

High Performance Silicon Nanowire Field Effect Transistors

Yi Cui,[†] Zhaohui Zhong,[†] Deli Wang,[†] Wayne U. Wang,[†] and Charles M. Lieber^{*,†,‡}

Department of Chemistry and Chemical Biology, and Division of Engineering and Applied Science, Harvard University, Cambridge, Massachusetts 02138

Received November 1, 2002

ABSTRACT

Silicon nanowires can be prepared with single-crystal structures, diameters as small as several nanometers and controllable hole and electron doping, and thus represent powerful building blocks for nanoelectronics devices such as field effect transistors. To explore the potential limits of silicon nanowire transistors, we have examined the influence of source-drain contact thermal annealing and surface passivation on key transistor properties. Thermal annealing and passivation of oxide defects using chemical modification were found to increase the average transconductance from 45 to 800 nS and average mobility from 30 to 560 cm²/V·s with peak values of 2000 nS and 1350 cm²/V·s, respectively. The comparison of these results and other key parameters with state-of-the-art planar silicon devices shows substantial advantages for silicon nanowires. The uses of nanowires as building blocks for future nanoelectronics are discussed.

Semiconductor nanowires (NWs)^{1–6} and carbon nanotubes (NTs)^{7–12} are attractive components for future nanoelectronics since they can exhibit a range of device function and at the same time serve as bridging wires that connect to larger scale metallization. For example, field effect transistors (FETs) have been configured from NWs^{1,3,4} and NTs^{7–11} by depositing the nanomaterial on an insulating substrate surface, making source and drain contacts to the NW or NT ends, and then configuring either a bottom or top gate electrode (Figure 1). This basic approach may serve as the basis for hybrid electronic systems consisting of nanoscale building blocks integrated with more complex planar silicon circuitry, although a number of issues including device performance, reproducibility, and integration will have to be addressed in order to realize such systems in the future.

In the case of NT FETs, considerable effort has been placed on improving key device parameters such as the carrier mobility and transconductance. For example, recent studies reported by Avouris and others^{9–12} have shown that the measured carrier mobility can be increased significantly by contact thermal annealing. The fact that NT samples consist of mixtures of semiconducting and metallic building blocks could, however, represent a hurdle to future developments in nanoelectronics.¹³ On the other hand, silicon nanowires (SiNWs) are always semiconducting, and the dopant type and concentration can be controlled during synthesis.¹ SiNW building blocks may also be more readily integrated into silicon industry processing and fabrication

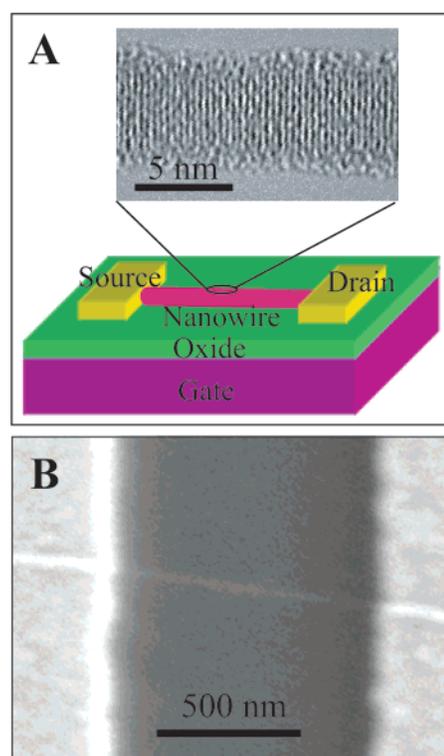


Figure 1. (A) Schematic of a SiNW FET showing metal source and drain electrodes with the NW and contacts on the surface of SiO₂/Si substrate. (inset) High-resolution transmission electron micrograph of a 5 nm diameter SiNW; the scale bar is 5 nm. (B) Scanning electron micrograph of a SiNW FET device; the scale bar is 500 nm.

than NTs,¹⁴ and thus might reduce barriers to the creation of hybrid structures.

* Corresponding author. E-mail: cml@cmliris.harvard.edu

[†] Department of Chemistry and Chemical Biology.

[‡] Division of Engineering and Applied Science.

