Re-examination of Impact of Intrinsic Dopant Fluctuations on SRAM Static Noise Margin

Fumihiko Tachibana and Toshiro Hiramoto

Institute of Industrial Science, University of Tokyo, 4-6-1 Komaba, Meguro-ku, Tokyo 153-8505, Japan
Phone: +81-3-5452-6264 Fax: +81-3-5452-6265, E-mail: fumihiko@nano.iis.u-tokyo.ac.jp

1. Introduction

With scaling of MOSFET dimensions, variations of CMOS characteristics due to random dopant fluctuations [1] as well as size variations have become larger and larger. The variations have a great impact on SRAM Cell Static Noise Margin (SNM), leading to the degradation of yield.

The deviations in SNM due to dopant fluctuations have been intensively investigated [2]. This paper has warned that four sigma of deviations in SNM due to intrinsic fluctuations alone exceeds the average SNM and the yield is severely degraded when \( L_g = 50 \text{nm} \). However, parameters assumed in Ref. [2] were based on 1997 NTRS where \( V_{\text{dd}} \) was very low (0.5V) and \( W_g \) equals to \( L_g \), which is significantly different from 2003 ITRS [3]. They assumed the worst condition of small \( \beta \) ratio (\( \beta = 1 \)) and very high temperature (400K). Moreover, they utilized an analytical model of SNM that had many approximations and ignored the body effect. Thus, more precise evaluations using realistic parameters are strongly required.

In this paper, average SNM (\( \text{SNM}_{\text{ave}} \)) and \( \sigma \text{SNM} \) at 298K for several technology generations based on 2003 ITRS are calculated using SPICE simulations. It is shown that five sigma of SNM deviations is ensured at \( L_g = 53 \text{nm} \) in 90nm node. It is also demonstrated that, although \( \sigma \text{SNM} \) rapidly increases in 65nm and 45nm nodes, four sigma of SNM is ensured even in 45nm node by adjusting \( L_g, V_{\text{dd}}, V_{\text{th}}, \) and DIBL.

2. Method

Fig. 1 (a) and (b) show the definition of SNM and the circuit schematic of a SRAM Cell, respectively. First, \( \sigma V_{\text{th}} \) due to dopant fluctuations is calculated by the cube model [2][4] using the device parameters in Table 1, where \( T_{\text{soc}} \) is the electrical oxide thickness. \( N_A \) is obtained by 2D device simulator [5]. Second, SNM of SRAM Cell is calculated by SPICE simulations. The SPICE model used is UCB’s PTM [6], and we have modified to follow device characteristics of low-operation-power (LOP) devices in 2003 ITRS. Changing \( V_{\text{th}} \) of one transistor, the sensitivity of SNM to variations in \( V_{\text{th}} \) of each cell transistor is obtained, as shown in Fig. 1 (c). Finally, joint \( \text{SNM} \) (when all transistors are independently fluctuated) is obtained by:

\[
\sigma \text{SNM} = \sqrt{\frac{\partial \text{SNM}}{\partial V_{\text{th}}}} + \sqrt{\frac{\partial \text{SNM}}{\partial V_{\text{th}}}} + \sqrt{\frac{\partial \text{SNM}}{\partial V_{\text{th}}}} + \sqrt{\frac{\partial \text{SNM}}{\partial V_{\text{th}}}}
\]

3. Results

Fig. 2 shows distribution density functions of SNM due to intrinsic \( V_{\text{th}} \) fluctuations at \( \beta = 1 \) and 1.5. Obtained values of \( \text{SNM}_{\text{ave}} \) and \( \sigma \text{SNM} \) are summarized in Table 2. At \( L_g = 53 \text{nm} \) in 90nm node, 5 sigma of SNM is ensured (\( \text{SNM}_{\text{ave}}/\sigma \text{SNM} > 5 \)) at \( \beta = 1.5 \). However, \( \text{SNM}_{\text{ave}}/\sigma \text{SNM} \) is less than 4 in 65nm (\( L_g = 32 \text{nm} \)) and 45nm (\( L_g = 22 \text{nm} \)) nodes.

To keep high yield in 65nm and 45nm nodes, it is strongly required to increase \( \text{SNM}_{\text{ave}} \) and suppress \( \sigma \text{SNM} \). The cell design to obtain high \( \text{SNM}_{\text{ave}}/\sigma \text{SNM} \) is discussed in the following. Fig. 3 (a) and (b) show the dependence of \( \text{SNM}_{\text{ave}} \) on \( V_{\text{dd}} \) and \( V_{\text{th}} \), respectively, indicating that changing both \( V_{\text{dd}} \) and \( V_{\text{th}} \) is important to raise \( \text{SNM}_{\text{ave}} \) effectively.

