Synthesis of ternary oxide Zn$_2$GeO$_4$ nanowire networks and their deep ultraviolet detection properties

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Ternary oxide Zn$_2$GeO$_4$ with a wide bandgap of 4.84 eV, as a candidate for fourth generation semiconductors, has attracted a great deal of attention for deep ultraviolet (DUV) photodetector applications, because it is expected to be blind to the UV-A/B band (290–400 nm) and only responsive to the UV-C band (200–290 nm). Here, we report on the synthesis of Zn$_2$GeO$_4$ nanowire (NW) networks by lower pressure chemical vapor deposition and investigate their corresponding DUV detection properties. We find that pure Zn$_2$GeO$_4$ NWs could be obtained at a growth pressure of 1 kPa. The DUV detection tests reveal that growth pressure exerts a significant effect on DUV detection performance. The Zn$_2$GeO$_4$ NW networks produced under 1 kPa show an excellent solar-blind photoresponsivity with fast rise and decay times ($t_{\text{rise}} \approx 0.17$ s and $t_{\text{decay}} \approx 0.14$ s).

1. Introduction

Recently, wide-bandgap metal oxide nanostructures have attracted extensive attention for potential application in next-generation electronics including transparent conductive electrodes, sensing elements, energy harvesting and storage devices, and optoelectronics. Among them, UV detection, especially, solar-blind deep ultraviolet (DUV) photodetection is emerging as a hot topic because of their wide applications in commercial and military fields, including flame or engine monitoring, environmental and biological research, space technology, and missile launch. To date, extensive attention has been paid to binary wide-bandgap materials for UV detection, such as ZnO, SnO$_2$, ZnS, MnO$_3$ and AlN. However, much less effort has been devoted to more complex systems, such as ternary oxides, probably due to the difficulty with the preparation of high quality ternary nanostructures. Generally, ternary oxide systems are more chemically and thermally stable, and are more competitive candidates for deep UV detection due to their larger bandgap and hence higher photon energy thresholds. Recently, several ternary oxides including Zn$_2$SnO$_4$, In$_2$Ge$_2$O$_7$, and ZnGa$_2$O$_4$ have been employed for DUV detection. Among these candidates, ternary oxide Zn$_2$GeO$_4$ has a wide bandgap of about 4.84 eV, which is expected to be blind to UV-A/B band (290–400 nm) and only responsive to UV-C band (200–290 nm). The Zn$_2$GeO$_4$ nanostructures, especially Zn$_2$GeO$_4$ nanowires (NWs), have attracted a great deal of attention because of large specific surface area, fast charge transport characteristics, high optical absorption. To utilize their full potential in DUV photodetection, Zn$_2$GeO$_4$ NWs should be facilely fabricated and integrated into DUV photodetectors (PDs) with fast response speed in a cost-effective manner. At the same time, there is a huge possibility in the field of wearable devices with further exploration on flexible substrate as well as self-powered photodetector. Previously, we have proposed that the response speed of metal oxide NW-based UV PDs could be improved by directly growing entangled NW array grown on SiO$_2$ by chemical vapor deposition (CVD). The interconnections in NW array creates NW–NW junction barriers which dominate the inter-wire charge transport. The UV illumination induces fast tuning of NW–NW junction barrier height, which contributes to the enhanced response speed of the NW-array UV PDs. Thus the Zn$_2$GeO$_4$ NW networks should bear great advantages in terms of PDs fabrication and also response speed.

Usually, growth of Zn$_2$GeO$_4$ NWs is conducted under a very stringent condition (low pressure $< 500$ Pa, and high temperature $\sim 1000^\circ$C). The effect of pressure on growth of Zn$_2$GeO$_4$ NWs and the corresponding solar blind UV detection properties have not been fully investigated. Generally, the growth rate of Zn$_2$GeO$_4$ NWs is proportional to the vapor pressure in the CVD
system. In addition, low vacuum level is also easy to achieve and maintain. Thus it would be desirable to grow high quality Zn$_2$GeO$_4$ NWs at a relatively higher pressure. In this paper, we report on synthesis of Zn$_2$GeO$_4$ NW networks at relatively higher pressure and investigate their DUV detection properties. We find that the pure Zn$_2$GeO$_4$ NWs could be only obtained at a growth pressure of 1 kPa or lower pressure; the higher pressure could lead to growth of Zn$_2$GeO$_4$ NW networks with impurities but at a higher growth rate. The DUV detection tests also reveal that growth pressure exerted a significant effect on DUV detection performance. The Zn$_2$GeO$_4$ NW networks produced under 1 kPa shows an excellent solar-blind photoresponsivity such as fast rise and decay times ($t_{\text{rise}} \approx 0.17$ s and $t_{\text{decay}} \approx 0.14$ s) justifying the potential of the Zn$_2$GeO$_4$ nanowires for solar-blind DUV detection.

