Chapter 2. Paper Review

2.1 Photodetectors of GaN Thin Film

Gallium nitride (GaN) has been considered to be one of the most promising materials for the fabrication of high responsivity and visible–blind ultraviolet (UV) detectors due to its unique properties, such as direct and wide band-gap and high-saturation electron drift velocity ($3X10^7$ cm/s) [11]. This material has been largely investigated in the last few years by virtue of its excellent mechanical, electrical and optical properties. The large direct gap makes it material of choice for ultraviolet (UV) detectors, whereas its robustness is ideal for applications to severe working conditions such us those of astronomy, flame detection, engine monitoring[12].

Several groups have reported the characterization of photoconductive [13–16], photovoltaic positive–intrinsic–negative (p–i–n) [17] nitride–based photodetectors and Schottky-based metal–semiconductor–metal (MSM) photodetectors[18,19]. GaN Schottky barrier devices have been shown to have high-speed and low-noise capabilities [20,21]. They often show a persistent photocurrent (PPC) [22,23], independent of the growth technique[24].

Due to its wide direct energy gap (Eg = 3:4 eV) and good transport properties, GaN is ideally suitable for intrinsic UV detectors with high responsivity at wavelengths shorter than 365 nm. So far, only a few papers have been devoted to the fabrication and characterization of photoconductive [25,26], Schottky barrier [27], and field-effect transistor GaN photodetectors [28].

We can get some paper ever report GaN thin film metal–semiconductor–metal photoconductive detectors have been fabricated on Si(111) substrates[29][30], and epilayer growth on 6H-SiC substrate[31] using metal organi chemical vapor deposition(MOCVD) [29][31], and thermal CVD [30].

In their work, they can get that photocurrent (PC) measurement of the GaN UV photoconductor gave a cutoff at 363nm~365 nm, about 3.4 eV and a continuous photoresponse in the ultraviolet region. The spectral responsivity remained nearly constant for wavelengths ranging from 250 to 365 nm. The maximum responsivity 800 A/W that we can find in GaN thin film literature [32].Table 2.1 list the data arranged from literature about GaN thin film metal–semiconductor–metal photoconductive detectors

For example, Fig. 2.1 [30] (a) shows photocurrent spectrum of the photoconductive detector based on the GaN epilayer on Si(111) substrate, these detectors exhibited a sharp cutoff at the wavelength of 365 nm and a high responsivity at a wavelength from 360 to 250 nm. Fig.2.1 (b) shows the relationship between the responsivity and the bias voltage was measured. A maximum responsivity of 2.53 A/W was achieved at 360 nm with a 7 V bias. The responsivity saturated when the bias voltage reached 7.2 V.

The saturation behavior can be explained by the sweep-out effect.

