Lithographically directed DNA assembly of carbon nanotubes for nanoelectronic applications

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Single wall carbon nanotubes (SWCNTs) combine nanometer size and outstanding electronic properties, making them prime candidates for future nanoelectronic applications. Dense arrays of aligned SWCNTs can be obtained by chemical vapor deposition, albeit without control over the tubes' electronic properties or position on a substrate. In recent years, solution based techniques have been developed to separate SWCNTs with different diameters and chiralities; however SWCNTs, whether grown on a surface or dispersed in solution, are notoriously difficult to organize into complex architectures, a key requirement for their exploitation in nanoelectronic applications. To address this issue we are developing approaches leading to the controlled and ordered arrangement of short SWCNT segments on lithographically patterned, chemically or energetically functionalized surfaces. In this work, we present a technique to direct the assembly of chirality-selected, DNA-wrapped SWCNT segments, with precise control over position and orientation. Single stranded DNA (ssDNA) wrapping enables efficient purification of single chirality-rich [primarily (6,5)], short SWCNT segments that are monodisperse in length[1,2]. Controlled placement of the SWCNT segments enables their integration with metal electrodes to form field-effect transistors at lithographically determined locations.

The process for directing the assembly of SWCNT segments is shown in Fig. 1. Electron-beam lithography combined with oxygen plasma treatment are used to pattern localized high surface energy (hydrophilic) regions on a low surface energy (hydrophobic) background [polyethylene glycol-(PEG)-passivated] substrate. Lines are patterned with lengths matching those of the SWCNT segments and widths varying from ~ 10 - 40 nm. The SWCNT segments are then allowed to assemble on the surface from an ionic buffer solution. The SWCNT segments selectively bind to the patterned hydrophilic regions as a function of the ionic strength of the buffer in which they are dispersed. By varying the width of the patterned lines, the binding yield of individual SWCNT segments can be optimized in a pattern-dependent manner (Fig. 2a and 2b). Notably, this approach can be used on both uniform surfaces and surfaces that have been pre-patterned with metal electrodes. In the case of unpatterned SiO_2 substrates, a PEG-silane is used; for substrates pre-patterned with Au electrodes, a mixed PEG-silane/PEG-thiol is used to simultaneously passivate the SiO_2 and the Au, respectively. Back-gated FETs (SiO_2 thickness: 300 nm) with source and drain electrodes deposited on top of single SWCNT segments demonstrate the switching behavior of semiconducting SWCNTs (Fig. 3a and 3b). The high resistance, hysteresis and shift of the threshold voltage in the source-drain current vs. gate voltage characteristics are probably due to the presence of the ssDNA wrapping the tube. Improved FET characteristics can be expected after removal of the DNA by annealing in an inert atmosphere.

In summary, we demonstrate how the combination of precise lithographic patterning and control over surface energy can be used to produce SWCNT FETs, with precise control over position and orientation. This approach is an important step towards the implementation of complex SWCNT-based devices and circuits.

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[1] Zheng, M. et al., *DNA-assisted dispersion and separation of carbon nanotubes,* Nature materials, 2003. 2(5): p.338-342.
[2] Zheng, M. et al., *DNA sequence motifs for structure-specific recognition and separation of carbon nanotubes,* Nature, 2009. 460: p.250-253.
[3] Zhang, L., et al., *Optical Characterizations and Electronic Devices of Nearly Pure (10,5) Single-Walled Carbon Nanotubes*, JACS 2009. 131: p.2454-2455.

