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High-sensitivity photovoltage based on the interfacial photoelectric effect in the $SrTiO_{3-\delta}$/Si heterojunction

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A high sensitivity photovoltaic effect has been observed in a heterojunction composed of n-type wide bandgap oxide $SrTiO_{3-\delta}$ and *p*-type Si fabricated by laser molecular beam epitaxy. The responsivity of open-circuit photovoltage can reach 10^4 V/W without any amplification under zero bias for the wavelength range from visible to near infrared light in nW-μW order. We attribute the high performance of the photovoltage responsivity to the interfacial photoelectric effects in the $SrTiO_{3-\delta}$/Si heterojunction. From the experimental results, some ideas can be generalized to improve photovoltaic efficiency and develop high sensitivity photodetectors with wide bandgap oxide materials and Si.

$SrTiO_{3-\delta}$/Si heterojunction, interfacial photoelectric effect, photovoltage

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1 Introduction

Perovskite oxide heterostructures have recently attracted more and more attention due to the intrinsic properties of perovskite oxides, interfacial effects and the prospects of technological applications [1–4]. The discovery of the generation of high-mobility two-dimensional electron gas at the interface between the two insulating perovskite oxides $LaAlO_3$ and $SrTiO_3$ has attracted much interest [5]. Later, superconductivity [6] and magnetic effects [7] were also observed in the $LaAlO_3/SrTiO_3$ heterostructure. It was proposed that the "electronic reconstruction" and "oxygen vacancies" are essential for the fundamental mechanism underlying those fascinating phenomena at the oxide interfaces [5]. We also reported an unusual positive magnetoresistance (MR) in $La_{0.9}Sr_{0.1}MnO_3/SrNb_{0.01}Ti_{0.99}O_3$ [8,9], ultrafast photoelectric effects in $La_{0.7}Sr_{0.3}MnO_3$/Si, $LaAlO_{3-\delta}$/Si and $La_{0.9}Sr_{0.1}MnO_3/SrNb_{0.01}Ti_{0.99}O_3$ [10–12], resistance switching in $BaTiO_3$/Si [13], the Dember effect of induced photovoltages in $La_{0.9}Sr_{0.1}MnO_3/SrNb_{0.01}Ti_{0.99}O_3$ and $La_{0.7}Sr_{0.3}MnO_3$/Si [14], electrical modulation of the MR in multi-p-n hererostructures of $SrTiO_{3-\delta}/La_{0.9}Sr_{0.1}MnO_3/SrTiO_{3-\delta}/La_{0.9}Sr_{0.1}MnO_3$/Si [15], as well as enhanced tunability in $La_{0.7}Sr_{0.3}MnO_3/BaTiO_3$ [16]. These results mentioned above have demonstrated that these novel properties have a dominating contribution from the interfacial effect in oxide heterostructures or the interface competition effect in multi-heterostructures. Interfacial effects have been a subject of great scientific curiosity and technological interest.

Previously, we reported the ultraviolet (UV) photovoltage characteristics of the $SrTiO_{3-\delta}$ (STO)/Si p-n junction [17]. In this letter, we present the high-sensitivity photovoltage based on the interfacial photoelectric effect in the $SrTiO_{3-\delta}$/Si heterojunction. The responsivity of open-circuit photovoltage reaches as high as 10^4 V/W without any amplification under zero bias for the wavelength range from

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visible to near infrared light in the nW-μW order.

2 Experimental

The STO thin films were epitaxially grown on p-type Si substrates with a resistivity of 12.95 Ω cm by a computer-controlled laser molecular-beam epitaxy system. Details of the growth conditions and the film characteristics are described elsewhere [18]. The thickness of the STO film is 20 nm. The monitoring results of *in situ* reflection high-energy electron diffraction and *ex situ* X-ray diffraction indicate that the STO films are epitaxially grown on the Si substrates and are single phased with the *c*-axis orientation. The Hall coefficient measurement confirms that the resistivity and carrier concentration of the STO films are 1.8×10^{-2} Ω cm and 4.83×10^{19} cm^{-3}, respectively [18].

