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A novel technique for predicting ionizing radiation effects of commercial MOS devices

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A nondestructive selection technique for predicting ionizing radiation effects of commercial metal-oxide-semiconductor (MOS) devices has been put forward. The basic principle and application details of this technique have been discussed. Practical application for the 54HC04 and 54HC08 circuits has shown that the predicted radiation-sensitive parameters such as threshold voltage, static power supply current and radiation failure total dose are consistent with the experimental results obtained only by measuring original electrical parameters. It is important and necessary to choose suitable information parameters. This novel technique can be used for initial radiation selection of some commercial MOS devices.

Keywords: prediction, ionizing radiation effects, commercial MOS devices, regression
PACC: 7340Q, 6180E

1. Introduction

In recent years, the space applications of commercial metal-oxide-semiconductor (MOS) devices have been studied widely.[1−7] Compared with the use of special radiation hardness techniques, the principal advantages for direct application of commercial MOS devices are their lower cost, shorter research period, much more easily changeable and replaceable performance, etc. Therefore, the commercial MOS devices can to a great extent meet the needs of space applications. As we know, the electrical properties of MOS devices after ionizing radiation will exhibit differences between different devices, or the same kind of devices from different manufactories, batches or chips. In order to increase application reliability, we must select the best ones from all of these different commercial MOS devices. The principal question is how to select them. Fleetwood *et al*[1] presented a new test standard for the application of commercial devices. Other authors reported on radiation testing of different sorts of commercial devices.[2,5,6] Some of the papers in the literature also discussed the problems which should be solved [3,4] during the application of commercial devices. Moreover, it has been reported that the ionizing radiation effects of 4007 inverters may be predicted by first pre-irradiating and then annealing them,[8] but this technique probably leaves slight radiation damage behind to reduce device reliability if annealing conditions were chosen unsuitably. In addition, Hughes [9] also reported that, by utilizing a technique related to a portion of MOS wafer, the ionizing radiation sensitivity of the accompanying device lots could be predicted. However, until now, little has been reported on the radiation prediction for commercial MOS devices, which is non-destructive and easy to operate. In this paper, we put forward a nondestructive selection technique, discuss its basic principle and application details, and finally use this technique to predict the electrical parameters at a required total radiation dose and the total radiation failure dose for 54HC04 (hex inverter) and 54HC08 (quad 2-input AND gate) circuits with high accuracy by measuring their original information parameters (IPs) only. The experimental results showed that, by means of a multiple linear regression technique, we can make a prediction of the electrical parameters and total dose failure limit for commercial MOS devices in an ionizing radiation environment. On the basis of predicted results, we can make a basic selection and classification for commercial MOS devices according to their radiation failure limit to meet the different needs of radiation hardness.

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2. Basic principles and application details of the non-damage selection technique

Because the original electrical parameters of commercial MOS devices depend strongly on process conditions and defects in the oxides, and the electrical parameters after irradiation also depend on radiation-induced defect charges in gate and field oxides and the original electrical parameters, therefore exact correlations between electrical parameters and radiation dose should exist. Meanwhile, as mentioned above, the electrical parameter values of commercial MOS devices usually exhibit a normal distribution. According to these basic ideas, we can predict the radiation effects of commercial MOS devices by means of measuring their original electrical parameters.

The essential part of the non-damage selection technique is the multiple linear regression analysis. Its key points include: (1) the choice of IPs concerning the electrical and process characteristics such as the threshold voltage and static power supply current, etc, and (2) the choice of radiation-sensitive characteristic parameters (RSCP) such as the threshold voltage shift and total radiation failure dose, etc. The principal procedure is to set up the relationships between IP and RSCP by means of regression equations. In order to set up regression equations, many samples will be irradiated before prediction. Once setting up regression equations, the prediction of radiation effects for non-irradiated samples of the same batch will be carried out by measuring their original IPs only. Therefore, the choice of suitable IPs is very important for increasing the prediction accuracy of RSCP. Usually, the key steps in setting up regression equations contain four points as follows:

(1) Data acquisition. The data to be measured include the IPs before irradiation and the RSCP after irradiation.

