Subthreshold Operation of Schottky Barrier Silicon Nanowire FET for High Sensitive Biosensing

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ABSTRACT

This paper presents that the sensitivity of Schottky barrier silicon nanowire field-effect transistors (SB-SiNWFETs) is strongly modulated by the back-gate voltage. The silicon nanowire FETs having a similar conduction mechanism to a n-channel metal oxide semiconductor field-effect transistor (nMOSFET) are simply produced by utilizing Schottky source and drain contacts. For the evaluation of the sensitivity, the current variation ratios are compared at various back-gate voltages under the various electrolyte potentials. The response exhibits that as the back-gate voltage increases, the absolute values of differential current increases while the current variation ratio converges to unity. The characteristics are complemented by monitoring the conductance response to the exchange of pH level in the time domain. The highest current variation ratio for the hydrogen ion appears at back-gate voltage of 1 V, which is located in the subthreshold regime. This corresponds to the electrolyte potential application method, and reveals that the operation in the subthreshold regime gives the significant enhancement in the sensitivity for the detection of electrically charged biological species.

Keywords: subthreshold; Schottky, silicon nanowire, field-effect transistor (FET), biosensor

1 INTRODUCTION

Metal oxide semiconductor field-effect transistors (MOSFETs) are the state-of-the-art technologies in current semiconductor industry. Basic operation mechanism is that the carrier conductance is modulated by the electrical field applied through the gate electrode thereby switching the electrical circuits [1]. Similarly, ion-sensitive field-effect transistors (ISFETs) being able to detect a chemical and biological species were developed by simply replacing the gate electrode on the MOSFETs with a chemically or biologically sensitive layer [2]. An attractive feature of such chemically sensitive FETs is the direct transduction of the chemical and biological event to the electrical property, which is easily observable and compatible to the wide-spread electronic devices. However, the sensitivity for the detection of biological species is limited because the depletion or accumulation of carriers, which is caused by binding the species on the planar gate surface, is confined in the surface region [3].

As nano-scale structures such as carbon nanotubes (CNTs) [4], and nanowires (NWs) [3, 5] are introduced to the chemical and biological sensors, the surface confinement occurred in the planar device is overcome. Since the structural confinement of the nano-scale structures produces the depletion or accumulation of carrier in the bulk rather than the surface, the sensitivity is extremely enhanced. Silicon nanowire (SiNW)-based sensors, in particular, have drawn much attention from researchers involved in developing chemical and biomolecular sensors due to ultra-high sensitivity, the controllability of the carrier density and CMOS compatibility.

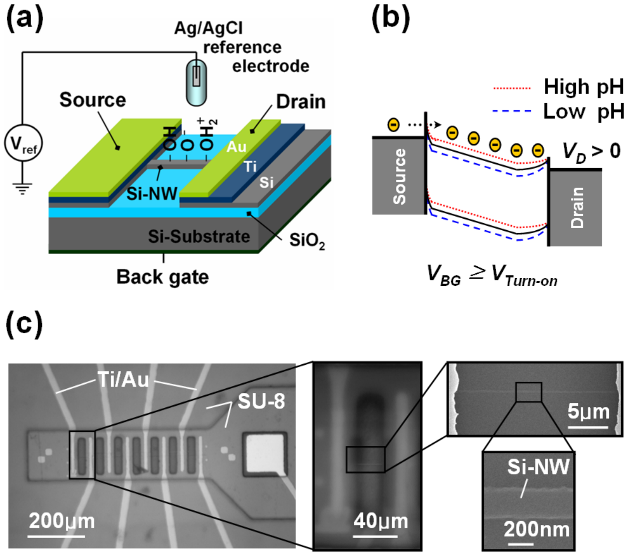

Figure 1: (a) Configuration of the device structure of SB-SiNWFET biosensor, (b) The schematically drawn energy-band diagrams of the SiNW channel between source and drain in the condition above turn-on back-gate voltage, positive drain bias, and high or low pH condition, and (c) The microscopic and scanning electron microscopic (SEM) images of the fabricated device.

Up to date, SiNW-based biosensors reported are nearly based on ohmic contacts. Although the ohmic contacts provide the reliable operation of the device, the complication of the fabrication process is inevitable. Recently, the nanowire sensors utilizing Schottky contacts have been demonstrated [6, 7]. The Schottky contacted SiNWFET or SB-SiNWFET biosensors can be fabricated by simply depositing a metal onto the semiconductor without the additional source-drain doping and activation process. Additionally, the Schottky contacts are an alternative to the conventional source-drain contacts. They offer several potential advantages over conventional devices at nanometer scale due to the abruptness of source-drain junctions, the reduction of extrinsic parasitic resistances, and extremely low off-current flow [8].