It is found that DIBL greatly affects \( \text{SNM}_{\text{ave}} \). Fig. 3 (c) shows the DIBL dependence of \( \text{SNM}_{\text{ave}} \), where it is assumed that \( V_{\text{th}} \) at \( V_{\text{dd}} = V_{\text{dd}}^0 \) is constant and only DIBL is changed. \( V_{\text{th}} \) at low \( V_{\text{dd}} \) in MOSFET with high DIBL is higher than that of MOSFET with low DIBL. This makes a difference in butterfly curves, as shown in Fig. 4. In order to keep \( \text{SNM}_{\text{ave}} \) high, DIBL should be suppressed.

\( L_g \) in LOP devices in 2003 ITRS is too aggressively scaled for SRAM applications. Another method to obtain high \( \text{SNM}_{\text{ave}}/\sigma \text{SNM} \) is to relax the \( L_g \) scaling. Fig. 5 shows \( L_g \) dependence of \( N_A \) and \( \sigma V_{\text{th}} \) with constant \( V_{\text{th}} \). As \( L_g \) becomes longer, the short channel effect is suppressed, resulting in lower \( N_A \) and smaller \( \sigma V_{\text{th}} \). Thus, \( \text{SNM} \) can be suppressed. Fig. 6 shows the distribution density functions of SNM using adjusted parameters, where \( L_g = 30 \text{nm} \), \( N_A = 4.45 \times 10^{18} \text{cm}^{-3} \), DIBL=80mV/V, \( V_{\text{dd}} = 0.8 \text{V} \), and \( V_{\text{th}} = 0.25 \text{V} \). The result indicates that \( \text{SNM}_{\text{ave}}/\sigma \text{SNM} \) is larger than 4, and four sigma of SNM can be ensured even in 45nm node by adjusting parameters. It should be noted that we considered the effect of dopant fluctuations alone. When size variations are taken into account, higher \( \text{SNM}_{\text{ave}} \) is required.

4. Conclusions

SRAM \( \text{SNM}_{\text{ave}} \) and \( \sigma \text{SNM} \) due to dopant fluctuations alone are re-examined based on LOP devices in 2003 ITRS using SPICE simulations. It is shown that 5 sigma of SNM is ensured in 90nm node at \( \beta = 1.5 \) and 4 sigma is ensured even in 45nm node by adjusting \( L_g, V_{\text{dd}}, V_{\text{th}} \) and DIBL.

Acknowledgements

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References
Table 1. Input parameters for simulations [3].

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<tr>
<th>Node</th>
<th>$L_g$ (nm)</th>
<th>$T_{ox}$ (nm)</th>
<th>$N_A$ (cm$^{-2}$)</th>
<th>$V_{dd}$ (V)</th>
<th>$I_{on}$ (µA/µm)</th>
<th>$V_{sat}$ (V)</th>
<th>DIBL (mV/V)</th>
<th>$\gamma = -dV_{th}/dV_{bs}$</th>
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<tbody>
<tr>
<td>90nm</td>
<td>53</td>
<td>2.3</td>
<td>1.84e18</td>
<td>0.9</td>
<td>530</td>
<td>0.26</td>
<td>100</td>
<td>0.1</td>
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<tr>
<td>65nm</td>
<td>32</td>
<td>1.9</td>
<td>3.82e18</td>
<td>0.8</td>
<td>570</td>
<td>0.26</td>
<td>140</td>
<td>0.09</td>
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<tr>
<td>45nm</td>
<td>22</td>
<td>1.3</td>
<td>6.69e18</td>
<td>0.7</td>
<td>770</td>
<td>0.22</td>
<td>160</td>
<td>0.07</td>
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</table>

Fig. 1. (a) Definition of SNM$_L$, (b) Schematic of SRAM Cell. Underlined four transistors affect SNM$_L$. (c) Sensitivities of SNM$_L$ to variations in $V_{th}$ of each transistor.

Table 2. Calculated values of SNM$_{ave}$, $\sigma V_{th}$, and $\sigma$SNM.

<table>
<thead>
<tr>
<th>Node</th>
<th>$\sigma V_{th}$ (mV)</th>
<th>$\sigma$SNM (mV)</th>
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<tbody>
<tr>
<td>90nm</td>
<td>36.4</td>
<td>105.9</td>
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<td>65nm</td>
<td>51.2</td>
<td>101.3</td>
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<td>45nm</td>
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<td>73.8</td>
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Fig. 2. Distribution density functions of SNM due to intrinsic $V_{th}$ fluctuations at $\beta=1$ and 1.5.

Fig. 3. The dependence of SNM$_{ave}$ on (a) $V_{dd}$, (b) $V_{th}$, and (c) DIBL in 45nm node at $\beta=1.5$.

Fig. 4. Butterfly curves for MOSFETs with two different DIBL in 45nm node at $\beta=1.5$.

Fig. 5. $L_g$ dependence of $N_A$ and $\sigma V_{th}$. Black and white symbols indicate $N_A$ and $\sigma V_{th}$, respectively.

Fig. 6. Distribution density functions of SNM after adjusting parameters. Four sigma of SNM is ensured in 45nm node at $\beta=1.5$. 

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