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Study and Fabrication of a Au/n-ZnO/p-Si Structure UV-Enhanced Phototransistor*

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Abstract: The fabrication and characterization of a Schottky-emitter heterojunction-collector UV-enhanced bipolar phototransistor (SHBT) are presented. The luminescence peak of the ZnO film is observed at 371nm in the PL spectrum. The sensitivity of the ultraviolet response from 200 to 400nm is enhanced noticeably, and the spectrum response at wavelengths longer than 400nm is also retained. The experiments show that the Au/n-ZnO/p-Si SHBT UV enhanced phototransistor enhances the sensitivity of the ultraviolet response noticeably. The UV response sensitivity at 370nm of the phototransistor is 5~10 times that of a ZnO/Si heterojunction UV enhanced photodiode.

Key words: Schottky; heterojunction; WBG semiconductor ZnO; UV phototransistor

PACC: 4280; 4270G; 6855

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1 Introduction

ZnO is a direct band gap semiconductor material with a band gap of 3.32eV and high chemical and temperature stability[1], and it can be widely used in UV detectors, solar cells, transparent electrodes, and UV blue photo LEDs and LDSs[2].

Using the 200~400nm UV photo-response of the wide band gap (WBG) material n-ZnO and the 400~1000nm response of the narrow band gap material p-Si as a heterojunction collector, a Au/n-ZnO structure as a Schottky emitter, and a transparent n-ZnO layer as a base, we designed and fabricated vertical Au/n-ZnO/p-Si Schottky emitter heterojunction collector bipolar UV-enhanced phototransistors (SHBTs)[3~5]. The device's *I-V*, *C-V*, and photo spectrum response characteristics have been tested, and the luminescence peak of the ZnO film has also been observed at 371nm in the PL spectrum[6]. The sensitivity of the ultraviolet response from 200 to 400nm has been enhanced noticeably, and the spectrum response at wavelengths longer 400nm, which is the response wavelength range of traditional Si photo-detectors, is also retained[7]. The experiments show that this phototransistor has noticeably enhanced the sensitivity of the ultraviolet response, and the UV response sensitivity at 370nm of the phototransistor is about 5 times that of a ZnO/Si heterojunction UV enhanced photodiode[8].

2 Experiment and technology

The structural schematic diagram of the phototransistor is shown in Fig. 1.

High quality, 200nm thick SiO_2 film was grown on p^+-Si substrates in oxidation furniture at 1050℃ with dry-wet-dry oxygen for 10, 40, and 10min. SiO_2 was etched off from the active region by MOCVD, and a layer of n-ZnO film with 500~1000nm thick was grown on the substrate with a direct current magnetism spattering reactor. After wet-etching away the ZnO film (remaining an active ZnO region), a 20nm SiO_2 film was spattered on the top. Then a SiO_2 window was etched, and a 10~20nm transparent Au-film was deposited by e-beam evaporation (EBE). After etching the Au-film, the Schottky-emitter of Au/n-ZnO and heterojunction-collector of n-ZnO/p-Si were finished. Furthermore, Al and Ti-Ni-Ag films were evapo-

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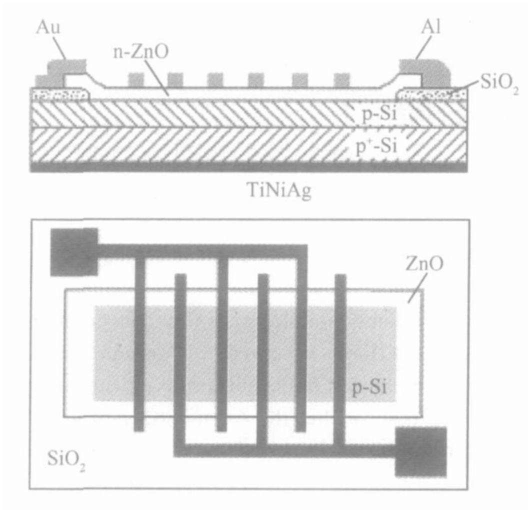

Fig. 1 Structure of the SHBT

rated on the ZnO window and p$^+$-Si substrate respectively and then etched and annealed at 400～450 ℃ with highly pure argon as an ohmic contact[3,10].

3 Principle and test analysis

Figure 2 is the diagram of the ideal energy band structure of the Au/ ZnO/ Si SHBT phototransistor.

