p^+-Si/i-Si/n-SiC heterostructure photodiode used in visible region

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In order to realize non-UV light operation, a Si film grown on SiC is used as a non-UV light-absorption layer, so as to develop the SiC-based photoelectronic devices applied in high temperature and high power regions. Energy-band structure and photoelectric properties of the p^+-Si/i-Si/n-SiC heterostructure are simulated by Silvaco-TCAD. And the p-i-n photodiode used in visible region was fabricated on 6H-SiC substrate successfully. Compared with the p-Si/n^+-SiC photodiode, the p^+-Si/i-Si/n-SiC photodiode exhibits better photoelectric performance, the photocurrent and the open-circuit voltage increase to 24.4mA/cm^2 and 156mV respectively under visible illumination of 0.6W/cm^2, especially the photocurrent increases by two orders of magnitude.

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1. Introduction

Silicon carbide (SiC) is an appropriate semiconductor material for the photoelectric devices applied in high temperature and high power regions due to its advantageous material properties. SiC photodiodes [1], Ni/4H-SiC Schottky photodiodes [2], 4H-SiC light-operated thyristors [3] and SiC optoinjected CCD [4] have been fabricated successfully. However, due to the wide bandgap of SiC, SiC-based photoelectric devices can only be driven by ultraviolet (UV) light, which essentially limit its application for a detection of visible and infrared light. In order to realize non-UV light operation, a Si film grown on SiC is used as a non-UV light-absorption layer, so as to develop the SiC-based photoelectronic devices [5-7]. In our previous works, p-Si/n^+-6H-SiC heterojunction non-UV photodiode was fabricated on 6H-SiC substrate and the non-UV light operation of the SiC devices was realized [6]. However, because of the interface defect states, the photocurrent and the maximum open-circuit voltage of the Si/SiC heterojunction were found to be J_{ph} =0.6mA/cm^2 and V_{oc}=92.0mV under non-UV light illumination of 0.6W/cm^2 respectively and didn't meet the expectations [7].

Considered the good long-wavelength photo-response caused by the wide depletion region, the p^+-Si/i-Si/n-SiC structure is used. In this paper, energy-band structure and photoelectric properties of the p^+-Si/i-Si/n-SiC heterostructure on 6H-SiC is simulated by Silvaco-TCAD. Meanwhile, the p-i-n photodiode used in visible region is prepared, and the device characteristics are investigated.

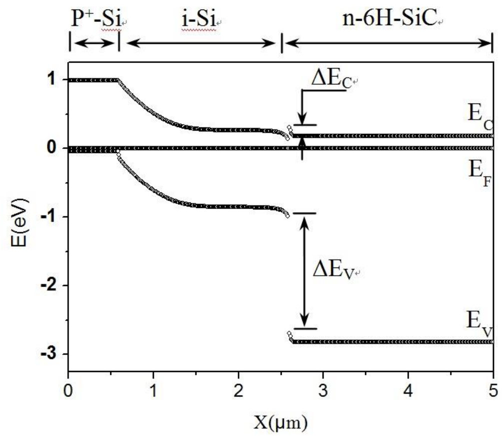

Fig. 1. Energy-band diagram for the p^+-Si/i-Si/n-SiC heterostructure in equilibrium.

2. Experimental

The p^+-Si/i-Si/n-SiC heterostructure was prepared on 6H-SiC substrate by low-pressure chemical vapor deposition. An 6H-SiC(0001) wafer of n-type doped (10^{17}cm^{-3}) was purchased from II-VI Inc.. The Si films were grown on 6H-SiC substrates at 850 ^{o}C. Silane (SiH_4), diborane (B_2H_6) and hydrogen (H_2) are used as a silicon source, a dopant source and a carrier gas, respectively. The growth rate of the Si films is about 2μm/h. Four-point probe test and non-contact resistivity test results indicate that the i-Si layer is n-type doped with a low doping concentration of ~1×10^{15}cm^{-3}, the p$^+$-Si layer is high doped with a doping concentration of ~1×10^{19}cm^{-3}. To investigate the electrical and photoelectric properties of the p$^+$-Si/i-Si/n-SiC heterojunction, the ohmic contacts on n-SiC substrate and p$^+$-Si layer were prepared by the deposition of Ni and Al respectively followed by rapid thermal annealing. Details of the epitaxial growth and the ohmic contact are described elsewhere [6].