Despite such advantages of Schottky contacts, there are few studies on the sensitivity of SB-SiNWFETs for the chemical and biological spices. Elfström *et al.* showed the detection capability of Schottky contacted silicon nanoribbon for the interaction between streptavidin and biotin [6]. They reported that the higher sensitivity is yielded for the thinner silicon layer. However, the relationship between the sensitivity and the back-gate voltage was not fully explored even in the ohmic contacted SiNWFETs [5].

Therefore, the relationship between the sensitivity and the back-gate voltage of SB-SiNWFET was examined with the field-effect generated between the SiNW and analytes in this paper. The sensitivity of the devices was evaluated by measuring the current variation in response to various electrical potentials applied to the electrolyte, and the exchange of pH levels at given back-gate voltage.

2 DEVICE CONFIGURATION

The device configuration of SB-SiNWFET is illustrated in Figure 1 (a). A SiNW is placed on a thin silicon oxide as an insulating material. The source and drain electrodes are produced by simply depositing Ti/Au layer. The Ti layer in contact with the semiconductor has the work function lower than that of Si so that Schottky contacts are formed at the interface of metal and silicon. The application of voltage to the back-gate modulates the energy band and the Schottky barrier width. The Ag/AgCl reference electrode is used to apply a potential to the electrolyte.

The working mechanism of the device for the electrically charged species (hydrogen ions) is schematically explained in Figure 1 (b) by using energy-band diagrams. Under the sufficiently high back-gate voltage, the barrier width approaches to few nanometers inducing tunneling through the barrier as a new electron transport. If the channel region is exposed to pH solutions, the band bending occurs in accordance with pH level. The detailed working mechanism of the SB-SiNWFET is described in elsewhere [7].

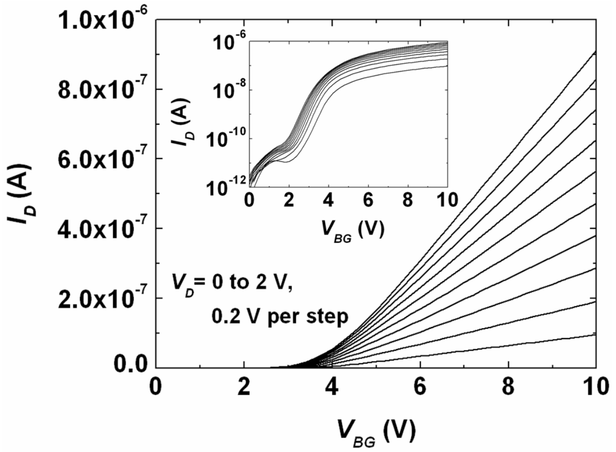

Figure 2: Drain current (I_D) versus back-gate voltage (V_{BG}) characteristic of the fabricated SB-SiNWFET measured at room temperature under the ambient condition. The inset shows the drain current plotted on a log scale with the same data.

SB-SiNWFETs were fabricated from a separation by implantation of oxygen (SIMOX) wafer having a 50 nm-thick silicon-on-insulator (SOI) and 100 nm-thick buried oxide (BOX) layer. The silicon layer is initially doped with boron to have a resistivity of 1-20 Ω·cm. For the formation of Schottky source and drain contacts, Ti/Au layers were deposited on the bare SIMOX substrate by sputtering, and the metal lines were patterned by photolithography and lift-off. The SiNW pattern was then created between the source and drain electrodes by electron beam lithography (EBL). The self-aligned SiNW channel was produced by transferring both nanowire patterns and metal lines to the SOI layer. In order to isolate the metal lines from the analytical solutions, a 12 μm-thick SU-8 layer was coated and patterned twice remaining a SiNW channel region exposed. Figure 1 (c) shows the microscopic images of a fabricated SB-SiNWFET with a 40 μm-long and 250 nm-wide SiNW channel. Only 20 μm-long SiNW channel is revealed via patterned SU-8 layer.

3 CHARACTERIZATION RESULTS AND DISCUSSION

To investigate the current-voltage (*I-V*) properties, a picoammeter (Keithley 6485) and a precision power supply (Agilent 6625A) were used under the computer control. Figure 2 shows typical drain current (I_D) versus back-gate voltage (V_{BG}) of the fabricated device under the ambient condition. Due to the high and thick Schottky barrier, the current conduction is significantly suppressed at low V_{BG} region. When the barrier is sufficiently narrowed for electrons to tunnel by increasing V_{BG}, the conduction mechanism of SB-SiNWFETs commences to follow the one of the n-channel MOSFETs: the exponential and linear increment of I_D below and above the threshold voltage, respectively.

