Photoelectric conversion characteristics of ZnO/SiC/Si heterojunctions*

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Abstract: A series of n-ZnO/n-SiC/p-Si and n-ZnO/p-Si heterojunctions were prepared by DC sputtering. Their structural properties, $I-V$ curves, photovoltaic effects and photo-response spectra were studied. The photoelectric conversion characteristics of n-ZnO/n-SiC/p-Si and n-ZnO/p-Si heterojunctions were investigated. It is found that the photoelectric conversion efficiency of the n-ZnO/n-SiC/p-Si heterojunction is about four times higher than that of the n-ZnO/p-Si heterojunction. The photovoltaic response spectrum indicated that the photoresponse curve of n-ZnO/n-SiC/p-Si increased more strongly than that of n-ZnO/p-Si with the wavelength increasing. It shows that the photoresponse of n-ZnO/p-Si can be enhanced when inserting a 3C-SiC layer between ZnO and Si. There is one inflexion in the photocurrent response curve of the n-ZnO/p-Si heterojunction and two inflexions in that of the n-ZnO/n-SiC/p-Si heterojunction. It is clear that the 3C-SiC plays an important role in the photoelectric conversion of the n-ZnO/n-SiC/p-Si heterojunction.

Key words: ZnO/SiC/Si heterojunction; photoelectric conversion; photoresponse spectrum
DOI: 10.1088/1674-4926/31/10/103002 **PACC:** 7240; 7340L; 8115G

1. Introduction

Solar cells are a clean, abundant and convenient energy source that has attracted increasing attention from researchers. Heterojunction solar cells, which consist of a wide band gap transparent conductive oxide and a single crystal silicon wafer, have a number of advantages, such as an excellent blue response, simple processing steps and low processing temperatures[1–4]. Zinc oxide (ZnO) has been widely studied due to its immense application potential in short wavelength optoelectronic devices and laser diodes[5–8]. It can be used as a coating on thin film photovoltaic cells, antireflective coatings in conventional silicon solar cells, light emitting diodes, and thin film transistors[9–12], etc. The ZnO/Si heterojunction solar cell is a candidate for silicon mono-junctions and low-cost solar cells. In the cell, ZnO film is used not only as solar cell's window but also as a p–n heterojunction partner[13, 14]. However, the photoelectric conversion efficiency of the ZnO/Si heterojunction is very low[15, 16]. Silicon carbide (SiC) is a wide gap semiconductor, which has high electron mobility, high transparency, high break down field and high thermal conductivity[17, 18]. Its band gap is about 2.3 eV (3C-SiC), which is larger than that of Si (1.1 eV) and smaller than that of ZnO (3.37 eV). If SiC is inserted between ZnO and Si, it can extend the utilizing range of solar spectrum of the ZnO/Si heterojunction. Thus, the ZnO/SiC/Si structure will have higher conversion efficiency than the ZnO/Si heterojunction. In our present work, a SiC layer is inserted between ZnO and Si to fabricate the ZnO/SiC/Si heterojunction. Then the photovoltaic effect and photoresponse spectrum of the heterojunction is investigated. As we know, there have never been reports about this work. It is expected that the ZnO/SiC/Si heterojunction can utilize solar energy across a wide spectrum.

2. Experiment

In the experiments, the 3C-SiC thin films with thickness of about 800 nm were deposited on p-Si substrates at about 1300 ℃ by our laboratory LP-MOCVD. Details of the growth procedure can be found elsewhere[19]. Then the n type ZnO films with thickness of about 200 nm were deposited on 3C-SiC/p-Si wafers by DC sputtering to create n-ZnO/3C-SiC/p-Si structures. For comparison, the n-ZnO thin films were also deposited directly on p-type Si substrates to produce n-ZnO/p-Si structures in order to compare the photoelectric properties of these different heterojunctions. In the sputtering, a zinc disc of diameter 50 mm with a purity of 99.99% was used as a target. High purity argon and oxygen were used as the sputtering and reactive gases, respectively. The substrates were placed on a graphite susceptor, whose distance from the target was about 4.5 cm, and it was heated by resistance elements. The reaction chamber was pumped to a base pressure of 8×10^{-3} Torr before deposition. All the samples were deposited at a substrate temperature of 300 ℃. The crystal structure was measured by X-ray diffraction (XRD) using a D/Max-rA type system with CuKα radiation (λ = 1.541 Å). The SnO_2 transparent conductive film was used as the electrode, which has been demonstrated as an ohmic contact by current–voltage characteristics. The photovoltaic effect of the samples was measured by using an incandescent lamp with a constant emitting power (12 mW), whose irradiation area was kept a constant, ϕ 6 mm. A YEW type 3036 $X-Y$ recorder was used to measure the current–voltage characteristics of samples under dark and illumination conditions. N LHX 150 type xenon light with 150 W power and WDS-5 grating monochromator was used to mea-

