**Indonesian Journal of Electrical Engineering and Computer Science**
Vol. 14, No. 1, April 2019, pp. 241~249
ISSN: 2502-4752, DOI: 10.11591/ijeecs.v14.i1.pp241-249 

# Compact modeling of strained GAA SiNW

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**Article Info**

***Article history:***

Received Jun 1, 2018
Revised Oct 10, 2018
Accepted Nov 25, 2018

***Keywords:***

3D
MOSFET
Strained GAA SiNW
TCAD

**ABSTRACT**

Strain-based on advanced MOSFET is a promising candidate for the future of CMOS technology. A numerical model is not favorable compared to a compact model because it cannot be integrated into most simulator software. Thus, a compact model is proposed to overcome the shortcomings in the analytical model. In this paper, a charge-based compact model is presented for long-channel strained Gate-All-Around Silicon Nanowire (GAA SiNW) from an undoped channel to a doped body. The model derivation is based on an inversion charge which has been solved explicitly using the smoothing function. The drain current model is formulated from Pao Sah's dual integral which is formed in terms of inversion charge at the drain and source terminals. The proposed model has been extensively verified with the numerical simulator data. The strained effect on the electrical parameters are studied based on inversion charge, threshold voltage and current-voltage (I-V) characteristics. Results show that the current, the inversion charge and the threshold voltage can be greatly improved by the strain. The threshold voltage was reduced approximately 40% from the conventional GAA SiNW. Moreover, the inversion charge was improved by 30 % and the on-state current has doubled compared to unstrained device.

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## 1. INTRODUCTION

An advanced MOSFET such as Gate-All-Around SINW (GAA SiNW) is introduced to overcome the shortcomings in the conventional MOSFET. The architecture of the gate completely surrounding the channel in GAA SiNW allows the device to have excellent gate control and able to minimize the short channel effects [1-2].

To understand the behavior of the device, an analytical model is required [1-10]. However, this modeling method is impractical because it is unable to extend into the circuit level simulator. The models need to be solved iteratively and this function(iteration) not provided in the circuit simulator such as Hspice. As a result of this limitation, more compact modeling works have been proposed which are needed for the design and characterization of the GAA SiNW at circuit level [14-19].

There is extensive literature on improving the model for a different condition such as undoped and doped body channel [2-10]. However, there is little work on device modeling using strain on GAA structure. From previous studies, strain-based on Ge fraction is used to boost up the current and lowering the threshold for conventional and advanced MOSFET structures [17-23]. For strain application in GAA structures, the existing models have used the analytical approach [22-23]. However, the model is limited to the threshold and is not enough to analyse the strain behaviour.

In order to enable the extension of the strained GAA into the circuit level, a compact model approach is introduced. In this paper, we present a compact model for strained GAA SiNW. This model can be derived from the analytical model and solved explicitly using the smoothing function. The model was incorporated with the interfaced trapped charge and fixed oxide charge. Moreover, the model is also valid for a practical range of doping. We have considered a long channel device to focus the effect of strain on device behaviour. This work can be used as a core model for strained GAA device. To validate our model, results are compared with publishing work and three-dimensional (3D) simulations obtained using Technology Computer Aided Design (TCAD) software.

## 2. MODELING OF STRAINED GATE ALL-AROUND SILICON NANOWIRE

Figure 1 illustrates the schematic diagram of the proposed model using the explicit method. In this model, fixed oxide ($\phi_f = v_{th} \ln(N_A / n_i)$) charge is considered to enumerate the actual fabrication environment especially for a thin oxide layer. The diameter and channel are defined at r-direction and y-direction, respectively.