(2) Data checking. The measured data should be checked to identify if they obey the normal distribution; if not, they will be abandoned.

(3) Calculation of correlation coefficients. The correlation coefficients can decide which IP should be selected among many electrical parameters.

(4) Setting up multiple linear regression equations between IP and RSCP, and calculating regression coefficients.

Usually, the multiple linear regression equations may be expressed as the following:

$$Y_i = b_0 + b_1 X_{i1} + b_2 X_{i2} + \cdots b_j X_{ij} + \cdots b_m X_{im}$$
$$(i = 1, 2, \ldots, n, \quad j = 1, 2, \ldots, m), \tag{1}$$

where, Y_i is the ith experimental value of RSCP, b_0, $b_1, \ldots, b_m$ are different regression coefficients, X_{i1}, $X_{i2}, \ldots, X_{im}$ are the ith experimental values for different IPs, n is the number of irradiated samples, and m is the number of IPs.

The single correlation coefficient r_j of the jth IP may be expressed as the following:

$$r_j = \left[\sum_{i=1}^{n}(X_{ij} - \overline{X}_j)(Y_i - \overline{Y})\right] \Big/ \left[\sum_{i=1}^{n}(X_{ij} - \overline{X}_j)^2 \times \sum_{i=1}^{n}(Y_i - \overline{Y})^2\right]^{1/2},$$

where

$$\overline{Y} = \sum_{i=1}^{n} Y_i/n,$$
$$\overline{X}_j = \sum_{i=1}^{n} X_{ij}/n. \tag{2}$$

We will use the magnitude of r_j to check the correlation extent of every IP. Basically, the variation range of r_j is $0 \leq r_j \leq 1$. For example, (1) $r_j < 0$ indicates a negative correlativity, and $r_j > 0$ a positive correlativity; (2) when r_j=1, it is completely correlative; (3) when r_j=0, it is non-correlative; (4) a higher correlation extent corresponds to a bigger r_j value.

The multiple correlation coefficient R for many IPs and the square sum of error (SSE) can be expressed as the following:

$$R^2 = \mathrm{SSE}/(n - m - 1), \tag{3}$$

$$\mathrm{SSE} = \boldsymbol{Y}^{\mathrm{T}}\boldsymbol{Y} - \boldsymbol{\beta}^{\mathrm{T}}\boldsymbol{X}^{\mathrm{T}}\boldsymbol{Y}, \tag{4}$$

with

$$\boldsymbol{Y} = \begin{pmatrix} Y_1 \\ \vdots \\ Y_n \end{pmatrix},$$

$$\boldsymbol{X} = \begin{pmatrix} 1 & X_{11} & \cdots & X_{1m} \\ 1 & X_{21} & \cdots & X_{2m} \\ \vdots & \vdots & \cdots & \vdots \\ 1 & X_{n1} & \cdots & X_{nm} \end{pmatrix},$$

$$\boldsymbol{\beta} = (X^{\mathrm{T}}X)^{-1}X^{\mathrm{T}}Y, \tag{5}$$

where $\boldsymbol{Y}^{\mathrm{T}}$ is the transpose matrix of Y, and $(\boldsymbol{X}^{\mathrm{T}}\boldsymbol{X})^{-1}$ is the reversed matrix of $(\boldsymbol{X}^{\mathrm{T}}X)$.

R will be saturated with the increase of number of IPs and lies in the range of $0 \leq R \leq 1$. So it is enough to obtain a better regression result for choosing the number of IP as 4 or 5. Higher correlation extent corresponds to a bigger value of R.

