Support Information for

Direct Mechano-Sliding Transfer of Chemical Vapor Deposition Grown Silicon Nanowires for Nanoscale Electronic Devices

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I. Nanowire Growth

The growth procedure of silicon nanowires (SiNWs) has been described elsewhere in detail previously¹⁻³. Silicon wafers with a 1000 nm-thick oxide layer and gold nanoparticles (AuNPs) of 20 nm diameter (Ted Pella) (Fig. S1a) were used as grown substrates and catalysts of SiNWs in chemical vapor deposition (CVD) system (Fig. S1d). The wafers were incised to be 8 mm \times 3 mm for the CVD growth and then further incised to be 2 mm \times 3 mm for DMST. The CVD growth used 1.8 sccm disilane (Matheson Gas Products, 99.998% Purity) as the reactant source and 0.3 sccm diborane (100 ppm, diluted in H₂) as the p-type dopant in 6.5 sccm H₂ as the carrier gas to synthesize Boron-doped p-type SiNWs at 460 °C for 25 min. After the growth, above gas sources were closed and 30 sccm Ar was used to cool CVD system for 1 h. Then the high-quality SiNWs (Fig. S1b, c) were obtained for the nanowire-transfer process and device fabrication.

II. Device Fabrication

Silicon wafers with a 1000 nm-thick oxide layer were incised to 15 mm \times 17 mm substrates and immersed in a sulfuric acid solution (30% H₂O₂:99.8% H₂SO₄, 3:7) at 110°C for 4 h, then cleaned in ultrapure water using ultrasonic for 15 min and dried with nitrogen. The marks to define the region for the SiNW transfer were fabricated on the cleaned substrates to obtain receptor substrates. The receptor substrates with wellaligned SiNWs on the surface were obtained by direct mechano-sliding transfer (DMST). Subsequently, region-protecting photolithography and ultrasonication were used to remove the redundant SiNWs and defined area for electrodes patterning. Then a standard photolithographic process (UV Exposure machine, BG-401A, China Electronics Technology Group Corporation) was implemented to open the pattern window for metal electrodes deposition, which consist of 8 nm Cr followed by 80 nm Au through thermal evaporation (ZHD-300, Beijing Technol Science). Before the electrode deposition, the oxide shell of the SiNWs in electrode pattern regions was removed by a buffered HF solution (40% NH₄F: 40% HF, 7:1) to form Ohmic contacts with metal electrodes. After the electrode deposition, 60 nm SiO_2 was deposited to form a protective layer for surface passivation and solution current screening through electron beam thermal evaporation (TEMD-600, Beijing Technol Science). Finally, photoresist lift-off was carried out through rinsing silicon wafers by plenty of acetone to obtain SiNW-based field-effect transistors (FETs) (Fig. S2c).

III. Surface Functionalization

Surface functionalized single-nanowire devices were prepared by cleaning and hydroxyl activating in oxygen plasma (15 Pa, 50 W for 30 s) and then immersing in 1% ethanol solution of 3-aminopropyltriethoxysilane (APTES) (Aladdin, 99%) for 30 min and rinsing for 1 min with ethanol dried by nitrogen, followed by baking at 120°C for 5 min (Fig. S3a). To prove the successful modification of the APTES on the SiNWs, we used a naked silicon wafer to follow the same method. In comparison with the Xray photoelectron spectroscopy (XPS) spectra on a bare silicon surface (Fig. S3b, grey), there is a clear indication of the emergence of a N1s peak after the APTES modification. As shown in Fig. S2b, the newly-formed N1s peak (Fig. S3b, black) with the binding energy of 399.8 eV are characteristic of nitrogen in -NH2 group, which results from the surface reaction of the APTES. The hairpin DNA was purchased from Takara Biotechnology, with the base sequence of H2N-(CH2)3-5'-TGAGG A TGGA TAGA T GCTTG CCTCA-3'. After annealing at 90 °C in buffer, a hairpin configuration was formed through the hybridization of the five bases in both 5' and 3' ends. As for DNA functionalization (Fig. S3c), the APTES-modified devices were immediately immersed into a 5% phosphate buffer solution (10 mM Na₂HPO₄, 1.8 mM KH₂PO₄, 2.7 mM KCl, 140 mM NaCl, pH 7.4) of glutaraldehyde (Aladdin, 99%) for 1 h. After rinsing with the phosphate buffer solution and dried with nitrogen, 50 µL hairpin DNA solution (1 µM hairpin DNA in 10 mM phosphate buffer solution) was dropped on the device surface for 12 h at 4°C. Before the electrical measurements, the device was rinsed by the phosphate buffer solution for 5 min and dried with nitrogen. Then 50 µL phosphate buffer solution was dropped on the device to provide a liquid environment.