The size of the samples used in the study was 3×4 mm^2 in area. For the photovoltaic and electrical measurements, two indium electrodes were painted on the surfaces of the STO film and Si substrate, respectively. The photoelectric properties were investigated by two continuous lights of 355 nm and 632.8 nm. The light spot diameter is 2 mm. During the measurements, the electrodes were always kept in the dark to prevent the generation of any electrical contact photovoltage.

3 Results and discussion

The current-voltage (*I*-*V*) characteristic of the STO/Si p-n junction is measured by tuning the applied voltage with a pulse-modulated voltage source at room temperature. The schematic diagram of the measurement circuit is shown in the right inset of Figure 1. Herein, an impedance *R* is in series with the STO/Si junction to provide protection. The forward bias is defined as the current flowing from the Si substrate to the STO. As shown in Figure 1, the junction exhibits a good rectifying behavior. The leakage current is as low as 1.7 μA, when −10 V is applied to the junction. From the left inset of Figure 1, the threshold voltage (diffusion potential, V_D) is about 0.12 V; at that point the current starts to obviously increase as a result of the application of a positive bias voltage.

In order to eliminate the effect of the external electric field and obtain the intrinsic properties, we measured the open-circuit photovoltage (V_{oc}) as a function of light power, which is shown in Figure 2. The photovoltaic signals were measured by a Keithley 2400 source meter with a 1 MΩ resistance (R_L) connected in parallel with the STO/Si heterojunction as shown in the top inset of Figure 2. All of the photoelectric measurements were carried out at room temperature. It can be seen from Figure 2 that the photovoltage increases sublinearly with the light intensity. The saturated light intensity is about 200 μW and the saturated photovoltage V_{oc} is 0.11 V which is coincident with the threshold voltage $V_D = 0.12$ V in Figure 1. In the bottom inset of Figure 2, the photovoltage V_{oc} displays a linear dependence on the incident light power at a range from 0.05 to 2 μW. In the linear region, the photovoltage sensitivity can reach as large as 1.3×10^4 V/W with zero bias, exhibiting a high sensitivity under weak light.

Figure 3 shows a normalized photoresponse spectrum of the STO/Si junction under zero bias illuminated by a 75 W xenon lamp in the wavelength range of 320–1100 nm. The light intensity is calibrated by a silicon photodetector and the spectral responsivity is measured by a monochromator. It can be seen that the photovoltage responsivity of the p-n junction under the illumination from visible to near infrared light is higher than that of UV light. In addition, the junc-

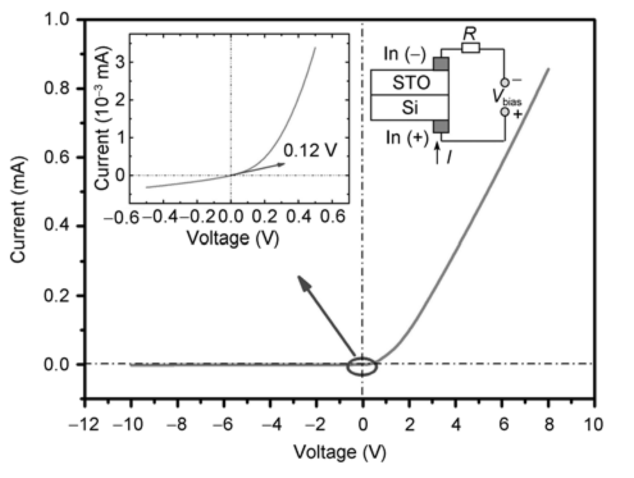

Figure 1 Current-voltage curve of an STO/Si heterojunction at room temperature. An enlarged part of the *I*-*V* curve in the voltage range of −0.5–0.5 V is shown in the left inset. The right inset shows the schematic circuit used for the measurement.

