Mobility Degradation of 28-nm Bulk MOSFETs Irradiated to Ultrahigh Total Ionizing Doses

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Abstract—Using the $Y$-function method, this paper experimentally investigates the effects of total ionizing dose up to 1 Grad on the channel mobility of a commercial 28-nm bulk CMOS process.

Keywords—Interface traps, mobility degradation, oxide-trapped charges, shallow trench isolation, total ionizing dose, 28-nm bulk MOSFETs, $Y$ function

I. INTRODUCTION

The total amount of energy absorbed by a MOSFET from incident ionizing radiation, measured by total ionizing dose (TID) using either a unit called rad or the SI unit called Gy [1]. TID-induced oxide- and interface-trapped charges influence electrical characteristics of electronic devices [2]. For example, it gives rise to a drive current loss by increasing the absolute threshold voltage and/or reducing the effective channel mobility [3]. The innermost electronics of CERN’s forthcoming high-luminosity Large Hadron Collider (HL-LHC) is anticipated to experience an unprecedented radiation level up to 1 Grad of TID and 1016 neutrons/cm2 of hadron fluence over ten years of operation [4]. This might lead to device degradation and even failure [5]. With the perspective of using advanced MOS technologies in the HL-LHC, we have been studying the radiation tolerance of a commercial 28-nm bulk CMOS process up to 1 Grad [3], [6]. Using the $Y$-function method [7], this paper experimentally investigates the effects of TID on the channel mobility in linear operation.

II. CHANNEL MOBILITY EXTRACTION

This work studies the drain-to-source current $I_{DS}$ in strong inversion of linear operation at a small value of drain-to-source voltage ($V_{DS} = 0.01\,\text{V}$). Using the drift-diffusion model for drain current $I_{DS} = W\mu_{eff}C_{ox}(V_{GB} - V_T) V_{DS}/L$ and the first-order model for mobility degradation $\mu_{eff} = \mu_0/[1 + \theta(V_{GB} - V_T)]$ gives the current-voltage expression:

$$I_{DS} = \frac{W}{L} \frac{\mu_0}{1 + \theta(V_{GB} - V_T)} C_{ox} (V_{GB} - V_T) V_{DS}, \quad (1)$$

where $W$ and $L$ are the effective channel width and length, respectively, $\mu_{eff}$ is the effective channel mobility, $\mu_0$ is the low-field channel mobility, $\theta$ is the effective mobility degradation coefficient, $V_{GB}$ is the gate-to-bulk voltage, $V_T$ is the charge threshold voltage, and $C_{ox}$ is the gate oxide capacitance per unit area. Differentiating $I_{DS}$ versus $V_{GB}$ for $G_m$ and combining it with (1), we obtain the well-known $Y$ function [7]:

$$\frac{I_{DS}}{\sqrt{G_m}} = \sqrt{\frac{W}{L}} \mu_0 C_{ox} (V_{GB} - V_T). \quad (2)$$

In strong inversion, $I_{DS}/\sqrt{G_m}$ is independent of $\theta$ and proportional to $V_{GB}$, as evidenced by the $I_{DS}/\sqrt{G_m}$ versus $|V_{GB}|$ curves in Fig. 1a-b and Fig. 1c-d. $V_T$ is defined as the $|V_{GB}|$ intercept of the linear extrapolation and $\mu_0$ is deduced from the slope of the extrapolated line. At high TID levels, narrow-channel MOSFETs demonstrate a higher $V_T$ shift and a more significant $\mu_0$ reduction than wide-channel MOSFETs.

To get an accurate extraction of $V_T$, $\mu_0$, and $\theta$, this linear extrapolation has to be applied in a sufficient strong inversion region [7]. This can be checked by the occurrence of the $3\theta V_T$ plateau at high values of $|V_{GB}|$. Combining the derived $G_m$ with (1) enables us to extract $\theta$:

$$\theta = \left[ \frac{I_{DS}}{G_m (V_{GB} - V_T)} - 1 \right] \frac{1}{V_{GB} - V_T}. \quad (3)$$

Fig. 1c-d and Fig. 1g-h confirm the $|V_{GB}|$ independence of $\theta$ in strong inversion. Due to the significant $V_T$ shift at high TID levels, narrow-channel pMOSFETs have a reduced $V_{GB}$ range with the validity of the $Y$-function method. Furthermore, the corresponding $\theta$ tends to be zero, indicating a negligible influence of $|V_{GB}|$ on the $\mu_{eff}$ of narrow-channel pMOSFETs.

III. GIGARAD-TID EFFECTS ON CHANNEL MOBILITY

Fig. 2 plots the calculated $\mu_{eff}$ using the extracted $V_T$, $\mu_0$, and $\theta$ versus $|V_{GB}| - V_T$. We observe a $|V_{GB}|$-independent mobility degradation, except for narrow-channel pMOSFETs that display a $|V_{GB}|$-independent $\mu_{eff}$ at high TID levels. This corresponds to their negligible $\theta$ at high TID levels. We also observe a higher $\mu_{eff}$ reduction for narrow-channel MOSFETs than wide-channel MOSFETs. Note that $\mu_0$ corresponds to $|V_{GB}| - V_T = 0$. As expected, the low-field electron mobility is around three times the low-field hole mobility.

The $\mu_0$ and $V_T$ variation is plotted versus TID in Fig. 3. We see a limited influence on $\mu_0$ (< 20%) and $V_T$ (< 7%) of wide-channel MOSFETs even at ultrahigh TID levels. This indicates the improved radiation tolerance of the advanced gate stacks. However, narrow-channel MOSFETs undergo a significant $\mu_0$ reduction up to 36% for nMOSFETs (Fig. 3a) and up to 73% for pMOSFETs (Fig. 3c). This is because narrow-channel MOSFETs are more sensitive to the TID-induced charge trapping related to the thick STI oxides. Near threshold, oxide-trapped charges near silicon/STI interfaces and trapped charges at silicon/STI interfaces act as Coulomb scattering centers that are believed to contribute to this significant mobility degradation. For narrow-channel nMOSFETs, the negative $V_T$ shift (Fig. 3b) mitigates the effect of $\mu_0$ reduction on the drive current. However, for narrow-channel pMOSFETs, oxide- and interface-trapped charges together increase $V_T$ up to 36% (Fig. 3d) and degrade $\mu_0$ up to 73% that considerably reduces the drive current and leads to a much worse situation.

IV. CONCLUSION

Using the $Y$-function method, we extract the channel mobility of commercial 28-nm bulk MOSFETs in strong inversion of linear operation before irradiation and at different TID levels. Extracted results confirm the enhanced radiation tolerance of wide-channel MOSFETs that is mostly due to the advanced
gate stacks in nanoscale CMOS technologies. Narrow-channel MOSFETs demonstrate a rather high mobility reduction that is attributed to the Coulomb scattering of the charge buildup related to the thick shallow trench isolation oxides.

REFERENCES


Fig. 1: $Y$–function $|I_{DS}|/\sqrt{C_{in}}$ (abel) and mobility degradation coefficient $\theta$ (cdgh) of $n$– (a–d) and $p$MOSFETs (e–h) versus gate-to-bulk voltage $V_{GB}$.

Fig. 2: Effective channel mobility $\mu_{eff}$ of $n$– (ab) and $p$MOSFETs (cd) versus overdrive voltage $|V_{GB} - V_T|$.

Fig. 3: Variation of low-field channel mobility $\mu_0$ (ac) and threshold voltage $V_T$ (bd) of $n$– (ab) and $p$MOSFETs (cd).