Improved performance of GaN metal-semiconductor-metal ultraviolet detectors by depositing SiO_2 nanoparticles on a GaN surface

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GaN metal-semiconductor-metal (MSM) ultraviolet detectors were investigated by depositing different density of SiO_2 nanoparticles (SNPs) on the GaN. It was shown that the dark current of the detectors with SNPs was more than one order of magnitude lower than that without SNPs and the peak responsivity was enhanced after deposition of the SNPs. Atomic force microscopy observations indicated that the SNPs usually formed at the termination of screw and mixed dislocations, and further current-voltage measurements showed that the leakage of the Schottky contact for the GaN MSM detector decreased with deposited the SNPs. Moreover, the leakage obeyed the Frenkel–Poole emission model, which meant that the mechanism for improving the performance is the SNPs passivation of the dislocations followed by the reduction in the dark current. © *2011 American Institute of Physics*. [doi:10.1063/1.3567943]

The wide direct bandgap energy and the excellent chemical and thermal stability of GaN make it particularly suitable for extreme environmental applications of ultraviolet (UV) detectors. However, the performance of GaN-based UV detectors is hindered due to high-density threading dislocation (over 10^9 cm^{-2}) of GaN, which has been proved to be the main path for the reverse-bias leakage of GaN-based devices.[1–4] Related investigations also demonstrate that the reverse-bias leakage at temperatures above 250 K obey the Frenkel–Poole emission model, which means carrier transportion via conductive dislocations.[5–7] To suppress the influence of conductive dislocations on reverse-bias leakage, many investigations have been carried out, such as microarea anodic oxidation,[8] thermal oxidation,[9] deposition of SiO_2 or SiN_x dielectric layer on GaN,[10] but all of these methods have a certain degree of drawback. For example, after depositing a dielectric layer on the GaN, semiconductor-metal (MS) contact changes to metal-insulator-semiconductor structure and the advantages of the GaN MS contact disappear. In this study, the deposition of dielectric nanoparticles on the GaN surface was proposed to lower the influence of dislocations that is easy to carry out and will not change the characteristics of the device structure. Moreover, recently dielectric SiO_2 nanoparticles (SNPs) have been employed in GaAs solar cells and their performance has improved.[11,12] To explore the role of the SNPs, GaN metal-semiconductor-metal (MSM) UV detectors were fabricated with and without depositing the SNPs on top of the GaN and their properties and related mechanisms were also investigated in detail. The results showed that the performance of the detector was much improved with depositing SNPs on the GaN.

Undoped GaN epilayers with screw dislocation densities of 3.81×10^8 cm^{-2} were grown on (0001) sapphire substrates by metalorganic chemical vapor deposition. The detailed growth process can be found in Ref. 13. Prior to fabricating MSM detectors, the SNPs were deposited on the top of GaN by radio frequency magnetron sputtering. Ni (150 nm) was deposited by electron-beam evaporation on all the samples for the interdigitated Schottky contacts. Standard photolithography and lift-off processes were used to fabricate the GaN MSM detectors. Finally, all the samples were annealed by rapid thermal annealing at 450 °C for 180 s. The fingers were 200 μm long and 10 μm wide with a spacing of 10 μm. Figure 1 displays the schematic device structures of the detectors with SNPs on GaN. Atomic force microscope (AFM) was employed to characterize the surface morphology of the GaN. Current-voltage (*I-V*) characteristic and spectral responsivity of the detectors were also measured. Details of the measurements are described elsewhere.[13]

Figure 2 shows the dark current of the three GaN UV detectors with SNPs densities of about 1.5×10^8 cm^{-2}, 7.6×10^7 cm^{-2}, and 0 (without the SNPs). The dark current value of the three detectors decreases more than one order magnitude as the SNPs density increased from 0 to 1.5×10^8 cm^{-2}. This demonstrates that the dark current of the GaN UV detectors is significantly reduced by depositing the SNPs on GaN. Our earlier results have shown that the screw dislocation is the paths of carrier transportation and has a strong influence on the dark current of the GaN detectors.[13]

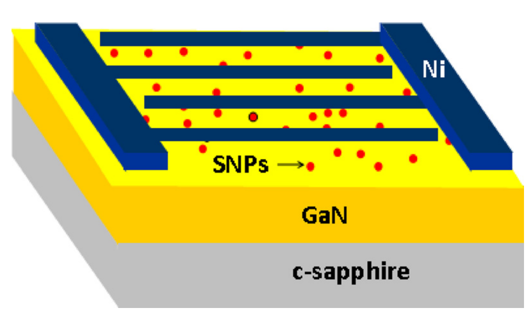

FIG. 1. (Color online) Schematic device structure of GaN MSM detector with SNPs deposited on GaN.