Initial transport studies of SiNW FETs showed relatively low transconductance and carrier mobility ($\sim 0.01 \text{ cm}^2/\text{V s}$).¹ Subsequent investigations of SiNW transistor characteristics in a crossed NW FET configuration⁴ indicated that the initial low transconductance and mobility values were due in part to poor contacts between the SiNWs and source-drain electrodes and are not intrinsic to the single-crystal NW building blocks (inset, Figure 1A). In this letter, we explore the limits of SiNW FETs by examining the influence of source-drain contact annealing and surface passivation on key transistor properties. Thermal annealing and passivation of oxide defects by chemical modification were found to increase the average transconductance from 45 to 800 nS and average mobility from 30 to 560 $\text{cm}^2/\text{V}\cdot\text{s}$ with peak values from 2000 nS and 1350 $\text{cm}^2/\text{V}\cdot\text{s}$, respectively. Comparison of these results and other key parameters with state-of-the-art planar silicon devices shows substantial advantages for the SiNWs as building blocks.

The SiNWs used in these studies are boron-doped (p-type), 10–20 nm diameter single-crystal structures, prepared by a nanocluster-mediated growth method described previously.¹⁵ The SiNWs were deposited onto oxidized silicon substrates (600 nm thermal oxide) from ethanol suspension. Electrical contacts to the SiNWs were made by defining source-drain electrodes separated by 800–2000 nm with electron-beam lithography and subsequent evaporation of 50 nm Ti and 50 nm Au. Rapid thermal annealing was carried out at 300–600 °C for 3 min in the forming gas (10% H_2 in He) to improve the contact and passivate Si– SiO_x interface traps.¹⁴ A typical SiNW device is shown in Figure 1B. Electrical transport measurements were performed in the air.

Source-drain contacts to SiNW FETs were made using Ti metal, and transport characteristics were studied as a function of annealing. In general, metal–silicon contacts have been well studied,^{14,16,17} and it is known that Ti can form a stable conducting silicide with a low Schottky barrier height on p-type silicon.^{16,17} Figure 2A shows the current (I) versus source-drain voltage (V_{sd}) behavior of a typical Ti-contacted SiNW device before and after thermal annealing. The I – V_{sd} curves become more linear and symmetric, the conductance increases 3-fold, and the transport behavior becomes more stable after annealing. To characterize the reproducibility of these observations, we have made similar measurements on over 50 devices. These results are summarized in a histogram showing the frequency that different values of two-terminal resistance were observed (Figure 2B). Before annealing, the resistance shows a large distribution ranging from $< \text{M}\Omega$ to $> \text{G}\Omega$ with an average of 160 $\text{M}\Omega$. In contrast, the resistance after annealing has a narrower distribution of 0.1 to 10 $\text{M}\Omega$ with an average of 0.62 $\text{M}\Omega$; that is, a 260 \times improvement in the two-terminal conductance. The increased two-terminal conductance and stability can be attributed in part to better metal–SiNW contacts, although passivation of defects at Si– SiO_x interface, which can occur during annealing,¹⁴ may also contribute to the observed enhancements.

We have also investigated how chemical passivation of the SiO_x shell surrounding the single-crystal SiNW cores affects transport behavior (Figure 3A), since the Si/ SiO_x