When the choice of IP and RSCP is finished, the multiple linear regression equations will be set up as follows:

$$\boldsymbol{Y} = \boldsymbol{X}\boldsymbol{b} \pm \boldsymbol{\varepsilon}, \tag{6}$$

$$\boldsymbol{b} = \begin{pmatrix} b_0 \\ \vdots \\ b_m \end{pmatrix}, \quad \boldsymbol{\varepsilon} = \begin{pmatrix} \varepsilon_1 \\ \vdots \\ \varepsilon_n \end{pmatrix},$$

where $\boldsymbol{b}$ is the regression coefficient matrix, and $\boldsymbol{\varepsilon}$ is the error matrix between experiment and regression under a given confidence. On the other hand, $\boldsymbol{b}$ and $\boldsymbol{\varepsilon}$ can be also expressed as $\boldsymbol{b} = \boldsymbol{\beta}^{\mathrm{T}}$ and $\boldsymbol{\varepsilon} = t\boldsymbol{\sigma}$, respectively. Here t is the qualitative limit that depends on both the value of $n - m - 1$ and the confidence (normally given as 5%). For example, when the confidence is 5% and n=26, m=2, t is equal to 2.069, obtained by looking up the experimental database.

3. Experiments

The experimental samples used for this article are the commercial MOS devices of 54HC04 and 54HC08.

In order to set up their regression equations, twenty-eight 54HC04 and seventeen 54HC08 circuits randomly taken from a patch of commercial MOS devices are irradiated by a ^{60}Co source with the radiation dose rate of 0.102 Gy/s and with different total radiation doses. During irradiation, each circuit has bias voltages as V_{dd}=4.5 V, V_{ss}=0 V and V_{in}=4.5 V with a converter connection for output terminals. For 54HC04 samples, the threshold voltage of three n-channel and three p-channel MOS field-effect-transistors (MOSFETs) (denoted as V_{tn1}, V_{tn2}, V_{tn3}, V_{tp1}, V_{tp2}, V_{tp3}), and the static power supply current with input voltage 0 or 5 V during measurement (denoted as I_{ss} (0 V) or I_{ss} (5 V)) are measured before and after irradiation, respectively. In addition to the direct current (DC) electrical parameters mentioned above, we also measure the alternating current (AC) electrical parameters such as rise time, fall time and delay time for every circuit. Then, the pre-radiation average value of $V_{\mathrm{tn}}(0)$ ($V_{\mathrm{tn}}(0)$= (V_{tn1}+V_{tn2}+V_{tn3})/3) and $V_{\mathrm{tp}}(0)$ ($V_{\mathrm{tp}}(0)$= (V_{tp1}+V_{tp2}+V_{tp3})/3), I_{ss0}(0 V) and I_{ss0}(5 V) are selected as IPs for every circuit. At the same time, when each circuit is irradiated with a total dose of D (where D=40 Gy), the average threshold voltage of three n-channel and three p-channel MOSFETs of $V_{\mathrm{tn}}(D)$ and $V_{\mathrm{tp}}(D)$, the static power supply current $I_{\mathrm{ss}D}$(0 V) and $I_{\mathrm{ss}D}$(5 V) are selected as RSCP. Of course, D may be chosen as other total radiation dose. For the 54HC08 circuit, we also select $V_{\mathrm{tn}}(0)$, $V_{\mathrm{tp}}(0)$, I_{ss0}(0 V) and I_{ss0}(5 V) as IPs besides G_{m0} which is the transconductance of drain current–input voltage curve of the first AND gate at drain current=10 μA. Also, $V_{\mathrm{tn}}(D)$, $V_{\mathrm{tp}}(D)$, $I_{\mathrm{ss}D}$(0 V), $I_{\mathrm{ss}D}$(5 V), G_{mD} and the radiation failure total dose D were selected as RSCP. The total radiation failure dose D means the dose at which circuit parameters or performance fails according to the American Military Standard.

For radiation prediction, the original IPs mentioned above for ten 54HC04 and ten 54HC08 circuits are measured.

