## Analysis and modeling of size dependent mobility enhancement due to mechanical stress

<sup>†</sup>Takuji Tanaka, Ken-ichi Goto, Ryou Nakamura, and Shigeo Satoh

FUJITSU Ltd.

50 Fuchigami, Akiruno, Tokyo 197-0833 Japan

Tel: +81-42-532-1253, Fax: +81-42-532-2514, E-mail: <sup>†</sup>tanaka.takuji@jp.fujitsu.com

**Abstract** We applied a BSIM3v3-like compact model in order to analyze size dependent low field mobility in MOSFETs. By using new extraction procedure, we have successfully extracted gate length dependence of mobility degradation and enhancement due to halo and mechanical stress. The new method is applicable to wide variation of device sizes, structures and materials.

**1** Introduction Recent studies clarified that mechanical stress can modulate the current in scaled MOSFETs [1]. Low field mobility  $\mu$  will continuously vary with the device size because of the mechanical stress. To correctly evaluate  $\mu$ , consideration of external series resistance  $R_{\rm sd}$  and mobility modulation due to perpendicular electric field  $E_{\perp}$ , channel dopant (e.g. halo or pocket) is required (Fig. 1). However, most conventional methods of  $R_{\rm sd}$  or  $\mu$  extraction [2–4] have limited validity since they assumed constant mobility between different gate lengths [5, 6]. An approach by dR/dL method [7] is difficult to detect continuous size dependency.

In this paper, we applied a BSIM3v3-like compact model to analyze  $R_{\rm sd}$  and size dependent low field mobility. We propose a novel extraction method (named "6c-5p" method), which realizes highly accurate parameter extraction and show it can measure mobility degradation or enhancement as a function of the gate length.

2 Mobility extraction method Our current model at the triode region (Eq. 1–4) is a simplified and modified BSIM3v3 [8] compact model and a modified Ref. 3 on  $A_{\text{bulk}}$ . The assumption is: measured  $I_{ds}$  is series of intrinsic FET with  $I_{ds0}$  and constant resistance  $R_{\text{sd}}$ ; first- and second-order mobility reduction factor  $\Theta_1$ ,  $\Theta_2$ ; simplified  $V_{g \text{ eff}}$  valid at strong inversion region.

$$V_{ds}/I_{ds} = V_{ds}/I_{ds0} + R_{\rm sd}$$
 (1)

$$I_{ds0} = (\mu_{\text{eff}} W C_{\text{ox}} / L_{\text{eff}}) V_{g \text{ eff}} V_{ds}$$

$$(2)$$

$$\mu_{\rm eff} = \mu_0 / (1 + \Theta_1 V_{g \, \rm eff} + \Theta_2 V_{g \, \rm eff}^2) \tag{3}$$

$$V_{g\,\text{eff}} = V_g - V_{\text{th}} - A_{\text{bulk}} V_{ds}/2 \tag{4}$$

$$U_0 = \mu_0 W C_{\rm ox} / L_{\rm eff}, \quad \Theta_{\rm 1eff} = \Theta_1 + U_0 R_{\rm sd} \tag{5}$$

$$\frac{1}{I_{ds}} = \frac{1}{U_0 V_{ds}} \left\{ \frac{1}{V_{g \text{ eff}}} + \Theta_{1\text{eff}} + \Theta_2 V_{g \text{ eff}} \right\}$$
(6)

$$g_m \equiv \frac{\partial I_{ds}}{\partial V_g}, \quad Y \equiv \frac{I_{ds}}{\sqrt{g_m}} = \sqrt{\frac{U_0 V_{ds}}{1 - \Theta_2 V_g \operatorname{eff}^2}} V_g \operatorname{eff} \quad [3] \quad (7)$$

$$\frac{Y^2}{V_{g\,\text{eff}}^2} = \frac{U_0 V_{ds}}{1 - \Theta_2 V_{g\,\text{eff}}^2}, \frac{I_{ds}}{V_{g\,\text{eff}}} = \frac{U_0 V_{ds}}{1 + \Theta_{1\text{eff}} V_{g\,\text{eff}} + \Theta_2 V_{g\,\text{eff}}^2}$$
(8)

The substrate charge effect is negligible  $(A_{\text{bulk}} = 0)$  at a symmetric bias condition  $V_d = -V_s = V_{ds}/2$  in our measurement ( $V_{ds} = 20 \text{ mV}$ ). We have confirmed good linearity of  $I_{ds}$  on  $V_{ds}$  by measuring that  $R_{\text{out}} (\equiv 1/(\partial I_{ds}/\partial V_{ds}))$  is independent of  $V_{ds}$ . A derived basic equation (Eq. 6) includes five model parameters "5p" ( $U_0, \Theta_1, \Theta_2, R_{\text{sd}}, V_{\text{th}}$ ).