J-V characteristics of the p$^+$-Si/i-Si/n-SiC heterostructure photodiode were measured with an Agilent 4155C semiconductor parameter analyzer. Photoelectric response was examined using a tungsten halogen lamp as visible light source [6].

3. Results and discussion

An approximate equilibrium energy-band diagram for the p$^+$-Si/i-Si/n-SiC heterostructure is shown in Fig. 1. In simulation, the bandgap and electron affinity of 6H-SiC are set as 3.0eV and 3.85eV [8], respectively. The doping concentration of the p$^+$-Si layer, i-Si layer and n-SiC substrate are set as 10^{19}cm^{-3}, 10^{15}cm^{-3} and 10^{17}cm^{-3}, which are consistent with the optimized parameters of the fabricated photodiode. Heterojunction barriers are formed at the i-Si/n-SiC interface. The energy offsets of the i-Si/n-SiC heterojunction in the conduction band and valance band are found to be ΔE_C=0.17eV and ΔE_V=1.71eV, respectively. Because electron affinity of poly-Si (~4.05eV) is close to that of 6H-SiC, the barrier height for electrons of i-Si/n-SiC is very low. The electrons are the dominated current carriers because the barrier is smaller for electrons as compared to holes.

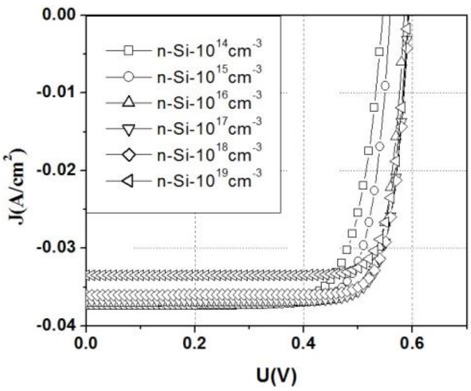

Fig. 2. Simulated photoelectrical characteristics of the p$^+$-Si/i-Si/n-SiC photodiode under visible illumination with different doping concentrations of i-Si layer.

The i-Si layer is the absorption and conversion region of the visible light in p-i-n photodiode, the doping concentration of the i-Si layer has a great influence on the photoelectric performance, therefore the J-V characteristics of the p$^+$-Si/i-Si/n-SiC structure under visible illumination with different i-Si doping concentrations are simulated, as shown in Fig. 2. Under visible illumination of 0.1W/cm^2, an apparent photodiode operation with a photoelectric effect is observed. When the doping concentration of the i-Si layer is 1×10^{19}cm^{-3}, the photocurrent J_{ph} and the maximum open-circuit voltage V_{OC} are 33.5mA/cm^2 and 0.60V, respectively. As the decrease of the i-Si doping concentration, the photocurrent increases remarkably. The carrier charges are mainly generated when the i-Si layer absorbs visible light, while the n-SiC substrate has no contribution to photoelectric conversion of the visible light. The low doping concentration of the i-Si layer is in favor of broadening the depletion layer and reducing the photocarrier recombination, and thus improving the photo-response. However, when the doping concentration is lower than 10^{16}cm^{-3}, the photocurrent increase is less obvious. This is due to the small broadening rate of the depletion layer when the i-Si doping concentration is low. Based on the simulation results and the actual preparation, 10^{15}cm^{-3} is considered to be a suitable doping concentration of the i-Si layer. The simulations also show that the photocurrent J_{ph} and the open-circuit voltage V_{OC} have the usual linear and logarithmic dependence on the illumination power when the illumination power density is less than 1W/cm^2.

