



Supporting Online Material for

**Three-Dimensional, Flexible Nanoscale Field-Effect Transistors as  
Localized Bioprobes**

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Published 13 August 2010, *Science* **329**, 830 (2010)  
DOI: 10.1126/science.1192033

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# Materials and Methods

## 1. Nanowire synthesis and characterization.

Single-crystalline nanowire probes were synthesized by a recently reported modulated nanocluster-catalysed VLS method (*S1*), where variations in pressure are used to introduce single-crystalline 120° kinks at well-defined points during growth. In a typical synthesis of uniform n-type 60° silicon nanowire probes, the total pressure was 40 torr and the flow rates of SiH<sub>4</sub>, PH<sub>3</sub> and H<sub>2</sub> were 1, 5 and 60 standard cubic centimetres per minute (sccm), respectively. Kinks were introduced by evacuation of the reactor ( $\sim 3 \times 10^{-3}$  torr) for 15 s, with a 20 s growth time between the two cis-linked kinks. Dopant modulated silicon nanowire probes were prepared by varying the silicon–phosphorus feed-in ratios at 200:1 and 10,000:1 for n<sup>+</sup>- and n-type segments, respectively (*S1*); the n-type active channel segment was grown for 30 s immediately following the second evacuation step. The nanowire probe structures were characterized with Zeiss Ultra55/Supra55VP field-emission SEMs and a JEOL 2010 field-emission TEM.

## 2. Device fabrication.

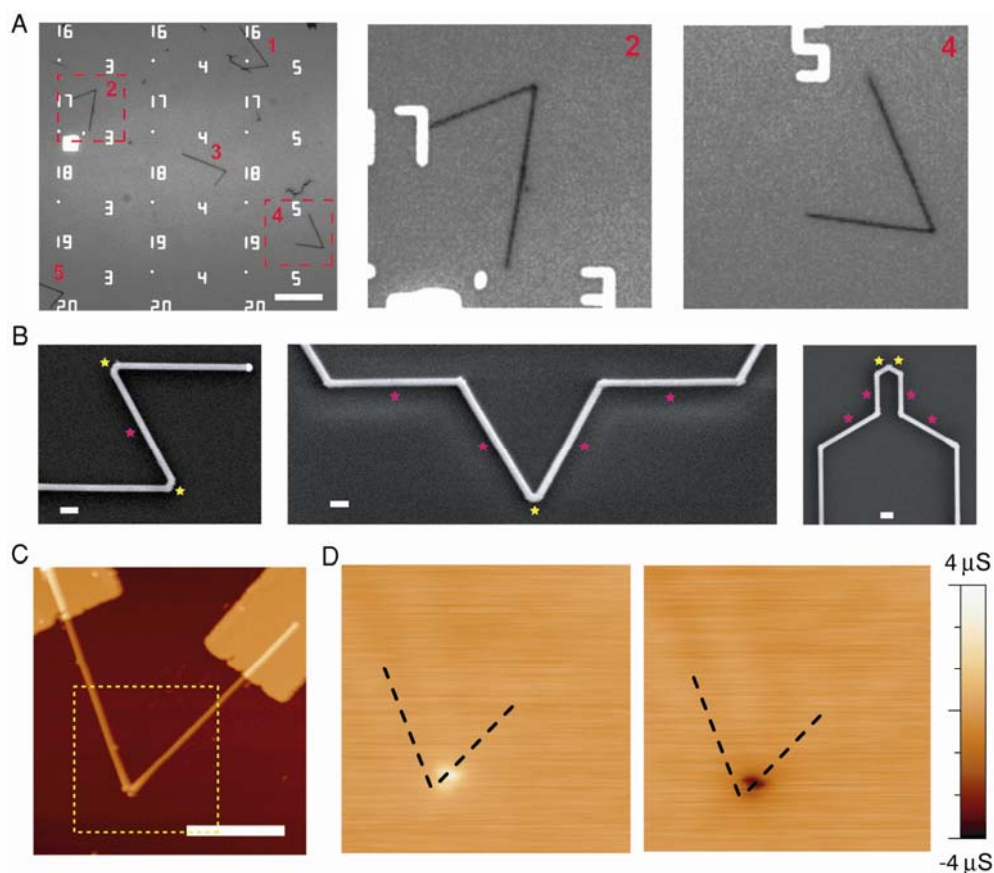
Devices were fabricated on silicon substrates (Nova Electronic Materials, n-type 0.005 V cm) with 100 nm thermal SiO<sub>2</sub> and 200nm Si<sub>3</sub>N<sub>4</sub> at the surface as described in **Fig. S3A**. Briefly, a poly(methyl methacrylate) (PMMA) layer was first patterned by electron-beam lithography (EBL) to form a relief layer. Nanoscale FET probe devices were fabricated by EBL with Cr/Pd/Cr metal interconnects after deposition of the synthesized nanowires from an isopropyl alcohol dispersion. The kinked nanowire probe devices were released by removal of the PMMA layer, and the built in stress in the interconnects yielded a predictable height and angle of the probe with respect to the substrate surface plane.

