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GaN MSM UV Detectors With Different Electrode Materials

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ABSTRACT The different electrode (In-In, Ni-Ni, Ni-In) MSM ultraviolet photodetectors were fabricated on GaN thin film which is grown on sapphire. The test result of the three electrode detectors show that the dark current of In-In device and Ni-Ni device are in the order of 10^{-8}A and 10^{-9}A, respectively, at bias of 5-10V. Asymmetric electrode (Ni-In) device has asymmetry dark current and a larger photocurrent than the symmetrical electrode devices. At the same time, Ni-In devices have a self-powered effect, under 0V bias, the photocurrent reaches 8×10^{-9}A, and the photoresponse is 5.4mA/W at 360nm.

INDEX TERMS MSM, ultraviolet photodetector, dark current, photocurrent.

I. INTRODUCTION

Ultraviolet photodetector is a prominent optoelectronic device, commonly used in optical fiber communication, image sensor, ozone sensing, leakage and radiation detection, astronomical research and remote control [1]. GaN is a direct wide band gap semiconductor, due to its unique properties, high breakdown voltage, high electron mobility, low dark current, high chemical and thermal stability. It is a potential photoactive material and effective UV photodetector [2], [3]. Therefore, GaN is widely used as the light-absorbing material for UV detector. Since the original matrix is not available in the growth process of GaN, foreign substrates such as sapphire, Si, SiC, etc. are used to grow epitaxial GaN films. In order to improve the performance of GaN-based UV detectors, different detector structures have been reported, such as p-i-n and metal-semiconductor-metal (MSM) devices [4], [5]. Among them, the MSM device simplifies the manufacturing process due to its simple structure, which has attracted the attention of most researchers. MSM geometry includes back-to-back metal semiconductor (MS) contacts where the same metal electrodes are defined as symmetrical MSM and different metal electrodes are defined as asymmetrical MSM device. Chang *et al.* reported using metal Ni and GaN to make symmetrical MSM device and using Ni/Au and GaN to make asymmetrical MSM device [6]. Self-powered UV MSM photodectectors has been reported, such as Guo *et al.* reported a self-powered MSM UV detector by emplying a "lateral polarity structure (LPS)" has a high photo-to-dark current ratio of 1.2×10^4 and peak responsivity of 933.7mA/W [7], and Zheng *et al.* Reported graphene contact AlN to form an ohmic contact device which achieved self-power phenomenon [8]. Guo *et al.* introduced two self-powered UV detector with a peak responsivity of 3.05A/W by using the built-in electric field of the GaN/Sn:Ga_2O_3 and GaN/Ga_2O_3 p-n junction to quickly separate photogenerated carriers [9], [10]. Su *et al.* used ITO, Au, Ni, Pt electrode materials and GaN to form MSM ultraviolet detectors, and a peak responsivity of 7.2A/W was obtained after 600°C annealing [11]. Li *et al.* reported MSM ultraviolet detectors used GaN with Ni and Au asymmetric electrode device which has greater optical response than symmetric devices [1]. Sun *et al.* reported AlGaN and GaN nanowires with Pt and Ru decoration to form UV detectors, and the devices responsivity and response time were significantly improved [12]–[14]. At the same time, Sun *et al.* also reported a GaN/AlGaN HEMT with a peak photoresponsivity of 6×10^7A/W [15]. The asymmetric electrode MSM structure is realized by using different metals to make the two electrodes on the GaN. Because the work function (WF) of the metal is different, the asymmetric electrode MSM device structure provides a built-in potential gradient, which can

