

Vertical Schottky ultraviolet photodetector based on graphene and top–down fabricated GaN nanorod arrays

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Abstract: GaN has been widely used in the fabrication of ultraviolet photodetectors because of its outstanding properties. In this paper, we report a graphene–GaN nanorod heterostructure photodetector with fast photoresponse in the UV range. GaN nanorods were fabricated by a combination mode of dry etching and wet etching. Furthermore, a graphene–GaN nanorod heterostructure ultraviolet detector was fabricated and its photoelectric properties were measured. The device exhibits a fast photoresponse in the UV range. The rising time and falling time of the transient response were 13 and 8 ms, respectively. A high photovoltaic responsivity up to 13.9 A/W and external quantum efficiency up to 479% were realized at the UV range. The specific detectivity $D^* = 1.44 \times 10^{10}$ Jones was obtained at -1 V bias in ambient conditions. The spectral response was measured and the highest response was observed at the 360 nm band.

Key words: graphene; GaN nanorods; ultraviolet photodetector; top–down fabrication

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1. Introduction

GaN has been widely used in the fabrication of ultraviolet photodetectors (UV PDs) because of its direct wide bandgap of 3.4 eV and excellent thermochemical stability^[1–4]. Typical GaN PD is based on photoconductivity, p–n junction, and Schottky barrier^[5–7]. A metal layer of about 5 nm is commonly used as the transparent conductive layer in GaN PD^[8]. However, this translucent metal has a low transmittance (10% absorption per nanometer), which blocks large amounts of light and reduces photoresponsivity. Moreover, because of low carrier mobility and short carrier lifetime, the photosensitive area of GaN photodetectors is usually limited to about 0.1 mm², which is detrimental to imaging applications^[9]. Graphene has excellent electrical conductivity (extremely high carrier mobility) and outstanding photopermeability from UV to infrared (2.3% per layer of absorption)^[10–12]. Furthermore, graphene is a kind of semi–metal that can form a Schottky junction with GaN^[13]. So it is expected to be a substitute for metal electrodes on GaN PD devices^[14, 15]. In addition to the function of transparent conductive electrodes, graphene can be used as an effective current transmission channel^[16]. At the graphene/GaN interface, the photo-generated carriers can be separated due to the built-in electric field. This type of carrier can migrate into graphene to produce a photocurrent^[17]. Due to the high defect density and low conductivity, the performance of conventional GaN-based photodetectors has been partially limited by the effi-

ciency of photocarrier collection. GaN nanowire (NW) arrays can provide larger average current densities of vertical devices^[18, 19]. A high-quality GaN nonpolar surface can be obtained without substrate lattice mismatch restriction and the stress release problem of GaN devices can be solved^[20]. At present, GaN or other nanowires are commonly grown directly from the substrate with the down–top mode by molecular beam epitaxy (MBE) or metal–organic chemical vapor deposition (MOCVD)^[21, 22]. However, this method is not only expensive but it is also difficult to control the morphology of nanowires. Another way to overcome these drawbacks is a top–down fabrication, using standard photolithography and etching to compose nanowires on a homogeneous film^[23, 24]. Vertically aligned semiconductor nanorods (NRs) have been demonstrated in this top–down approach. However, until now, there have been few studies involving graphene and GaN nanorods in photodetectors.

In this work, the top–down fabrication of GaN nanorods was realized by dry and wet etching of GaN. Further, graphene–GaN nanorod vertical Schottky ultraviolet detectors were manufactured and measured. Excellent photoelectric properties, such as light response rate and specific detection rate, have been obtained.

2. Experimental

Two kinds of GaN epitaxial layers were grown on *c*-plane sapphire. Where 2 μm GaN thin film was used to characterize the etching rate of dry etching, optimize the wet etching process and measure the photoluminescence spectrum. A 500 nm n–GaIn / 1 μm n⁺–GaIn structure was used to fabricate a vertical Schottky ultraviolet detector. The doping concentrations of the n⁺–GaIn and n–GaIn were about $5 \times 10^{18} \text{ cm}^{-3}$

