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REGULAR ARTICLE

Temperature Impact on the Characteristics of *N*-Channel GaP Fin Field Effect Transistor (GaP-FinFET)

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This study analyzes the effects of temperature on transfer characteristics, threshold voltage, I_{ON}/I_{OFF} ratio, drain induced barrier lowering (DIBL), and sub-threshold swing (SS) in N-Channel Gallium Phosphide (GaP) Fin Fied Effect Transistor (FinFET). GaP-FinFET's temperature properties have been studied using the (MuGFET) simulation tool. Because of the lower I_{ON}/I_{OFF} ratio, higher DIBL, and higher SS at higher temperatures, the results show a detrimental impact of increased working temperature on the use of GaP-FinFET in electronic circuits, such as digital circuits and amplifier circuits. Furthermore, the best situation for using a transistor as a temperature nano-sensor is when it is in the ON state.

Keywords: GaP, FinFET, N-Channel, Temperature, Sensor.

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1. INTRODUCTION

The nanometer has been equally important to science in the first ten years of the twenty-first century as the micrometer was in the previous one. The manufacture of various new nano-devices with a variety of applications in medicine, biomaterials, electronics, and energy production has been the focus of significant studies published recently in Nanoscience and Nanotechnologies. [1-4]

Numerous novel device structures have been thoroughly investigated as the conventional silicon metal-oxide-semiconductor field-effect transistor (MOSFET) approaches its scaling limits. Among them, the fin-shaped field effect transistor (FinFET) has garnered considerable interest from researchers in the semiconductor industry and in academia. The semiconductor temperature sensor works best in embedded applications (i.e., for use within a particular equipment). [5]

The basic temperature and current-voltage properties of a transistor provide the basis of how most semiconductor temperature sensors work [6]. The base and collector of the bipolar transistor sensor are connected to operate it in diode mode. By coupling the gate to the source or drain of a MOSFET, a sensor can be created. Due to the need for transistors, diodes, resistors, and capacitors to be ever-smaller, silicon nanowires have drawn a lot of interest from the electronics sector. These devices' functionality and extra uses are dependent on the characteristics of the channel's form. The creation of a new class of ultra-small transistors and more potent computer chips that employ semiconductor FinFETs may be the subject of future studies in this area. Technology for manufacturing nanowire FETs is still being developed. Before a transition to modern MOSFETs can be made, more innovation is needed.

Based on the I_{ON}/I_{OFF} ratio and subthreshold swing (SS), Colinge et al. [7] compared the new transistor structure to the planer MOSFET. This team created devices with thin silicon-on-insulator nanowire channels that were 30 nm wide and had a rectangular cross section. The highest performance to date in the gated resistor device family is provided by these transistor devices, which produce I_{ON}/I_{OFF} ratios of 106 with SS close to the optimal MOSFET limit of 60 mV/decade at ambient temperature. [7-8]

To fully understand device physics and determine the performance boundaries of FinFETs, simulation is essential. Tools for simulation can assist experimental efforts to speed up the development of FinFETs [9], lower their cost, pinpoint their advantages and disadvantages, and show that they can be scaled down to the nanoscale range. [10]

2. METHODOLOGY

The creation of the transfer characteristics (I_d-V_g) of the transistor is the first step in this examination of the impact of temperature on the N-channel GaP-FinFET structure. Using a simulation tool called MUGFET, the transfer characteristic (I_d-V_g) of N-channel GaP-FinFET is simulated in this study. Purdue University is where the MUGFET simulation software tool is created [11-12]. The variables used in this simulation stage to determine the transfer characteristics of N-channel GaP-FinFET are shown in Table 1. The transfer characteristics of N-channel GaP-FinFET [drain current (I_d) - gate voltage (V_g)] of N-channel GaP-FinFET at V_d = 1 V (ON condition) with various temperature values (0, 25, 50, 75, 100, 125, and 150°C produced by MUGFET, these characteristics are shown in Fig. 1. These results are used as a data file for analyzing the effects of temperature on the transistor's characteristics, including the Subthreshold swing (SS), drain-induced barrier lowering (DIBL), and threshold voltage (V_T).