### 3. Cellular recordings.

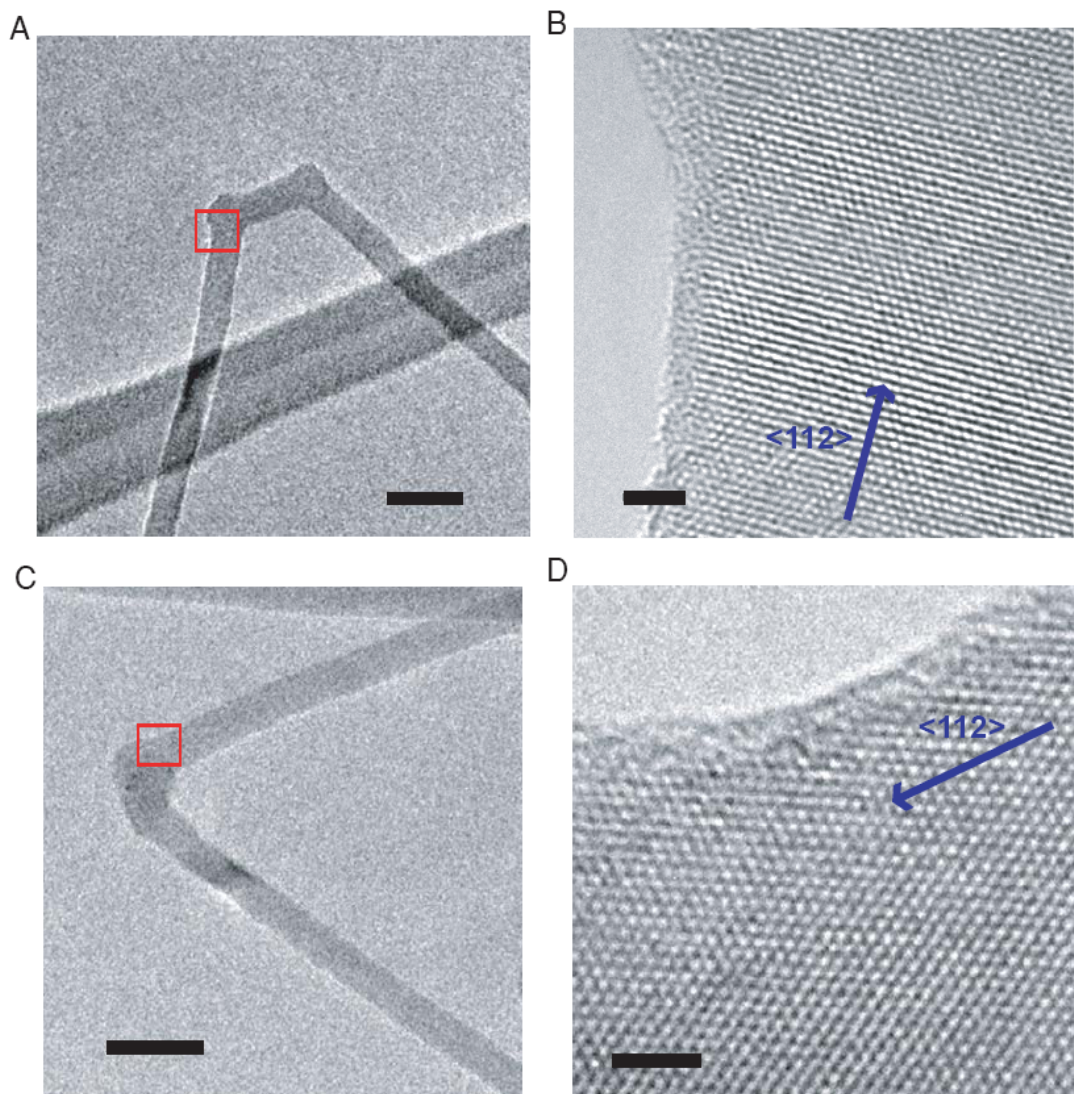
HL-1 cells and embryonic chicken cardiomyocytes were cultured using published protocols (*S2,S3*). Device chips were cleaned with O<sub>2</sub> plasma (50 sccm of O<sub>2</sub>, 50 w, 0.5 Torr, 1 min) and the nanowire surfaces were then modified by vesicle fusion (*S4*), where vesicles were formed using 1,2-dimyristoyl-sn-glycero-3-phosphocholine (DMPC, Avanti Polar Lipids Inc) containing 1% 1-myristoyl-2-{12-[(7-nitro-2-1,3-benzoxadiazol-4-yl) amino] dodecanoyl}-sn-glycero-3-phosphocholine (NBD-lipid, Avanti Polar Lipids Inc) as a fluorescent reporter. The detailed procedure for nanowire phospholipids modification is as follows: (1) Dissolve 100 mg of lipids powder in 20 ml of chloroform. (2) The solution is desiccated in N<sub>2</sub> flow and stored under vacuum overnight. (3) Add deionized water into the dried lipid (0.5 ml water per 1 mg of lipid), and at least 2 h is allowed for hydration. (4) Five cycles of freezing (in liquid nitrogen) and thawing (in water bath at 50 °C) are applied to the lipid suspensions. (5) The vesicle suspensions are sonicated and filtered. (6) Add vesicle suspensions into device chamber half filled with buffer solution and wait for at least 0.5 h to allow nanowire surface modification with lipids. (7) Rinse nanowire devices with excess buffer solution to clean the loosely bound vesicles.

