GaN Schottky barrier photodetectors with a low-temperature GaN cap layer

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By using organometallic vapor phase epitaxy, we have prepared i-GaN/low-temperature (LT) GaN/Ni/Au (sample A) and i-GaN/Ni/Au (sample B) Schottky barrier UV photodiodes (PDs). It was found that we could significantly reduce the leakage current and achieve a much larger photocurrent to dark current contrast ratio by introducing a LT GaN on top of the conventional nitride-based UV PDs. With incident light wavelength of 350 nm and a -1 V reverse bias, it was found that the measured responsivity was around 0.1 and 0.37 A/W for samples A and B, respectively. Furthermore, it was found that the operation speed of sample A is slower than that of sample B due to the highly resistive LT–GaN layer induced large RC time constant. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1570519]

Gallium nitride (GaN) is one of the most promising materials for the fabrication of high-sensitive visible-blind UV detectors, since it has a large direct band gap energy (3.41 eV at room temperature) and a high saturation electron drift velocity (310 cm/s).[1] The superior radiation hardness and high temperature resistance of GaN also make it a suitable material for UV detectors working in extreme conditions. In the past few years, various types of GaN-based photodetectors have been proposed, such as $p-n$ junction photodiodes (PDs),[2] $p-i-n$ PDs,[3,4] $p-\pi-n$ PDs,[5] Schottky barrier PDs,[6] and metal–semiconductor–metal (MSM) photodetectors.[7–9] Compared with $p-n$ junction PDs, the fabrication process of Schottky barrier PDs is much easier. The response speed of Schottky barrier PDs is also faster due to the limitation of minority-carrier storage problem in $p-n$ junction PDs. However, leakage current in Schottky barrier PDs is also higher due to the large thermionic emission current in Schottky barrier PDs, as compared to the diffusion current in $p-n$ junction PDs for a given built-in voltage. To reduce the leakage current in Schottky barrier PDs, it is necessary to achieve a high Schottky barrier height at the metal/semiconductor interface. Various metals[10–13] and transparent conducting oxide films[14,15] have been deposited on GaN to achieve high performance Schottky barrier PDs. In addition to the choice of contact metals, the leakage current of Schottky barrier PDs also depends strongly on the properties of the topmost semiconductor layer. Previously, it has been shown that one can significantly reduce gate leakage current in GaAs field effect transistors (FETs) by utilizing a low temperature (LT) GaAs layer.[16,17] A similar concept has been applied to GaN-based MSM PDs.[18] In this study, we deposited a LT GaN layer on top of undoped i-GaN layer, and fabricated nitride-based UV Schottky barrier PDs with a LT GaN cap layer. The optical and electrical properties of the fabricated PDs will be reported.

Samples used in this study were all grown on c-face (0001) sapphire (Al_2O_3) substrates by organometallic vapor phase epitaxy (OMVPE).[15] As shown in Fig. 1, a 3-μm-thick Si-doped n^+-GaN ($n=3\times10^{18}$ cm^{-3}) layer was grown at 1060°C. On top of this n^+-GaN layer, we subsequently grew a 0.3-μm-thick undoped GaN (i-GaN) followed by a 50-nm-thick LT GaN as the cap layer (i.e., sample A). The growth temperature of the LT GaN cap layer was 550 °C. It should be noted that this LT GaN cap layer behaves like an insulator with a sheet resistivity larger than 10^9 $\Omega/\Box$. Samples without the LT GaN cap layer were also prepared for comparison (i.e., sample B). As shown in Fig. 1, nitride-based Schottky barrier PDs were then fabricated by dry etching,[19] deposition of Ti/Al on exposed n^+-GaN as Ohmic contact, deposition of semitransparent Ni/Au (3 nm/10 nm) on LT GaN as Schottky barrier metal,[20] and deposition of Ti/Au (50 nm/1 μm) on Ti/Al and Ni/Au to serve as the bonding pad. The diameter of the fabricated circular PDs was kept at 500 μm. Spectral responsivity of these Schottky barrier PDs was measured using a Xe arc lamp and a calibrated monochromator as the light source. Output power of the monochromatic light was measured with a calibrated Si photodiode and then illu-

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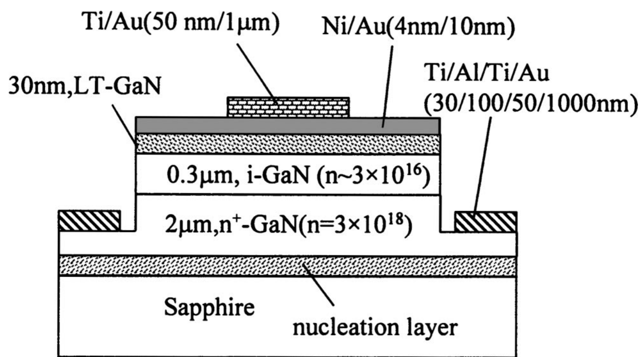


FIG. 1. Schematic structure of the n^{+}-GaN/i-GaN/LT–GaN/Ni/Au Schottky barrier diode (sample A).

minated onto the front side of PDs. Noting that, the output powers of monochromatic light were kept at 20 μW during the measurement of spectral responsivity. Transit response was also evaluated by using a 337 nm N_2 laser with a 0.5 ns excitation pulse to optically excite the fabricated PDs. The intensity of the 337 nm light pulse was kept at 1 mW/cm^2. A 500 MHz oscilloscope with a 1000 Ω load resistance was then used to measure the impulse response.

