

**Supporting Information for**

# **Large-Area, Ultrathin Metal-Oxide Semiconductor Nanoribbon Arrays Fabricated by Chemical Lift-Off Lithography**

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## Materials and Methods

**Materials:** Prime quality 4" Si{100} wafers (P/B, 0.001-0.005  $\Omega$ -cm, thickness 500  $\mu$ m ) were purchased from Silicon Valley Microelectronics, Inc. (Santa Clara, CA, USA). Sylgard 184® silicone elastomer kits (lot #0008823745) were purchased from Ellsworth Adhesives (Germantown, WI, USA). (7–8% Vinylmethylsiloxane)–(dimethylsiloxane) copolymer, platinum divinyltetramethyl-disiloxane complex in xylene, and (25–30% methylhydrosiloxane)–(dimethylsiloxane) copolymer were all purchased from Gelest Inc. (Morrisville, PA, USA) and used as received. 2,4,6,8-Tetramethyl-2,4,6,8-tetravinylcyclotetrasiloxane, indium(III) nitrate hydrate (99.999%), iron nitrate, thiourea, ammonium hydroxide, hydrogen peroxide, ethylenediaminetetraacetic acid disodium salt dihydrate (EDTA), and acetic acid were purchased from Sigma-Aldrich (St. Louis, MO, USA) and used as received. Commercially available HD-DVD-R recordable 1 $\times$  speed 15 GB blank discs and DVD-R recordable 16 $\times$  speed 4.7 GB blank discs (Memorex) were purchased and used as received. The SPR 700-1.2 photoresist and MF-26A developer were obtained from the Integrated Systems Nanofabrication Cleanroom (ISNC) at UCLA. Water was deionized before use (18.2 M $\Omega$  cm) using a Milli-Q system (Millipore, Billerica, MA).

**Substrate fabrication:** A 100 nm SiO<sub>2</sub> film was thermally grown on Si{100} wafers. If needed, SiO<sub>2</sub>/Si wafers are also available for purchase at Silicon Valley Microelectronics, Inc. (Santa Clara, CA, USA). Next, 10 nm Ti and 30 nm Au films were deposited onto In<sub>2</sub>O<sub>3</sub> films using a CHA solution electron-beam evaporator at high vacuum (10<sup>-8</sup> Torr) with an evaporation rate of 0.1 nm/s. The Au/Ti/In<sub>2</sub>O<sub>3</sub>/Si substrates were then annealed in a hydrogen flame for ~10 s to remove adsorbed organic contaminants on the Au surfaces. Substrates were then immersed into an ethanolic 1 mM 11-mercapto-1-undecanol solution overnight for self-assembled monolayer formation on Au surfaces.

**Preparation of HD-DVD and DVD masters:** Commercially available HD-DVD-R recordable 1× speed 15 GB blank discs and DVD-R recordable 16× speed 4.7 GB blank discs were used to produce masters for patterning. Both HD-DVD and DVD discs have similar structures and therefore the preparation processes are the same. The HD-DVD discs were cut into wedge-shaped pieces. A razor blade was used to separate the discs at the edges between Layer II and Layer III in **Figure 1a**, and jagged edges were removed. The transparent part of the discs with the dye (Layer III in **Figure 1a**) were then rinsed with ethanol to remove the dye from the surfaces. The slices were then put into a beaker of ethanol for 1-2 min. After that, they were blow dried under a N<sub>2</sub> flow.

