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4H-SiC Avalanche Photodiodes for 280 nm UV Detection

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Abstract We designed and fabricated 4H-SiC PIN avalanche photodiodes (APD) for UV detection. The thickness of an intrinsic layer in a PIN structure was optimized in order to achieve the highest quantum efficiency at the wavelength of interest. The optimized 4H-SiC PIN APDs exhibited a maximum external quantum efficiency of >80 % at the wavelength of 280 nm and a gain greater than 40000. Both electrical and optical characteristics of the fabricated APDs were in agreement with those predicted from simulation.

Keyword avalanche photodiode silicon carbide UV detection

1. Introduction

Solid-state UV detectors potentially have the benefit of cheap and portable devices while photomultiplier tubes are fragile, bulky, and costly. Si or GaAs-based UV photodiodes are currently available in market but exhibit inherent limitations. The main drawback of these narrow bandgap semiconductor photodiodes is degradation due to high energy radiation. Other problems include poor signal-to-noise ratio in the deep-UV range and sensitivity to visible and infrared photons [1]. At this point of view, silicon carbide (SiC) is a suitable material for detection of UV radiation because of its large energy bandgap (~3.2 eV) and extremely low intrinsic concentration. In addition, SiC can be utilized in harsh environment and/or for high temperature applications. Potential applications include missile plume or jet engine detection, for use in biological agent warning systems, etc. III-nitrides have also been attractive because of its tunable spectral responses but their high dislocation densities caused by lattice mismatch with a foreign substrate have limited their performance [2].

A PIN photodiode is a popular type of solid-state photodetectors and generally the signal-to-noise ratio can be further enhanced by operating it in the avalanche breakdown region; avalanche mode operation. In this work, we employed 4H-SiC PIN APDs and optimize the PIN structure to achieve the highest quantum efficiency at the wavelength of interest, i.e. 280-290 nm. Potential applications are non-line-of-sight covert communication and specific bio-agent detection

2. Device Design

Figure 1 shows a schematic cross-sectional view of the PIN APD studied in this work. The structure consists of an n^+ anode layer, an n^- intrinsic layer (multiplication region), and a p^+ cathode layer from top to bottom. To lower the electric field nearest the mesa sidewall (to prevent surface leakage and device degradation), the APD mesas have a beveled-edge profile. This is particularly important in the highest electric field regions, those in the vicinity of the depletion region. A beveled mesa with a small slope angle of 10° was used in this work. Using n-type doped materials for the top layer is beneficial as the diffusion length of minority holes in n-type 4H-SiC has been reported to be longer than that of minority electrons in p-type [3, 4]. As a result, more carriers can diffuse into the avalanche region and thus give rise to higher photocurrents particularly at high photon energies where the photon penetration depth is shallow [5].

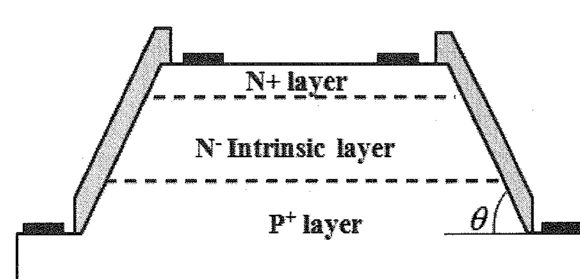

Fig 1. Schematic cross-sectional view of 4H-SiC PIN APD.

The design goal of PIN structures was to enhance the quantum efficiency and lower the dark in order to improve the signal-to-noise ratio. In general, increasing an intrinsic layer thickness will reduce the dark current and increase the breakdown voltage. However, it should be noted that air arcing limits the applicable bias to the device. The structure was designed to keep the avalanche process occurring without the air arcing problem. Since the wavelength of interest in this study is very short, the incident photons are absorbed near the surface and need to diffuse into the multiplication region. Therefore, the thickness of the intrinsic layer has to be determined taking account of the diffusion process. The effects of an intrinsic layer thickness on electrical and optical characteristics were studied using a commercial software package from SILVACO. Detail information about physical models and material parameters used for simulation can be found in ref [6]. The thickness was varied from 600 nm to 3000 nm. The avalanche behavior simulated is shown in figure 2. As expected, the breakdown voltage increases as the intrinsic thickness increases. For example, the breakdown voltage for a 3000 nm intrinsic layer is around 570 V.

