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Communication

High-Precision Fitting of Simulation Parameters for Circuit Aging Effect

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Abstract: To take the influence of the aging effect on circuit performance into account at the early design stage, it is necessary to establish an accurate aging simulation model. However, there is a great discrepancy in the reversely deduced MOSFET transistor degradation from the aging model. To deal with that problem, a method is proposed in this paper that establishes the conversion relationship between the simulation parameters and the degradation of MOSFET transistor parameters. The degradation values were converted into model parameters that characterize the aging effect in SPICE, and the results show that aging simulation accuracy was improved to within 0.1%, which would bring great convenience to circuit reliability simulation and analysis. Lastly, we analyze the aging effect on the ring oscillator circuit via the model.

Keywords: aging simulation; reliability modeling; SPICE model; integrated circuit

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1. Introduction

With the continuous development of semiconductor technology, the physical limits of MOSFET transistors are unceasingly expanding and many new issues related to reliability are raised. Autonomous driving, biomedical electronics, and advanced integrated circuits all require high reliability to meet the required operating lifetimes. The aging effect degrades the MOSFET transistor and circuit performance. The main factors affecting reliability are negative bias temperature instability (NBTI) [1,2] and hot carrier injection (HCI) [3,4], which manifest themselves as an increase in absolute threshold voltage (V_{th}) and a reduction in the MOSFET transistor current (I_{ds}), thus degrading circuit performance such as speed, gain, and data stability [5]. Degradation caused by NBTI is partially recovered after removing the stress voltage [6,7], while the degradation caused by HCI is mostly permanent [8,9]. By modeling and simulating the degradation, the impact of the aging effects on performance can be evaluated at the design stage to optimize the reliability of the circuit and improve performance, thus greatly improving the reliability of the system and reducing maintenance costs.

As computer-aided design (CAD) technology becomes mature and sophisticated, most integrated circuits are modeled and simulated before fabrication, which contributes to characterizing the circuit reliability. A reliability simulation program calculates the degradation of the MOSFET transistor via the established aging model. Then, the aging effect parameters in the Simulation Program with Integrated Circuit Emphasis (SPICE) model are obtained through the corresponding conversion coefficient, and aging simulations are then performed to predict the circuit lifetime. This paper shows that there is a large error with the conversion coefficient calculated by the traditional method when inversely using the aging simulation parameters to infer the degradation values of MOSFET transistor parameters. Focusing on this problem, a method of calculating the conversion coefficients with high precision is proposed to improve the accuracy of aging simulations. The HCI effect is taken as an example to elaborate the method in detail. We adopted the 0.18 μm technology in our experiment because of the significance of the HCI effect in deep sub-micron circuits. This method also applies to the NBTI effect.

2. Lifetime Model and Simulation Parameters

The premise of characterizing circuit aging effects is to establish an accurate accelerated lifetime model that is integrated into circuit simulation software. The degradation of MOSFET transistor parameters is calculated via an aging simulation. Then, the values are converted into the aging parameter in the SPICE model. The degradation of all MOSFET transistors in the circuit can be comprehensively simulated to characterize the influence of the aging effect on circuit performance.

2.1. Accelerated Life Model

Most HCI lifetime models are based on the "lucky electron" model [10,11]. Generated interfacial traps (ΔN_{it}) have a power-law relationship with the electric field (E_{m}) at the drain, drain–source current (I_{ds}), and stress time (t), which can be described as follows:

$$\Delta N_{\text{it}} = A \cdot \left[\frac{I_{\text{ds}}}{W} \exp\left(-\frac{\Phi_{\text{it,e}}}{q\lambda_{\text{e}} E_{\text{m}}} \right) \cdot t \right]^n \tag{1}$$

where W is the channel width, $\Phi_{\text{it,e}}$ is the critical energy for electrons to generate interfacial traps, λ_{e} is the mean free path of the hot electron, and A is a process dependent constant. According to this model, the MOSFET transistor degradation can be established as follows:

$$Dam = V_{\text{gs}}{}^{r\_vgs} \cdot V_{\text{ds}}{}^{r\_vds} \cdot L^{r\_L} \cdot W^{r\_W} \cdot time \tag{2}$$

$$\Delta D = A \cdot Dam^{r\_time} \tag{3}$$

where r_time, r_vds, r_vgs, r_L , r_W and A are fitting parameters via the test data. Dam is the number of holes or electrons entering the oxide layer due to the aging effect. ΔD denotes the degradation of the MOSFET transistor parameters, such as V_{th} and I_{dsat}. V_{ds} and V_{gs} are the mean drain–source voltage and gate–source voltage, respectively. $time$ is the stress time.

First, some initial properties of the MOSFET transistor should be measured to ensure that MOSFET transistors are in good condition without manufacturing defects as a reference for subsequent experiments. Normally, the measured MOSFET transistor parameters include threshold voltage (V_{th}), transconductance (G_{m}), and saturation drain current (I_{dsat}). The aging model is obtained by fitting the test data and extracting the corresponding parameters [12]:

$$\Delta V_{\text{th}} = \left(1.25 \times 10^{-8}\right) \cdot V_{\text{gs}}{}^{0.2299} \cdot V_{\text{ds}}{}^{12.22} \cdot L^{-3.27} \cdot W^{-0.1088} \cdot time^{0.55} \tag{4}$$

$$\Delta I_{\text{dsat}} = \left(4.7 \times 10^{-8}\right) \cdot V_{\text{gs}}{}^{0.09278} \cdot V_{\text{ds}}{}^{9.833} \cdot L^{-2.45} \cdot W^{-0.1} \cdot time^{0.55} \tag{5}$$

When V_{ds}, V_{gs}, W, L and $time$ are known, the degradation of V_{th} and I_{dsat} at this moment can be obtained according to Equations (4) and (5).

The above-mentioned model can only obtain the degradation of MOSFET transistors. To simulate the aging effect at the circuit level, it is necessary to establish the relationship between the degradation of the MOSFET transistor parameters and the simulation parameters of the aging effect, which facilitates accurate parameter conversion, thus realizing high-precision aging-effect simulation.

2.2. Simulation Parameters of the Aging Effect

According to the physical model of the MOSFET transistor [13], I_{ds} is related to both mobility (μ_0) and threshold voltage (V_{th0}) at zero bias, while V_{th} is only related to V_{th0} at zero bias.

$$I_{ds} = \mu_0 \cdot C_{ox} \cdot \frac{W}{L}\left(V_{gs} - V_{th0} - \frac{1}{2}V_{ds}\right) \cdot V_{ds} \quad (6)$$

$$V_{th} = V_{th0} - \frac{Q_f}{C_{ox}} - \frac{Q_{it}}{C_{ox}} \quad (7)$$

We used the BSIM4.3 version of the SPICE model. In the model library, the formulas of calculating the threshold voltage and mobility of the MOSFET transistor under the given bias condition via μ_0 and V_{th0} are expressed as follows:

$$\begin{cases} V_{th} = V_{th0} + \delta V_{thmis} \\ \mu = \mu_0 + \delta \mu_{mis} \end{cases} \quad (8)$$

where δV_{thmis} and $\delta \mu_{mis}$ are the parameters considering the process corner. On this basis, we added the parameters considering the aging effect:

$$\begin{cases} V_{th} = V_{th0} + \delta V_{thmis} + \delta V_{thage} \\ \mu = (\mu_0 + \delta \mu_{mis}) \cdot \delta \mu_{age} \end{cases} \quad (9)$$

In general, δV_{thage} is calculated by subtracting the initial value that is without degradation ($V_{thfresh}$) from the test after the accelerated stress ($V_{thaging}$). That is, $\delta V_{thage} = V_{thaging} - V_{thfresh}$. $\delta \mu_{age}$ is the ratio of the difference from the initial value divided by the initial value. That is, $\delta \mu_{age} = \left(\mu_{aging} - \mu_{fresh}\right)/\mu_{fresh}$. Therefore, the initial value of δV_{thage} is 0, and the initial value of $\delta \mu_{age}$ is 1. These two parameters are closely related to the degradation of the MOSFET transistor due to the aging effects. The values of δV_{thage} and $\delta \mu_{age}$ are related to the degradation degree. It is crucial to accurately establish the conversion relationship between them, and the degradation of the MOSFET transistor parameters.