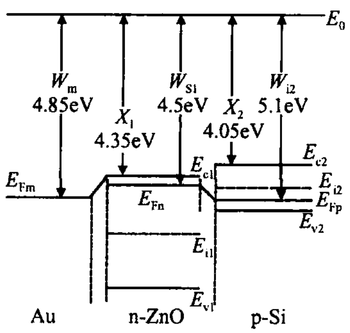

Fig. 2 Energy band of Au/ n-ZnO/ p-Si structure

The W_m (work function) of Au is 4.85eV, the X_1 and W_{S1} of n-ZnO are 4.35 and 4.5eV, and the X_2 and W_{S2} of p-Si are 4.05 and 5.1eV. According to the thermic emission of a Schottky barrier diode, the current equation is

$$J = J_0 (e^{qV/nkT} - 1)$$

where J is the current density, q is the charge of an electron, k is the Boltzmann constant, and T is the absolute temperature. The saturation current density J_0 is given by

$$J_0 = R^* T^2 e^{-\phi_{ns}/kT} X$$

where R^* is the Richardson constant with a theoretical value of about 32A/ (cm^2 · K^2)[11]. The effective area of the Au/ n-ZnO Schottky barrier diode is 2mm^2 and the ideality factor n is about 1.8. At room temperature, $kT \approx 0.026$eV. According to the following equation,

$$\Phi_{ns} = W_m - X_1 = (4.85 - 4.35)\text{eV} = 0.5\text{eV}$$

the Schottky barrier is 0.5eV and the reverse leakage current I_0 is 1.02×10^{-10}A at a reverse voltage of 5V. Figure 3 shows the I-V characteristics of the SBD at reverse voltage. The curve " dark light " is the reverse leak current with 5×10^{-8}A at reverse 5V, the curves " room light " and " UV-light " are photospectrum responses at reverse bias[11].

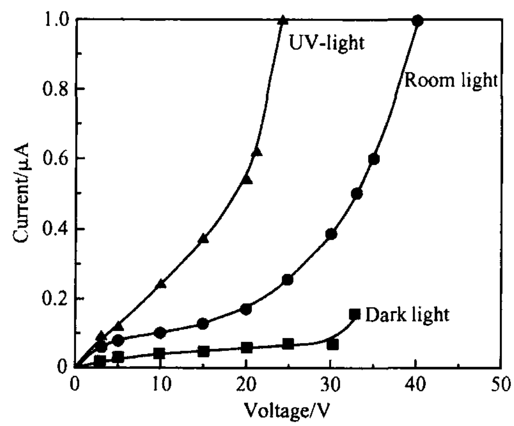

Fig. 3 I-V characteristics of Au/ n-ZnO SBD

The C-V characteristics of the Au/ n-ZnO SBD are shown in Fig. 4. The effective chip area is A = 2mm^2 (1mm × 2mm), the peak value capacitance is 35pF with zero bias, and the minimum capacitance is 2.5pF at 4 and -4V. The structure of the SBD is designed as an inter-digital so the capacitance curve is symmetrical.

The I-V characteristics of the n-ZnO/ p-Si heterojunction collector are shown in Fig. 5. According to the semiconductor heterojunction theory, the ϕ_{np} is $W_{S1} - W_{S2}$, there W_{S1} and W_{S2} are function of N_D and N_A respectively. Because n-ZnO and p-Si are wide and narrow band gap semiconductors respectively, the value of qV_D varies significantly with N_D and N_A, so it is very important to choose the concentrations of p-Si and n-ZnO. In this study, $N_A \approx 8 \times 10^{16}$cm^{-3} and $N_D \approx 10^{17} \sim 10^{18}$cm^{-3} were chosen to obtain a well-formed qV_D. The forward turn on V_t shown in Fig. 5 is about 0.3 to 0.4V, and the breakdown voltage V_{bc} is about -6V[8].

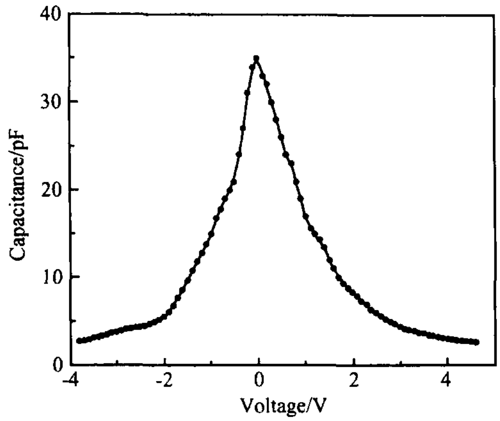

Fig. 4　C-V characteristics of Au/ n-ZnO SBD

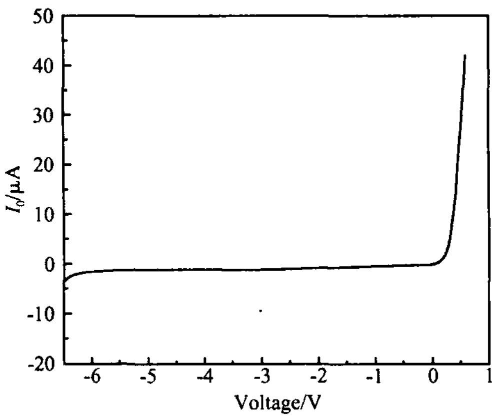

Fig. 5　I-V characteristics of n-ZnO/ p-Si

Figure 6 shows the photocurrent response of the n-ZnO/ p-Si heterojunction collector with an optical wavelength ,according to the formula[8] :

$$\lambda = \frac{hc}{E_g} = \frac{1.24}{E_g} (\mu\text{m})$$

where the cut off wavelength of λ is about 373.5nm for E_g = 3.32eV for ZnO. The photocurrent I_p is about 0.14 ,0.17 ,and 2.2μA at 373 ,400 , and 425nm respectively. For I_p = 0.14μA at λ_m = 373nm ,the input photo power is 5μW ,and the output $I_p^2 R$ is about 0.4μW($R = 2 \times 10^6 \Omega$) ,so η is about 8 %.

