Characteristics of GaN-based p-i-n photodetector at low temperature and performances of MCT/GaN-based infrared/ultraviolet dual-colour detector

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Abstract. The performances of GaN-based p-i-n photodiode at low temperature are studied. The current-voltage characteristics at different temperatures were measured. The turn-on voltage of GaN-based p-i-n detector decreases from 3.7 V to 3.0 V as temperature increases from 91 K to 286 K. The series resistance and ideality factor of the GaN-based detector is calculated. Values of series resistance are 1508Ω, 453Ω, 353Ω and 295Ω, at 91 K, 174 K, 224 K and 286 K, respectively. The values of ideality factors are 43.7, 15.4, 12.6 and 11.9, respectively. The spectral response of GaN p-i-n photodiode was measured at different temperature. The results show that with the temperature decreasing, the peak response wavelength gets shorter, and the responsivity gets smaller. The structure of ultraviolet/infrared MCT (mercury cadmium tellurium)/GaN-based dual-colour detector is designed. MCT medium wave photovoltage photodetector is employed in dual-colour detector. The responsivities of GaN-based detector and MCT-based detector were measured. The dual-colour device can realize the detection of the light between 240 nm and 330 nm, and light between 3.2 µm and 5.8 µm.

1. Introduction
Recently, gallium nitride (GaN) based detectors have been investigated intensively because of their wide direct band gap, high breakdown fields, and high-temperature operation. They are applicable in flame detection, chemical/biological sensing, optical communication and scientific research [1-3]. However, gallium nitride (GaN) based detectors can only get information in the range of 200-365 nm. To collect more information, many dual-colour and multi-colour detectors are investigated these years. A. Rogalski etc. reported infrared dual-colour detector, sensitive to short-wavelength (SW) and long-wavelength (LW) infrared light [4], offering good performance. AlGaN/PZT ultraviolet/infrared dual-colour detector has also been presented [5]. MCT-based detector covers the whole infrared wavelength, and the fabrication of the device develops very well, the performance of MCT-based detector is

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excellent [6-8]. Hitherto, as far as we know, there have been no reports about MCT/GaN-based dual-colour detector.

In this paper, MCT/GaN-based medium-wavelength (MW) infrared and ultraviolet detector is presented. MCT-based infrared detectors have excellent performance at the temperature of liquid nitride, GaN-based ultraviolet detectors commonly work at room temperature, and the performance of GaN-based device of this dual-colour detector at low temperature proves to be important. The current-voltage characteristics and spectrum of GaN-based device from 90 K to 300 K are investigated intensively. Series resistance and ideality factor of the GaN-based detector at different temperature are calculated. The reason why as temperature decrease the responsivity becomes smaller is discussed. Spectrums of GaN-based detector and MCT-based detector in the MCT/GaN-based detector are given, respectively. The dual-colour device can detect the ultraviolet light between 240 nm and 330 nm, and infrared light between 3.2 \( \mu \text{m} \) and 5.8 \( \mu \text{m} \).

2. Experiment

GaN materials were grown in a metal-organic chemical vapor deposition (MOCVD) reactor on double-side polished sapphire substrates. The template consisted of a 500 nm AlN buffer to improve the crystal quality. The structure consisted of a 0.6 \( \mu \text{m} \) Si-doped n type Al\(_{0.2}\)Ga\(_{0.8}\)N layer, a 0.2 \( \mu \text{m} \) unintentionally doped GaN layer, and a 0.2 \( \mu \text{m} \) Mg-doped p type GaN layer. Carrier concentrations in these layer were estimated by Hall-effect measurement, with the results of 2\( \times \)10\(^{18} \) cm\(^{-3} \), 1\( \times \)10\(^{16} \) cm\(^{-3} \) for electron concentration in the n-Al\(_{0.2}\)Ga\(_{0.8}\)N and i-GaN layers, respectively, and 2\( \times \)10\(^{17} \) cm\(^{-3} \) for hole concentration in the p-GaN layer. A Ni/Au/Ni/Au (20 nm/20 nm/20 nm/20 nm) p-type contact was evaporated on surface of p-GaN, and annealed in air atmosphere to form ohmic contact. Circle mesas were defined via standard photolithography technology and inducted coupled etching (ICP) under Cl\(_2\), BCl\(_3\) and Ar plasmas. Ti/Al/Ti/Au (30 nm/30 nm/50 nm/50 nm) was deposited via thermal evaporation. Devices were passivated with SiO\(_2\) of 300 nm. Finally, 20 nm/300 nm Cr/Au metal pads were deposited.