3. Fitting of Aging Simulation Parameters

The degradation of MOSFET transistor parameters is expressed as variation in the simulation parameters (δV_{thage} and $\delta \mu_{age}$) in the SPICE model. By changing these parameters, the degradation of the MOSFET transistor and circuit can be simulated.

3.1. Problem Statement

First, the MOSFET transistor simulation is conducted under normal operating voltage (δV_{thage} and $\delta \mu_{age}$ are the initial values). Through direct-current (DC) simulation, the initial I_{dsat} is obtained on the I_d-V_d curve, and the initial V_{th} is obtained on the I_d-V_g curve according to the maximal transconductance method. Then, the corresponding relation is established by studying the impact of the change in simulation parameters on V_{th} and I_{dsat}.

3.1.1. The Influence of Mobility

To quantify the influence of $\delta \mu_{age}$ on V_{th} and I_{dsat}, the value of $\delta \mu_{age}$ can be varied, while other parameters remain unchanged, as shown in Table 1. I_{dsat1} and V_{th1} are the values after changing $\delta \mu_{age}$. The corresponding degradation values of MOSFET transistor parameters can be computed via Equations (10) and (11):

$$\Delta I_{dsat1} = (I_{dsat1} - I_{dsat})/I_{dsat} \quad (10)$$

$$\Delta V_{th1} = V_{th1} - V_{th} \quad (11)$$

Table 1. Change in the value of $\delta\mu_{\text{age}}$.

Parameter	Value	Value	Value	Value	Value
$\delta\mu_{\text{age}}$	0.85	0.9	1	1.1	1.15
δV_{thage}	0	0	0	0	0

In a group of simulations, when we shifted the mobility of the MOSFET transistor by about 10% ($\delta\mu_{\text{age}}$ = 1.1), it caused a shift in the I_{dsat} of the MOSFET transistor of about 17.087 µA. Through other sets of simulations, the A_{11} coefficient could be obtained from the following relation:

$$\Delta I_{\text{dsat1}} = A_{11} \cdot \Delta\mu_{\text{age}} \tag{12}$$

When $\delta\mu_{\text{age}} = 1.1$, there was a shift in the V_{th} of the MOSFET transistor of about 0.00015 mV. Through other sets of simulations, the A_{21} coefficient could be calculated from the following relation:

$$\Delta V_{\text{th1}} = A_{21} \cdot \Delta\mu_{\text{age}} \tag{13}$$

where $\Delta\mu_{\text{age}} = \left(\delta\mu_{\text{age}} - 1\right)/1$.

3.1.2. Influence of Threshold Voltage

To quantify the influence of δV_{thage} on V_{th} and I_{dsat}, the value of δV_{thage} can be changed, while other parameters remain unchanged, as shown in Table 2. Similarly, the I_{dsat2} and V_{th2} are the values after changing δV_{thage}. The corresponding degradation of ΔI_{dsat2} and ΔV_{th2} can be obtained. In a group of simulations, when we shifted the threshold voltage of MOSFET transistor about 30 mV (δV_{thage} = 0.03), which causes a shifting in the I_{dsat} of MOSFET transistor about 5.731 μA. Through other sets of simulations, the coefficient A_{12} can be computed from the relation:

$$\Delta I_{\text{dsat2}} = A_{12} \cdot \Delta V_{\text{thage}} \tag{14}$$

Table 2. Change in value of δV_{thage}.

