Sensitivity of silicon nanowires in biosensor applications

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Abstract. A 2-dimensional simulation tool was designed to investigate the threshold voltage behaviour for a silicon nanowire constructed in a top down approach on silicon on insulator (SOI) material. The simulation shows, assuming a positive charge of +1·10^{11} cm^{-2} between the silicon/silicon dioxide interface and negatively charged surface states on top of the nanowire that the threshold voltage increases with decreasing height of the nanowire.

1. Introduction
Silicon nanowires have been reported as promising building blocks for future highly sensitive, label-free biosensors [1,2,3] using electrical detection. Nanowires can be fabricated in various ways either using a top-down approach with lithography and reactive ion etching or by bottom-up techniques with CVD growth [4,5,6]. The top-down approach has the advantage of being well known to semiconductor industry as well as allowing easy alignment of the nanowires making it possible for large scale mass fabrication whereas the bottom-up technique promises small diameter nanowires fabricated in a homogeneous and easy way. The difficulties with the bottom-up technique are the alignment and contacting procedures. However both techniques have been seen detecting proteins such as streptavidin and DNA in a highly selective and sensitive way down to the femto-molar range [5].

By decreasing the nanowire width and/or height, the surface to volume ratio is increased which makes the nanowires more sensitive due to surface charges surrounding the nanowire affecting the conduction. The sensitivity is often defined as a conduction ratio as the nanowire surface charges are altered through viruses, surface states or other molecules [3,7]. However, as the nanowire is exposed to solutions of various kinds the conduction ratio may not always be completely straight forward as a parameter. The $I_{DS} - V_{DS}$ characteristics of a bare nanowire as fabricated are often similar to the characteristics of a MOS transistor. However, when a solution is added to the nanowire surface the characteristics is changed in a dramatic way resulting e.g. in a voltage shift in the $I_{DS} - V_{DS}$ characteristics [8]. We propose that the threshold voltage should be the guiding parameter when measurements are done and that the threshold voltage shift should be used as a definition of sensitivity.

Previous simulations have investigated the threshold voltage as the mobility and the interface charge have been altered [9]. In this report we investigate the threshold voltage as the height of the nanowire is decreased assuming firstly a positive charge between the silicon/silicon dioxide interface and secondly a negative charge on the surface of the nanowire using a 2-dimensional simulation in...
cross section along the nanowire, keeping the mobility and surface charge constant. The nanowire is simulated as fabricated from silicon on insulator (SOI) material. The simulation is done in a standard simulation package (ISE-TCAD).

2. Experiment
A two-dimensional simulation tool was constructed to investigate the properties of the nanowire as the height of the top silicon layer is decreased assuming a positive charge between the silicon/silicon dioxide interface and a negative charge on top of the nanowire. The positive interface charge is set to \( +1 \cdot 10^{11} \text{ cm}^{-2} \) which is in agreement with values reported on earlier [10]. There are various ways in which to charge the surface of the nanowire but here we only study a negative charge of \(-1.5 \cdot 10^{11} \text{ cm}^{-2}\).

Figure 1 shows the nanowire device in cross section along the nanowire as designed from a SOI wafer where the positive and negative charges are shown with repeated ‘+’ and ‘-’ signs respectively similar to a real situation e.g. in a biosensor experiment. The contacts shown are source (S), drain (D) and back gate (G) and they are of Schottky type with a barrier set to 0.46 eV assuming TiW/Si contacts. Figure 2 shows the dimensions of the device as designed in ISE-TCAD with a silicon dioxide structure drawn on top of the silicon nanowire, 1 µm of length, where a charge between the silicon/silicon dioxide interface can be applied. The length of the silicon dioxide structure is chosen such that the length of it agrees with the length of our nanowire reported on earlier [6], i.e. because of the impact of the side walls of the nanowire the conducting channel will be affected as the surface is charged. Here, only the top side is investigated. The height of the nanowire, \( t \), can be varied. The silicon in this device is lowly doped p-type \( 1 \cdot 10^{15} \text{ cm}^{-3} \).

The conduction mechanism in this device is through electrons in an inversion current layer. The \( I_{DS} - V_{DS} \) characteristics of this device is shown below in figure 3 for \( t = 100 \text{ nm} \) at different back gate voltages, \( V_{GS} \). The behavior is similar to a field effect transistor where the current goes to saturation at higher drain source voltages because of a pinch off of the channel. The \( I_{DS} - V_{GS} \) characteristics can be
obtained from figure 3 and this is plotted in figure 4 at $V_{DS} = 1.0$ V. From this plot, the threshold voltage, $V_{TH}$, can be extrapolated [11] as is shown.

As the thickness, $t$, is decreased the impact from the negative charges at the 1 µm long silicon/silicon dioxide interface affects the conducting electron channel progressively and thus the current should decrease. The result on the threshold voltage must therefore be an increase. The $I_{DS} – V_{GS}$ characteristics is shown in figure 5 for $t = 25$, 50, 75 and 100 nm extrapolated as shown before at $V_{DS} = 1.0$ V. The behavior is in agreement with the fact that decreasing thickness gives a higher threshold voltage under the circumstances described above which is shown in figure 6 where the threshold voltage is plotted vs. thickness verifying this behavior.
3. Conclusions
Using a two-dimensional cross section along the nanowire and assuming a positive charge between the silicon/silicon dioxide interface and a negative charge on top of the nanowire surface we have shown that the threshold voltage increases with decreasing thickness of the silicon nanowire. As recently demonstrated [12], this results in a higher sensitivity for surface charges. This effect is of high importance for future work as dimensions are decreased for increased sensitivity of nanowire biosensors.

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References
[1] Li Z, Chen Y, Li X, Kamins T I, Nauka K and Williams R S 2004 Nano Letters 4 (2) 245-247
[2] Hsu J-F, Huang B-R, Huang C-S and Chen H-L 2005 J. J. Appl. Phys. 44 (4B) 2626-2629
[3] Patolsky F, Zheng G, Hayden O, Lakadamyali M, Zhuang X and Lieber C M 2004 PNAS 101 (39) 14017-14022
[4] Cui Y, Wei Q, Park H and Lieber C M 2001 Science 293 1289
[5] Stern E, Klemic J F, Routenberg D A, Wyrembak P N, Turner-Evans D B, Hamilton A D, LaVan D A, Fahmy T M and Reed M A 2007 Nature 445
[6] Juhasz R, Elfström N and Linnros J 2004 Nano Letters 5 (2) 275-280
[7] Li Z, Rajendran B, Kamins T I, Li X, Chen Y and Stanley Williams R 2005 Appl. Phys. A 80 1257-1263
[8] See fig. 5 in Stern et. al 2007 Nature 445
[9] Ashcroft B, Takulapalli B, Yang J, Laws G M, Zhang H Q, Tao N J, Lindsay S, Gust D and Thornton T J 2004 Phys. Stat. Sol 241 (10) 2291-2296
[10] Seo K-I, Sharma S, Yasseri A A, Stewart D R and Kamins T I 2006 Electrochemical and Solid-State Letters 9 (3) G69-G72
[11] Sze S M 1981 Physics of semiconductor devices 2nd Ed. Wiley Inc. New York
[12] Elfström N, Linnros J 2007 unpublished