

Electronic Transport Characteristics of Gallium Nitride Nanowire-based Nanocircuits

V.M. Ayres, B.W. Jacobs, Q. Chen, L. Udpa, Y. Fan, N. Tram, A. Baczewski, S. Kumar and M. Crimp

College of Engineering
Michigan State University
East Lansing, MI 48824, USA

J. Halpern and M. He

Department of Chemistry
Howard University
Washington, D.C. 20059, USA

M.A. Tupta

Keithley Instruments, Inc.
Cleveland, OH 44139, USA

R. Stallcup and A. Hartman

Zyvex Corporation
Richardson, Texas 75081, USA

Abstract—Electronic transport studies of a two-phase gallium nitride nanowire are explored. Current-voltage measurements are taken of gallium nitride based three terminal field effect transistors fabricated via electron beam lithography. The measurements indicate a working field effect transistor utilizing a global back gate configuration. Very high current levels within the nanowire are reported. Direct transport measurements are also taken via two nanomanipulator probes. High current levels in this experiment are also observed. Scanning Probe Recognition Microscopy is used to detect the contact pad and nanowire radial boundary, and a nanowire auto-focus experiment is reported.

Keywords: Nanowire; Nanocircuit; Gallium Nitride; Scanning Probe Recognition Microscopy

I. INTRODUCTION

Over the past decade nanowires and nanotubes made from a wide variety of materials have demonstrated extraordinary electronic, mechanical and chemical characteristics. Gallium nitride (GaN) nanowires are particularly promising due to an inherently wide bandgap coupled with structurally induced electronic and optical confinement [1]. Gallium nitride-based nanocircuits have recently been shown to be viable for wide range of electronic and optical applications. GaN nanowire field effect transistors [2,3,4] and logic devices [5] have shown desired characteristics of high transconductance and good switching, and room temperature UV lasing has been reported for GaN nanowire systems [6,7] as well as good field emission properties [8].

Understanding the interactions of gallium nitride nanowires within a nanocircuit architecture is critically important to the

maximizing the potential of the GaN nanowire building block. In particular details of the electronic transport and carrier injection require fundamental elucidation. We will present details of our recent investigations of electronic transport and carrier injection.

II. MATERIALS AND METHODS

The ~50-100 nm gallium nitride nanowires were grown in a direct reaction of metal gallium vapor with flowing ammonia at 850-900°C without a catalyst as reported in Reference [9]. These had a two-phase coaxial zinc-blende/wurtzite structure, shown in Figure 1 and reported in Reference [10]. A field effect transistor design using a GaN nanowire as an n-type semiconducting channel was used in the experiment (GaN FET). The nanowires were dispersed on a highly doped p-type silicon substrate covered with a 150 nm dielectric layer of thermally grown silicon dioxide. The GaN FET source and drain contacts were patterned using electron beam lithography, with Ti/Au used for the conducting source and drain material. The backside of the wafer was stripped of silicon dioxide using hydrofluoric acid and Ti/Au was evaporated to form the global back gate.

Electronic transport characteristics were measured in two-point and four-point probe configurations using a Keithley 4200-SCS ultra low noise electronic characterization system and a Keithley-Zyvex KZ100 nanoprobe system, in which specially sharpened ~30 nm radius tungsten nanoprobe are coupled with the 4200-SCS and experiments are performed under direct SEM observation. These experiments were carried out at the corporate laboratories of Keithley Instruments, (Cleveland Ohio), and Zyvex Corporation,

(Richardson Texas). Carrier injection is under investigation using Scanning Probe Recognition Microscopy, a new scanning probe microscope modality under development by our group in partnership with Veeco Instruments, Santa Barbara, CA. [11]