To extract model parameters, we propose a pair of new reference values  $Y^2/V_{g\,\mathrm{eff}}^2$  and  $I_{ds}/V_{g\,\mathrm{eff}}$  in addition to four conventional values  $I_{ds}$ ,  $1/I_{ds}(\propto R_{\mathrm{out}}$  at low  $V_{ds})$ ,  $g_m$ , Y.

The pair has the merit that the sensitivity of  $\Theta_{1\text{eff}}$  and  $\Theta_2$  is independent and that of  $U_0$  is the same each other (Eq. 8). Since those six reference curves "6c" derived from  $I_d-V_g$  (Fig. 2) have different sensitivity (Tab. 1), we have referred all "6c" at the same time in the parameter extraction.

The parameter extraction has done by the five steps: (1) we extracted  $U_0$ ,  $\Theta_{1\rm eff}$ ,  $\Theta_2$ ,  $V_{\rm th}$  in each  $L_{\rm eff}$  (Fig. 2) selfconsistently between a set of  $(U_0, \Theta_{1\rm eff}, \Theta_2)$  and  $V_{\rm th}$ . The extracted  $V_{\rm th}$  was slightly (~ 55 mV) larger than linearlyextrapolated  $V_{\rm th}$  from  $g_{m\,\rm max}$ . (2) we extracted  $R_{\rm sd}$  by plotting  $\Theta_{1\rm eff}-U_0$  among all  $L_{\rm eff}$ 's [3]. Note that errors of  $L_{\rm eff}$ and  $L_{\rm eff}$ -dependent  $\mu_0$  never affect on the  $R_{\rm sd}$  extraction. The result (Fig. 3(a)) shows the assumption of constant  $R_{\rm sd}$  and  $\Theta_1$  for all different  $L_{\rm eff}$  is valid. (3) we re-extracted  $U_0$  with the extracted  $\Theta_1$ ,  $R_{\rm sd}$ . (4) we extracted  $L_{\rm eff}$  by C-V, SEM, TEM measurement (Fig. 3(b)) and by the inverse modeling method [9]. (5) we calculated  $I_{ds0}$ ,  $\mu_0$  using the extracted  $R_{\rm sd}$ ,  $L_{\rm eff}$ ,  $U_0$ . An error of  $L_{\rm eff}$  (and W,  $C_{\rm ox}$ ) may affect on  $\mu_0$  only at this step.

**3 Result and discussion** Figure 5 shows the result of  $I_{ds}$ - $V_g$  and its derivatives comparing measurement and model for all  $L_{\rm eff}$  range. We have found that the model is very accurate and the extracted parameter set is highly reliable in all range of  $L_{\rm eff}$  from 2 µm to  $\lesssim 20$  nm. The calculated current and mobility by our method is found to be equivalent to the well calibrated device simulation (Fig. 2, 4).

We calculated  $g_{m \max}$  of intrinsic MOSFET using  $I_{ds0}$  with  $R_{sd}$  correction. It is found that corrected  $g_{m \max}$  is much larger and not saturated with decreasing  $L_{eff}$  in contrast to raw  $g_{m \max}$  without  $R_{sd}$  correction (Fig. 6(a)). The corrected  $g_{m \max}$  was found to be proportional to  $U_0$  (Fig. 6(b)), showing the corrected  $g_{m \max}$  and the extracted  $U_0$  are consistent.

The extracted  $\mu_0$  decreases with decreasing  $L_{\rm eff}$  (Fig. 7, filled symbols). It is expected to mobility reduction due to heavy halo (or pocket) dose. By comparing  $\mu_0$  among the various SiN cover thickness (Fig. 7, open symbols), the enhancement of  $\mu_0$  due to mechanical stress has found to reach a peak at  $L_{\rm eff} \sim 200$  nm.

Since our method relies only on the model accuracy, the application is not limited in this case and it can treat other structures (e.g. SOI, double gate) and materials (e.g. high-k).

