New Mechanism of Body Charging in Partially Depleted SOI-MOSFETs with Ultra-Thin Gate Oxides

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Abstract

The aggressive scaling of the gate oxide leads to direct gate tunneling current, which affects the floating-body effects in partially-depleted SOI MOSFETs. Experiments and simulations show that the gate-to-body current charges the body causing an unexpected 'kink' effect to occur at low drain voltage. This kink results in a second peak of transconductance, whose time-dependent behavior and practical consequences are investigated.

1. Introduction

With the shrinking of the gate oxide in the ultra-thin range (sub-2 nm), the increasing gate tunneling current adversely impacts the consumption and performance of CMOS circuits [1]. An interesting consequence of tunnel currents is the modification of the floating-body voltage in partially-depleted (PD) SOI MOSFETs. The gate-to-body current becomes strong enough to charge ($V_{G1} > 0$ for NMOS) or discharge the body of the device, hence resulting in unusual *Gate-Induced Floating-Body Effects* (GIFBE).

In this paper, we examine for the first time the impact of GIFBE on transconductance and drain current characteristics. Systematic experiments, presented in section 2, demonstrate that specific GIFBE appear, even at low V_D, in SOI MOSFETs with ultra-thin gate oxides. Dimensional and temporal aspects are investigated and their practical importance is outlined. In section 3, numerical simulations are performed which corroborate the experimental data and clarify the behavior of GIFBE.

2. Experimental basis

2.1. Devices

PD-SOI MOSFETs were fabricated on conventional Unibond wafers (t_{BOX} = 400 nm) with a 0.12 µm CMOS technology from STMicroelectronics. The silicon film was 150 nm thick, the body doping was $\approx 1\text{x}10^{18}$ cm^{-3} and the gate oxide was 2 nm thick. The results discussed next correspond to N-MOSFETs with channel lengths and widths in the range 0.1–10 µm.

2.2. Electrical characteristics

The drain current characteristics (Figure 1), measured at low drain voltage (V_D = 0.1 V), show a sudden increase of the drain current near $V_G \approx 1$ V. This unexpected 'kink' on the drain current gives rise to a second peak in transconductance, which can exceed by up to 40 % the normal peak (for $V_G \approx 0.5$ V).

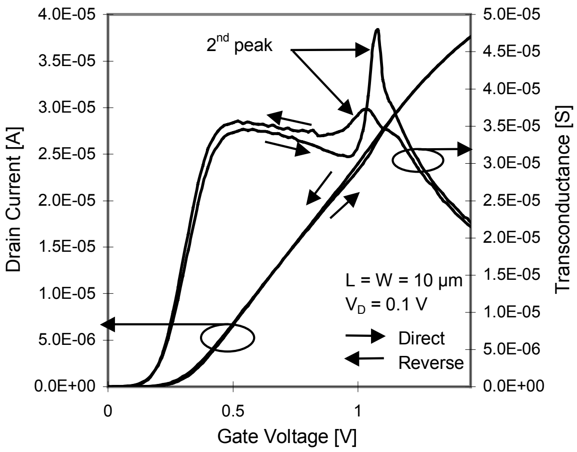

Figure 1. $I_D(V_G)$ and corresponding $g_m(V_G)$ characteristics measured by scanning the gate voltage in the direct and the reverse directions.

An immediate consequence is that this kink alters the accuracy of conventional parameter extraction methods. For example the 'linear' function $Y(V_G) = I_D/\sqrt{g_m}$ is frequently used to determine the threshold voltage and carrier mobility [2]. However, as illustrated in Figure 2, $Y(V_G)$ curves become non-linear (with a strong distortion in the kink region, for $V_G \approx 1$ V), and rather inefficient.

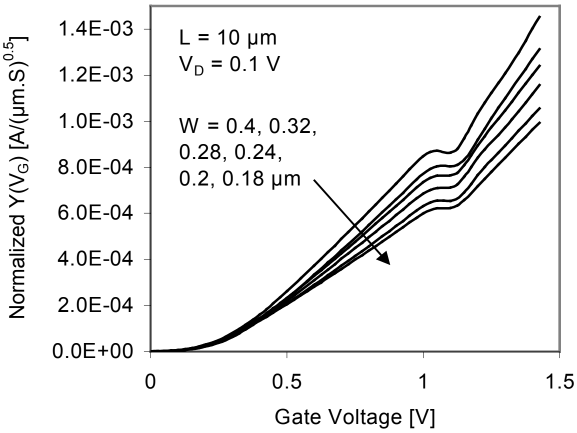

Figure 2. $Y(V_G) = I_D/\sqrt{g_m}$ for various channel widths.

