Silicon Nanowire Metal-Oxide-Semiconductor Field Effect Transistor NBTI Effect Modeling and Application in Circuit Performance Simulation

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ABSTRACT

A Negative Bias Temperature Instability (NBTI) model for the P-typed Silicon based nanowire MOS field effect transistor (SNWFET) and its application in the circuit simulation is studied in this paper. The model is derived from the reaction-diffusion (R-D) theory and calibrated by the measurement data. It is experimentally shown that the rate of threshold voltage change of the SNWFET is not constant but varies with stress time under pure electrical stress condition. Overall, it follows a single exponential function with a nominal value of 0.25 under the NBTI stress condition. In addition, it is observed from the derived model and measurement data that the hydrogen diffusion constant varies from 0.8 to 0.52 as the recovery time increases in the recovery process. The developed model has been implemented into a circuit simulator and the effects of NBTI on the delays of the digital gates and oscillator circuits have been evaluated.

Keywords: nanowire, NBTI, modeling, reaction-diffusion, circuit.

1. INTRODUCTION

Silicon-based nanowire MOS field effect transistor (SNWFET) has been considered to be the most promising alternative over traditional bulk CMOS technology for modern Integrate Circuits (IC) [1-5]. Recent study of transport mechanisms and device physics for SNWFET has made significant progress [6-9]. On the other hand, reliability of the SNWFETs is less frequently addressed.

Negative Bias Temperature Instability (NBTI) [10, 11] is one of the most important reliability issues for device and IC application. Although NBTI of silicon nanowire MOSFETs had been study experimentally [2], a compact model for this degradation is not available. The reaction-diffusion (R-G) theory [12-16] has been used for the planar long channel MOSFETs’ NBTI degradation prediction, but only very few reports can be found on the application of this theory to SNWFET reliability study [17].

In this work, The Negative Bias Temperature Instability (NBTI) for the P-typed Si-nanowire MOS field effect transistor (SNWFET) is studied based on a proposed model which is experimentally verified. Its application to predict circuit degradation caused by NBTI has been shown through circuit simulation with HSPICE.

2. NBTI MODEL FOR SNWFETS

The device studied in this work was a Twin Silicon Nanowire MOSFET [2]. The 3-D structure of the device is shown in Fig 1 and the detail fabrication process of this device had been reported in [18]. The Silicon nanowire has a diameter of 10nm and a gate oxide thickness of 3.5nm with a TiN metal gate. The gate length of the device is 427nm and the absolute value of the threshold voltage is about 0.22V.

![Fig.1. The 3-D schematic view of the Twin Silicon Nanowire MOSFET.](image)

To simplify the theoretical derivation, the SNWFET is considered to be a gate-all-around MOSFET with the schematic structure shown in Fig 2.

![Fig.2. (a) Cylindrical MOSFET with channel radius R; the gate oxide surrounds the channel.(b) Hydrogen diffused from the Si-oxide interface along](image)

The schematic description of the R-G theory [17] around the cross-section of the silicon nanowire is shown in Fig 3. Si-H bonds at the Si-oxide interface are broken down under the gate voltage stress or high temperature and diffused away towards the metal gate. The R-G principle assumed the following: (1) the diffusion species is H; (2) the oxide is thick and much larger than the diffusion distance of hydrogen atom (H); and (3) the H’s diffused into the gate metal are not stored and never come back in the recovery process.

![Fig.3. The schematic description of R-G model on the silicon nanowire cross-section.](image)

2.1 Stress Process

A simple physical model causing NBTI at the Si-oxide interface is described by [17]
Si-H+h+ ⇔ Si•+H

The Si-H bond is broken into a dangling bond and a free hydrogen atom. When the negative voltage stress was applied to the gate, H diffused towards the metal gate and got trapped in the Si-oxide interface. The captured inversion holes lead to increased threshold voltage as a result of this stress process.

The interface trap generation process is governed by \[16, 17, 19-21\]

\[ \text{interface trap density, and } N_{i0} \text{ is the density of hydrogen atoms at the Si-oxide interface.} \]

The interface trap generation is initially slow such that

\[ \frac{dN_i}{dt} \approx 0, \quad N_i \gg N_e \]

Therefore, we have

\[ k_i N_e P = k_i N_e N_{i0} \]

The hydrogen diffusion obeys the Fick' second law \[17\],

\[ \frac{dN_H}{dt} = D_H N^2 \]

Where \( D_H \) is the hydrogen diffusion constant in SiO\(_2\) \[22\].

