Planar Ultraviolet Photodetectors Formed by Si Implantation into p-GaN

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Planar GaN-based p-n−-n+ photodetectors were formed through Si implantation into p-GaN. When the reverse bias was below 4 V, the photodetectors showed nearly constant dark current around 20 pA. The dark current was somewhat higher as compared to the dark current observed in conventional epitaxial grown p-i-n photodiodes. Increase in dark current may be due to the incomplete damage (induced by implantation) removal. Spectral response measurements revealed that peak responsivity was around 11.4 mA/W at 360 nm for the planar p-n−-n+ UV photodetectors with a reverse bias of 1 V. It was also found that visible (450 nm)-to-UV (360 nm) rejection ratio was around 700.

Gallium nitride (GaN) is a promising semiconductor that has a number of advantages for the applications in optical and electronic devices. In the past few years, various types of GaN-based photodetectors have been demonstrated, such as p-n junction diodes,2 p-i-n diodes,3 and metal-semiconductor-metal (MSM) photodetectors.4,5 GaN-based p-i-n photodetectors have high breakdown voltage, low dark current, and high responsivity. Combined, these qualities make p-i-n photodetectors an attractive solution for practical applications. However, most GaN-based devices are grown on insulating sapphire substrates. Thus, it is always necessary to etch away part of the GaN layers to form the anode and cathode electrodes on the same surface of sapphire. In other words, conventional GaN-based p-i-n photodetectors are not a vertical and planar device. Such nonplanarity could result in several negative aspects for discussed photodetectors. For example, leakage current may increase with the periphery of the device, which may happen due to surface recombination resulting from the etched surface. For a detector array, the planar detectors should be beneficial for the packaging process, allowing back-illumination and manufacture of the flip-chip, needed for combination with readout integrated circuits. Doping through thermal diffusion assumes the presence of two conditions: a very high temperature and long time processing. These conditions are necessary because diffusion coefficients of dopant atoms in GaN are extremely small.6 Ion implantation is expected to be a very attractive doping technique in GaN because it provides selected area doping, which is a crucial technology in fabricating planar devices. Previously, we have published reports on fabrication of GaN n+−p junction diodes formed by Si implantation into p-GaN.7 In this study, we demonstrated a planar p-n−-n+ UV photodetector fabricated by Si implantation into p-GaN.

Device Structure and Fabrication

As shown in Fig. 1, the layer structure of the planar p-n−-n+ UV photodetector consists of two Si-implanted layers in the p-GaN epitaxial layer. The n−-GaN layer was first formed through triple Si implantation. The overall depth and dose of implantation were around 0.2 μm and 1.04 × 1013 cm−2, respectively. Next, the n+−GaN layer was formed by another Si triple implantation onto the foregoing n−-GaN layer, and the overall depth and dose of implantation were about 0.1 μm and 1.02 × 1015 cm−2, respectively.

To activate the Si implants, the implanted samples were then thermally annealed at 1100°C for 60 s by rapid thermal annealing (RTA). The electron concentration of the implanted n−-GaN and n+−GaN layers was around 5 × 1017 and 3 × 1018 cm−3, respectively, as determined by Hall-effect measurements. Ti/Al/Ti/Au (25:100:50:150 nm) was deposited onto the surface of implanted n+−GaN as n-ohmic contacts, and Ni/Au (5:10 nm) was deposited onto the surface of the p-GaN region as p-ohmic contacts. The areas of p, n−, and n+ regions were estimated to be 0.19, 0.02, and 0.24 mm2, respectively.

Current–voltage (I–V) characteristics of the devices were measured by an HP4156C semiconductor parameter analyzer at room temperature. Spectral responsivities of the Si-implanted planar p-n−-n+ photodetectors were also measured using an Xe arc lamp and a calibrated monochromator as the light source. It should be noted that optics, including lenses and fibers, used for the measurements of spectral responsivity were all made by UV-grade fused silica to minimize the UV absorption. Typically, the absorption rate was well less than 10% when the light wavelength was longer than 300 nm.

Results and Discussion

Figure 2 shows a typical I–V characteristic of Si-implanted GaN p-n−-n+ photodetectors taken under dark and illumination. When the reverse bias was below 4 V, the photodetectors showed nearly constant dark current around 20 pA. This value is comparable to those observed for conventional GaN-based UV photodetectors.2-5 However, the dark current increased drastically when the reverse bias became higher than 4 V. The increase in dark current may be due to the presence of trap levels within the bandgap of implanted GaN, which give rise to high leakage current but also slow transient recombination.

As the light wavelength was longer than 300 nm, the spectral responsivity of the Si-implanted planar p-n−-n+ photodetectors was measured by an Xe arc lamp and a calibrated monochromator as the light source. It should be noted that optics, including lenses and fibers, used for the measurements of spectral responsivity were all made by UV-grade fused silica to minimize the UV absorption. Typically, the absorption rate was well less than 10% when the light wavelength was longer than 300 nm.

Figure 1. Schematic device structure in cross-sectional view.

![Figure 1](Image)
photodetectors with reverse bias of 1, 3, and 5 V. It was found that the wavelength of 350 nm.

Figure 3. Spectra responses of the typical Si-implanted planar p-n−-n+ GaN photodetectors taken under dark and illumination.

