Impact of Elliptical Cross-Section on Some Electrical Properties of Gate-All-Around MOSFETs

Shankaranand Jha, Ashok Kumar and Subindu Kumar

Abstract--- Silicon (Si) Gate-All-Around (GAA) MOSFETs offers full electrostatic control over the gate which makes them promising candidates for the next generation complimentary metal-oxide-semiconductor field-effect transistors (CMOS) devices. Due to variations in the growth condition, the cross-section of GAA MOSFETs is often elliptical instead of being perfectly circular. This elliptical cross section changes the effective diameter of the silicon core which in turn affects the electrical properties of the device. In this paper we analyze the impact of elliptical cross-section of multi-channel Si GAA MOSFET on some electrical properties such as threshold voltage, drain current, and so on. The dependence of such properties on doping concentration, thickness of the oxide (insulator), channel dimension and number of conducting channels are also presented.

Keywords--- Aspect Ratio, Effective Diameter, MOSFET, Multi-Channel

I. INTRODUCTION

THE near-ideal characteristics of Gate-All-Around (GAA) MOSFET makes it a promising candidate for the next-generation nanoscaled circuits. The symmetry of GAA MOSFET has enabled the research community to go in for various approximations in the derivation of the characteristics of the device which would otherwise have been very complex. GAA MOSFETs do not have corner effects [1] due to the circular cross-section and cylindrical body. Furthermore, by solving the Poisson/drift-diffusion equation in cylindrical co-ordinates, the electrical characteristics of GAA devices can be modeled analytically [2,3]. Recently CMOS compatible multi-channel (MC) GAA MOSFETs having diameters ≤ 5 nm has been demonstrated with excellent performance [4].

Due to limitations in the fabrication process, the cross section of GAA devices is not circular. The fabricated structures may have elliptical cross section with different major and minor axis lengths [5-7]. The geometric aspect ratio

(AR) of the elliptical GAA MOSFET is defined as the ratio of the length of the major axis (a) to that of the minor axis (b). As a special case, when a and b are equal, the structure is perfectly circular. The ideally circular cross section of GAA MOSFET may not give the optimized circuit performance. The effect of elliptical cross-section on the electrical characteristics have not been widely discussed or analyzed. In this paper we emphasize on the electrical characteristics of MC elliptical GAA MOSFETs for a wide range of diameters.

II. LITERATURE SURVEY

There are several research papers in the frontier of modern electronics which deals with the fabrication, theoretical modeling, and analysis of perfectly circular GAA MOSFETs [8-10]. The cross-section of fabricated GAA devices, which take part in real time circuit operation, may be elliptical. There are few reports which have emphasized on the modeling and analysis of such elliptical GAA devices. The pioneer works on elliptical GAA MOSFETs include the studies of Li and Hwang [11] on the effects of geometry AR on elliptical GAA transistor using 3D coupled device-and-circuit simulations.

The universality of short-channel effects in undoped-body silicon nanowire MOSFETs having elliptical cross section was proposed by Bangsaruntip et al. [12]. They have shown that the short-channel effects of undoped-body GAA MOSFETs can be improved by shrinking the body dimensions. Zhang et al. [13] proposed the concept of effective radius to convert elliptical GAA MOSFETs into equivalent circular GAA

Figure 1: (a) Structure of GAA MOSFET, (b) Cross sectional view and (c) Schematic of an elliptical GAA with the major axis length, 'a' and minor axis 'b'.

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MOSFETs for studying short-channel effects. They found that the elliptical GAA MOSFETs that have the same effective radius exhibit the same short channel effects and I_{ON}/I_{OFF} ratio.

III. THEORETICAL DETAILS

Figure 1(a) represents the structure of a GAA MOSFET. The cross section is shown in Figure 1(b). Figure 1(c) represents the schematic of an elliptical GAA with the major axis length, 'a' and minor axis 'b'. The aspect ratio is defined as a/b . The overall threshold voltage, V_{th} , of the GAA MOSFET is given by $V_{th} = V_{th0} + \Delta V_t + \Delta V_{QM}$ [14],[15]. V_{th0} is the threshold voltage that is similar to that of the bulk MOSFETs [16] and ΔV_t is the additional component of the threshold voltage due to the special geometry of GAA MOSFETs given by [14]

$$V_{th0} = \Delta\phi + 2\phi_f + \frac{Q_{dep}}{C_{OX}} - \frac{1}{\beta} \ln \left(\frac{2\beta q N_a \epsilon_{Si}}{C_{OX}^2} \right) \quad (1)$$

$$\Delta V_t = -\left(\frac{1}{\beta}\right) \ln \left(\frac{2C_{ox}}{\beta q N_a d_{eff}} \right) [1 - \exp(-\frac{q^2 N_a d_{eff}^2}{16\epsilon_{Si} kT})] \quad (2)$$

where

- $\Delta\phi$ work function difference between the gate material and silicon body;
- C_{OX} $2\epsilon_{OX}/[d_{eff} \ln(1+2t_{OX}/d_{eff})]$. Effective oxide capacitance per unit gate area;
- t_{OX} thickness of the gate oxide;
- d_{eff} effective diameter of the elliptical silicon body [13];
- C_{total} total oxide capacitance;
- ϕ_f Fermi potential;
- Q_{dep} $qN_a d_{eff}/4$. Depletion charge density per unit gate area;
- N_a impurity concentration in the silicon body;
- $(1/\beta) = kT/q$. Thermal voltage.

