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Temperature Characteristics of Silicon Nanowire Transistor Depending on Oxide Thickness

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Among various sensing and monitoring techniques, sensors based on field effect transistors (FETs) have attracted considerable attention from both industry and academia. Owing to their unique characteristics such as small size, light weight, low cost, flexibility, fast response, stability, and ability for further downscaling, silicon nanowire field effect transistor (SiNW-FET) can serve as an ideal nanosensor. It is the most likely successor to FET-based nanoscale devices. However, as the dimensions (channel length and diameter) of SiNWT channel are shrinking down, electrical and temperature characteristics of SiNWTs should be affected, thereby degrading transistor performance. Although applications of SiNWTs as biological and/or chemical sensors have been extensively explored in the literature, less attention has been devoted to utilize such transistors as temperature sensors. Therefore, this paper characterizes the temperature sensitivity of SiNWT depending on the channel oxide thickness and also presents the possibility of using it as a nano-temperature sensor. The MuGFET simulation tool was used to investigate temperature characteristics of the nanowire. Current-voltage characteristics with different values of temperature and with different thickness of the nanowire gate (oxide thickness (T_{OX}) = 1, 2, 3, 4, and 5 nm), were simulated. Metal-oxide-semiconductor (MOS) diode mode connection was suggested for measuring the temperature sensitivity of SiNWT. Several operating voltages (0.25 to 5 V) with various working temperature (250 to 450 K) were investigated. The obtained results show that the highest temperature sensitivity was achieved by increasing oxide thickness to 5 nm. The impact of the considered temperature on SiNWT characteristics demonstrates the possibility of utilizing it as a temperature nanosensor.

Keywords: SiNWT, Temperature sensitivity, MuGFET, Simulation.

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1. INTRODUCTION

Nowadays, the evolution of new technologies in micro- and nanoelectronics industry is measured by the distinction in miniaturization scale to ultra-micro dimensions. Design and fabrication of conventional metal oxide semiconductor field effect transistor (MOSFET) beyond sub-10 nm channel length become challenging issues due to short channel effects, such as leakage current, electrostatic limits, source-to-drain tunneling are very difficult, which causes a critical problem in terms of circuit reliability especially in complementary metal-oxide-silicon (CMOS). To overcome this issue, new 3D structures of transistors, including silicon nanowire transistors (SiNWT), were developed [1, 2]. That incredible reaching has changed the world of nanotechnology. The downsizing of transistors to the nm region means more investigations in the field of nanoscale materials and nanoscience as well is a demand. The nanometre has been as significant to science as the micrometre was in the previous century [3, 4].

Recently, with the emergence of the Internet of Things (IoT), sensors have become crucial components that can monitor and continuously track various physical stimulus parameters and update information to the Internet [5-10]. Driving by a wide variety of nanotechnology applications, nanosensors are regarded as one of the key technologies with the ability to sense different changes at nano-scale measurements. This is due to their excellent flexibility, stretch ability and stability [11, 12].

Many innovative device structures have been extensively explored when the planner MOSFET approached its downscaling limits. Amongst them, SiNWT which has pulled a magnificent attention from researchers to both, academic and semi-conductor industry as well [13].

Temperature management is a growing issue, especially in electronics industry, and research is underway to develop the electronic device network structures [14]. In this case – temperature management – sensors are needed to measure these nano-effects. Temperature has a significant effect on the system performance and the expected life of electronic products especially with the increasingly dense circuitry in a single chip [15].

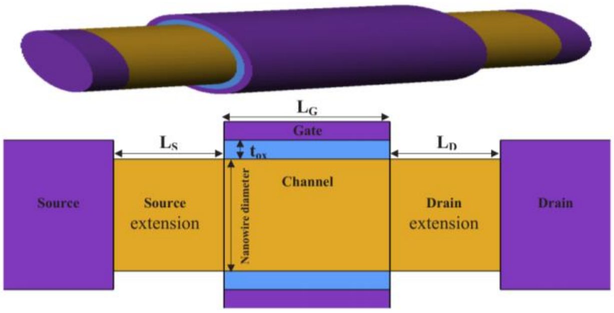

Fig. 1 – SiNWT structure

As depicted in Fig. 1, nanowire is an extremely thin wire of identical material or configuration with a length on a demand of some nanometers (nm) or more less. It has a nanostructure, with the span of the de-

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mand of a nanometer (10^{-9} m). A nanowire in electronics engineering is a circular or rectangular cross-sectional nanostructure that has a thickness or diameter constrained to tens of nanometers or less and an unconstrained length. Numerous diverse types of nanowires exist, including metallic such as Ni, Pt, Au, etc., semiconducting such as Si, InP, GaN, etc., and insulating like SiO_2, TiO_2. The nanowires could be used in the near future to link ever tinier components into very small circuits. Using nanotechnology, such constituents led to create out of chemical combinations [16, 17].