2.3. Directional and temporal scanning

The magnitude and position of the 2nd peak of transconductance depend on the measuring conditions. The peak is reduced as the gate voltage is scanned in the reverse direction (Figure 1). The peak is shifted toward a lower gate voltage when the time of measurement increases.

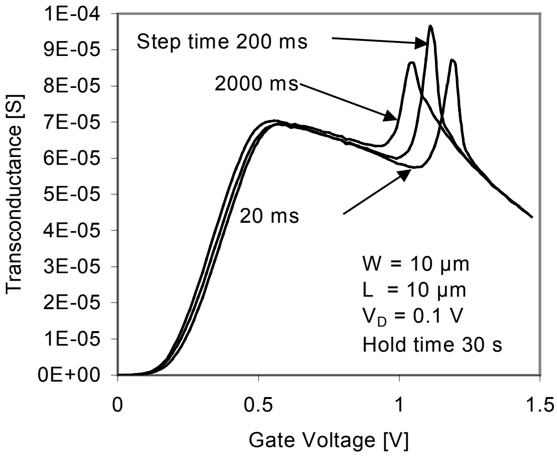

Figure 3. Transconductance for different step times (fast and slow measurements).

In order to clarify the time-dependence of this floating-body effect, we have recorded the transient variation of the drain current after pulsing the gate from zero bias to strong inversion. A usual current overshoot is observed in Figure 4 : the body is instantly charged by majority carriers released from the depletion layer and equilibrium is reached slowly by carrier recombination [2]. The striking feature is that when V_G pulse increases, the transient process becomes faster (for $0.9 < V_G < 1.1$) and is finally cancelled for $V_G = 1.2$ V. This trend suggests that an alternative mechanism, which allows the body charge to recover equilibrium, is enabled at high V_G. Considering that the transconductance peak and the suppression of the transient current occur in the same V_G range, we conclude that these two effects share the same origin : the gate-to-body tunneling current. At high V_G, the tunneling current becomes large enough to control the body charging and make it less sensitive to transient effects induced by capacitive coupling.

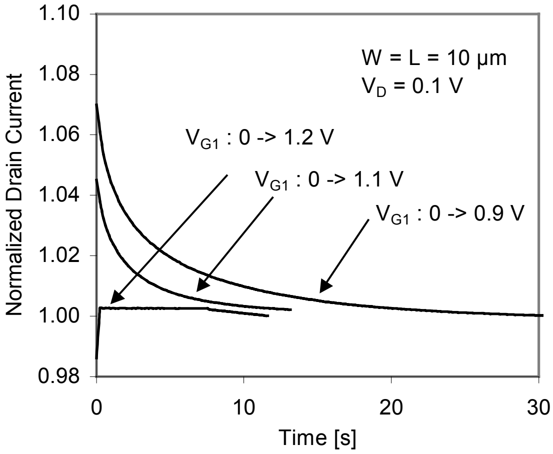

Figure 4. Drain current transients for different pulses on the gate.

The role of the gate current is confirmed in figure 5: as the gate voltage before the pulse is increased from 0 (pulse 0 to 1V) to 0.4 V (pulse 0.4 to 1V), the transient changes from overshoot to undershoot (see section 3.2).

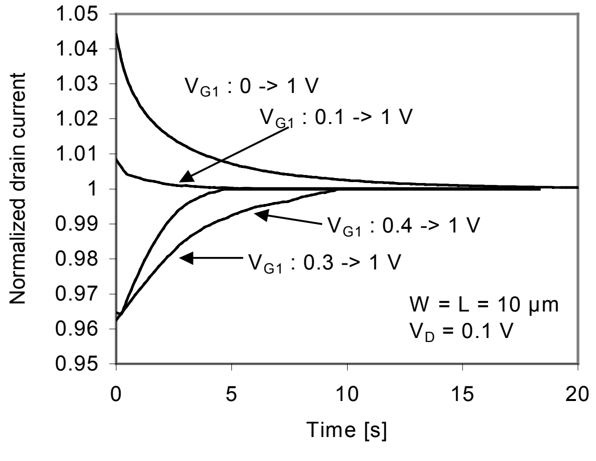

Figure 5. Single drain current transients for four different front gate pulses.