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* Project supported by the National Natural Science Foundation of China (No. 50532070) and the Funds of Chinese Academy of Sciences for Knowledge Innovation Program (No. KJCX3.5YW.W01).

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Received 10 May 2010, revised manuscript received 9 June 2010

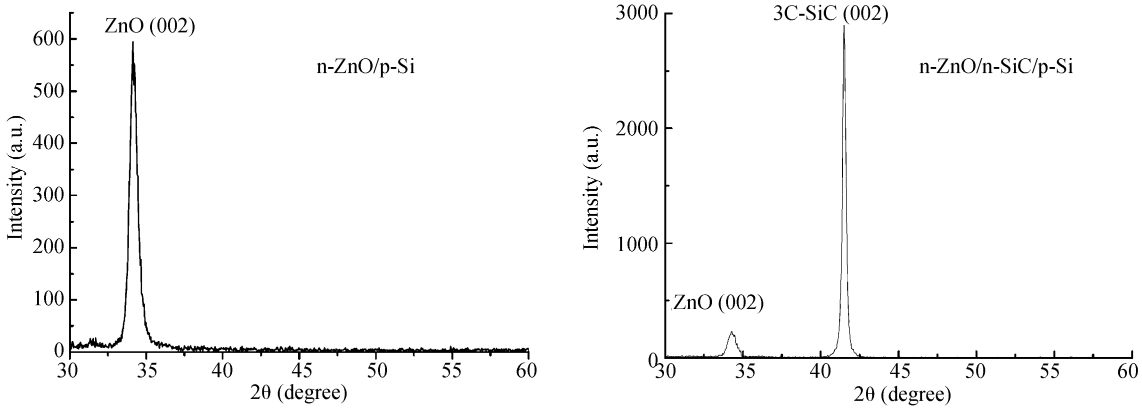

Fig. 1. X-ray diffraction patterns of n-ZnO/p-Si and n-ZnO/3C-SiC/p-Si structures, respectively.

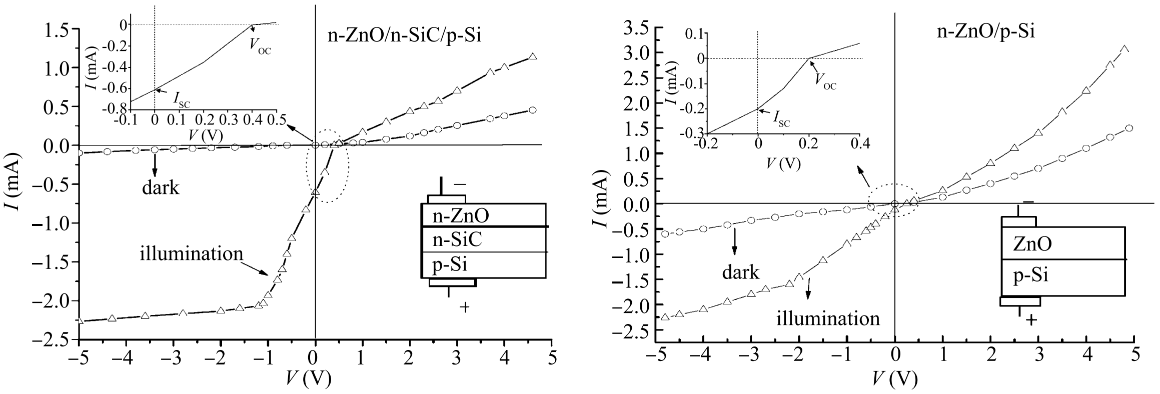

Fig. 2. I–V characteristics of n-ZnO/n-SiC/p-Si and n-ZnO/p-Si heterojunctions measured under dark and illumination conditions.

sure the photoresponse spectrum. All the measurements were performed in air at room temperature.