Parameter	Value	Value	Value	Value	Value
$\delta\mu_{\text{age}}$	1	1	1	1	1
δV_{thage}	−0.02	0	0.03	0.06	0.1

When $\delta V_{\text{thage}} = 0.03$, there was a shift in the V_{th} of the MOSFET transistor of about 24.6 mV. Through other sets of simulations, the A_{22} coefficient could be obtained from the following relation:

$$\Delta V_{\text{th2}} = A_{22} \cdot \Delta V_{\text{thage}} \tag{15}$$

The specific results are shown in Figures 1 and 2: ΔV_{th} was only related and proportional to ΔV_{thage}. $\Delta\mu_{\text{age}}$ had little effect on it and could be ignored. However, ΔI_{dsat} with ΔV_{thage} and $\Delta\mu_{\text{age}}$, it was inversely proportional to ΔV_{thage} and proportional to $\Delta\mu_{\text{age}}$. Therefore, the relationship between the degradation MOSFET transistor and the aging parameters could be established [14]:

$$\begin{bmatrix} \Delta I_{\text{dsat}} \\ \Delta V_{\text{th}} \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \begin{bmatrix} \Delta\mu_{\text{age}} \\ \Delta V_{\text{thage}} \end{bmatrix} \tag{16}$$

where $A_{11} = 0.9984$, $A_{12} = -1.1157$, $A_{21} \approx 0$, $A_{22} = 0.82$. After the degradation values of MOSFET transistor parameters had been obtained, the $\delta\mu_{\text{age}}$ and δV_{thage} in SPICE model could be calculated on the basis of this relationship, and the simulation model of circuit aging could be established.

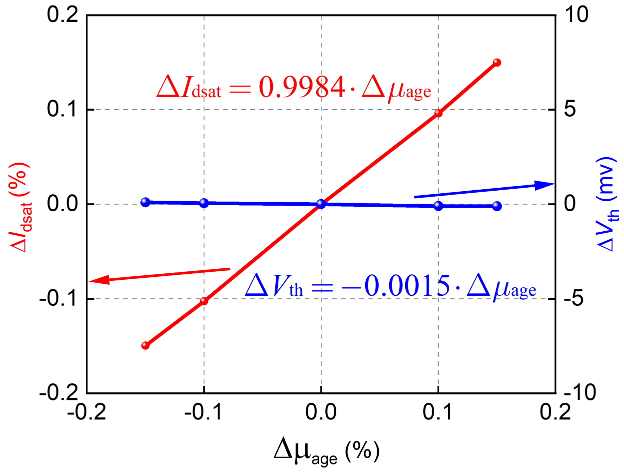

Figure 1. Effect of $\Delta\mu_{age}$ on the degradation of MOSFET transistor parameters.

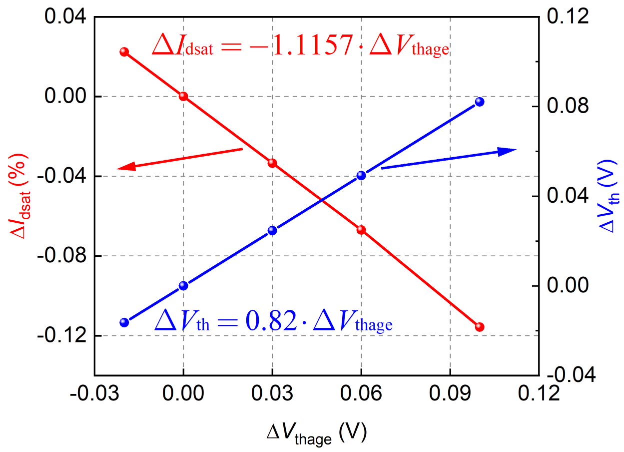

Figure 2. Effect of ΔV_{thage} on the degradation of MOSFET transistor parameters.