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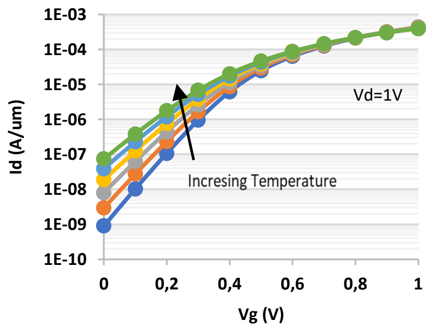
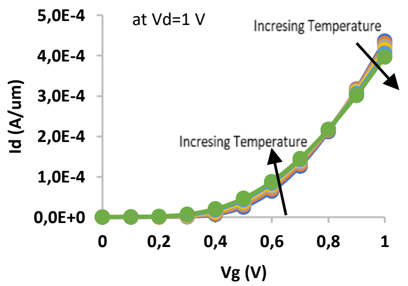
Table 1 – Parameters of N-Channel GaP-FinFET.

Parameter	**Value**
Channel length (*L*)	45 nm
Fin width (*W*)	30 nm
Oxide thickness (SiO_2)	2.5 nm
Channel concentration	1×10^6 cm $^{-3}$



(a)



(b)

Fig. 1 – Transfer characteristics with working temperature, (a) current in logarithmic scale, (b) current in linear scale

3. RESULTS AND DESCUSSIONS

This study used the simulation tool MuGFET to investigate how working temperature affects FinFET properties. The settings listed in Table 1 were used to simulate how temperature affects the properties of N-channel GaP-FinFETs. The transfer characteristics [drain current (I_d) - gate voltage (V_g)] at $V_d = 1$ V with various temperature values (0, 25, 50, 75, 100, 125, and 150 °C are shown in Fig. 1. According to the transfer characteristics, the current (I_d) rises as the temperature (T) rises.

According to Taur's calculations [13], the gate current density range for gate leakage current is 1 A/cm^2 to 10^4 A/cm^2 at 1 nm thick gate oxide and 0 V to 1 V gate voltage range. As a result, the leakage current at the 900 nm^2 transistor gate area is 900×10^{-14} A at $V_g = 0$ V and 900×10^{-10} A at $V_g = 1$ V, which is incredibly low and has no impact on the drain current according to the characteristics in Fig. 1.

According to the transfer characteristics, whether the state is OFF ($V_g = 0$ V) till $V_g = 0.8$ V, the current increases as the temperature rises and decreases with increasing working temperature for $V_g = 0.9$ V to ON state ($V_g = 1$ V). According to the traits of the resistance-temperature dependence of semiconductor-based devices, this finding can be attributed to the lowering channel resistance with rising operating temperature [14]. This figure also shows that in the temperature impact region, the higher current occurs at 125 °C.

Temperature affects the ON and OFF states threshold voltage V_T, ON-state V_T drops linearly while the OFF-state V_T rises linearly as temperature rises (Fig. 2). With rising gate voltage, the impact of temperature on current ($\Delta I_d/\Delta T$) grows, reaching its maximum impact at $V_g = 1$ V. The main variables that govern how well a transistor performs in digital or analog circuits, such as V_T, I_{ON}/I_{OFF} ratio, and drain-induced barrier lowering (DIBL), tend to be significantly impacted by this phenomenon.

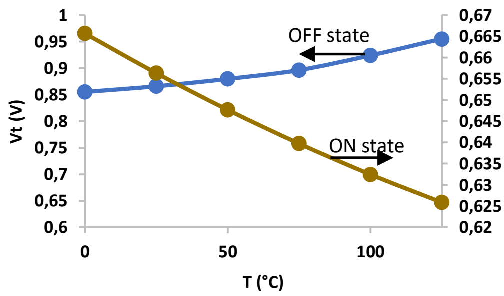


Fig. 2 – Threshold voltage (VT) versus temperature characteristics.