**Hard PDMS (*h*-PDMS) stamps:** For soft PDMS, which should be prepared before starting the *h*-PDMS preparation process, a mixture of Sylgard® 184 elastomer base and curing agent (10:1) was thoroughly mixed and degassed in a vacuum desiccator. For *h*-PDMS, 3.4 g (7–8% vinylmethylsiloxane)–(dimethylsiloxane) copolymer, 18 µL of platinum divinyltetramethyldisiloxane complex in xylene, and 50 µL of 2,4,6,8-tetramethyl-2,4,6,8-tetravinylcyclotetrasiloxane were mixed and degassed for <5 min. Then 1 g of (25–30% methylhydrosiloxane)–(dimethylsiloxane) copolymer was added and mixed gently. The mixture was poured onto HD-DVD masters and spin-coated at 1000 rpm for 40 s. Stamps were annealed at 65 °C for 15 min. Soft PDMS was then poured onto the backsides of the *h*-PDMS stamps and annealed at 65 °C overnight.

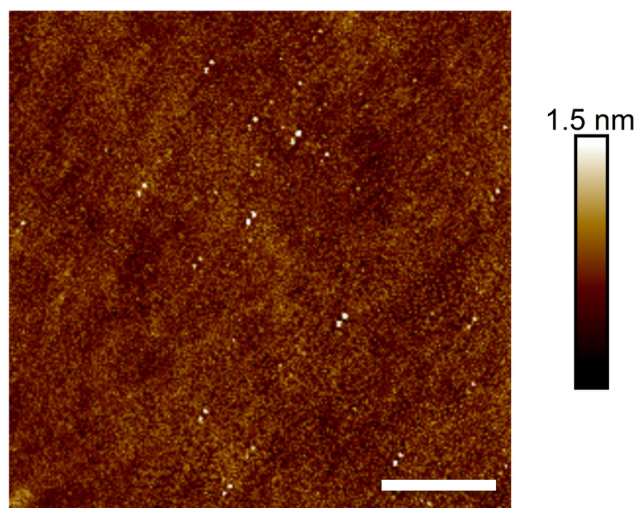
After the final curing step, stamps were slowly peeled away from masters and stored in clean petri dishes. Stamps were rinsed with ethanol and dried under N<sub>2</sub> flow before use. Clean PDMS stamps were treated in oxygen plasma (Harrick Plasma, Ithaca, NY, USA) for 40 s at a power of 18 W and a pressure of 10 psi to generate activated surfaces. A pair of tweezers was used to place PDMS stamps onto substrates without applying a vertical compression force. In the stamp removal

process, one pair of tweezers was used to hold the substrates and another pair was used to lift off the stamps.

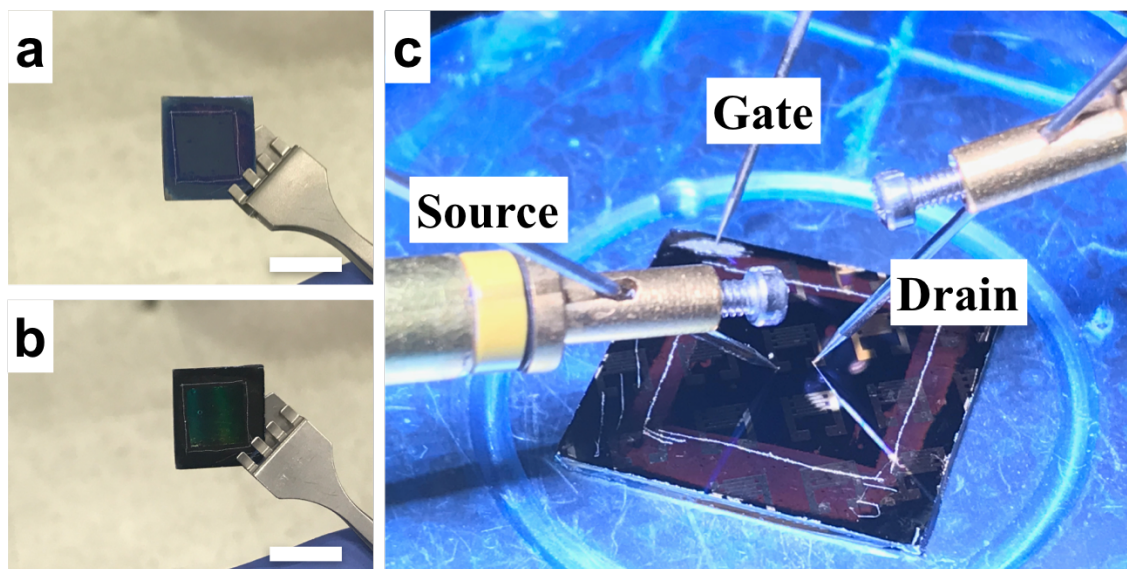
**Wet etching:** After PDMS stamp removal from SAM-functionalized substrates, each substrate was immersed into an aqueous solution of 20 mM iron nitrate and 30 mM thiourea to etch the Au films selectively. The etching rate was  $\sim 1$  nm/min and the samples were put into the etching solution for 30 min. Substrates were then rinsed with deionized (DI) water and dried under  $N_2$ . Substrates were immersed into a solution containing 0.42 g EDTA, 1 mL hydrogen peroxide, and 0.42 mL ammonia hydrate in 10 mL deionized water for  $\sim 3$  min to etch through the 10 nm Ti layer. The  $In_2O_3$  was then removed from the exposed areas by immersion in acetic acid for 10 min. Samples were annealed at 100 °C for 1 h after the wet etching process.