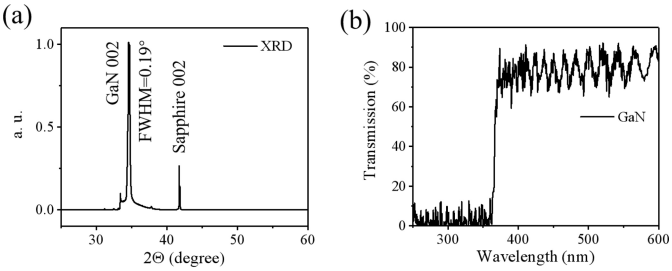

FIGURE 1. **XRD (a) and transmission (b) of GaN. The XRD result shown GaN (002) FWHM is 0.19 degree and the transmission drops rapidly at 365nm.**

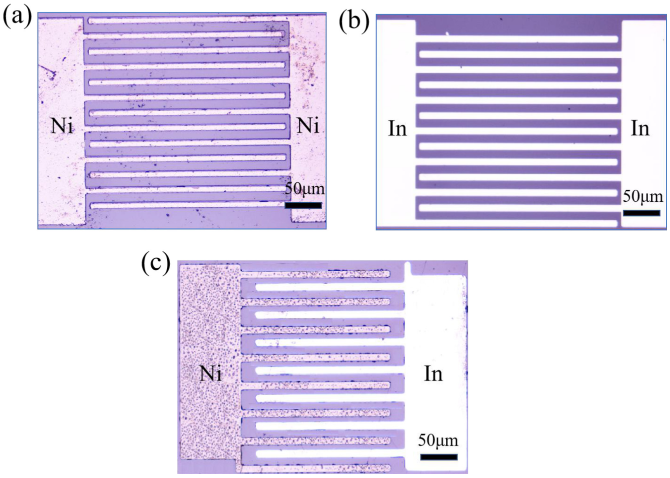

FIGURE 2. **Optical microscope image of Ni-Ni (a), In-In (b) and Ni-In (c) devices.**

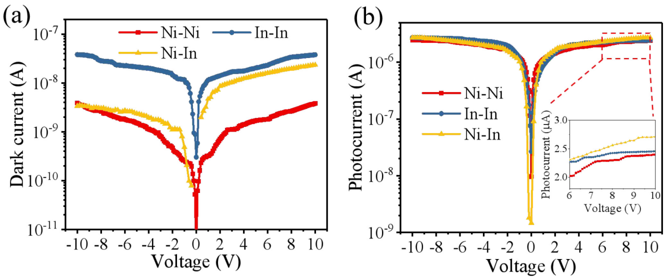

FIGURE 3. **The dark current (a) and photocurrent of Ni-Ni, In-In and Ni-In devices.**

reduce the schottky barrier height (SBH) and improve current conduction under forward biased. A GaN-based MSM ultraviolet detector was fabricated, and the influence of the MSM structure contact (the combination of Ni and In) was compared with the symmetric electrode MSM structure by using asymmetric metal design [16]. The photocurrent, dark current and photoresponsivity changes of UV detectors with various metals as electrodes are analyzed, and the reasons for the performance changes of different devices are probed. On the other hand, the asymmetric electrode Ni-In device has a self-powered phenomenon, and the photoelectric response and responsivity under 0V bias are tested and analyzed. It provides a theoretical and experimental basis for improving the UV detection performance of MSM devices.

II. EXPERIMENT

A 100nm buffer layer material (AlN) is deposited on sapphire (002) by metal organic chemical vapor deposition (MOCVD), then a un-doped 2μm thick GaN (light absorbing layer) material was grown on buffer layer. Fig. 1 shows the GaN high resolution X-ray diffraction (HRXRD) symmetric (002) plane rocking curve result reveals full width at half maximum (FWHM) of 0.19 degree, and the transmission of GaN drops rapidly from close to 80% to 0% at 365nm. We used photolithography and magnetron sputtering at room temperature to deposit about 300nm thick Ni (or In) metal electrode for symmetrical and asymmetric devices. Fig. 2 shows the Optical microscope image of GaN-based Ni-Ni (a), In-In (b) and Ni-In (c) MSM UV devices. The total area, interdigitated electrode width and spacing of the MSM device is 400×400μm, 10μm and 10μm, respectively.