ΔV_{QM} is another additional component which takes into account the changes in V_{th} due to the nanometric diameter of GAA devices. Other variables, such as n_i , q , k , T , ϵ_{OX} , and ϵ_{Si} , have their usual physical meanings. The saturated drain current, I_{DSat} of a coaxially gated n-channel GAA MOSFET can be expressed as [14]:

$$I_{DSat} \approx \frac{\mu(\pi d_{eff})}{L} C_{OX} \left[\frac{1}{2} (V_{gs} - V_{th})^2 - \frac{1}{\beta^2} e^{\beta(V_{gs} - V_{th} - V_{ds})} \right] \approx \frac{\pi d_{eff} \mu}{2L} C_{OX} (V_{gs} - V_{th})^2 \quad (3)$$

where

- μ mobility of the charge carriers under consideration;

Figure 2: Percentage change in effective diameter with minor axis 'b' corresponding to AR = 2.0 and 0.5.

L channel length of the GAA structure;

For our computations we have considered a $1\mu\text{m}$ long n-channel GAA MOSFET with SiO_2 as the gate dielectric. It is worth mentioning here that in this work, we have considered long channel devices, which are still of technological importance, to eliminate short channel effects so that the contribution of GAA structure is highlighted. Since the geometry AR of elliptical GAA structure is seldom larger than 2.0 [13] and in order to keep our computation within presentable limits, we have varied the AR from 0.5 to 2.0. This range of AR is obtained by keeping 'b' fixed and varying 'a' for a particular set of computation. As a special case, AR=1.0 gives us a circular cross section.

IV. RESULTS AND DISCUSSION

The results of our computations for n-channel devices are shown in Figures 2–9. The percentage change in effective diameter for various minor axis, corresponding to AR = 2.0 and 0.5 is depicted in Figure 2. 0% corresponds to a perfectly circular cross-section having AR = 1.0. For AR > 1.0, there is an increase in the effective diameter which is shown in the positive axis of Figure 2. For AR < 1.0, the results of our computations are reversed. This is in consistence with the results reported by Zhang et al [13]. This variation in the effective diameter in turn affects the threshold voltage and drain current of an elliptical GAA device. Figure 3 represents the variation of the threshold voltage of nMOS GAA with channel doping concentration for AR ranging from 0.5 to 2.0 corresponding to $b = 1.5$ and 20 nm. A change in the AR results in the change of the effective diameter which in turn changes the threshold voltage of the device. We observe that for both $b = 1.5$ and 20 nm, V_{th} corresponding to a particular AR remains constant for lightly and moderately doped channel. For highly doped channel, V_{th} shoots up for all ARs. The V_{th} shooting is more pronounced for larger elliptical cross sections. The impact of doping concentration on the threshold voltage of perfectly circular GAA was reported in [14]. We obtained a similar nature as illustrated in Figure 3, where we

Figure 3: Variation of threshold voltage with channel doping concentration for different ARs corresponding to $b = 1.5$ and 20 nm.

Figure 4: Variation of the threshold voltage with AR for different metal work functions corresponding to $b = 1.5$ and 20 nm.

have considered a number of device ARs including a perfectly circular GAA having $AR = 1.0$.

Figure 4 depicts the variation of V_{th} with AR for different metal work functions, ϕ_m , corresponding to $b = 1.5$ and 20 nm. As expected, the V_{th} corresponding to a lower value of ϕ_m for a particular AR is the least. For larger cross sections, there is a monotonic decrease in V_{th} with AR. It could be inferred that on one hand decreasing ϕ_m reduces the value of V_{th} and on the other hand, for larger GAA cross section, V_{th} increases as we decrease the AR. Selecting a proper value of V_{th} is a trade-off between (1) the metal work function and (2) the geometry of the GAA device.

Figure 5 shows the current driving capability of elliptical GAA MOSFET for various ARs corresponding to different minor axis. We have taken into account the saturated drain current which increases monotonically with the AR. We observe that a circular GAA with $AR=1.0$ is an optimized structure as the current driving capability can be further enhanced by increasing the AR. It is also found that devices

Figure 5: Variation of the saturated drain current with AR for $b = 1.5, 2.5, 10$ and 20 nm.