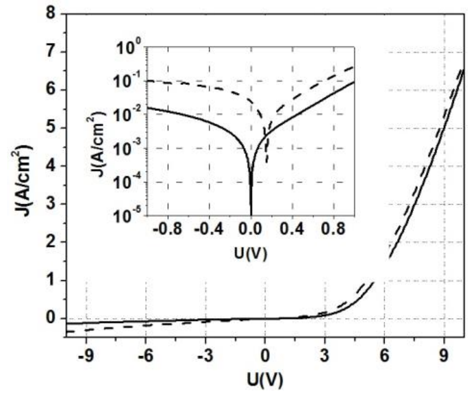

Fig. 3. The electrical and photoelectrical characteristics of the fabricated p$^+$-Si/i-Si/n$^+$-SiC heterojunction photodiode.

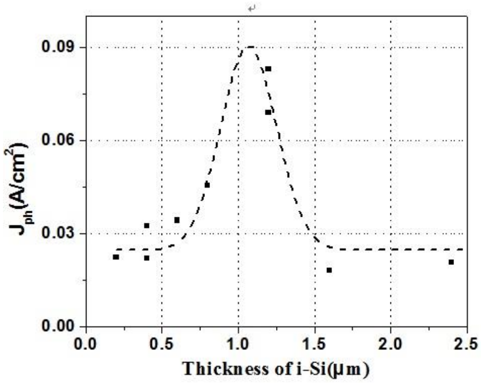

Fig. 4. The J_{ph} of the fabricated p$^+$-Si/i-Si/n-SiC heterojunction photodiode with different i-Si thickness under visible illumination.

J-V characteristics of the fabricated p^+-Si/i-Si/n-SiC photodiode are measured at room temperature, as shown in Fig. 3. The solid and the dashed lines represent the dark and illuminated J-V characteristics, respectively. Based upon the above analysis, the doping concentration of the i-Si layer is controlled as $10^{15}cm^{-3}$. The photodiode indicates good rectifying behavior with rectifying ratio up to 50 at ±5V. The turn-on voltage is about 1.8V. Compared with the p-Si/n^+-SiC photodiode [6], the p^+-Si/i-Si/n-SiC photodiode exhibits better photoelectric performance, the photocurrent and the open-circuit voltage increase to J_{ph}=24.4mA/cm^2 and V_{OC}=156mV respectively under visible illumination of 0.6W/cm^2, especially the photocurrent J_{ph} increases by two orders of magnitude. This is mainly because the wide depletion region of the i-Si layer enhances the photoelectric conversion efficiency. Moreover, the p-i-n structure restrains the direct effect of the Si/SiC interface defect states, and the high doped p^+-Si layer is beneficial to reduce the contact resistance of the Al ohmic electrode, which are also suggested as the reasons for the performance improvement.

Fig. 4 shows the photocurrent of the fabricated p^+-Si/i-Si/n-SiC heterojunction photodiode with different i-Si thickness under visible illumination of 0.6W/cm^2. When the i-Si thickness changes from 0.2μm to 2.4μm, the photocurrent of the p^+-Si/i-Si/n-SiC photodiode has a decline trend after an initial ascent. The Gauss fitting curve based on test data shows that the maximum photocurrent density of 90.0mA/cm^2 is obtained when the i-Si thickness is 1.1μm. when the thickness is less than 1.1μm, the entire i-Si layer is depleted, the visible light absorption region broadens as the thickness increase, therefore the photocurrent increases. However, as the thickness is more than 1.1μm, the i-Si layer is not depleted, the thickness increase is not able to broaden the depleted layer, but raises the series resistance of the photodiode, and thus the photocurrent reduces.

4. Conclusions

Energy-band structure and photoelectric properties of the p^+-Si/i-Si/n-SiC heterostructure is simulated by Silvaco-TCAD. And the p-i-n photodiode used in visible region was fabricated on 6H-SiC substrate successfully. Compared with the p-Si/n^+-SiC photodiode, the p^+-Si/i-Si/n-SiC photodiode exhibits better photoelectric performance, the photocurrent and the open-circuit voltage increase to 24.4mA/cm^2 and 156mV respectively under visible illumination of 0.6W/cm^2, especially the photocurrent increases by two orders of magnitude.

Acknowledgments

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