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Photoconduction studies on GaN nanowire transistors under UV and polarized UV illumination

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Abstract

Photoconduction studies have been carried out with single crystal GaN nanowires. The nanowire transistors exhibited a substantial increase in conductance upon UV light exposure. Besides the selectivity to different light wavelengths, extremely short response and recovery time have also been obtained, as well as the great reversibility of the nanowire between the high and low conductivity states. In addition, a polarization anisotropy effect was demonstrated and studied for GaN nanowires working as polarized UV detectors. The nanowire conductance varied periodically with the polarization angle of the incident light (θ), which can be well fitted into a function of $\cos^2\theta$.
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1. Introduction

Because of its wide direct bandgap (3.4 eV), GaN is expected to be an ideal candidate for ultraviolet applications. Many optoelectronic devices based on GaN, and its ternary and quaternary alloy epilayers have been realized by now, such as ultra-bright light-emitting diodes (LEDs) [1], laser diodes [2] and UV photodetectors [3]. On the other hand, nanoscale structures such as one dimension nanowires are attracting increasingly more attention because of their enormous potential as fundamental building blocks for nanoscale electronic and photonic devices [4]. GaN nanowires have, therefore, become the focus of peoples interest nowadays for their concomitant advantages of possessing both excellent optoelectronic properties and nanoscale dimensions. Fairly many techniques have been developed to synthesize high quality GaN nanowires [5–9] and precisely controlled growth of single crystal GaN nanowires have been achieved recently [10]. Besides the research work focusing on the nanowire synthesis, their optical and electronic properties have also been extensively investigated, such as n-type and p-type GaN nanowire field effect transistors (FETs) [11,12], p–n junctions [13] and optical pumped single gallium nitride nanowire laser [14]. GaN nanowires also have great potential to work as nanoscale photodetectors. Due to their primary bandgap of 3.4 eV, these nanowires are suitable for detection of UV light with wavelength $\leqslant$365 nm. This is in sharp contrast to previously reported In_2O_3 and SnO_2 UV detectors [15,16], whose indirect bandgaps ~2.6 eV set their operation regime to wavelength $\leqslant$477 nm. An additional unique advantage of GaN is that alloys of GaN and InN can be synthesized to produce $In_xGa_{1-x}N$, whose bandgap can be continuously varied over a wide range, thus leading to photodetectors with different cut-off wavelengths.

In this Letter, we report our approach to use individual GaN nanowire FETs as UV light sensors. The nanowire sensors exhibited superior performance in many aspects, such as the sensitivity, the response speed and the reversibility. In addition, distinctive response to two primary UV wavelengths of 365 and 254 nm was observed, as a direct consequence of the 3.4 eV GaN bandgap. Furthermore, single GaN nanowire FETs

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showed pronounced polarization anisotropy in conductance under illumination of linear polarized UV lights. This linear dichroism (LD) effect can be used in many applications such as integrated photonic circuits, optical switches and optical detectors.

2. Experimental

GaN nanowires were synthesized by thermal chemical vapor deposition (CVD) method. A gallium source was positioned at the center of a quartz tube that was inserted in a horizontal tube furnace. Si/SiO_2 substrates coated with mono-dispersed gold clusters of well-defined diameters were placed at downstream of the furnace for collecting growth products. The Ga source was heated to 900 °C and the reaction was carried out by flowing ammonia at 20 standard cubic centimeters per minute (sccm) for 15 min. The growth follows the well-known vapor–liquid–solid (VLS) growth mechanism, where thermally generated Ga first alloyed with the gold clusters, then grew out and reacted with NH_3 to form GaN once the Au/Ga alloy was supersaturated by continued supply of Ga vapor. Fig. 1 shows the scanning electron microscopy (SEM) image of the as-grown GaN nanowires. The single crystallinity of the nanowires was confirmed by transmission electron microscopy (TEM) and selected area electron diffraction (SEAD) analysis [10]. Single-nanowire-based FETs were then fabricated using a previously reported technique [10]. GaN nanowires were first deposited on a degenerately doped silicon wafer covered with 500 nm SiO_2. Photolithography and successive Ti/Au deposition were performed to pattern the source and drain electrodes on individual GaN nanowires. The SEM image in Fig. 1 inset shows a top view of the device used in the following measurements. The nanowire has a diameter of 15 nm and a channel length of 2 μm between the source and drain electrodes with the silicon substrate used as a back gate.

