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Influence of threading dislocations on GaN-based metal-semiconductor-metal ultraviolet photodetectors

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The influence of threading dislocations on the properties of GaN-based metal-semiconductor-metal (MSM) ultraviolet photodetectors was investigated. It was found that screw dislocations had a strong influence on the dark current of the photodetectors, while edge dislocations had the predominant effect on their responsivity. The dark current increased as the screw dislocation density increased due to their lowering of the Schottky barrier height. However, the responsivity of the photodetectors decreased with increasing edge dislocation density because of the dangling bonds along those edge dislocation lines which enhance the recombination of photogenerated electron-hole pairs. The results suggest that reducing both the screw and edge dislocation densities is an effective way to improve the photoelectric property of GaN-based MSM ultraviolet photodetectors. © *2011 American Institute of Physics*. [doi:10.1063/1.3536480]

GaN is one of a number of very promising candidate materials for ultraviolet (UV) photodetectors because of its wide band gap and good thermal and chemical stability. However, high density threading dislocations (TDs) exit in GaN epilayers due to poor matching in the lattice constant and the difference in the thermal expansion coefficients between the GaN epilayer and a substrate such as sapphire, SiC, or Si.[1–3] As is well known, high TD densities do not seem to seriously degraded the performance of light-emitting diodes because of the vertical character of the TDs and the shorter minority carrier diffusion lengths in III nitrides. However, the TDs cause unacceptably short lifetimes for laser diodes and excessive leakage current under reverse bias for *p-n* junction devices such as field-effect transistors and high-electron-mobility transistors. Until now, the role of the TDs in the GaN epilayer on a GaN-based photodetector has been unclear. In this letter, the influence of TDs in the GaN layer on MSM UV photodetectors is investigated. It is found that the TDs have a significant effect on the properties of GaN-based MSM photodetectors. The screw dislocations cause a sharp increase the dark current, while edge dislocations result in a dramatic reduction their responsivity.

Unintentionally doped GaN epilayers with different TD densities were grown on *c*-plane sapphire substrate by metal organic chemical vapor deposition. First, a ~25 nm thick GaN buffer layer was deposited at 550 °C, then the temperature was ramped up to 1050 °C and a 3 μm thick undoped GaN was deposited. Trimethylgallium and ammonia were used as Ga and N precursors, respectively. In the subsequent process of fabricating the MSM detectors, Ni/Au (30/100 nm) was deposited by electron-beam evaporation on all the samples for the interdigitated Schottky contacts and then the samples were treated by rapid thermal annealing at 500 °C for 300 s. The fingers were 200 μm long and 5 μm wide with a pitch of 10 μm, as shown in Fig. 1. The devices were fabricated using standard photolithography to pattern photo-

resist for subsequent metallization and liftoff to form metal Schottky contacts on the GaN.

A Keithley 237 electrometer was employed to measure the current-voltage (*I-V*) performance of the GaN-based MSM photodetectors. During the measurement of the optical spectral response of the devices, a Xe arc lamp was used as the optical source for the spectral responsivity studies. A mechanical chopper modulated the incident light, and a lock-in amplifier recorded the photocurrent from the MSM
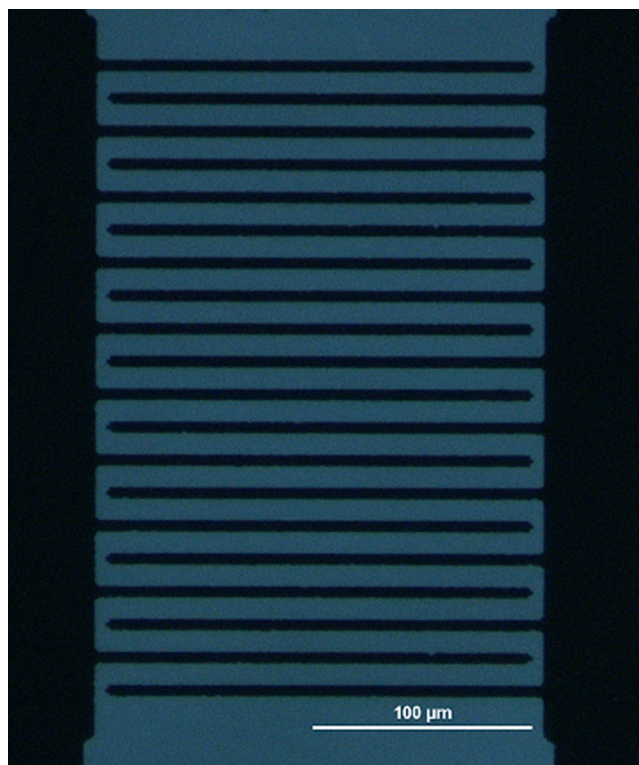

FIG. 1. (Color online) Top view of Ni/Au Schottky contacts GaN MSM device showing interdigitated geometry. Finger length is 200um, width is 5 μm, and space is 10 μm.

