High Performance n-Type Carbon Nanotube Field-Effect Transistors with Chemically Doped Contacts

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ABSTRACT

Short channel (~80 nm) n-type single-walled carbon nanotube (SWNT) field-effect transistors (FETs) with potassium (K) doped source and drain regions and high-κ gate dielectrics (ALD HfO2) are obtained. For nanotubes with diameter ~1.6 nm and band gap ~0.55 eV, we obtain n-MOSFET-like devices exhibiting high on-currents due to chemically suppressed Schottky barriers at the contacts, subthreshold swing of 70 level on the electrical characteristics of the nanotube devices are discussed.

Single-walled carbon nanotubes (SWNTs) are promising for future high performance electronics such as field effect transistors (FETs) owing to their various unique properties including ballistic transport with relatively long mean free paths and high compatibility with high-κ dielectrics imparted by their unique chemical bonding and surface stability.1~12 While much has been done to achieve high performance p-type nanotube FETs through contact optimization, dielectric integration and lateral scaling, progress on n-FETs has been slow partly due to the difficulty in affording low Schottky (SB) contacts for high on-states and at the same time achieving high on/off ratios with small diameter (or large band gap) tubes.7 Here, by invoking chemical doping, high-κ dielectrics, and new device design, we demonstrate n-type SWNT FETs with performance matching or approaching the best p-type nanotube FETs and surpassing the state-of-the-art Si n-MOSFET.

SWNT synthesis,13 atomic layer deposition (ALD) of HfO2,10,14,15 (t_{ox} = 8 nm) and details of device fabrication are similar to those described previously. In Figure 1, we first show the electrical properties of a back-gated (t_{SiO2} = 10 nm, Figure 1a) semiconducting SWNT (d ~ 1.4 to 1.5 nm, channel length L ~ 150 nm) between Pd source/drain S/D device before and after K-doping (details of doping described previously16~18). The as-made device is a p-type FET with I_{on} ~ 5 μA and linear conductance of G_{on} ~ 0.3 e2/h (Figure 1b). I_{on} is lower than the expected,19 20 ~25 μA per tube as limited by the existence of a SB7 (height ~ 0.1 eV, width ~ t_{SiO2}) between Pd and the d = 1.4~1.5 nm tube. After heavily n-doping the device with potassium in vacuum, I_{on} and G_{on} increase to over 20 μA and e2/h (Figure 1b) respectively, suggesting high metal-semiconductor contact transparency (T_{MS} ~ 1) and quasi ballistic transport within the nanotube. The current–voltage (I_{d},V_{g}) characteristics of the device become largely gate independent, corresponding to a near-metallic n+ state of the SWNT (Fermi level well within the conduction band) due to heavy electron donation by K. This result clearly shows that n-doping of the semiconducting SWNT is highly effective in suppressing SBs and increasing the electron transmission probability T_{MS} to the conduction band of SWNTs at the Pd-tube contacts.

Having established that chemical doping can afford high on-current injection into the n-channel of a SWNT, we then moved onto constructing n-type SWNT FETs with n+−i−n+ structures (with heavily doped S/D regions, Figure 2a), similar in principle to conventional n-MOSFETs.20 We patterned top-gate stack (gate length L_{g} ~ 80 nm) on individual SWNTs on p+Si/SiO2 (~500 nm) substrates.

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without overlapping the Pd (15 nm thick) metal S/D (distance \(L \approx 250\) nm). The top-gate stack consisted of an \(\sim 8\) nm thick HfO\(_2\) dielectric layer and \(\sim 0.5/15\) nm Ti/Pd gate metal atop formed by an ALD and liftoff technique.\(^{10,14,15}\) The nanotube segments outside the gate stack are fully exposed for K vapor doping to form \(n^+\) regions (Figure 2a). ALD of HfO\(_2\) on SWNTs provides excellent electrostatic modulation of the channel conductance without degrading the transport property of the 1D nanotube channels.\(^{3,9,10}\) This is another key element in affording high performance \(n\)-type SWNT FETs.

Prior to K doping, the devices operated as p-MOSFETs (Figure 2b blue curve) when the two ends of the tube were

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**Figure 1.** \(n\)-Doping of nanotubes by K vapor. (a) AFM image of a nanotube device (top panel) and schematic drawing of K doping of the device (bottom panel). The K vapor was generated by applying a current across an alkaline metal dispenser\(^{16}\) for a few minutes (\(\sim 1-10\) min, depending on the desired doping level). (b) \(I_{ds}-V_{gs}\) characteristics of a device before and after K-doping at two gate voltages \(V_{gs} = -3\) V (red) and 0 V (green). Heavy \(n\)-doping of the nanotube along its entire length resulted in highly conducting near-metallic behavior with no significant gate dependence. All measurements were conducted in vacuum (\(\sim 10^{-5}\) Torr). The chemical doping effects were found to reverse upon exposure to ambient environment due to the reactivity of K atoms. Potentially, passivation methods or air-stable dopants could be used to avoid air sensitivity.