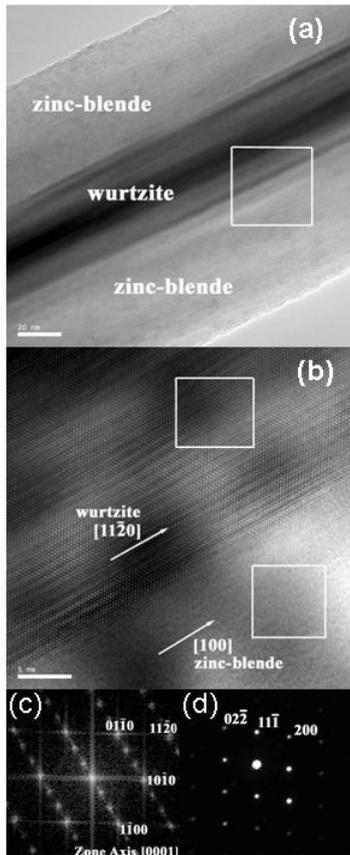


Figure 1. (a) TEM and (b) high resolution TEM of two-phase coaxial homostructure GaN nanowires used in the experiments. The boxed area in (a) is shown in (b). Nanodiffraction, selected area electron diffraction and fast fourier transforms were used to identify (c) the inner phase as wurtzite and (d) the outer phase as zinc-blende. The two boxed areas in (b) are shown in (c) and (d).

III. NANOCIRCUIT ELECTRONIC TRANSPORT MEASUREMENTS

Current-voltage measurements were taken at Keithley Labs on a Keithley 4200-SCS which offers very low noise and low current measurements. The Keithley 4200-SCS is uniquely suited for this application because high levels of noise can arise while analyzing the GaNFETs. Measurements indicate this FET has a good on-off ratio and is capable of handling high current. Currents measured in these devices approached $30\mu\text{A}$, which is similar to findings from other groups [12,13], is very high considering the nanowire dimensions. The current density can thus be approximated as $\sim 2.4\text{mA}\cdot\mu\text{m}^{-2}$. Although the nanowire is capable of very high current densities, the gate voltages needed to achieve this are somewhat above accepted levels. A gate voltage step of -30V to 30V was needed to clearly show current change based on gate voltage modulation. These gate levels, however, are not feasible in most devices.

Other discrepancies include unpredictability of the device at negative drain-source voltages, where the gate-source voltage variation does not seem to affect the drain current as much. The reason for this anomaly is unknown at this time, but is being investigated further.

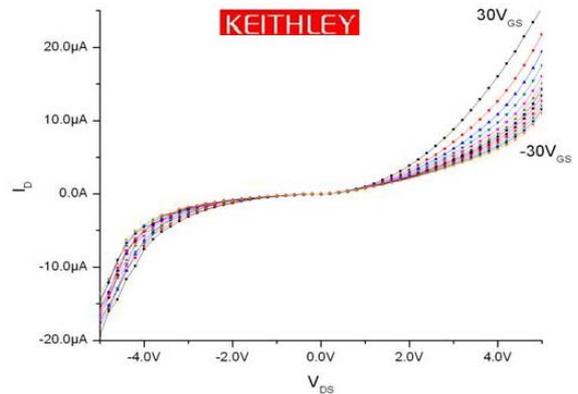


Figure 2. Current-Voltage characteristics for GaN nanowire FET showing effect of gate-source and drain-source voltage variation.

IV. NANOWIRE ELECTRONIC TRANSPORT MEASUREMENTS

Further two-point and point-point probe measurements were performed in the Keithley-Zyvex KZ100 nanoprobe system under direct SEM observation. The nanoprobe arrangement for the four-point measurements is shown in Figure 3(a). Placement of a probe tip resulted in the nanowire break. The probes labeled 2 and 3 were lifted out of contact with the nanowire and the probe labeled 1 was placed in direct contact with the cleaved open end as shown in Figure 3(b). The probe labeled 4 remained on the gold contact pad as shown in Figure 3(a).

The current density to breakdown was then investigated. The results confirmed the high current capacity previously discussed. In a typical example $10\mu\text{A}$ of current was achieved, as shown in Figure 3(c). Electrical breakdown with pull apart in the middle of the nanowire occurred at greater than $50\mu\text{A}$. The gold contact pad near probe 4 did not display any sign of local heating.

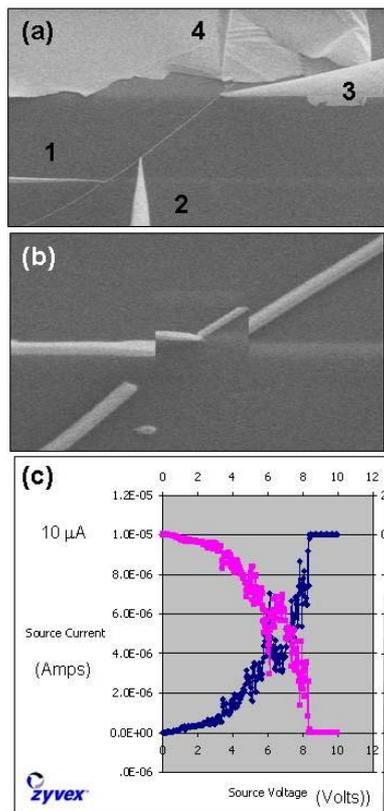


Figure 3. (a) Nanoprobe arrangement for the four-point measurements (b) Probe 1 placed in direct contact with the cleaved nanowire open end. (c) example high current density IV characteristic.

