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A new definition of threshold voltage by constant slope for analysis of statistical variations of MOSFETs

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Abstract We have proposed a new definition of threshold voltage by constant slope ($V_{\mathrm{th\,sl}}$) for analysis of statistical variations of MOSFETs. We have analyzed characteristic of $V_{\mathrm{th\,sl}}$: value, statistical variation, correlation comparing that of conventional V_{th} by constant current and V_{th} by extrapolation. Extraction of $V_{\mathrm{th\,sl}}$ is simple, easy, fast and robust and its errors are well suppressed in measurement. $V_{\mathrm{th\,sl}}$ is found to be one of a best parameter for analysis of statistical variations.

1 Introduction Recently, statistical variation of MOSFETs in electric characteristics is one of most serious issue in scaled VLSIs. The threshold voltage (V_{th}) is one important parameter to analyze MOSFET electric characteristics and many kind of definition of V_{th} has been proposed and commonly used. In measurement of statistical variation, a V_{th} whose extraction is easy, fast and robust is required. However, several commonly-used V_{th}'s have some shortage on this purpose. V_{th} defined by constant current ($V_{\mathrm{th\,c}}$) is difficult to define effective gate length L and width W and uncertain L and W lead to some errors. V_{th} defined by extrapolation ($V_{\mathrm{th}\,x\,\mathrm{max}}$) takes long time in extraction because it requires measurement of I_d–V_g with wide range and small V_g step and an extraction procedure of maximum of differential is often affected by noise and parasitic resistance.

In this paper, we propose a new definition of threshold voltage by constant slope ($V_{\mathrm{th\,sl}}$) for analysis of statistical variations. We discuss characteristic of $V_{\mathrm{th\,sl}}$: value, statistical variation, correlation comparing that of V_{th} by constant current and V_{th} by extrapolation and show the validity of $V_{\mathrm{th\,sl}}$ as a parameter for analysis of statistical variations.

2 Basis of threshold voltage by constant slope $V_{\mathrm{th\,sl}}$ is defined by V_g that gives a constant slope S_{th} (Fig. 1(a)), where $S \equiv \partial V_g/\partial(\log_{10} I_{ds})$ is as same as commonly used "subthreshold slope" at the subthreshold region. If I_{ds} follows a model equation $I_{ds} = (\mu_{\mathrm{eff}} C_{\mathrm{ox}} W/L) \times f(V_g, V_d)$ [1], $1/S = \partial \log I_{ds}/\partial V_g = \partial \log f(V_g, V_d)/\partial V_g$ is independent of C_{ox}, L, W and depend only on the shape of the curve $f(V_g, V_d)$. In measurement, S–V_g was found to be independent of L (Fig. 1(b)). Therefore, $V_{\mathrm{th\,sl}}$ does not affected by uncertainty of L and W. Ref. 2 proposed V_{th} defined by V_g which gives minimum of S from the similar motivation. However, its extraction will not be robust because second order differential of $\log I_{ds}$ is required and due to leak currents at subthreshold region.

In Tab. 1, V_{th}'s discussed in this paper are listed. $V_{\mathrm{th\,c\,W}}$ and $V_{\mathrm{th\,c\,LW}}$ are conventional V_{th} defined by constant current. $V_{\mathrm{th\,g}_{m\,\mathrm{max}}}$, $V_{\mathrm{th}\,\beta_{\mathrm{max}}}$ is given by intercept of I_{ds}–V_g, $\sqrt{I_{ds}}$–V_g at $I_{ds} = 0$ extrapolating from maximum of $\partial I_{ds}/\partial V_g$, $\partial\sqrt{I_{ds}}/\partial V_g$, respectively. In Fig. 2(a), we compare $V_{\mathrm{th\,c}}$ and $V_{\mathrm{th\,sl}}$ in I_d–V_g, S–V_g plots. We show some worst case of measured variation of I_d–V_g in a wafer of an experimental lot in Fig. 2(b). The hump at subthreshold region is large and cause larger variation of $V_{\mathrm{th\,c}}$ in constrast to I_d–V_g at the strong inversion region. However, the variation of $V_{\mathrm{th\,c}}$ is not strongly related to that of the function of circuit because subthreshold region is not so important for the function of circuit.

Figure 3 shows measured I_{ds} which gives constant slope $S_{\mathrm{th}} = 0.2, 0.4$ V/decade normalized by L/W in MOSFETs with various size of L as a function of L at low V_d. S_{th} is roughly corresponds to $I_{\mathrm{th\,LW}}$ from 5×10^{-7} A to 5×10^{-6} A. It shows the V_g region for $V_{\mathrm{th\,sl}}$ extraction is much larger than subthreshold and than commonly-used I_{th} for $V_{\mathrm{th\,c}}$ and is much smaller than that for $V_{\mathrm{th}\,x\,\mathrm{max}}$ extraction. It makes advantage of easier, faster and more robust measurement because limited V_g region is required in $V_{\mathrm{th\,sl}}$ extraction.

