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The Essential Requirements of ISFET Sensors for Biochemical Detection

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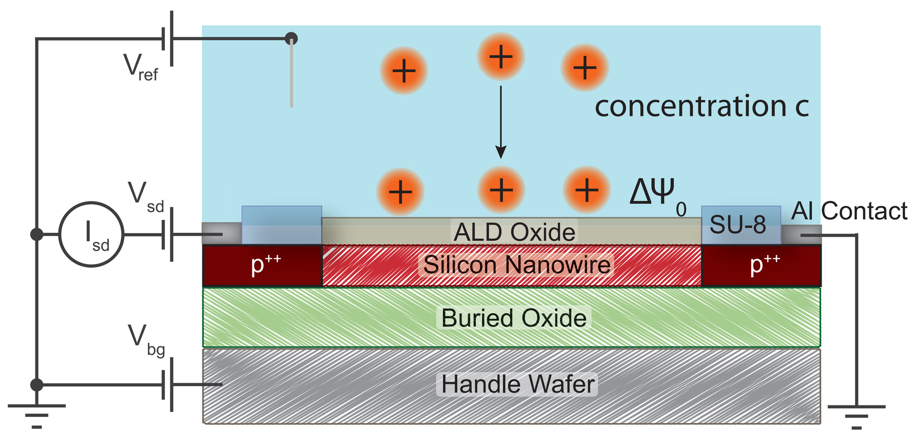
nanowire sensor

Abstract

Ion-sensitive field-effect transistors (ISFETs) based on silicon nanowires (SiNW) have attracted substantial interest for various chemical and biochemical sensing applications. [1-4] To quantify the sensor performance, the signal-to-noise ratio (SNR) has to be considered. We investigate how the SNR is affected by different surface materials and geometries of the nanowires. On one hand, the signal or response is mainly determined by the properties of the nanowire surface and does not dependent on the nanowire width[5,6]. We further show how competing reactions can influence the response towards a targeted species. On the other hand, the noise is dominated at low frequencies by 1/f noise, typical to FETs. We find that the noise is smaller for wider nanowires[7].

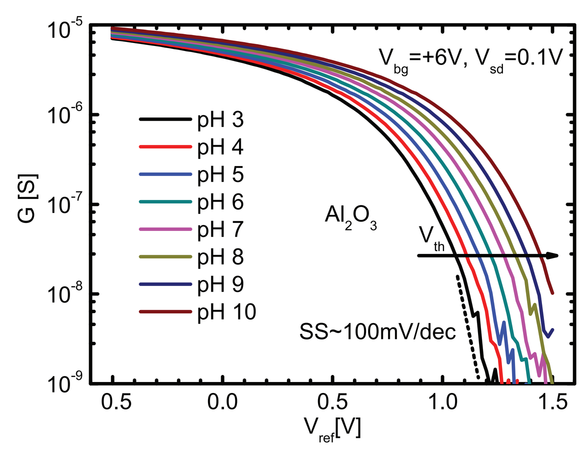
Figure of Merit: Signal-to-noise Ratio

Signal-to-noise ratio (SNR) is the key metric describing the performance of a sensor. In the case of ISFET sensors, the signal (response) is given by a change in surface potential $\Delta\Psi_0(c)$ upon changing the bulk concentration c of the targeted analyte.



The noise ultimately limits the resolution of the sensor. To compare the noise with the response, it has to be related to a change in surface potential $\Delta\Psi_{0,min}$.

$$\mathrm{SNR} = \frac{\text{response (c)}}{\text{noise}} = \frac{\Delta\Psi_0\,(c)}{\Delta\Psi_{0,min}}$$



The shift in threshold voltage is read out in the subthreshold regime.

pH-response: Effect of Surface[5,6†]

The response of ISFETs to pH can be described using the site-binding model.[8]
The high surface hydroxyl group density N_S of Al_2O_3 and HfO_2 results in a linear pH response of ≈ 56 mV/pH, which is close to the Nernst limit.