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TABLE I. The carrier concentration, Hall mobility, XRC-FWHM of the (002) and (102) plan and the screw (N_{screw}) and edge (N_{edge}) dislocation densities for sample A, B, and C.

Sample No.	Carrier concentration (cm^{-3})	Hall mobility (cm^2/Vs)	FWHM of XRC (arcsec)		N_{screw} (cm^{-2})	N_{edge} (cm^{-2})
			(002)	(102)		
A	3.84×10^{16}	322	350	448	2.46×10^8	1.54×10^9
B	3.78×10^{16}	283	210	628	8.85×10^7	4.21×10^9
C	3.59×10^{16}	190	274	838	1.51×10^8	7.51×10^9

barrier photodetector. The system was calibrated with an UV-enhanced Si detector. All the measurements were carried out at room temperature. Table I lists the carrier concentration, the Hall mobility and the full width at half maximum (FWHM) of the x-ray rocking curve (XRC). The screw and edge dislocation densities calculated from the XRC-FWHM value[4] are also shown in Table I. It is worth to noting that the screw and edge dislocation densities also include the screw and edge component of the mixed-type dislocation, respectively.

The dark current of many of these MSM photodetectors was investigated, with most of them showing a nearly symmetrical characteristics and for opposite biases the dark current was almost the same, indicating that good a Schottky contact have been formed between the GaN epilayer and Ni/Au metal contact. However, the dark current values of the MSM photodetectors were different from one to another at a given voltage. Figure 2 displays the dark current of the three typical GaN-based MSM UV photodetector samples, A, B and C. The dark current values of the three samples follows a sequence of B < C < A. Comparing the main parameters of the three samples as listed in Table I, they have almost the same carrier concentrations but different dislocation densities, and it is the screw dislocation densities of the samples are consistent with B < C < A, while the edge dislocation densities of the samples follow the sequence A < B < C. These results suggest that the lower screw dislocation densities are, then the lower the dark current is in the GaN MSM photodetectors and the edge dislocations seem to have little effect on the dark current.

To further understand the mechanism of how the screw dislocation affects the dark current of the GaN-based MSM photodetectors, we studied the Schottky barrier height (SBH) of the three photodetector samples. On one side, Ni/Au (30/100 nm) was used for the interdigitated Schottky contacts and Indium was used as the Ohmic contact. The SBH was determined from the forward I-V results in terms of the thermionic emission model. The relationships between the SBH and XRC-FWHM of the (002) plane are shown in Fig. 3. It is clear that sample B which has the narrowest XRC-FWHM of the (002) plane, has the highest SBH while sample A with the broadest XRC-FWHM of the (002) plane has the lowest SBH. This suggests that the screw dislocations might reduce the SBH between the GaN epilayer and metal contact and lower SBH then results in higher dark current of the GaN-based MSM photodetectors. The effect of the TDs on the surface morphology of GaN epilayer could account for the decrease of SBH between the GaN and Ni/Au interdigitated Schottky contacts. It has been reported that a pinned step is formed on the GaN surface when a threading dislocation with a screw component intersects the free surface of a crystal.[5] The dislocations will cause a surface displacement equal to the component of the Burgers vector normal to the surface. The pin steps and the surface displacement caused by the screw TDs introduce lateral variations of the electrical properties of the interface and create a defect state near the surface, which thus lowers the SBH. Furthermore, it has been proved that for GaN Schottky contact, the reverse currents were spatially highly nonuniform and that dislocations with a screw component were accompanied by a high current density.[6] Therefore, at the location of screw TDs, the electrons find it easier to overcome the contact barrier, which is another reason why the screw TDs reduce the effective SBH. Since the pure edge dislocations do not have a component of the Burgers vector perpendicular to the surface, no steps would be generated or terminated. Thus the edge TDs do not have a remarkable effect on the Schottky contact between the GaN and Ni/Au interdigitated Schottky contacts.