**4 Conclusion** By the newly developed "6c-5p" method, we have successfully extracted the gate length dependence of mobility degradation/enhancement due to halo and mechanical stress without disturbance of series resistance for the first time. The new method is widely applicable to analysis and modeling of future advanced MOSFETs.

## References

- [1] S. Ito et al., IEDM Tech. Digest p.247, 2000.
- [2] Y. Taur et al., IEEE Elec. Dev. Lett. 13 p.267, 1992.
- [3] C. Mourrain et al., Int. Conf. Microelec. Test Struct. p.181, 2000.
- [4] B. Cretu et al., Electron. Lett. 37 p.717, 2001.
- [5] Y. Taur, IEEE Elec. Dev. 47 p.160, 2000.
- [6] H. van Meer et al., IEEE Elec. Dev. Lett. 13 p.133, 2000.
- [7] K. Rim et al., IEDM Tech. Digest p.43, 2002.
- [8] Y. Chang et al., IEEE Elec. Dev. 44 p.277, 1997.
- [9] Takuji Tanaka et al., IEDM Tech. Digest p.887, 2002.



Figure 1: Schematic illustration of MOSFET with mechanical stress. To correctly extract mobility, consideration of  $R_{\rm sd}$  and mobility modulation due to several effects is required.



Figure 2:  $I_{ds}-V_g$  and five plots derived from the  $I_{ds}-V_g$  curve. We propose new reference value  $Y^2/V_{g \text{ eff}}^2$  and  $I_{ds}/V_{g \text{ eff}}$  (Eq. 8), which are better to check errors of  $U_0$ ,  $\Theta_{1\text{ eff}}$ , and  $\Theta_2$ . We have extracted five model parameters "5p" ( $U_0$ ,  $\Theta_1$ ,  $\Theta_2$ ,  $R_{sd}$ ,  $V_{th}$ ) by referring those six curves "6c" (Table 1).



Figure 3: (a)  $R_{\rm sd}$ ,  $\Theta_1$ , and (b)  $L_{\rm eff}$  extraction. Note that errors of  $L_{\rm eff}$  and  $L_{\rm eff}$ -dependent  $\mu_0$  never affect on  $R_{\rm sd}$  extraction.



horizontal position [nm] Figure 4: Electron mobility averaged along with the vertical direction, where well calibrated device simulation and the compact model are compared. It is found that the compact model is equivalent to the device simulation and the outside of the metallurgical junctions can treat as a constant series resistance.



Figure 5: Gate length dependence of  $I_{ds}-V_g$  and its derivatives. The model well fits the measurement from  $L_{\rm eff} \sim 2 \,\mu$ m to  $L_{\rm eff} \lesssim 20$  nm.



Figure 6:  $g_{m \max}$  vs.  $L_{\text{eff}}$  and  $U_0$  comparing with and without  $R_{\text{sd}}$  correction.  $I_{ds0}$  with  $R_{\text{sd}}$  correction is calculated by Eq. 1 as shown in inset: an example of  $I_{ds}$  and  $g_m$  at  $L_{\text{eff}} = 20$  nm.



Figure 7:  $L_{\rm eff}$  dependence of low field mobility  $\mu_0$  at  $V_g = V_{\rm th}$  (filled) relative to ( $L_{\rm eff} = 2 \,\mu m$ , thin SiN cover), and (open) relative to (each  $L_{\rm eff}$ , thin SiN cover), comparing nMOSFETs with various SiN cover thickness.

Table 1: Sensitivity of parameters to six functions. ' $\bigcirc$ ', ' $\bigcirc$ ', ' $\bigtriangleup$ ', ' $\bigstar$ ', and ' $\_$ ' denotes quite high, high, middle, low, and no sensitivity, respectively.  $\Theta_{1\text{eff}} = \Theta_1 + R_{\text{sd}}U_0$ .

		$V_{\rm th}$	$U_0$	$\Theta_{1\mathrm{eff}}$	$\Theta_2$
conventional	$I_d$	0	$\bigcirc$	$\triangle$	X
	$1/I_d$	X	$\triangle$	$\triangle$	$\times$
	$g_m$	X	0	0	$\times$
	Y [3,4]	$\times$	0		0
new	$Y^2/V_{g\mathrm{eff}}^2$	$\triangle$	$\odot$		0
	$I_d/V_{g\mathrm{eff}}$	$\triangle$	$\odot$	0	$\times$