Photoconductivity of GaN Nanowires

K. Teker[*,1], J. Otto[*], and A. Siemann[*]

[1] College of Engineering, Istanbul Sehir University, Istanbul, Turkey
kasifteker@sehir.edu.tr or kteker@frostburg.edu
[*] Mechanical Engineering, Frostburg State University,
101 Braddock Road, Frostburg, MD 21532, U.S.A.

ABSTRACT

Gallium nitride nanostructures continue to attract great interest due to their applications in optoelectronic devices (UV photodetectors, photosensors, and light-emitting devices), high-power/high temperature electronics, nanosensing, and piezoelectric nanogenerators. This paper presents photoconductivity investigation of the GaN nanowires. GaN nanowires have been synthesized by chemical vapor deposition using Ga and NH_3 as source materials on SiO_2/Si substrate at 1100^{o}C under H_2 as carrier gas. Nanowire FET devices have been fabricated. Photoconductivity studies of the GaN nanowires have been conducted at various light sources with wavelengths of 254 nm, 365 nm, 532 nm and 633 nm using a semiconductor parameter analyzer. The grown nanowires and devices have been characterized by SEM, XRD, and semiconductor parameter analyzer.

Keywords: Photoconductivity, GaN nanowires, Photosensors

1 INTRODUCTION

Gallium nitride has been a key material in semiconductor technology advancement, particularly in the optoelectronics field. Furthermore, unique fabrication techniques of nanostructures allow realization of various device geometries, such as axial or coaxial heterostructures. GaN nanostructures have been used to fabricate field effect transistors [1], high brightness light emitting diodes [2], lasers [3], and photodetectors [4].

Due to the advancements in fabrication techniques, nanostrutured 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 photoconductivity, which could open up new and superior applications in photodetectors, photovoltaics, optical switches, image sensors, and biological and chemical sensing.

Synthesis of GaN nanowires via chemical vapor deposition has been been reported [5- 10]. CVD is the most widely used method to fabricate nanostructured materials due to its low cost, high yield, and simplicity of operation. This paper presents photoconductivity investigation of the GaN nanowires. GaN nanowires have been produced by chemical vapor deposition using Ga and NH_3 as source materials on SiO_2/Si substrate at 1100^{o}C under H_2 as carrier gas.

2 GAN NANOWIRE GROWTH

Nanowire growth has taken place in a resistively heated hot-wall 25-mm horizontal LPCVD reactor. Si and SiO_2/Si substrates were used. Catalyst materials 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^{o}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^{o}C. Then, the furnace naturally cooled down to room temperature.

Figure 1 shows SEM image of ultra-dense GaN nanowires grown at 1100^{o}C under H_2 on Au –particle SiO_2/Si substrate. The GaN nanowire diameters are in the range of 15 nm to 50 nm and lengths up to hundred microns. The growth scheme of nanowires mostly obeys the vapor-liquid-solid (VLS) mechanism by using metallic catalytic agents. It is believed that the formation of liquid droplets of Ga-N-catalyst induces the VLS growth of nanowires. Furthermore, chemical analysis of the grown nanowires has been done by Energy-dispersive X-ray spectroscopy (EDS). The EDS spectrum has shown the presence of Ga, N, Si, and O elements, where Si and O peaks come from the SiO_2/Si substrate. This result confirmed that the nanowires are composed of Ga and N elements.

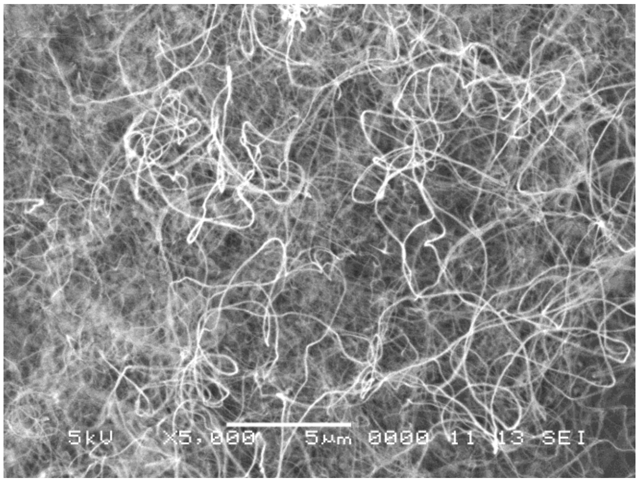

Figure 1. SEM image of ultra-high density of GaN nanowires grown at 1100°C under H_2 on Au-particles, as catalysts.

XRD measurements were carried out using Cu Kα radiation (λ = 1.54 A°) to determine the structure of the GaN nanowires and a typical spectrum is shown in Figure 2. The diffraction peaks in the spectrum were indexed to a hexagonal wurtzite crystal structure. The lattice constants derived from the peak positions were a = 0. 3188 nm and c = 0.5180 nm, which agree well with the reported values of GaN crystals.