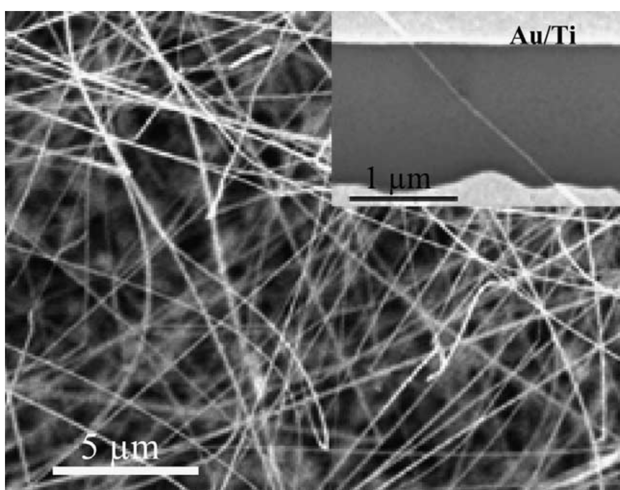

Fig. 1. SEM image of GaN nanowires grown from 10 nm Au clusters. Inset: SEM image of a GaN nanowire transistor showing a nanowire contacted by two Au/Ti electrodes.

3. Results and discussion

Current vs. voltage (I–V) measurements with the GaN nanowire FETs were carried out under different illumination environments. Our experiment involved a double-wavelength handheld UV lamp of 254 and 365 nm in wavelength fixed at a distance of approximately 2 cm away from the nanowire transistor, which was kept under practical conditions, i.e., in air, at room temperature and under indoor incandescent light during the measurements. The power density is 3 mW/cm^2 for 254 and 365 nm UV. Fig. 2a shows three I–V curves

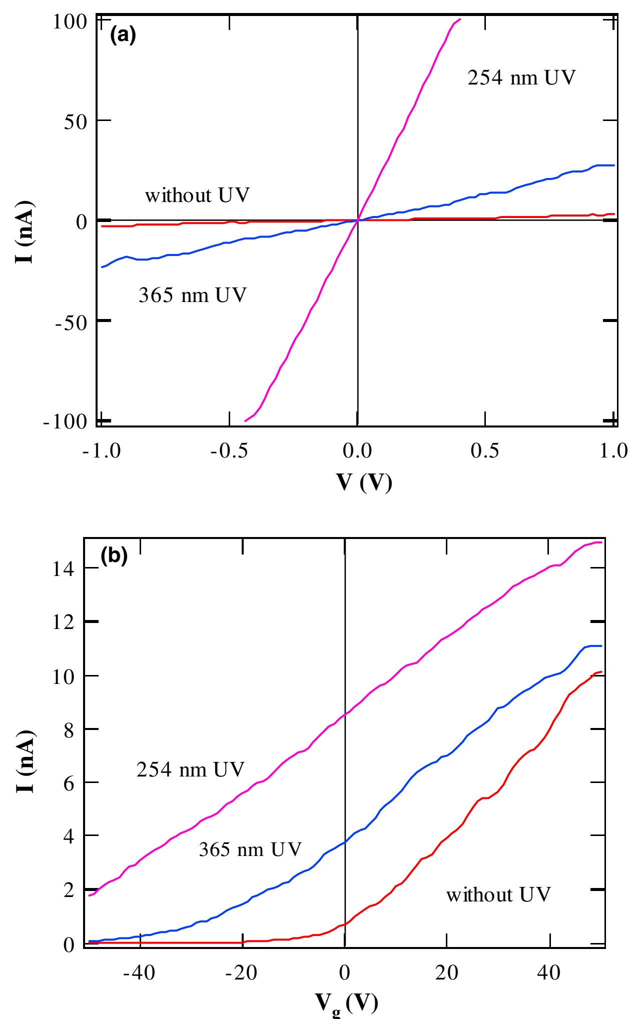

Fig. 2. (a) I–V curve of GaN nanowire before and after exposed to 254 nm and 365 nm UV light. (b) I–V_g curve of the device at fixed drain-source bias $V = 50$ mV before and after exposed to UV light.