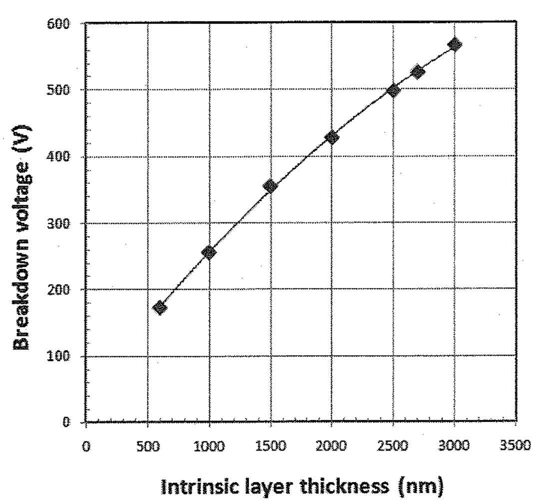

Fig 2. Simulated electrical avalanche characteristics as a function of the intrinsic layer thickness.

The quantum efficiency was also investigated as a function of the intrinsic layer thickness. As shown in figure 3, the quantum efficiency in the long wavelength regime tends to enhance as the intrinsic layer thickness increases whereas it is relatively constant at wavelengths below ~270 nm. Such a phenomenon is due to significant decrease in absorption depth and increase in surface reflection in the short wavelength regime. At wavelengths longer than ~270 nm, PIN APDs with a thicker intrinsic layer have more number of photons in the intrinsic region resulting in higher photo-generated current. However, such enhancement is not observed anymore when the intrinsic layer thickness exceeds the absorption depth. It also has to be noted that the maximum quantum efficiency is observed at longer wavelengths as the intrinsic layer thickness increases. Because the wavelength of interest in this work is 280 nm, the PIN APD was designed to have a 2.7 μm thick intrinsic layer that would result in the highest quantum efficiency and responsivity according to simulation results.

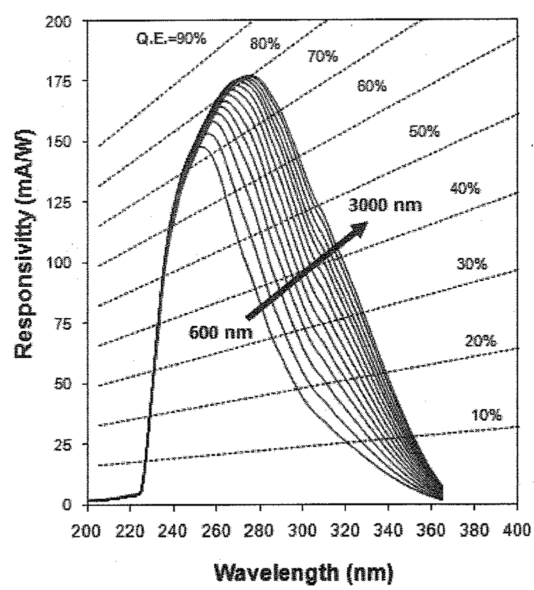

Fig 3. Simulated quantum efficiency and responsivity characteristics as a function of the intrinsic layer thickness. The increment of the layer thickness between lines is 200 nm.

3. Device Characteristics

Devices were fabricated at GE Global Research, USA. An ICP dry etching process was used for device mesa isolation. Patterned photoresist masks were reflowed by baking prior to the etching step to implement a beveled mesa with a small angle, i.e. 10~15%. After mesa isolation, the surface was passivated with a thermally grown SiO_2 layer. Ni and Ti/Al/Ti/Ni metal schemes were deposited to form the n-type and p-type ohmic contacts, respectively, and annealed simultaneously at 1050 °C in nitrogen ambient. Prior to ohmic metal deposition, the passivation layer on the ohmic region was selectively removed by wet etching. Ti/Au was deposited on top of the ohmics to form metal pads. Finally, the surface passivation in the active window region was removed. Figure 4 shows the microscope image of a fabricated 500 × 500 μm^2 APD.

