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Gallium nitride nanowire devices and photoelectric properties

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ABSTRACT

This paper presents an investigation of photoelectric properties of the CVD-grown multi-prong GaN nanowires. The multi-prong growth mechanism produces uniform high density long GaN nanowires, which is very significant for scale-up manufacturing opportunities. Photoelectric studies of the GaN nanowires have been conducted at various light sources with wavelengths of 254 nm and 365 nm. The 254 nm-light exposure resulted in a larger photocurrent increase compared to that of 365 nm-light exposure, which is attributed to the larger number of the photogenerated carriers owing to the higher photon energy. The positive photoelectric response of the GaN nanowires is attributed to the molecular sensitization mechanism. Furthermore, the GaN nanowires devices exhibited moderate persistent photocurrent. These findings suggest a reduced surface recombination process due to the depletion surface charge layer. In summary, the multi-prong GaN nanowires could be utilized as photoconductors, photodetectors, and various photosensing elements in many highly integrated optoelectronic devices.

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1. Introduction

One-dimensional semiconductor materials have attracted a great deal of interest due to their tempting potential applications toward fabricating future nanoscale electronic and optoelectronic devices [1]. Gallium nitride is one of the most widely used semiconductor materials for electronic and optoelectronic applications due to its high electron mobility, tunable bandgap, and direct energy bandgap ($E_g = 3.4\,\text{eV}$). GaN nanowires are excellent building blocks for the applications in nanophotonics [2,3], particularly in UV range. GaN nanostructures have been used to fabricate field effect transistors [4], high brightness light emitting diodes [5], lasers [6], and photodetectors [7]. Due to the advancements in fabrication techniques, nanostructured materials can now be produced in more controlled ways. These advancements open up new opportunities for utilizing superior properties of these low-dimensional materials. One of the most interesting study areas of the nanostructured materials is their photoelectric properties, which could open up new and superior applications in photodetectors, photovoltaics, optical switches, image sensors, and biological and chemical sensing.

Nanomaterials are very suitable for optoelectronic applications due to their high photosensitivity and photoconductive gain compared to that of bulk materials. These superior characteristics stem from the presence of very high density of surface states due to large surface-to-volume ratio in nanowires. Based on the previous photoemission spectroscopy studies on GaN surfaces, Fermi-level pinning is expected at about 0.5–0.6 eV below the conduction band edge [8]. Nanowires have a depletion space charge layer due to the pinning of the Fermi energy at the surface [9]. This depletion space charge layer results in separation of electrons and holes such that electrons move to the inner part, while the holes move to the surface of the nanowire. Consequently, the spatial separation of electrons and holes will significantly enhance the photocarrier lifetime, which results in extremely high photoconductive gain. The photoconductive gain is one of the most vital parameters related to the photocarrier collection efficiency.

The unique and superior properties of nanowires attract great interest due to possibility of realization of efficient and highly integrated optoelectronic devices. Therefore, researchers have been investigating the photoelectric properties of various nanostructured materials. Han et al. have first reported photoconductivity studies of GaN nanowires for nanoscale light sensors applications [10]. Following that, Kang et al. [11] reported the photoconductivity investigation of GaN nanowire bundles, which showed very substantial persistent photocurrent behavior similar to the photoresponse of some GaN thin films [12–14]. Calarco et al. demonstrated persistent photocurrent response of

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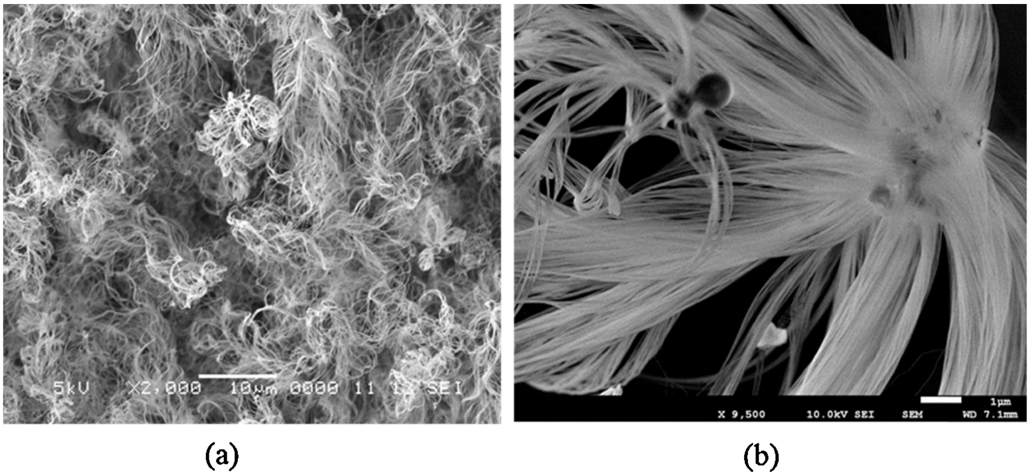

(a) (b)

Fig. 1. SEM images of ultra-high density multi-prong grown GaN nanowires synthesized at 1100 °C under H_2 with different catalysts: (a) Ni-coated Si; (b) Au-nanoparticles on SiO_2/Si substrate. The nanowires originate from the large size (~0.5–3 μm) catalyst droplets.

