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High sensitive and ultrafast UV photodetector based on ZrO_2 single crystals

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The fast-response ultraviolet (UV) photoelectric effect in ZrO_2 single crystals with interdigitated electrodes has been investigated experimentally at room temperature. The photovoltage of ZrO_2 single crystals exhibits a linear dependence on applied bias and light power density. The photocurrent responsivity to the UV light with a wavelength of 253.65 nm is 9.8 mA/W. For the photovoltaic pulse, a rise time of 501 ps and a full width at half maximum of 1.5 ns have been obtained, when the ZrO_2 single crystal is illuminated by a 266 nm pulsed laser. These results indicate that the ZrO_2 single crystal is a promising candidate for UV photodetectors.

photoelectric effect, ultraviolet photodetector, ZrO_2 single crystals

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1 Introduction

Ultraviolet (UV) selective and sensitive photodetectors present a wide range of civil and military applications, such as chemical and biological analyses, flame detection, inter-satellite communications and astronomical studies. Although Si and GaAs-based photodetectors are sensitive in visible and infrared regions, they exhibit some inherent limitations in UV detection, like device aging due to UV irradiation and necessary extra filters to block out visible and infrared photons. The wide bandgap materials including III-V nitrides, silicon carbide, zinc oxide, and diamond, are attractive choices for UV detection. Their stable physical properties and intrinsic visible blindness stimulate extensive investigations by many groups [1–4]. However, the UV detectors based on these materials demand a complicated and delicate fabrication process and high-cost manufacture.

Recently, there has been increasing interest in the photodetector based on single-crystal oxides. Zhao et al. have observed nanosecond or picosecond photovoltaic pulses in the miscut $LaSrAlO_4$, Nb-doped $SrTiO_3$ and quartz single crystals [5–7]. In our previous work, we reported the high sensitive visible-blind $SrTiO_3$ UV photodetector and solar-blind $LaAlO_3$ UV photodetector based on their single crystals [8–9]. These single-crystal detectors need no complicated fabrication process and present high sensitivity in the UV region. Therefore, they are some of the potential candidates for low cost UV photodetectors.

Zirconium oxide (ZrO_2) is a technically important material, widely used in many optical fields acting as high-reflectivity laser mirrors, filters, and waveguides as well as high-k gate dielectrics due to its high refractive index, large optical band gap, low optical loss and high dielectric constant [10–14]. Meanwhile, zirconium oxide has excellent thermal and chemical stability and large resistance against high temperatures and oxidation. Photoelectric characteristic of ZrO_2 single crystal has been reported in our previous

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paper, in which the ZrO_2 single crystal can respond to UV light with a wavelength less than 270 nm at the external bias [15]. In this paper, we further report a highly sensitive solar-blind photodetecor based on the ZrO_2 single crystal. Compared with the $LaAlO_3$ solar blind photodetector, the present ZrO_2 single crystal detector can respond to UV light with a wider optical detection window (200–270 nm).

2 Experiments

The ZrO_2 single crystal wafers used in the present work are the double-polished ZrO_2 substrates with a purity of 99.99%. The in-plane size of ZrO_2 wafer is 10 mm×10 mm and the thickness is 0.5 mm. An Au layer with a thickness of 100 nm was deposited onto the ZrO_2 wafers by electron-gun evaporation. The conventional UV lithography and etching technique were employed to fabricate Au interdigitated electrodes. The finger width w of the interdigitated electrodes is equal to the separated spacing s as shown in the upper inset of Figure 1. The range of w and s varies from 10 μm to 50 μm for different detectors. Due to the shadowing effect of electrodes, the active area (the area directly exposed to radiation) is only 15 mm^2.

The photoelectric properties of the ZrO_2 UV detectors were investigated by using a programmable DC voltage source, a monochromatic Hg lamp (253.65 nm) and a fourth harmonic of an actively passively mode-locked Nd:YAG laser (266 nm, 25 ps, and 12.7 $\mu J/mm^2$). The schematic measurement circuit is shown in the lower inset of Figure 1. The DC voltage source supplies a bias voltage V_B, and the ZrO_2 detector is in series with a sampling resistance R. The voltage signal across R is recorded by a 2.5 GHz digital oscilloscope.

