Impact of Ambient Temperature on Electrothermal Characteristics of Gate-All-Around Nanosheet FETs

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ABSTRACT.

In this paper, the impact of ambient temperature on self-heating effects (SHEs) of 5nm gate-all-around nanosheet FETs (NS-GAAFETs) is investigated. The electrical characteristics of DC and AC, as well as the thermal characteristics of steady and transient state, are analyzed. Through numerical evaluations, it is shown that the ambient temperature strongly affects the electrothermal characteristics of NS-GAAFETs. With the ambient temperature increasing, the performances of NS-GAAFETs significantly deteriorate, where the on-off ratio ION/IOFF and sub-threshold swing SS decrease by 90.5% and 19.5% respectively.

Keywords: Nanosheet; GAA; SHEs; Electrothermal.

1. INTRODUCTION

With the continuous reduction of the process node, NS-GAAFETs with their excellent gate control capabilities and tunable channel widths have replaced FinFETs to become the new core devices [1]. However, NS-GAAFETs suffer from severe self-heating effects (SHEs), which are restricted by their 3D stacked structure and the reduced thermal conductivity of materials with the constraints of the geometry [2,3]. The reduction of process nodes leads to higher integration density, higher temperatures, and more severe SHEs, further resulting in performance degradation and lifespan reduction [4,5]. Therefore, it is extremely imminent to study the electrothermal characteristics of NS-GAAFETs to promote further development of the integrated circuit industry.

The rest of this paper is organized as follows. The second section introduces the device structure and calibration results of the N-type NS-GAAFET. The third section analyzes and discusses the fundamental electrothermal characteristics, and the impact of ambient temperature on the electrothermal characteristics of NS-GAAFETs. The fourth section summarizes the work.

2. DEVICE STRUCTURE AND CALIBRATION RESULTS

2.1 Device Structure

This article utilizes Synopsys' Technology Computer Aided Design (TCAD) tool to construct 5nm NS-GAAFET. This device is designed according to the requirements of IRDS [6] and IMEC [7]. The N-type NS-GAAFET constructed is shown in Figure. 1, and the specific parameters of this device structure are shown in Table 1.

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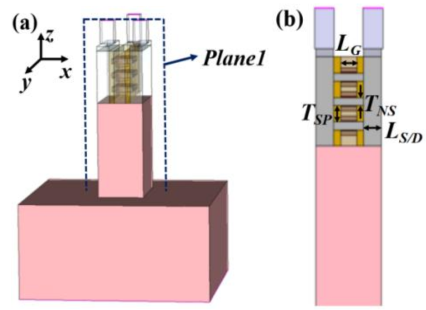

Figure 1. N-type NS-GAAFET (a) the 3D structure and (b) the 2D cross-section along plane1.

Table 1. Parameters of Device Structure.

Symbol	Quantity	Value
L_G	Gate length	12 nm
T_{SP}	Spacer thickness	5 nm
L_{NS}	Length between adjacent channels	10 nm
N_{NS}	Number of channels	3
W_{NS}	Channel width	40 nm
T_{NS}	Channel thickness	5 nm
$L_{S/D}$	Source/Drain length	13 nm
EOT	Equivalent oxide thickness	1 nm
N_{CH}	Doping concentration of the channel	1×10^{15} cm^{-3}
$N_{S/D}$	Doping concentration of the source/drain	1×10^{21} cm^{-3}
N_{BULK}	Doping concentration of the bulk	1×10^{18} cm^{-3}
N_{SUB}	Doping concentration of the substrate	1×10^{15} cm^{-3}

2.2 Calibration Results

The physical model determines the specific behavior of the device. The complete calibration process can be listed as follows. Build the device structure. Then, we select appropriate physical models and set corresponding boundary conditions. Performing electrothermal simulation, the transfer characteristic curve of saturation region is obtained. Calibrate the sub-threshold region by adjusting the work function of the gate metal and calibrate the saturation region by adjusting the mobility. In the following sections, we assume drain voltage as *Vds* and gate voltage as *Vgs*, respectively.

Figure. 2 indicates that under the conditions of *Vds* = 0.7V and *Vgs* = 0.7V, the simulation results match the experimental data well [8]. Therefore, the electrothermal simulation platform based on the N-type NS-GAAFET is established.