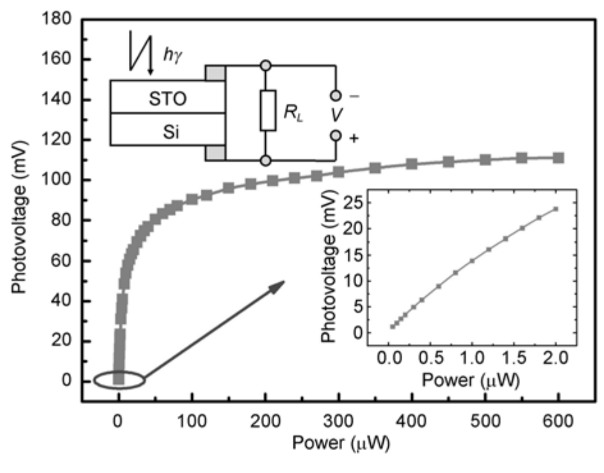

Figure 2 The photovoltage as a function of light power (λ = 632.8 nm) measured at room temperature. The top inset shows the schematic diagram of the photoelectric measurement. An enlarged part of the linear photovoltage response for the light power in the range of 0.05–2 μW is shown in the bottom inset.

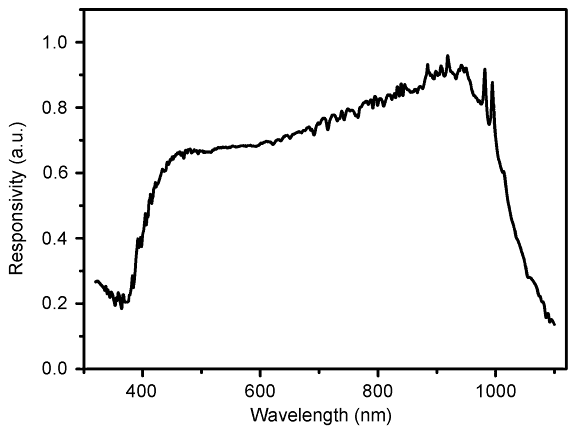

Figure 3 The normalized photoresponse spectrum of the STO/Si junction without bias in the wavelength range of 320–1100 nm.

tion exhibits a higher response under the UV light compared with detectors based on silicon (http://www.zolix.com.cn/templates/channel/index_141_362.html), which indicates that the device composed of the STO/Si heterostructure can be considered as a UV-enhanced photodetector.

As is well known, a p-n heterojunction is formed when depositing a layer of n-type STO thin film on the p-type Si substrate. The electrons with higher density in n-type STO film than those in Si should diffuse into Si, and the holes with higher density in Si than those in STO should diffuse into STO. The diffusion causes a built-in electric field to form in the space charge region around the interface. With the illumination of light, photon-induced carriers, electrons and holes, are separated by the built-in field at the interface and hence cause the photovoltage we measured. In order to understand the mechanism of the above experimental results, the schematic band diagrams of the movement of carriers in the STO/Si p-n heterostructure are plotted in Figures 4(a) and (b). The carrier concentrations measured by Hall measurement are about 1.45×10^{15} cm^{-3} for Si and 4.83×10^{19} cm^{-3} for $SrTiO_{3-\delta}$, respectively. Thus, the space charge region (depletion layer) is mainly located on the side of the Si through the diffusion of carriers. The energy gaps of Si and $SrTiO_3$ are 1.12 and 3.2 eV, respectively, and that of $SrTiO_{3-\delta}$ is thought to be very close to $SrTiO_3$. As shown in Figure 4(a), when the STO film is illuminated under visible light, the incident light can pass through the STO film into the Si; since the photon energy is larger than the band gap of Si and lower than that of STO, the photon-induced carriers are created only in the Si around the interface. The photon-induced carriers, electrons and holes are separated by the built-in field at the interface with hardly any recombination and cause the photovoltage we measured. As shown in Figure 4(b), when the STO film is illuminated under UV light, the photon energy is larger than the band gaps of STO and Si, so the STO film absorbs a great part of the photons and only a small part of the photons can reach the Si side. The photon-induced carriers are mostly created in STO and separated by the built-in field at the interface, so in this case, the recombination of photon-induced carriers in STO is inevitable. Therefore, the junction has a higher sensitivity when the STO film is illuminated by visible light than for the case of UV light. In addition, the junction has a higher response under the UV light compared with the detectors based on silicon because the STO film absorbs UV light and creates the photon-induced carriers.