4. Experimental results and discussion

By means of KyPlot software and the irradiation experiments of twenty-eight 54HC04 circuits, the regression results of $V_{\mathrm{tn}}(D)$, $V_{\mathrm{tp}}(D)$, $I_{\mathrm{ss}D}$(0 V) and $I_{\mathrm{ss}D}$(5 V) are shown in Table 1. From the experimental data, we can see the following conclusions: (1) $V_{\mathrm{tn}}(0)$ is the best choice of IP for the prediction of $V_{\mathrm{tn}}(D)$ due to its higher single correlation coefficient (r=0.895); similarly, $V_{\mathrm{tp}}(0)$ is the best one for the prediction of $V_{\mathrm{tp}}(D)$ because of its higher r value (r=0.762); (2) the regression results for all RSCP are of high accuracy when choosing $V_{\mathrm{tn}}(0)$, $V_{\mathrm{tp}}(0)$, I_{ss0}(0 V) and I_{ss0}(5 V) as IPs due to their high R value (particularly for the regression of $V_{\mathrm{tn}}(D)$; in this case, R=0.929 and maximum error=1.4%). After setting up regression equations, when we measure the original values of $V_{\mathrm{tn}}(0)$, $V_{\mathrm{tp}}(0)$, I_{ss0}(0 V) and I_{ss0}(5 V) for non-irradiated samples in the same batch respectively, we can predict their electrical parameters at a total dose of 40 Gy. Similarly, we can also predict their parameters at other radiation total dose after setting up corresponding regression equations.

As a practical application of this prediction technique, we predict $V_{\mathrm{tn}}(D)$, $V_{\mathrm{tp}}(D)$, $I_{\mathrm{ss}D}$(0 V) and $I_{\mathrm{ss}D}$(5 V) for ten 54HC04 circuits at a total dose of 40 Gy respectively, which are shown in Table 2. The results clearly indicate that the prediction accuracy of electrical parameters is very high, no matter whether

the threshold voltage or the static power supply current is employed. Also, we note that different original electrical parameters correspond to different radiation responses.

Table 1. Correlation coefficients and parameter prediction for 54HC04 samples.

Predicted parameters	r				R	Max. error
	$V_{tn}(0)$	$V_{tp}(0)$	$I_{ss0}(0\,V)$	$I_{ss0}(5\,V)$		
$V_{tn}(D)$	0.895	0.614	–0.670	–0.288	0.929	1.4%
$V_{tp}(D)$	0.233	0.762	0.0549	0.0829	0.814	1.78%
$I_{ssD}(0\,V)$	–0.457	–0.447	0.427	0.182	0.555	144.4%
$I_{ssD}(5\,V)$	–0.505	–0.384	0.385	–0.141	0.660	6.2%

Remarks: the regression equations for different parameters are shown in the following:

$V_{tn}(D)$=0.187+0.873 $V_{tn}(0)$+0.217 $V_{tp}(0)$–9.758×10^7 $I_{ss0}(0\,V)$+1.856× 10^7 $I_{ss0}(5\,V)$±0.00769,

$V_{tp}(D)$=–0.139+0.00865 $V_{tn}(0)$+0.959 $V_{tp}(0)$+1.415×10^8 $I_{ss0}(0\,V)$+1.574×10^7 $I_{ss0}(5\,V)$±0.0131,

$I_{ssD}(0\,V)$=–2.881×10^{-6}–3.430×10^{-6} $V_{tn}(0)$–6.492×10^{-6} $V_{tp}(0)$+2501.419 $I_{ss0}(0\,V)$+29.228 $I_{ss0}(5\,V)$ ±3.517×10^{-7},

$I_{ssD}(5\,V)$=5.592×10^{-9}–5.009 $V_{tn}(0)$–8.760 $V_{tp}(0)$+0.617 $I_{ss0}(0\,V)$–0.604 $I_{ss0}(5\,V)$±1.179×10^{-10}.

Note: D=40 Gy.

Table 2. Comparison between original, predicted and experimental V_{tn}, V_{tp}, $I_{ss}(0\,V)$ and $I_{ss}(5\,V)$ for ten 54HC04 samples.