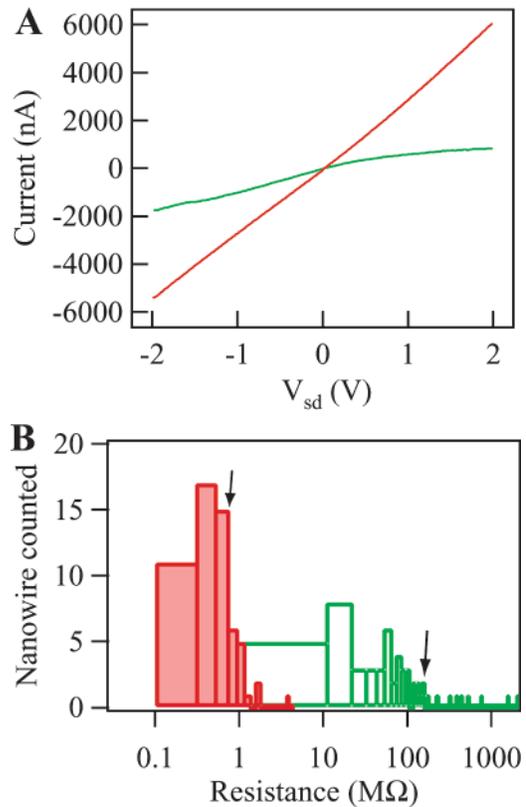


Figure 2. (A) I vs V_{sd} measured on the same SiNW before (green) and after (red) thermal annealing. (B) Histogram of Ti-contacted SiNW resistance determined from measurements before (open green bars) and after (filled red bars) contact annealing. The arrows mark the average resistance values for the two distributions.

interface and SiO_x surface defects could compensate the applied gate voltage and trap and scatter carriers.¹⁴ Surface modification was carried out by reaction with 4-nitrophenyl octadecanoate. This specific reagent was chosen since it will lead to a stable and relatively nonpolar Si–O–C ester linkage.^{19,20} Conductance (I/V_{sd}) versus backgate voltage (V_g) measurements were carried out before and after modification to assess clearly the effect of surface chemistry on characteristics of a specific SiNW FET.

In a typical device (Figure 3B), the conductance responds weakly to V_g before modification. In contrast, the conductance is extremely sensitive to V_g after modification and can be shut off at $V_g \sim 2.5 \text{ V}$ with an on/off ratio over 4 orders of magnitude. The transconductance after modification is an order of magnitude larger than before modification. Using a cylinder on an infinite plate model,¹ we estimate a hole mobility of 1000 $\text{cm}^2/\text{V}\cdot\text{s}$. This mobility is substantially larger than obtained in conventional Si devices. To assess the reproducibility of this surface chemistry and corresponding dramatic improvements in device behavior, we carried out experiments on a number of distinct SiNW devices. The summary of these results (Figure 3C and D) shows that transconductance and mobility increase an order of magnitude after modification. Significantly, the highest and the average hole mobility values of 1350 and 560 $\text{cm}^2/\text{V}\cdot\text{s}$ in p-SiNWs are more than an order of magnitude larger than the value for bulk Si, $\sim 40 \text{ cm}^2/\text{V}\cdot\text{s}$, at a comparable effective

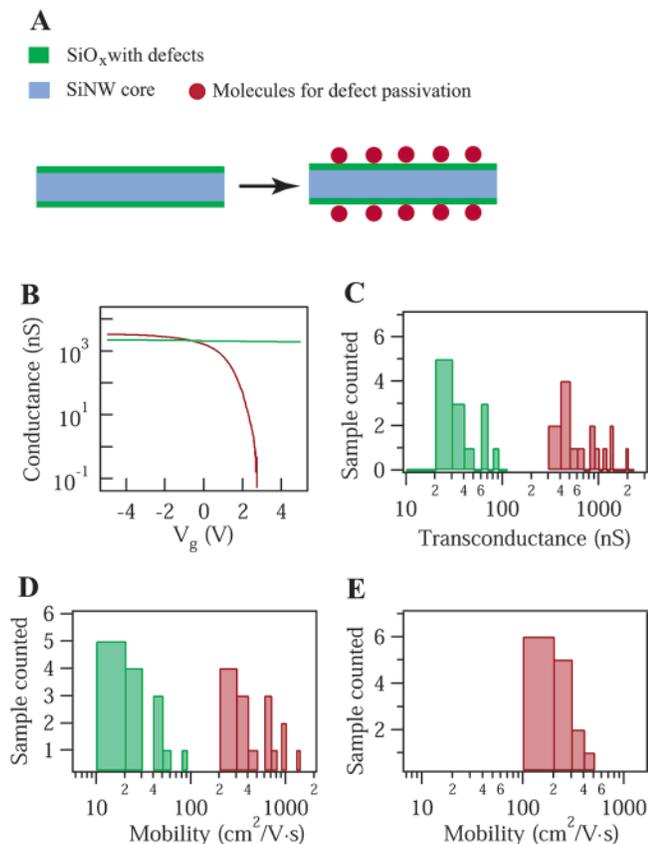


Figure 3. (A) Schematic illustrating surface defect passivation. (B) Conductance vs V_g measured on the same SiNW before and after 4-nitrophenyl octadecanoate modification. Histograms of SiNW transconductance (C) and mobility (D) before and after 4-nitrophenyl octadecanoate modification. (E) Histogram of SiNW mobility values after modification with tetraethylammonium bromide. In plots (B) to (E), the green (red) color designates before (after) surface modification.