After the device was fabricated, the photoelectric performance of three devices were measured by the UV detector integrated test system which composed of optical table, xenon lamp (200-800nm), monochromator (Bandpass: 5nm), optical power meter, and Keithley 2636B in air and at room temperature. The source meter applies a scanning voltage ranging from −10V to 10V to the electrodes at both ends of the device. Through the digital source meter, the Ni-Ni, In-In and Ni-In devices IV data is shown in Fig. 3. In-In device dark current (Id) is 3.8×10^{-8}A at 10V bias, and it is basically symmetrical under positive and negative bias. The dark current of Ni-Ni device is symmetrical too, and the dark current of the device is 4.2×10^{-9}A. The dark current of Ni-In device changes asymmetrically under positive and negative bias. Under negative bias, the dark current of Ni-In device is basically same as Ni-Ni device, while under positive bias, the dark current of the device is basically kept consistent with In-In device.

Fig. 3 (b) shows the changes of photocurrent (I_P), when a bias voltage of 10V is applied under 13mW optical power for three MSM devices. For Ni-In, In-In and Ni-Ni MSM UV detectors, the photocurrent values are 2.6, 2.47 and 2.3μA, respectively. The relationship of three devices photocurrent at the same voltage is I_P (Ni-In) > I_p (In-In) > I_P (Ni-Ni).

The Fig. 4 (a–c) is the response of the three devices when the illumination is turned on and off under different bias. Under the same bias, the maximum response current of the three devices is basically the same as the photocurrent. The current rise time is between 20 and 30ms, and the relaxation time is between 30 and 40ms. Fig. 4 (d) shows the photoresponsivity of three devices. The devices reach the maximum photoresponsivity at 360nm, and Ni-Ni device, In-In device, Ni-In device photoresponsivity are 0.76, 0.9, and 1.1 A/W, respectively, at 8V bias.

During the test of the Ni-In device, it was found that there was a photoelectric response under 0V bias. The test result is shown in Fig. 5. Fig. 5(a) is the time-photoelectric

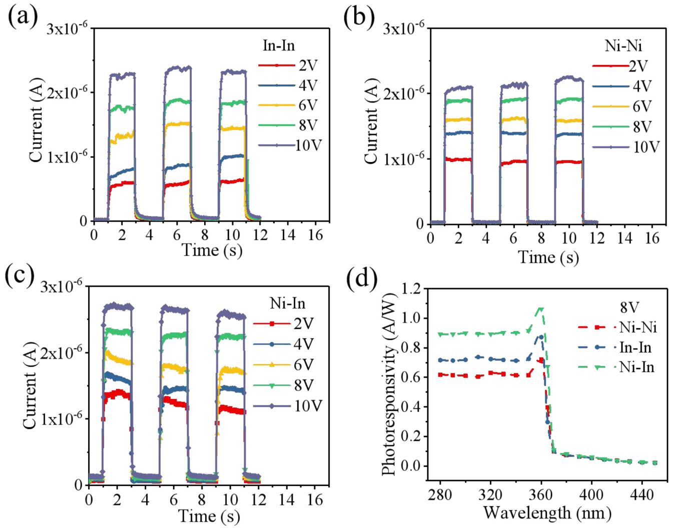

FIGURE 4. Is the time-photoelectric response and Photoresponsivity of three different devices, time response of In-In device (a), Ni-Ni device (b) and Ni-In device (c), the photoresponsivity (d) of three devices.

