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# Characterization, Functionalization, and Assembly of Silicon Based Nanowires and their Applications in FETs and Sensor Devices
# 硅納米線表徵，功能化，組裝及其在場效應晶體管與傳感器中的應用

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# CHARACTERIZATION, FUNCTIONALIZATION, AND ASSEMBLY OF SILICON BASED NANOWIRES AND THEIR APPLICATIONS IN FETs AND SENSOR DEVICES

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# Abstract

Electronic devices are being in small sizes and of better performance. Yet, challenges come along since further miniaturization of devices require even higher precision technology and the traditional planar fabrication technology will soon reach its limit. One dimensional (1-D) nano-scale materials have brought possibilities for overcoming the difficulties and their potential to be applied in the electronic industry has created excitement all over the world. In this project, p-type and n-type silicon nanowires (SiNWs) were synthesized by electroless template method and thermal evaporation method respectively. To align the disordered nanowires, micro-fluidic system was used to assemble them to fabricate field effect transistors (FETs) based on SiNWs and silicon nanotubes (SiNTs), and gas sensor devices based on palladium (Pd) functionalized SiNWs.

Micro-channels with widths of 500μm, 200μm and 100μm were used in the micro-fluidic system. Micro-channels of smaller widths were observed to lead to better nanowire alignment. More than 90% nanowires and nanoribbons can be aligned to the same direction within ±5% degree when the channel width is down to 100μm. With this kind of technique, 2,5,8 11-tetra-(t-butyl)-perylene (TBP) nanowires, 9,10-Diphenyl anthracene (DPA) nanoribbons, SiNWs, SiNTs and zinc oxide (ZnO) nanowires were aligned successfully.

In order to investigate the properties of the SiNWs based FETs, template method was used to synthesis the p-type SiNWs by etching boron doped silicon wafers. The SiNW FETs shows an increase in the conductivity and higher saturation voltage with a more negative gate voltage. The P-type SiNWs have a hole mobility of 8.5 cm$^2$/V-s, and an on-off ratio about $10^4$ in air. The hole mobility increases one order to 76 $cm^2/V$-s in vacuum, with an on-off ratio larger than $10^4$.

SiNWs decorated by Pd nano-particles were used for hydrogen detection. The SiNWs were fabricated via a thermal evaporation method using Tin (Sn) catalyst. The as-grown SiNWs were chemically treated to remove surface oxide and then coated with a thin layer of Pd nano-particles. A gas sensor was fabricated with the Pd-functionalized SiNWs. The sensor showed better sensitivity to hydrogen and faster responding time than the macroscopic Pd metal wire hydrogen sensor.

Single-crystalline ZnS/Si core-shell nanowires have been synthesized via a two-step thermal evaporation method. The nanowires have uniform diameters of 80-200 nm with lengths range from several to several tens of micrometers. Single crystalline Si nanotubes can be obtained by chemical etching away the ZnS core from ZnS/Si structure. Investigation on FETs fabricated from the Si nanotube suggests that the non-doped Si tube shows weak n-type semiconductor properties, induced by point defects and surface states.

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Figure 5.5 (a) Real time current response of pure SiNWs in 5% $H_2$. The inset shows schematic diagram of the device, and the chamber used in experiments. (b) Current response of Au coated SiNWs in 5% $H_2$ and Pd coated SiNWs in 5% $NH_3$ and $N_2O$. (c) Real time current response of Pd-coated SiNWs in 5% H2. The inset images show the enlarged current response (upper) and a SEM image (below) of the device.

Figure 6.1 (a) An XRD spectrum of the ZnS/Si core-shell nanowires. C-ZnS stands for ZnS with cubic structures. Arrows in spectrum show the existence of a small quantity of wurtzite structured ZnS. (b) An SEM image of the as-grown wire-like products.

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An HRTEM image taken at Si side. (f) A schematic diagram of the formation process of ZnS/Si core-shell nanowires.

Figure 6.4 (a) An SEM image of as-grown nanowires. (b) Corresponding CL image of emission at 470 nm at room temperature showing stronger emissions from the shells. (c) Room- and low-temperature CL spectra of ZnS/Si core-shell nanowires.