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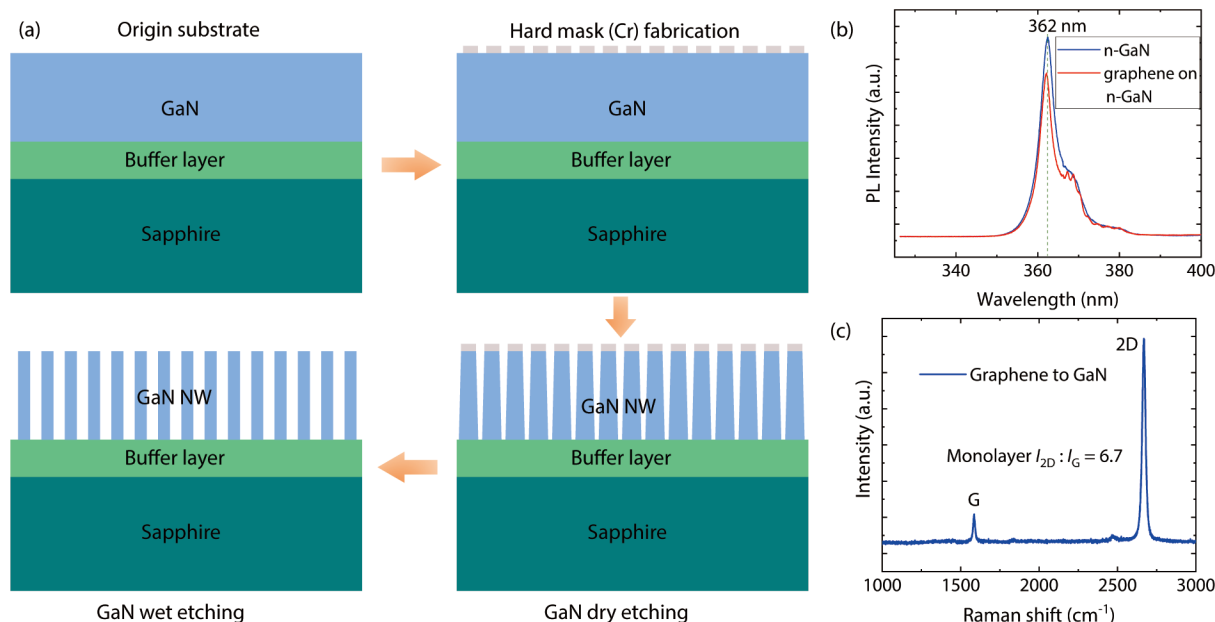


Fig. 1. (Color online) (a) The process schematic diagram of the preparation of GaN nanorods. (b) The PL spectra of GaN before and after graphene transfer. (c) The Raman spectra of graphene grown on copper foil.

and $2 \times 10^{16} \text{ cm}^{-3}$, respectively.

The top-down structure of GaN nanorods was fabricated by the GaN dry and wet etching process. The process diagram is shown in Fig. 1(a). First, the Cr mask was patterned by lithography and ion beam etching (IBE). Second, GaN was etched by inductively coupled plasma (ICP) etching equipment. Finally, wet etching by tetramethylammonium hydroxide (TMAH) solution was used to eliminate the sidewall damage induced by dry etching and form the nanorod's array structure.

The morphology of nanorod arrays was observed by scanning electron microscopy (SEM). The quality of GaN and graphene was evaluated by photoluminescence (PL) and Raman spectroscopy, respectively. Fig. 1(b) shows the PL spectra of GaN before and after graphene transfer. Strong near-band edge emission of GaN substrate indicates fewer defects. The peak at 362 nm coincides with the bandgap of GaN about 3.4 eV. When the graphene was transferred to the GaN substrate, the intensity of the PL peak decreased. The attenuation of PL intensity after graphene transfer happens because graphene also has an amount of light absorption in the ultraviolet region (about 5% per layer at 360 nm)^[25]. Fig. 1(c) shows the Raman spectra of graphene grown on copper foil. The G peak ($\sim 1586 \text{ cm}^{-1}$) and the 2D peak ($\sim 2685 \text{ cm}^{-1}$) are two characteristic peaks of graphene in Raman spectroscopy. Moreover, the peak at $\sim 1350 \text{ cm}^{-1}$ in defected graphite is called the D peak. The intensities of G and 2D peak are represented by I_G and I_{2D} , respectively. The layers of graphene are usually determined by $I_{2D} : I_G$ ^[26]. The high ratio of $I_{2D} : I_G$ (~ 6.7) and the absence of D peaks indicate that the monolayer graphene has few defects.

For photodetector fabrication, the photolithography for nanometer-level nanorods was performed by electron beam photolithography (EBL). An ohmic contact layer (Ti/Al/Ni/Au, 30/130/50/150 nm) was fabricated on the surface of n⁺-GaN and annealed at N₂ environment (850 °C for 30 s). Then, SiO₂ isolation layer (200 nm) was formed around the n⁻-GaN mesa

by plasma enhanced chemical vapor deposition (PECVD) and reactive ion etching (RIE) process. Graphene transfer, photolithography, O₂ plasma etching, and H₂ annealing at 450 °C were carried out to cover the exposed n⁻-GaN surface with graphene. The cyclic Schottky electrode (Ni/Au, 50/100 nm) was formed on the peripheral graphene.