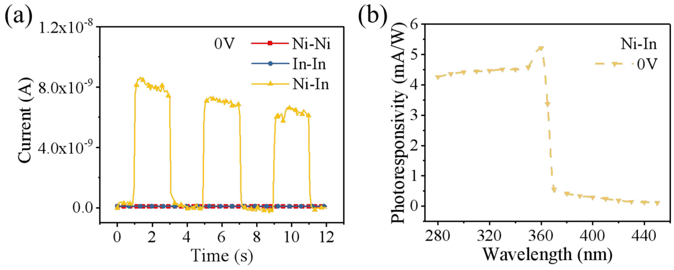

FIGURE 5. Ni-Ni, In-In and Ni-In devices time response (a) and Ni-In device Photoresponsivity (b) at 0V bias.

response of Ni-In device under 0V bias. When the UV source is turned off and on multiple times, the current rises as the UV source turned on, and the magnitude of the photocurrent is close to 8×10^{-9}A each time. The photocurrent measured under 0V bias indicates that the Ni-In device has a self-powered phenomenon. At the same time, we tested the UV responsivity of the Ni-In device for different wavelengths at 0V bias. The responsivity results are shown in Fig. 5(b), it still rises rapidly at 365nm and reaches the maximum responsivity 5.4mA/W at 360nm.

III. DISCUSSION

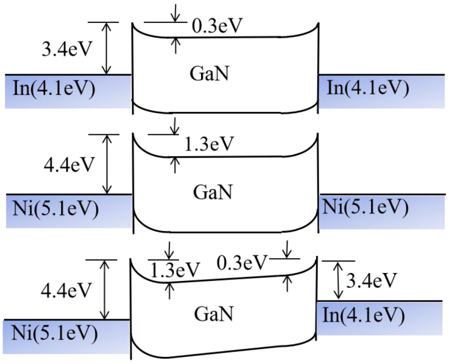

FIGURE 6. Schematic diagram of the contact barrier height of three different electrode devices.

Fig. 6 depicts the energy band diagrams of three different photodetectors without bias conditions and UV illumination. Here, the Schottky barrier height of the Ni/GaN junction is higher than the Schottky barrier height of In/GaN junction because Ni has a higher work function than In. Under the applied bias, these photogenerated electrons and holes are collected through Ni and In contacts, respectively. The dark current of Ni-In device with different electrode structures is not symmetric, which can be attributed to the difference in the work function of the asymmetrically contacted metals. When unintentionally doped GaN electron affinity is lower than the work function of the metal which contact with GaN, it will result in the formation of ohmic contact. When the metal work function is higher than the electron affinity of GaN formed Schottky contact. The Schottky barrier height (SBH) of the GaN-metal interface can be calculated according to the Mott model:

$$\phi_s = \phi_m - \chi \tag{1}$$

Here, ϕ_s is the barrier height of the Schottky junction, ϕ_m is the work function of the metal, and χ is the electron affinity of GaN. Ni and In are used as different electrodes to contact GaN to form asymmetric MSM device. The SHB of Ni/GaN junction is 1.3eV, while the SHB of In/GaN junciton is 0.3eV. Due to the difference in the Schottky barrier of the asymmetric contact, a built-in potential gradient is formed inside GaN between the two electrodes, which results in the asymmetric MSM device structure with enhanced current characteristics. In addition, this behavior can be explained as follows: considering that under bias conditions, the entire potential drop will cross the reverse-biased MS junction and results in a smaller dark current in the UV detector. For asymmetric device, the positive bias on the Ni electrode is forward, while the negative bias on the In electrode is backward. Here, the dark current of ideal photodetector can be defined by the following formula:

$$I_D = AA^*T^2 \exp\left(-\frac{\phi_b}{kT}\right)\left(\exp\frac{qV}{nTk} - 1\right) \tag{2}$$

Because dark current decays exponentially with the increase of SBH (Φ_b), the dark current will be higher for contacts with a lower Schottky barrier. The Ni-In asymmetric MSM device shows the highest dark current comparing with In-In and Ni-Ni MSM devices at 6-8V bias. This is due to the built-in electric field provided by Ni-In MSM device which enhances the transfer of carriers between the electrodes. In addition, when a negative bias is applied to the Ni contact, which will make it a reverse bias. The dark current should be driven by the reverse biased Ni electrode, therefore, the Ni-In device dark current as Ni-Ni devices.