Another important parameter for the phototransistor is the direct current gain β[11] :

$$\beta = \frac{1}{\frac{W_B^2}{2\tau_B D_p} + \frac{D_n}{D_p} \times \frac{W_B}{L_p} \times \frac{N_D}{N_A}}$$

For giving N_D , N_A , D_n , D_p , τ_B ,and L_p ,the parameter W_B has a very important influence on the magnitude of β. Because the thickness of n-ZnO ≈ W_B , we alternated the thickness of the n-ZnO film from 200 to 500nm at different deposition times and gas

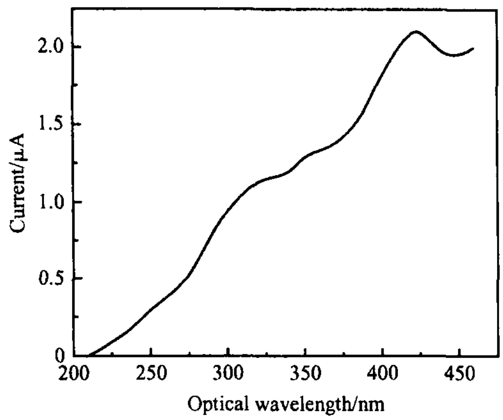

Fig. 6　Photo-current response at optical wavelengths

streamflows and other procedure conditions. Figure 7 shows the characteristics of the UV light photocurrent gain at different I_b (bias current) . For some samples , β is about 3 to 5 times (V_{CE} range from 2 to 5V and the thickness of n-ZnO film is about 300nm) .

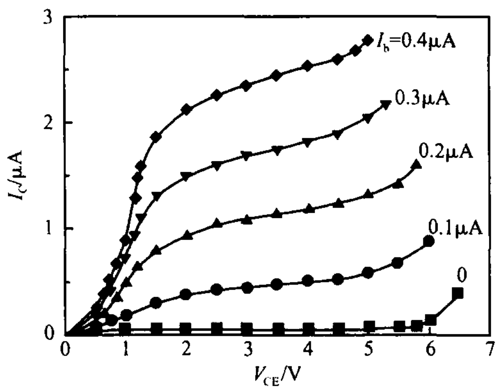

Fig. 7　UV light photocurrent response of SHBT for different VCE

In addition ,because the electron mobility of n-ZnO material is much lower than in n-Si material , and the n-ZnO film is not a perfect crystal[13] ,the value of β for a ZnO SHBT is much smaller than for a Si-pnp transistor. The ZnO is a UV transparent , wide band gap semiconductor , so a UV-enhanced bipolar phototransistor with a Au/ n-ZnO/ p-Si structure is a better device for UV and sunlight detection.

Figure 8 is a photograph of the original device. There are four identical SHBT phototransistors on a single chip , and each has its own emitter and base pin , and the back is their common collector pin.

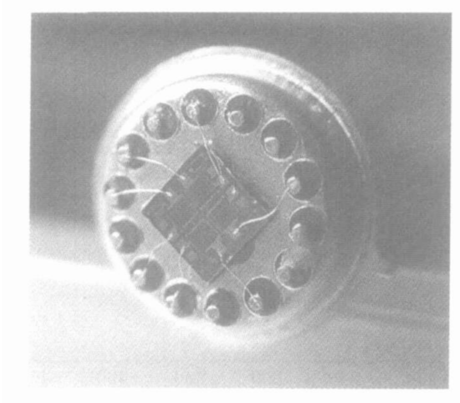

Fig. 8 Photograph of the original device

4 Conclusion

We have fabricated a Schottky-emitter heterojunction-collector bipolar UV-enhanced phototransistor by adopting a Au/ n-ZnO/ p-Si structure. The sensitivity of the UV light response from 200 to 400nm is enhanced, while retaining the response to visible light. The UV photocurrent gain is about 3～5 times. Although the β of the SHBT is lower than that of a Si phototransistor, the SHBT still has a much better UV-light response.

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Au/ n-ZnO/ p-Si 结构的紫外增强型光电三极管的研制 *

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摘要: 研究和制作了一种新型 Au/ n-ZnO/ p-Si 结构的肖特基发射极、异质结集电极紫外增强双极型光电三极管. 分析了器件原理, 测试了 I-V 特性、C-V 特性以及器件的光谱响应, 从 200 到 400nm 的紫外光响应灵敏度得到明显增强而对大于 400nm 的可见光的响应特性得到保留. 实验显示 Au/ n-ZnO/ p-Si 结构的紫外增强型的光电三极管对紫外光的响应明显增强, 对 371nm 波长的紫外光的灵敏度是普通 n-ZnO/ p-Si 异质结紫外光电二极管道的 5～10 倍.

关键词: 肖特基; 异质结; 宽带隙半导体 ZnO; 紫外光电三极管

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