Electrical transport measurements were implemented using the Keithley2636A dual-channel digital source meter. A semiconductor laser of 365 nm was used to detect the light response related to the UV wavelength.

3. Results and discussions

The final morphology of GaN nanorods was determined by the corrosion rate of TMAH wet etching. The corrosion rate was affected by solution concentration and temperature. We observed the basic process of GaN nanorods formation by SEM at different etching time. As shown in Fig. 2(a)–2(d), the corrosion time is 3, 5, 10, and 15 min, respectively. It can be seen that the OH⁻ ion in TMAH reacts preferentially with the atoms on the sidewall of the nanorod. The Ga and N atoms dissolve into the solution to form reactants. Because the surface atoms on the sidewalls of the nanorods have open bonds (the dangling bonds are very dense), the sidewall etching rate for this step will be very fast and continue until it reaches the nonpolar *m*-plane ($\bar{1}\bar{1}00$). After the formation of the *m*-plane, the TMAH wet etching process was carried out to gradually obtain the GaN nanorods with both sidewalls of the *m*-plane.

Through experimental exploration, we obtained more optimized TMAH wet etching conditions. TMAH : H₂O was 1 : 3, water bath temperature was 80 °C, and corrosion time was 17 min. Then, a GaN nanorod array with ideal morphology was obtained. The SEM measurement results are shown in Fig. 2(e). The diameter of the nanorods is about 335 nm and the height is about 1.14 μm. Although the non-polar *m*-plane of the sidewall of GaN nanorods has a lower etching rate compared with other planes, it can also be etched in the

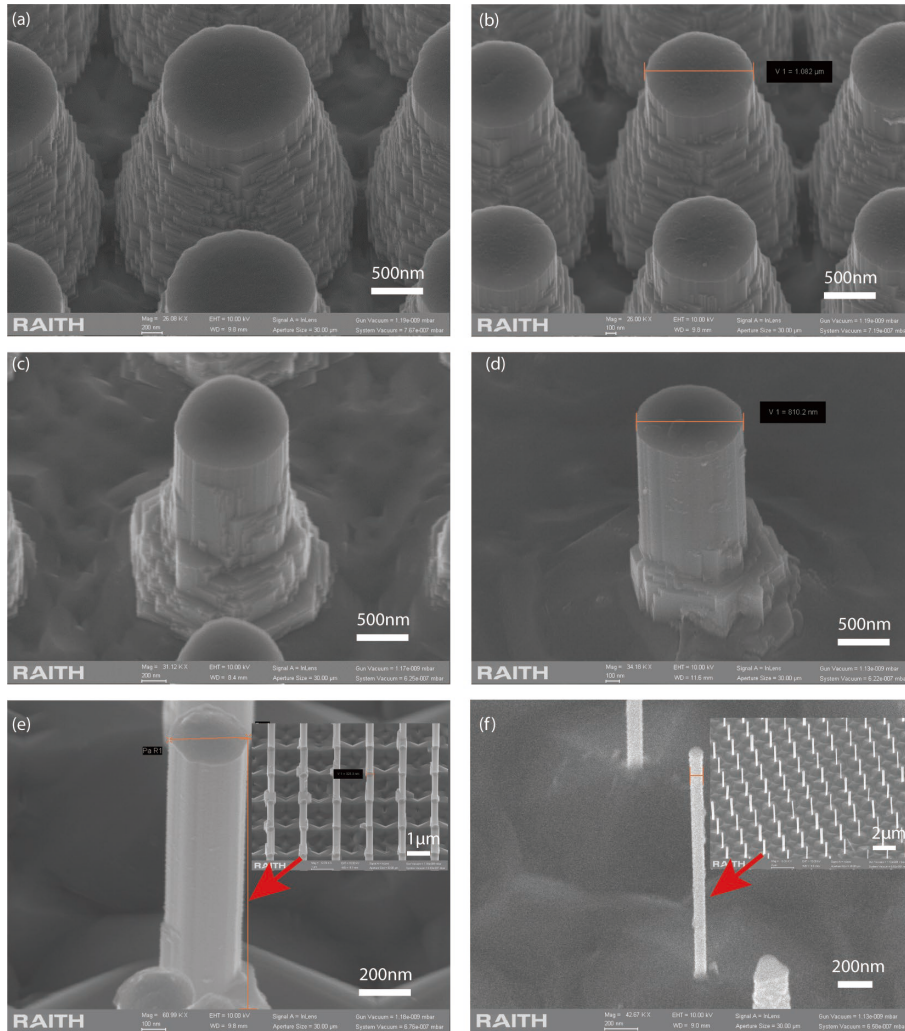


Fig. 2. The basic process of GaN nanorod formation by SEM at different etching time: (a) 3, (b) 5, (c) 10, (d) 15, (e) 17, and (f) 22 min.