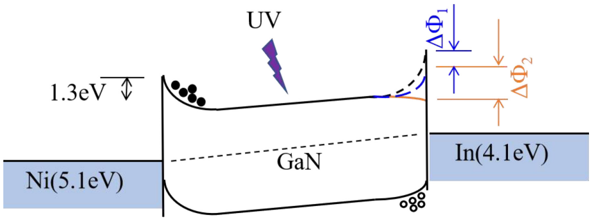

FIGURE 7. **Energy band change of Ni-In device under light irradiation.**

The change law of three devices photocurrent is basically same. This is because GaN absorbs light under illumination produced photogenerated carriers. After the separation of photogenerated carriers, electrons are deposited in conduction band, resulting in reduction of the Schottky barrier. Therefore, the photocurrent performance of three devices is not much different.

Fig. 7 is the schematic diagram of contact barrier changes of Ni-In devices under UV illumination. When positive voltage was applied to the Ni, the photogenerated holes drifted to the In/GaN junction traps and produced net positive change Q_s since the sum of the positive depletion change due to uncompensated donors and the trapped holes creating change must be equal to the metal negative, the depletion charge must have decreased if charged surface states occurred. This indicated that the built-in voltage would be reduced correspondingly, leading to a decrease in the Schottky barrier height, $\Delta\phi_1$,

$$\Delta\phi_1 = \frac{Q_s d}{2\varepsilon\varepsilon_0} \tag{3}$$

where d is the depletion width at the In/GaN junction, ε_0 is the permittivity of tree space, and ε is the relative dielectric permittivity. Furthermore, the lower work function of In compared to Ni further reduced the Schottky barrier height $\Delta\phi_2$ at the In/GaN junction. It can explain the self-powered and high responsivity when positive voltage was applied to Ni. Considering the Schottky barrier height of In/GaN junciton is 0.3eV. The photogenerated carriers are separated by the built-in electric field driving. The accumulation of holes in the In/GaN junction caused the Schottky barrier height reduce. Finally, the In/GaN junction is transformed into ohmic junction. Under UV illumination, the Ni-In device is equivalent to a diode, under the built-in electric field driving, the photogenerated carriers cross the In/GaN junction to form a photocurrent, produced a self-driving effect.

IV. CONCLUSION

Through the use of GaN to contact different metal electrodes to form different three types of UV detector production and photoelectric parameter testing, it is found that different metal materials have different work functions, so they form different contact barriers. The height of the contact barrier affects dark current of the device, and the photogenerated carriers will affect the contact barrier, resulting in the photocurrent of the three different devices being relatively close. Through this experiment, it can be found that the Ni-In device can keep a larger photocurrent at positive bias than Ni-Ni and In-In devices, so it has the largest photoresponsivity. Due to the separation of the photogenerated carriers under the action of the built-in electric field for Ni-In device.The accumulation of the carriers leads to the reduction of the contact barrier, therefore, the Ni-In device can self-powered and it has a photoelectric response at 0V bias.

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The authors declare no conflicts of interest. The data that support the findings of this study are available from the corresponding author upon reasonable request.

REFERENCES

[1] D. Li *et al.*, "Effect of asymmetric Schottky barrier on GaN-based metal-semiconductor-metal ultraviolet detector," *Appl. Phys. Lett.*, vol. 99, no. 26, 2011, Art. no. 261102.

[2] O. Katz, V. Garber, B. Meyler, G. Bahir, and J. Salzman, "Gain mechanism in GaN Schottky ultraviolet detectors," *Appl. Phys. Lett.*, vol. 79, no. 10, pp. 1417–1419, 2001.

[3] S. K. Jain *et al.*, "GaN-UV photodetector integrated with asymmetric metal semiconductor metal structure for enhanced responsivity," *J. Mater. Electr. Mater. Electron.*, vol. 29, pp. 8958–8963, Mar. 2018.