3 Measurement of statistical variation We prepared test patterns specialized to measure layout dependence of I–V. Those patterns are set in the 16×16 transistor matrix per a chip as similar to Ref. 3. We fabricated a wafer by 65 nm technology and measured I_{ds}–V_d and I_{ds}–V_g characteristic of typically 5120 transistors per one monitor pattern.

3.1 Comparison of V_{th}'s Figures 4 and 5 show correlation plot of $V_{\mathrm{th\,sl}}(0.4)$ versus $V_{\mathrm{th\,g}_{m\,\mathrm{max}}}$ at a linear region and versus $V_{\mathrm{th}\,\beta_{\mathrm{max}}}$ at a saturation region, respectively. At most case, $V_{\mathrm{th\,sl}}$ and $V_{\mathrm{th}\,x\,\mathrm{max}}$ are on the line of $V_{\mathrm{th\,sl}} - V_{\mathrm{th\,g}_{m\,\mathrm{max}}} = 0.21 \sim 0.22$ at linear region and $V_{\mathrm{th\,sl}} - V_{\mathrm{th}\,\beta_{\mathrm{max}}} = 0.33 \sim 0.34$ at saturation region, respectively. It shows $V_{\mathrm{th\,sl}}$ and $V_{\mathrm{th}\,x\,\mathrm{max}}$ are strongly correlated and the behavior of variation is very similar. Correlation plot of various threshold voltage $V_{\mathrm{th\,sl}}$, $V_{\mathrm{th\,c\,W}}$ and $V_{\mathrm{th\,c\,LW}}$ versus $V_{\mathrm{th}\,x\,\mathrm{max}}$(Fig. 6) shows that correlation of $V_{\mathrm{th\,sl}}$ and $V_{\mathrm{th\,c}}$ is weak and some different phenomena are affected.

3.2 Distribution of $V_{\mathrm{th\,sl}}$ Figure 7 shows cumulative probability of various threshold voltages in sets of the MOSFETs with size of $L = 1000$ nm, $W = 1000$ nm and $L = 60$ nm, $W = 140$ nm. It shows the distribution of V_{th} is almost the same among different definitions. Figure 8 shows standard deviation σV_{th} at $V_d = V_{dd}$ in each device size normalized by $\sqrt{LW}$ as a function of $\sqrt{LW}$, where various threshold voltages $V_{\mathrm{th\,c\,W}}$ at $I_{\mathrm{th\,W}} = 1\times10^{-7}$ A/μm, $V_{\mathrm{th\,c\,LW}}$ at $I_{\mathrm{th\,LW}} = 1\times10^{-7}$ A, $V_{\mathrm{th}\,\beta_{\mathrm{max}}}$, and $V_{\mathrm{th\,sl}}(0.4)$ are compared. It shows the dependence of σV_{th} is almost the same between $V_{\mathrm{th}\,\beta_{\mathrm{max}}}$ and $V_{\mathrm{th\,sl}}$ and σV_{th} of $V_{\mathrm{th}\,\beta_{\mathrm{max}}}$ and $V_{\mathrm{th\,sl}}$ is smaller than that of $V_{\mathrm{th\,c\,W}}$ and $V_{\mathrm{th\,c\,LW}}$. It is because constant current V_{th}'s $V_{\mathrm{th\,c\,W}}$ and $V_{\mathrm{th\,c\,LW}}$ is affected and $V_{\mathrm{th\,sl}}$ and $V_{\mathrm{th}\,\beta_{\mathrm{max}}}$ is not affected by leak currents (junction leak, GIDL, and source/drain leak from unselected DUTs) and by hump at subthreshold.

4 Conclusion We have proposed a new definition of threshold voltage by constant slope ($V_{\mathrm{th\,sl}}$). Extraction of $V_{\mathrm{th\,sl}}$ at slope $S_{\mathrm{th}} = 0.4$ V/decade was found to be simple, easy, fast and robust and its errors are well suppressed in measurement. $V_{\mathrm{th\,sl}}$ is one of a best parameter for analysis of statistical variations.

References

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[2] Kazuo Aoyama, Specification of Japanese Patent Application Unexamined Publication No. Hei 6-252395. Disclosed in 1994. (in Japanese).