TMAH solution for a long time. As a result, the diameter of the nanorods was further reduced to a minimum of 78 nm (Fig. 2(f)) as corrosion time continued to increase.

A graphene–GaN nanorod array heterojunction ultraviolet detector was fabricated. Fig. 3(a) shows the cross-sectional structure of the device, with graphene in contact with n–GaN nanorods forming Schottky structures and n⁺–GaN in contact with metal electrodes forming ohmic contacts. Fig. 3(b) is an optical microscope image of the device structure. The square region in the middle is the main light-sensitive region of the device. The area was designed between 100 × 100 μm² and 300 × 300 μm². The inset is an SEM image of the GaN nanorods. The size of nanorod arrays was consistent with the design value with the diameter of 500 nm and interval of 300 nm. The *I*–*V* characteristics of graphene–GaN nanorods photodetectors in darkness and light are compared as shown in Figs. 3(c) and 3(d). With bias varying from –5 to 5 V, Fig. 3(c) shows a significant increase in photocurrent when illuminated with a 365 nm UV light source as compared with darkness. $I_{\text{photo}} : I_{\text{dark}}$ is about 100. The inset of Fig. 3(c) shows that the ideality factor and barrier height were 1.42 and 0.73 eV at the darkness, respectively. It can be seen that the device has excellent detection ability in the band of 365 nm. Fig. 3(d) shows the *I*–*V* curve of the *y*–logarithmic transformation at 100% laser power in the dark and under ultraviolet light. Asym-

metric *I*–*V* curves show that the Schottky junction has a rectifying behavior in the dark.

To study the periodicity and sensitivity of the detector to ultraviolet light, we test the switching frequency characteristics of the device. Fig. 3(e) shows the variation of current with time at the drain voltage (V_{DS}) of –5 V under the cyclic ultraviolet illumination of the detector. The band of ultraviolet light was 365 nm and the period was 0.1 s. In a light switching cycle, the photocurrent increased rapidly and then stabilized after reaching the peak. When the light was turned off, the photogenerated carriers gradually fell from the conduction band to the valence band, and the photocurrent decreased rapidly until all of the photogenerated carriers were exhausted. As can be seen from the changes of detector current during the four UV illumination periods in Fig. 3(e), the photoresponsivity of the detector has excellent periodicity and stability. For the sensitivity of the detector, the rise time (τ_r) was measured from 10% to 90% of the signal peak value. The decay time (τ_f) was from 90% to 10%^[27]. As shown in Fig. 3(f), the graphene–GaN nanorods ultraviolet detector has a τ_r of 13 ms at the beginning of illumination and a τ_f of 8 ms from the time used to turn off. This is mainly attributed to the effect of the graphene–GaN nanorods' heterojunction. For the GaN nanorods structure, the incident light has an increased contact area with the GaN and can be reflected and

