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Gallium Nitride Nanowire Nanodevices

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ABSTRACT

Field effect transistors (FETs) based on individual GaN nanowires (NWs) have been fabricated. Gate-dependent electrical transport measurements show that the GaN NWs are n-type and that the conductance of NW–FETs can be modulated by more than 3 orders of magnitude. Electron mobilities determined for the GaN NW FETs, which were estimated from the transconductance, were as high as 650 $cm^2/V \cdot s$. These mobilities are comparable to or larger than thin film materials with similar carrier concentration and thus demonstrate the high quality of these NW building blocks and their potential for nanoscale electronics. In addition, p–n junctions have been assembled in high yield from p-type Si, and these n-type GaN NWs and their potential applications are discussed.

One-dimensional nanostructures such as nanowires (NWs) and nanotubes are attractive building blocks for nanoelectronics since their morphology, size, and electronic properties make them suitable for fabricating both nanoscale devices and interconnects.[1] For example, single-walled carbon nanotubes have been used as building blocks to fabricate room-temperature field effect transistors (FETs),[2,3] diodes,[4] and recently an inverter.[5] However, there are substantial limitations on the use of nanotubes for integrated nanoelectronics or even simple device arrays, because semiconducting and metallic nanotubes are obtained simultaneously during growth.[1,6]

In contrast, recent studies from our laboratory have demonstrated that the chemical and physical characteristics of NWs, including composition, size, electronic and optical properties, can be rationally controlled during synthesis in a predictable manner,[7−12] thus making these materials attractive building blocks for assembling electronic and optoelectronic nanosystems. For example, a number of nanodevices, such as FETs,[9,10] bipolar transistors,[13] inverters,[13,14] light emitting diodes (LED),[10] and even logic gates,[14] have been assembled from these well-defined semiconductor NWs. To date, the active devices have been based on low band-gap semiconductor materials, such as silicon and indium phosphide, although wide band-gap materials, such as GaN, are attractive candidates for short wavelength optoelectronic devices[15] and high-power/high-temperature electronics.[16,17] GaN is also an intrinsically attractive material for assembling active nanoscale devices, where the surface-to-volume ratio is large, since it is known that there are few surface states acting as recombination centers in the band gap.[18] Despite these attractive features and recent reports of the synthesis of GaN NWs and nanoclusters,[19−21] investigations of devices based on GaN nanomaterials have not been reported.

Here we describe the fabrication and properties of nanoscale FETs based on individual GaN NWs. The GaN NWs were synthesized via a laser-assisted catalytic growth (LCG) method described previously.[7,19] Field-emission scanning electron microscopy (FE-SEM) images of the GaN samples (Figure 1a) show that the NWs have diameters and lengths on the order of 10 nm and 10 μm. High-resolution transmission electron microscopy (TEM) and electron diffraction studies also demonstrate that the NWs are single crystals with a wurtzite structure (Figure 1b). In addition, TEM images show that the lattice is continuous to the edge of the GaN NWs (Figure 1b, lower inset), and contrasts the 1−2 nm thick native amorphous oxide found on Si and InP NWs.[8−12] This observation for the GaN NWs is consistent with a report that GaN terminates in a monolayer thick native oxide[22] and has advantages for fabrication of nanodevices (see below).

The GaN NW FETs studied in this work (Figure 2a) were prepared by dispersing a suspension of GaN NWs in ethanol onto the surface of an oxidized silicon substrate (1−10 Ωcm resistivity, 600 nm SiO_2, Silicon Sense, Inc.), where the underlying conducting silicon was used as a global back gate.[9,10,13] Source and drain electrodes were defined by electron beam lithography followed by electron beam evaporation of Ti/Au (50/70 nm), and electrical transport measurements were made at room temperature.[9] Figure 2b shows a set of typical current vs source-drain voltage ($I-V_{sd}$) data obtained from a single GaN NW−FET at different gate voltages (V_g). The two-terminal $I-V_{sd}$ curves are all linear, thus indicating that the metal electrodes make ohmic contacts to the GaN NWs. The gate-dependence of the $I-V_{sd}$ curves also shows that the GaN NWs are n-type; that is, the