doping concentration.¹⁶ The higher mobilities observed in our SiNW devices may arise from improved structural perfection and cylindrical morphology, although additional studies are needed to address unambiguously this point. We also note that these SiNW values are not upper bounds since contacts and surface passivation have not been optimized.

To obtain additional information about the origin of these passivation results, we have carried out other experiments. First, the effect of chain length on characteristics of SiNW FETs was investigated. Immediately after modification, 18-carbon and 6-carbon chains gave similar transport results, although the lifetime of the observed improvement was >1 week and 1 day, respectively. These results suggest that accessibility of the surface to water hydrolysis may control stability of the passivation, and moreover, that the passivation of polar surface sites, such as SiO^- , is important to the observed improved transport behavior. Second, and to test this idea, we have modified SiNW surfaces with tetraethylammonium bromide solutions. Significantly, tetraethylammonium-modified NWs also show the significant increases in the transconductance and mobility (Figure 3E).

In addition, it is worth noting that our SiNW FETs are structurally and chemically analogous to the silicon-on-insulator (SOI) structures being developed for future genera-

Table 1. Comparison of the Key Device Parameters between Si Nanowire and SOI FET

	nanowire raw data	nanowire ²² covered data	planar Si device ²¹
gate length (nm)	800–2000	50	50
gate oxide thickness (nm)	600	1.5	1.5
mobility ($\text{cm}^2/\text{V}\cdot\text{s}$)	230–1350	230–1350	
I_{on} ($\mu\text{A}/\mu\text{m}$)	50–200	2000–5600	650
I_{off} ($\text{nA}/\mu\text{m}$)	2–50	4–45	9
subthreshold slope (mV/decade)	174–609	60	70
transconductance ($\mu\text{S}/\mu\text{m}$)	17–100	2700–7500	650

tion microelectronics.²¹ To explore this analogy in quantitative terms, we have compared key characteristics of SiNW FETs with state-of-the-art planar metal-oxide-semiconductor FETs (MOSFETs) fabricated using SOI²¹ (Table 1). First, the hole mobility, which is ca. independent of device size, is an order magnitude larger than that in planar Si devices with comparable dopant concentrations. Since the mobility determines how fast charge carriers move in the conducting channel, it is one key parameter affecting the raw device speed. Ignoring other factors, our mobility implies that terahertz operation could be achieved in a ~ 2000 nm SiNW FET.

For direct comparison of other key parameters, the SiNW FET results have been scaled²² using the SOI FET gate length of 50 nm and gate oxide thickness of 1.5 nm. Significantly, the scaled on-state current (I_{on}) for the SiNW FET is larger than state-of-the-art Si FETs, and moreover the average subthreshold slope approaches the theoretical limit¹⁶ and the average transconductance is ca. 10 times larger. These improvements could lead to substantial benefits for high-speed and high-gain devices. The SiNW FET devices also have larger leakage currents, but this issue could be addressed by implementing pn-diodes at the source and drain contacts as in conventional MOSFETs. This comparison suggests that efforts to make smaller SiNW FETs and explicitly test scaling predictions could have an important impact in the future.

In conclusion, we have performed studies addressing the limits of p-type SiNW FETs. Source-drain contact thermal annealing and surface passivation were found to improve significantly the FET performance with increases in the average transconductance from 45 to 800 nS and average mobility from 30 to 560 $\text{cm}^2/\text{V}\cdot\text{s}$, with peak values of 2000 nS and 1350 $\text{cm}^2/\text{V}\cdot\text{s}$, respectively. In addition, comparison of scaled SiNW FET transport parameters with those for state-of-the-art planar MOSFETs show that SiNWs have the potential to exceed substantially conventional devices, and thus could be ideal building blocks for future nanoelectronics.