For potential calibration, the nanoFET or the probe tip sensitivity/transconductance was measured within an error of 3% using the global watergate experiments (Fig. S4A). Nanoscale FET recording and cell manipulation were carried out in Tyrode solution (pH ~ 7.3) with a 100 mV DC source voltage (*S3*) at 37 °C. The current was amplified with a home-built multi-channel current/voltage preamplifier, filtered with a 3kHz low pass filter (CyberAmp 380), and digitized at a 50 kHz sampling rate (Axon Digi1440A). Voltage clamp was performed with an Axopatch 200B (Molecular Device Systems) using glass pipettes pulled on a P-97

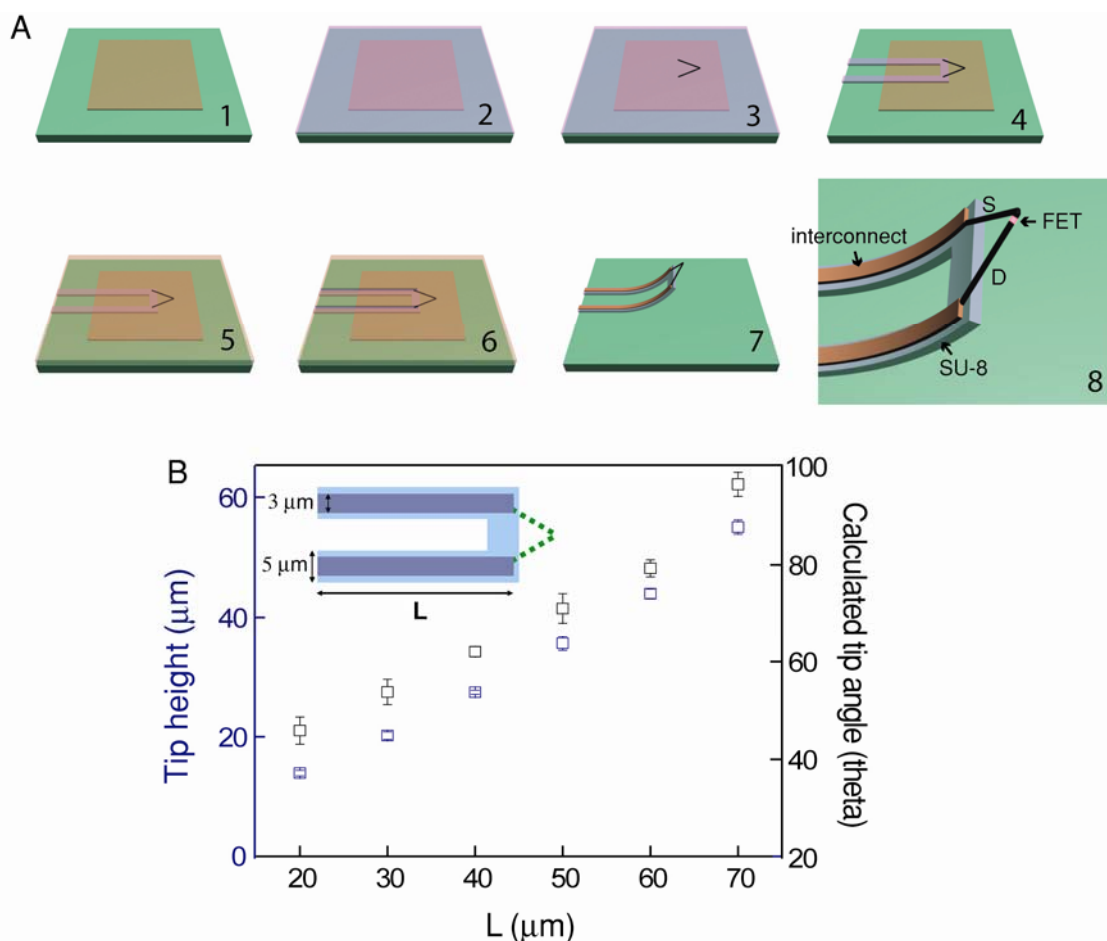
Flaming/Brown Micropipette Puller (Sutter Instruments). Ag/AgCl reference electrodes were used in all recording experiments.