According to Equations (4), (5) and (16), two simulation parameters, $\delta\mu_{age}$ and δV_{thage}, were calculated. However, when we used the two obtained parameters to reversely deduce the degradation of MOSFET transistor parameters, if the degradation of the MOSFET transistor parameters was greater than 5%, the error was large, as illustrated in Figure 3. The result shows that the actual test value of ΔI_{dsat} was 8.63%, while the simulation result exceeded 10%, and the error was as high as 19.8%, which is unacceptable for engineering.

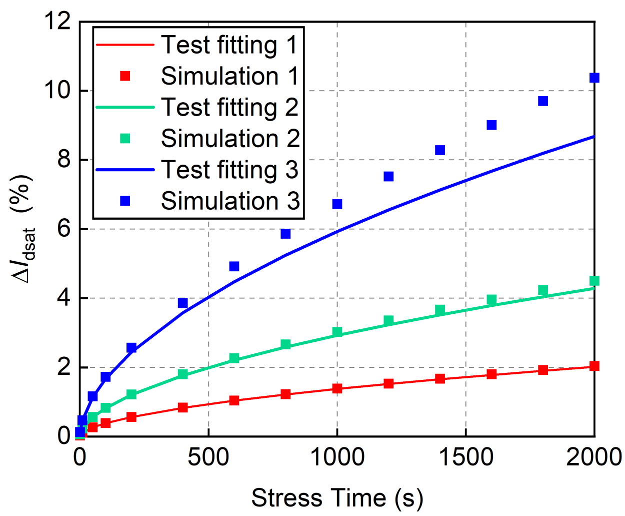

Figure 3. Simulation and test curves of I_{dsat} degradation under different bias conditions (traditional).

3.2. Coefficient Fitting Based on the Variable Control Method

To solve this problem, we studied the correlation between simulation parameters and the degradation of MOSFET transistor parameters. Equation (16) could achieve parameter conversion via a simple addition when ΔV_{th} was only affected by $\delta V_{\mathrm{thage}}$. The result is shown in Figure 4, and the error was less than 0.03%. However, when $\delta V_{\mathrm{thage}}$ and $\delta \mu_{\mathrm{age}}$, both had an influence on the ΔI_{dsat} of the MOSFET transistor. In addition to considering the respective influence coefficients on I_{dsat} degradation, there had to be joint influence coefficients on the degradation of I_{dsat}:

$$I_{\mathrm{dsat}} \cdot (1 + \Delta I_{\mathrm{dsat}}) = I_{\mathrm{dsat}} \cdot (1 + A_{11} \cdot \Delta \mu_{\mathrm{age}}) \cdot \left(1 + A_{12} \cdot \Delta V_{\mathrm{thage}}\right) \quad (17)$$

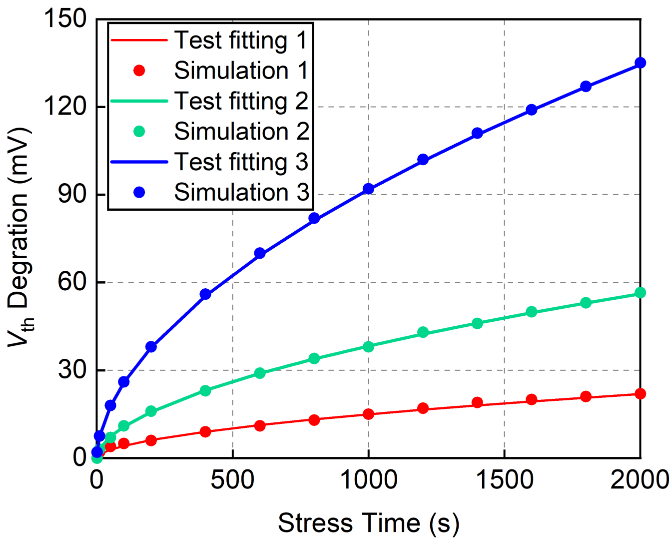

Figure 4. Simulation and test curves of V_{th} degradation under different bias conditions (traditional).