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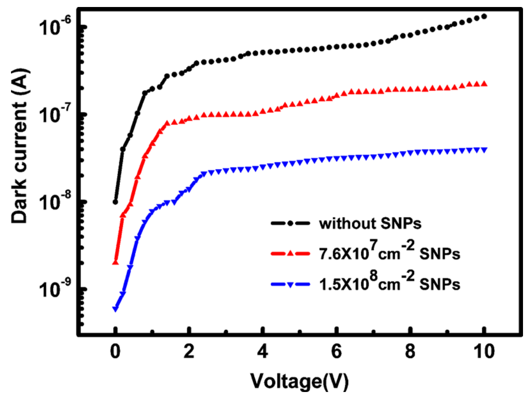

FIG. 2. (Color online) Dark *I-V* characteristics of GaN detectors with different SNP density.

Thus, the SNPs on GaN perhaps have a role to passivate the defect paths of carrier transport.

To understand the mechanism of the dark current reduced with depositing the SNPs, further investigations have been carried out. The surface morphology of the GaN with the SNPs was measured by AFM, as shown in Fig. 3. Distinct atomic steps with terraces characterize the GaN and a few depressions located at the end of the pinned steps. According to previous reports,[14,15] this kind of surface depression is caused by the terminations of the dislocations with a screw component in the GaN. Besides, the SNPs always form at the terminations, as indicated in Fig. 3 by arrows. This suggests that the defect state and carrier transporting paths underneath the Ni Schottky contacts and between the interdigitated metals are perhaps passivated (covered) by the SNPs and thus the dark current of the detectors is reduced. The more SNPs that are deposited, the more defects that are passivated and the lower dark current of the detectors is. Furthermore, the reverse-bias leakage of the three samples with different SNPs density has also been studied at room temperature. The circle Schottky contact is also Ni (150 nm) processed the same as the GaN MSM detector and an In dot is used as Ohmic contact. Figure 4 shows the reverse-bias leakage of the three samples with different SNP densities. The reverse-bias leakage dramatically reduces by about four orders magnitude with the SNPs density increasing from 0 to

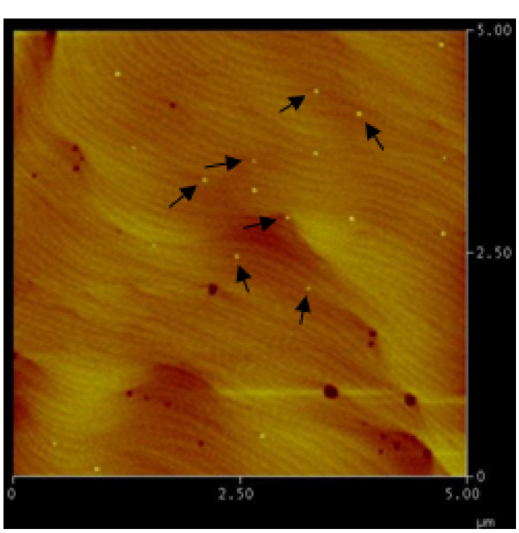

FIG. 3. (Color online) The AFM of the GaN with SNP deposited.

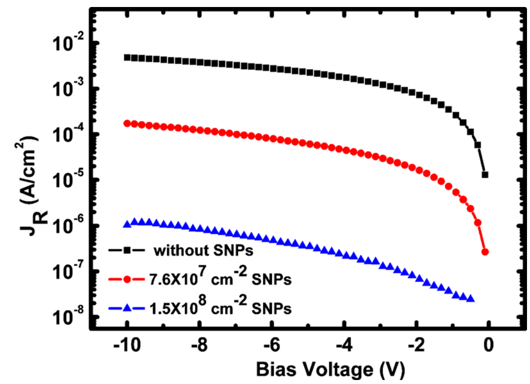

FIG. 4. (Color online) Reverse-bias current density (J_R)-voltage (V) characteristics of GaN detectors with different SNP density.

1.5×10^8 cm^{-2}. Based on Frenkel–Poole emission, the current density is given by[16,17]

$$J = CE_b \exp\left[-\frac{q(\phi_t - \sqrt{qE_b/\pi\varepsilon_o\varepsilon_s})}{KT}\right], \tag{1}$$

where E_b is the electric field in the semiconductor barrier at the MS interface, ϕ_t is the barrier height for electron emission from the trap state, ε_o is the permittivity of free space, ε_s is the relative dielectric permittivity at high frequency, K is the Boltzmann's constant, and T is the temperature.