Epoxy adhesive was plastered on the MCT-based infrared devices, and then followed by GaN-based ultraviolet detector adhering on it. Stabilization of epoxy was much better than other glue at low temperature. Before that, the filter film which allows 3-5 \( \mu \text{m} \) wavelength light transmits through was deposited on the substrate side of GaN-based detectors. The profile of GaN-MCT dual-colour detector is given in figure 1.

![Figure 1](image_url). The cross structure of MCT/GaN-based dual-colour detector.
3. Results and discussion

3.1. I-V characteristics of GaN-based detector at different temperature from 91 K to 286 K

![Current-voltage characteristics at different temperatures.](image)

Current-voltage characteristics under bias voltage from -5 V to 5 V were measured with a Keithley236 semiconductor parameter analyzer in the temperature range from 91 K to 286 K. Figure 2 shows that current at forward bias becomes higher as the temperature goes higher. Table 1 shows the electric parameters calculated from I-V curves. As shown in table 1, the turn-on voltage of GaN-based p-i-n detector decreases from 3.7 V to 3.0 V as temperature increases from 91 K to 286 K. It is clearly seen that the current at reverse bias becomes higher as temperature goes higher. The current under -5 V bias at 286 K is about 2 orders of magnitude larger than that at 91 K. The curve at 91 K between 0 V and 5 V is easily separated into two parts, the slope of the first part between 0 V and 3.7 V is lower, than that of the second part between 3.7 V and 5 V. The slope of the first part at 174 K is higher than that at 91 K, and lower than that at 286 K. This is mainly due to the variable series resistance at different temperature. The series resistance of the diode is calculated from the current-voltage characteristics under forward bias according to

\[
\frac{dV}{dI} = R_s + \frac{nkT}{q}
\]

As discussed in reference [9-10]. Values of series resistance are 1508 Ω, 453 Ω, 353 Ω, 295 Ω at 91 K, 174 K, 224 K and 286 K, respectively. It is an exponential decay with temperature increasing. The mechanism of this phenomenon will be discussed in another paper. In addition, the ideality factor is extracted [10] in order to gain insight into the conduction mechanisms operating in the GaN-based p-i-n detector. The values are 43.7, 15.4, 12.6 and 11.9 for device at 91 K, 174 K, 224 K and 286 K, respectively. R. McClintock [10] reported that the ideality factor is expected to have a value between 1 and 2, if n is closer to 2, recombination current dominates, if closer to 1, diffusion current dominates. The ideality factor they calculated was 2.89, and it fell well outside of this range. The explanation they gave was that the weak Schottky-like nature of the p contact created a second diode in series with the p-i-n junction.
Table 1. The turn-on voltage, series resistance and ideality factor of GaN-based detector at different temperatures.

| Temperature (K) | 91  | 174 | 224 | 286 |
|-----------------|-----|-----|-----|-----|
| Turn-on voltage (V) | 3.7 | 3.4 | 3.2 | 3.0 |
| Series resistance (Ω) | 1508 | 453 | 353 | 295 |
| Ideality factor | 43.7 | 15.4 | 12.6 | 11.9 |