Figure 6.5 (a) A TEM image of Si tubes. Inset is the ED image. (b) An EDX spectrum taken from the Si tube. (c) I-V measurement for a single ZnS/Si core-shell nanowire at zero gate voltage. Upper inset image is the model of a FET device and the lower inset SEM image of fabricated electrode. (d) Gating effect of the nanowire. Inset shows the change of current with gate voltage at a constant drain-source voltage.

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## List of Symbols and Abbreviations

| | |
|---|---|
| Ag | silver |
| $AgNO_3$ | silver nitride |
| APTES | 3-aminopropyltriethoxysilane |
| Ar | Argon |
| Au | gold |
| BF | bright field |
| Ca | calcium |
| CL | cathodoluminescence |
| Cu | copper |
| CVD | chemical vapor deposition |
| DC | direct current |
| DF | dark field |
| DPA | 9,10-Diphenylanthracene |
| EDS | energy dispersive spectrometer |
| EELS | electron Energy Loss Spectroscopy |
| FET | eield effect transistor |
| FCC | face center cubic |
| $FeCl_3$ | iron chloride |
| GaAs | gallium arsenide |
| GaN | gallium nitride |
| GaP | gallium phosphide |
| Ge | germanium |

| | |
|---|---|
| $H_2$ | hydrogen |
| $H_2O_2$ | hydrogen peroxide |
| $H_2SO_4$ | sulfuric acid |
| HF | hydrofluoric acid |
| HRTEM | high resolution Transmission Electron Microscopy |
| InAs | indium arsenide |
| InP | indium phosphide |
| LB | Langmuir-Blodgett |
| MOS | metal-oxide-semiconductor |
| MPTMs | 3-mercaptopropyltrimethoxysilane |
| $N_2O$ | nitrous oxide |
| $NH_3$ | ammonia |
| Ni | nickel |
| OAG | oxide-assisted growth |
| OM | optical microscopy |
| PCB | printed circuit board |
| Pd | palladium |
| $PdCl_2$ | palladium chlorid |
| PDMS | polydimethylsiloxane |
| PNA | peptide nucleic acid |
| Pt | platinum |
| Re | reynolds number |
| SAED | selected area electron diffraction |

| | |
|---|---|
| SEM | scanning electron microscope |
| Si | silicon |
| SiC | silicon carbide |
| SiGe | silicon-germanium |
| SiNT | silicon nanotube |
| SiNW | silicon nanowire |
| SiO | silicon monoxide |
| Sn | tin |
| $SnO_2$ | tin oxide |
| STM | scanning tunneling microscope |
| STEM | scanning Transmission Electron Microscopy |
| TBP | 2,5,8,11-tetra-(t-butyl)-perylene |
| TEM | transmission electron microscopy |
| UV | ultraviolet |
| VLS | vapor-liquid-solid |
| $WO_3$ | tungsten oxide |
| XRD | X-ray diffraction |
| ZnO | zinc oxide |
| ZnS | zinc sulfide |
| ZnSe | zinc selenide |
| Ag | silver |
| $AgNO_3$ | silver nitride |
| APTES | 3-aminopropyltriethoxysilane |

| | |
|---|---|
| Ar | argon |
| Au | gold |
| BF | bright field |
| Ca | calcium |
| CL | cathodoluminescence |
| Cu | copper |
| CVD | chemical vapor deposition |
| DC | direct current |
| DF | dark field |
| DPA | 9,10-Diphenylanthracene |
| EELS | electron energy loss spectroscopy |
| FET | field effect transistor |
| FCC | face center cubic |
| $FeCl_3$ | iron chloride |
| GaAs | gallium arsenide |
| GaN | gallium nitride |
| GaP | gallium phosphide |
| Ge | germanium |
| $H_2$ | hydrogen |
| $H_2O_2$ | hydrogen peroxide |
| $H_2SO_4$ | sulfuric acid |
| HF | hydrofluoric acid |
| HRTEM | high resolution transmission electron microscopy |

| | |
|---|---|
| InAs | indium arsenide |
| InP | indium phosphide |
| MOS | metal-oxide-semiconductor |
| MPTMs | 3-mercaptopropyltrimethoxysilane |
| $N_2O$ | nitrous oxide |
| $NH_3$ | ammonia |
| Ni | nickel |
| OAG | oxide-assisted growth |
| OM | optical microscopy |
| PCB | printed circuit board |
| Pd | palladium |
| $PdCl_2$ | palladium chloride |
| PDMS | polydimethylsiloxane |