Consequently, design and characterization of SiNWT as a temperature nanosensor for enabling continuous temperature monitoring with superior detection capabilities, high sensitivity, mechanical flexibility, and low-cost fabrication processes, is highly demanded. Accordingly, this work proposes designs and characterizes of SiNWT as a temperature nanosensor based on temperature properties.

The remaining part of this paper is structured as follows: The next section introduces adopted methods for this study. Section III presents simulation results and discussions. Finally, the conclusions are drawn up in Section IV.

2. RESEARCH METHODOLOGY

2.1 MuGFET Simulator

Simulation tools for electronic devices have become increasingly important to understand the physics behind the structures of new devices. Simulators can also help to identify device strengths, weaknesses, and retrenchment costs and illustrate the extensibility of these devices in the nm range. Consequently, MuGFETs simulator is utilized in this research for the analysis and performance evaluation of SiNWFET structure's dimensions. In this paper, we used MuGFET simulation tool to investigate the temperature characteristics of SiNWT. The MuGFET can choose either PADRE or PROPHET simulations, which are both developed in Bell Laboratories. The PROPHET is a partial differential equation profiler for 1, 2, or 3 dimensions. On the other hand, PADRE is a device-oriented simulator for 2D or 3D devices with arbitrary geometry. This software provides many useful characteristic curves for SiNWTs for engineers and for deep understanding of physics. The MuGFET simulation tool also provides self-consistent solutions of the Poisson and drift-diffusion equation. MuGFET is used to simulate the motion of transport objects in the calculation of the characteristics for nanowire. Usually, experimental works can be supported by simulations to further explore the development of MuGFETs for nano-dimensional characterization.

2.2 Simulation Setup

Firstly, suitable parameters and dimensions of SiNWT were selected for simulations; these parameters include transistor dimensions (channel length (L), channel diameter (D), and oxide thickness (T_{OX})). After that, simulations were conducted for different temperatures (T), variable operating voltages, V_{DD} and V_g. The detailed simulation parameters are listed in Table 1. Then, after simulation is completed, the *I-V* data have been extracted according to the chosen parameter in each simulation scenario. After completing the considered oxide thickness along with the considered temperatures and voltages, the temperature characteristics of the SiNWT, which depend on variation of drain current as a performance metric of transistor sensitivity to varying temperature, were analyzed. The output SiNWT characteristic curves under various conditions and for different parameters were considered. Finally, the optimal values were identified for best temperature sensitivity and stability of SiNWT as a temperature nanosensor.

2.3 Temperature Sensitivity

Delta (Δ) expresses the 4th letter in the Greek alphabets which is spell as 'D' in the English alphabets. In general physics and mathematics, delta is the standard symbol to represent change in some quantity, viz. the differences between two numbers, measurements, etc. In this work, delta is used to measure and observe the drain current Id, where simulation results arrange many matrices according to Vg as a function of Id. It is calculated here by subtract the two values of Id for two different operating voltages.

Table 1 – Simulation parameters

Parameters	Value
Channel length, L	100 nm
Channel diameter, D	45 nm
Oxide thickness, T_{OX}	(1, 2, 3, 4,and 5) nm
Channel concentration p-type	10^{16} cm^{-3}
Channel concentration n-type	10^{19} cm^{-3}
Temperature	250, 275, 300, 325, 350, 375, 400, 425, 450 K
V_{DD}	0.25-5.0 V (0.25 V step increment)
Vg	0.25-5.0 V (0.25 V step increment)

3. RESULTS AND DISCUSSION

Current-Voltage (I_d-V_g) characteristics of SiNWT for each oxide thickness at a temperature of 225, 250, 275, 300, 325, 350, 375, 400, 425 and 450 K were simulated with the following channel parameters: 100 nm length, 45 nm diameter, channel concentration (p-type) is equal to 10^{16} cm^{-3}, source and drain concentration (n-type) is 10^{19} cm^{-3}. The oxide thickness values will be $T_{OX} = 1$, 2, 3, 4 and 5 nm).

