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Direction Dependent Electrical and Optical Properties of Gallium Nitride Nanowires

R. Makkena [a], H. Li [b], B. Alphenaar [a] and M. Sunkara [b]

[a] Department of Electrical and Computer Engineering, University of Louisville, Louisville, Kentucky 40292, USA

[b] Department of Chemical Engineering, University of Louisville, Louisville, Kentucky 40292, USA

Corresponding Authors Addresses: mahendra@louisville.edu or brucea@louisville.edu.

Abstract

Gallium Nitride (GaN) nanowires are synthesized in two distinct directions the <10-10> a-direction and the <0001> c-direction using a direct nitridation scheme. Field effect transistors are then fabricated using the as-synthesized 'a' and 'c' direction nanowires. Gate dependent electrical transport measurements performed on the a-direction nanowires showed an increase in conductivity with the applied gate bias while no gate dependent conductivity is observed in the case of 'c' direction nanowires. The electron mobility for the a-direction GaN nanowire FETs is estimated to be 170 cm^2/V-s .Photo luminescence (PL) and UV-Vis absorption spectroscopy measurements show that the band gap of nanowires grown in a-direction blue shifts by about 50-70 meV when compared to the wires grown in c- direction.

Introduction

Gallium nitride is a technologically important material and because of its interesting properties like wide band gap and high quantum efficiency, it is being considered as a prime candidate for optoelectronic and high speed / high temperature electronic applications (1-3). Gallium Nitride, due to its anisotropic and polar nature, could exhibit direction dependent properties (4, 5). Thus, it is highly important to understand about the direction dependent properties for high-power high-temperature electronics. Field effect transistors (FETs) (6), schottky diodes (7), p-n junctions (6, 8) and UV light sensors (9) have all been fabricated using GaN nanowires as building blocks. The mobility of these nanowires was estimated to be between 2.15 - 650 cm^2/V-s (6, 10). The data were obtained using GaN nanowires produced using a number of processes. So, no conclusions could be made about the direction dependent nature of electrical properties of GaN nanowires. In this work, we specifically aimed at producing direction specific nanowires of similar diameters and characterized them for their electrical and optical properties.

Typically, the synthesis of GaN nanowires is accomplished using either catalyst assisted (11) or oxygen assisted (12) techniques. Control over the growth direction has been shown recently using catalyst assisted technique by epitaxy with single crystal templates (11). Previously, we showed that direct nitridation could be used to grow GaN nanowires from molten Ga without using Au as a catalyst (13). Later, we also showed the control over the growth direction of the nanowires without the need for any single crystal template (14). In this paper, GaN nanowires are grown in two distinct directions<10-10> a-direction and <0001> c-direction in high densities and with diameters around 20 nm on amorphous quartz and a number of other substrates (14). Supersaturation of gallium droplets with nitrogen led to the nucleation and growth of GaN nanowires along the <0001> direction whereas, the chemical vapor transport of gallium in the presence of dissociated ammonia led to the growth of nanowires along the <10-10> direction. We then fabricated a- and c- direction GaN FETs and characterized them for direction dependent electrical and optical properties.

Experimental Procedure

Direction specific nanowire synthesis

The control in the growth direction of the nanowires was achieved by controlling the Ga flux during direct nitridation in disassociated ammonia. The nitridation of Ga droplets at high Ga flux led to GaN nanowire growth in the c-direction, while nitridation with a low Ga flux leads to growth in the a-direction. Scanning electron microscopy images of the synthesized nanowires are shown in Figure 1a. and 1b. c-direction GaN nanowire growth from Ga droplets is typically observed on spontaneous nucleation followed by basal growth. In this case, the nanowires are expected to grow in the c-direction due to expected alignment of the basal (0001) planes of the GaN crystal nuclei with the molten Ga surface (15). The presence of hydrogen in the gas phase during the growth reduced the wettability of GaN with Ga, thereby restricting the lateral propagation of the nuclei and leading to the 1D growth. High resolution transmission electron microscopy analysis of the nanowires grown in the c-direction shows a regular occurrence of stacking errors along the length of the nanowire, but no amorphous sheath oxide is observed on the surfaces (inset of Fig. 1a).

GaN nanowires grown in the a-direction have been obtained from experiments utilizing the controlled vapor transport of Ga in the presence of dissociated ammonia on quartz substrates (Fig. 1b). The synthesized nanowires did not show any Ga metal droplets at the tips. This may be because of the long shutdown periods involved with cooling the substrate stage and the tiny Ga droplets could have easily been evaporated. From the TEM analysis of the nanowires (inset of Fig. 1b), it can be observed that the a-direction nanowires are free from stacking faults, dislocations and also contain no amorphous sheath.

