

Nanowire Array Biosensor

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Summary:

In this work, we performed analytical and numerical studies of a nanowire array field-effect biosensor. The concept of the electrical double layer is applied in conjunction with a nanowire junctionless FET model. The model accounts for biosensing dynamics, and the sensor's sensitivity is evaluated for femtomolar variations of biomolecule concentration within the analyte solution. The signal-to-noise ratio (SNR) is also estimated, providing a lower bound on the detectable concentration.

Keywords: Nanowire array, biosensing, FET, sensitivity

Introduction

Nanowire (NW)-based biosensors have gained significant attention in recent years due to their exceptional sensitivity to low concentrations of biological analytes and the relative simplicity of their fabrication processes. For sensing applications, the surface of a semiconductor nanowire is usually functionalized with molecular receptors that are selectively designed to bind to target biomolecules. This surface modification enables the specific immobilization of biological entities—such as proteins, nucleic acids, or pathogens—onto the nanowire surface. These surface-bound biological charges then modulate the current through the NW FET; thereby, the biological event is converted into a measurable electrical signal. Understanding and simulating the complex physical and chemical interactions occurring in these biosensors is vital for improving their performance and optimizing their design.

Design-oriented analytical and numerical models have been developed for single-NW-based biochemical sensors [1,2]. The developed models predict sensor sensitivity even when the biomolecule concentration is in the femtomolar range. While single-NW devices offer simplicity and scalability, sensor architectures based on arrays of nanowires present distinct advantages. Specifically, NW array FET biosensors demonstrate enhanced sensitivity and improved signal stability [3]. This is largely due to the increased surface area for molecular binding and the statistical averaging effect provided by the multiple sensing elements within the array.

Methodology

In this work, we generalize the biosensor model from [2] and apply it to a silicon NW array biosensor. The system under study is illustrated in Fig. 1. The Si NW array is immersed in an analyte solution, which replaces the conventional metallic gate in NW FETs. The 'gate voltage' is applied via a reference electrode immersed in the solution. The source and drain potentials are applied directly to the bottom and top of the nanowires, as in regular FET devices (see Fig. 1a). We consider n-doped Si NWs covered with an array of y-shaped nanopillars designed to detect biomolecules (see Fig. 1b). Antibody-antigen binding is a spontaneous chemical reaction which is enthalpy driven, meaning that no external energy is required to enable the binding. The formation of paratope/epitope molecular interfaces results in a creation of a charged area very close to NW, which modulates NW FET current. The diffusion charge of ions in the solution is also considered. The concept of electric double layer is applied in the analyte solution and NW junctionless FET analytical model [4] is used to model the transducer part of the sensor. We assume that the functionalized layer on the NW has low permeability and that the ion partitioning from the solution is negligible. Under these conditions, the biological charges are separated from the NW surface by the insulating layer with (t_{eff}) thickness, see Fig. 1b, consisting of the functionalized layer and the oxide. Then we consider that each NW in a cylindrical volume is surrounded by an analyte solution of thickness (l), see Fig. 1b. The symmetry boundary

conditions are applied on the virtual surface of this cylindrical volume.

Results

To better understand how the spatial arrangement of nanowires influences sensing performance, we carried out a comprehensive analysis of the electric potential distribution in the surrounding analyte solution using COMSOL simulations (illustrated in Fig. 2). Since biological charge binding is a time-dependent process, the electric potential is plotted at different time points. These simulations help identify optimal nanowire placement strategies that maximize interaction with target molecules while minimizing noise.

A key metric in evaluating biosensor performance is the signal-to-noise ratio (SNR), which becomes especially critical when detecting extremely low analyte concentrations, such as those in the picomolar to femtomolar range. Our study includes an estimation of the SNR, showing reasonable values even at femtomolar concentrations.

References

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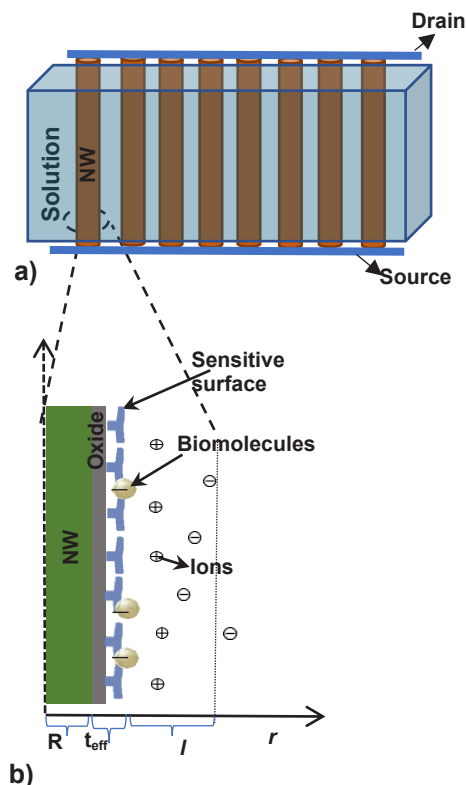


Fig. 1. a) Schematic structure of NW array biosensor, b) the surface coverage and surrounding solution of a single NW.

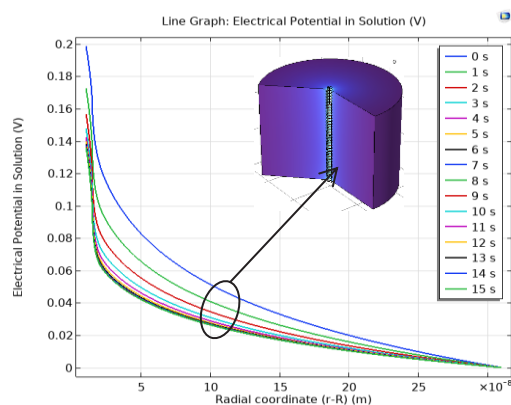


Fig. 2. Electrical potential distribution in analyte solution surrounding a single NW at different time slots.