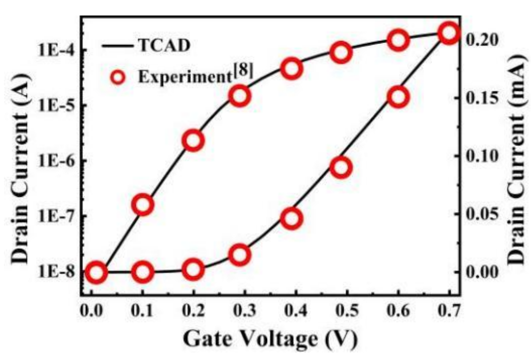

Figure 2. The transfer characteristic curves of the calibrated device and the experimental data.

3. ELECTROTHERMAL CHARACTERISTICS OF NS-GAAFET

3.1 Electrical characteristics of DC and AC

In this section, on the basis of the simulation platform established in section 2, the DC and AC electrical characteristics of the N-type NS-GAAFET without SHEs are studied. Figure. 3(a) shows the transfer characteristic curves of linear and saturation region, respectively. The on-state current I_{ON} is 50.54 μA when V_{gs} = 0.7V and V_{ds} = 0.05V.

Table 2 denotes the key electrical parameters when V_{gs} = 0.7V and V_{ds} = 0.7V. The off-state current I_{OFF} is 5.7 nA, the on-state current I_{ON} is 236.4 μA, the on-off ratio I_{ON}/I_{OFF} is 4.2×10^4, the threshold voltage V_{th} is 0.167 V, and the sub-threshold swing SS is 75.2 mV/dec.

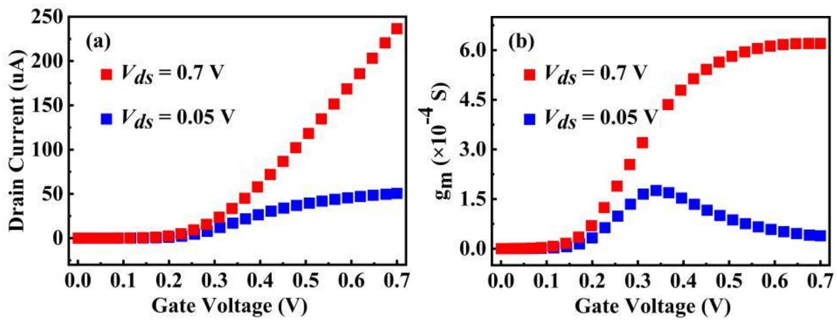

Figure 3. N-type NS-GAAFET (a) transfer characteristics and (b) trans-conductance characteristics.

Table 2. Device Electrical Parameters.

Symbol	Quantity	Value
I_{ON}	On-state current	236.4 μA
I_{OFF}	Off-state current	5.7 nA
I_{ON}/I_{OFF}	On-off ratio	4.2×10^4
V_{th}	Threshold voltage	0.167 V
SS	Sub-threshold swing	75.2 mV/dec

Figure 3(b) shows the trans-conductance characteristics of the N-type NS-GAAFET with different gate voltages. The maximum trans-conductance in the linear region is 1.8×10^{-4} S, and the maximum trans-conductance in the saturation region is 6.2×10^{-4} S.

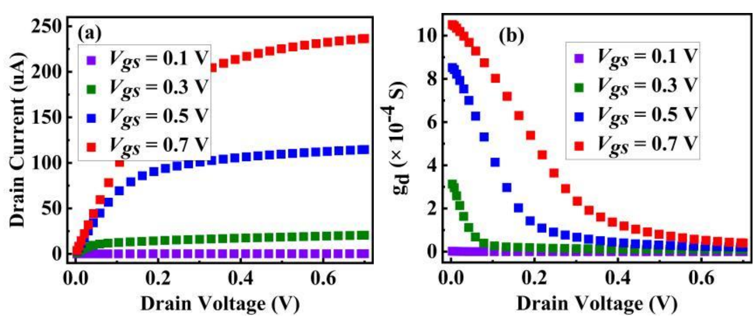

Figure 4. N-type NS-GAAFET (a) output characteristics and (b) conductance characteristics.