A lot of research work has discussed the behavior of dislocations in GaN,[7–11] and it has been proved that open-core screw dislocations have nanopipes at their center and
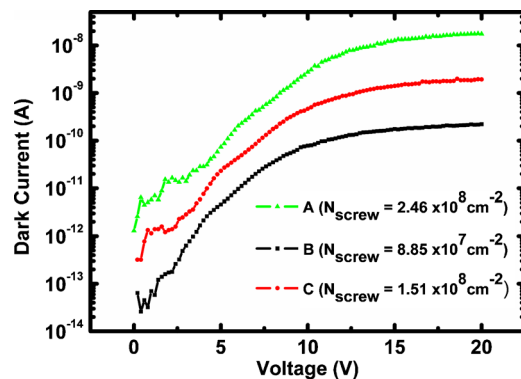
FIG. 2. (Color online) The correlation between the dark current and the voltage of samples A, B and C.
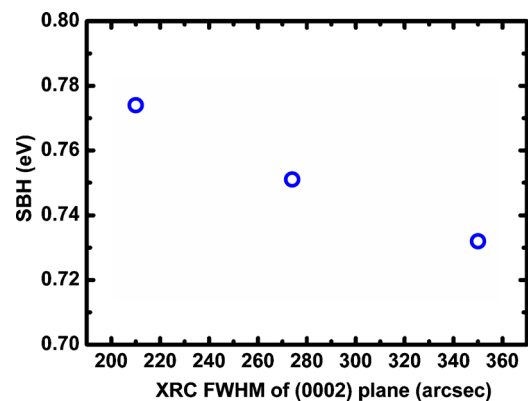
FIG. 3. (Color online) The relationships between the SBH and DCXRD FWHM at the (0002) plane.
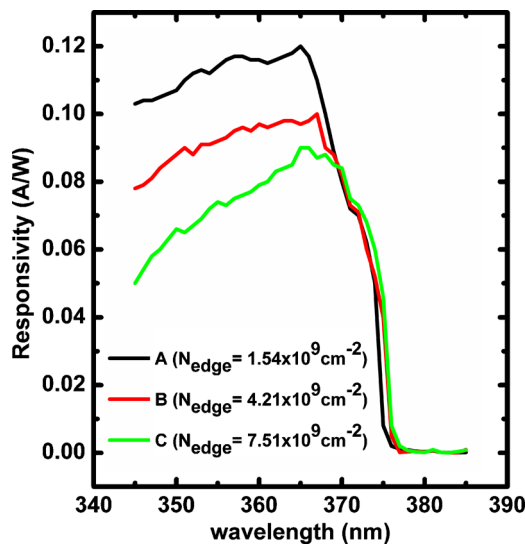
FIG. 4. (Color online) The spectral response of the samples of A, B and C at 5V bias.

that these nanopipes have a significant influence on the reverse-bias *I-V* characteristics.[12] This can also explain why the dark current becomes higher with increasing the screw dislocation densities in the GaN-based MSM photodetectors, since the nanopipes can act as electron transport paths resulting in the increase of the reverse-bias voltage current. However, there are no nanopipe characters in the edge TDs, thus the dark current of GaN MSM photodetectors is not sensitive to the edge TDs.

The responsivity of the GaN-based MSM photodetectors is also investigated. Most of the samples show a high responsivity near the band edge of GaN which decreases with decreasing wavelength due to the reduced photopenetration depth and increasing recombination of surface photogenerated carriers. Figure 4 shows the spectral responses of the three GaN-based MSM photodetectors, all of which are measured at 5 V bias. It is clearly shown that the peak responsivity of sample A is the highest, and sample C is the lowest. Here, an effect of the screw dislocation on the responsivity of the photodetectors can be excluded because sample A should have the lowest responsivity and sample B should have the highest, if the screw TDs influence the responsivity strongly. It is worth to noting that Sample A has the lowest edge dislocation density and Sample C has the highest. Thus, it could be concluded that the responsivity strongly depends on the edge dislocation density.

It is well known that there are many dangling bonds along the edge dislocations lines and these may provide acceptor traps and form negatively charged scattering centers in *n*-type GaN.[13] Weimann *et al.* have proposed a model to explain the observed low transverse mobility in GaN by the scattering of electrons at charged dislocation lines.[13] Scanning capacitance microscopy measurements experimentally confirmed the presence of fixed negative charges in the vicinity of dislocations.[7] According to the results of Hall measurements listed in Table I, while the three unintentionally doped samples have almost the same carrier concentrations, the electron mobility of the three samples are very different.

The electron mobility of the undoped GaN epilayer decreases with the increase of the edge dislocation density. Among the three undoped samples, the edge dislocation density of sample A is the lowest and correspondingly the electron mobility is the highest. This phenomenon can be interpreted that the edge dislocation acts as charge defect traps in the GaN and these charge defect traps can increase the recombination probability of photogenerated electron-hole pairs and thus reduce the responsivity of GaN-based MSM photodetectors. Furthermore, since the photocurrent in these MSM photodetectors primarily comes from the drift current, the negatively charged scattering center may have a strong influence on the photogenerated holes. This may be another reason why the responsivity of the GaN-based MSM photodetectors becomes lower as density of edge dislocation increases. However, screw dislocations at the centers of growth spirals do not appear to be charged because of the small diameter nanopipes,[14] therefore, the screw TDs do not have a significant effect on the responsivity of the photodetectors.

In summary, we have investigated the effect of TDs on the property of GaN-based MSM photodetectors. It is found that the dark current of the GaN photodetectors increases with decreasing screw dislocation density and the responsivity of the photodetectors decreases with increasing edge TDs. These results suggest that decreasing both the screw and edge dislocations is necessary to fabricate the GaN-based MSM photodetectors with a lower dark current and higher responsivity.

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