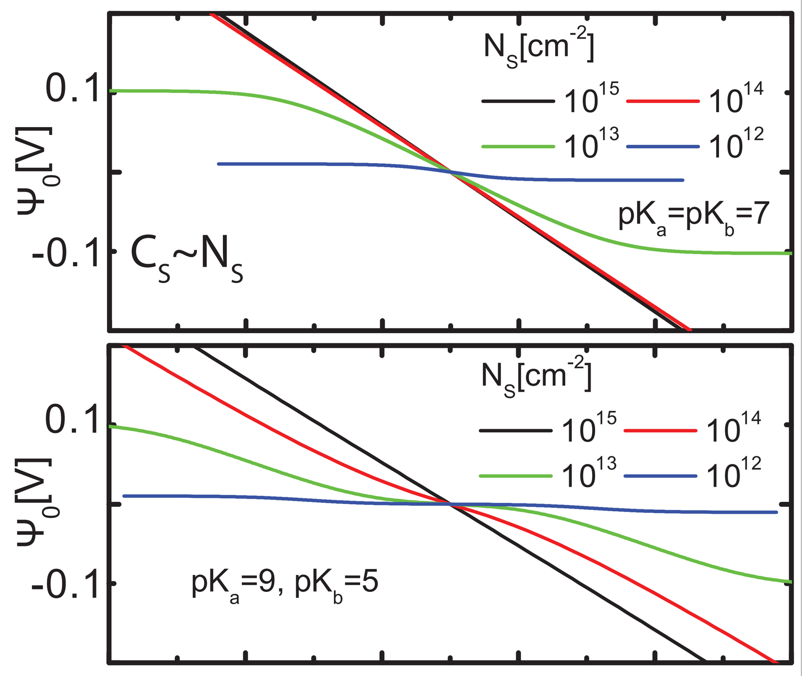
$$\frac{\Delta V_{th}}{\Delta pH} = \ln(10)\cdot\frac{k_B T}{e}\cdot\alpha \quad \approx 60mV/pH$$

at room temperature

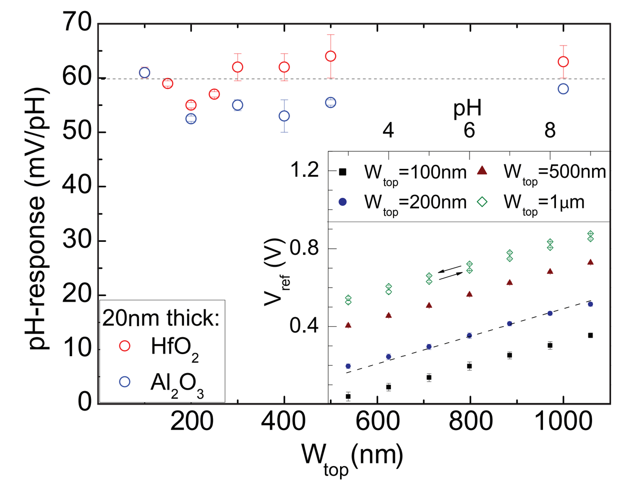
The ability of the surface to take up/release protons from/to the solution is given by C_s, which is proportional to N_S.