The I_{OFF} and I_{ON} temperature characteristics are shown in Fig. 3. Our research shows that whereas I_{OFF} increased exponentially with rising temperatures, I_{ON} decreased linearly with rising temperatures. Fig. 4 illustrates how temperature affects I_{ON}/I_{OFF}, one of the key variables in employing transistors in digital electronic circuits. These variables have a close connection to the I_d-V_g features. Fig. 4 shows the relationship between temperature and I_{ON}/I_{OFF}. The maximum value of I_{ON}/I_{OFF} occurs at 0°C and subsequently exponentially drops, as seen in Fig. 4. The optimal I_{ON}/I_{OFF} current ratio is at its highest value for many electrical circuit applications, including amplifiers and digital circuits.

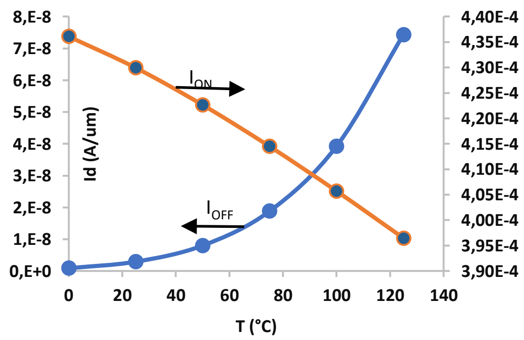


Fig. 3 – (a) (I_{ON}) and (I_{OFF}) currents versus temperature characteristics

The fluctuation in Subthreshold Swing (SS) with temperature is also shown in Fig. 5. SS related to the slope of the I_d vs V_g graph, with Id scaled logarithmically, is used to define SS. With rising temperature, SS increases linearly. The optimal value of SS is the lower one and optimal value is 60 mV/dec. The lower value for

SS is found at 0°C for both ON and OFF states, which also happens to be the best values. To achieve lower SS and a greater I_{ON}/I_{OFF} ratio, FinFET may be used in electronic circuits with reduced temperature requirements because of the results for I_{ON}/I_{OFF} and SS temperature characteristics.

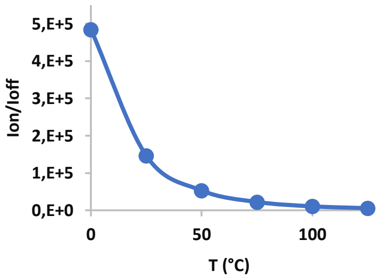


Fig. 4 – I_{ON}/I_{OFF} current ratio versus temperature characteristics

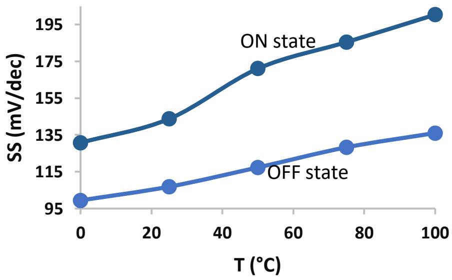


Fig. 5 – Sub-threshold swing (SS) versus temperature characteristics

DIBL is the lateral shift of the transfer characteristic curves in the sub-threshold regime (ΔV_T) divided by the drain voltage differential (ΔV_d) of the two curves, which is expressed in units of (mV/V). A crucial measure for analyzing MOSFET properties is DIBL [15].

The FinFET's operating temperature (T), which nearly climbs as the temperature increases from 0°C to 150°C, affects DIBL as shown in Fig. 6. Due to this high impact of T on DIBL, the transistor performs poorly in electrical circuits. The greater carrier velocity for n-type FinFETs as the fin width decreases is the likely cause of the large effect of temperature on the current in FinFET [16]. With channel cross-section scaling, the carrier velocities of n-type FinFETs do not appreciably change [16]. Additionally, in highly downscaled MOSFETs, the effective carrier injection velocity (V_{inj}) from the source to the channel controls the drain saturation current [17]. The concept of mobility does not exist in ballistic transport, and the drive current is instead controlled by the carrier injection velocity, which is a material property [16].