2. Experimental

Zn$_2$GeO$_4$ nanowires were synthesized via a facile CVD method. 0.421 g mixture of ZnO, GeO$_2$, and diamond powders (molar ratio of 2 : 1 : 3) was loaded in a ceramic boat which is located at the center of quartz tube furnace. A piece of Si substrate (500 nm SiO$_2$/Si) coated with 3 nm Au films was covered just above the source materials. 100 standard cubic centimeter per minute (sccm) Ar was introduced into the chamber as carrier gas. The tube furnace was then heated to 960 °C within 68 min. Once the temperature reached 600 °C, 1.5 sccm oxygen was introduced into the furnace. To evaluate the effect of pressure on Zn$_2$GeO$_4$ NW networks growth, the pressure in the chamber was set to 0.5 kPa, 1 kPa, 2 kPa, 5 kPa and 15 kPa, respectively. The furnace was kept at 960 °C for 15 min, and then the oxygen was switched off and the furnace was cooled naturally down to room temperature. After growth, a layer of white or gray materials were obtained on the SiO$_2$/Si substrates. The final products were characterized and analyzed by a SEM (JSM-7800F, JEOL) equipped with an EDX detector, XRD (D8 ADVANCE, BRUCKER), and a HRTEM (Tecnai G2-F20, FEI). The Raman spectra were collected on a Renishaw system excited by an argon laser of 488 nm wavelength.

The devices were fabricated according to processes reported in our previous works.$^{1,2,30}$ A two-end metal-semiconductor-metal structured Zn$_2$GeO$_4$ NW network DUV PD was prepared by applying silver paint onto Zn$_2$GeO$_4$ NW networks to form two silver electrodes with internal space around 8 mm and enough thickness. Electrical properties such as $I$–$V$ curves and photoresponse performance were measured at room temperature on a PW-400 probe station system with a sourcemeter (4200-SCS, Keithley) and a 256 nm LED lamp (LDLS, EQ-1500) whose power is 1.76 mW cm$^{-2}$.

3. Results and discussion

The morphologies of the Zn$_2$GeO$_4$ NW networks synthesized at different pressures are shown in Fig. 1. The nanowires have a high density, as individual nanowires entangle with each other, which will be beneficial for UV photodetector fabrication. The insets to Fig. 1 show enlarged images of the as-prepared products. Fig. 1a shows the Zn$_2$GeO$_4$ NW networks...
synthesized at 0.5 kPa, the NWs are about 40–90 nm in diameter (seen in the inset of Fig. 1a). The SEM image in Fig. 1b shows that the Zn$_2$GeO$_4$ NWs grown at 1 kPa have an average diameter of around 130 nm. The NW sample grown at 2 kPa could reach 200 nm in diameter (Fig. 1c). By further increasing the growth pressure to 5 kPa, we obtained Zn$_2$GeO$_4$ NWs with an average diameter of 300 nm. It is obvious that the diameter of NWs increases with the growth pressure if the other growth conditions are kept unchanged. The effect of growth pressure on the diameter is caused by the change in supersaturation. The vapor of Zn and Ge is determined by the local temperature, so the rate of producing the Zn and Ge vapor it can be assumed to be

![Fig. 2](image)

Fig. 2 XRD patterns of Zn$_2$GeO$_4$ NWs grown at different pressures. (a) 0.5 kPa; (b) 1 kPa; (c) 2 kPa; and (d) 5 kPa.