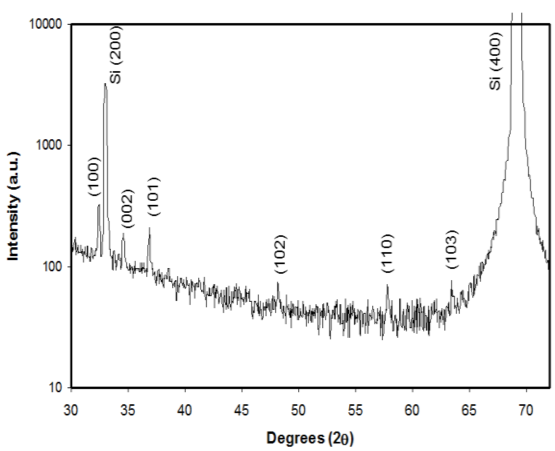

Figure 2. XRD pattern of the GaN nanowires indicating hexagonal wurtzite structure.

3 GAN NANOWIRE PHOTOCONDUCTIVITY MEASUREMENTS

First, GaN naowire based devices have been fabricated using standard microfabrication processes. Figure 3 shows SEM image of the aligned nanowires between electrodes by Dielectrophoresis. Electrodes (10nm Ti/ 90nm Au) were constructed using standard microfabrication techniques onto SiO_2/Si substrate. The average spacing between electrodes is about 3 µm.

Initially, nanowires were suspended in isopropyl alcohol. A micropipette was used to apply ~ 2 µL of nanowire solution to the surface of the patterned substrate. Then, AC voltage (V_{pp}= 5V, f = 10 kHz) was applied via a function generator about 40 seconds. Once the drop was removed, the AC signal was turned off. Following that, the devices were annealed at 300 °C in air under 1N of static load to improve the contacts between nanowires and the gold electrodes.

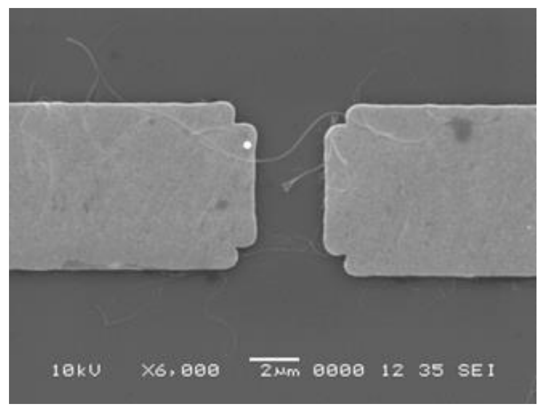

Figure 3. SEM image of the aligned GaN nanowires between electrodes.

Figure 4 shows the *IV* curve of the device, which indicates that GaN nanowires maintain their electrical properties through the alignment and placement process. The *IV* curve also indicates that the annealing process is very successful.

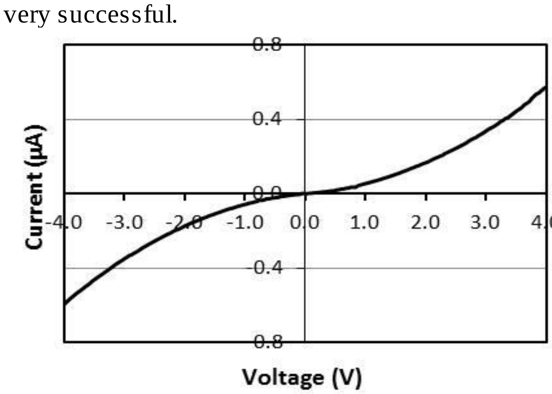

Figure 4. *IV* curve of the aligned GaN nanowires.

Next, photoconductivity studies have been conducted. Under light exposure, a change in conductivity could take place mostly due to a change in carrier concentration:

$$\Delta\sigma = \sigma_{\text{light}} - \sigma_{\text{dark}} = e.\Delta n.\mu \qquad (1)$$

where $\Delta\sigma$ is the change in conductivity, e is the electronic charge, Δn is the change in carrier concentration, and μ is the carrier mobility. As shown in equation (1), the magnitude of the change in conductivity depends on the number of photogenerated carriers. The increase in photoconductivity is even higher for nanoscale materials due to presence of high density of surface states. This characteristic makes nanowires very attractive as photosensing elements in many highly-integrated optoelectronic devices.

Figure 5 shows the photocurrent-time response of the devices under the irradiation of 254 nm UV light at 3 V bias. It exhibits significant positive and fast photocurrent response to the UV light exposure. Furthermore, photocurrent decay has been very rapid after the illumination ended, which indicates the absence of defect traps. This also confirm that the GaN nanowires have very high optical quality.

