Silicon nanowire based sensors for life-science applications

Steffen Strehle
Outline

- Why are nanowires interesting?
- Lieber Group research
- Nanowire VLS synthesis and device fabrication
- Basics of silicon nanowire sensors
- Sensing of the neurotransmitter dopamine
- Summary/Acknowledgment
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➢ similar to current electronic devices (i.g. FET) but potentially revolutionary concepts will emerge (i.g. quantum properties)

➢ nanoscale building blocks with precisely controlled and tunable properties

➢ best defined and controlled classes of nanoscale building blocks compared to, for example, carbon nanotubes

➢ serve as a one-dimensional platforms for nanodevices

➢ demonstrated nanometer-scale applications:

- field-effect transistors (FETs)
- p-n diodes
- light-emitting diodes (LEDs)
- bipolar junction transistors
- complementary inverters
- nano-scale lasers
- complex logic gates
- basic computational circuits
- gas & bio-chemical sensors
- solar cells / thermoelectric devices

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focused on the "bottom-up" paradigm for nanotechnology
- design and synthesis of nanoscale building blocks, elucidation of the fundamental properties
- methods for complex integrated assembly of nanostructures

11 grad students
11 PostDocs

Charles M. Lieber

over 300 papers & 35 patents

Current fields of research:
- bio-chemical sensors
- cell-nanowire interfaces
- nanowire based solar cells
- logic nanowires circuits
- synthesis principles

http://cmliris.harvard.edu

Nature 430, 61 (2004)]

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VLS: Vapor-Liquid-Solid
→ metal catalyzed nanowire growth

SiH₄, Si₂H₆, SiCl₄

H₂, Ar, He

B₂H₆, PH₃

Au

Si Substrate

- metal evaporation/colloids
- Au particle size determines wire diameter
- single crystal wires epitaxial/non-epitaxial
- overcoating leads to tapering
- doping by second gas
Radial and axial homo- or heterostructures possible

MRS Bulletin, 2003, July, 486
poly-L-lysine adsorption on substrate
- gold nanoparticle adsorption
- SiNWs CVD growth step
- sonication of growth substrate
- or other transfer techniques
→ device fabrication by micro-technological technologies

Contacts are made by photo- or e-beam lithography and subsequent metal evaporation.

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Summary/Acknowledgment
➢ nanoscale FETs can overcome limitations of planar semiconductor devices

➢ binding to the NW surface can lead to depletion or accumulation of carriers in the “bulk” of the nanometer diameter structure and increase sensitivity to the point of single-molecule detection

➢ silicon is always semiconducting compared to CNTs and Si technology is established

➢ doping type and level controls the sensitivity of SiNW

➢ massive knowledge about oxide surface modifications available

the sensitivity is highest in the so-called sub-threshold regime near carrier depletion (i.e., $\lambda_{\text{Si}} \gg r$) but non-linear
- nanowire sensors need to be calibrated in terms of device-to-device variation

- strong correlation between the bio-sensor gate dependence \( (dI_{ds}/dV_g) \) and the absolute response (absolute change in current, \( \Delta I \))

Nano Lett. 10 (2010) 547

- “water gate” measurements can be used for calibration

WG sweep: +/- 0.1 V
Debye screening length

- scale over which mobile charge carriers (e.g. electrons) screen out electric fields

\[
\kappa^{-1} = \sqrt{\frac{\varepsilon_r \varepsilon_0 k_B T}{2 e^2 I N_A}} = C \sqrt{\frac{\varepsilon_r}{I}} \rightarrow \text{water, RT} \quad \kappa^{-1} [\text{nm}] \approx \frac{0.304}{\sqrt{I (M)}}
\]

- $I$ is the ionic strength of the electrolyte
- $\varepsilon_0$ is the permittivity of free space
- $\varepsilon_r$ is the dielectric constant
- $k_B$ is the Boltzmann constant
- $T$ is the absolute temperature in kelvins
- $N_A$ is the Avogadro number
- $e$ is the elementary charge

\begin{itemize}
  \item 0.01xPBS: ~7 nm
  \item 0.1xPBS: ~2 nm
  \item 1xPBS: ~0.7 nm
\end{itemize}

Nano Letters, 2007, 7, 3405
pH effect

- changing pH values (H$_3$O$^+$ / OH$^-$) cause a charge carrier depletion or accumulation in the NW due to the field effect
- can be exploited for pH sensing but interferes easily with other sensing experiments
➢ pH sensor: 3-aminopropyltri-ethoxysilane (APTES) modified pSiNW

➢ at low pH: the -NH group is protonated to NH₃⁺: positive gate

➢ at high pH: -SiOH is deprotonated to -SiO₂⁻.
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➢ imbalances in dopamine concentration can lead to neurological disorders like the Parkinson disorder

➢ controlled therapeutic delivery require rapid and accurate determination of neurotransmitter concentrations with high sensitivity

➢ label-free real-time measurement of catecholamines can be achieved electrochemically, yet limited in terms of bio-compatibility and spatial resolution

➢ phosphate modified TiO$_2$ should react with dopamine almost selectively $\rightarrow$ change of the TiO$_2$ charge is the gate voltage

➢ nanowire sensors can potentially provide spatial resolution and high sensitivity

\[\text{Dopamine (DA)}\]  
\[\text{Ascorbic acid (AA)}\]
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➢ nanowires are a one-dimensional platforms for nanodevices
➢ nanowire based bio-/chemical-sensors allow a label free detection with high sensitivity
➢ screening length effects, pH sensitivity and device calibration were discussed
➢ the nanowires synthesis by VLS and device fabrication were briefly presented
➢ the sensing of dopamine using TiO$_2$ modified pSiNW was shown

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