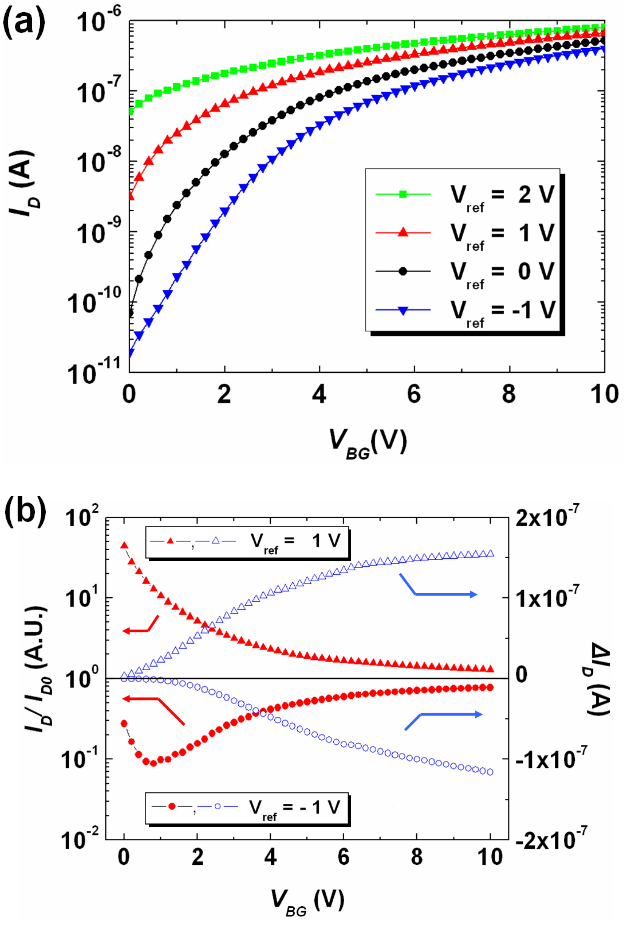

Figure 3: (a) I_D - V_{BG} characteristics in response to various electrolyte potentials (V_{ref}) (b) The current variation ratio and the differential current for the change of V_{ref} from zero to -1 V or 1 V as a function of the back-gate voltage. The drain voltage is fixed at 1 V.

Above the threshold voltage the electrons flows through the strong inversion layer generated at the silicon/oxide interface. The measured threshold voltage is about 3.7 V at V_D = 1 V. Since the thinner the gate oxide layer is, the lower the threshold voltage is, the threshold voltage of the device with a 100 nm-thick BOX layer is lower than the one with a 375 nm-thick BOX layer [7].

In order to investigate the relation between the surface charge sensitivity and the back-gate voltage in the solution phase, the electrolytic environment was produced by applying a 10 µl droplet of phosphate buffers (10 mM, pH 7.0) with NaCl (100 mM) over the sensing area where the SiNW was exposed. The potential in the electrolyte, V_{ref}, is controlled by the Ag/AgCl reference electrode which tip is slightly dipped in the droplet of the electrolyte. Figure 3 (a) shows the gate transfer characteristics of a SB-SiNWFET under the various V_{ref}. The measurements were conducted by increasing V_{BG} from 0 to 10 V with an incremental step of 0.2 V at the constant V_D of 1 V.

At V_{ref} = 0, the current flow is exponentially increased as V_{BG} is increased up to about 3 V. Above this voltage the current flow shows a linear characteristic dominantly. The turning point, V_{BG} = 3 V in this case, is considered to be the threshold voltage under the electrolytic environment. Since the SB-SiNWFETs exhibit the characteristics of nMOSFET under the positive back-gate condition, the increased (decreased) electrolyte potential shifts the threshold voltage negatively (positively). Figure 3 (b) shows the ratio of drain (I_D) current and base current (I_{D0} at V_{ref}= 0 V and pH = 7) and differential current (ΔI_D) when V_{ref} is increased from 0 to 1 V and decreased from 0 to -1 V. The absolute values of ΔI_D both for V_{ref}, = ±1 V are increased with V_{BG}, which is due to the increment of the transconductance. Meanwhile, the values of I_D/I_{D0} are converges to unity as V_{BG} increases. The reason is that the base current level (I_{D0}) is much higher than the differential current (ΔI_D) for larger V_{BG}. Since the current variation ratio (I_D/I_{D0}) is regarded as the sensitivity in SiNW-based biosensors, a high sensitivity is obtainable below the threshold voltage, so-called the subthreshold regime.