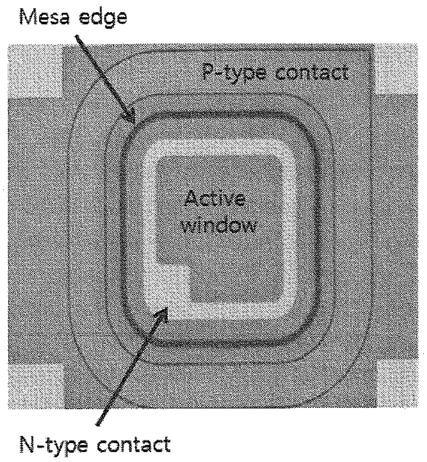

Fig 4. A microscope image of a fabricated 4H-SiC PIN APD.

Typical current-voltage characteristics of a fabricated APD are shown in figure 5. The measured breakdown voltages were in agreement with the predicted values. The photocurrent was measured under UV incident light of 300 nm wavelength. The gain of >40000 was observed for this 500 × 500 μm^2 APD.

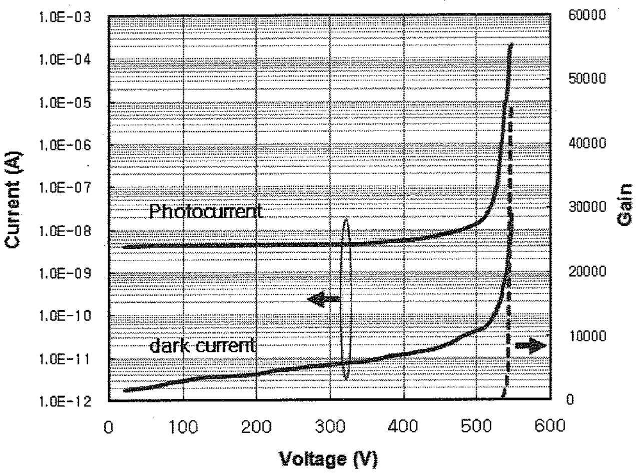

Fig 5. Current-voltage characteristics of a fabricated APD with and without UV illumination.

Photoresponsivity was measured using focused UV light whose diameter, i.e. < 200 μm, was much smaller than the active window region. Typical photoresponsivity of the fabricated APD is shown in figure 6. The maximum responsivity measured was 185 mA/W at the wavelength of 280 nm and the corresponding quantum efficiency was >80 %. This value is the state-of-the-art value for 4H-SiC APDs.

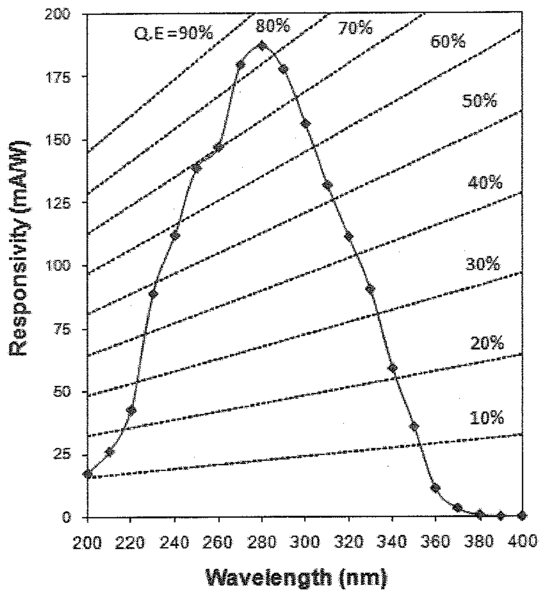

Fig 6. The measured photoresponsivity and quantum efficiency of the fabricated 4H-SiC PIN APD.

4. Summary

We successfully designed a high quantum efficiency 4H-SiC PIN APD for deep-UV detection utilizing a two-dimensional device modeling tool. The intrinsic region of a PIN structure was optimized in order to achieve the highest quantum efficiency at 280 nm. Both current-voltage and optical characteristics of fabricated APDs were in agreement with the simulated results. The fabricated APD exhibited external quantum efficiency of >80 % at the wavelength of 280 nm.

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