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Table 1: List of threshold voltages by several definitions. L and H in the V_d column denotes it is valid at low V_d (linear region) and high V_d (saturation region), respectively.

parameter	V_d	definition
$V_{\mathrm{th\,sl}}(S_{\mathrm{th}})$	LH	V_g at $S \equiv \partial V_g/\partial(\log_{10} I_{ds}) = S_{\mathrm{th}}$ (constant slope)
$V_{\mathrm{th\,c\,W}}(I_{\mathrm{th\,W}})$	LH	V_g at $I_{ds}/W = I_{\mathrm{th\,W}}$ (constant current)
$V_{\mathrm{th\,c\,LW}}(I_{\mathrm{th\,LW}})$	LH	V_g at $I_{ds}L/W = I_{\mathrm{th\,LW}}$ (constant current)
$V_{\mathrm{th\,g_{m\,max}}}$	L	extrapolation of I_{ds}–V_g from maximum of $\partial I_{ds}/\partial V_g$
$V_{\mathrm{th}\,\beta_{\max}}$	H	extrapolation of $\sqrt{I_{ds}}$–V_g from maximum of $\partial\sqrt{I_{ds}}/\partial V_g$

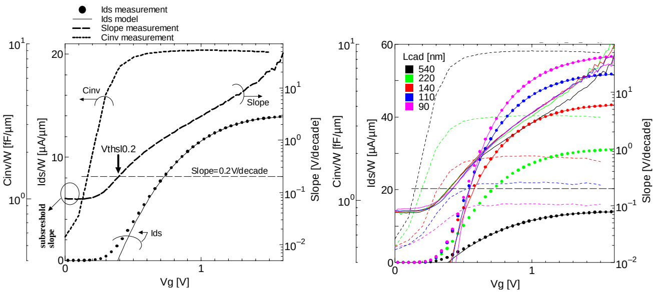

Figure 1: Measured gate capacitance C_{inv}, I_d/W, and slope $S \equiv \partial V_g/\partial(\log_{10} I_{ds})$ as a function of V_g. (a) Definition of threshold voltage by constant slope $V_{\mathrm{th\,sl}}$ and (b) L dependency.

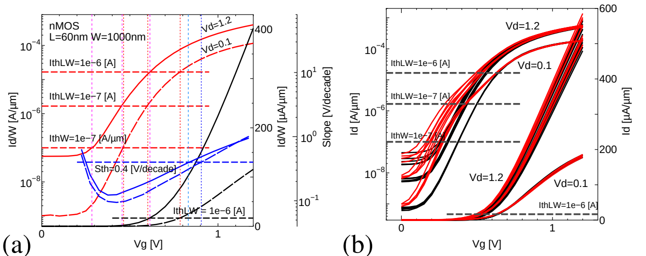

Figure 2: (a) Comparison of threshold voltage by constant current $V_{\mathrm{th\,c\,W}}$, $V_{\mathrm{th\,c\,LW}}$ and constant slope $V_{\mathrm{th\,sl}}$. (b) a worst case of measured I_{ds}–V_g variation. $V_{\mathrm{th\,c\,W}}$ and $V_{\mathrm{th\,c\,LW}}$ may affect hump of I_d–V_g at the subthreshold region.

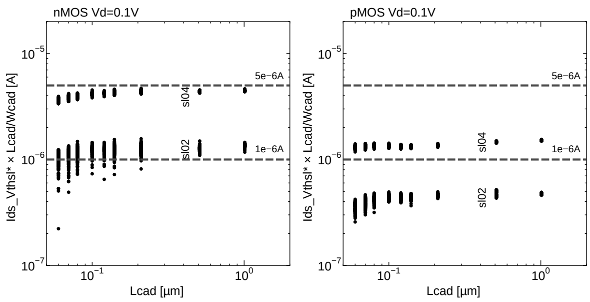

Figure 3: Measured I_{ds} which gives constant slope $S_{\mathrm{th}} = 0.2, 0.4$ V/decade normalized by L/W in MOSFETs with various size of L as a function of L.

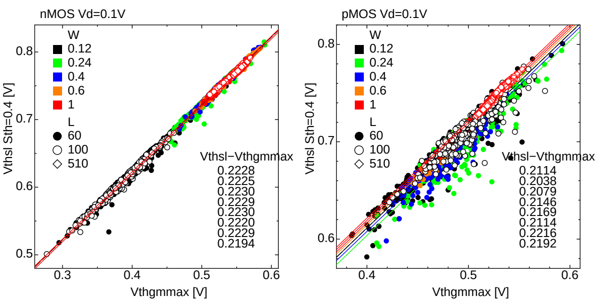

Figure 4: Correlation plot of $V_{\mathrm{th\,sl}}$ at $S_{\mathrm{th}} = 0.4$ V/decade versus $V_{\mathrm{th\,g_{m\,max}}}$ at linear region.