3. Result and discussion

3.1. X-ray diffraction

Figure 1 shows the X-ray diffraction patterns of n-ZnO/p-Si and n-ZnO/3C-SiC/p-Si structures, respectively. From these patterns we found that n-ZnO/p-Si only had a high diffraction peak of ZnO (002) at 2θ value of 34.25, which demonstrated that the sample grew along the c-axis oriented perpendicular to the substrate surface. For the n-ZnO/n-SiC/p-Si, only diffraction peaks corresponding to the ZnO (002) at 2θ value of 34.30 and 3C-SiC (002) at 2θ value of 41.50° diffraction were observed, which demonstrated that the n-ZnO/n-SiC/p-Si heterojunction had good quality.

3.2. Photovoltaic effect

Figure 2 shows the I–V characteristics of n-ZnO/n-SiC/p-Si and n-ZnO/p-Si heterojunctions measured under dark and illumination conditions, respectively. The n-ZnO/p-SiC/p-Si and n-ZnO/p-Si heterojunctions all have good p–n junction properties measured under dark conditions. When the samples were illuminated by an incandescent lamp, both the n-ZnO/n-SiC/p-Si and n-ZnO/p-Si heterojunctions generated photovoltaic effects and the reverse current increased strongly with increasing reverse voltage. It was also observed that the n-ZnO/n-SiC/p-Si heterojunction had better photoelectric conversion characteristics and the photocurrent reached a saturated current of about –2.4 mA at a reverse voltage of about 1 V.

Table 1. Open circuit voltage ($V_{\rm oc}$) and short circuit photocurrent ($I_{\rm sc}$) of samples.

Parameter	n-ZnO/n-SiC/p-Si	n-ZnO/p-Si
$V_{\rm oc}$ (mV)	380	200
$I_{\rm sc}$ (μA)	600	220

The open circuit voltage ($V_{\rm oc}$) and short circuit photocurrent ($I_{\rm sc}$) of these samples were measured. The values are listed in Table 1. It is known that the photoelectric conversion efficiency of the samples is proportion to $V_{\rm oc}I_{\rm sc}$. According to calculations by using the values listed in Table 1, we found that the photoelectric conversion efficiency of the n-ZnO/n-SiC/Si heterojunctions was about four times higher than that of the n-ZnO/p-Si heterojunctions.

3.3. Photoresponse spectrum

The photo-response properties of the n-ZnO/p-Si and n-ZnO/n-SiC/p-Si heterojunctions have been characterized by photovoltaic response spectrum (Fig. 3) and photocurrent response spectrum (Fig. 4). These two spectra were all measured by using an LHX 150 type xenon light with 150 W power and a WDS-5 grating monochromator.

In Fig. 3, the two electrodes, front electrode and back electrode, were deposited on the surface of the ZnO film and on the back of the Si substrate, respectively. The photovoltage be-

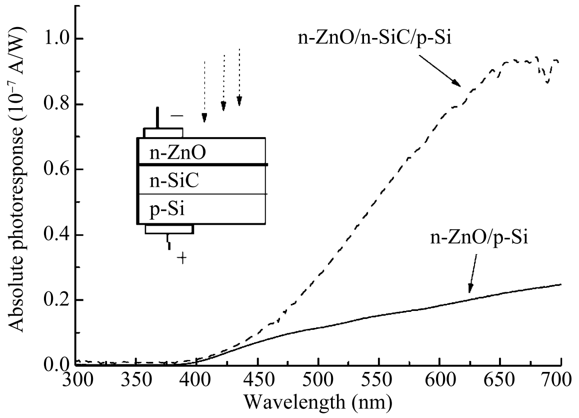

Fig. 3. Photovoltage response spectrum of n-ZnO/p-Si and n-ZnO/n-SiC/p-Si heterojunctions.