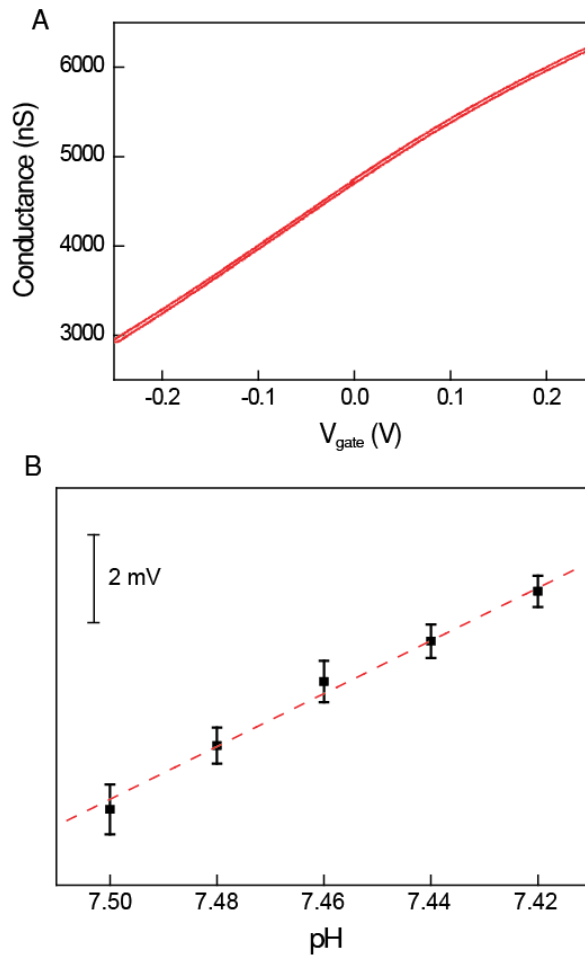
**Fig. S1. High yield kinked nanowire nanoprobe with integrated transistor elements.** **A**, Bright field optical microscope images. Five 80 nm, 60° kinked nanowires are registered within a 120×120 μm<sup>2</sup> region, which represents a typical starting nanowire density on device fabrication chips. The zoom-in images of #2 and #4 nanowires are shown in the middle and right panel, respectively. Scale bar, 20 μm. **B**, SEM images of complex kinked nanowire probes with double 60° junctions (left), 60° (middle) and 0° (right) kinked nanowires with extended arm configurations. The segments that connect *cis*-conformations (yellow stars) are all shorter than 250 nm, while those that have *trans*-conformations (magenta stars) are longer than 650 nm, consistent with the data shown in Fig. 1C, and demonstrate that conformation control is maintained in independent syntheses. Scale bars, 200 nm. **C** and **D** are atomic force microscopy (AFM) and scanning gate microscopy (SGM) images of a 60° kinked nanowire device, respectively. The scale bar in **C** is 2 μm. Measurements were carried out with a Digital Instruments Nanoscope IIIa AFM and metal-coated tips (Nanosensors, PPP-NCHPt). The SGM conductance maps were acquired in lift mode with lift height of 20 nm. The SGM images were recorded with a  $V_{\text{tip}}$  of +10 V (**D**, left) and -10 V (**D**, right), respectively, and  $V_{\text{sd}}$  of 0.5 V. The dark and bright regions correspond to reduced and enhanced conductance, respectively. The SGM data demonstrate the successful synthetic integration of an n-type field effect transistor (FET) immediately adjacent to the 60° probe tip, where the length of the active region of the FET is ~200 nm.