![Fig. 3](image)

Fig. 3 (a) HRTEM image of single Zn$_2$GeO$_4$ NWs grown at pressure of 1 kPa. Inset (a) is the corresponding SAED pattern, indicating that the growth direction of nanowire is [001]. Inset (b) shows the low magnification TEM image. (b) Raman spectrum of the Zn$_2$GeO$_4$ NWs grown at pressure of 1 kPa.
gesting that ZnO is easier to grow along with Zn2GeO4 at higher pressure. This also suggests that the pure Zn2GeO4 NWs could only be obtained at a relatively lower growth pressure.

The effect of growth pressure on the product quality and purity was investigated by XRD technique, as shown in Fig. 2. As seen in Fig. 2a and b, when the growth pressure are 0.5 kPa and 1 kPa, the diﬀraction (SAED) pattern of inset (a) can be attributed to the symmetric and asymmetric stretching vibrations of Ge–O–Zn bonds, respectively.28,29 According to the previous report, the peak around 754 cm$^{-1}$ was usually associated with oxygen defects in Zn$_2$GeO$_4$.30 However, it is visible this peak was not detectable in as-synthesized nanowires, indicating that there are negligible oxygen defects in the present Zn$_2$GeO$_4$ nanowires. It also suggested a high-quality crystal structure of the final products.

To examine the response time of the Zn$_2$GeO$_4$ nanowires UV photodetector, a LED lamp with wavelength of 256 nm and energy density of 1.76 mW cm$^{-2}$ was used as a light source. The time-dependent photocurrent at 8 V bias with multiple UV on/off cycles was measured at room temperature, in which both the “on” and “off” times of the UV illumination were 20 s. It is well-known that oxygen molecules absorbed on the surface of Zn$_2$GeO$_4$ act as electron acceptors to form O$_2^-$ by capturing free electrons from the surface in dark, creating a low conductive depletion layer near the Zn$_2$GeO$_4$ surface.1,2,27,28 Upon UV illumination, the photogenerated holes in Zn$_2$GeO$_4$ migrate to the surface and neutralize the O$_2^-$ ions, while the unpaired electrons significantly enhance the conductivity of the sample. The

Fine structures of individual Zn$_2$GeO$_4$ nanowires were then characterized using HRTEM. The low magnification TEM images of Zn$_2$GeO$_4$ NWs synthesized under pressure of 1 kPa are shown in Fig. 3a. The corresponding inserts give HRTEM images recorded along the [110] zone axis. Specifically, the measured lattice distances was calculated to be about 0.71 nm and 0.31 nm which can be assigned to separations of the adjacent (110) and (113) planes, respectively. From the selected area electron diﬀraction (SAED) pattern of inset (a), it can be deduced that the preferred growth direction of a single nanowire is along the [001] direction.33 Combined the SAED and the high-resolution TEM (HRTEM) data, the formation of single crystalline nanowire could be confirmed readily. Simultaneously, the HRTEM also documented the high single-crystal quality of the samples, no defects were seen. It is obviously the excellent quality and high aspect ratios make the as-synthesized Zn$_2$GeO$_4$ nanowires become promising candidates for optoelectronic devices.

Fig. 3b shows the local atomic structure of the Zn$_2$GeO$_4$ nanowires which was further investigated by Raman spectroscopy. The most prominent peak around 800 cm$^{-1}$ which corresponds to the stretching vibration of GeO$_4$ tetrahedra could be observed from the plot. The peaks at 746 and 776 cm$^{-1}$ could be attributed to the symmetric and asymmetric stretching vibrations of Ge–O–Zn bonds, respectively.28,29 According to the previous report, the peak around 754 cm$^{-1}$ was usually associated with oxygen defects in Zn$_2$GeO$_4$.30 However, it is visible this peak was not detectable in as-synthesized nanowires, indicating that there are negligible oxygen defects in the present Zn$_2$GeO$_4$ nanowires. It also suggested a high-quality crystal structure of the final products.