According to Eq. (1), $\log(J/E_b)$ should be a linear function of $\sqrt{E_b}$ for current transport by Frenkel–Poole emission, i.e.,

$$\log(J/E_b) = \frac{q}{KT}\sqrt{\frac{qE_b}{\pi\varepsilon_o\varepsilon_s}} - \frac{q\phi_t}{KT} + \log C. \tag{2}$$

Assuming a linear dependence of E_b with V_R, $\log(J/V_R)$ should be a linear relationship with $\sqrt{V_R}$. Figure 5 shows $\log(J/V_R)$ as a function of $\sqrt{V_R}$ for all three samples. All of them follow the expected evolution predicted by Eq. (2), which means the leakage in our case obeys the Frenkel–Poole emission model. It has been reported that the leakage associated with the Frenkel–Poole emission results from the threading dislocations with a screw component in the GaN layer.[18] Therefore, the leakages of the Ni/GaN Schottky contacts are reduced by depositing the SNPs since the paths of carrier transports via trap states to conductive dislocations are suppressed by the SNPs. Considering the AFM observations and *I-V* measurements, it can be concluded that the

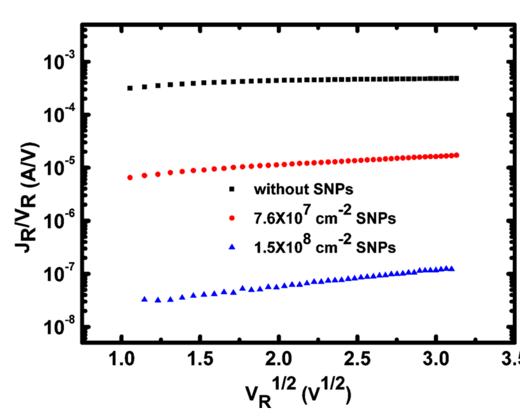

FIG. 5. (Color online) Reverse current density J_R divided by the reversed bias V_R vs square root of V_R for GaN detectors with different SNP values.

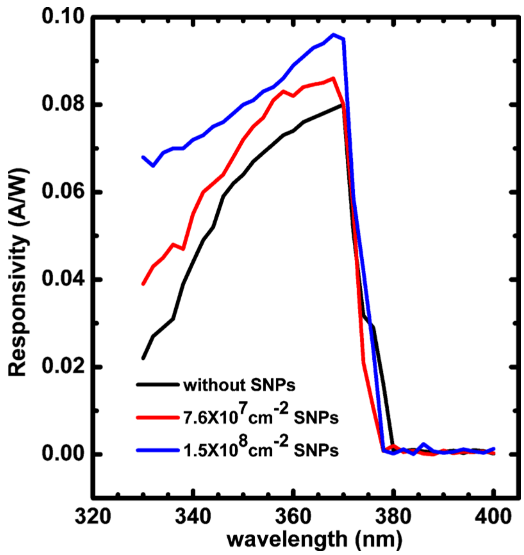

FIG. 6. (Color online) The spectral responsivity of the GaN detectors with different SNP density at 5 V applied bias.

mechanism of lowering the dark current of the GaN MSM detector with the SNPs is due to the SNPs passivating the dislocation and then the paths of carrier transports through the conductive dislocations are suppressed.

The response spectra of the GaN MSM detectors with different SNP density have also been investigated (Fig. 6). The peak responsivity occurs at around 368 nm for the detectors and it increases from 0.079 to 0.096 A/W as the SNP density increases from 0 to 1.5×10^8 cm^{-2}. As discussed above, the screw and mixed dislocations in the GaN are passivated by the SNPs. However, it has been proved that the edge dislocations and not the screw dislocations lead to the reduction in the peak responsivity of the GaN UV detectors because of the negatively charged scattering centers along the edge dislocations.[13] Moreover, the edge dislocations have no Burgers vector component parallel to **c**, i.e., the [0001] direction, and they cannot form termination pin steps on the GaN surface.[19,20] Thus, the SNPs passivating the dislocation is cannot be the predominant factor enhancing the spectral response. Another possible explanation is that the SNPs on the GaN scatter the incident light and thus increase optical absorption. It is well known that surface texture scattering is a effective method for increasing transmission,[21,22] meanwhile, the SNPs enhancing the optical absorption efficiency have been demonstrated on GaAs solar cell.[11,12] Since the SNPs are not a homogeneous film, the enhancement of scattered incident light increases as the SNPs density increases.

In conclusion, we have demonstrated improved performance of the GaN UV detectors by depositing the SNPs on GaN. The dark current decreased by increasing the density of SNPs because of SNPs passivating the associated conductive dislocations. In addition, the spectral response of the GaN MSM detector was also enhanced by the SNPs. The results suggested that depositing the SNPs atop GaN surface is a meaningful way to fabricate high performance GaN MSM detectors.

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