Figure 6: Variation of the saturated drain current with AR for multi-channel GAA MOSFETs. 'N' denotes the number of channels.

with larger cross section can furnish more current than their smaller counterpart. This is in consistence with (3). In Figure 6 the variation of the saturated drain current with AR is plotted for GAA MOSFETs having number of conducting channel(s) $N = 1, 20$ and 40 . One of the most interesting characteristics of MC GAA devices is that the current driving capability can be increased by increasing the number of channels, keeping the geometrical aspect and the physical dimensions unchanged.

The dependence of the saturated drain current on the oxide thickness for $b = 1.5$ and 20 nm corresponding to various ARs has also been investigated and the results are depicted in Figure 7. The drive current can be increased to a large extent by reducing the oxide thickness. In an effort to increase the drive current on one hand by reducing the oxide thickness beyond 1.5 nm, the gate tunneling current may increase on the other hand. An optimized selection of the oxide thickness is necessary for designing GAA devices. It is also observed that for a fixed oxide thickness, the drive current is more for an AR of 2.0 .

Figure 7: Variation of the saturated drain current with gate oxide thickness for different ARs corresponding to $b = 1.5$ and 20 nm.

Inverters form the basic building block of complex digital circuits. The performance of the inverter depends on the structure of the n- and p-MOSFETs. As one of the most important performance parameters in CMOS digital circuits, propagation delay is of concern to designers and users. A simple way of analysing the propagation delay is to replace the device with its On-Resistance, extract the load capacitance and calculate the RC time constant. Several approaches use such strategy for the transient analysis. In this work, we have emphasized on the average On-Resistance, which is an important electrical parameter of coaxially gated MC GAA MOSFET for determining the propagation delay of digital circuits. Figure 8 shows the variation of average On-Resistance of n-channel GAA device with AR corresponding to various conducting channels for $b = 1.5$ and 20 nm. We observe that the On-Resistance decreases monotonically with AR. Figure 8 also depicts that the On-Resistance of GAA devices can be drastically decreased by increasing the number of conducting channels. These, in turn, affect the transient characteristics of the circuit significantly, as shown in Figure

Figure 8: Variation of ON-resistance with AR for number of channels 2, 50 and 100 corresponding to $b = 1.5$ and 20 nm.

Figure 9: Plot of output fall time of MC n-GAA MOSFET with number of conducting channels corresponding to various ARs. The inset shows the discharging path from the load capacitance to ground through n-type GAA device.

9, where the variation of output fall time (τ_{PHL}) of n-type MC elliptical GAA MOSFET is plotted against number of conducting channels corresponding to various ARs. The output fall can be expressed as $\ln(2)\tau_n$, where $\tau_n (= R_{avg,n}C_L)$ is the time constant related to the discharging of the n-MOS, as illustrated in the inset of Figure 9. C_L is the load capacitance which includes the parasitic output capacitance of the inverter, the interconnect capacitance and the gate capacitance of the next stage circuit. In this work C_L has been considered to be 50 fF. To validate and compare our approach, we have computed the τ_{PHL} of GAA MOSFET based circuits with the parameters reported by Buddhharaju et al [4], Huang et al [17] and Rustagi et al [8]. The average deviation was found to be less than 5%.

One of the advantages offered by multi-channel GAA MOSFETs is that the drain current can be tuned by solely increasing (decreasing) the number of conducting channels, which in turn modifies τ_{PHL} , and hence the propagation delay of circuits utilizing GAA devices. We observe a drastic reduction in the fall time with increasing number of conducting channels in n-MOS. In this work, we have focused on the fall time of n-type GAA device. However, for calculating the average propagation delay of CMOS circuits, the output rise time needs to be computed. In case of planar CMOS inverters, to compensate for the low value of hole mobility for achieving symmetry in rise and fall times, with fixed gate length L , the width W for the p-MOS is kept typically $\sim 2\times$ higher than that of n-MOS [16]. In case of GAA MOSFETs (similar to the case of FinFETs), the 'diameter' (similar to the 'width' of planar MOSFETs) is fixed and is same for both the n-MOS and the p-MOS devices. Therefore, the low values of hole mobility can be compensated by choosing larger number of channels for p-MOS transistors [4]. To obtain equal rise and fall time of a MC GAA MOSFET based complementary circuit, care has to be taken to increase the number of conducting channels of p- GAA MOSFET

simultaneously maintaining the ratio 1:2. It is also worth mentioning here that output fall time may be brought down to few pico-seconds by increasing the number of conducting channels, as shown in Figure 9. Use of 100 channels per GAA device has also been reported in the literature [4].

V. CONCLUSION

To summarize, we have investigated the effect of AR, channel doping concentration, metal work function, number of conducting channels and gate oxide thickness on some electrical parameters of MC elliptical GAA MOSFET. Some techniques are discussed which may be useful for optimized design of GAA devices. Through our computations, we have shown that the transient characteristics of MC GAA devices can be improved by tuning the number of conducting channels. We have also established that GAA MOSFETs having ideally circular cross section do not give the optimized device characteristics.

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