Figure 2. Logarithmic current–voltage characteristics of typical Si-implanted p-n−-n+ GaN photodetectors under reverse bias. It was found that the solar response of photodetectors. Trap levels are most likely associated either with process damage or with structural defects, including point defects. One can see that the UV-illuminated I–V curves showed saturation behavior even when the reverse bias was larger than 4 V. However, a visible-illuminated I–V curve is similar to the dark I–V curve, showing a marked increase when the reverse bias was larger than 4 V. The reasons for such behavior are not well-known. One would like to assume that the saturation behavior in illuminated I–V characteristics may occur due to the quench effect of trap levels, because the samples were illuminated by above-bandgap light (wavelength < 360 nm). In other words, the defect levels within the bandgap, which give rise to trap-assisted tunneling current at high reverse bias, were filled by photogenerated carriers and thereby became inactive. As a result, the UV-illuminated I–V curves showed saturation behavior rather than a marked increase when reverse bias exceeded 4 V, as shown in Fig. 2. Although trap levels are not further discussed in this research, a detailed study would help us improve the performance of photodetectors. Additionally, one can also see that the contrast ratio of photocurrent to dark current is around 104 because the sample was illuminated by UV light with a wavelength of 350 nm.

Figure 3 represents the spectral responsivities of the Si-implanted p-n−-n+ photodetectors under reverse bias. It was found that the cutoff occurred at around 365 nm. When the incident wavelength was shorter than 365 nm, responsivities decreased in accordance with the wavelength rather than a flat response. In theory, the penetration depth of incident photons will decrease with an increase in photon energy when the incident photon energy is significantly higher than the GaN bandgap energy. Thus, significant decrease in short-wavelength responsivities can be explained by high absorption of incident photons at the surface layer. In other words, only a few photons reached the depletion layer next to the n−-GaN/p-GaN interface. The penetration depth was only 0.1 μm for the photons with energy of around 3.4 eV in GaN, because GaN has a very high absorption coefficient (> 105 cm−1) for such high-energy photons. Furthermore, absorption coefficient increases significantly with impurity concentrations and has been widely recognized in conventional semiconductors. In this case, the absorption coefficient should be higher than the reported value (~103 cm−1) because our samples contained a large number of Si and Mg atoms incorporated by the implantation process and the epitaxial doping process, respectively. As a result, the penetration depth should be smaller than 0.1 μm for the incident photons that featured energy of around 3.4 eV in GaN. When the device was illuminated with a short-wavelength photon (< 360 nm), the photogenerated carriers had to diffuse to the depletion region around the p/n interface to contribute photocurrent. In this case, the diffusion length should be shorter than the typical value of Ld = 500–1000 Å,18 because high-density defects exist in the Si-implanted GaN. As a result, the responsivities apparently decreased with the incident wavelength, because high-energy (short-wavelength) photons were mostly absorbed by the surface GaN layer before they reached the depletion layer. Additionally, minority carriers generated in this n+–GaN layer recombined, immediately hindering the collection of photocurrent. Therefore, it is necessary to have a shallow p-n junction near the device surface to allow effective absorption of high-energy photons at the depletion layer. The presence of p-n junction would allow the generation of electron-hole pairs and result in subsequent separation caused by electric field to contribute photocurrent. The thickness of n−–GaN and n+–GaN layer used in this study was about 0.2 and 0.1 μm, respectively. Only few photons, with energy close to GaN bandgap energy, could reach deeper to produce electron-hole pairs in the depletion region. Thus, one could maximize photocurrent by increasing depletion width or raising the p-n junction close to the surface via the adjustment of implantation depth. The depletion width depends both on material resistivity of the region to be depleted and the applied reverse bias. In other words, one could increase depletion width by choosing highly resistive (i.e., low-doping) materials on both sides of the junction. However, low-resistivity materials are required for the formation of good n-ohmic and p-ohmic contacts. Thus, the materials used should represent a compromise of qualities between material resistivity and contact resistance.

Analyzing Fig. 3, we can see that the visible (450 nm)-to-UV (360 nm) rejection ratio around 700 can be extracted from the spectral response. The Si-implanted GaN p-n−-n+ photodetectors, biased at −1 V, have responsivity of around 11.4 mA/W at 360 nm. It is clear that these values are smaller than those observed in epitaxial p-i-n photodetectors. The difference is due to the fact that the ratio of illuminated area to opaque electrode area of the Si-implanted GaN p-n−-n+ photodetectors being smaller than that of conventional epitaxial p-i-n photodetectors. Thus, the difference is the main cause of smaller responsivity. In addition, higher defect density observed in Si-implanted GaN p-n−-n+ photodetectors, taking place due to the incomplete removal of implantation damage, will also result in poor responsivity. Conventional epitaxial p-i-n photodetectors have a well-controlled thickness and resistivity of the absorption layer. In contrast, the junction of the experimental implanted samples cannot be defined clearly due to potentially projected straggle in Si distribution. Thus, low peak responsivity could also be attributed to the nonoptimum design of device geometry. Setting the aforementioned drawbacks aside, the Si-implanted GaN p-n−-n+ photodetectors still have several advantages, including simple epitaxial structure and planar type.
Conclusion

We have demonstrated planar visible-blind GaN-based p-n^-n^+ photodetectors, using the n^-n^+ junction and n^-p junction, by implanting Si ions into p-GaN epitaxial layer. The typical leakage current was as low as 20 pA at 4 V. When the reverse bias was below 4 V, the dark current maintained a very small value of around 20 pA. For the spectral responsivity, the visible (450 nm)-to-UV (360 nm) rejection ratio could reach up to 700.

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