Sensors and Actuators B 199 (2014) 291–300

Contents lists available at ScienceDirect

Sensors and Actuators B: Chemical

journal homepage: www.elsevier.com/locate/snb

Electrical characterization of high performance, liquid gated vertically stacked SiNW-based 3D FET biosensors

Elizabeth Buitrago[a,*], Montserrat Fernández-Bolaños Badia[a,b], Yordan M. Georgiev[c,1], Ran Yu[c], Olan Lotty[c], Justin D. Holmes[c], Adrian M. Nightingale[d], Hoël M. Guerin[a], Adrian M. Ionescu[a]

[a] Nanoelectronic Devices Laboratory (Nanolab), École Polytechnique Fédéral de Lausanne (EPFL), 1015 Lausanne, Switzerland
[b] IBM Research – Zurich, Säumerstrasse 4, CH-8803 Rüschlikon, Switzerland
[c] Materials Chemistry and Analysis Group, Department of Chemistry and Tyndall National Institute, University College Cork, Lee Maltings, Dyke Parade, Cork, Ireland
[d] Imperial College London, South Kensington, London SW7 2AZ, UK

ARTICLE INFO

Article history:
Received 22 January 2014
Received in revised form 24 March 2014
Accepted 27 March 2014
Available online 3 April 2014

Keywords:
ISFET
Sensor
FinFET
SiNW
GAA
Ion sensitive field effect transistor

ABSTRACT

A 3D vertically stacked silicon nanowire (SiNW) field effect transistor featuring a high density array of fully depleted channels gated by a backgate and one or two symmetrical platinum side-gates through a liquid has been electrically characterized for their implementation into a robust biosensing system. The structures have also been characterized electrically under vacuum when completely surrounded by a thick oxide layer. When fully suspended, the SiNWs may be surrounded by a conformal high-κ gate dielectric (HfO_2) or silicon dioxide. The high density array of nanowires (up to 7 or 8 × 20 SiNWs in the vertical and horizontal direction, respectively) provides for high drive currents (1.3 mA/μm, normalized to an average NW diameter of 30 nm at V_{SG} = 3 V, and V_d = 50 mV, for a standard structure with 7 × 10 NWs stacked) and high chances of biomolecule interaction and detection. The use of silicon on insulator substrates with a low doped device layer significantly reduces leakage currents for excellent I_{on}/I_{off} ratios $>10^6$ of particular importance for low power applications. When the nanowires are submerged in a liquid, they feature a gate all around architecture with improved electrostatics that provides steep subthreshold slopes (SS < 75 mV/dec), low drain induced barrier lowering (DIBL < 20 mV/V) and high transconductances (g_m > 10 μS) while allowing for the entire surface area of the nanowire to be available for biomolecule sensing. The fabricated devices have small SiNW diameters (down to $d_{NW} \sim 15$–30 nm) in order to be fully depleted and provide also high surface to volume ratios for high sensitivities.

1. Introduction

1.1. SiNW FET sensors

Silicon nanowire field effect transistors (SiNW FETs) have provided a versatile platform for the ultra-sensitive and selective detection (through surface modification) of simple molecules [1,2], ions [1,3], and biological entities such as viruses [2], proteins [1], and DNA [4], ever since Cui et al. [1] produced the first SiNW pH sensor based on the pioneering work of Bergveld [5,6]. The interest in nanostructures for sensing stems from their ultra-small dimensions that give rise to large surface to volume ratios (S/V). For such structures, a small number of charged biomolecules on the surface can efficiently modulate the conduction channel making the devices greatly sensitive in comparison to the planar (surface only) ion sensitive field effect transistor (ISFET) sensor that Bergveld introduced. SiNWs have therefore been widely utilized as FET-based biosensors since their first implementation. Nonetheless, their transistor characteristics in a liquid environment have seldom been thoroughly studied. Therefore in the present work, a 3D vertically stacked SiNW-based structure has been electrically characterized as gated through a liquid by a backgate and one or two