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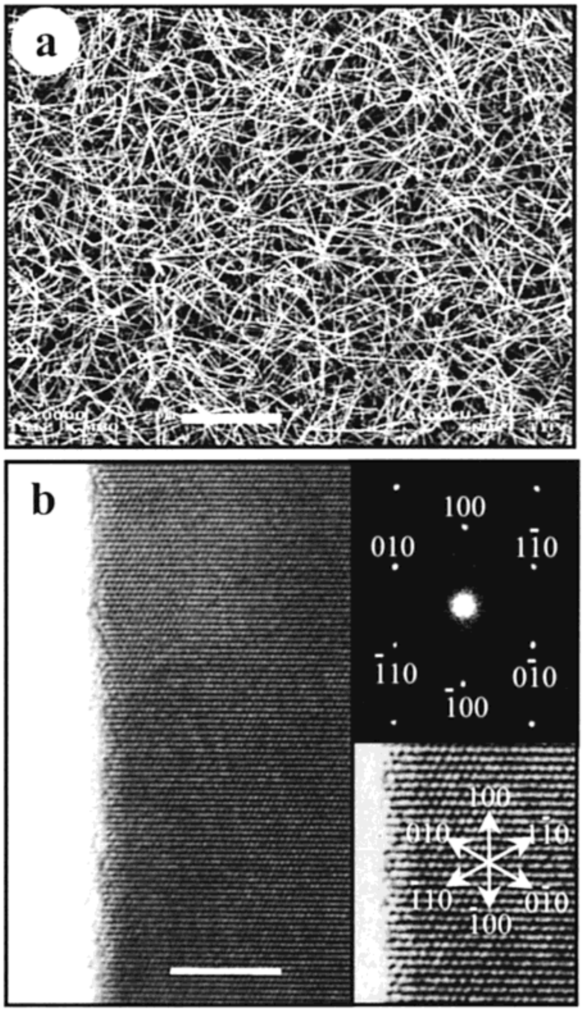

Figure 1. (a) FE-SEM image of GaN NWs. Scale bar is 2 μm. (b) (left) Lattice resolved TEM image of one GaN NW. The (100) lattice planes are visible perpendicular to the wire axis. Scale bar is 5 nm. (top right) The electron diffraction pattern was recorded along the ⟨001⟩ zone axis. (lower right) Lattice-resolved TEM image that highlights thin native oxide layer at the NW edge. The crystallographic planes are indicated.