Fig. 4a shows the absorption spectrum of Zn$_2$GeO$_4$ nanowires on quartz substrate. The absorption peak of the nanowires locates at about 243 nm, indicating that the incorporation of germanium oxide makes the absorption spectrum of shift to deep ultraviolet. This observation reveals that the Zn$_2$GeO$_4$ NWs exhibit high wavelength selectivity in the UV-C region, as compared with the binary oxides, such as ZnO and SnO$_2$.30–35 The bandgap of the Zn$_2$GeO$_4$ nanowires could also been obtained by fitting the absorbance with respect to the photon energy, as shown in Fig. 4b. The bandgap obtained from Tauc plot is 4.84 eV, which is in good agreement with the reported results.30

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![Image](https://example.com/image.jpg)
photoelectric characteristic images of Zn$_2$GeO$_4$ nanowire networks under different pressures (0.5–5 kPa) with a period of 20 s are shown in Fig. 5. As shown in Fig. 5a, upon UV illumination, the current would first rapidly ramp to 130 nA from the dark current, then it increases tardily to 140 nA, and as UV illumination is off, the current would promptly fall to the original level. From Fig. 5b, it can be seen that current dramatically expands from the dark current to 44 nA, which is associated to UV illumination, and then it gradually goes down to around 37 nA, and when UV illumination is off, the current would swiftly decline to around the original level. It is evident that upon UV illumination, the current would first quickly change to 31 nA from the dark current, and then decrease gently to 30 nA, and as UV illumination is off, the current would first speedily descend to 17 nA and then slowly decay to around the dark current from Fig. 5c. As shown in Fig. 5d, upon UV illumination, the current would first drastically go up to 16 nA from the dark current, followed by a slow rise to 16.5 nA, and as UV illumination is off, the current would first sharply reduce to 15 nA and then drop to around the original level by inches. It is clear that by switching on and off the electron beam, the devices run with good repeatability with fast response (<1 s).

It is obvious that the device (under a bias of 8 V) shows a good stability, as well as fast rise and decay times, as illustrated in Fig. 6. If we define $t_r$ and $t_d$ as the times required for the current to increase from 10% to 90% of the peak value or vice versa, then the response and recovery time of the photodetectors prepared from Zn$_2$GeO$_4$ NWs grown at 0.5 kPa can be calculated to be 1.68 s and 0.11 s, respectively. From the curve, it can be seen that the typical response time of the Zn$_2$GeO$_4$ NW network UV PD with nanowires synthesized under 1 kPa is about 0.17 s and it has a steep falling edge, giving a recovery time of 0.14 s. The measured $t_r$ and $t_d$ of the Zn$_2$GeO$_4$ NW network UV PD made of NWs grown at 2 kPa can be deduced to be 0.11 s and 2.48 s, respectively. On the contrary, the device fabricated from Zn$_2$GeO$_4$ NW synthesized under 5 kPa has the response and recovery time of $t_r = 0.94$ s and $t_d = 3.15$ s respectively.

It is found that the rise process (0.17 s) of the Zn$_2$GeO$_4$ NW network UV PD with nanowires synthesized under 1 kPa is much faster than that of Zn$_2$GeO$_4$ NW PD obtained from nanowires grown at 0.5 kPa (1.68 s) and 5 kPa (0.94 s), while the rise stage of Zn$_2$GeO$_4$ NW network PD prepared from NWs produced at 1 kPa is also comparable with that of the device with nanowires grown at 2 kPa (0.11 s). Likewise, the resetting process of the PDs with NWs grown 1 kPa (0.14 s) is much faster than the devices corresponding to 2 kPa (2.84 s) and 5 kPa (3.15 s), while the decay stage of the Zn$_2$GeO$_4$ NW PD produced at 1 kPa is also comparable with that of NW device grown at 0.5 kPa (0.11 s). This is much better than most reported PDs based on Zn$_2$GeO$_4$ nanostructures, as shown in Table 1.