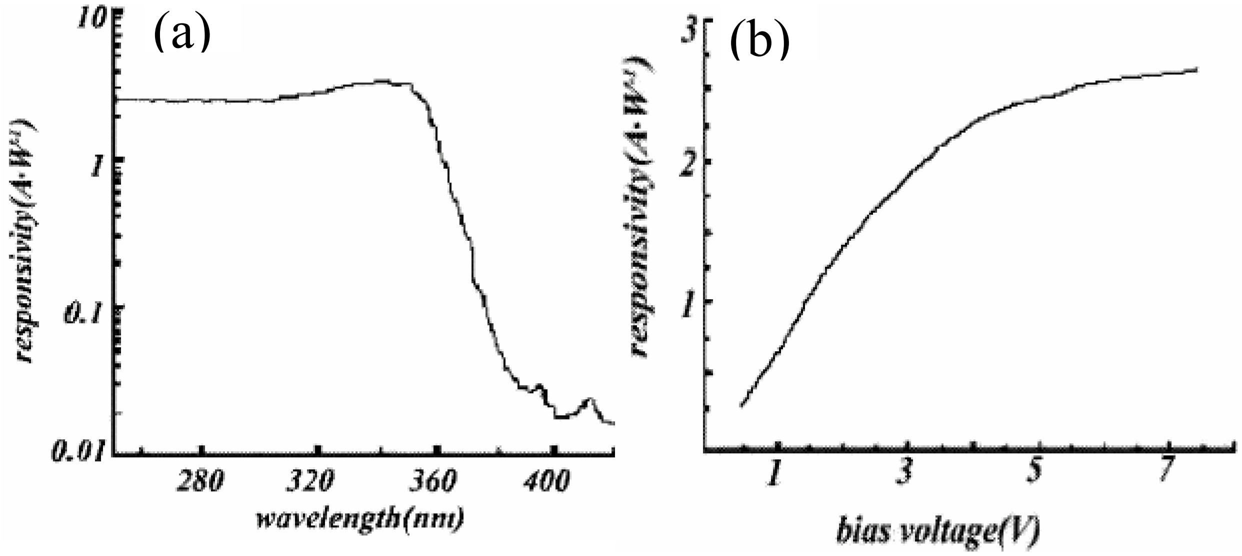


Fig. 2.1 (a) Spectral response of MSM UV detector based on GaN thin film [30].

(b)Voltage-dependent responsivity of MSM UV detector based on GaN thin film [30].

Table 2.1

Literature Review: GaN thin film M-S-M photoconductive detectors

Substrate (Electrode)	Apparatus	Responsivity (A/W)	Journal	Year [reference]
6H-SiC (Au)	MOCVD	Maximum responsivity : 133(A/W) achieved at 360nm under a 5V bias	Jpn. J. Appl. Phys	1999 [31]
Si(111) (Al)	Thermal (vacuum)	Maximum responsivity : 2.53(A/W) under a 7V bias	Inter. J. Mod. Phys	2002[30]
Si(111) (Al)	MOCVD	Maximum responsivity : 6.9(A/W) at 357nm under a 5V bias Non-ohmic contect : 3 (A/W)	Appl. Phys. Lett	2000[29]
Al2O3 (0001)	MOCVD	Maximum responsivity : 800(A/W) achieved at 360nm	J. Appl. Phys.	1997[32]
c-Al2O3 (0001)	MOCVD	Maximum responsivity : 20(A/W) under 400K-500K, achieved at 325nm laser.	Sensors and Actuators	2004[33]
Al2O3 (00-1) (Ti/Au Ni/Au)	MOCVD	Maximum responsivity : 0.15(A/W) achieved at 363nm under a 3V bias	Appl. Phys.Lett	1998 [7]
Al2O3 (0001) (Ti/Au)	MOCVD	Maximum responsivity : 0.13(A/W) achieved at 320nm under a 2V bias	Appl. Phys.Lett	1993 [17]
Al2O3 (Pt/Au)	MOCVD	Maximum responsivity : 0.02(A/W) achieved at 325nm laser under a 5V bias	Appl. Phys.Lett	1998[9]

From Fig. 2.2 (a) and (b) show the measurement of dark current and responsivity of both the ohmic contact and non-ohmic contact detectors[34]. It's seen in Fig.2.3 that prove the ohmic contact detector exhibits a higher responsivity with a wider linear increase range of the applied voltage as compared with the non-ohmic contact detector.

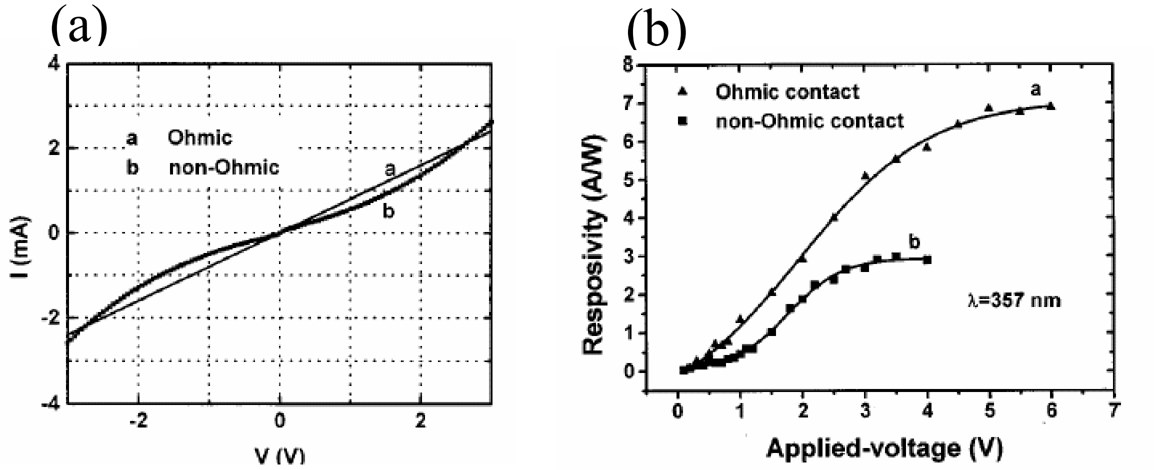


Fig. 2.2 (a) I–V characteristics of an ohmic contact detector and a non-ohmic contact[34].