	1#	2#	3#	4#	5#	6#	7#	8#	9#	10#
Orig. $V_{tn}(0)$/V	0.850	0.853	0.850	0.850	0.857	0.850	0.840	0.840	0.847	0.853
Exp. $V_{tn}(D)$/V	0.730	0.743	0.740	0.740	0.747	0.737	0.730	0.720	0.733	0.743
Pred. $V_{tn}(D)$/V	0.734	0.743	0.740	0.740	0.750	0.736	0.726	0.726	0.734	0.741
Relative error/%	0.55	0	0	0	0.40	0.14	0.55	0.83	0.14	0.27
Orig.$-V_{tp}(0)$/V	0.937	0.920	0.923	0.933	0.910	0.940	0.950	0.937	0.937	0.933
Exp.$-V_{tp}(D)$/V	1.007	0.983	0.993	1.001	0.987	1.030	1.027	1.003	1.003	1.001
Pred.$-V_{tp}(D)$/V	1.003	0.990	0.994	1.004	0.981	1.012	1.018	1.006	1.006	1.007
Relative error/%	0.40	0.71	0.10	0.30	0.61	1.75	0.88	0.30	0.30	0.60
Orig. $I_{ss0}(0\,V)/10^{-11}$A	9.50	7.30	6.20	6.80	6.50	6.00	7.10	7.90	7.00	4.70
Exp. $I_{ssD}(0\,V)/10^{-6}$A	6.30	2.60	3.80	2.70	3.20	4.40	2.50	8.40	5.60	3.90
Pred. $I_{ssD}(0\,V)/10^{-6}$A	5.50	3.60	3.80	4.60	2.80	4.80	6.10	5.40	5.00	3.90
Relative error/%	12.7	38.5	0	70.4	12.5	9.1	144	35.7	10.7	0
Orig. $I_{ss0}(5\,V)/10^{-10}$A	9.00	9.10	8.80	8.20	8.90	8.40	9.60	8.70	9.10	8.50
Exp. $I_{ssD}(5\,V)/10^{-9}$A	1.70	1.60	1.70	1.60	1.60	1.80	1.70	1.80	1.70	1.60
Pred. $I_{ssD}(5\,V)/10^{-9}$A	1.70	1.60	1.70	1.70	1.60	1.70	1.70	1.70	1.70	1.70
Relative error/%	0	0	0	6.25	0	5.56	0	5.56	0	6.25

Note: D=40 Gy.

For 54HC08 circuits, the regression results of $V_{tn}(D)$, $V_{tp}(D)$, $I_{ssD}(0\,V)$, $I_{ssD}(5\,V)$ and the total irradiation failure dose D are shown in Table 3 when choosing $V_{tn}(0)$, $V_{tp}(0)$, $I_{ss0}(0\,V)$, $I_{ss0}(5\,V)$ and G_{m0} as IPs. The experimental data suggest that, apart from similar electrical parameter prediction with 54HC04 circuits, the total radiation failure dose for each sample can be predicted with a higher prediction accuracy only by the calculation of D regression equation after measuring original electrical parameters of $V_{tn}(0)$, $V_{tp}(0)$, $I_{ss0}(0\,V)$, $I_{ss0}(5\,V)$ and G_{m0}. In addition, the transconductance G_{m0} can also be chosen as IP due to its better correlativity with D, $V_{tp}(D)$ and $I_{ssD}(5\,V)$. As a practical application example for this technique, the predicted and experimental D, $V_{tn}(D)$, $V_{tp}(D)$, and $I_{ssD}(0\,V)$ for ten 54HC08 circuits are shown in Table 4. The data manifest that the predictions for most of devices are close to the experimental results, which proves once again that the nondestructive selection technique is a very useful and effective method for the prediction of radiation responses and radiation selection of commercial MOS devices.

Table 3. Correlation coefficients and parameter prediction for 54HC08 samples.