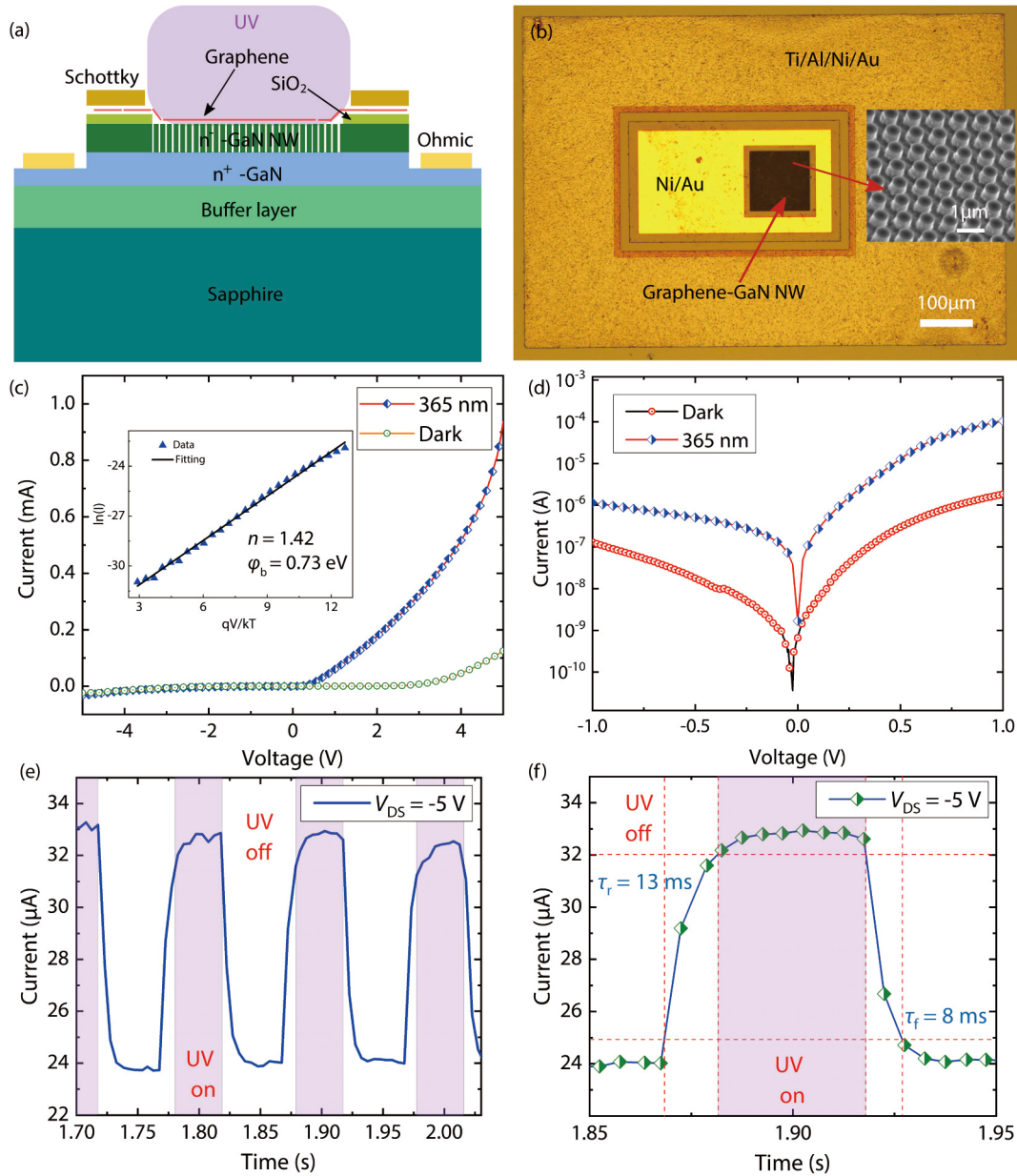


Fig. 3. (Color online) (a) The cross-sectional structure of the graphene–GaN nanorod array heterojunction ultraviolet detector. (b) An optical microscope image of the device structure, and the inset is an SEM image of GaN nanorods. (c, d) The I – V characteristics of graphene–GaN nanorods photodetectors in darkness and light. (e, f) The variation of current with time at the bias of -5 V under the cyclic ultraviolet illumination of the detector.

absorbed many times. Then, more photo-generated current can be generated and transported to the electrode under the action of an external electric field to form a photocurrent. Therefore, compared with GaN thin film, the vertical GaN nanorod arrays have a higher surface volume ratio and surface carrier recombination ability, thus enormously improving the photo-carrier generation and recombination efficiency. In addition, the heterostructure between graphene and GaN nanorods contributes significantly to the rapid response of the detector.

Fig. 4(a) shows the band structure of the graphene–GaN nanorod array heterostructure. When graphene was exposed to GaN nanorods, electrons from GaN nanorods near the heterojunction interface flow into graphene. This happens because the Fermi level of GaN nanorods is higher than graphene^[13]. After electron accumulation in graphene to a cer-

tain extent, the space charge region will be formed at the interface, and the electron accumulation on the graphene side will carry a negative charge. Because of the gap in the GaN nanorods, graphene is partially suspended on the nanorods, which enhances the electron transport capacity of graphene. Furthermore, the band of GaN nanorods can bend upward at the interface when the electron migration leaves the donor with a positive charge, and the built-in electric field is generated^[28]. When ultraviolet light irradiates the detector, it is absorbed by the GaN nanorods after passing through the graphene transparent electrode. The photons provide the electrons in the valence band with energy, causing them to jump into the conduction band, creating a photonic hole in the valence band and a photonic electron in the conduction band, which is called the photo-generated carrier pair. It is rapidly separated by the built-in electric field of the heterojunc-