MBE-grown very thick (diameter > 100 nm) GaN nanowires [9]. They claimed that the photocurrent response strongly depends on the nanowire diameter. More recently, Chen et al. reported a high photocurrent gain of the GaN nanowires [15]. In fact, the reported photocurrent gain values were significantly higher than that of GaN thin films. In attempts to fabricate high performance nanoscale photosensitive devices, various nanostructures such as ZnO nanowire [16], ZnSe nanobelt [17], In_2Se_3 nanobelt [18], CdS nanobelt [19], AlN nanowire [20], and WO_3 nanowires [21] have been investigated. Despite the very promising results, more research and improvements in fabrication and device design are required for the realization of practical nanoscale photosensitive devices.

This paper presents photoconductivity investigation of the CVD-grown multi-prong GaN nanowires, for the first time to the author's knowledge. Moreover, very practical and cost-effective nanowire device fabrication scheme has been used. More importantly, this study aims to compare photoconductivity of the CVD-grown multi-prong GaN nanowires to MBE-grown GaN nanowires. Although the MBE-grown GaN nanowires with diameter < 100 nm did not exhibit any persistent photocurrent [9], CVD-grown multi-prong GaN nanowires with diameter < 50 nm exhibited moderate persistent photocurrent (this work). This contrast in size dependence of nanowire photoconductivity can be attributed to the narrower width of the depletion space charge region of the CVD-grown multi-prong GaN nanowires compared to that of MBE-grown GaN nanowires. It has been reported that the width of the depletion space charge region is smaller for CVD-grown nanowires compared to the MBE-grown nanowires [15]. These findings also emphasize the importance of synthesis techniques on physical properties of nanostructured materials.

GaN nanowires have been synthesized by chemical vapor deposition using Ga and NH_3 as source materials on SiO_2/Si substrate at 1100 °C under H_2 as carrier gas. Nanowire FET devices have been fabricated. Systematic photoconductivity studies of the GaN nanowires have been conducted at various light sources with wavelengths of 254 nm and 365 nm and different power levels. Moreover, the mechanisms leading to these photoconductive behaviors of the GaN nanowires were discussed in details. This paper is designed to address the following concepts: (i) multi-prong nanowire growth, (ii) nanowire device fabrication, and (iii) photoresponse characteristics of the GaN nanowires to various UV lights.

2. Experimental details

GaN nanowire growth has taken place in a resistively heated hot-wall 25-mm horizontal LPCVD reactor [22]. Si and SiO_2/Si substrates were used. Catalyst materials (Ni, Au) have been placed on SiO_2/Si substrate. The substrates were ultrasonically cleaned in acetone, isopropyl alcohol, de-ionized water and dried with nitrogen. Nanoparticle solution was applied to the substrate surface and dried. A quartz boat containing both the substrate and Ga (99.999% purity, about 40 mg) was loaded into the CVD reactor. Then, the reactor was evacuated and purged three times with hydrogen (99.999%). After purging cycles, the reactor was heated to targeted growth temperature (1100 °C) under carrier gas. Then, the growth was carried out by flowing NH_3 (99.99%) and H_2 gases through the reactor for typically about 15 min. The gas flow rates were controlled by mass flow controllers and set to 300 sccm for both H_2 and NH_3. After the growth, NH_3 was shut off and the reactor cooled down under H_2 flow until 250 °C. Then, the furnace naturally cooled down to room temperature.

To characterize the photoelectrical properties of the GaN nanowires, field-effect transistor (FET) devices have been fabricated using standard microfabrication processes. A set of electrodes (10 nm Ti/90 nm Au) with an average spacing about 3 μm were constructed onto SiO_2/Si substrate. The photoconductivity measurements were conducted under atmospheric and room temperature conditions with UV illumination (Spectroline handheld E-series) and Keithley 4200 SCS semiconductor parameter analyzer attached to a probe station. The grown nanowires and devices have also been characterized by scanning electron microscopy (SEM, JEOL JSM 6060 and JEOL 7600F SEM with Oxford Inca EDS), X-ray diffraction (XRD, Rigaku 300 and Bruker D8 Discover), and transmission electron microscopy (TEM, JEOL JEM 1011).

3. Results and discussion

Fig. 1 shows SEM image of ultra-dense GaN nanowires grown at 1100 °C on Ni-coated Si substrate and Au-particle SiO_2/Si substrate. The GaN nanowire diameters are in the range of 15–50 nm and lengths up to 100 μm. It is worth noting that the nanowire growth takes place through multi-prong growth mechanism. In multiple prong growth, more than one nanowire grows from one particle and the nanowires have smaller radii than the catalyst cluster/particle. In single-prong growth, nanowire diameter is

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