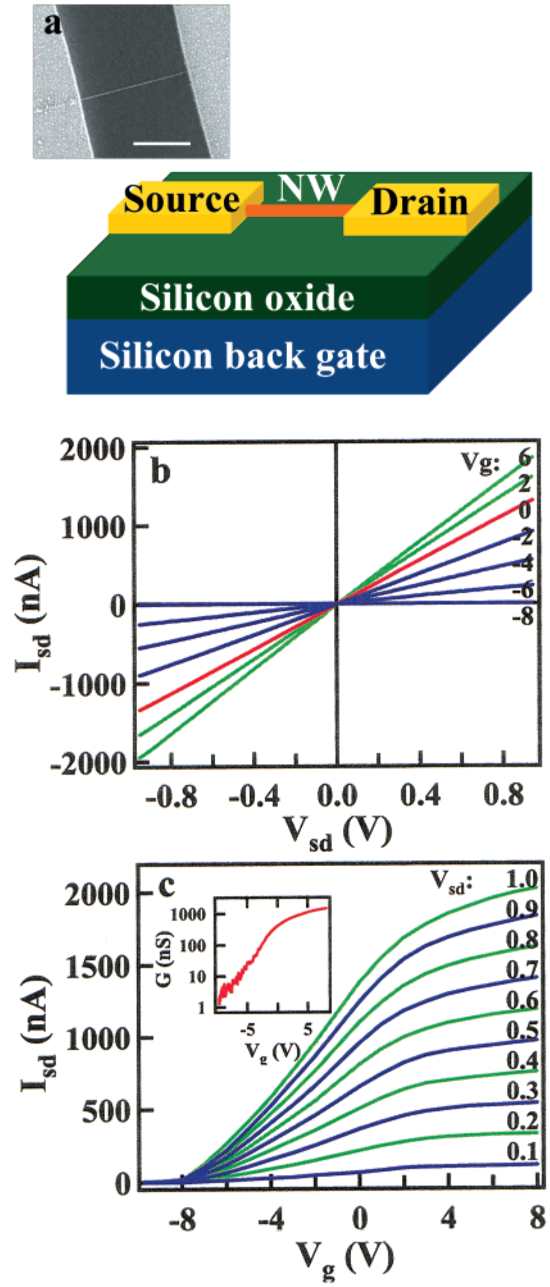

Figure 2. (a) Schematic of a NW FET, and (inset) FE-SEM image of a GaN NW FET. Scale bar is 2 μm. (b) Gate-dependent $I-V_{sd}$ data recorded on a 17.6 nm diameter GaN NW. The gate voltages for each $I-V_{sd}$ curve are indicated. (c) $I-V_g$ data recorded for values of $V_{sd} = 0.1-1$ V. (inset) Conductance, G, vs gate voltage.

conductance of the NW increases (decreases) with increasingly positive (negative) V_g. Based on previous studies of bulk materials,[23] we can attribute the n-type behavior in nominally undoped GaN to the nitrogen vacancies and/or oxygen impurities.

The transfer characteristics of the GaN NW FETs have also been examined. The I vs V_g for a GaN NW device recorded at different source-drain voltages (Figure 2c) are characteristic of an n-channel metal-oxide-semiconductor FET.[24] Moreover, these data demonstrate that the conductance modulation of the GaN NW FET exceeds 3 orders of magnitude by changing the gate voltage from −8 to +6 V. This relatively large switching voltage is due in large part to the thick (600 nm) oxide dielectric layer used in our test device and could be easily reduced by using a thinner gate dielectric.

In addition, we have investigated the carrier concentration and carrier mobilities in these n-type GaN NW FETs. The electron carrier density was estimated from the total charge, Q_{tot}, in the NW: $Q_{tot} = CV_{th}$, where C is the NW capacitance and V_{th} the threshold voltage required to deplete the NW. The capacitance is given by $C \cong 2\pi\epsilon\epsilon_0 L/\ln(2h/r)$, where ϵ is dielectric constant, h is the thickness of the SiO_2 dielectric, L is the length, and r is radius of GaN NW.[9] The electron carrier densities, $n_e = Q/(e{\cdot}\pi r^2 L)$, were found to be in the range 10^{18} to 10^{19}cm^{-3} for our devices. The mobility of the carriers can be estimated from transconductance of the FET,[2b,9] $dI/dV_g = \mu(C/L^2)V_{sd}$, where μ is the carrier mobility. Plots of dI/dV_g versus V_{sd} were found to be linear for GaN NW FETs, as expected for this model, and from the slopes ($= \mu(C/L^2)$) of these curves we calculated the electron

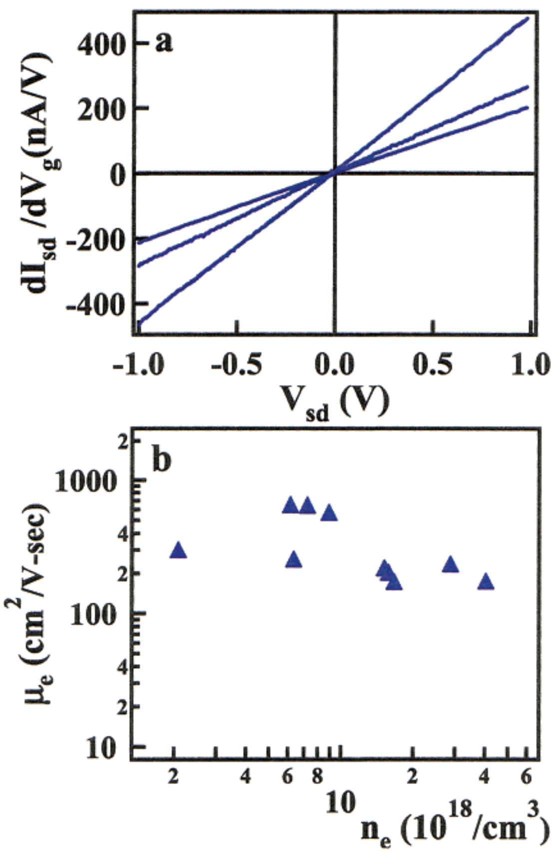

Figure 3. (a) dI/dV_g vs V_{sd} data recorded on three different devices. The mobilities of these devices were 640, 560, and 300 cm^2/V·s. (b) Electron mobilities of 10 different devices as a function of electron density, n_e.

