Indium Nitride Nanowire Growth by Chemical Vapor Deposition and Electrical Characterization

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ABSTRACT

The III-nitrides have attracted great interest due to their wide range of applications from high efficiency solid-state lighting and photovoltaics to high-power and high temperature electronics. This paper presents a detailed study of InN nanowire morphology changes originating from the process parameters by chemical vapor deposition using In and NH_3 as source materials on SiO_2/Si substrates. Nickel catalysts with various forms have been used. The growth experiments have been carried out at temperatures between 800 and 1100ºC under H_2 as carrier gas. Significant changes in nanowire size and morphology have been observed in accordance with the variations in process parameters. The sources of these variations and the growth mechanisms are discussed. In fact, the InN nanowire diameters range from 10 nm to 250 nm; and lengths up to 50 μm depending on the catalyst initial form. The grown nanowires and devices have been characterized by scanning electron microscopy (SEM), transmission electron microscopy (TEM), and semiconductor parameter analyzer.

Keywords: InN nanowires, chemical vapor deposition, morphology control in nanowires

1 INTRODUCTION

The III-nitrides have attracted great interest due to their wide range of applications from high efficiency solid-state lighting and photovoltaics to high-power and high temperature electronics [1-3]. InN has received great attention due to its unique properties such as large drift velocity at room temperature, small effective electron mass, high mobility at room temperature, and narrow band gap of 0.7–0.9 eV [4-7]. Furthermore, unique fabrication techniques of nanostructures allow realization of various device geometries, such as axial or coaxial heterostructures.

Due to the advancements in fabrication techniques, nanostrutured materials can now be produced in various methods. These advancements open up new opportunities for utilizing superior properties of these low-dimensional materials. Additionally, one dimensional (1D) InN nanowires have attracted interest in growth and potential applications owing to their band gap and electrical charge transport tunability. Various synthesis methods including chemical vapor deposition[8] and molecular beam epitaxy [9] have been used for fabrication of InN nanowires.

This paper presents a detailed study of InN nanowire morphology changes originating from the process parameters by chemical vapor deposition using In and NH_3 as source materials on SiO_2/Si substrate.

2 EXPERIMENTAL DETAILS

Nanowire growth has been carried out in a resistively heated hot-wall 25-mm horizontal LPCVD reactor. Si and SiO_2/Si substrates were used. Nickel catalysts (20 nm nanoparticles and 20 nm thin film) 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 In (99.9 % purity, about 70 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 under carrier gas. Then, the growth was carried out by flowing NH_3 (99.99%) and H_2 gases through the reactor for about 80 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 completion of growth, NH_3 was shut off and the reactor cooled down under H_2 flow until 250ºC, and then cooled down to room temperature.

The samples have been characterized by scanning electron microscopy (SEM, JEOL JSM 6060 and JEOL 7600F SEM with Oxford Inca EDS), x-ray diffraction (XRD, Rigaku 300), transmission electron microscopy (TEM, JEOL JEM 1011), and semiconductor parameter analyzer.

3 RESULTS AND DISCUSSION

Figure 1 shows SEM image of InN nanowires grown at 1100ºC under H_2 on a Ni-coated Si substrate. The nanowire growth yield on Ni-coated Si substrate is very high and nanowires are mostly in bundles. The nanowire diameters are in the range of 10 nm to 35 nm and lengths up to several tens of microns. In fact, no nanowire growth was observed for growth temperatures until 1000ºC; and the growth yield has increased with temperature and reaching highest yield at 1100ºC. The morphology of the InN nanowires is very similar to the GaN nanowires with multi-prong growth morpholgy, which was reported earlier [10]. Moreover, the growth scheme of nanowires mostly obeys the vapor-liquid-solid (VLS) mechanism by using metallic catalytic agents.