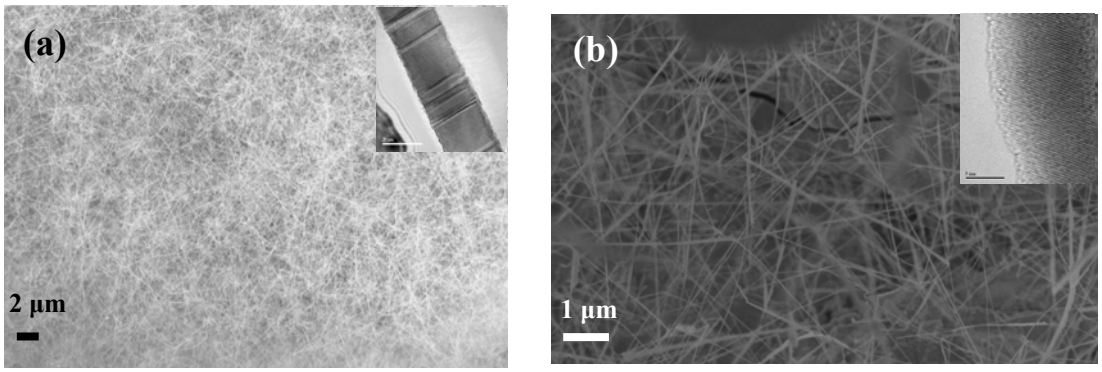

Figure 1. (a) FE-SEM image of the 'c'-direction nanowires, and inset is the TEM image of an individual 'c'-direction nanowire. Scale bar is 20nm (b) FE-SEM image of the 'a'-direction nanowires, and inset is the TEM image of an individual 'a'-direction nanowire. Scale bar is 5nm

Fabrication

The GaN nanowires as synthesized in both a- and c-directions were used to fabricate single nanowire FETs. The fabrication procedure is as follows. A grid is defined on the surface of an oxidized silicon wafer (100nm SiO_2) using e-beam lithography, and Ti/Au (10/20 nm) alignment marks were deposited using electron beam evaporation (the grid thus formed can be observed in the figure 2b.). The GaN nanowires are then transferred on to the substrate by pressing the silicon wafer onto the growth substrate and in this way the wires stick on the surface of the grid patterned silicon wafer. The nanowires are then located on the grid using SEM. Source and drain electrodes were defined using e-beam lithography followed by electron beam evaporation of Ti/Au(10/40nm). The back side of the doped silicon wafer was used as the gate. The last step in the fabrication is to pattern the bonding pads and leads interconnecting the e-beam contacts using optical lithography. SEM images of a completed device are shown in figures 2a and 2b.

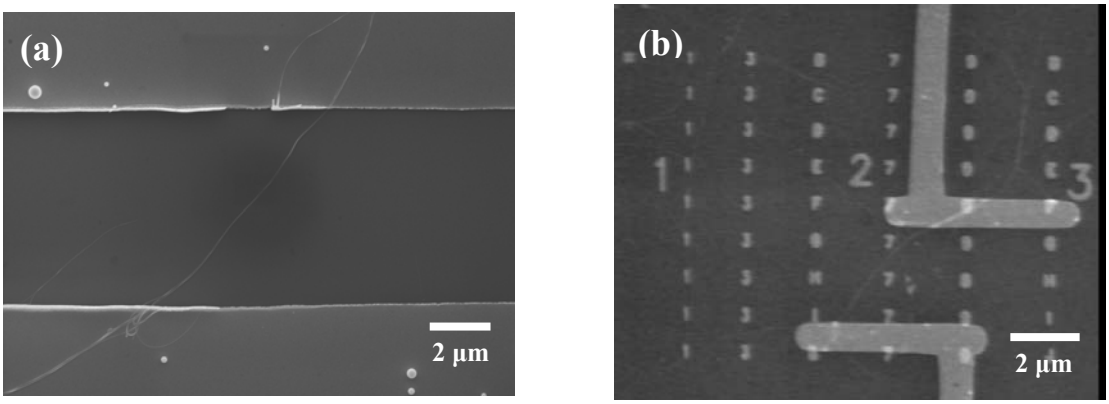

Figure 2. (a) FE-SEM image of the single GaN NW FET fabricated (b) FE-SEM image of an FET and the grid patterned using e-beam lithography used to locate the position of the nanowires can also be seen in the back ground.

Results and Discussion

Photoluminescence and UV-vis absorption measurements were performed on the as-synthesized GaN nanowires samples containing both a- and c-direction nanowires on amorphous quartz substrate in order to compare these results with the values obtained previously (14). The photoluminescence data (figure 3) shows that the near band-edge emission peak blue shifts by 70meV for a-direction nanowires compared to the nanowires grown in c-direction. This value is slightly higher than the previously reported value of 50 meV (14). The bandgap of the GaN depends on the crystallographic orientation because of polarization in the c-direction of GaN crystals (5). The difference in band-gap that we observe is much smaller than what has been previously reported. (11). The discrepancy could be due to the differences with the planes surrounding our c-direction nanowires.