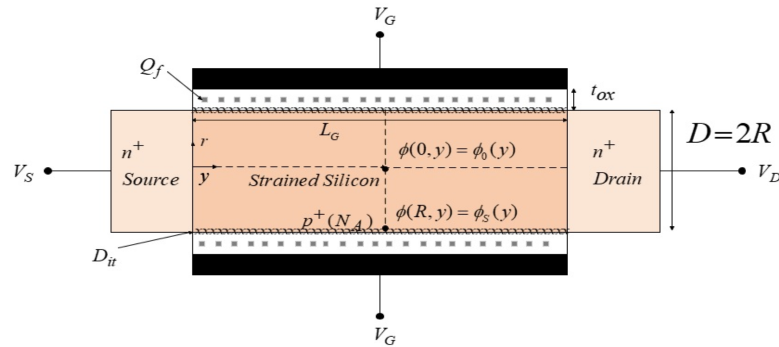


Figure 1. Cross sectional diagram for n-type strained Gate All Around GAA SiNW

One dimensional (1D) Poison-Boltzmann for GAA SiNW Figure 1 can be represented in cylindrical coordinate as

$$\frac{1}{r}\frac{d}{dr}\left(\frac{rd\phi}{dr}\right) = q\frac{N_a}{\varepsilon_{si}}(1+e^{\beta\left(\phi - V_{ch} - 2\phi_f\right)}) \tag{1}$$

where $r$ and $\phi$ are defined as the radial of the GAA and potential at the channel region due to gate biasing. The constant, $\beta$, is defined as $1/v_{th}$, where $v_{th}$ is the thermal voltage. This model can be used for both the undoped and doped channel. The quasi-fermi potential along y-axis (channel) is assumed as constant and fermi potential can be explicitly calculated as $\phi_f = v_{th}\ln(N_A / n_i)$ with intrinsic doping body, $n_i = 1.45 \times 10^{10} cm^{-3}$. The potential at the surface ($\phi_s$) and center region ($\phi_o$) can be determined using the following boundary conditions:

$$\left.\frac{\delta\phi}{\delta r}\right|_{r=0} = 0,\ \phi_{(r=0)} = \phi_0,\ \phi_{(r=R)} = \phi_s \tag{2}$$

The vertical electric field ($E_s$) at the surface can be formulated as

$$-E_s = \left.\frac{d\phi}{dr}\right|_{r=R} = \frac{Q_{inv} + Q_{dep}}{\varepsilon_{si}} \quad (3)$$

where $q_{inv}$ and $q_{dep}$ are inversion charge and depletion at the channel. By solving equation (2) and (3), the changes of potential at r-direction can be simplified as

$$\frac{d\phi}{dr} = \frac{Q_{dep}}{\varepsilon_{si}} + \frac{2Q_{dep}}{R}\left(\frac{1}{Q_{dep} + q_{inv}}\right) e^{\frac{\phi_s - V_{ch} - 2\phi_f}{v_{th}}} \left(1 - e^{\frac{\phi_s - V_{ch} - 2\phi_f}{v_{th}}}\right) \quad (4)$$

The final solution of surface potential can be represented as

$$\phi_s = 2\phi_f + V_{ch} + v_{th}\ln(Q_{in}) + v_{th}\ln\left(\frac{R}{v_{th}\varepsilon_{si}}\right) + v_{th}\ln\left(1 + \frac{Q_{in}}{Q_{dep}'}\right) - v_{th}\ln\left(e^{\frac{-qN_aR^2}{4\varepsilon_{si}}}\left(e^{\frac{-qN_aR^2}{4\varepsilon_{si}}} - 1\right)\right) \quad (5)$$

where $q_{dep}' = C_{ox}v_{th}/H'$ is defined in terms of the doping effect ($H'$) and structural parameter which were taken from [16-17]. From the Gauss Law, the charge can be calculated as

$$Q_t = C_{ox}\left(V_{GS} - V_{fb} + \frac{Q_f}{C_{ox}} - \phi_s\eta\right) \quad (6)$$

where $C_{ox}$ is the oxide gate capacitance, $V_{fb}$ is the flatband voltage and $\eta$ is the variable related to the interfaced trapped charge which is significant at heavily body doping ($\eta = 1 + qD_{it}/C_{ox}$). Thus, for undoped and lightly doped cases, $\eta$ can be set as 1[10]. The equation in (6) can be rearranged to form a unified charge control model (UCCM) adapted from [11] by replacing the equation (5) into equation (6). The final form of UCCM model can be formulated as