The carrier transport characteristics in the semiconductor vary according to the strength of the perpendicularly applied electrical field (gate voltage). The characteristics are divided into two regimes on the basis of threshold voltage. Above the threshold voltage, the current is driven by drift and flows through the strong inversion layer. Since the electron density in the strong inversion layer is proportional to the gate voltage, the the current variation ratio for low V_D ($0 \leq V_D \leq V_{Dsat}$) is expressed as a linear function of the threshold voltage shift [1].

$$I_D/I_{D0} = 1 - \frac{\Delta V_T}{\left(V_G - V_{T0}\right) - V_D/2}, \qquad (1)$$

where $\Delta V_T = V_T - V_{T0}$. On the contrary, in the subthreshold regime the drift-current component is negligible, and the diffusion-current component (free-carrier) becomes dominant. The free carrier density changes exponentially as the gate voltage changes. Therefore, the current variation ratio is exponentially proportional to the shift of threshold voltage [1].

$$I_D/I_{D0} = \exp\left(\frac{-q\Delta V_T}{nkT}\right) \qquad (2)$$

where n, k ,and T are 1 + C_d/C_{ox}, Boltzmann's constant, and absolute temperature, respectively. The depletion layer and gate oxide capacitance are denoted by C_d and C_{ox}, respectively. Consequently, the current flow is sensitive to the change of not only the back-gate voltage but also the electrical charges on the surface of SiNW.

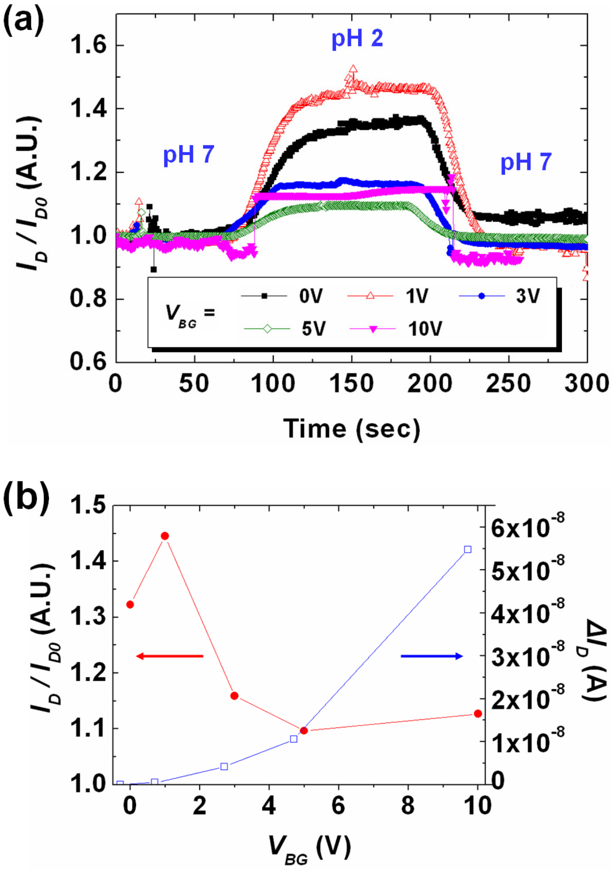

Figure. 4: (a) Current variation ratio in the time domain for the fabricated SB-SiNWFET in response to pH solution at various back-gate voltages (V_{BG}) and fixed drain voltage of 1 V, and (b) the current variation ratio and the differential current as a function of the back-gate voltage when the pH solution changes from pH 7 to pH 2.

These characteristics are confirmed in the time domain by using such electrically charged species as hydrogen ions. In order to make a flow-cell, the device was capped with the separately fabricated PDMS layer, which has a 500 µm-wide microfluidic channel for the delivery of analytical solutions. Figure 4 (a) shows the time-dependent response to the variation of pH level. Since the lower the pH value is, the higher the surface potential is generated, the change of pH level from 7 to 2 shifts the threshold voltage negatively and consequently increases the conductance. The current variation ratio and the differential current are summarized in Figure 4 (b). Like the characteristics of the electrolyte potential applying method, ΔI_D is increased and I_D/I_{D0} is decreased as V_{BG} is increased. The maximum value of I_D/I_{D0} appears at V_{BG} of about 1 V, implying that the highly sensitive biosensing is possible with the back-gate voltage maintained in the subthreshold regime or reduced as low as possible.

4 CONCLUSION

A simple structured silicon nanowire FET biosensor with a 40 µm-long and 250 nm-wide channel was successfully developed using Schottky source/drain contact without complex doping and activation process. It exhibits powerful sensitivity modulation with respect to the back-gate voltage. A high sensitive detection of hydrogen ions was achievable in the subthreshold regime where the mobile charge carriers are induced not by strong inversion but by depletion and weak inversion. Therefore, the back-gate voltage should be maintained in the subthreshold regime to detect electrically charged biological species with a high sensitivity.

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