UV-vis absorption studies on the synthesized GaN nanowires showed similar results. These measurements performed on the as-synthesized GaN nanowires showed absorption peaks separated by about 50 meV (Figure 4), indicating that the bandgap for a-direction nanowires is blue-shifted by about 50 meV. Detailed study of the dependence of band-gap on the growth direction is currently being performed and will be reported later.

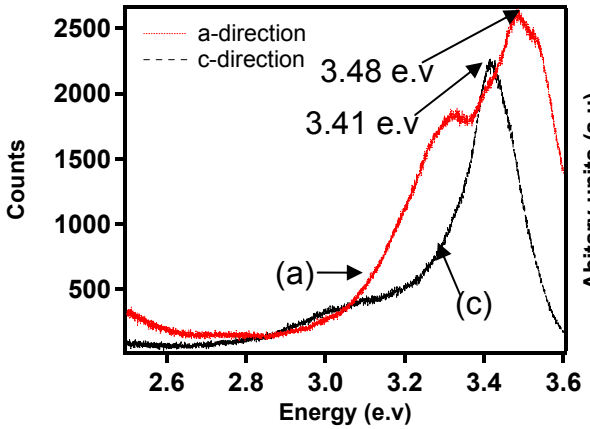

Figure 3. Photoluminescence data obtained on as synthesized 'a' direction and 'c' direction GaN NWs.

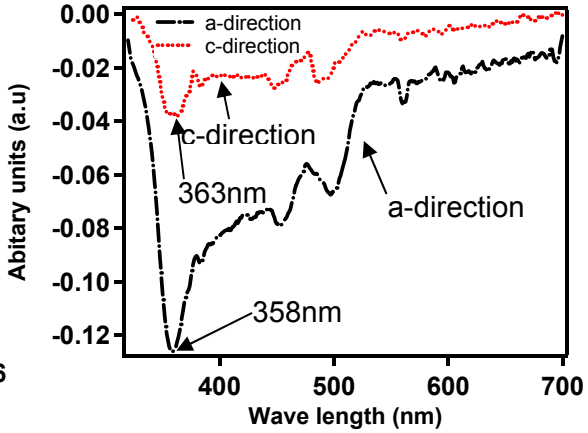

Figure 4. UV vis absorption data obtained on as synthesized 'a' direction and 'c' direction GaN NWs.

The electrical transport measurements were carried out at room temperature. Figure 5a shows the I_{sd} (source to drain current) - V_{sd} (source to drain voltage) curves obtained for two terminal measurements as a function of gate bias. These curves show that there is an increase in conductivity as the applied gate bias increases from -10 to +10 V. Hence, we can say that the GaN nanowires are n-type. The transfer characteristics of the same device have also been examined. Figure 5b shows I_{sd}- V_g recorded for V_{sd} varying from 0.1mv to 1.0mv. These curves are similar to an n-channel MOSFET, as has been previously reported (6, 10).

The carrier concentration was calculated to $10^{18}cm^{-3}$ which is given by equation [1](6).

$$\eta_e = Q/ (e.\ \pi.r^2L) \qquad [1]$$

Where η_e = carrier concentration of the nanowire
r = radius of the nanowire
L= length of the nanowire
Q = total charge in the nanowire which is given by equation. [2]

$$Q = CV_{th} \qquad [2]$$

Where V_{th} = threshold voltage
C = nanowire capacitance which is given by equation [3]

$$C \approx 2\Pi\varepsilon\varepsilon_o L /\ln (2h/r) \qquad [3]$$

Where ε = dielectric constant
h = thickness of the SiO_2 dielectric

The value obtained for the carrier concentration was similar to the values which were obtained previously (5). The carrier mobility of the nanowire was then estimated from the gate modulation characteristics using the relation

$$dI/dV_g = \mu(C/L^2)\, V \qquad [4]$$

Where μ = carrier mobility
V = bias voltage

The carrier mobility was calculated to be 170cm^2/V-s which is some what in the middle range of the values reported for room temperature previously (5).