V. SCANNING PROBE RECOGNITION MICROSCOPY OF NANOCIRCUITS

Scanning Probe Recognition Microscopy (SPRM) is a new scanning probe microscope modality under development by our group in partnership with Veeco Instruments, Santa Barbara, California [14]. In SPRM, we give the Scanning Probe Microscope system itself the power to return to a specific nanoscale feature of interest through feature recognition coupled with adaptive scan plan generation and implementation. It is a recognition-driven and learning approach, made possible through combining Scanning Probe Microscope piezoelectric implementation with on-line image processing and dynamically adaptive learning algorithms. The human operator interaction is now focused on the decision-making level, rather than the execution level.

SPRM has been implemented within our group in the main atomic force and scanning tunneling modes. The SPRM experiments are performed on a specially adapted Multimode Nanoscope IIIA (Veeco Instruments) in ambient air. For the nanocircuits investigation, several aspects of the GaNFETs are currently under investigation, which require the ability to auto-focus the scan path to proceed from the conducting contact pad onto the semiconducting GaN nanowire, while avoiding the insulating oxide layer.

Our implementation, shown in Figure 4, uses real-time captured information to detect the contact pad (user defined

region), the contact pad-nanowire linear junction, and the nanowire radial boundary. Our current implementation also has adaptive learning capability with statistical methods used in boundary detection adjustment to improve accuracy.

The resulting nanowire auto-focus using SPRM is shown in Figure 4. The image captured by standard SPM is shown in Figure 4 (a). (dotted lines are used to artificially enhance the low relief contact pad boundaries). The scan plan generation, shown in Figure 4 (b), shows that our scanning scheme can detect and predict boundaries reliably. Thus, we can scan back and forth only on the interested region, which starts from the left side (green points) and ends with right side (black points) in Figure 4 (b). We can see that the scanning scheme can follow changes of boundaries very well because of the adaptive learning algorithm. The captured real-time auto-focused image is shown in Figure 4 (c). This is a still image from an .mpg movie clip of the top to bottom auto-focused scan that starts from a small region on the contact pad and proceeds along the nanowire. The regions that are not actually scanned are padded with 0 (dark blue region) for display.

VI. DISCUSSION

Gallium nitride field effect transistors reported here may be a viable solution in many electronic devices. The high current density that these nanowires can achieve may be desirable in high current, high power applications. The device itself, however, needs to be improved so as to lower gate-source voltage levels thus making this device design more practical. Optical applications are also being realized and the biphasic nature of these nanowires may provide an optical confinement element similar to optical fibers. The possibility of carrier and exciton confinement in these nanowires may provide a wide variety of electronic device applications.

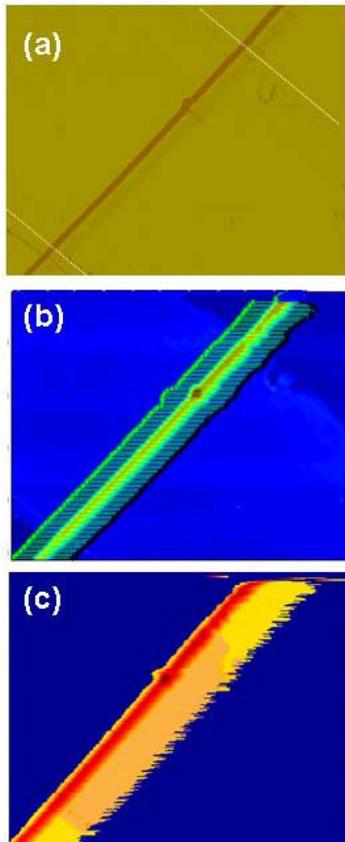


Figure 4. Scanning scheme implementation for GaN anocircuit: (a) Image captured by standard SPM. The contact region boundaries are delineated by white dotted lines. The image size is 5x5 microns. (b) Scanning scheme showing lines of the scan plan; (c) Real-time image captured by SPRM system using the auto-focused scanning scheme along the nanowire. The height variation at the contact regions is also visible.

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