3.2. The spectrum of GaN-based detector at different temperature

The spectral dependence of the photoresponse was measured with a Xe-arc lamp source coupled to a grating monochromator. The relative response was calibrated with a large square area UV-enhanced Si detector. Figure 3 shows the response of the GaN-based p-i-n photodiode at different temperatures. We observe that as temperature becomes higher, the responsivity of the device becomes larger, and the largest peak responsivity at 280 K is about 0.106 A/W at 362 nm. This is because the depletion gets wider as temperature increases. From the fit of quantum efficiency, it is observed that the width of the depletion affects the quantum efficiency severely, and with wider depletion width, quantum efficiency is larger. It is consistent with the experiment result: as temperature becomes higher, the width of depletion region gets wider, and the quantum efficiency becomes larger [11]. The short wavelength edge of spectral response lies at 300 nm, corresponding to the band gap of Al$_{0.2}$Ga$_{0.8}$N, and the long wavelength edge is at 366 nm, corresponding to the band gap of GaN. The quantum efficiency of the photodiode at 280 K is calculated from spectral responsivity, and the largest value is 36.4%. The unitary spectral response curves at different temperature from 155 K to 280 K are shown in figure 4. The peak response wavelength changes from 356 nm to 362 nm as the temperature goes from 155 K to 280 K.

The shape of the spectrum at different temperatures is nearly the same, only with the peak wavelength shifting. The difference is attributed to the decrease of GaN band gap when the temperature becomes higher. The band gap of GaN versus temperature is given as follow [12-13]:

$$E_g(T) = E_g(0) - \frac{\alpha T^2}{(\beta + T)}$$

Where $E_g(0)$ is the band gap of GaN at 0 K, $\alpha$ is the temperature coefficient $dE_g/dT$, and $\beta$ is the character temperature related to Debye temperature. It is obvious from the formula that as temperature increases the band gap of GaN becomes smaller, consistent with the trend of our experiments.
3.3. MCT/GaN-based dual-colour detector

Current-voltage characteristics under bias voltage from -0.5 V to 0.5 V were measured with a Keithley236 semiconductor parameter analyzer at 90 K. The spectral responsivity of GaN-based detector in MCT/GaN-based dual-colour device was measured with a Xe-arc lamp source coupled to a grating monochromator, and it is not calibrated. The response of MW MCT-based detector of dual-colour device was measured with Varian 3100 FT-IR at 90 K.

It is observed from figure 5 that the leakage current of GaN-based detector at -0.5 V is fairly larger than the GaN-based device we show before. This is mainly because the quality of GaN crystal is worse than before. As observed in figure 6, the peak response wavelength is at about 308 nm. The dark
current at zero bias is about $10^{-11}$ A; as a result, the response current at the wavelength which should not create photocurrent cannot be neglected.

There are two windows for the dual-colour detector, which is 240 nm-330 nm for GaN-based device, and 3.2 $\mu$m-5.8 $\mu$m for MCT-based photovoltage device. Photocurrent measurement was performed under front illumination. The ultraviolet light between 240 nm and 330 nm is absorbed by the GaN-based detector, and the infrared light transmits through the GaN-based detector. Because of the filter film adhering on the sapphire side of GaN, the light between 3.2 $\mu$m-5.8 $\mu$m can transmit into the MCT-based detector. The MCT/GaN-based dual-colour detector shows that it can realize both ultraviolet and infrared radiation detection.

4. Conclusions
The fabrication and measurement of GaN-based detectors are reported. From the current-voltage characteristics with different temperature, it is observed that the current under both forward and reverse bias voltage becomes higher as the temperature increases. The resistance and ideality factor get smaller, the responsivity of GaN-based device becomes larger, and the peak response wavelength becomes longer as the temperature becomes higher. The peak responsivity is about 0.106 A/W at 362 nm at 280 K, corresponding to the quantum efficiency of 36.4%. The MCT/GaN-based dual-colour detector is presented. The leakage current at 0V of GaN-based detector in dual-colour device is quite large due to the bad quality of material, resulting in the low signal-to-noise ratio. The spectrum of MCT-based detector is shown. Finally, the MCT/GaN-based ultraviolet and infrared dual-colour detector is realized, and it can detect the light between 240 nm and 330 nm, and light between 3.2 $\mu$m and 5.8 $\mu$m.

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