$$\frac{Q_{in}}{C_{ox}} + \eta v_{th}\ln(Q_{in}) + \eta v_{th}\ln\left(1 + \frac{Q_{in}}{Q_{dep}'}\right) = V_{GS} - V_0 - \eta V_{ch} \quad (7)$$

where $V_0$ is the threshold voltage for GAA SiNW can be explicitly calculated as

$$V_0 = \Delta\phi + 2\phi_f - \frac{Q_f}{C_{ox}} + \frac{Q_{dep}}{C_{ox}} + \eta v_{th}\ln\left(\frac{R}{2v_{th}\varepsilon_{si}}\right) - \eta v_{th}\ln\left[1 - \exp\left(\frac{-qN_aR^2}{4\varepsilon_{si}}\right)\right] \quad (8)$$

Meanwhile, the threshold voltage with strained effect can be formulated as

$$V_{0_strain} = V_{fb_strain} + \phi_{s_strain} + \frac{Q_{dep}}{C_{ox}} + \eta v_{th} \ln(\frac{R}{2v_{th}\varepsilon_{si}}) - \eta v_{th} \ln\left[1 - \exp\left(\frac{-qN_a R^2}{4\varepsilon_{si}}\right)\right] \tag{9}$$

where $V_{fb_strain}$ and $\phi_{s_strain}$ are the strain parameter based on Ge fraction (x) which can be found in [17-18]. The new form of UCCM model with strain can be represented as

$$V_{GS} - V_{0_strain} - V_{ch} - \eta v_{th} \ln(q_{dep}') = \frac{Q_{in}}{C_{ox}} + \eta v_{th} \ln(\frac{Q_{in}}{Q_{dep}'}) + \eta v_{th} \ln(1 + \frac{Q_{in}}{Q_{dep}'}) \tag{10}$$

The implicit equation from (7-8) can be solved explicitly using the following function as suggested in [13]:

$$f(z;s,G) = \ln(\sqrt{z+z^2}) + sz - G = 0 \tag{11}$$

The final solution of function g can be represented as

$$z = \sqrt{(\frac{1}{2s^2})^2 + \left(\frac{1}{s}\right)^2 \ln^2(1+e^G)} - \frac{1}{2s^2} \tag{12}$$

where z is the explicit form of function g which can be applied on UCCM model to solve the charge model just like in [11]. Thus, the initial and final solution of explicit charge model for strained GAA SiNW can be represented as

$$Q_{in_0} = -\frac{2\eta^2 C_{ox}^2 v_{th}^2}{Q_{dep}'} + C_{ox}\sqrt{(\frac{2\eta^2 C_{ox}^2 v_{th}^2}{Q_{dep}'})^2 + 4\eta v_{th}^2 \ln^2(1 + \exp\left[\frac{V_{GS} - V_{0_strain} - \eta V_{ch}}{2\eta v_{th}}\right])} \tag{13}$$

$$Q_{in} = -\frac{2\eta^2 C_{ox}^2 v_{th}^2}{Q_{dep}'} + C_{ox}\sqrt{(\frac{2\eta^2 C_{ox}^2 v_{th}^2}{Q_{dep}'})^2 + 4\eta v_{th}^2 \ln^2(1 + \exp\left[\frac{V_{GS} - V_{th_f} - \eta V_{ch}}{2\eta v_{th}}\right])} \tag{14}$$

where $V_{th_f}$ is the final explicit threshold based on initial inversion charge and depletion charge is formulated as

$$V_{th_f} = V_{0_strain} + 2\eta v_{th} \ln(1 + \frac{Q_{in_0}}{Q_o}) \tag{15}$$

The current model can be derived from the following equation as

$$I_{DS}dy = \mu 2\pi R q_{in}.dV_{ch} \tag{16}$$

where $\mu$ is the mobility for the electron or hole, R is the radius of the channel, and $V_{ch}$ is the fermi potential which varies from source to drain along the channel. By solving the equation (15), the final drain current model is simplified as

$$I_{DS} = \mu \frac{2\pi R}{L_G}\left[2v_{th}(Q_{ins} - Q_{ind}) + \frac{1}{2C_{ox}}(Q_{ins}{}^2 - Q_{ind}{}^2)\right] + \mu \frac{2\pi R}{L_G}\left[v_{th}Q_{dep}\ \ln(\frac{Q_{ind}+Q_{dep}}{Q_{ins}+Q_{dep}})\right] \tag{17}$$