**Fig. S2. TEM images of ultrathin 60° nanowire probes.** The segment lengths between adjacent 120° *cis*-kinks in **A** and **C** are ~50 nm and ~15 nm, respectively. **B** and **D** are high-resolution TEM (HRTEM) images recorded in the red square regions of single 120° kinks marked in **a** and **c**, respectively. HRTEM images show that the nanowires are single crystalline and that their arms follow the <112> growth orientation (**B**, **D**, blue arrows), consistent with our previous report (*S1*). All TEM images were acquired with the electron beam perpendicular to the 2D plane of the kinked nanowires. Scale bars, 50 nm in **A** and **C**, and 2 nm in **B** and **D**.



**Fig. S3. 3D, flexible nanoscale FET probe fabrication.** **A**, Key fabrication steps include: (1) deposition and patterning of poly(methyl methacrylate) (PMMA, MicroChem Corp., Newton, MA) layer by electron-beam lithography (EBL); (2) deposition of SU-8 2000.5 (MicroChem Corp., Newton, MA) resist over the entire chip; (3) deposition of kinked nanowires from isopropanol solution; (4) EBL patterning and subsequent curing (180 °C, 20 min) of 300-400 nm SU-8 structure (pink) that will serve as flexible mechanical support for metal interconnects; (5) deposition and (6) EBL patterning of methyl methacrylate (MMA) and PMMA double layers resist; and finally, (7) sequential Cr/Pd/Cr (1.5/50-80/50-80 nm) metal thermal evaporation and plasma-enhanced chemical vapor deposition of 40-60 nm  $\text{Si}_3\text{N}_4$  interconnect passivation. The kinked nanowire probe devices are released from the (substrate) by removal of the initial PMMA layer during the lift-off process, where the built in stress in the Pd/Cr metal layers leads to predictable height and angle of the nanowire probe with respect to the substrate surface plane. The device tip is detailed in panel-8. **B**, Dependence of the tip height and angle versus the length of relieved metal. The measurements were done in PBS solution for metal layers with Cr/Pd/Cr thickness of 1.5/75/50 nm. Inset, schematic of the typical device geometry.



**Fig. S4. 3D nanoscale FET probe characterization in aqueous solution.** **A**, Conductance vs. water-gate voltage ( $V_{\text{gate}}$ ) measurement for a typical free-standing nanoprobe. The nanowire device sensitivity or transconductance, *i.e.* the slope of the linear fit, is  $6.8 \mu\text{S/V}$  at zero  $V_{\text{gate}}$  in PBS solution. The data was recorded with a 100 mV DC source voltage, and the current was amplified with a home-built multi-channel current/voltage preamplifier, filtered with a 3 kHz low pass signal conditioner (CyberAmp 380), and digitized at a 50 kHz sampling rate (Axon Digi1440A). We note that the sensitivity values measured from such global watergate experiments can directly be used for potential calibration of nanoFET probes in single cell recordings within an error of 3 %. **B**, Calibrated FET surface potential change vs. solution pH. The slope of the linear fit (red dashed line) yields a pH sensor response of  $59.7 \text{ mV/pH}$ . The sensitivity limit is  $\sim 0.02 \text{ pH}$ , with  $\text{S/N} > 1.3$ . The error bars denote  $\pm 1$  standard deviation. Data was recorded in a microfluidic channel as illustrated in Fig. 2D, inset. The pH sensing measurements were conducted using a lock-in amplifier with a modulation frequency of 79 Hz, time constant of 30 ms, amplitude of 30 mV; The DC source-drain potential is zero. A Ag/AgCl reference electrode was used in **A** and **B**.





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