To determine the other aspects of sensing performance, the responsivity ($R$), external quantum efficiency (EQE) and detectivity ($D^*$) corresponding to the detectors of different growth
pressures were calculated. The responsivity of the Zn$_2$GeO$_4$ nanowires UV photodetectors is defined as the ratio of the response current to the illumination power on photodetector as given by:\textsuperscript{15,33,40}

$$ R = \frac{\Delta I}{P S} $$

(1)

where $\Delta I$ is the response current (current difference between photocurrent and dark current), $P$ is the incident UV power density, and $S$ is the active device area. In this experiment, the UV illumination power density is 1.76 mW cm$^{-2}$, the active area is 4 mm$^2$. The external quantum efficiency (EQE) is given by the following relation:

$$ \text{EQE} = \frac{hcR}{e\lambda} $$

(2)

where $h$ is the Plank’s constant and $e$ is the absolute value of electron charge (1.6 $\times$ 10$^{-19}$ C), $\lambda$ is the wavelength of incident light, and the wavelength is 256 nm. Furthermore, if we consider the shot noise as the major portion of the total noise, detectivity ($D^*$) in units of jones, an index to evaluate the photoresponse, can be expressed as following equation:\textsuperscript{15,36,40-43}

$$ D^* = \frac{RS^2}{(2eI_d)^{1/2}} $$

(3)

where $I_d$ is the dark current, $S$ is the effective area of the detectors and $e$ is the electron charge. The responsivity, external quantum efficiency and detectivity of various photodetectors were listed in the Table 2.

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**Table 1** Comparison of Zn$_2$GeO$_4$ and other ternary oxide nanostructures based photodetector parameters between this work and the previous reports

| Photodetectors                  | Bias (V) | UV light (nm) and power density (mW cm$^{-2}$) | Rise time (s) | Decay time (s) | Ref. |
|--------------------------------|----------|-----------------------------------------------|---------------|----------------|------|
| Zn$_2$GeO$_4$ NW               | 3        | $\lambda = 254, P = \lambda$                | 0.6           | 1.5            | 9    |
| Zn$_2$GeO$_4$ NW mats          | 20       | $\lambda = 254, P = 0.2$                     | 0.3           | 0.2            | 30   |
| Zn$_2$GeO$_4$ NW               | 8        | $\lambda = 245, P = 0.05$                    | 12            | 0.6            | 37   |
| In$_2$Ge$_2$O$_5$ NW mats       | 20       | $\lambda = 254, P = 0.85$                    | 15            | 1.5            | 38   |
| Zn$_2$GeO$_4$ NW               | 3        | $\lambda = 254, P = 0.85$                    | 3             | <1             | 38   |
| ZnGa$_2$O$_4$ NW               | 5        | $\lambda = 350, P = 0.53$                    | 15            | 10             | 39   |
| Zn$_2$GeO$_4$ NW networks       | 8        | $\lambda = 256, P = 1.76$                    | 0.17          | 0.14           | This work |

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**Fig. 6** Enlarged view of typical rise and decay curves for Zn$_2$GeO$_4$ NW network PD synthesized at different pressures with and without UV illumination. (a) 0.5 kPa; (b) 1 kPa; (c) 2 kPa; and (d) 5 kPa.
The entanglement between Zn$_2$GeO$_4$ NWs is beneficial to response speed through the mechanism of Schottky barriers at the junctions between the interconnected Zn$_2$GeO$_4$ NWs. On the other hand, the entanglement in Zn$_2$GeO$_4$ NWs usually formed in high density Zn$_2$GeO$_4$ NWs at the cost of photo-to-dark current ratio. There are two main factors for high dark current. First, only very few Zn$_2$GeO$_4$ NWs on the top of Zn$_2$GeO$_4$ NW networks could absorb and be excited by UV illumination. Second, there would form a Zn$_2$GeO$_4$ film on the substrate as the reaction proceeds and contribute to the high dark current.

While the structure of interconnection of Zn$_2$GeO$_4$ NWs has fast response time, the electrical signal of the material is weak, which affects the value of the responsivity, external quantum efficiency and detectivity of photodetectors.

Table 2  The parameters of responsivity, external quantum efficiency and detectivity corresponding to PDs of different growth pressures

| Photodetectors of different growth pressures | Responsivity ($R$) | External quantum efficiency (EQE) | Detectivity ($D^*$) |
|-------------------------------------------|---------------------|----------------------------------|-------------------|
| 0.5 kPa                                    | $1.7 \times 10^{-3}$ A W$^{-1}$ | 0.82%                            | $4.25 \times 10^9$ jones |
| 1 kPa                                      | $5.11 \times 10^{-4}$ A W$^{-1}$ | 0.25%                            | $2.03 \times 10^9$ jones |
| 2 kPa                                      | $2.98 \times 10^{-4}$ A W$^{-1}$ | 0.15%                            | $9.22 \times 10^8$ jones |
| 5 kPa                                      | $4.26 \times 10^{-3}$ A W$^{-1}$ | 0.02%                            | $1.27 \times 10^8$ jones |

Fig. 7  Schematic of the carrier generation and NW–NW junction barrier for electron transfer in the network device. (a) Carrier generation in a single Zn$_2$GeO$_4$ NW; (b) carrier generation and transport in Zn$_2$GeO$_4$ NW.