## 3. RESULTS AND ANALYSIS

Figure 2 shows the comparison results of current-gate voltage (ID-VG) graph between the implicit model in (7) and proposed model in (13) which have been solved explicitly for unstrained GAA SiNW. The proposed model is considerably valid because both models indicate similar trends as can be seen in Figure 2(a) and Figure 2(b). The proposed model is then extended for strain application at the channel area of GAA SiNW.

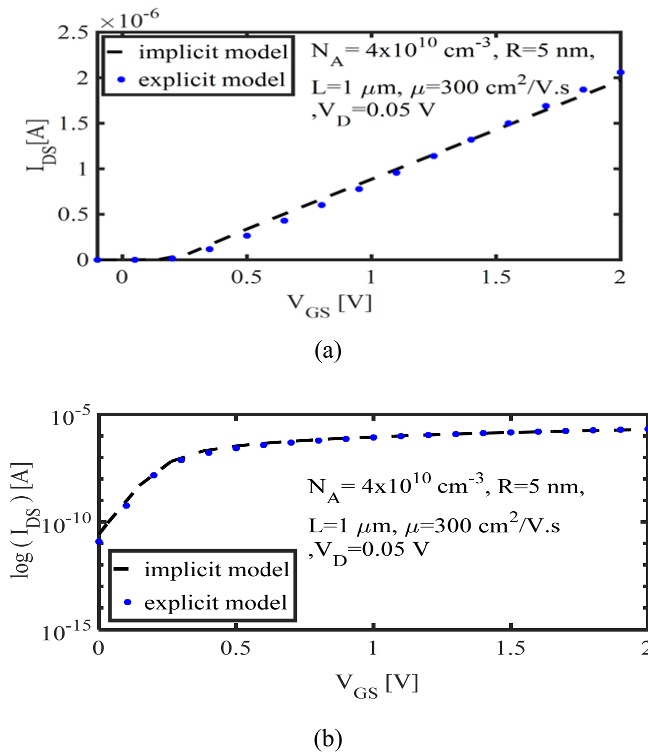


Figure 2. $I_{DS}$-$V_{GS}$ characteristic of implicit and explicit of GAA SiNW with $Q_f = 3\times10^{10}\ cm^{-2}$ (x=0) (a) Linear scale (b) Log scale

Another validation method is performed to identify the compatibility of strain in the proposed model (equation (14)). Figure 3 indicates that the I-V curves of both model and simulator agreed well (using Ge fraction, x=0.4). The significant outcomes prove that the model is applicable for strain device.

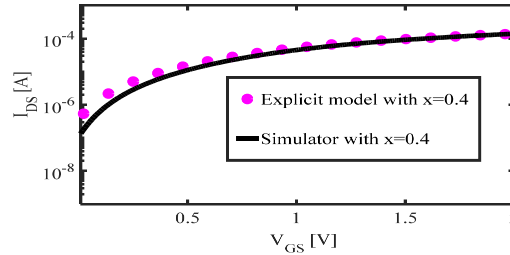


Figure 3. $I_{DS}$-$V_{GS}$ characteristic of explicit model and simulator for strained GAA SiNW
( $N_A = 5\times10\,cm^{-3}, t_{ox} = 2\,nm, L = 1\,\mu m, V_D = 1V$ )

The dependence of Id-Vg on strain is presented in Figure 4. The results indicate that the current is increased significantly as the strain levels are varied from x=0 to x=0.4. The current increment is almost doubled compared to the unstrained device. Other than that, with the strain application, the threshold voltage also shows a great improvement when operating voltage is reduced by ~40 % even without a further downscaling on its dimension. The trend of the on current and threshold changes align with reported data from [17-18,20]. From these findings, device performance is significantly improved with strain application.