Predicted parameters	r					R	Max. error
	$V_{\rm tn}(0)$	$V_{\rm tp}(0)$	$I_{\rm ss0}(0\,{\rm V})$	$I_{\rm ss0}(5\,{\rm V})$	G_{m0}		
D	0.39	0.080	0.011	–0.35	–0.36	0.53	11.7%
$V_{\rm tn}(D)$	–0.12	–0.34	–0.067	–0.010	–0.032	0.47	13.96%
$V_{\rm tp}(D)$	–0.15	0.70	0.37	0.10	0.36	0.74	6.61%
$I_{{\rm ss}D}(0\,{\rm V})$	0.12	0.29	0.074	0.016	0.011	0.42	33.33%
$I_{{\rm ss}D}(5\,{\rm V})$	0.28	–0.20	–0.24	–0.20	–0.40	0.50	650.83%

Remarks: the regression equations for different parameters are shown in the following:

D=2.09×10^2–66.8 $V_{\rm tn}(0)$+60.9 $V_{\rm tp}(0)$–1.37×10^{10} $I_{\rm ss0}(0\,{\rm V})$–3.06×10^{10} $I_{\rm ss0}(5\,{\rm V})$–2.72 ×10^5 G_{m0}±8.30,

$V_{\rm tn}(D)$=3.32–4.64 $V_{\rm tn}(0)$–1.25 $V_{\rm tp}(0)$–1.80×10^8 $I_{\rm ss0}(0\,{\rm V})$–4.99×10^8 $I_{\rm ss0}(5\,{\rm V})$–1477.17 G_{m0}±0.16,

$V_{\rm tp}(D)$=–2.54+2.89 $V_{\rm tn}(0)$+1.11 $V_{\rm tp}(0)$+7.46×10^7 $I_{\rm ss0}(0\,{\rm V})$+4.18×10^7 $I_{\rm ss0}(5\,{\rm V})$+1729.38 G_{m0}±0.076,

$I_{{\rm ss}D}(0\,{\rm V})$=–7.54×10^{-5}+1.23×10^{-4} $V_{\rm tn}(0)$+2.65×10^{-5} $V_{\rm tp}(0)$–1.34×10^3 $I_{\rm ss0}(0\,{\rm V})$+1.41×10^4 $I_{\rm ss0}(5\,{\rm V})$+4.01×10^{-2} G_{m0} ±4.18×10^{-6},

$I_{{\rm ss}D}(5\,{\rm V})$=6.18×10^{-8}–5.56×10^8 $V_{\rm tn}(0)$+6.2010 $V_{\rm tp}(0)$–6.66 $I_{\rm ss0}(0\,{\rm V})$–7.53 $I_{\rm ss0}(5\,{\rm V})$–7.11×10^{-5} G_{m0}±1.56×10^{-9}.

Note: D is the total failure dose.

Table 4. Comparison between original, predicted and experimental $V_{\rm tn}$, $V_{\rm tp}$, $I_{\rm ss}(0\,{\rm V})$ and total radiation failure dose D for ten 54HC08 samples.

	1#	2#	3#	4#	5#	6#	7#	8#	9#	10#
Orig. $V_{\rm tn}(0)$/V	0.790	0.796	0.790	0.770	0.793	0.790	0.780	0.790	0.793	0.783
Exp. $V_{\rm tn}(D)$/V	0.360	0.587	0.493	0.553	0.523	0.530	0.467	0.560	0.477	0.573
Pred. $V_{\rm tn}(D)$/V	0.440	0.526	0.546	0.513	0.474	0.520	0.518	0.542	0.479	0.490
Relative error/%	22.2	10.4	10.8	7.23	9.37	1.89	10.9	3.21	4.19	14.5
Orig.–$V_{\rm tp}(0)$/V	0.937	0.920	0.923	0.933	0.910	0.940	0.950	0.937	0.937	0.933
Exp.–$V_{\rm tp}(D)$/V	0.840	0.910	0.933	0.867	0.890	0.940	0.907	0.923	0.900	0.893
Pred.–$V_{\rm tp}(D)$/V	0.874	0.962	0.986	0.908	0.924	0.972	0.952	0.990	0.936	0.933
Relative error/%	4.05	5.71	5.68	4.73	3.82	3.40	4.96	7.26	4.00	4.48
Orig. $I_{\rm ss0}(0\,{\rm V})/10^{-11}$A	10.0	9.10	4.80	12.0	6.70	1.10	2.00	2.70	3.30	0.99
Exp. $I_{{\rm ss}D}(0\,{\rm V})/10^{-6}$A	9.40	4.10	6.60	4.60	5.90	5.70	7.30	4.60	7.20	3.80
Pred. $I_{{\rm ss}D}(0\,{\rm V})/10^{-6}$A	7.44	5.55	5.08	5.83	6.79	5.73	5.58	5.04	6.61	6.19
Relative error/%	20.9	35.4	23.0	26.7	15.1	0.53	23.6	9.57	8.19	62.9
Exp. D/Gy	62.00	56.00	58.00	54.00	58.00	56.00	56.00	56.00	54.00	54.00
Pred. D/Gy	59.50	57.87	56.22	53.85	58.11	54.23	54.64	58.79	58.40	55.73
Relative error/%	4.0	3.3	3.1	0.3	1.4	3.2	2.4	5.0	7.5	5.4