3 Results and discussion

Figure 1 shows the steady-state photoelectric response of ZrO_2 wafer with a finger width of 10 μm under irradiation of the Hg lamp. Here the power density of Hg lamp is 0.53 mW/cm^2. The sampling resistance R is 1 MΩ. The change of voltage across R before and after illumination is taken as the photoelectric signal. As shown in Figure 1, the photovoltage is high (low) when the Hg lamp is switched on (off). A big photovoltage of 780 mV is achieved at 10 V bias.

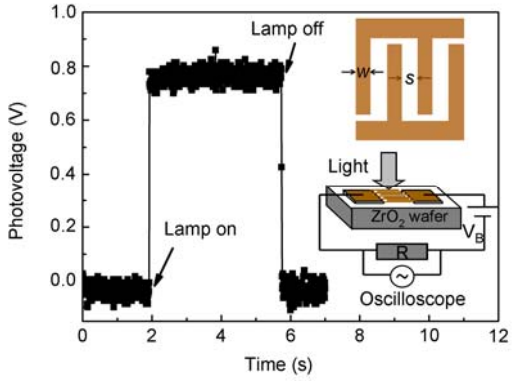

Figure 1 (Color online) Photovoltage of the ZrO_2 single crystal with a 10 μm finger width under irradiation of Hg lamp at 10 V bias.

The linearity of the detector responding to optical power density has also been verified. The optical power density of Hg lamp can be adjusted by altering the distance between the Hg lamp and the detector. Figure 2 shows the photoelectric response versus optical power density for a detector with a 10 μm finger width at 10 V bias. By a simple calculation considering the power density of incident light and the active area of the detector, we can obtain a photovoltaic responsivity of 9.8×10^3 V/W and a photocurrent responsivity of 9.8 mA/W. The corresponding quantum efficiency η can be deduced to be 4.8%, according to the formula $\eta=R_i h\nu/q$, where R_i is the photocurrent responsivity, h the Plank constant, ν the frequency of incident light, and q the charge of one electron [16]. We did not observe any photovoltaic signal when the ZrO_2 single crystal was irradiated by a 532 or a 632 nm laser. To characterize the photocarriers of samples used in the present work, we measured the optical absorption spectrum by using a SpectraPro500i spectrometer. The inset of Figure 2 shows the UV-visible absorption spectrum of ZrO_2 single crystal. The absorption peak and absorption edge are located at 250 nm and 270 nm, respectively. The optical band gap of ZrO_2 can be determined by the absorption spectrum to be about 4.7 eV. From the absorption spectrum, it can be seen that the ZrO_2 single crystal only responds to UV light with a wavelength less than 270 nm and its response peak is located at about 250 nm.

Figure 3(a) shows the photoelectric response of ZrO_2 detectors with different finger widths as a function of applied bias. The photovoltages increase linearly with the bias for all detectors and do not show any trace of saturation. Figure 3(b) illustrates the variation of photovoltage with the finger width at different biases. It is clear that the photovoltage

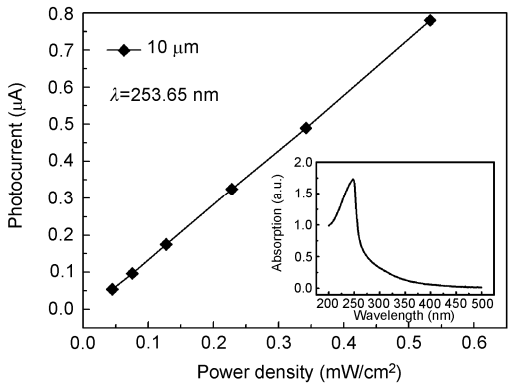

Figure 2 Photocurrent variation with the optical power density for the ZrO_2 single crystal with a 10 μm finger width. The inset figure shows the absorption spectrum of ZrO_2 single crystal.

increases quickly with the decreasing finger width. According to the theory of the photoconductive detector [16], the photoelectric gain g is proportional to the carriers' lifetime τ_l and inversely proportional to the carriers' transit time τ_t between the neighboring contacts. And τ_t is determined by the equation $\tau_t = l/\upsilon = l/\mu E = l^2/\mu V_b$, where l is the interspace between finger contacts, ν the carriers' drift velocity, μ the average mobility, E the electric field between fingers and V_b the biased voltage. From the equation, we can easily know that τ_t is proportional to the square of finger width l. Due to the decrease of finger width, the transit time τ_t decreases, and so the photoelectric gain g and the photoresponse are enhanced greatly. Our experimental data are in good agreement with the theory.