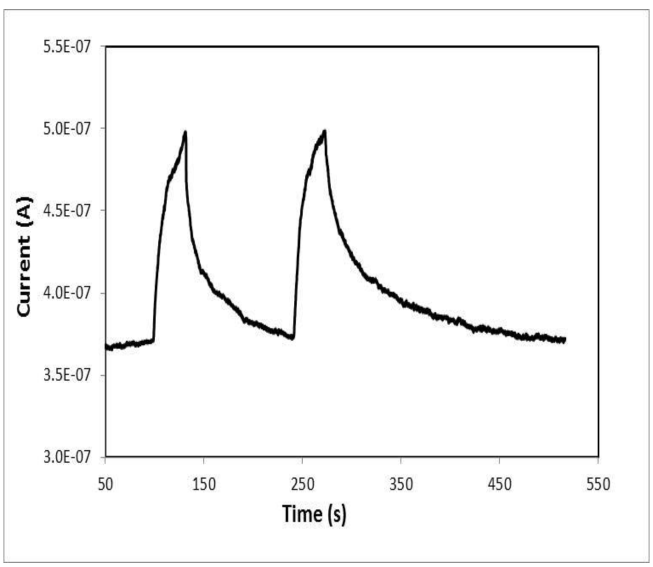

Figure 5. Photocurrent-time response of the GaN nanowire device under the irradiation of 254 nm UV light at 3 V bias.

The measurements were repeated at different wavelengths and power levels. The wavelengths of 532 nm and 633 nm did not yield any increase in photoconductivity. Conversely, the 365 nm UV light exposure caused a significant positive photocurrent response. In fact, the response was very similar to that of 254 nm UV light. The only difference is that the magnitude of the change is smaller, which suggests that the efficiency of photogenerated carriers depends on the wavelength of the irradiated light source.

Similar studies have shown positive photocurrent response for semiconductor nanowires [11-12]. A mechanism was proposed to explain the reasons for high photocurrent response. Upon light exposure at photon energies higher than bandgap energy, electron-hole pairs are generated ($h\nu \longrightarrow e^- + h^+$). Then, the photogenerated holes move to the surface and discharge the negatively charged adsorbed oxygen ions. Thus, oxygen is desorbed from the surface with the following:

$$O_2^- + h^+ \longrightarrow O_2\,(g) \qquad (2)$$

The unpaired electrons are collected at the cathode and contribute to the photocurrent. As the carrier lifetime increases, this proposed mechanism enhances the nanowire photoresponse and thereby results in a very high photoconductive gain.

4 CONCLUSIONS

The photoconductivity investigation of GaN nanowires has successfully been demonstrated. The measurements have been conducted at various light sources at wavelengths of 254 nm, 365 nm, 532 nm and 633 nm. The 254 nm and 365 nm UV light irradiation have resulted in significant positive photocurrent responses. Furthermore, photocurrent decay has been very rapid after the illumination ended, which indicates the absence of defect traps. Nevertheless, the wavelengths of 532 nm and 633 nm did not yield any increase in photoconductivity. These results suggest that GaN nanowires very attractive as photosensing elements in many highly-integrated optoelectronic devices.

REFERENCES

[1] Y. Huang, X. Duan, Y. Cui, and C.M. Lieber, Nano Lett, 2, 101, 2002.
[2] H.M. Kim, Y.H. Choo, H. Lee, S.I. Kim, S.R. Ryu, D. Y. Kim, T.W. Kang, and K.S. Chung, Nano Lett, 4, 1059, 2004.
[3] H. Zhou et al., Appl. Phys. Lett, 91, 181112, 2007.
[4] C.J. Novotny et al., Nano Lett, 8, 775, 2008.
[5] K. Teker and J. A. Oxenham, “Transition from Microscale-Faceted Structures to Ultra-Dense GaN Nanowires”, Mat. Res. Soc. Symp. Proceedings, Vol. 1302, DOI: 10.1557/opl.2011.214, 2011.
[6] J.K. Jian, X.L. Chen, Q.Y. Tu, Y.P. Xu, L. Dai, and M. Zhao, J. Phys. Chem. B, 108, 12024, 2004.
[7] J.C. Wang, S.Q. Feng, and D.P. Yu, Appl. Phys. A, 75, 69, 2002.

[8] C.C. Tang, S.S. Fan, H.Y. Dang, P. Li, Y.M. Liu, Appl. Phys. Lett, 77, 1961, 2000.
[9] X. M. Cai, A.B. Djurisic, and M.H. Xie, Thin Solid Films, 515, 984, 2006.
[10] Z. Wu, M.G. Hahm, Y.J. Jung, and L. Menon, J. Mater. Chem, 19, 463, 2009.
[11] R. Calarco , M. Marso, T. Richter, A.I. Aykanat, R. Meijers, A.V Hart, T. Stoica, and H. Luth, Nano Lett, 5, 98, 2005.
[12] C. Soci, A. Zhang, B. Xiang, S.A Dayeh, D.P Aplin, J. Park, X.Y Bao, Y.H Lo, and D. Wang, Nano Lett, 7, 1003, 2007.