Figure 2 shows dark $I-V$ characteristics of the GaN Schottky barrier PDs. Under reverse bias, it was found that the dark current was near a constant of around 1×10^{-10} A for sample A. In contrast, the dark current of sample B was much larger and increased rapidly as the reverse bias increased. This could be attributed to the fact that the highly resistive LT GaN cap layer between Ni/Au and i-GaN could result in a thicker and higher potential barrier, as compared to conventional Schottky barrier PDs (i.e., sample B). In other words, the leakage current in GaN Schottky barrier PDs with a LT–GaN cap layer (i.e., sample A) was much smaller and less dependent on the applied reverse bias. The near constant ultrahigh resistance of sample A is also a plus when the PDs are connected to the readout circuits in focal plane arrays. Under forward bias, it was found that turn on voltage of samples A and B was 4.5 and 0.9 V, respectively. The high turn on voltage observed from sample A could be attributed to its high barrier height and the fact that injected carriers are compensated by poor crystal quality related trap levels within the band gap of LT GaN. Under forward bias, trap levels in LT GaN are filled by forward carrier injection. Therefore, LT GaN will become less insulating. Thus, a

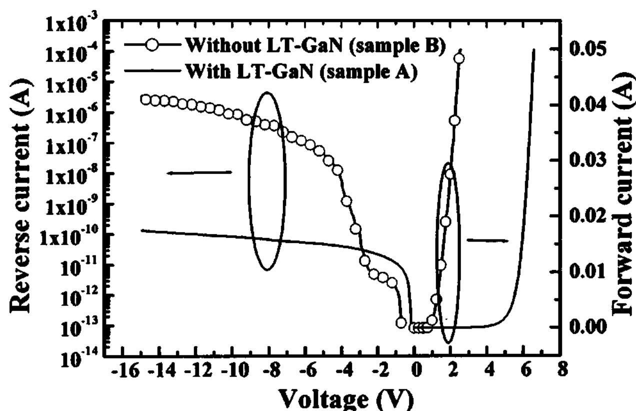
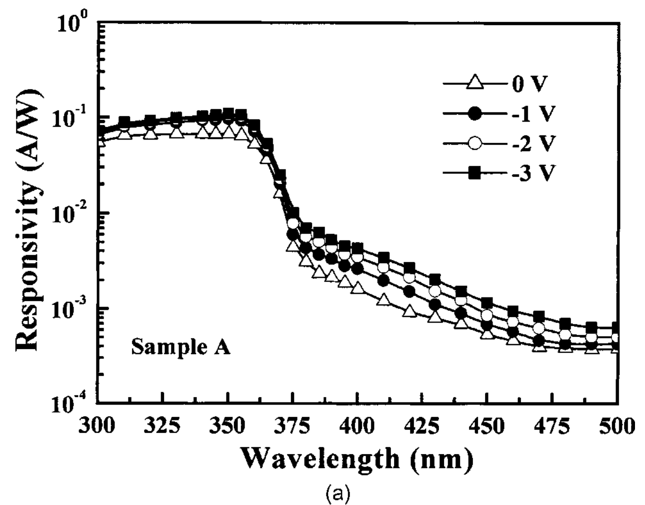


FIG. 2. $I-V$ curves taken in dark for samples A and B.



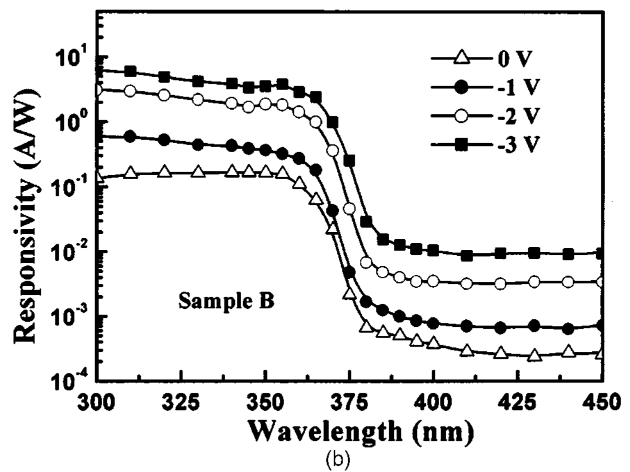


FIG. 3. Spectral responsivity of (a) samples A and (b) B measured at different reverse biases.

