not only an ultrafast process but also a highly sensitive process.

The mechanism of photovoltage in the tilted LTO wafer, similar to $SrTiO_3$ and $LaAlO_3$ single crystals [20–22], can be understood as follows: the LTO single crystal absorbed the incident photons and generated the photo-carriers (electrons and holes) as well as a thermal gradient field. According to thermoelectric theory, the lateral thermoelectric field $E(\alpha) = (S_{ab} - S_c)\sin 2\alpha(\mathrm{d}T/\mathrm{d}z)/2$, where S_{ab} and S_c are the Seebeck coefficients of the LTO crystal along the *ab* plane and *c*-axis, α is the vicinal cut angle and $\mathrm{d}T/\mathrm{d}z$ denotes the temperature gradient in the direction of irradiation (perpendicular to surface) [25]. The thermoelectric field leads to the separation of photo-carriers in the lateral direction and results in the photovoltage between the two electrodes. As mentioned above, the photovoltage in the tilted LTO is a combinational process of photoelectric effect and thermoelectric effect. In addition, our experimental results show that no photovoltaic signal was observed when the photon energy of the incident light is smaller than the bandgap of the LTO single crystal. The

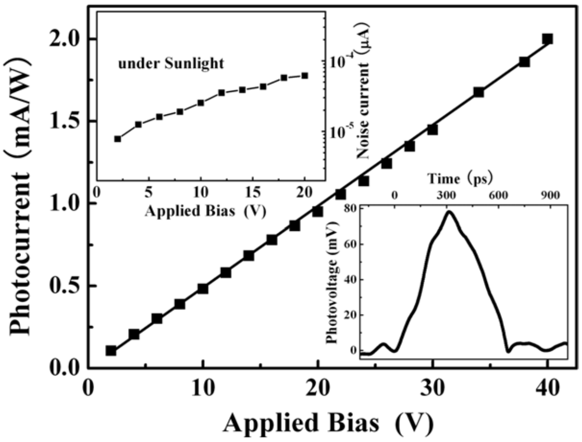

Figure 3. The bias dependence of photocurrent responsivity of LTO with 10 μm width interdigitated electrodes under a Hg lamp illumination. The top inset shows the noise current measured under sunlight. The bottom inset displays the transient photoelectrical response irradiated by a 266 nm laser pulse with 25 ps duration at 10 V bias.

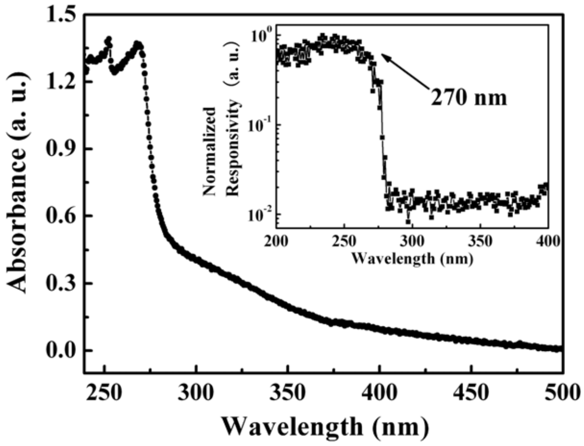

Figure 4. The absorption spectra of LTO single crystal. The inset displays the normalized spectra responsivity of LTO wafer with 10 μm width interdigitated electrodes at 20 V bias.

experimental results not only indicate that the photoelectrical effect plays an important role in the photoelectric process but also suggest that the LTO single crystal has the property of solar blindness.

Based on the fast-response photoelectrical effect in the tilted LTO mentioned above, we have further investigated the application of the LTO single crystal in UV detection with 10 μm interdigitated electrodes under an external bias. Figure 2 displays the relationship of photovoltage of a LTO wafer with 10 μm width interdigitated electrodes and the power density of the Hg lamp. The inset of figure 2 displays the schematic of the measurement circuit. The photovoltages are measured by a 10 MΩ resistance under 20 V applied bias. The magnitudes of photovoltages increased linearly with the power density of the Hg lamp.

Figure 3 exhibits the photocurrent responsivity of a LTO wafer with 10 μm width interdigitated electrodes as a function of the applied bias under a continuous Hg lamp illumination. The photocurrent increases linearly with the applied bias, and the photocurrent sensitivities are 1 mA W^{-1} and 2 mA W^{-1} at 20 V and 40 V biases, respectively. The top inset of figure 3 shows the variation of noise current under sunlight with the applied bias. The noise current was measured directly under the illumination of sunlight outdoors at midday. The noise current under sunlight irradiation is 61 pA at 20 V bias, suggesting the potential application of the LTO photodetector working under sunlight without any filters.

As shown in the bottom inset of figure 3, the transient photoresponse of the LTO wafer with 10 μm width interdigitated electrodes at 10 V bias was measured under the same experimental conditions with the 10° tilted LTO in figure 1. The rise time and the FWHM are 228.5 ps and
AQ3 366.1 ps, respectively. Compared with the result in figure 1, the photovoltaic sensitivity is six times bigger in magnitude than that in figure 1. The experimental result shows that it is an effective method using the interdigitated electrodes and external bias to improve photovoltaic sensitivity.

Figure 4 shows the absorption spectrum of the LTO wafer used in this study. The absorption peak and absorption edge are located at about 270 nm and 280 nm, respectively. The bandgap of the LTO single crystal, determined by the absorption spectrum, is about 4.6 eV. It is in agreement with the report of other groups [19]. The inset of figure 4 displays the normalized responsivity of the LTO wafer at 20 V bias measured by a monochromator with a 30 W D_2 lamp. The LTO single crystal exhibits a maximum responsivity at about 235 nm and a sharp cutoff wavelength appears at about 270 nm, which is in good agreement with the absorption spectrum. The cutoff wavelength corresponds to the photo-energy of 4.6 eV, indicating that the photoelectric effect is a bandgap excitation process. The LTO detector has a high wavelength selectivity, which suggests that the device has an intrinsic characteristic of solar blindness.

4. Summary

In conclusion, we have systematically studied the photoelectric effects in LTO single crystals at ambient temperature. A photoresponse of rise time 143 ps was observed in the 10° tilted LTO single crystal. The photocurrent increases linearly with the applied bias and light power density for the untilted LTO wafer with 10 μm interdigitated electrodes, and the photocurrent sensitivities reach 1 mA W^{-1} and 2 mA W^{-1} at 20 V and 40 V biases, respectively. The noise current under sunlight is only 61 pA at 20 V bias and the sharp cutoff wavelength is at about 270 nm. Compared with the photodetectors based on $SrTiO_3$ [23] and $LiNbO_3$ [24], it
is a significant advantage for the LTO photodetector that it AQ4
exhibits a sharp cutoff wavelength at about 270 nm, which is located in the solar-blind region. In addition, the LTO is based on a commercial LTO single crystal and does not need a complex fabrication process. The experimental results proved the promising and potential application of LTO single crystal in ultrafast solar-blind detection. Further studies, such as designing of new configurations, and improvement of the quantum efficiency and sensitivity, are being planned.

Acknowledgments

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