Assume that hydrogen atoms at Si-oxide interface diffused along the radius (R) of the Si nanowire and linearly dependent on the hydrogen diffusion distance \( D_{i0} \), the interface state density due to the diffusion can be written \[17\] as

\[ N_i(t) = \frac{1}{2 \pi R L} \int_{-L}^{+L} N_{i0} \left( 1 - \frac{r - R}{\sqrt{D_{i0}}} \right) 2\pi rdr \]

Combining Equation (5) and Equation (3), we have

\[ N_i(t) = \sqrt{\frac{k_i N_e P}{2 R k_i}} \left( \frac{R \lambda}{6} \right)^{1/2} \]

Where \( \lambda \) is the hydrogen diffusion distance, \( \lambda = \sqrt{D_{i0}} \).

In the case that \( R \ll \lambda \), Equation (6) can be approximated by

\[ N_i(t) = \frac{k_i N_e P}{2 R k_i} \left( \frac{R \lambda}{6} \right)^{1/2} \]

The inversion hole density \( P \) depends on the oxide electric field \[14\] and the gate capacitance,

\[ P = C_{ox}(E_{ox} - V_{ox}) \]

\[ E_{ox} = (V_{gs} - V_{th}) \]

As a result, the inversion hole density can be obtained from Equation (8)

\[ P = C_{ox}(V_{gs} - V_{th}) \]

Considering that \( \Delta V_{th} = q N_{i0}/C_{ox} \), the \( V_{th} \) degradation is derived from Equation (7) and (9),

\[ \Delta V_{th}(t) = \frac{q N_{i0}(t)}{C_{ox}} = \frac{q L_{ox}}{e_{ox} e_{ox}} \sqrt{\frac{k_i N_e}{R k_i}} \frac{C_{ox}}{C_{ox} (V_{gs} - V_{th})} \left( \frac{R \lambda}{2} \right)^{1/2} \]

The general form of \( V_{th} \) degradation can be obtained from Equation (10) as

\[ \Delta V_{th}(t) = \frac{q N_{i0}(t)}{C_{ox}} = \frac{q L_{ox}}{e_{ox} e_{ox}} \sqrt{\frac{k_i N_e}{R k_i}} \frac{C_{ox}}{C_{ox} (V_{gs} - V_{th})} \left( \frac{R \lambda}{2} \right)^{1/2} \]

In Equation (11), \( n=1/4 \) if the diffusing species is H, and \( n=1/6 \) if the diffusing species is H\(_2\), \( C = (1/2) \exp(−E_a/kT) \) \[20\] is the diffusion constant. \( T_0 \) is another constant with a value \( T_0=10^4 \text{s/nm}^2 \) and \( E_0=0.49 \text{eV} \) and \( E_0=0.335 \text{V/nm} \) for the H\(_2\) model. \( E_0=0.12 \text{eV} \) and \( E_0=2.0 \text{V/nm} \) for H model \[13\]. \( K \) is the field acceleration pre-factor and \( E_{ox} \) is the oxide electric field. \( R \) is the radius of the Si nanowire and other parameters contained their normal meaning. Noting that the diffusing species used here is H so that \( n=1/4 \), \( E_0=0.12 \text{eV} \) and \( E_0=2.0 \text{V/nm} \) is used in this work.

From Equation (11), the exponential of \( t \) varies from 0.5 to 0.25. This result is consistent with the different slopes of \( \Delta V_{th} \) vs stress time as shown in Fig 4.

The \( \Delta V_{th} \) vs stress time relationship of Si-nanowire MOSFET in the stress process is shown in Fig 5. The average value of \( n \) is maintained at approximately 0.24, which is very near to the theoretical value of \( n=1/4 \). Therefore, the \( \Delta V_{th} \) vs stress time relationship in Equation (11) can be simplified to \( \Delta V_{th} \sim 0.25 \), and subsequently, \( K = 5.2 \times 10^4 \) is obtained.
2.2 Recovery Process

Assuming that the recovery of NBTI followed the same principle as that of stress. The relationship $N_s(t) = N_s^0 \left( R \lambda / [2 + \lambda^2 / 6] \right)$ is also applied to the back-diffusion of hydrogen in the oxide during the recovery process. The decrease in interface state density $N_s^a(t)$ due to passivation was

$$N_s^a(t) = N_s^0 (t_f) \left( R \lambda \left[ \frac{2}{6} \right] + \frac{\lambda^2}{6} \right)$$

where $t_f$ is the time when the stress is completed. $N_s^a(t_f)$ represents the hydrogen density at the beginning of the recovery. $\lambda_0 = \sqrt{D_\lambda J}$ is the back-diffusion constant, $\zeta$ is the ratio between the diffusion constants of stress and recovery process, and $N_s^a(t_f)$ is the result of the stress process.