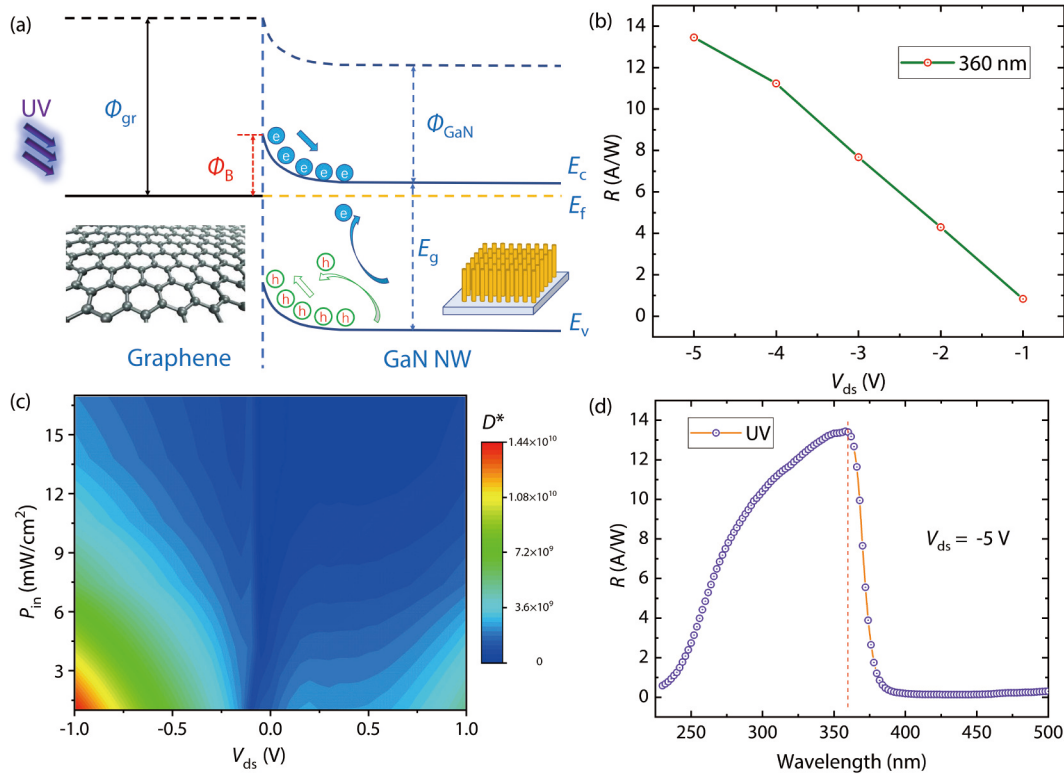


Fig. 4. (Color online) (a) The band structure of the graphene–GaN nanorod array heterostructure. (b) A curve of device photoresponsivity as bias voltage changes. (c) The bias voltage and light power as a function of D^* . (d) The spectral response curve of the detector at the bias of -5 V.

tion and is collected by the electrode to become the photocurrent.

Photoresponsivity (R) is one of the important parameters of the photodetector. It is defined as the ratio of the photocurrent output to the incident light power over the active region of the detector, which can be expressed as^[29]:

$$R_{\lambda} = \frac{I_{ph}}{P_{\lambda}S}, \quad (1)$$

where I_{ph} is the photocurrent irradiated by incident light, P_{λ} is the optical power density, and S is the effective illumination area. R is a parameter used to demonstrate the ability of a detector to produce photocurrent at a given wavelength and optical power. Fig. 4(b) shows a curve of device photoresponsivity as bias voltage changes. It can be seen that the R decreased as bias voltage decreased, and the maximum response of the device is 13.9 A/W. External quantum efficiency (EQE) is the ratio of the number of electric load currents (N_c) collected to the number of photons (N_i) of the photocurrent produced by the irradiated device. The external quantum efficiency can be expressed as follows^[29]:

$$EQE = \frac{N_c}{N_i} = \frac{hc}{e\lambda}R, \quad (2)$$

where h is the Planck constant, c is the speed of light, e is the electron charge, and λ is the wavelength of the input light. Furthermore, the EQE of the device was about 479%, which indicates that there was an internal gain in the device. Based on the heterojunction structure of graphene and GaN nanorods, photoelectron hole pairs are produced when the energy of incident light corresponds to the bandgap width of

semiconductor. Under the reverse bias, the electron hole pairs are ionized by the collision with the lattice in the process of motion and are excited again to produce the gain. Because the structure of nanorod arrays increase the number of photogenerated carriers, both the gain and the EQE increase^[28]. One of the other most important quality factors of photodetectors is the specific detectivity (D^*), which can be expressed as^[29]:

$$D^* = \frac{R\sqrt{A}}{\sqrt{2qi_d}}, \quad (3)$$

where A is the area of the device region and i_d is the dark current of the device. As shown in Fig. 4(c), D^* increases with increasing bias voltage and decreases with increasing light power. The D^* was about 1.44×10^{10} Jones when the bias was -1 V at 1% light power.