**Field-effect transistor device fabrication:** Interdigitated Au source and drain electrodes (45  $\mu m$  length, 1300  $\mu m$  width) were patterned on top of the  $In_2O_3$  nanoribbons to obtain uniform current distributions. Electrodes were patterned by standard photolithography. The 10 nm Ti and 30 nm Au films were deposited *via* a CHA solution e-beam evaporator at high vacuum ( $10^{-8}$  Torr) at an evaporation rate of 0.1 nm/s.

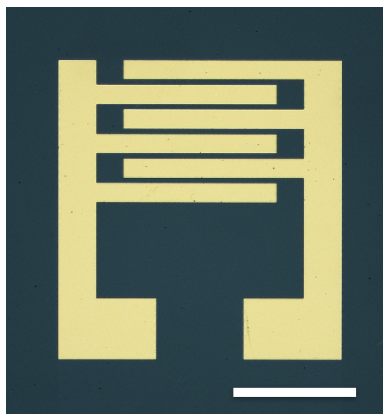
**Substrate characterization:** Scanning electron microscope (SEM) images were obtained using a Zeiss Supra 40VP scanning electron microscope with an Inlens SE Detector (Inlens secondary electron detector). Atomic force microscope (AFM) imaging was performed on a Bruker FastScan system (Bruker, Billerica, MA) under PeakForce tapping mode with a ScanAsyst-Air cantilevers (Bruker, spring constant =  $0.4 \pm 0.1$  N/m). Electronic performance measurements were carried out on a manual analytical probe station (Signatone, Gilroy, CA) equipped with a Keithley 4200A (Tektronix, Beaverton, OR) semiconductor parameter analyzer. Optical images were taken with a digital camera attached to a Zeiss Axiotech optical microscope.



**Figure S1.** Atomic force microscope image of In<sub>2</sub>O<sub>3</sub> films. The average roughness (Ra) is ~0.06 nm. The scale bar is 1 μm.



**Figure S2.** Images of the fabricated devices and test configuration. (a,b)  $\text{In}_2\text{O}_3$  nanoribbons on a  $1.5\text{ cm} \times 1.5\text{ cm}$  Si wafer. The  $1\text{ cm} \times 1\text{ cm}$  square region in the center contains the nanoribbons. The rainbow colors in the central region of the bottom image (b) indicate light interference from the periodic nanoribbon pattern. (c) Device test configuration using a probe station with bottom gate and top source/drain electrodes.



**Figure S3.** Photograph of a representative device with the interdigitated electrode configuration. The widths and lengths of the inter-digital electrodes are 1300 and 45  $\mu\text{m}$ , respectively. The scale bar is 1000  $\mu\text{m}$ .