Fig. 2 and Fig. 3 illustrate the changes in ΔI_d with increasing temperature in the V_{DD} ranges from 0 V to 5 V, step 0.25 V, for oxide thickness $T_{OX} = 1$ and 5 nm (minimum and maximum T_{OX}). It is obvious that the maximum temperature sensitivity (max. ΔI_d) occurs lower temperature values, the sensitivity decreases linearly with increasing temperatures for all operating voltages. The highest sensitivity for $T_{OX} = 1$ nm was achieved for 1.75 V operating voltage as shown in Fig. 3, whereas it was Tox = 5 nm at 3.5 V as illustrated in Fig. 4. In between, the temperature sensitivity changed as well as the operating voltage varied to 2.25, 2.75, and 3 V for $T_{OX} = 2$, 3, and 4 nm, respectively.

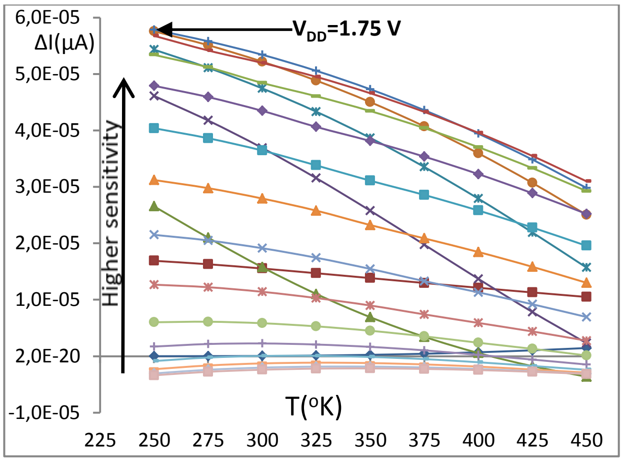

Fig. 2 – Temperature sensitivity at T_{OX} = 1 nm

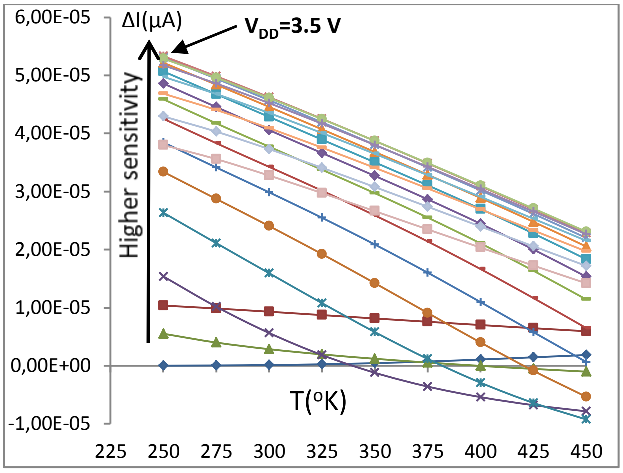

Fig. 3 – Temperature sensitivity at T_{OX} = 5 nm

For the sake of brevity, figures for other oxide thickness were omitted. Only the temperature characteristics of SiNWT for the lowest and the highest (T_{OX}) of this study are illustrated in figures. The changes in ΔI_d with respect to operating voltages for the considered temperature are displayed in Fig. 4 and Fig. 5 for the highest and the lowest oxide thicknesses. It is noticeable in Fig. 4 and Fig. 5 that the lower temperature is the higher transistor sensitivity with variable operating voltages, V_{DD} and V_g. It can also be noticed that as the operating voltages increase, the transistor becomes more stable regardless of the surrounding temperature. The best oxide thickness for temperature sensitivity was 5 nm because this thickness results in a higher velocity of carriers and lower channel resistance. Consequently, temperature has a positive impact on the I_d-V_g characteristics of SiNWT, which makes it a good candidate to be used as temperature nanosensor.

Fig. 6 depicts the optimized operating voltage (V_{DD}) according to the best temperature sensitivity and channel oxide thickness. The optimized operating voltage V_{DD} is extracted from the obtained temperature sensitivity peak values for each channel oxide thickness (1, 2, 3, 4, and 5 nm). As demonstrated in Fig. 6, the temperature sensitivity increases linearly with increasing T_{OX}.