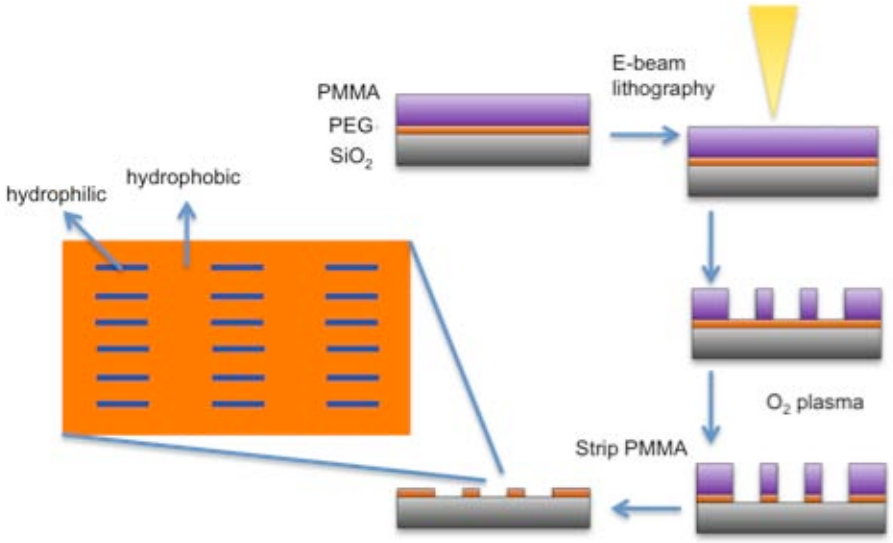

Figure 1. Schematic of the process for forming hydrophilic regions matching the SWCNT segment size.

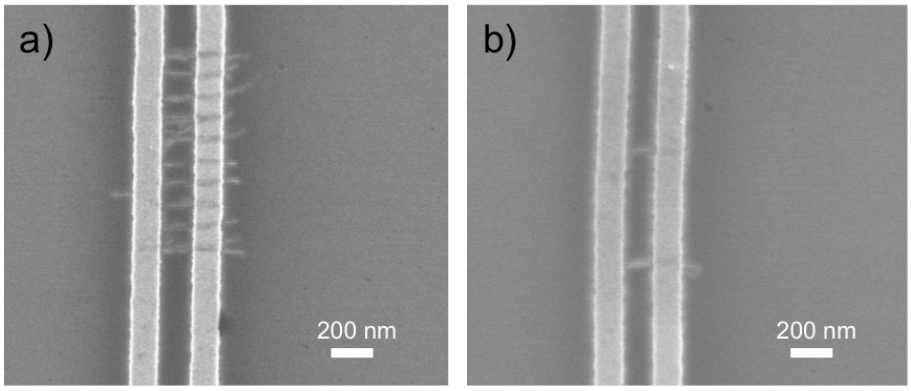

Figure 2. SEM images of directed assembly of SWCNT segments upon electrodes with spacings of (a) 100 nm and (b) 500 nm.

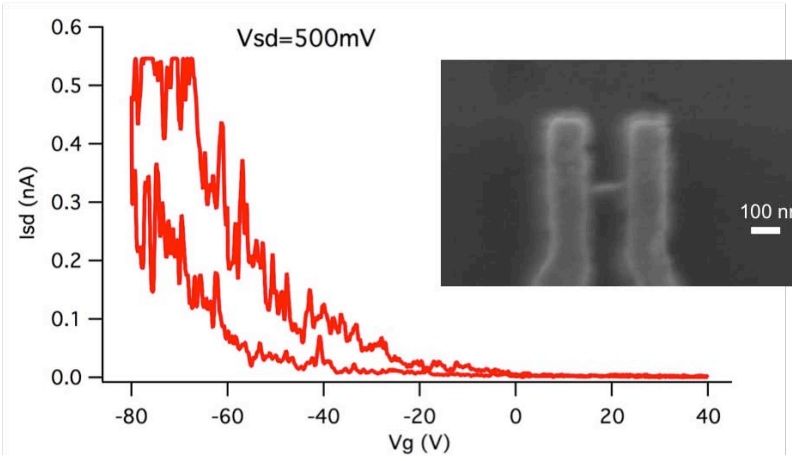

Figure 3. Source-drain current vs. gate voltage characteristics for a single SWCNT device (V_{sd}=500 mV). Inset: SEM image of the device. Electrodes are patterned on top of the SWCNT segment.