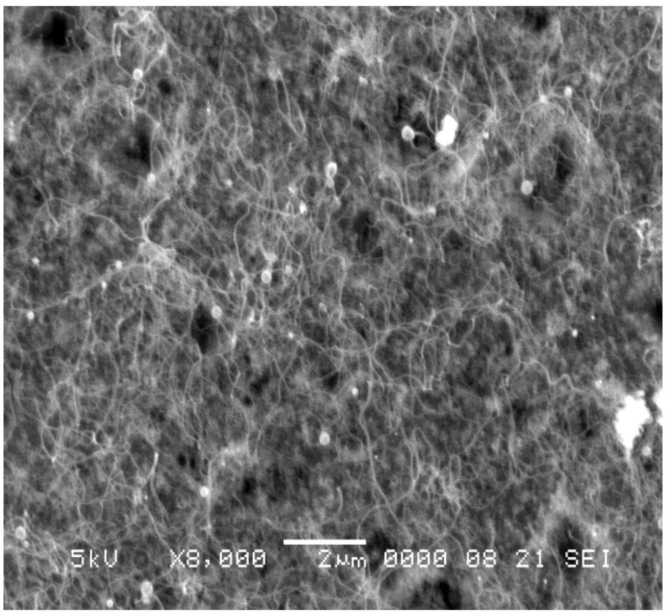

Figure 1. SEM image of high density of InN nanowires grown at 1100ºC under H_2 on a Ni-coated Si substrate.

Figure 2 shows SEM image of InN nanowires grown at 1100ºC under H_2 with Ni nanopaticles on a SiO_2/Si substrate. Ni particle-applied SiO_2/Si substrate has yielded low density of thicker nanowires with zigzag and sharp-kinked morphologies. In fact, the InN nanowire diameters can reach to 250 nm with the lengths up to 50 μm. These morphologies can be attributed to the fluctuations in mass transport during growth.

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 mostly determined by the catalyst size, whereas in multi-prong growth the nanowire diameter is not directly matched to the size of the catalyst droplets. The growth only takes place at catalyst/nanowire interface thereby sidewalls do not grow independently of the axial growth.

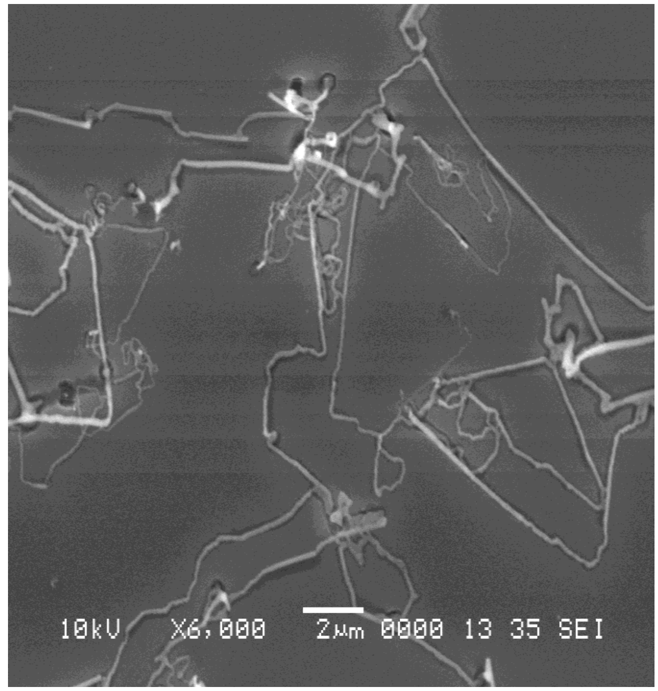

Figure 2. SEM image of zigzag and sharp-kinked InN nanowires grown at 1100ºC under H_2 with Ni nanoparticles on a SiO_2/Si substrate.

Furthermore, chemical composition analysis of the grown nanowires has been done by Energy-dispersive X-ray spectroscopy (EDS). The EDS spectrum has shown the presence of In, N, Si, and O elements, where Si and O peaks come from the SiO_2/Si substrate. This result confirmed that the nanowires consist of In and N elements.

Next, InN nanowire based devices have been fabricated using standard microfabrication processes. Figure 3 shows SEM image of the aligned Inn nanowires between gold electrodes by dielectrophoresis. Electrodes (10nm Ti/ 90nm Au) were fabricated using standard microfabrication processes onto SiO_2/Si substrate. The 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 = 10-100 kHz) was applied via a function generator about 40 seconds. Once the drop was dried, the AC signal was turned off. Finally, the devices were annealed at 300ºC to improve the contacts between nanowires and the gold electrodes before the electrical measurements.