Note: D is the total failure dose.

Apart from the four- or five-parameter regression mentioned above, we have also performed single-, two- and three-parameter regression separately for the prediction of threshold voltage $V_{\rm tn}(D)$, which are shown in Table 5. We find again that the prediction accuracy strongly depends on the selection and number of IPs. For example, R is the biggest for four-parameter regression; however, R is the smallest for the single-parameter $I_{\rm ss0}(5\,{\rm V})$ regression. In addition, saturation of R occurs when the IP number increases from one to three. Moreover, both the number of irradiation test samples and dispersion of parameter value have a significant influence on prediction accuracy. It is necessary to indicate that the choice of IP depends on the type and size of devices. For example, for 54HC04 and 54HC08 circuits, choosing original threshold voltage, static power supply current or transconductance as IPs is because the measurements of these parameters are easily carried out and these parameters are radiation sensitive. However, for some more complex devices, we must choose other parameters as their IPs in order to obtain the best parameter prediction. For example, we may choose the gain of the sample as one of its IPs for the linear operational amplifier. In addition, we have also noted that the prediction accuracy of the static power supply currents ($I_{{\rm ss}D}(0\,{\rm V})$ and $I_{{\rm ss}D}(5\,{\rm V})$) is lower. This is probably attributed to the fact that these parameters do not have a good linear dependence on the IPs.

Table 5. Comparison of R value between one-, two-, three- and four-parameter regression for the prediction of $V_{tn}(D)$ in 54HC04 samples.

	Multiple-parameter regression	R
Four-parameters	$V_{tn}(0)$, $V_{tp}(0)$, $I_{ss0}(0\,V)$ and $I_{ss0}(5\,V)$	0.929
Three-parameters	$V_{tn}(0)$, $V_{tp}(0)$ and $I_{ss0}(0\,V)$	0.925
Two-parameters	$V_{tn}(0)$ and $V_{tp}(0)$	0.913
One-parameter	$V_{tn}(0)$	0.895
One-parameter	$V_{tp}(0)$	0.614
One-parameter	$I_{ss0}(0\,V)$	–0.670
One-parameter	$I_{ss0}(5\,V)$	–0.289

Note: D=40 Gy.

5. Conclusions

In summary, a non-damage selection technique used for predicting ionizing radiation effects of commercial MOS devices is put forward and discussed in relation to its theoretic principles and practical applications. In order to increase the prediction accuracy, it is necessary and important to choose IPs with a high individual correlation coefficient. The prediction accuracy depends strongly on the proper selection and number of IPs. As a practical application of this technique, the average threshold voltage of three n-channel and three p-channel MOSFETs, the static power supply current and the total radiation failure dose for the 54HC04 and 54HC08 commercial devices are predicted with very high prediction accuracy by measuring some original IPs only. The predicted parameters, particularly for the total radiation failure dose, are very helpful for the radiation selection of commercial MOS devices.

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