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. Enhanced conduction was observed for UV illumination of both wavelengths; however, the magnitude differed significantly. The zero-bias conductance before and after 365 nm UV light exposure is calculated to be 1.3 and 23.4 nS, respectively. Illumination with 254 nm UV light can bring the GaN nanowire to a more conductive state with a conductance of 258.3 nS. The enhanced conductivity under UV light illumination is attributed to the photo-generated carriers in the semiconducting nanowire. UV light with wavelength of 254 nm has a photon energy of 4.88 eV, sufficiently large to excite electrons across the 3.4 eV bandgap of GaN. As for the UV light with a wavelength centered at 365 nm, the average photon energy (3.39 eV) is slightly lower than the GaN bandgap. However, there still exist photons with higher energies due to the non-zero spectrum width, which can generate electron–hole pairs, thus enriching the carrier concentration along the nanowire. This explains the observed photo-enhanced conductivity under the 365 nm UV light, as well as the selective response to the UV light at different wavelengths. Current vs. gate voltage (I–V_g) curves with drain-source bias fixed at $V = 0.1$ V were plotted in Fig. 2b, where negative gate voltages progressively reduced the current through the nanowire by several orders of magnitude. This typical n-type transistor characteristic exhibited by the GaN nanowires is attributed to the nitrogen vacancy in the GaN crystal lattice. The I–V_g curves recorded under different conditions allow us to obtain more information about the device during the UV illumination processes. As shown in Fig. 2b, threshold gate voltages of the nanowire FET under 254 and 365 nm UV light were found to be around −60 and −26.7 V, compared to the threshold voltage of −0.5 V before light exposure. The electron concentrations n can be estimated from the formula $n = CV_T/L$, where V_T and L are the threshold gate voltage and channel length (2 μm) of the nanowire FET. C is the nanowire capacitance, given by $C = 2\pi\varepsilon\varepsilon_0 L/\ln(2h/r)$ with h being the thickness of the SiO_2 layer (500 nm) and r the nanowire radius (7.5 nm). The carrier concentrations along the GaN nanowire are thus estimated to be 4.9×10^5, 4.2×10^6 and 6.6×10^7 cm^{-1} without UV, with 365 and 254 nm UV, respectively, showing increases up to orders of magnitude upon UV illumination. We did not observe notable difference in the slopes (dI/dV_g) of the linear sections of the I–V_g curves, indicating that light illumination has little effect on the mobility of the charge carriers (μ), which is determined by the equation $dI/dV_g = \mu\ (C/L2)$ V. Our analysis reveals that the photo-enhanced conductivity is mainly dominated by the increases in carrier concentrations and the variation of the mobility has a rather limited role.

Besides the high sensitivity we mentioned above, our GaN nanowire UV sensors also showed advantages in the response speed, as can be seen from the current vs. time curves plotted in Fig. 3. In Fig. 3a, the current was monitored at a bias of $V_g = 0$ and $V = 0.1$ V while UV light was turned on and off repeatedly for five cycles. The conductance of the nanowire showed a rapid increase from 0.72 to 56 nS upon exposure to 254 nm UV light. Detailed data analysis (Fig. 3b) revealed that the conductance of the nanowire increased to 58.4% of its saturation value within 1 s after UV lamp was turned on, and reached 81.9% within 2 s. The GaN nanowire sensor also exhibited an extremely high recovery speed due to the fast hole–electron recombination process, as seen in the sharp current drop when the light was turned off. During UV light illumination, a stable high-conductivity state can be obtained and no obvious decay was observed within the illuminating period (~100 s). The on/off sensing cycles can be repeated many times

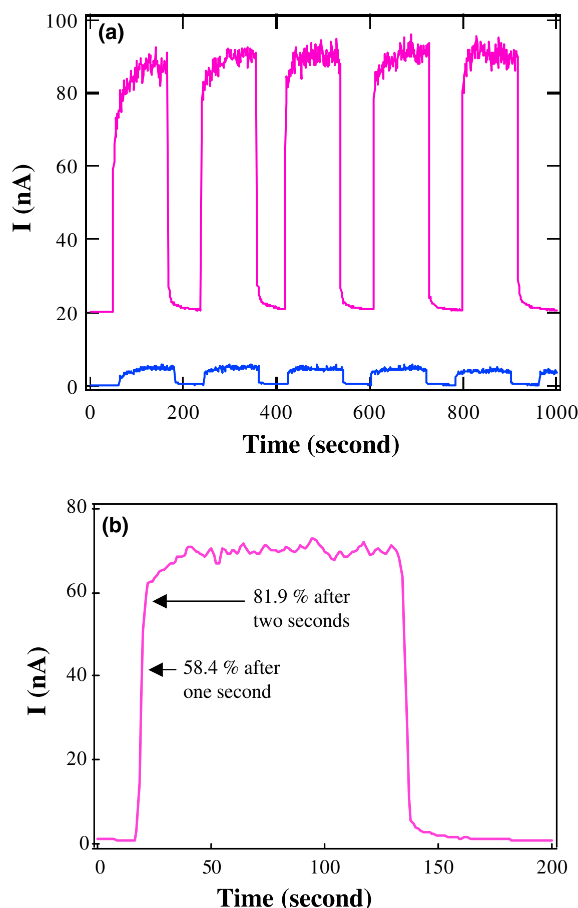

Fig. 3. (a) Current vs time for the GaN nanowire with UV light repeatedly turned on and off. The red curve (offset by 20 nA) is measured with illumination of 254 nm UV, while the blue curve corresponds to 365 nm UV light. The current was measured at $V = 0.1$ V and $V_g = 0.1$ V. (b) One cycle of the GaN nanowire response to 254 nm UV light. (For interpretation of the references to colour in this figure legend, the reader is referred to the web of this article.)

without any detectable degradation, as evident in Fig. 3a. We also plotted the data recorded with 365 nm UV light in Fig. 3a (lower curve). The nanowire sensor showed a relatively small sensitivity to this wavelength as majority of the photons cannot excite electrons across the GaN bandgap. However, we can still observe the rapid response and recovery from the curve, as well as the reversibility of the device.