[4] B. Pandit and J. Cho, "Metal–semiconductor–metal ultraviolet photodiodes based on reduced graphene oxide/GaN Schottky contacts," *Thin Solid Films*, vol. 660, pp. 824–827, Aug. 2018.

[5] M. Garg, B. R. Tak, V. R. Rao, and R. Singh, "Improvement in self-powered GaN-based symmetric metal-semiconductor-metal ultraviolet photodetectors by using phenol-functionalized Porphyrin organic molecules," in *Proc. 4th IEEE Int. Conf. Emerg. Electron. (ICEE)*, 2018, pp. 1–4.

[6] S. Chang, M. Chang, and Y. Yang, "Enhanced responsivity of GaN metal-semiconductor-metal (MSM) photodetectors on GaN substrate," *IEEE Photon. J.*, vol. 9, no. 2, Apr. 2017, Art. no. 6801707.

[7] C. Guo *et al.*, "Self-powered ultraviolet MSM photodetectors with high responsivity enabled by a lateral n+/n− homojunction from opposite polarity domains," *Opt. Lett.*, vol. 46, no. 13, pp. 3203–3206, 2021.

[8] W. Zheng, R. Lin, J. Ran, Z. Zhang, X. Ji, and F. Huang, "Vacuumultraviolet photovoltaic detector," *ACS Nano*, vol. 12, no. 1, pp. 425–431, 2018.

[9] D. Y. Guo *et al.*, "Self-powered ultraviolet photodetector with super high photoresponsivity (3.05 A/W) based on the GaN/Sn:Ga_2 O_3 pn junction," *ACS Nano*, vol. 12, no. 12, pp. 12827–12835, 2018.

[10] P. G. Li *et al.*, "Construction of GaN/Ga_2O_3 p-n junction for an extremely high responsivity self-powered UV photodetector," *J. Mater. Chem. C*, vol. 5, no. 40, pp. 10562–10570, 2017.

[11] Y. K. Su *et al.* "GaN metal-semiconductor-metal ultraviolet sensors with various contact electrodes," *IEEE Sens. J.*, vol. 2, no. 4, pp. 366–371, Aug. 2002.

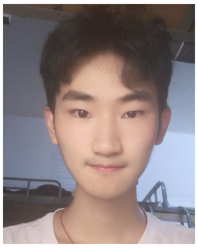
[12] D. Wang *et al.*, "Pt/AlGaN nanoarchitecture: Toward high responsivity, self-powered ultraviolet-sensitive photodetection," *Nano Lett.*, vol. 21, no. 1, pp. 120–129, 2021.

[13] S. Fang *et al.*, "Tuning the charge transfer dynamics of the nanostructured GaN photoelectrodes for efficient photoelectrochemical detection in the ultraviolet band," *Adv. Funct. Mater.*, vol. 31, no. 29, 2021, Art. no. 2103007.

[14] D. Wang *et al.*, "Highly uniform, self-assembled AlGaN nanowires for self-powered solar-blind photodetector with fast-response speed and high responsivity," *Adv. Opt. Mater.*, vol. 9, no. 4, 2021, Art. no. 2000893.

[15] H. Zhang *et al.*, "Demonstration of AlGaN/GaN-based ultraviolet phototransistor with a record high responsivity over 3.6×10^7 A/W," *Appl. Phys. Lett.*, vol. 118, no. 24, 2021, Art. no. 242105.

[16] J. Liao, C. Wu, R. Zhang, Y. Li, and T. Li, "Fabrication and research of MSM UV detectors with different electrode materials," in *Proc. 5th IEEE Electron Devices Technol. Manuf. Conf. (EDTM)*, 2021, pp. 1–3.



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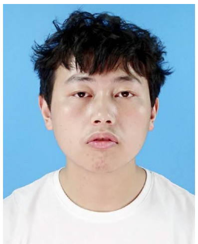

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