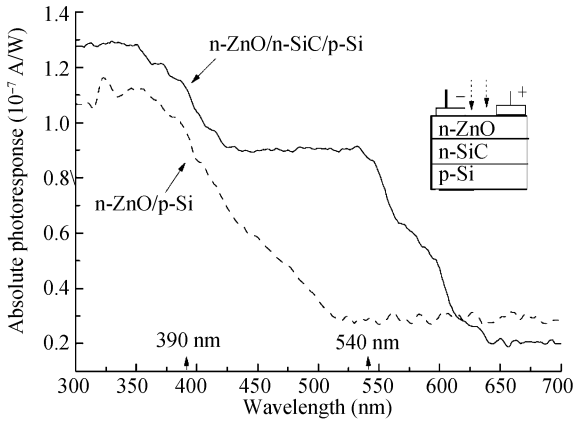

Fig. 4. Photocurrent response spectrum of n-ZnO/p-Si and n-ZnO/n-SiC/p-Si heterojunctions.

tween the two electrodes of the samples irradiated at different wavelength was measured. Figure 3 shows that the n-ZnO/p-Si and n-ZnO/n-SiC/p-Si heterojunctions both generate photovoltage after 380 nm, which almost equals the band gap energy of ZnO. However, the photoresponse of the n-ZnO/n-SiC/p-Si increases more strongly than that of the n-ZnO/p-Si with increase in wavelength. It is clear that the photoresponse of the n-ZnO/p-Si can be enhanced by inserting a 3C-SiC layer between the ZnO and Si.

In Fig. 4, the two electrodes of the sample were manufactured on the same surface of ZnO film to measure the photocurrent of the ZnO film irradiated at the different wavelengths. While the energy of incident light is near or greater than the band gap energy of the semiconductor material, the incident photon can be absorbed to generate electron–hole pairs, and then form the photocurrent[20]. While the energy of incident light is lower than the band gap energy of the semiconductor material, the incident ray will transmit this material. In Fig. 4, it is clear that the n-ZnO/p-Si and n-ZnO/n-SiC/p-Si have different photocurrent response curves. For the n-ZnO/p-Si structure, when the wavelength of the incident light was shorter than 390 nm, whose energy was almost equal to the band gap energy of ZnO, the photocurrent through the ZnO film was high, because the ZnO absorbs light energy and generates photocurrent. When the incident wavelength was larger than 390 nm, the incident light transmitted the ZnO film so that the photocurrent decreased quickly. However, there are two inflexions in the photocurrent response curve of the n-ZnO/n-SiC/p-Si heterojunctions. The energy of these inflexions at 390 nm and 540 nm correspond to the band gap energy of ZnO and 3C-SiC, respectively. When the incident wavelength was shorter than 390 nm, the photocurrent was also high as the n-ZnO/p-Si. When the incident light wavelength was from 390 to 540 nm, the incident photon energy was absorbed by SiC. It should affect the photocurrent measured on ZnO film. In the experiment, the effect of Si was not observed because the incident photon energy measured here is higher than that of the band gap of Si. Therefore, these results demonstrate that the 3C-SiC layer enhances the photoelectric conversion efficiency. The 3C-SiC plays an important role in the photoelectric conversion of the n-ZnO/n-SiC/p-Si heterojunction. This is useful for fabricating solar cells.

4. Conclusion

In our present work, a series of n-ZnO/n-SiC/p-Si and n-ZnO/p-Si heterojunctions were prepared by DC sputtering. It was found that the photoelectric conversion efficiency of the n-ZnO/n-SiC/p-Si heterojunctions was about four times that of the n-ZnO/p-Si heterojunctions. The photoresponse spectrum indicated that the photoresponse curve of the n-ZnO/n-SiC/p-Si heterojunctions increased more strongly than that of n-ZnO/p-Si heterojunctions as the wavelength increased. SiC could absorb the incident light whose wavelength was located between the band gap value of ZnO and Si, and enhance the photoelectric conversion efficiency. Therefore, the SiC layer played an important role in the photoelectric conversion of the n-ZnO/n-SiC/p-Si heterojunction. It was suggested that the n-ZnO/n-SiC/p-Si heterojunction could be a good candidate for solar cells.

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