Further studies on the photo-detecting properties of GaN nanowires have been carried out using polarized UV light. The quasi one-dimensional nanowires have a very sharp contrast between their radial and longitudinal dimensions, which has accounted for the polarization response we observed in the following experiment. Fig. 4a is a schematic picture of the polarization anisotropy measurement setup. A linear polarizer was mounted between the 254 nm UV lamp and the nanowire detector to polarize the incident beam along certain directions. By rotating the UV polarizer, the angle between the linear UV light and the nanowire can be adjusted. Fig. 4b shows the polarization anisotropy effect of the GaN nanowire sensor, where the nanowire conductance showed a periodic dependence ($\cos^2\theta$) on the polarization angle (θ). The mechanism underlying the polarization-dependent conductance can be understood as follows: The nanowire diameter (~15 nm) is much smaller compared with the wavelength of the 254 nm UV light. As a result, an incident electric field that is perpendicular to the nanowire would be effectively attenuated due to the confinement in this normal direction [17]. In contrast, electric fields parallel to the nanowire can be readily adsorbed since no confinement exists along this longitudinal direction. This leads to the enriched carrier concentration and enhanced conductivity we have observed. At polarization angles between these two vertical directions, the conductance of the nanowire was continuously modulated and showed an oscillation with a period of π. From the maximum ($G_{||} = 2.2$ nS) and minimum ($G_{\perp} = 1.6$ nS) conductance observed under a parallel and a perpendicular field, the polarization ratio of photoconductance (σ) was calculated to be 0.16 according to $\sigma = (G_{||} - G_{\perp})/(G_{||} + G_{\perp})$. This polarization ratio is comparable to a value ~0.33 recently observed with carbon nanotube devices [18]. The finite conduction measured with the light polarization angle perpendicular to the GaN nanowire long axis is likely related to the scattering of the incident light by the surroundings (such as the metal electrodes, the electrode pads and the bonding wires). The randomly scattered lights can cause an increase of the background single, thus suppressing the polarization ratio. With smaller incident beam size that is comparable to the length of the device channel, a much greater ratio is expected.

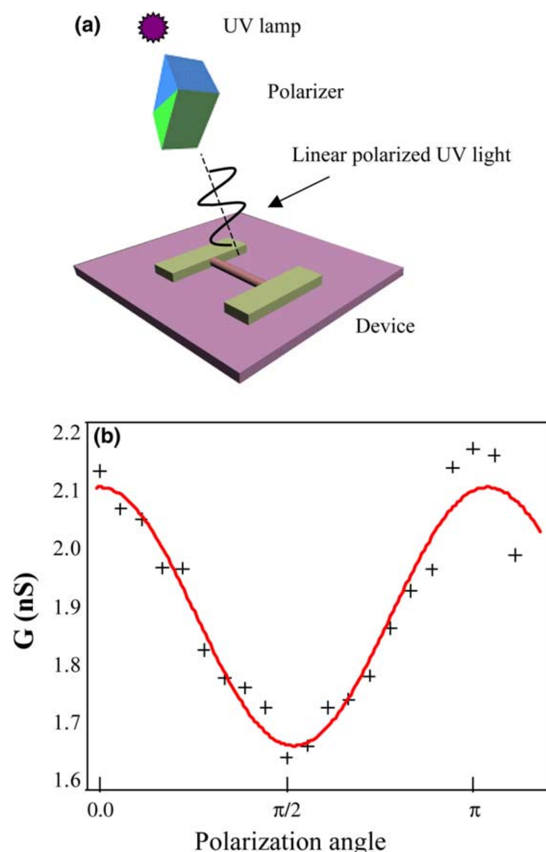

Fig. 4. (a) Schematic of the experimental setup for polarization anisotropy measurements. (b) Conductance of the GaN nanowire transistor vs the angle of the polarizer. The dots are experimental data and the solid curve is a fit following a function of $\cos^2\theta$.

4. Conclusions

In summary, UV light sensors based on GaN nanowires were fabricated. The conductance of GaN nanowires increased dramatically upon exposure to UV light with wavelengths of 254 and 365 nm. Differential response to UV illumination at different wavelengths has also been observed and studied. The nanowire sensors showed very fast response and recovery speed. We have also investigated the polarization-dependent conductivity exhibited by the GaN nanowires. The polarization ratio of the photoconduction was derived to be 0.16 for our device.

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