

Sensing with Silicon Nanowire Field-Effect Transistors

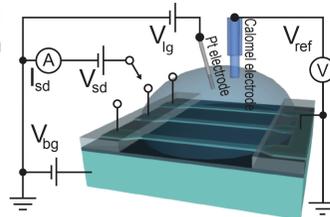
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Silicon nanowire FETs as sensing units

Small semiconductor FETs such as silicon nanowires can serve as sensing units in integrateable bio- and chemical sensors.¹⁻³ Charged species at the nanowire surface can lead to depletion or accumulation of carriers in the FET channel, modulating its conductance.

The nanowire arrays are fabricated in a SOI wafer. Gate voltage is applied via the silicon substrate below. In solution, an additional gate voltage can be applied via a Pt electrode (dual-gating).³⁻⁵ A calomel reference electrode measures the effective liquid potential.



Main Achievements:

- > Routine operation of NW arrays;
- > Various surface modification schemes;
- > Understanding of pH and electrolyte effects;
- > Differential measurements;
- > Specific ion sensing.

Fabrication of nanowire arrays

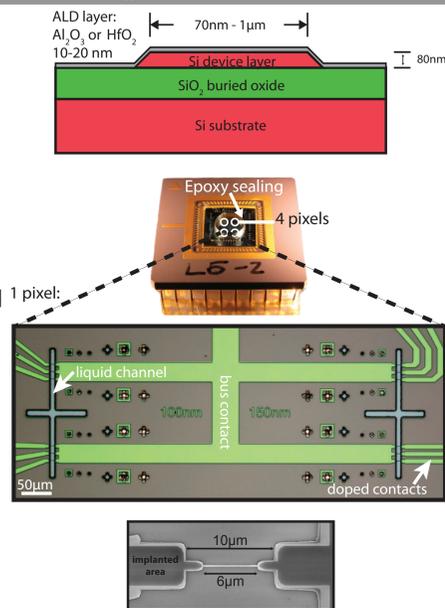
Summary of the top-down fabrication process:

Device structuring: 48 NWs are defined by e-beam lithography on a SOI wafer. Dry and wet etching to shape the NWs.

Ohmic contacts: contact areas are heavily doped by ion implantation and annealing. Aluminum pads are evaporated and annealed for optimal contact.

ALD interface oxide: the whole device is coated with a thin Al₂O₃ or HfO₂ layer (a) to prevent leakage currents and (b) to optimize sensing properties

Packaging: micro-channels are defined in SU-8, sample is wire-bonded into chip carrier, and sealed with epoxy.



pH sensing and electrolyte effects⁶

Close to ideal pH sensitivity:

Conductance G of a NW vs. liquid potential at different pH values. The threshold voltage shift is read out in the subthreshold regime and plotted vs. pH (inset). According to the Bergveld model, this shift is described by

$$\Delta V_{th} = \ln(10)kT/e \cdot \alpha \cdot \Delta \text{pH}, \text{ where}$$

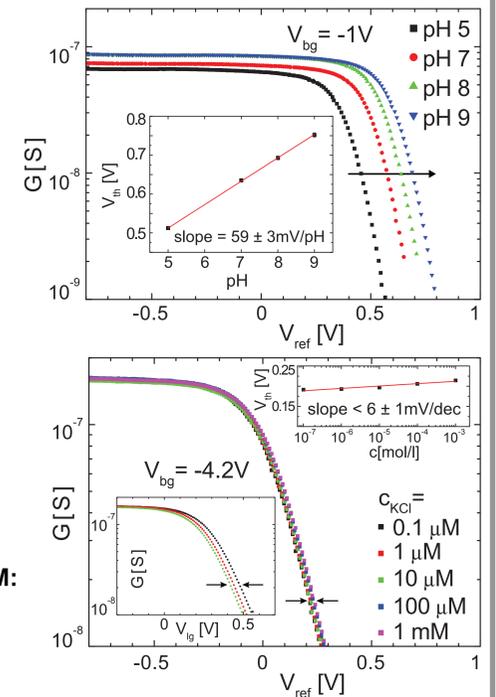
$$\alpha = C_{dl} / (C_{dl} + C_s) \leq 1.$$

C_{dl} : double-layer capacitance
 C_s : surface buffer capacitance

The observed pH response is very close to the ideal Nernstian value of $\ln(10)kT/e \approx 59.5 \text{ mV/pH}$ at RT ($\alpha \approx 1$).