(b)Voltage-dependent responsivity of the ohmic contact detector and the non-ohmic contact detector[34].

The low responsivity of the non-ohmic detector might be due to the decrease in the photocurrent gain. The metal-GaN interfaces with the band structure scheme as shown in Fig. 2.3, can be understood as two back-to- back Schottky contact barriers that could reduce the photocurrent gain.

Because the contact barrier can cause a built-in electric field ε in GaN, the electric field on the right-hand side will repel the transition of the carriers,

especially at the low applied voltage, thereby reducing the possibility of their reaching the electrode as shown in Fig. 2.3 and because the electrons cannot inject easily in the detectors from the left-hand side, the photocurrent gain of non-ohmic contact detectors will be smaller than the ohmic ones.

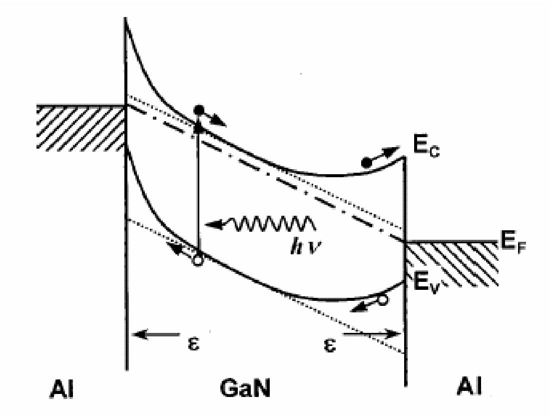
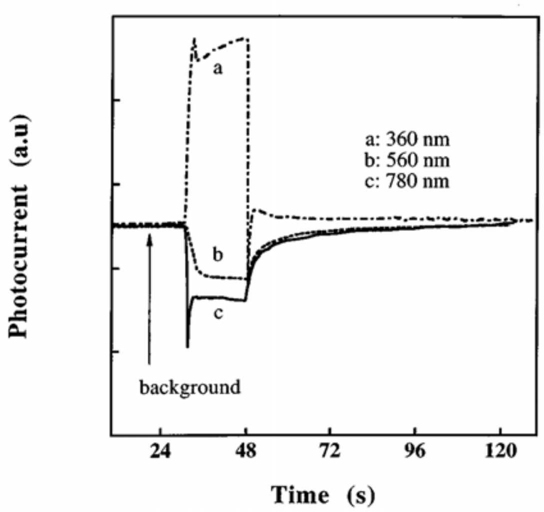


Fig. 2.3 Schematic band diagram of detectors with contact barriers. Solid line is the non-ohmic contact case, dot line is the ohmic contact case.

In some case, optical quenching due to deep centers in the band-gap has been observed to deteriorate the photoconductivity in GaN photoconductors, which is considered harmful for the UV detection applications[32]. In general, the detected sources contain light with different wavelengths. The reduced responsivity of the GaN photoconductor could be related to the quenching effect.

Fig. 2.4 shows the reduction of the photocurrent of a GaN photoconductor, when illuminated by a He-Ne laser with the wavelengths of 560nm and 780nm (curve b.c). As contrary, the photocurrent increases under the illumination of the wavelength of 360nm (curve a in Fig. 2.4), the quenching effect which is especially conspicuous in the near band gap region. This could deteriorate the output signal from the photoconductor.

Therefore, processes for removing or saturating deep centers are employed to reduce the quenching effect.



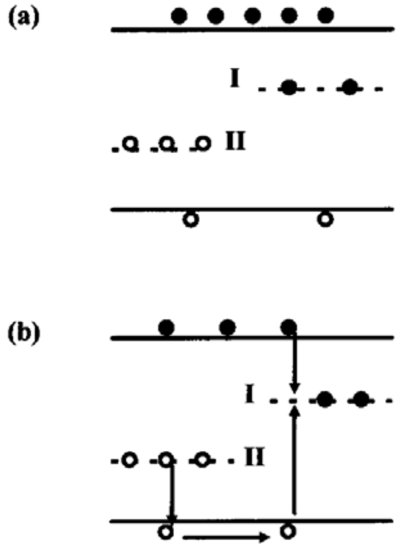


Fig.2.4 Transient photocurrent showing optical quenching by 560 and 780 nm lights. The background is the photocurrent of the detector with 365 nm light [32].