The transient photoresponse of the detector was measured by a fourth harmonic of an actively passively modelocked Nd:YAG laser with a wavelength of 266 nm and pulse duration of 25 ps. To reduce the influence of the circuit in the measurement and the long tail of the decay time due to the RC effect in a photovoltaic signal, we connected a 50 Ω load resistance in parallel with the ZrO_2 single crystal. Figure 4 shows a typical transient photoelectric response of ZrO_2 detector with a 10 μm finger width at 10 V bias. The response curve presents a rise time of ~501 ps and a full width at half maximum (FWHM) of 1.5 ns. This indicates that the studied detector has a high-speed photoresponse characteristic.

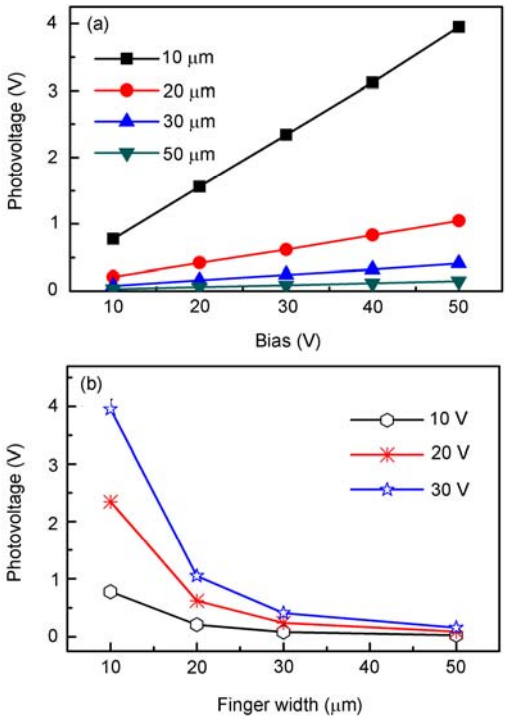

Figure 3 (Color online) (a) Bias dependence of the photocurrent for various electrode geometries. (b) Photovoltage as a function of finger width for different biases.

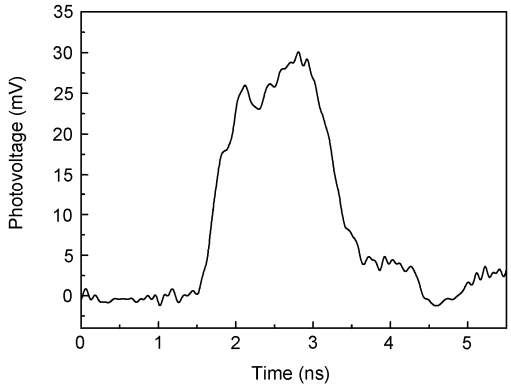

Figure 4 Transient photoresponse of the ZrO_2 single crystal with a 10 μm finger width at 10 V bias.

4 Conclusions

In conclusion, we have fabricated the highly sensitive and ultrafast UV photodetectors based on ZrO_2 single crystals with interdigitated finger electrodes. The photovoltage scales linearly with the bias and the power density. For the ZrO_2 single crystal with a finger width of 10 μm at 10 V bias, the photocurrent responsivity at 253.65 nm can reach as high as 9.8 mA/W, which meets commercial requirements. The response time is found to be in picosecond order. It is noteworthy that the present UV detectors are based on commercial ZrO_2 single crystals, which do not need complicated fabrication techniques and processes. The interdigitated electrode configuration contains a convenient and mature fabrication technology, which can be obtained with a large active area and is easy to be integrated with the planar circuit fabrication process. All of these excellent qualities demonstrate that the ZrO_2 single crystal detector in our configuration is a promising candidate for UV detection.

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