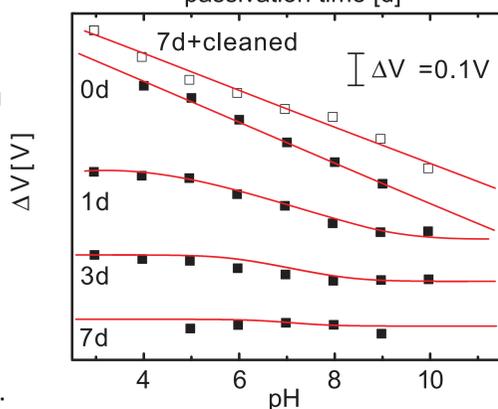
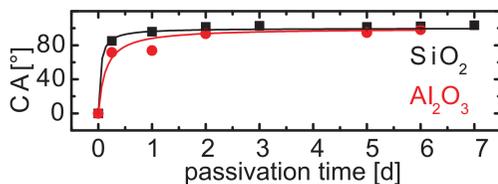
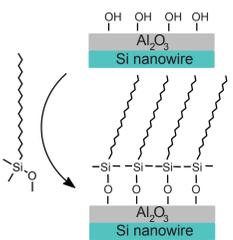
Negligible electrolyte effect at $c < 10 \text{ mM}$:

Varying the ionic strength changes C_{dl} . However, almost no potential change is visible, since the sensitivity parameter $\alpha \approx 1$ and $C_s \gg C_{dl}$ (for Al₂O₃).



Surface passivation⁷

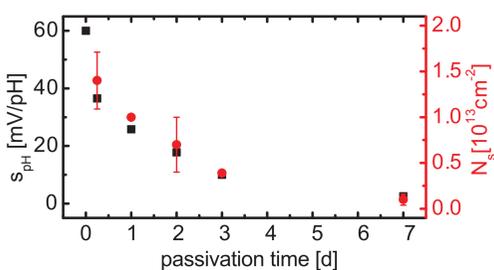
Vapor deposition of a silane with a long alkyl chain (C18) was used to passivate the Al₂O₃ surface. Contact angle (CA) was measured to get some information on the reaction progress.



The pH response ΔV of several samples was tested, showing a **decreasing pH sensitivity with increasing surface coverage**.

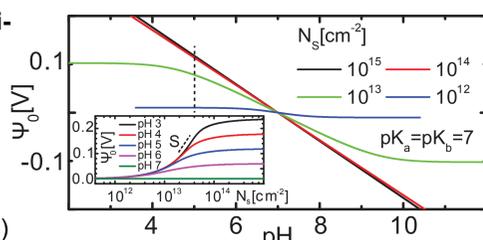
The site-binding model (SBM, lines) was used to fit the data (squares). The number of surface sites N_s was extracted from the fits.

A reduction of N_s by three orders of magnitude is achieved after **7 days**, resulting in a **pH insensitive** surface.



We define an average pH sensitivity $s_{pH} = \Delta V_{max} / (\text{pH}_{sat2} - \text{pH}_{sat1})$ and plot it together with N_s . Both quantities were taken from the above plot.

Fully passivated NW could be used as pH reference electrodes.

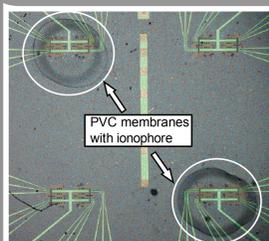


Partially passivated surface is sensitive to δN_s , caused by adsorption of neutral species.