$$\alpha = \frac{C_S}{C_{dl} + C_S} \leq 1$$

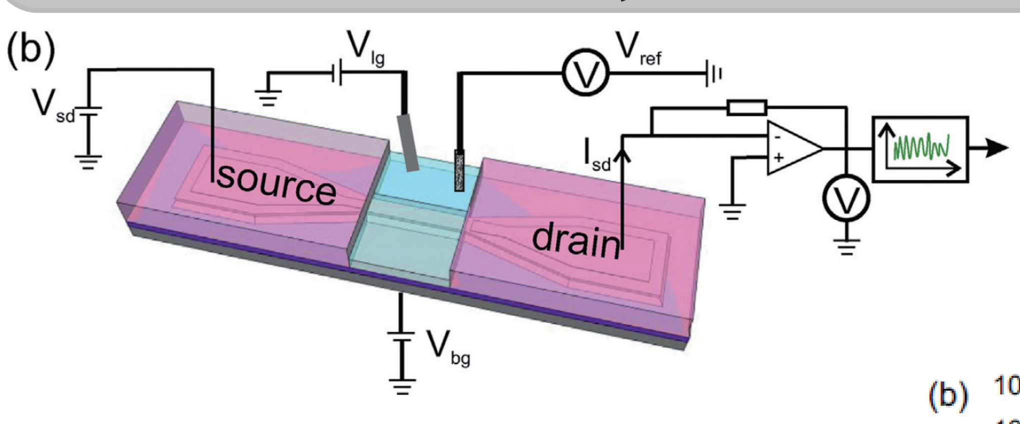
C_s: surface buffer capacitance
C_{dl}: double-layer capacitance



For an ideal pH sensor, the goal is to achieve a very high number of surface hydroxyl groups, which leads to α≈1. However α does not depend on the dimensions of the FET.



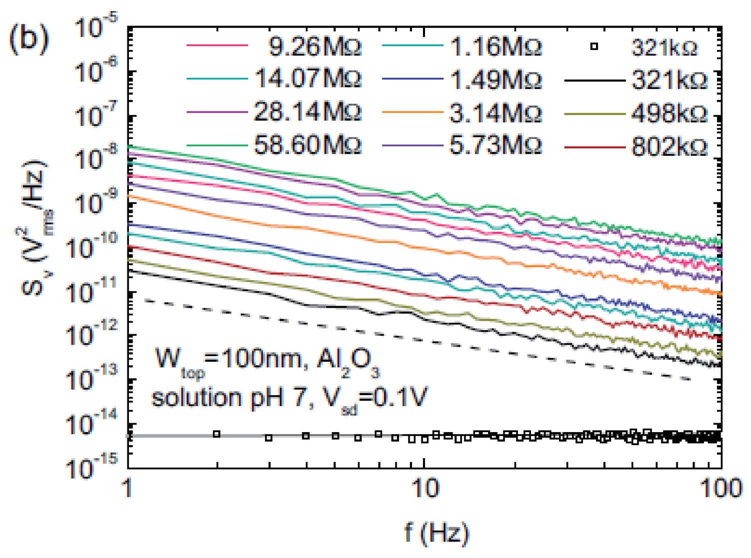
Low Frequency 1/f Noise[7]



In semiconductor devices, 1/f noise is the dominant noise source at low frequencies.

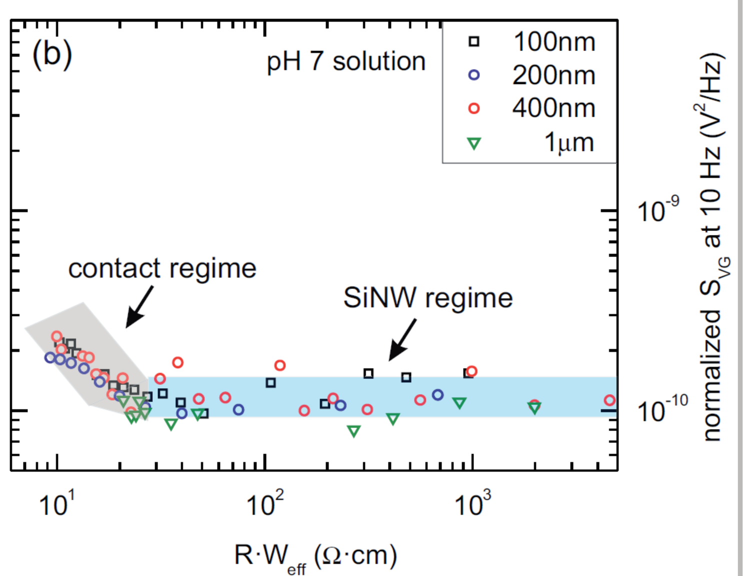
We measure the power voltage noise density $S_V(f)$ of nanowires with different widths.