Fig.2.5 Model for optical quenching: (a) photoconductor illuminated with above band gap light, (b) addition of the sub-band gap energy light to (a) [32].

2.2 Photodetectors of Nanowires

Nanowires and nanotubes may become important building blocks for nanoscale optoelectronics[35] since they can function as miniaturized devices as well as electrical interconnects. Nano-devices such as field-effect transistors[36,37], single-electron transistors[38,39], metal-semiconductor junctions[40,41], and intermolecular crossed junctions[42,43] have been demonstrated.

This section gives the background knowledge on the photoconduction of GaN nanowire transistors and their counterparts based on ZnO.

2.2.1. Photoconduction studies on GaN nanowire transistors under UV illumination[44]

Photoconduction studies have been carried out with single crystal GaN nanowires. The nanowire transistors exhibit a substantial increase in conductance upon UV light exposure. Besides the selectivity to different light wavelengths, extremely short response and recovery time have been also obtained, as well as the great reversibility of the nanowire between the high and low conductivity states. The SEM image in the inset in Fig.2.6 shows a top view of the device used in the measurements described as follows. The nanowire has a diameter of 15 nm and a channel length of 2 μm between the source and drain electrodes , and silicon substrate is used as a back gate.

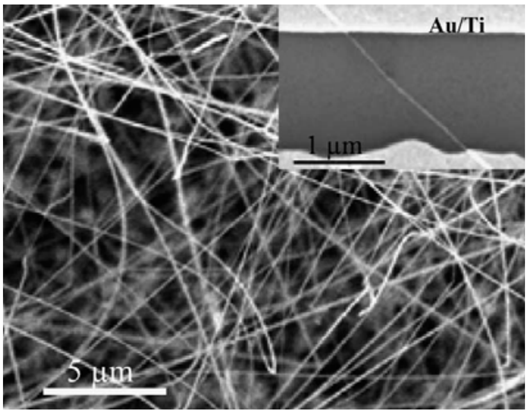
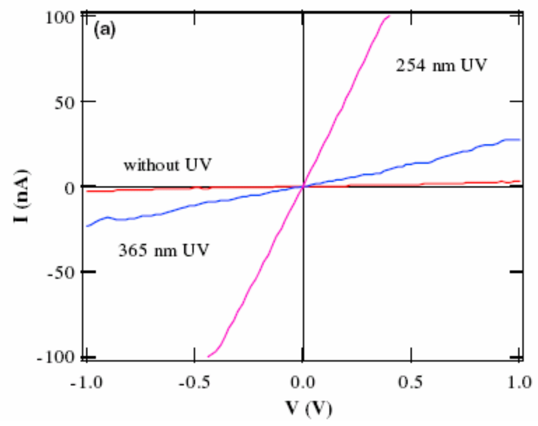


Fig. 2.6 SEM image of GaN nanowires grown from 10 nm Au clusters. Inset: SEM image of a GaN nanowire transistor with two Au/Ti contact electrodes [44].

Fig. 2.8 shows three I–V curves taken at V_g (gate bias) 0 V under indoor incandescent light and upon exposure to UV light at wavelengths of 365 and 254 nm, respectively. Detailed data analysis (Fig. 3b) revealed that the conductance of the nanowire increases up to 58.4% of its saturation value within 1 s after UV lamp was turned on, and reaches 81.9% within 2 s. The GaN nanowire sensor also exhibits an extremely high recovery speed due to the fast hole–electron recombination process.



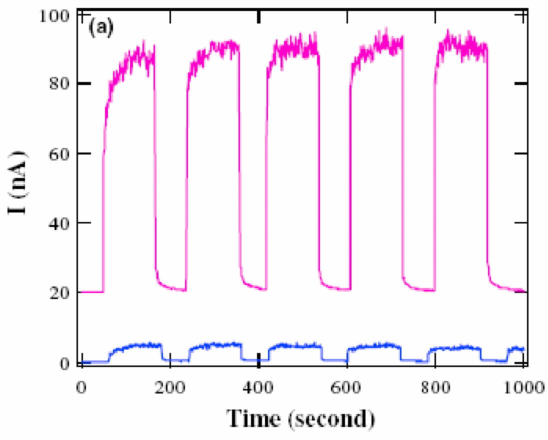


Fig. 2.7 I–V curve of GaN nanowire before and after exposed to 254 nm and 365 nm UV light [44].