Define sensitivity $S = \delta \psi_0 / \delta N_s$.

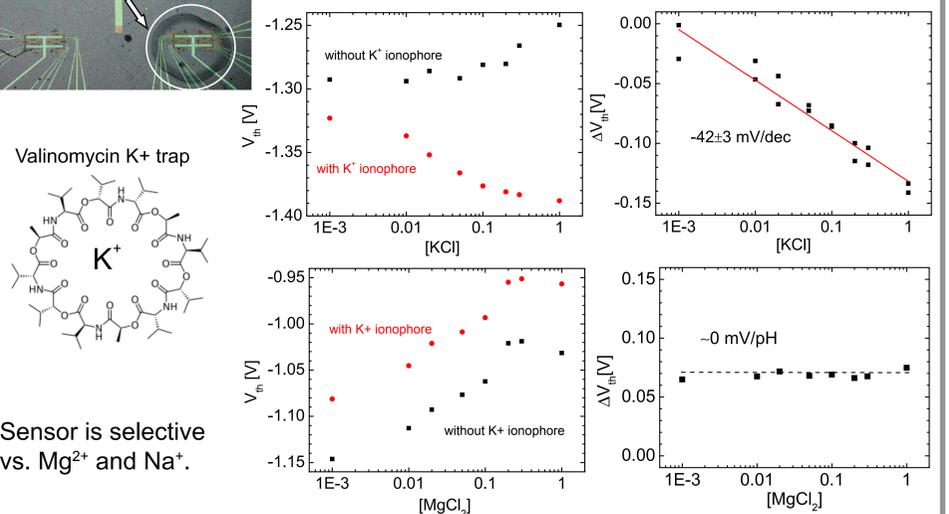
Estimated detection limit:
 $\delta N_s \approx 170 \mu\text{m}^{-2} \text{Hz}^{-1/2}$ (at 10 Hz, pH = 3)

Ion sensing in a differential setup



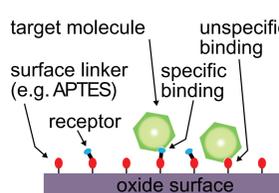
Subtract reference (black) from the sensor signal (red).

This gives a differential sensor signal:

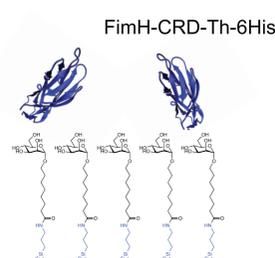


Outlook: Biosensing

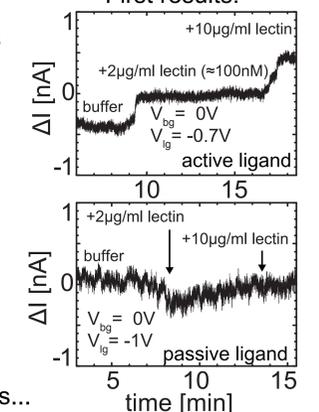
General picture:



Our system:



First results:



Next steps:

- reduce volumes and response time (microchannels)
- study buffer concentration and pH dependence
- try different linker lengths, other linkers, lectin mutants...

References:

- [1] Y. Cui et al., *Science* **293**, 1293 (2001).
- [2] E. Stern et al., *Nature* **445**, 05498 (2007).
- [3] O. Knopfmacher et al., *Nano Lett.* **10**, 2268 (2010).
- [4] O. Knopfmacher et al., *Procedia Chem.* **1**, 678 (2009).
- [5] A. Tarasov et al., *Appl. Phys. Lett.* **98**, 012114 (2011).
- [6] O. Knopfmacher et al., *ChemPhysChem* **13**, 1157 (2012).
- [7] A. Tarasov et al., submitted to *Langmuir* (2012).