Using Fig. 3 as a guide, it is possible to use FinFET as a temperature nano-sensor. The greatest value of the OFF current sensitivity with temperature variation ($\Delta I_{OFF}/\Delta T$) is 1.4×10^{-9} A/(μm°C), and it increases exponentially with rising temperature. The greatest value of the ON current sensitivity with temperature variation, $\Delta I_{ON}/\Delta T$, is 2.46×10^{-7} A/(μm°C), and it falls linearly with rising temperature. Therefore, the ON current is ideal for employing the transistor as a nano-sensor for measuring temperature. Fig. 7 displays the changes in $\Delta I_{ON}/\Delta T$ and $\Delta I_{OFF}/\Delta T$ with temperature.

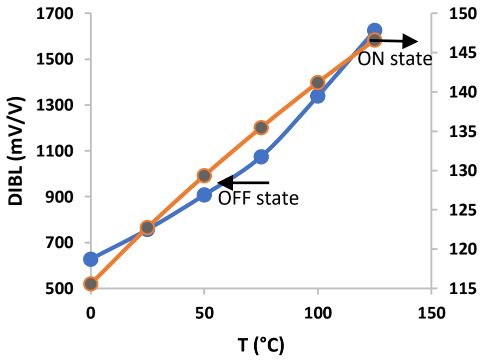


Fig. 6 – DIBL versus temperature characteristics

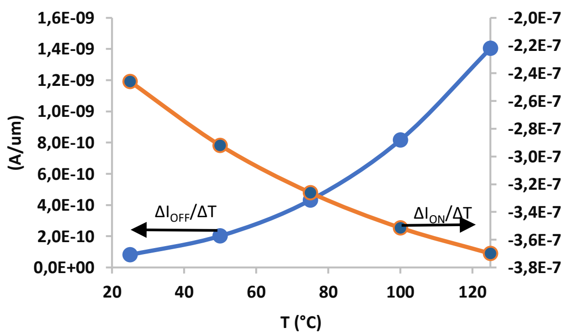


Fig. 7 – ($\Delta I_{OFF}/\Delta T$) and ($\Delta I_{ON}/\Delta T$) versus temperature characteristics

4. CONCLUSION

This paper uses MuGFET as a simulation tool to investigates the temperature characteristics and sensitivity of N-channel GaP-FinFETs. The findings show that employing FinFET in electronic circuits with high-temperature settings, such as digital circuits and amplifier circuits, has a negative impact on FinFET's electrical characteristics. To achieve lower SS and DIBL with a greater I_{ON}/I_{OFF} ratio, FinFET may be used in electronic circuits at the lowest temperature as possible, depending on the results for I_{ON}/I_{OFF}, SS, and DIBL with temperature characteristics. Additionally, FinFET's higher current sensitivity ($\Delta I_d/\Delta T$) made it ideal for use as a temperature sensor in the ON state. In conclusion, a transistor's current-voltage properties are negatively impacted by increased temperature, rendering it unsuitable for use in electronic circuits. Based on the transistor's ON state, a good temperature nano-sensor could be created, though.

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Вплив температури на характеристики *N*-канального польового транзистора GaP Fin (GaP-FinFET)

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У цьому дослідженні аналізується вплив температури на характеристики передачі, порогову напругу, співвідношення I_{ON}/I_{OFF}, зниження бар'єру, викликаного стоком (DIBL), і підпорогове коливання (SS) у *N*-канальному фосфідному галієвому транзисторі (FinFET). Температурні властивості GaP-FinFET були вивчені за допомогою інструменту моделювання (MuGFET). Через нижче співвідношення I_{ON}/I_{OFF}, вищий DIBL і вищий SS при вищих температурах результати показують шкідливий вплив підвищеної робочої температури на використання GaP-FinFET в електронних схемах, таких як цифрові схеми та схеми підсилювачів. Крім того, найкращою ситуацією для використання транзистора як температурного нанодатчика є його увімкнений стан.

Ключові слова: GaP, FinFET, *N*-канал, Температура, Сенсор.