IV. Electrical Measurement

Electrical characterization of single- or multi-nanowire devices was conducted at room temperature in the ambient and under the air condition by using an Agilent 4155C semiconductor analyzer and a Karl Süss (PM5) manual probe station. A global back gate was adopted through applying gate voltage on heavily doped silicon substrates of devices. The transfer characteristic curves of the APTES-modified devices were measured in a liquid environment through dropping 50 µL phosphate buffer solution with different pH (10 mM phosphate buffers with 100 mM NaCl, the pH was adjusted by adding HCl or NaOH) on the device. The transfer characteristic curves of DNAmodified devices were measured in a liquid environment through dropping 50 µL phosphate buffer solution (10 mM Na₂HPO₄, 1.8 mM KH₂PO₄, 2.7 mM KCl, 140 mM NaCl, pH 7.4) on the device. Real-time electrical measurement was carried out on a probe station in the ambient and under the liquid condition of different pH solutions prepared by 10 mM phosphate buffers with 100 mM NaCl and flowed through a polydimethylsiloxane- (PDMS) based microfluidic channel (Fig. S4) at a flow rate of $20 \,\mu$ L/min. The PBS solutions with different pHs from 8.0 to 6.0 were injected into the PDMS-based microfluidic channel in sequence. Five sections of the 10 µL PBS solution with each pH were pre-introduced into the microfluidic tube for detection under each pH condition. As shown in Fig. S4b, each section of the solution was divided by tiny air bubbles to prevent the mixture of each section before injected into the PDMS-based microfluidic channel. HF2LI lock-in amplifier (Zurich Instruments) was used to hold source-drain voltage at 0.3 V and gate voltage at -0.1 V for attaining linear region of transfer curves. The real-time current was amplified by a DL1211 preamplifier working at 107 V/A gain and collecting data at 500 Hz bandwidth and 255 Hz sampling rate.



Fig. S1. Growth procedure of SiNWs. (a) 10 nm-diameter AuNPs dispersing on substrates as catalysts. (b) SEM image of SiNWs grown by Au-catalyzed CVD. (c) High-resolution TEM image of single-nanowire. (d) Illustration of the CVD system.



Fig. S2. Electrode fabrication. (a-c) Photomask used for mark, protection region and electrodes fabrication in lithography, respectively. (d) Optical image of a SiNW-FET device. (e) Different magnifications of the photomask design pattern for electrode fabrication. The zoomed image from the red rectangular regions is magnified to the following panel.



Fig. S3. Surface modification of SiNWs by APTES. (a) Schematic of the surface functionalization of the SiNWs by the APTES. (b) High-resolution N1s XPS spectra before (grey) and after (black) the APTES modification. A N1s peak with the binding energy of 399.8 eV (red) indicates the successful functionalization of -NH2. (c) Schematic of the surface functionalization of the SiNWs by DNA hairpin.



Fig. S4. The real-time pH sensing realized by a PDMS microfluidic channel. (a) Optical image of PDMS-based microfluidic channel. (b) Schematic of injection of PBS solutions with different pHs through a microfluidic tube. Five sections of the solution were pre-introduced into the microfluidic tube and divided by air bubbles to avoid the solution mixture.

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