Figure. 4(a) shows the output and conductance characteristics of the N-type NS-GAAFET. We set the values of Vgs are 0.1V, 0.3V, 0.5V, and 0.7V, respectively. Correspondingly, the drain-source currents are 0.13 μA, 20.5 μA, 114.6 μA, and 236.4 μA when Vds = 0.7V. Figure. 4(b) denotes that the conductance gd decreases with the growth of drain voltage. Simultaneously, gd increases as the gate voltage increases. The maximum conductance values under different conditions of Vgs are 1.7×10-6 S, 3.1×10-4 S, 8.5×10-4 S, and 1.1×10-3 S, respectively.

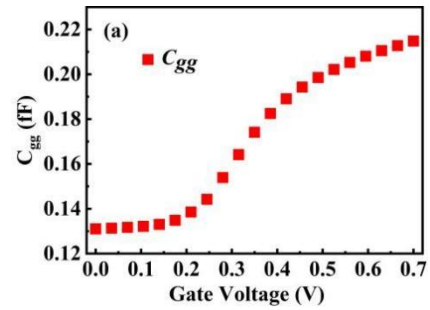

Figure 5. Gate-to-gate capacitance versus gate voltage.

The analysis of the AC characteristics of the N-type NS-GAAFET provides a theoretical basis for the electrothermal co-simulation of the device. We obtain the gate capacitance characteristics of the N-type NS-GAAFET by grounding the source, drain and body electrodes, and scanning the gate voltage at a frequency of 1MHz. The variation of gate-to-gate capacitance C_{gg} versus different gate voltage is shown in Figure. 5.

3.2 Thermal characteristics of steady and transient state

We plot the influence of SHEs on the transfer characteristic of saturation region in Figure. 6. As the gate voltage Vgs increases, the lattice temperature of the device also increases, while the electron mobility decreases, which lead to the degradation of the drain-source current Ids ultimately. We find that Ids is hardly affected by SHEs, when Vgs is relatively small. On the contrary, the degradation percentage of Ids is as high as 11.95%, when Vgs reaches 0.7V.

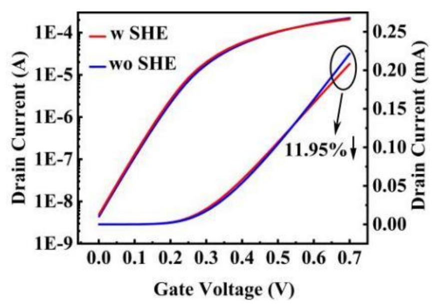

Figure 6. The influence of SHEs on the transfer characteristic.

Assuming the peak temperature is Tpeak, the lattice temperature distribution of the N-type NS-GAAFET is shown in Figure. 7(a). Figure. 7(b) shows that Tpeak is 411.6 K.

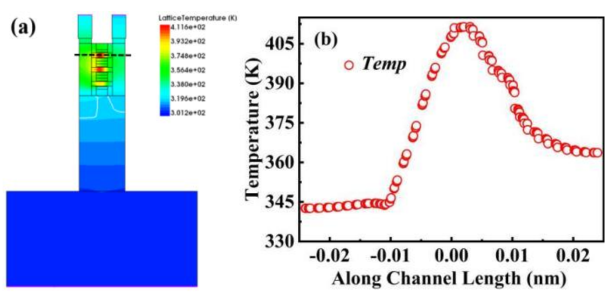

Figure 7. N-type NS-GAAFET (a) lattice temperature distribution and (b) lattice temperature distribution curve along the channel length.

We set the ambient temperature to 300K, Vds to 0.7V, and the working frequency F of Vgs to 1GHz with an amplitude of 0.7V when studying the transient electrothermal characteristics of the N-type NS-GAAFET. Figure. 8(a) shows the variation of Vgs and temperature versus different time. The result indicates that the Tpeak of the N-type NS-GAAFET is 405.1K at the falling edge of the voltage.

Figure. 8(a) denotes that the temperature of the NS-GAAFET has not yet reached a steady state when F is 1GHz. In order to reach the stable temperature of the device, we set F = 100MHz. Figure. 8(b) shows that the Tpeak is 411.6 K which is larger than the value of Tpeak when F = 1GHz.