**Figure 2.** High performance nanotube n-MOSFET. (a) AFM image and schematic of a nanotube MOSFET. Note that two steps of electron beam lithography with an over-layer positioning accuracy of \(\sim 50\) nm were used to form Pd S/D and gate stack, respectively. (b) \(I_{ds}-V_{gs}\) curves for a nanotube (\(d \approx 1.6-1.7\) nm) MOSFET before (blue) and after (red) K-doping. Before K-doping for the p-FET, a back gate voltage of \(-15\) V was applied to obtain electrostatically p-doped contacts. For the n-FET, the back gate was grounded during the measurements after the contacts were chemically doped by K. (c) \(I_{ds}-V_{gs}\) output characteristics of the device before (p-FET, blue) and after (n-FET, red) K-doping. From low to high current curves, the top-gate voltages are \(V_{gs} = 0.2\) to \(-1\) V in \(0.2\) V steps for the p-FET and \(V_{gs} = -0.2\) to \(0.6\) V in \(0.2\) V steps for the n-FET.
electrostatically hole-doped by a back-gate. Upon exposure to K vapor in vacuum, the S/D regions became n-doped while the top-gated channel regions remained intrinsic due to blocking of K by the gate stack. This afforded n$^+ -$i-$n^+$ n-type nanotube MOSFETs. The electrical properties of a SWNT ($d \sim 1.6$–1.7 nm; $E_g \sim 0.55$ eV) MOSFET before (p-type) and after K-doping (n-type) in vacuum are shown in Figure 2b,c. The n-FET (K-doped S/D) and p-FET (electrostatically doped S/D) showed near-symmetrical characteristics with similar on-currents $I_{on} \sim 8 \mu A$ at $V_{gs} = 0.5$ (Figure 2c). The transconductance were ($dI_{ds}/dV_{gs}$)$_{\text{max}} \sim 20 \mu A/\text{V}$ and $\sim 10 \mu A$ for n- and p- FETs, respectively. Both devices exhibited excellent switching characteristics with subthreshold swings $S = dI_{ds}/dV_{gs} \sim 70$–80 mV/decade (Figure 2b), near the theoretical limit of the $S \sim 60 \text{ mV/decade}$. Note that at $V_{ds} = 0.5 \text{ V}$, a high $I_{on}/I_{off} \sim 10^6$ was achieved for the nanotube n-MOSFET with no significant ambipolar p-channel conduction (Figure 2b red curve). These characteristics are the best reported to-date for n-type nanotube FETs enabled by the MOSFET geometry with chemically doped S/D, high-$\kappa$ dielectrics, and transparent metal–tube contacts. In such a MOSFET-like geometry, the gate electric fields result in bulk switching of the nanotube directly under the gate stack with little effect to the Schottky barriers at the metal–tube junctions.

We next investigated the effects of the contacts doping level on the electrical characteristics of our nanotube n-FETs. The doping level was varied by adjusting the exposure time of the devices to K atoms. Figure 3a (dashed curve) shows the switching properties for the same device in Figure 2 but at a higher degree of n-doping of the S/D contacts. The on-current of the device increased from $\sim 8 \mu A$ to $15 \mu A$ at $V_{ds} = 0.5 \text{ V}$ (Figure 3b), attributed to further enhanced transparency at the Pd–tube junctions and lower series resistance in the n$^+$ nanotube segments. The on-current increase was, however, accompanied by a more obvious ambipolar p-channel conduction, an increase in the minimum leakage current ($I_{min}$), and a reduction of $I_{on}/I_{min}$ from $10^6$ to $10^4$ (Figure 3a dashed curve). The enhanced $I_{min}$ is attributed to the thinning of the band-to-band tunneling barriers (resulting in an increase in the transmission probability $T_{bb}$) and reduction of the activation energy barriers for the thermionic emission of electrons at the doped-contact/channel junctions (Figure 3d). In addition to $I_{on}$ and $I_{min}$, the ambipolar hole leakage current at large negative voltages is also enhanced at the higher doping level, once again, due to the decrease in the band-to-band tunneling barriers.

The results above suggest that for $d \sim 1.6 \text{ nm}$ and band gap $E_g \sim 0.55$ eV SWNTs, a moderate doping level for the n$^+$ S/D regions is optimum for high performance nanotube n-MOSFET with $I_{on} \sim 8 \mu A$, $S \sim 70 \text{ mV/decade}$, small leakage current ($I_{on}/I_{off} \sim 10^6$), and little ambipolar conduction. Comparing to our best p-type SWNT FETs, the current n-FET is better in lower off-state and less ambipolar conduction (due to the MOSFET geometry and smaller tube diameter) but lower in on-current due to the series resistance in the S/D nanotube segments and nonideal n-type contacts at this doping level. Careful attention must be paid in controlling the chemically doped S/D contacts for carbon nanotube MOSFETs in order to balance $I_{on}$ and $I_{on}/I_{off}$. This is in contrast to the Si MOSFETs where band-to-band tunneling is not significant and the leakage currents are mostly independent of the S/D doping profiles, at least in the $>100 \text{ nm}$ length scales. The enhanced band-to-band tunneling in nanotube devices is attributed to smaller energy band gaps, smaller effective carrier mass, and symmetric conduction and valance band states. Potentially, larger band gap (smaller diameter) nanotubes can be integrated as the active device components in order to allow for lower band-to-band leakage currents even at very high contact doping levels, enabling higher on-state currents and lower leakage currents.

We note that the n-channel on-state conductance of the nanotube FET with highly n-doped contacts exhibits little temperature dependence from 300 to 10 K and oscillations in $I_{on}/V_{gs}$ at low temperatures due to quantum interference effects (Figure 3c). This confirms the absence of thermionic current to the conduction band of SWNTs at the Pd/n$^+$ SWNT contacts for the heavy K-doping case (with high $I_{on} \sim 20 \mu A$). The SB height between a conventional semiconductor (e.g., Si) and a metal is relatively insensitive to doping level in the semiconductor due to Fermi level pinning by surface states. Ohmic contacts to a conventional semiconductor are obtained by heavy doping to afford ultrathin SB
For nanotubes with diameter ~1.6 nm and band gap ~0.55 eV, we obtain n-MOSFET exhibiting high on-currents, subthreshold swings of 70 mV/decade, small ambipolar conduction and high on/off ratios up to $10^6$ at a drive voltage of 0.5 V. The results compare favorably with the state-of-the-art silicon n-MOSFETs and demonstrate the potential of SWNTs for future complementary electronics.

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**References**


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