The spectral response curve of the detector at the bias of -5 V is shown in Fig. 4(d). The response peak of the detector was located in the 360 nm band. At a wavelength less than 360 nm, the device also had a certain photoresponsivity with gradual decay. When the wavelength was more than 360 nm, the photoresponsivity of the device decreased sharply. This happens because the space-charge region of the Schottky device is located on the semiconductor's surface and the reduction of quantum efficiency is suppressed. Because the number of photons decreases at the same light power, the photoresponsivity of the shortwave region decreases in part. GaN has a bandgap of 3.4 eV and a wavelength of 360 nm for photons of the same energy, indicating that the main working region of such detectors is still on the semiconductor side, and graphene does not cause any change in absorption

Table 1. The performance comparison of graphene (G) and Ga-based materials heterostructure photodetectors.

Material	Response band (nm)	Bias (V)	Responsivity (A/W)	EQE (%)	D^* (Jones)	τ_r/τ_f (ms)	Ref.
G-GaN NW	357	1	25	–	–	–	[14]
G-GaAs NW	532	0	0.00154	–	–	0.071/0.194	[30]
G-Ga ₂ O ₃ NW	258/365	–5	$3 \times 10^4/0.185$	–	–	9/8	[31]
G-GaN	325	10	0.36	87.5	1×10^{10}	5.05/5.11	[17]
G-AlGaIn/GaN	300/350	–2	0.56/0.079	–	–	–	[32]
G-GaN NR	360	–5	13.9	479	1.44×10^{10}	13/8	This work

when substituted for metal. The performance comparison of graphene (G) and Ga-based materials heterostructure photodetectors has been listed in Table 1. The device in this work has comparable detection ability at the UV range to other works.

4. Conclusion

In conclusion, GaN nanorods were fabricated by dry etching with ICP and wet etching with TMAH. Furthermore, a graphene-GaN nanorod heterostructure ultraviolet detector was fabricated and its photoelectric properties were measured. The ideality factor and barrier height were 1.42 and 0.73 eV at the darkness, respectively. When illuminated by a 365 nm UV light source, the photocurrent is improved obviously. $I_{\text{photo}} : I_{\text{dark}}$ was about 100. This showed that the device has excellent detection ability at the UV range. The rising time and falling time of the transient response were 13 and 8 ms, respectively. A high photovoltaic responsivity up to 13.9 A/W and EQE up to 479% were realized at the UV range. D^* is about 1.44×10^{10} Jones at –1 V bias in ambient conditions. The spectral response was measured and the highest response was also observed at the 360 nm band.

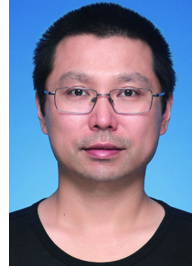
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References