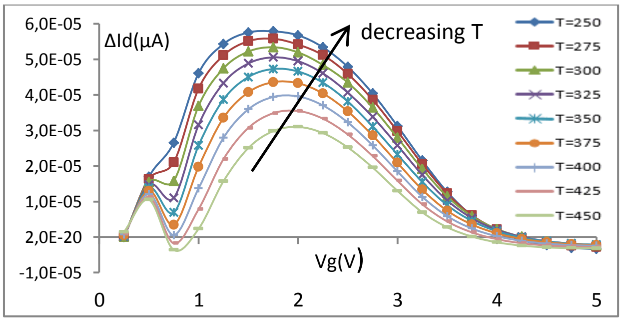

Fig. 4 – ΔI_d vs. V_g of SiNWT at T_{OX} = 1 nm

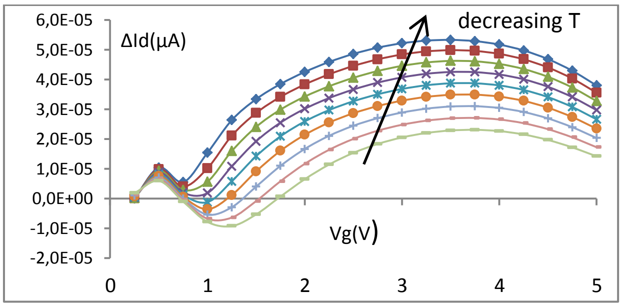

Fig. 5 – ΔI_d-V_{DD} characteristics of SiNWT at T_{OX} = 5 nm

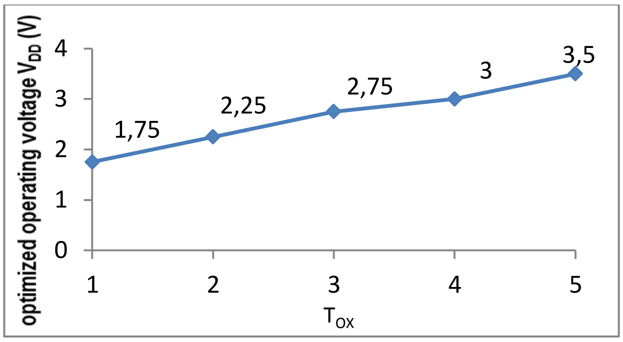

Fig. 6 – Optimized operating voltage V_{DD} with oxide thickness based on best temperature sensitivity

4. CONCLUSIONS

The impact of the working temperature on the characteristics of SiNWT along with the opportunities of using SiNWT as a temperature nanosensor were investigated in this paper. Different values of temperature (225, 250, 275, 300, 325, 350, 375, 400, 425 and 450 K) effects on SiNWT characteristics were studied with different oxide thickness T_{OX} = 1, 2, 3, 4 and 5 nm. The results prove the higher temperature sensitivity of SiNWT with 5 nm channel oxide thickness. The best sensitivity was obtained for lower temperature ranges and higher operating voltages. SiNWT can be a good candidate to work as a temperature nanosensor.

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Температурні характеристики кремнієвого нанопровідного транзистора у залежності від товщини оксиду

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Серед різних методів зондування та моніторингу датчики на основі на польових транзисторів (FET), привернули значну увагу як з боку промисловості, так і з академічних кіл. Завдяки своїм унікальним характеристикам, таким як невеликі розміри, легка вага, низька вартість, гнучкість, швидка реакція, стабільність і можливість подальшого зменшення масштабу, кремнієвий нанопровідний транзистор (SiNW-FET) може служити ідеальним наносенсором. Це найбільш імовірний наступник нанорозмірних пристроїв на базі FET. Однак, оскільки розміри (довжина та діаметр) каналу SiNWT зменшуються, електричні та температурні характеристики SiNWT повинні змінитися, тим самим погіршуючи роботу транзистора. Хоча застосування SiNWT як біологічних та/або хімічних сенсорів широко вивчено в літературі, менше уваги було приділено використанню таких транзисторів як датчиків температури. Отже, ця робота присвячена дослідженню температурної чутливості SiNWT в залежності від товщини оксидного каналу, а також представляє можливість використання його як нанотемпературного датчика. Інструмент моделювання MuGFET був використаний для дослідження температурних характеристик нанодроту. Моделювалися вольт-амперні характеристики з різними значеннями температури і з різною товщиною затворів нанодротів (товщина оксиду T_{OX} = 1, 2, 3, 4 і 5 нм). Для вимірювання температурної чутливості SiNWT було запропоновано підключення до діодного режиму метал-оксидного напівпровідника (MOS). Було досліджено кілька робочих напруг (від 0.25 до 5 В) з різною робочою температурою (250-450 K). Отримані результати показують, що найвища температурна чутливість досягалася за рахунок збільшення товщини оксиду до 5 нм. Вплив розглянутої температури на характеристики SiNWT свідчить про можливість його використання як наносенсора температури.

Ключові слова: SiNWT, Чутливість до температури, MuGFET, Моделювання.