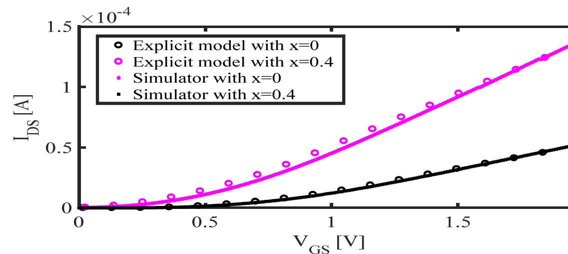


Figure 4. IDS-VGS characteristic of strained GAA SiNW for different strain level
( $N_A = 5\times10^{10}\,cm^{-3}, t_{ox} = 2\,nm, L = 1\,\mu m, V_D = 1V$ )

The current increment due to strain can be justified using charge density of electrons. Charge density dependence on the strain can be observed in Figure 5 with different levels of body doping. The concentration of carriers is increased by 30 % as the strain level is increased from $2.7\times10^{-6}\ C/cm^{-2}$ to $3.5\times10^{-6}\ C/cm^{-2}$, as shown in Figure 5(a) for undoped body. This increment will lead to current enhancement and improve the switching speed improvement of the device. Meanwhile, when the channel was doped with $1\times10^{15}\,cm^{-3}$, the carriers reduced from $2.8\times10^{-6}\ C/cm^{-2}$ Figure 5(a) to $2.2\times10^{-6}\ C/cm^{-2}$ Figure 5(b) at x=0. However, the lost carriers compensated by the strain(x=0.4).

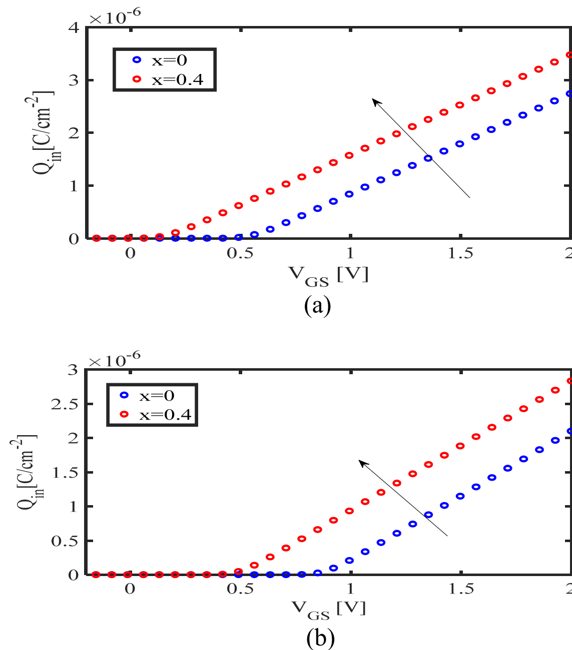


Figure 5. $Q_{in}$-$V_{GS}$ characteristics of strained GAA SiNW for different strain at (a)undoped body (b) doped body

( $N_A = 2\times10^{15}\, cm^{-3}, t_{ox} = 2\, nm, L = 1\, \mu m, V_D = 0.6V$ )

## 4. CONCLUSION

In this work, compact modeling of strained GAA SiNW is presented and the results are compared to the unstrained device. The compact model technique has been extended for strain application resulting in better electrical properties compared to conventional GAA SiNW. The proposed model has been verified with the numerical model and 3D simulator data. By inducing strain in the channel area, the electrical properties of the device have improved significantly including on current, threshold voltage, and charge carrier density. The on current is doubled up compared to the unstrained channel. In addition, threshold voltage was reduced by 40 % depending on the Ge fraction. Besides, the inversion charges were also affected by the strained effect due to the carrier density enhancement with the increment of 30 %.

## ACKNOWLEDGEMENTS

The authors would like to appreciate the financial support from Ministry of Higher Education (MOHE) under the Fundamental Research Grant Scheme (FRGS) vot no 1535. Also thanks to the Research Management Centre (RMC) of Universiti Tun Hussein Onn Malaysia (UTHM) and Universiti Teknologi Malaysia (UTM) for providing outstanding research environment and facilities to make this work is possible.

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