The left-hand side of the Equation (17) is I_{dsat} after MOSFET transistor degradation, and the right-hand side is the I_{dsat} caused by aging parameters $\Delta V_{\mathrm{thage}}$ and $\Delta \mu_{\mathrm{age}}$, which can be simplified as below:

$$\Delta I_{\mathrm{dsat}} = A_{11} \cdot \Delta \mu_{\mathrm{age}} + A_{12} \cdot \Delta V_{\mathrm{thage}} + A_{11} \cdot \Delta \mu_{\mathrm{age}} \cdot A_{12} \cdot \Delta V_{\mathrm{thage}} \quad (18)$$

Equation (18) shows that there was such a large error because of the omission of the last term and the joint influence of the two parameters on the degradation of I_{dsat}. Thus,

$$\begin{bmatrix} \Delta I_{\mathrm{dsat}} \\ \Delta V_{\mathrm{th}} \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \begin{bmatrix} \Delta \mu_{\mathrm{age}} \\ \Delta V_{\mathrm{thage}} \end{bmatrix} + \begin{bmatrix} A_{11} \cdot \Delta \mu_{\mathrm{age}} \cdot A_{12} \cdot \Delta V_{\mathrm{thage}} \\ 0 \end{bmatrix} \quad (19)$$

According to the accelerated lifetime model or test, we could obtain the values of ΔI_{dsat} and ΔV_{th}. The corresponding $\Delta \mu_{\mathrm{age}}$ and $\Delta V_{\mathrm{thage}}$ could be calculated from Equation (19). Then, the values of $\delta \mu_{\mathrm{age}}$ and $\delta V_{\mathrm{thage}}$ could be changed via the Alter instruction in SPICE to simulate the aging effect of the circuit. The result is shown in Figure 5. No matter what the degradation value was in the display range, the simulation accuracy was within 0.047%, which is in line with the actual demand.

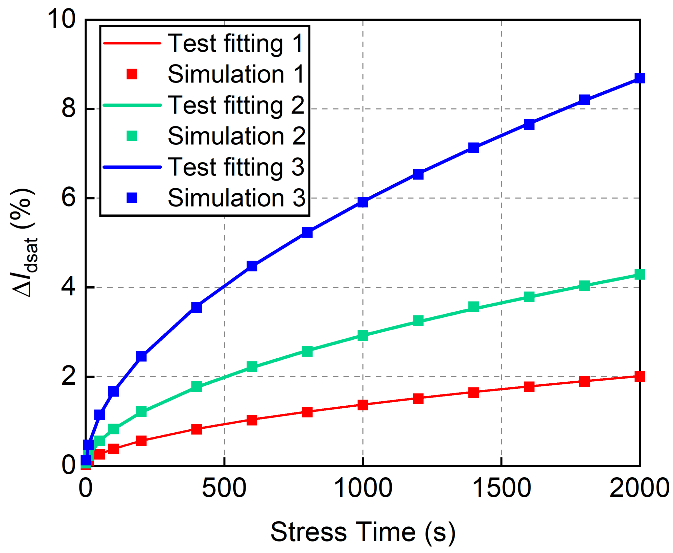

Figure 5. Simulation and test curves of I_{dsat} degradation under different bias conditions after modification (based on the variable control method).

However, the coefficient matrix is nonlinear and can only be realized by solving nonlinear equations. To facilitate the realization through programming, this paper proposes a second method to calculate the conversion coefficient, which can form a linear matrix that establishes a high-precision simulation model.