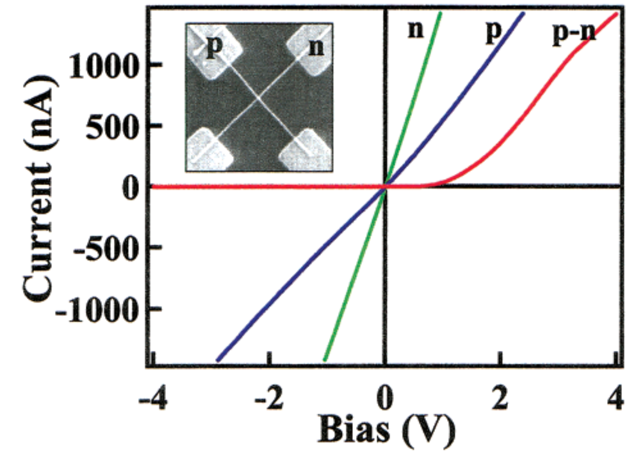

Figure 4. *I*−*V* behavior of a n-GaN NW (green), a p-Si NW (blue), and the corresponding n-GaN/p-Si NW junction (red). (inset) FE-SEM image of a crossed n-GaN/p-Si NW junction. Si NWs were produced by reported methods.[9,12]

mobilities. The mobilities determined in this way for 10 devices ranged from 150 to 650 cm^2/V·s. Significantly, these mobilities are comparable to or larger than values reported for thin film GaN materials, 100−300 cm^2/V·s, at comparable carrier concentrations,[25] and are substantially larger than those reported for carbon nanotube FETs, ca. 20 cm^2/V·s.[2b] Plots of the electron mobility versus carrier concentration (Figure 3b) also show that there is little dependence of the mobility on electron density. This observation suggests that a common scattering process not related to dopants limits the mobility. Additional studies addressing this point and the potential for further increasing carrier mobility are currently in progress.

The large carrier mobilities observed in the GaN NW FETs makes them attractive building blocks for functional electronic devices. For example, a p−n junction can be readily obtained using fluidic assembly to cross n-GaN and p- Si NWs (Figure 4).[14,26] *I*−*V* measurements made on the individual GaN and Si NWs show a linear response characteristic of ohmically contacted semiconductors, while the *I*−*V* data recorded across the p−n junction exhibits clear current rectification with a turn-on voltage of ca. 1 V in forward bias. These results are highly reproducible: clear current rectification was observed in over 95% of around 100 crossed p−n NW devices studied, and, moreover, 85% of the devices exhibited turn-on voltages of ca. 1 V. We believe that the reproducible assembly of crossed NW structures with predictable electrical properties will enable us also to explore the assembly and properties of integrated p−n junction arrays and more complicated functional electronic circuits. For example, these p−n junctions can be used to configure logic gates[14] and can function as ultraviolet and blue LEDs and LED arrays when forward biased.[27]

In summary, we have shown that single crystal GaN NWs can serve as building blocks for the assembly of nanodevices. NW FETs made from individual n-type GaN NWs exhibit good switching behavior with gate-dependent conductance variations exceeding 3 orders of magnitude. Electron mobilities as high as 650 cm^2/V·s were observed in the GaN NW FETs and are comparable to or larger than bulk materials and substantially larger than nanoscale FETs produced from carbon nanotubes. In addition, we have shown that p−n diodes can be readily assembled from n-type GaN and p-type Si NWs and that these junctions exhibit highly reproducible rectifying behavior. The reproducible behavior exhibited by the devices created from these GaN NWs suggests significant promise for bottom-up assembly of more complicated electronic and optoelectronic nanosystems, and thus could open up many exciting opportunities in nanoscale science and technology.

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