* Corresponding author. Tel.: +41 774688526.
E-mail addresses: elizabeth.buitrago@epfl.ch (E. Buitrago), montserrat.fernandez-bolanos@epfl.ch (M.F.-B. Badia), yordan.georgiev@tyndall.ie (Y.M. Georgiev), ran.yu@tyndall.ie (R. Yu), olanlotty@gmail.com (O. Lotty), justin.holmes@tyndall.ie (J.D. Holmes), adrian.nightingale06@imperial.ac.uk (A.M. Nightingale), hoel.guerin@epfl.ch (H.M. Guerin), adrian.ionescu@epfl.ch (A.M. Ionescu).
[1] On leave of absence from the Institute of Electronics of the Bulgarian Academy of Sciences, Sofia, Bulgaria.

http://dx.doi.org/10.1016/j.snb.2014.03.099
0925-4005/

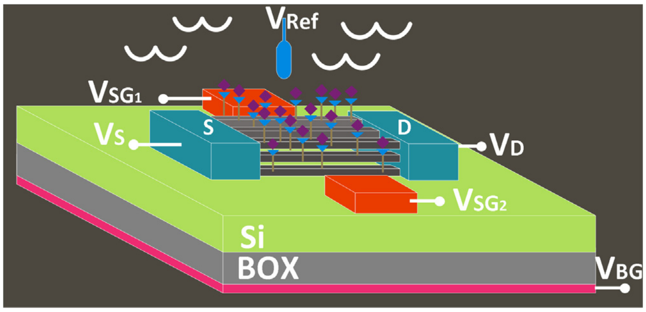

Fig. 1. Schematic of 3D vertically stacked SiNW FET biosensor. Three rows of three NWs vertically stacked in between source and drain anchors, two side-gates and a reference electrode (not used here) on a SOI substrate.
Adapted from [9].

symmetrical platinum side-gates (SG_1, SG_2, Fig. 1). Our results were briefly introduced previously [7] but more thoroughly explained here. The device and fabrication details of such structure have been presented previously in [8,9].

1.2. Principle of operation

An ISFET is a device analogous to a metal oxide semiconductor field effect transistor (MOSFET) for which the metal gate has been separated from the gate oxide and replaced by a reference electrode (RE) or local side-gate electrode. The electrode makes contact with the gate dielectric through the liquid that contains the analyte to be sensed (e.g., pH concentration).

For a conventional MOSFET, in the linear region when $V_G > V_{\rm th}$ (and $V_d < V_G - V_{\rm th}$) the drain current I_d relationship with respect to V_G (with V_G being the gate voltage, V_d the drain voltage and $V_{\rm th}$ the threshold voltage) is given in Eq. (1) [10]:

$$I_d = C_{\rm ox}\mu \frac{W}{L}\left[(V_G - V_{\rm th})V_d - \frac{1}{2}V_d^2\right] \quad (1)$$

$C_{\rm ox}$ is gate oxide the capacitance per unit area, W and L are the width and length of the channel, μ is the electron mobility. With the threshold voltage (Eq. (2)):

$$V_{\rm th} = \frac{\phi_M - \phi_{\rm Si}}{q} - \frac{Q_{\rm ox} + Q_{\rm ss} + Q_B}{C_{\rm ox}} + 2\phi_f \quad (2)$$

ϕ_M and $\phi_{\rm Si}$ are the work function of the gate electrode and the silicon respectively, q is the elementary charge and $Q_{\rm ox}$, $Q_{\rm SS}$ and $Q_{\rm B}$ are the oxide charge, interface charge and depletion layer charge in the silicon accordingly. Finally, ϕ_f is the Fermi level difference between doped and intrinsic silicon.

In analogy, for an equivalent ISFET device, adsorbed charged molecules (e.g., H^+ ions) produce a surface potential φ_0 on the gate oxide resulting in $V_{\rm th}$ change (Eq. (3)):

$$V_{\rm th} = V_{\rm ref} - \varphi_0 + \chi^{\rm sol} - \frac{\phi_{\rm Si}}{q} - \frac{Q_{\rm ox} + Q_{\rm ss} + Q_B}{C_{\rm ox}} + 2\phi_f \quad (3)$$