3.3. Coefficient Fitting Based on Multiple Systems of Equations

Since $\delta\mu_{age}$ and δV_{thage} both had an influence on the degradation of I_{dsat}, the common influence of the two parameters on I_{dsat} should be considered when extracting the coefficients. Namely, $\delta\mu_{age}$ and δV_{thage} were changed simultaneously, as shown in Table 3. According to engineering experience, two groups of $\Delta\mu_{age}$ and ΔV_{thage} were determined, and then a simulation was carried out under each group of conditions. The degradation of the MOSFET transistor parameters was acquired via simulation as follows:

$$\begin{cases} \Delta I_{dsat1} = A_{11} \cdot \Delta\mu_{age1} + A_{12} \cdot \Delta V_{thage1} \\ \qquad\quad = A_{11} \cdot 0.01 + A_{12} \cdot 0.03 \\ \Delta I_{dsat2} = A_{11} \cdot \Delta\mu_{age2} + A_{12} \cdot \Delta V_{thage2} \\ \qquad\quad = A_{11} \cdot 0.04 + A_{12} \cdot 0.06 \end{cases} \tag{20}$$

Table 3. Simulation parameter reference values.

Parameter	Value	Meaning	Value	Meaning
$\Delta\mu_{age}$	0.01	Increase 1%	0.04	Increase 4%
ΔV_{thage}	0.03	Increase 30 mV	0.06	Increase 60 mV

By solving for Equation (20), coefficients A_{11} = 0.8945, A_{12} = −1.0892 were obtained and entered into Equation (16) for simulation; the obtained result is illustrated in Figure 6. The error of the coefficients extracted through this method was controlled within 0.0961% when simulating the degradation of the MOSFET transistor. This could also meet practical needs, and the program of this approach is straightforward.

According to the simulation parameters based on multiple systems of equations, we simulated the aging effect (including HCI and NBTI) of the ring oscillator, and its schematic is shown in Figure 7. We simulated the circuit working in a 125-degree environment for 5 years, and its stress voltage was the normal operating voltage, namely, 1.8 V. Under the influence of the aging effect, the oscillation frequency dropped from 72.84 to 72.69 MHz;

the simulation result is illustrated in Figure 8. This was mainly because of an increase in the V_{th} of the MOSFET transistors.

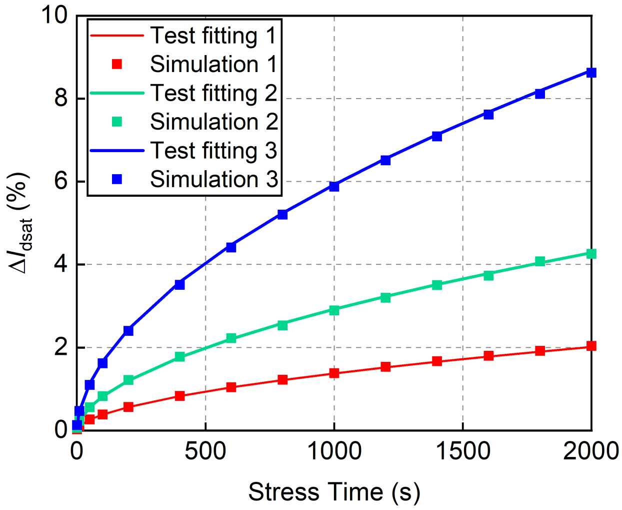

Figure 6. Simulation and test curves of I_{dsat} degradation under different bias conditions after modification (based on multiple systems of equations).

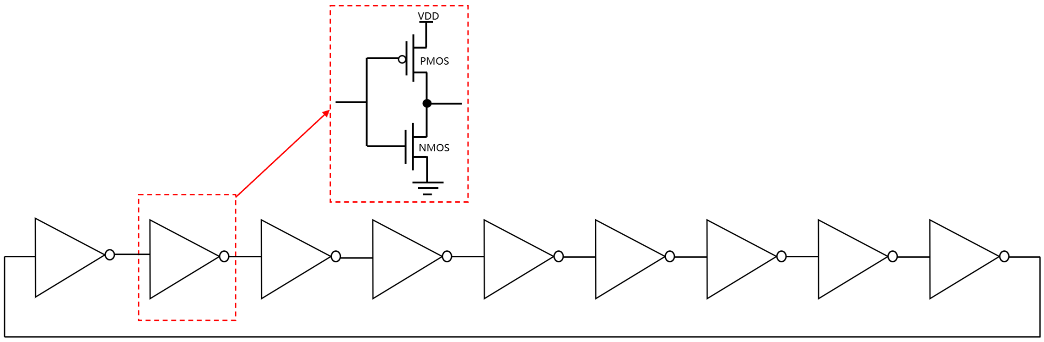

Figure 7. Schematic of the ring oscillator.