Acknowledgment. We thank H. Park and L. Lauhon for helpful discussion. C.M.L. acknowledges the Defense Advanced Research Projects Agency for generous support of this work.

References

- (1) Cui, Y.; Duan, X.; Hu, J.; Lieber, C. M. *J. Phys. Chem. B* **2000**, *104*, 5213.

- (2) Cui, Y.; Lieber, C. M. *Science* **2000**, *291*, 891.
- (3) Duan, X.; Huang, Y.; Cui, Y.; Wang, J.; Lieber, C. M. *Nature* **2000**, *409*, 66.
- (4) Huang, Y.; Duan, X.; Cui, Y.; Lathon, L. J.; Kim, K.-H.; Lieber, C. M. *Science* **2001**, *294*, 1313.
- (5) Huang, Y.; Duan, X.; Cui, Y.; Lieber, C. M. *Nano Lett.* **2002**, *2*, 101.
- (6) Duan, X.; Huang, Y.; Lieber, C. M. *Nano Lett.* **2002**, *2*, 487.
- (7) Tans, S.; Verschueren, A.; Dekker, C. *Nature (London)* **1998**, *393*, 49.
- (8) Martel, R.; Schmidt, T.; Shea, H. R.; Hertel, T.; Avouris, Ph. *Appl. Phys. Lett.* **1998**, *73*, 2447.
- (9) Wind, S. J.; Appenzeller, J.; Martel, R.; Derycke, V.; Avouris, Ph. *Appl. Phys. Lett.* **2002**, *80*, 3817.
- (10) Derycke, V.; Martel, R.; Appenzeller, J.; Avouris, Ph. *Nano Lett.* **2001**, *1*, 453.
- (11) Martel, R.; Derycke, V.; Lavoie, C.; Appenzeller, J.; Chan, K. K.; Tersoff, J.; Avouris, Ph. *Phys. Rev. Lett.* **2001**, *87*, 256805.
- (12) Rosenblatt, S.; Yaish, Y.; Park, J.; Gore, J.; Sazonova, V.; McEuen, P. L. *Nano Lett.* **2002**, *28*, 869.
- (13) Lieber, C. M. *Sci. Am.* **2001**, *285*, 50.
- (14) Wolf, S.; Tauber, R. N. *Silicon Processing for the VLSI Era*; Lattice Press: Sunset Beach, CA, 1986; Vols. 1, 2 .
- (15) Cui, Y.; Lathon, L. J.; Gudiksen, M. S.; Wang, J.; Lieber, C. M. *Appl. Phys. Lett.* **2001**, *78*, 2214.
- (16) Sze, S. M. *Physics of Semiconductor Devices*; John Wiley & Sons: New York, 1981.
- (17) Gambino, J. P.; Colgan, E. G. *Mater. Chem. Phys.* **1998**, *52*, 99.
- (18) SiNW surfaces were cleaned in O₂ plasma (20 W, 60 s, 0.4 Torr O₂) followed by reaction in (a) the pyridine solution with 0.5 mg/mL (dimethylamino)pyridine (Aldrich) and 1 mg/mL 4-nitrophenyl octadecanoate (or 4-nitrophenyl hexanoate, Aldrich) for 6 h, or (b) 1 M tetraethylammonium bromide (Aldrich) aqueous solution for 30 min. The devices were then rinsed and dried with nitrogen gas.
- (19) Iler, R. K. *The Chemistry of Silica*; Wiley: New York, 1979.
- (20) Scriven, E. F. V. *Chem. Soc. Rev.* **1983**, *13*, 129.
- (21) Chau, R. *Proc. IEDM* **2001**, 621.
- (22) The measured SiNW FET values (column 2) were scaled to the dimensions of a state-of-the-art MOSFET²¹ (column 4) assuming the contact resistance is much smaller than the channel resistance and the resistance of channel is proportional to length, and calculating the capacitance based on the cylinder on infinite plate model¹ and the current per unit width using a NW diameter 20 nm. Calculations do not account for interface trap states, and thus it should be possible to increase the transconductance further.

NL025875L