$V_{\rm ref}$ is the reference electrode potential, φ_0 is the surface potential and $\chi^{\rm sol}$ the solution's dipole moment. For a fixed $V_{\rm ref}$, only the surface potential changes as a function of pH. The drain current for an ISFET then becomes (Eq. (4)):

$$I_d = C_{\rm ox}\frac{W}{L}\left[\left(V_G - V_{\rm ref} - \varphi_0 + \chi^{\rm sol} - \frac{\phi_{\rm Si}}{q} - \frac{Q_{\rm ox} + Q_{\rm SS} + Q_B}{C_{\rm ox}} + 2\phi_f\right)V_d - \frac{1}{2}V_d^2\right] \quad (4)$$

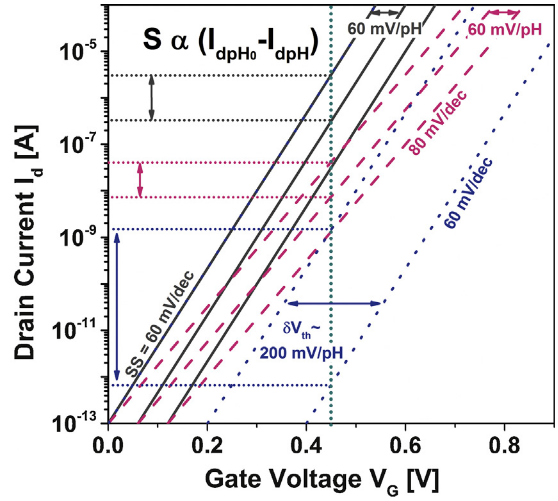

Fig. 2. I_d–V_G curves illustrating how the drain current and hence the sensitivity changes with a change of pH that induces a $V_{\rm th}$ shift of 60 mV/pH (grey-solid and pink-dashed curves) and 200 mV/pH (blue-dotted), for a transistor with a SS slope of 60 mV/dec (grey) and 80 mV/dec (pink), in the subthreshold region.(For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

The surface potential change $\Delta\varphi_0$ with respect to a pH value change $\left(d\varphi_0/d{\rm pH}\right)$ has been derived from the site-binding (SB) and Gouy–Chapman–Stern (GCS) model [11–15], Eq. (5):

$$\frac{d\varphi_0}{d{\rm pH}} = 2.303\alpha\frac{kT}{q} \quad (5)$$

With κ being the Boltzmann constant, T the absolute temperature and α is the dimensionless sensitivity parameter ($\alpha = 0$–1), Eq. (6):

$$\alpha = \frac{1}{(2.3\kappa T C_{\rm diff}/q^2\beta_{\rm int}) + 1} \quad (6)$$

$C_{\rm diff}$ is the differential capacitance that depends on the sensing solution's ion concentration and the $\beta_{\rm int}$ is the intrinsic buffer capacitance of the dielectric. The sensitivity parameter therefore reaches unity depending on the gate dielectric utilized, the ionic concentration of the solution and temperature. The resulting threshold voltage shift $\Delta V_{\rm th}$ in the I_d–$V_{\rm ref}$ characteristic reaches the thermodynamic Nernst limit of 59.5 mV/pH (at room temperature $T = 300$ K) as the sensitivity parameter α approaches unity.

1.3. Sensitivity

Typically in literature, the sensitivity S is defined as the absolute $S = (I_{d\psi 0} - I_{d\psi 1})$ or the relative variation of current or conductance G, $S = (I_{d\psi 0} - I_{d\psi 1})/I_{d\psi 0}$ due to a difference in the external potential (sensing event) with $I_{d\psi 0}$ being the baseline current and $I_{d\psi 1}$ being the current induced by the sensing event. Fig. 2 illustrates how the inherent transistor characteristics of the FET device, namely the subthreshold slope $SS = dV_{\rm SG}/d(\log_{10} I_d)$ and the $\Delta V_{\rm th}$ shift resulting from the electric field induced by a sensing event both represent an upper limit to the sensitivity of a given device when biased in the subthreshold region. It is well known that for a field effect transistor the subthreshold slope is limited to ~60 mV/dec (at room temperature). The current change per pH (and hence the sensitivity of the device) reaches a maximum of 1 dec/pH for a device with a SS of 60 mV/dec for which a pH change induces an ideal Nerstenian $V_{\rm th}$ shift of almost 60 mV/pH at room temperature (grey-solid curves, Fig. 2). Even if the sensing surface can provide a Nerstenian response of ~60 mV/pH ($\alpha \to 1$) if the subthreshold slope of