2.4. Dimensional effect

The analysis of GIFBE was completed by investigating the influence of the transistor size. It can be seen, in figures 6 and 7, that the gate voltage which enables the 2nd peak of transconductance is weakly dependent of the length and width of the channel. By contrast, the magnitude of the peak is greatly attenuated as the width (Figure 6) or length (Figure 7) are reduced. It is known that FBE are lowered by enhanced contributions from junctions and isolation sidewalls in short and narrow channels, respectively. In our case, these contributions remain noticeable but cannot offset totally the role of the gate current.

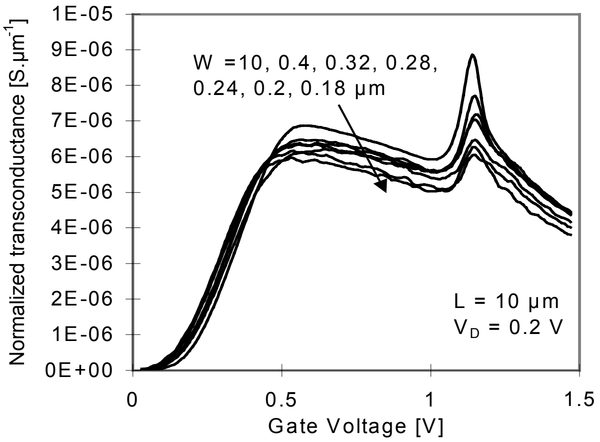

Figure 6. Normalized transconductance for various channel widths.

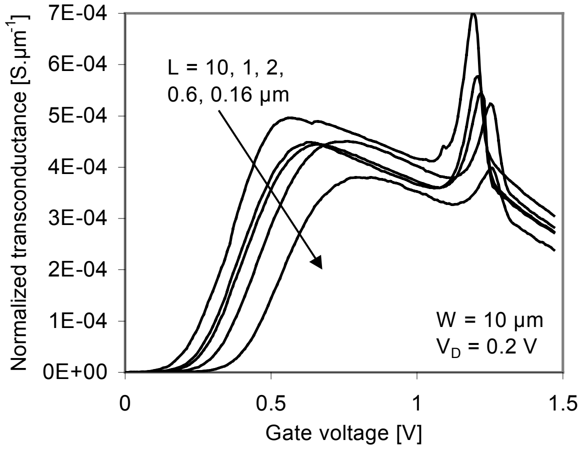

Figure 7. Normalized transconductance for various channel lengths.

3. Analysis

The results above consistently indicate that GIFBE are due to the control of the body charge by the gate-to-body current. Full confirmation and further details were obtained from numerical simulations performed with ELDO™ simulator and BSIM3SOI V2.2.2 model [3].

3.1. Impact of gate current

The main direct tunneling currents are illustrated in figure 8 : ECB stands for electron tunneling from channel (silicon conduction band), EVB for electron tunneling from Si valence band (leaving holes in the body), and HVB for hole tunneling into Si valence band [1, 4].

In ultra-thin gate oxides, the gate-to-body current (mainly holes resulting from EVB) becomes significant enough to charge or discharge holes in the body, according to the applied gate voltage. Body charging leads to a raise in body voltage and a change of the device characteristics, that can give rise to supplementary (and unsuitable) FBE and history effects [4].

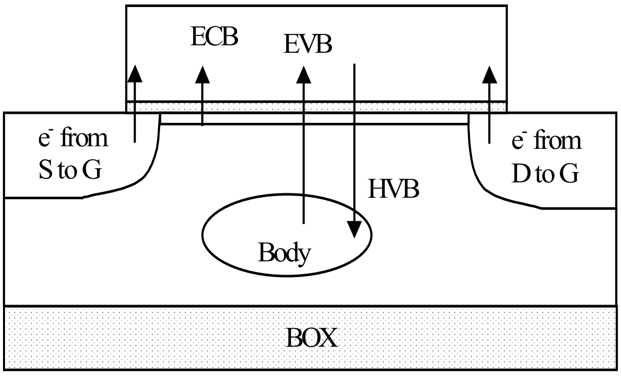

Figure 8. Schematic diagram of gate tunneling current in a PD SOI-MOSFET under inversion and low drain voltage.

3.2. Simulations and discussion

The simulations confirm the strong correlation between GIFBE, body potential and gate tunneling current. Figure 9 shows transconductance curves calculated with the same parameters as in the experiment of figure 3. The second peak of the transconductance is clearly visible and can be explained by the corresponding variation of the body voltage (figure 10). For $V_G < 1$ V, the body potential increases instantly by capacitive coupling. The influence of step time reflects the relaxation process via carrier recombination : shorter the step time, higher the body potential. For $V_G > 1.1$ V, the gate-to-body tunneling current comes into play and further raises the body potential. No correlation with step times is observed in this region, simply because the body relaxation is inhibited by the gate current which continuously supplies majority carriers. This extra charging mechanism is totally independent of capacitive coupling and fully coincides with the onset of the 2nd transconductance peak. The tunneling gate current is therefore unique responsible for GIFBE.