In order to test the above explanations, we further measured the photovoltaic responses with 355 nm UV light and 632.8 nm visible light. Figure 5 shows the photovoltage variations with the light power under the illuminations of 355 nm and 632.8 nm, respectively. Both of the photovoltages vary linearly with the light intensity at a range from 0.05 to 2 μW, and the photovoltage sensitivity of 632.8 nm visible light is about 3.1 times as large as that of 355 nm UV light, which is consistent with the photoresponse spectrum shown in Figure 3. This demonstrates the enhanced photovoltage responsivity in the visible region.

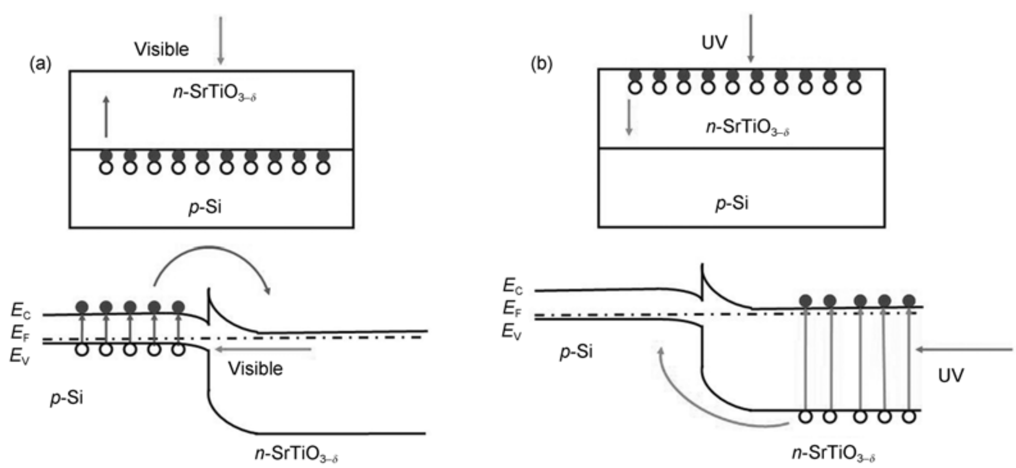

Figure 4 Schematic diagrams of the movements of electrons (solid circle points) and holes (open circle points) in the STO/Si junction under (a) visible light and (b) UV light.

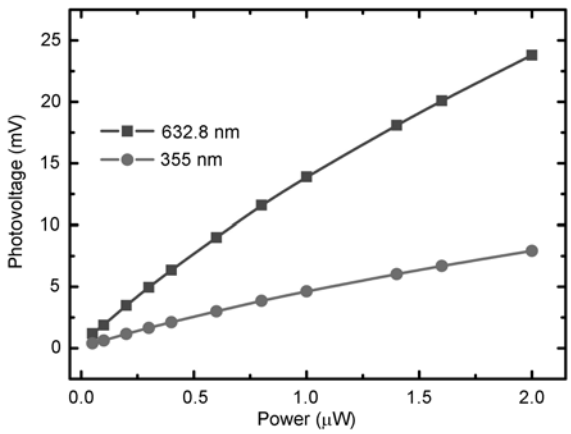

Figure 5 The photovoltage variations with the light power under the illuminations of 355 nm UV light and 632.8 nm visible light.

4 Conclusions

In summary, high sensitivity photoelectrical characteristics have been observed in an STO/Si p-n heterojunction. The STO/Si heterojunction shows a high photovoltage responsivity of 10^4 V/W without bias in the wavelength range from visible to near infrared light in the nW–μW order. The experimental results show that the photovoltage can be greatly enhanced when the incident photon energy is larger than the band gap of Si and lower than that of STO. The interfacial photoelectric effect plays an important role in this process. It suggests that many potential applications of the high-sensitivity photovoltage in these heterojunctions are composed of the wide-bandgap oxide and Si, such as photodetectors, solar cells and others.

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