- [1] Dubey A, Mishra R, Hsieh Y H, et al. Aluminum plasmonics enriched ultraviolet GaN photodetector with ultrahigh responsivity, detectivity, and broad bandwidth. *Adv Sci*, 2020, 7, 2002274
- [2] Gundimeda A, Krishna S, Aggarwal N, et al. Fabrication of non-polar GaN based highly responsive and fast UV photodetector. *Appl Phys Lett*, 2017, 110, 103507
- [3] Liu L, Yang C, Patanè A, et al. High-detectivity ultraviolet photodetectors based on laterally mesoporous GaN. *Nanoscale*, 2017, 9, 8142
- [4] Yu R X, Wang G D, Shao Y L, et al. From bulk to porous GaN crystal: Precise structural control and its application in ultraviolet photodetectors. *J Mater Chem C*, 2019, 7, 14116
- [5] Fang S, Wang D H, Wang X N, et al. Tuning the charge transfer dynamics of the nanostructured GaN photoelectrodes for efficient photoelectrochemical detection in the ultraviolet band. *Adv Funct Mater*, 2021, 31, 2103007
- [6] Wang D H, Liu X, Fang S, et al. Pt/AlGaIn nanoarchitecture: Toward high responsivity, self-powered ultraviolet-sensitive photodetection. *Nano Lett*, 2021, 21, 120
- [7] Razeghi M, Rogalski A. Semiconductor ultraviolet detectors. *J Appl Phys*, 1996, 79, 7433
- [8] Katz O, Garber V, Meyler B, et al. Gain mechanism in GaN Schottky ultraviolet detectors. *Appl Phys Lett*, 2001, 79, 1417
- [9] Lee C J, Kang S B, Cha H G, et al. GaN metal-semiconductor-metal UV sensor with multi-layer graphene as Schottky electrodes. *Jpn J Appl Phys*, 2015, 54, 06FF08
- [10] Wang S J, Geng Y, Zheng Q B, et al. Fabrication of highly conducting and transparent graphene films. *Carbon*, 2010, 48, 1815
- [11] Yang G, Li L H, Lee W B, et al. Structure of graphene and its disorders: A review. *Sci Technol Adv Mater*, 2018, 19, 613
- [12] Wang J, Song J, Mu X, et al. Optoelectronic and photoelectric properties and applications of graphene-based nanostructures. *Mater Today Phys*, 2020, 13, 100196
- [13] Lin F, Chen S W, Meng J, et al. Graphene/GaN diodes for ultraviolet and visible photodetectors. *Appl Phys Lett*, 2014, 105, 073103
- [14] Babichev A V, Zhang H, Lavenus P, et al. GaN nanowire ultraviolet photodetector with a graphene transparent contact. *Appl Phys Lett*, 2013, 103, 201103
- [15] Xu K, Xu C, Xie Y Y, et al. Graphene GaN-based Schottky ultraviolet detectors. *IEEE Trans Electron Devices*, 2015, 62, 2802
- [16] Wang S Y, Chen R S, Ren Y, et al. Highly-rectifying graphene/GaN Schottky contact for self-powered UV photodetector. *IEEE Photonics Technol Lett*, 2021, 33, 213
- [17] Tian H J, Liu Q L, Hu A Q, et al. Hybrid graphene/GaN ultraviolet photo-transistors with high responsivity and speed. *Opt Express*, 2018, 26, 5408
- [18] Yu F, Rümmler D, Hartmann J, et al. Vertical architecture for enhancement mode power transistors based on GaN nanowires. *Appl Phys Lett*, 2016, 108, 213503
- [19] Wang D H, Liu X, Kang Y, et al. Bidirectional photocurrent in p-n heterojunction nanowires. *Nat Electron*, 2021, 4, 645
- [20] Yu F, Yao S B, Römer F, et al. GaN nanowire arrays with nonpolar sidewalls for vertically integrated field-effect transistors. *Nanotechnology*, 2017, 28, 095206
- [21] Prabaswara A, Min J W, Subedi R C, et al. Direct growth of single crystalline GaN nanowires on indium tin oxide-coated silica. *Nanoscale Res Lett*, 2019, 14, 45
- [22] Zhang X D, He T, Tang W B, et al. Thermal oxidation of AlGaIn nanowires for sub-250 nm deep ultraviolet photodetection. *J Phys D*, 2020, 53, 495105
- [23] Liu G N, Wen B M, Xie T, et al. Top-down fabrication of horizontally-aligned gallium nitride nanowire arrays for sensor development. *Microelectron Eng*, 2015, 142, 58
- [24] Behzadrad M, Nami M, Wostbrock N, et al. Scalable top-down approach tailored by interferometric lithography to achieve large-area single-mode GaN nanowire laser arrays on sapphire substrate. *ACS Nano*, 2018, 12, 2373
- [25] Bae S K, Kim H, Lee Y, et al. Roll-to-roll production of 30-inch graphene films for transparent electrodes. *Nat Nanotechnol*, 2010, 5, 574
- [26] Ferrari A C, Meyer J C, Scardaci V, et al. Raman spectrum of

- graphene and graphene layers. *Phys Rev Lett*, 2006, 97, 187401
- [27] Zhang H C, Liang F Z, Song K, et al. Demonstration of AlGaN/GaN-based ultraviolet phototransistor with a record high responsivity over 3.6×10^7 A/W. *Appl Phys Lett*, 2021, 118, 242105
- [28] Zeng C H, Lin W K, He T, et al. Ultraviolet-infrared dual-color photodetector based on vertical GaN nanowire array and graphene. *Chin Opt Lett*, 2020, 18, 112501
- [29] Shen G Z, Chen H R, Lou Z. Growth of aligned SnS nanowire arrays for near infrared photodetectors. *J Semicond*, 2020, 41, 042602
- [30] Wu Y, Yan X, Zhang X, et al. A monolayer graphene/GaAs nanowire array Schottky junction self-powered photodetector. *Appl Phys Lett*, 2016, 109, 183101
- [31] He T, Zhao Y K, Zhang X D, et al. Solar-blind ultraviolet photodetector based on graphene/vertical Ga₂O₃ nanowire array heterojunction. *Nanophotonics*, 2018, 7, 1557
- [32] Kumar M, Jeong H, Polat K, et al. Fabrication and characterization of graphene/AlGaIn/GaN ultraviolet Schottky photodetector. *J Phys D*, 2016, 49, 275105



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