Supposing that hydrogen diffusion in the oxide also exists during the recovery process. $N_s^a$ is the generated interface trap density, $N_s^b$ is the recovered one, and $t_f$ is the start point of the recovery process.

$$N_s = N_s^0 - N_s^a = N_s^0 (1 - \frac{N_s^a}{N_s^0}) = N_s^0 \left[ 1 - \frac{R \lambda D(t - t_f)}{2 + \lambda^2} + \frac{\zeta D(t - t_f)}{6} \right]$$

where $t_f$ is the time when the stress is completed, $N_s^0$ is the hydrogen density at the beginning of the recovery, $\lambda_0 = \sqrt{D_\lambda J}$ is the back-diffusion constant, $\zeta$ is the ratio between the diffusion constants of stress and recovery process, and $N_s^a(t_f)$ is the result of the stress process.

The relationship of the interface trap variation in the recovery process is assumed to be the same as the stress process with the forward reaction rate $k_f$ to be 0 [20].

$$\frac{dN_s}{dt} = k_f (N_s - N_s^a) P - k_n N_s N_n^0$$
$$k_f = 0$$

$$\frac{dN_s}{dt} = -k_n \left[ (N_s^a - N_s^b) - (N_s^0 - N_n^0) \right]$$

Due to the slow degradation of $N_s$ at the beginning of the recovery, the variation $dN_s/dt = 0$.

$$\frac{dN_s}{dt} = -k_n \left[ (N_s^a - N_s^b) - (N_s^0 - N_n^0) \right] = 0$$

$$N_s^b = N_s^0$$

Combining Equation (13) and (16), the remained interface trap density is given by

$$N_s = N_s^0 - N_s^b = N_s^0 (1 - \frac{N_s^a}{N_s^0}) = N_s^0 \left[ 1 - \frac{R \lambda D(t - t_f)}{2 + \lambda^2} + \frac{\zeta D(t - t_f)}{6} \right]$$

Considering $\Delta V_a = qN_s/C_{ox}$,

$$\Delta V_a = \Delta V_a^0 \left[ 1 - \frac{R \lambda D(t - t_f)}{2 + \lambda^2} + \frac{\zeta D(t - t_f)}{6} \right]$$

where $\zeta_{beginning} = 0.8$ and $\zeta_{long-term} = 0.53$ correspond to the beginning and longer term of the recovery process.

The two values of $\zeta$ at the different recovery process is due to the special structure of the nanowire device. In the beginning, hydrogen atoms which diffused into the oxide are far from the Si-oxide interface. The back diffusion not only takes place along the radius direction, but also spread out at the cylindrical surface.

Figure 6 shows the final model including the stress and recovery process. The model calculation is compared with experiment data in the same figure. The entire stress process agrees well with the H based R-G model, but the recovery model is composed of two parts due to the different diffusion constant $\zeta$.

![Figure 6. The final model including the stress and recovery process.](image)

3. SUB-CIRCUIT RELIABILITY SIMULATION

Figure 7 shows the framework for analyzing the degradation of circuit performance with the NBTI model we developed. The compact model of nanowire transistor combined with the NBTI degradation model is transformed to an aging model by verilog-A. The aging model is then implemented into HSPICE to perform simulation with given circuit netlists. Finally, the circuit performance degradation is predicted by simulation.

![Figure 7. The framework for analyzing the degradation of circuit performance with the NBTI model.](image)

3.1 Ring Oscillator Degradation

The degradation of seven stage ring oscillator is predicted by HSPICE with the NBTI model described above. The stress is done at $V_{dd} = 1.2V$ and the temperature $T$ was held at 378K (105°C). The linear relationship of frequency degradation and stress time is shown in Figure 8. The degradation is nearly 13% at 1000s and it is mainly due to the approximation of the R-G model.

3.2 Digital Gates Degradation

Simulations of digital gates, such as NOT, NAND, NOR gates are performed at $V_{dd} = 1.2V$ and $T=378K$ (105°C).
The delays of various digital gates at different stress time are shown in Fig.9.

![Fig 8. Frequency degradation for 7 stage ring oscillator.](image)

![Fig 9. The comparison of digital gate delays for NOT, NAND, NOR gate.](image)

4. CONCLUSION

This paper presented a predictive model for the NBTI of P-typed Si-nanowire MOSFET device accounting for both stress and recovery process. Based on the R-D principle as well as the hydrogen (H) diffusion model in cylindrical coordinates, the key parameters of the model are extracted by fitting experimental data. According to the prediction, the slope of the NBTI degradation is not a constant equal to 0.25, but followed a function of the nanowire radius. This result is consistent with the experimental data. Our model is well fitted in the stress process and the longer term of the recovery process. In the recovery process, the hydrogen diffusion constant varies from 0.8 to 0.52 as the recovery time increases.

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