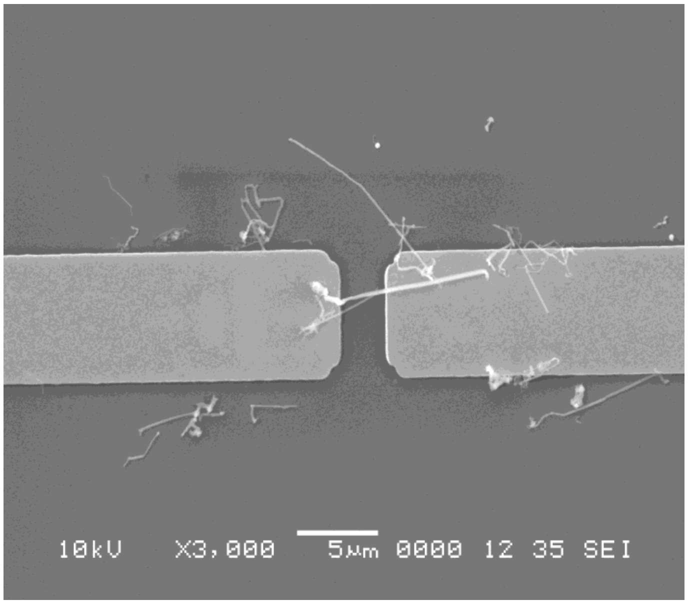

Figure 3. SEM image of the aligned thick InN nanowire between electrodes.

Figure 4 shows the *IV* curve of the InNNW device, which indicates that InN nanowires maintain their electrical properties through the alignment process. The *IV* curve also indicates that the annealing process is very successful. In fact, the InN nanowire devices show very high current levels reaching to several micro ampere current levels.

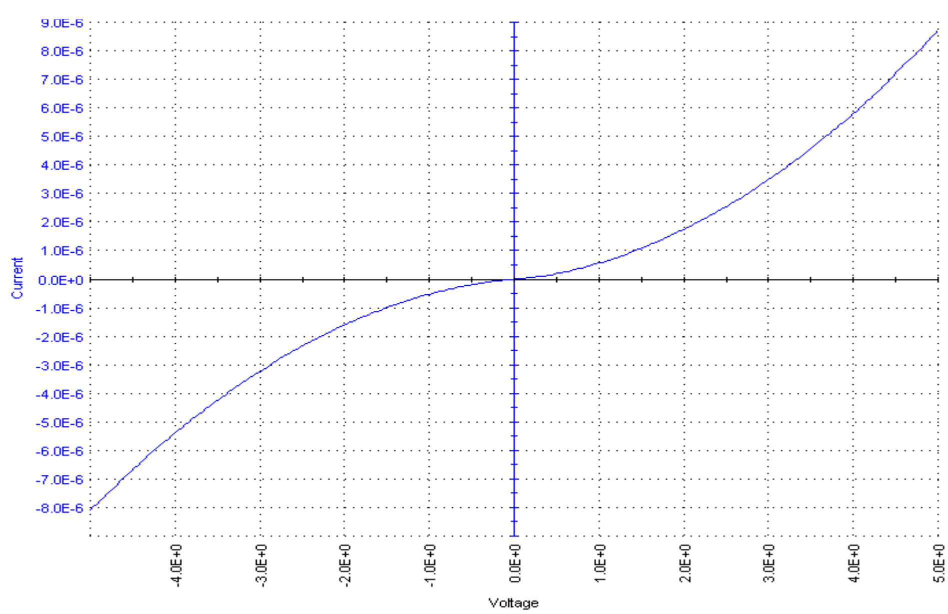

Figure 4. *IV* curve of the aligned InN nanowires.

4 CONCLUSIONS

A study of InN nanowire morphology variations with process parameters has successfully been demonstrated. Significant changes in nanowire morphology and density have been observed between Ni-coated Si substrate and Ni particle-applied SiO_2/Si substrate. The optimum growth temperature for the highest nanowire density was 1100ºC. In fact, the nanowire growth yield was very high for Ni-film catalyst, while Ni nanoparticle catalysts has yielded low density of thicker nanowires with zigzag and sharp-kinked morphologies. The InN nanowire diameters range from 10 nm to 250 nm; and lengths up to 50 µm depending on the initial catalyst form. Subsequently, InN nanowire based devices have been fabricated. These nanowire devices, even for a single nanowire device, resulted in very high current levels reaching to several micro ampere current levels. These results suggest that InN nanowires could be very attractive for ultrahigh speed field effect transistor circuits with significantly reduced power consumption.

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