In ambient conditions, oxygen molecules...
would adsorb on the surface of Zn$_2$GeO$_4$ NW to form O$_2^-$ by capturing free electrons from NW surface through O$_2$ (g) + e$^-$ → O$_2^-$ (ad), creating a lowly conductive surface depletion layer, as shown in Fig. 6a. Under the UV irradiation, the electron–hole pairs are generated by directly exciting electrons from the valence band to conduction band, which increases carrier density significantly in the NWs. The photon-generated holes would migrate to the surface and discharge the adsorbed oxygen ions through O$_2^-$ (ad) + h$^+$ → O$_2$ (g), resulting in a reduction in the depletion barrier thickness. The increase in carrier concentration and oxygen desorption caused by hole-trapping process contribute to an apparent enhancement of conductance in the NW networks. As the UV illumination is turned off, holes recombine with electrons, meanwhile oxygen re-adsorb on Zn$_2$GeO$_4$ NW surface by capturing electrons returning the device to initial low conductivity state.

In addition to the same photoconductive mechanism of photogeneration of free carriers, compared with single NW PD, network devices have another unique conducting mechanism that is the transport of carriers across the interface between neighboring NWs. As Fig. 6b illustrates, the resistance of two crossed NWs was dominated by the NW–NW junction barrier, rather than the resistances of the NW themselves. In the Zn$_2$GeO$_4$ NW PD, electrons must overcome the NW–NW junction barrier when tunneling from one NW to another as shown in Fig. 6b. It is reported that the electron–hole transfer barrier originates from the surface depletion layers and the depletion layer would be narrowed upon UV illumination on account of the increase of carrier density, which is equivalent to a lowering of the effective barrier height. It makes electrons more likely to transport in the networks upon UV irradiation and hence resulting in the increment of current, as illustrated in Fig. 4.

Compared with the previously reported devices with slow response and recovery time, the fast recovery time 0.14 s for our Zn$_2$GeO$_4$ NW photodetectors can be attributed to the NW–NW junction barrier dominated conductance. Typically, because it needs a long time for the oxygen diffusion and re-adsorption to deplete the NW channel, the NW conductance is still higher than its initial value within a short period upon turning off the UV light. For the NW network structures, the depletion barrier can be analogous to two back-to-back Schottky barriers, as the UV light is switched on, which is much lower in the effective barrier height due to the greatly incremental carrier density. The dominate role of the junction barrier would cause a current decay almost approaching its initial value within a short period for our devices. The modulation of barrier height induced by irradiation is typically much faster than the oxygen diffusion process on the order of several minutes or hours. This paper demonstrates that the response and recovery time can be enhanced by using NW networks with NW–NW barrier dominated conductance. It can be seen that apart from no requirement for intense and expensive lithography processes, the simple and feasible preparation technics also allows potential large-scale device fabrication.

4. Conclusion

In conclusion, we have prepared wide-bandgap Zn$_2$GeO$_4$ NW networks by CVD at lower pressures (0.5–5 kPa) and investigated their corresponding DUV detection performance. We found that the pure Zn$_2$GeO$_4$ NWs could be obtained at 1 kPa or lower pressure. The Zn$_2$GeO$_4$ NW networks produced under 1 kPa exhibited efficient response for UV photodetection. The network devices showed response and recovery time of 0.17 s and 0.14 s, respectively, which can be attributed to the NW–NW junction barrier dominant conductance. The large bandgap 4.84 eV makes the NW materials promising for UV-C detection with high wavelength selectivity. The network-enabled fast response and recovery time as well as facile fabrication processes may also be extended to other ternary metal oxide nanomaterials.

Conflicts of interest

There are no conflicts to declare.

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