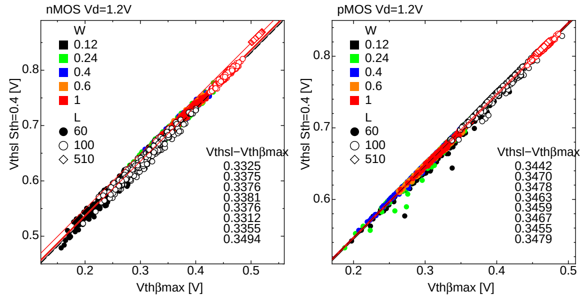

Figure 5: Correlation plot of $V_{\mathrm{th\,sl}}$ at $S_{\mathrm{th}} = 0.4$ V/decade versus $V_{\mathrm{th}\,\beta_{\max}}$ at saturation region.

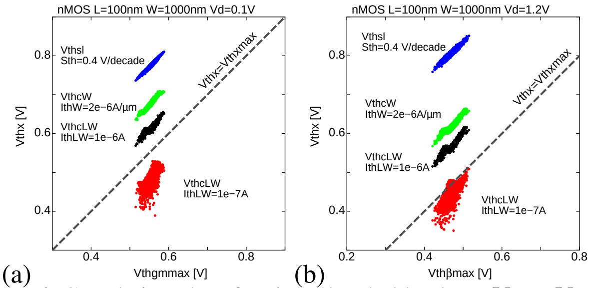

Figure 6: Correlation plot of various threshold voltage $V_{\mathrm{th\,sl}}$, $V_{\mathrm{th\,c\,W}}$ and $V_{\mathrm{th\,c\,LW}}$ versus (a) $V_{\mathrm{th\,g_{m\,max}}}$ at linear region and (b) $V_{\mathrm{th}\,\beta_{\max}}$ at saturation region.

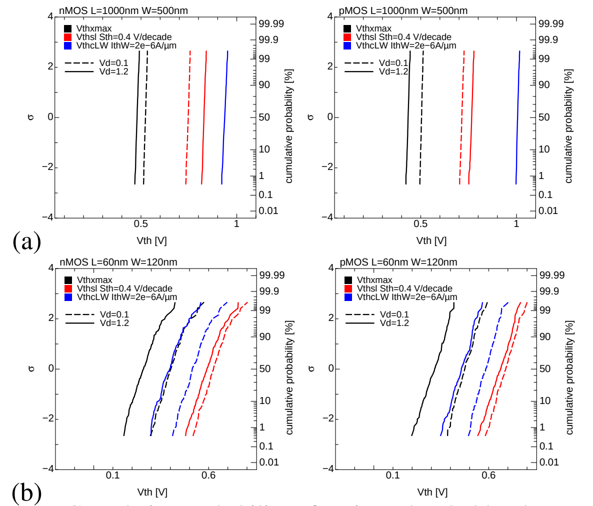

Figure 7: Cumulative probability of various threshold voltages. (a) $L = 1000$ nm, $W = 1000$ nm, (b) $L = 60$ nm, $W = 120$ nm.

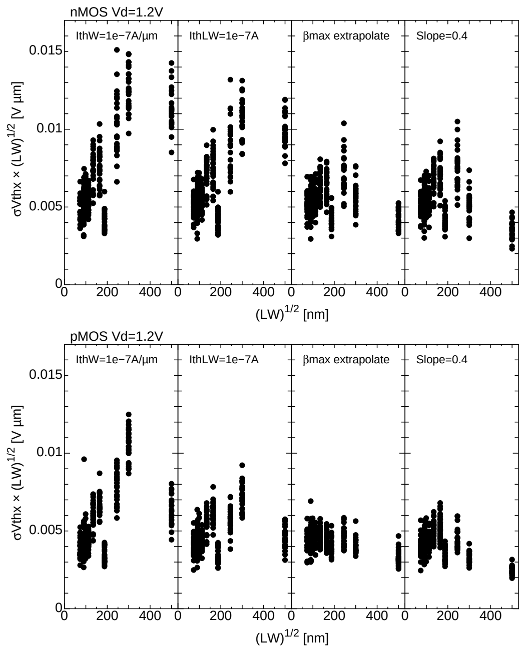

Figure 8: Standard deviation σV_{th} in each device size normalized by $\sqrt{LW}$ as a function of $\sqrt{LW}$ comparing among various threshold voltages $V_{\mathrm{th\,c\,W}}$, $V_{\mathrm{th\,c\,LW}}$, $V_{\mathrm{th}\,\beta_{\max}}$, and $V_{\mathrm{th\,sl}}$.