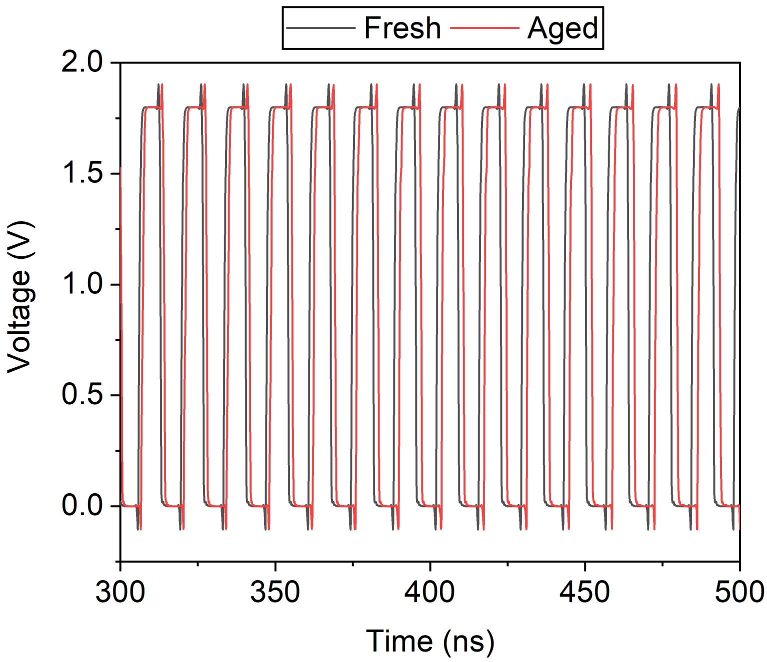

Figure 8. Simulation of the aging effect of the ring oscillator.

4. Summary and Outlook

There is a large error in the simulation parameters when calculating the MOSFET transistor degradation; thus, it is difficult to establish a high-precision aging model for circuits. To solve this problem, a method for calculating the high-precision fitting coefficient was proposed based on variable control. The coefficients that reflect how the simulation parameters impact MOSFET transistor degradation were extracted separately, and the impact coefficient of interaction was added on the basis of this conception, which also improved the accuracy of the model. However, in order to facilitate the solution with programming, the linear coefficient matrix needed to be established. Therefore, the aging parameters were changed at the same time to obtain their synergistic impact coefficients on the degradation of the MOSFET transistor parameters. The simulation results show that the proposed method is easy to implement while ensuring accuracy, which provides convenience for circuit-level aging simulations. We simulated the aging effect of a 9-order ring oscillator, and the results show that this aging model could predict the lifetime of the circuit.

The current method only applies two SPICE model parameters, namely, threshold voltage and mobility. In the following research, multiple SPICE model parameters could be used to characterize the aging effect (such as adding saturation speed and on-resistance), and other aging effects can be considered to further improve aging simulation accuracy.

Author Contributions: X.Y.: conceptualization, data curation, investigation, methodology, visualization, and writing—original draft, review, and editing. Q.S.: formal analysis, funding acquisition, and writing—review and editing. J.Z.: supervision and validation. C.W.: project administration, resources, and software. M.Y.: data curation and investigation; Y.Z. and S.W.: formal analysis. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: the authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

HCI	Hot carrier injection
NBTI	Negative bias temperature instability
CAD	Computer-aided design
DC	Direct current
SPICE	Simulation program with integrated circuit emphasis

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