Fig. 2.8 Current vs time for the GaN nanowire with UV light repeatedly turned on and off. The red curve (offset by 20 nA) is measured with illumination of 254 nm UV, while the blue curve corresponds to 365 nm UV light [44].

2.2.2 Photoconduction studies on ZnO nanowire Photodetectors and Optical Switches [45]

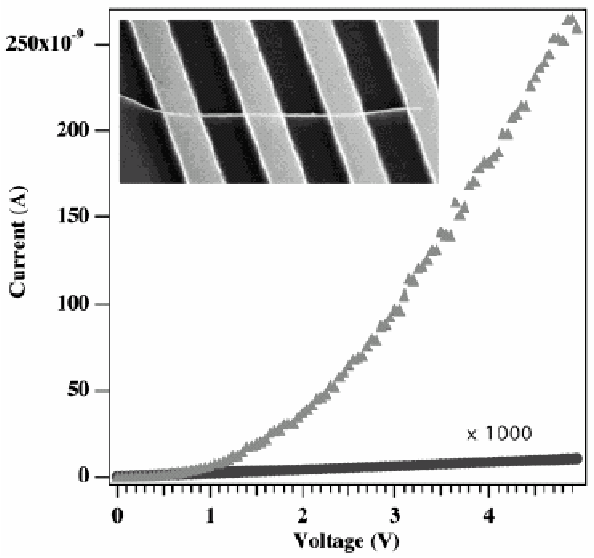
Here, they show the possibility of creating highly sensitive nanowire switches by exploring the photoconducting properties of individual semiconductor nanowires.

The conductivity of the ZnO nanowires is extremely sensitive to ultraviolet light exposure. The light-induced conductivity increase allows us to reversibly switch the nanowires between “OFF” and “ON” states.

Four-terminal measurements of individual ZnO nanowires indicate that they are highly insulating in the dark with a resistivity above 3.5 MΩ cm. When the nanowires are exposed to ultraviolet (UV)-light with wavelengths below 380 nm (handheld UV-lamp, 0.3 mWcm±2, 365 nm), the nanowire resistivity decreases by typically 4 to 6 orders of magnitude. Fig.2.10 show the comparison of the current-voltage (I-V) curves measured on a 60 nm nanowire in the dark and upon UV-light exposure.

Fig.2.11 plots thephotoresponse as a function of time as the UV-lamp was
switched on and off. It is evident that the nanowires can be reversibly switched between the low and the high conductivity state. The rise and decay times of the fastest nanowire switches are below our detection limit, which is roughly 1 s.

These photoconducting nanowires could serve as highly sensitive UV-light detectors, chemical and biological sensors, and switching devices for nanoscale optoelectronic applications,



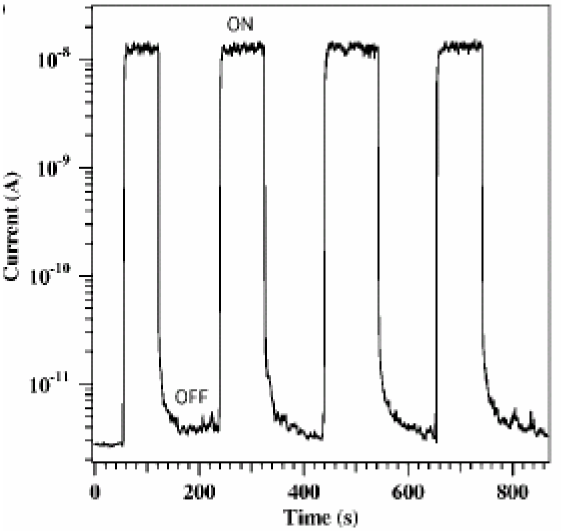


Fig.2.9. I-V curves show dark current (●) and photocurrent (▲) of a single ZnO nanowire under 365 nm UV-light illumination[45].

Fig.2.10. Reversible switching of a ZnO nanowire between low and high conductivity states when the handheld UV-lamp was turned on and off. The bias is 1 V[45].