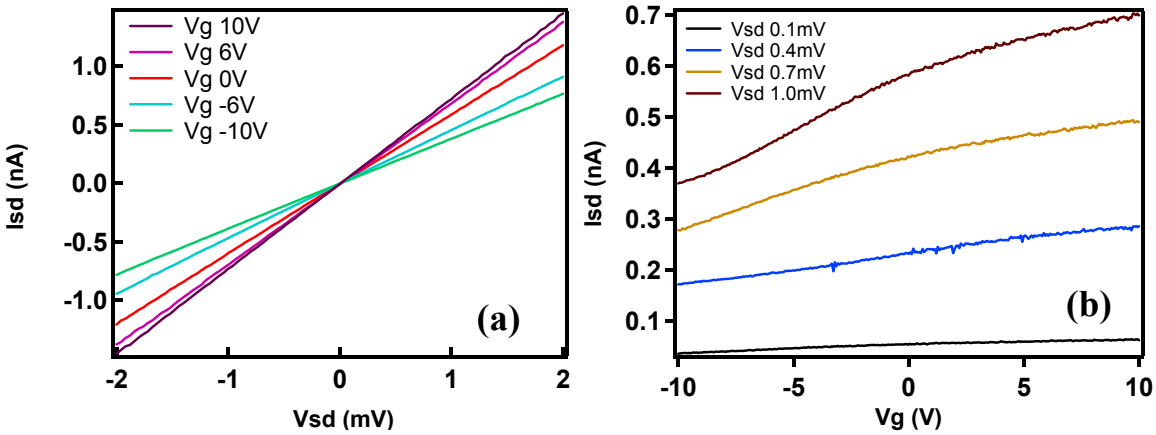

Figure 5. (a) Gate dependent $I_{sd} - V_{sd}$ data recorded on an 'a' direction GaN NW FET. The gate voltage was varied from +10v to -10V. (b) $I_{sd} - V_g$ data recorded on the same device for values of $V_{sd} =$ 0.1, 0.4, 0.7.1.0 mV.

Similar measurements were performed on transistor structures made from c-direction wires. We observe that the zero gate bias resistance of c-direction wires is always much higher than the resistance of a-direction wires. Resistances for various devices fabricated using both a- and c-direction nanowires are show in Table I. We can observe that a-direction nanowires have resistances in the order of few hundreds of KΩ's and the c-direction nanowires have resistance in the order of few GΩ's.

Comparison of resistance values for a- and c-direction nanowires (Table I)

Resistance value of a-direction NWs (KΩ's)	Resistance values of c-direction NWs (GΩ's)
1000	16.7
796	9
693	2.3

In addition to this, the gate dependent electrical transport measurements were carried out for the FETs fabricated using c-direction nanowires. From the characteristics thus obtained for the I_{sd} - V_{sd} for different gate biases (figure 6) we can observe that the gate bias has no effect on the FETs and no increase (decrease) in conductivity was observed with respect to the gate bias. We can observe from the PL data (figure 3) that as synthesized a-direction nanowires have a peak at 3.3ev which is in the energy range for range for impurity bound excitons (16) might be responsible for the conductivity observed in the a-direction nanowires. But, this peak is not to be observed in the as synthesized c-direction nanowires. We are now working on PL measurements at low temperature in order to have better understanding of differences in near band edge states.

Stacking faults which are present in the as synthesized c-direction nanowires seem to have some sort of effect on the conductivity observed in these nanowires. Further investigations are being carried out regarding the electric transport properties of 'c' direction nanowires.

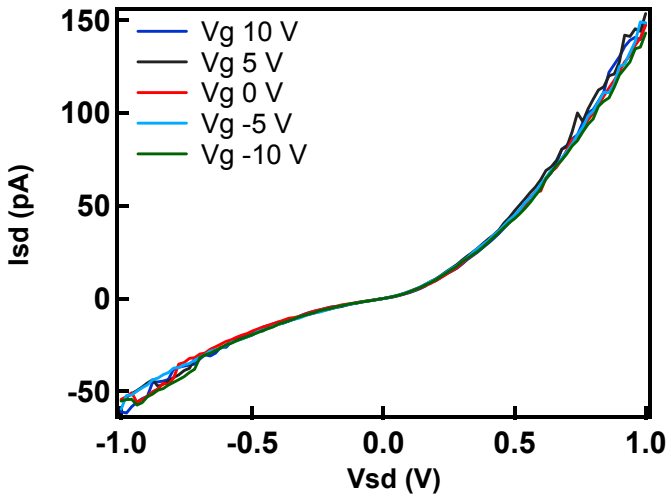

Figure 6. Gate dependent I_{sd} – V_{sd} data recorded on a 'c' direction GaN NW FET. The gate voltage was varied from +10v to -10V.

Conclusions

We have synthesized GaN nanowires in two distinct directions 'a'<10-10> and 'c'<0001>. Single nanowire based FETs were fabricated using the synthesized nanowires and electrical transport measurements were performed at room temperature. We have shown that FETs fabricated using a-direction have an effect in conductivity with the applied gate bias which was not observed in the case of c-direction nanowires. We have also shown that the band gap of nanowires grown in a-direction blue shifts by about 50-70 meV when compared to the wires grown in c- direction.

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