sharp rise in the forward current can be observed as the forward bias increase over the trap-filled-limit voltage,[21] V_{TFL}, which depends on the thickness and trap density of LT GaN layer. It should be noted that LT GaN is very different from LT GaAs. It is known that as-grown LT GaAs is very conductive with the carrier transport dominated by carrier hopping through deep defect bands.[5] On the other hand, annealed LT GaAs becomes highly resistive. Thus, annealed LT GaAs is suitable to serve as the buffer layer in metal–semiconductor FETs or as the gate insulator layer in metal–insulator–semiconductor FETs. In contrast, our preliminary results show that no significant difference in resistivity can be observed between the as-grown LT GaN and the annealed LT GaN. We would like to suggest that more detail studies should be performed to inspect the annealing effects on the microscopic structures of LT GaN.

Figures 3(a) and 3(b) show spectral response of samples A and B, respectively. It was found that cutoff occurred at around 365 nm (the absorption edge of GaN) for both samples. With incident light wavelength of 350 nm and a -1 V reverse bias, it was found that the measured responsivity was around 0.1 and 0.37 A/W for samples A and B, respectively. Such a dramatic difference could be attributed to the fact that incident photons ($\lambda = 350$ nm) are partially absorbed by the LT–GaN cap layer and the photogenerated

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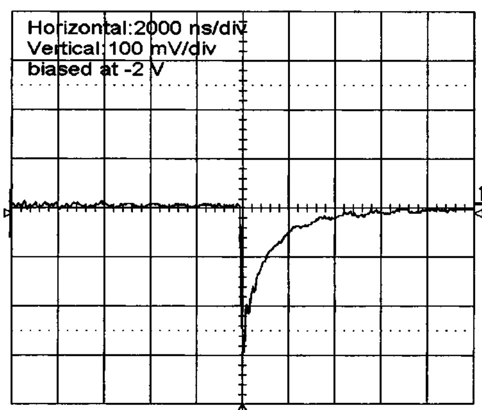

FIG. 4. Typical temporal response of sample A measured at a reverse bias of -2 V.

carriers will compensate trap levels in LT GaN. As a result, the photocurrent and responsivity will both become smaller for sample A. It was also found that the responsivity decreased slowly as the wavelength of the incident light increased from 380 to 480 nm for sample A. In contrast, the responsivity of sample B in this wavelength region was near a constant. The below band gap absorption observed from sample A could again be attributed to the defect levels within the band gap of the LT GaN cap layer. Photons in this wavelength region could still excite electrons from deep levels to conduction band, or excite electrons from valence band to deep levels in sample A. Furthermore, it was found that the responsivity of sample A is less bias dependent. In contrast, the much stronger bias dependent responsivity of sample B suggests that there might exist some internal gain in this particular Schottky barrier PD, even at low biases. The exact origin of this internal gain is not clear yet. One possible origin is photoconductive gain induced by the surface defects of sample B. If this is the case, our result seems to imply that LT GaN cap layer could effectively passivate surface defects on the undoped GaN layer. However, this statement is slightly speculative. Further studies need to be performed to clarify this point.

Figure 4 shows a typical transient response when sample A was biased at -2 V. It can be seen that the photoresponse of sample A decreased exponentially with an impulse full width at half maximum (FWHM) of around 0.5 μs. Similar behavior was observed from sample B with a slightly smaller impulse FWHM of 0.4 μs. These results suggest that the operation speed of the fabricated PDs is limited by the RC time constant of the devices. Under a -2 V applied bias, it was found that the measured capacitance of samples A and B is around 65 and 83 pF, respectively. The smaller total capacitance of sample A is attributed to the introduction of the LT GaN layer and thus an additional capacitance, C_{LT}, in series with the original device. Although the total capacitance of sample A is smaller, its series resistance should be much larger than that of sample B due to the introduction of the highly resistive LT GaN layer. Thus, the operation speed of sample A is slower than that of sample B. In other words, although we could significantly reduce the leakage current and achieve a much larger photocurrent to dark current contrast ratio by introducing a LT GaN on top of the conventional nitride-based UV PDs, operation speed of the i-GaN/LT GaN/Ni/Au Schottky barrier PDs is also slower than the conventional i-GaN/Ni/Au Schottky barrier PDs.

In summary, i-GaN/LT–GaN/Ni/Au (sample A) and i-GaN/Ni/Au (sample B) Schottky barrier UV PDs were prepared by OMVPE. It was found that we could significantly reduce the leakage current and achieve a much larger photocurrent to dark current contrast ratio by introducing a LT GaN on top of the conventional nitride-based UV PDs. With incident light wavelength of 350 nm and a -1 V reverse bias, it was found that the measured responsivity was around 0.1 and 0.37 A/W for samples A and B, respectively. Furthermore, it was found that the operation speed of sample A is slower than that of sample B due to the highly resistive LT–GaN layer induced large RC time constant.

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