The measured voltage noise can be referred to the gate which gives the gate referred voltage noise $S_{VG}(f)$.



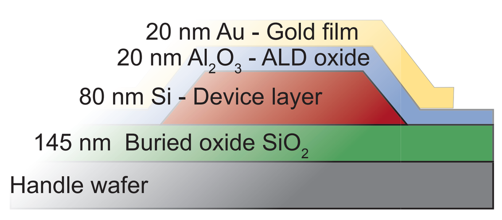
The measured data is in good agreement with the trap state model, assuming trapping/detrapping of trap states at the Si/oxide interface as source of the noise:

$$S_{VG} = \frac{e^2 N_{ot}}{f W_{eff} L C_{ox}^2}$$



The gate-referred voltage noise decreases with increasing wire width according to $S_{VG}\sim 1/W_{eff}$.
To minimize 1/f noise, large structures are prefered!

Conclusion: Gold-coated Nanowires[9]



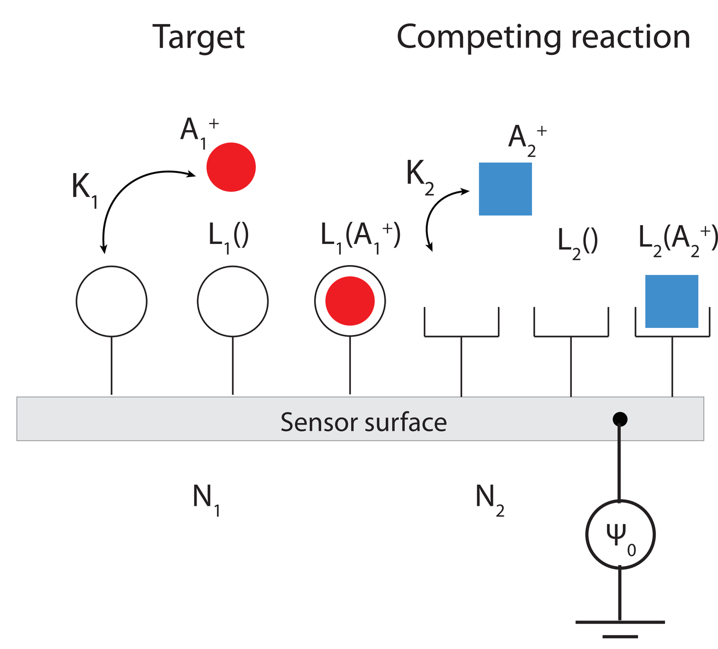
Gold-coated nanowire ISFETs as a platform for specific sensing experiment:

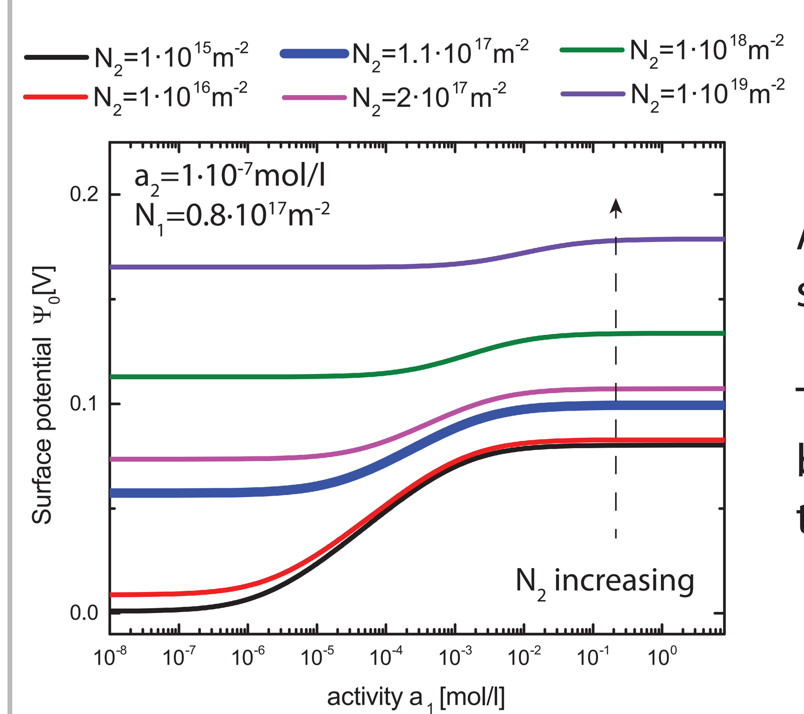
- Gold is an (almost) inert material (low pH response)
- Well-established surface chemistry for functionalizations
- Ideal candidate for differential measurements

Competing Surface Reactions[¶]

To achieve a specific sensing of proteins or ions other than protons, the surface needs to be modified. However, the intrinsic non-selective sensitivity of oxide surfaces greatly complicates the selective sensing of the targeted species. A large surface buffer capacitance C_S leads to an almost constant surface pH which compensates any potential changes due to the binding of targeted species. Therefore oxide surfaces are not good candidates for specific detection experiments unless full passivation can be achieved.

To study this effect more in detail, we investigate the simplest case of two reactions on a surface. We assume that the surface has some intrinsic sensitivity to A_2^+ via the binding site $L_2()$. It is functionalized with ligand $L_1()$ to detect A_1^+ specifically. The total number of ligands is N_1. N_2 is the number of the binding sites involving $L_2()$.

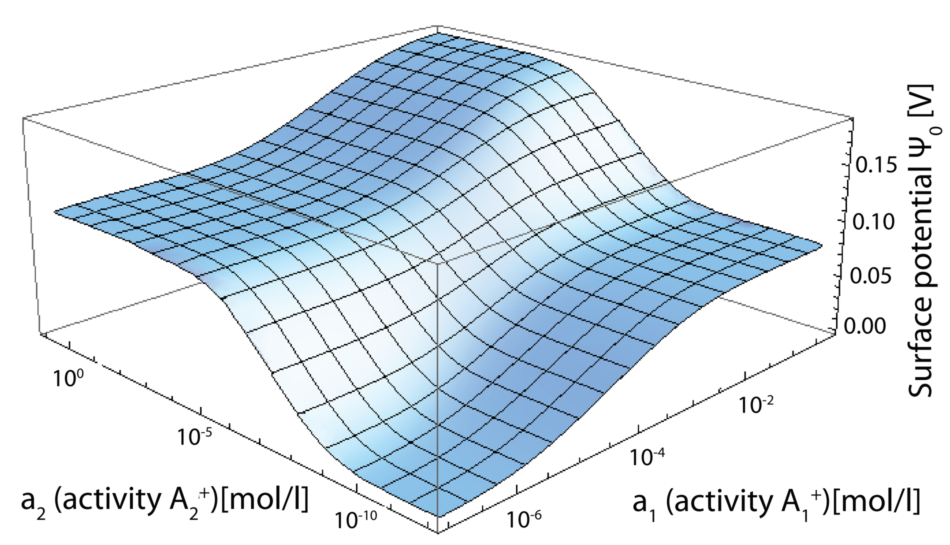




A large N_2 suppresses the response of the sensor to the targeted species.

The activity range where the target analyte can be detected highly depends on the surface potential Ψ_0.

In order to maximize the response to the targeted species, the response to all competing reactions must be minimized!



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PAUL SCHERRER INSTITUT PSI

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