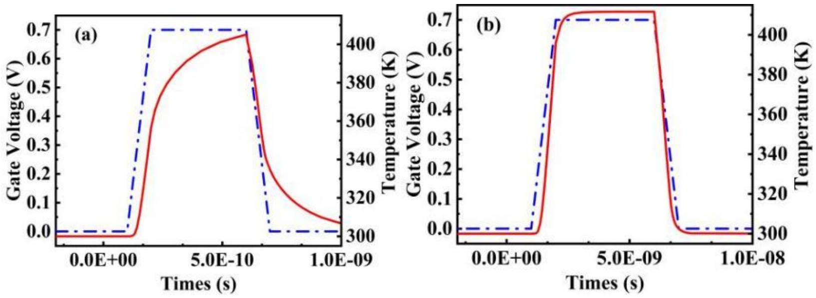

Figure 8. Transient response curves (a) F = 1GHz and (b) F = 100MHz.

3.3 Impact of ambient temperature

Temperature is a very important factor that affects the performance of the device, so it is necessary to evaluate the reliability of NS-GAAFETs by studying the variation of ambient temperature [9, 10].

We plot the impact of ambient temperature on the transfer characteristic in Figure. 9. We find that the off-state current Ioff increases from 5.69 nA to 58.4 nA as the ambient temperature Tamb increases from 300 K to 360 K. Simultaneously, as the ambient temperature rises the on-state current Ion of the device decreases from 208.2 μA to 202.3 μA, the on-off ratio decreased from 3.7×104 to 3.5×103 and the sub-threshold swing SS in the saturation region increases from 75.2 mV/dec to 89.9 mV/dec.

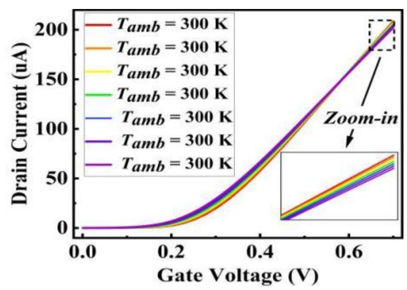

Figure. 9 Impact of ambient temperature on the transfer characteristic.

According to the definition of thermal resistance, Rth is proportional to the temperature difference, which is given by

$$R_{th} = \frac{T_{peak} - T_{amb}}{P} \tag{1}$$

where Tpeak is the peak lattice temperature of the device, Tamb refers to the ambient temperature, and P represents the power of the device.

The peak lattice temperature Tpeak of the device rises from 411.6 K to 477.2K when Tamb increases from 300 K to 360 K. The thermal resistance Rth increases from 0.77K/uW to 0.83K/uW, representing with the increment of 7.2%. The thermal resistance Rth can be used to characterize the heat dissipation capability of a device. A smaller thermal resistance indicates better heat dissipation capability, whereas a larger thermal resistance indicates poorer heat dissipation capability.

Table 3 lists the performance parameters of the N-type NS-GAAFET related to the temperature. In addition, the impact of ambient temperature on the threshold voltage Vth is also presented. We find that Vth shows a decreasing trend as the temperature rises.

Table 3. Temperature Related Performance Parameters.

T_{amb} (K)	300	310	320	330	340	350	360
I_{ON} (μA)	208.2	207.3	206.3	205.4	204.4	203.4	202.3
I_{OFF} (nA)	5.7	9.0	13.8	20.5	29.7	42.1	58.4
I_{ON}/I_{OFF}	3.7×10^4	2.3×10^4	1.5×10^4	1×10^4	6.9×10^3	4.8×10^3	3.5×10^3
V_{th} (V)	0.167	0.158	0.149	0.14	0.131	0.123	0.114
SS (mV/dec)	75.1	77.6	80.1	82.6	85.0	87.5	89.9
T_{peak} (K)	411.6	422.6	433.5	444.4	455.4	466.3	477.2
R_{th} (K/uW)	0.77	0.78	0.79	0.80	0.81	0.82	0.83

4. SUMMARY

In this article, we have investigated that the electrical characteristics of DC and AC, as well as the thermal characteristics of steady and transient of NS-GAAFETs. In addition, we have studied the impact of ambient temperature on self-heating effects (SHEs) of the device. The results have shown that with the growth of ambient temperature Tamb, the electrothermal characteristics of NS-GAAFETs deteriorate significantly. Among them, ION/IOFF, Tpeak, SS, and Rth deteriorate by 90.5%, 15.9%, 19.5%, and 7.2%, respectively. There is a smaller influence on ION, which is decreasing by 2.8%.

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