Keeping in mind the prevailing role of the gate current, we now can easily explain the directional, temporal and dimensional dependencies of the current. A stronger kink was observed in Figure 1 for direct V_G scan. In this case, the gate-to-body current increases remarkably as the gate voltage reaches 1 V and results in a sudden change of the body potential and threshold voltage, which is materialized by a hump in the drain current characteristics. In the reverse direction, the body is pre-charged and its potential is high. Below 1 V, the gate-to-body current becomes low enough so that the body voltage slowly decreases by carrier recombination. The current hump is much softer and the 2nd peak of transconductance is attenuated.

The time-dependence of the transconductance is fully reproduced in the simulations of figure 9. The 2^{nd} peak shifts towards a lower gate voltage as the step time augments. For slow measurements, the initial raise in body potential (due to capacitance coupling) is partly compensated by relaxation, so that the body re-charging by gate current is effective at a lower gate voltage.

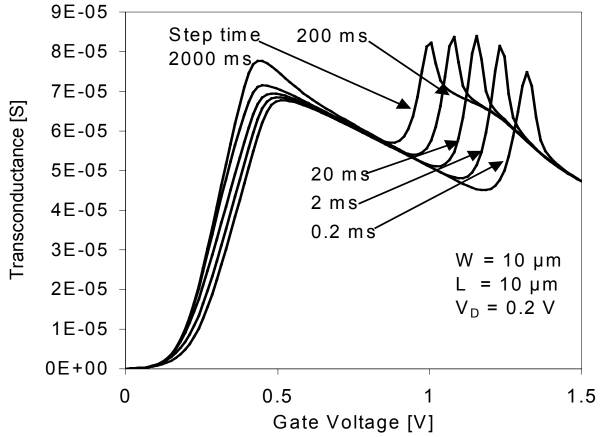

Figure 9. Transconductance versus gate voltage (stepped by 15 mV with various delay time).

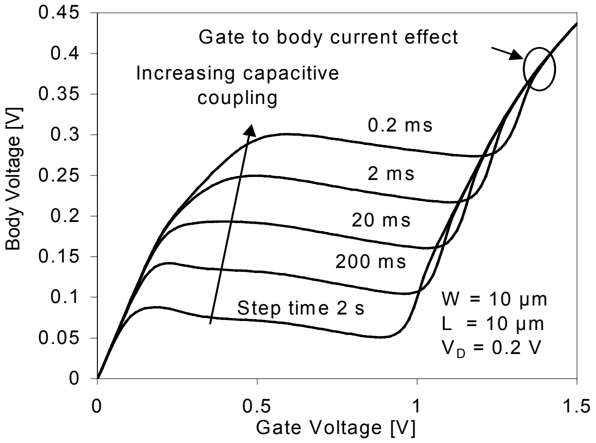

Figure 10. Body voltage as a function of gate voltage (stepped by 15 mV with various delay time).

The transient behavior of the drain current is consistent with this explanation. Two distinct cases, governed by different mechanisms, are observed in Figure 4. When the gate is pulsed from 0 to 0.9 V, the gate-to-body current is too small and does not contribute to the body charging. The overshoot is dominated by the holes expelled from the depletion layer and accumulated in the body, which are gradually eliminated by recombination. For larger gate pulses (1.1 and 1.2 V), the gate-to-body tunneling current becomes high enough and masks the effect of carrier recombination. The gate current controls totally the body charge, hence equilibrium is rapidly reached and the overshoot effect vanishes.

When V_G is pulsed from 0.4 to 1 V, the transient aspect changes qualitatively (Figure 5). The depletion layer already exists before the pulse, hence fewer carriers are expelled into the body whose potential increases less. The shape of the transient is defined by the imbalance between the body potential V_{b0} reached just after the pulse (by capacitive coupling) and the steady-state value $V_{b\infty}$ (governed by the equilibrium between gate-to-body and junction currents). If $V_{b0} > V_{b\infty}$, we obtain the normal overshoot behavior. In the opposite case ($V_{b0} < V_{b\infty}$), the body potential has to increase with time which is reflected by a current undershoot. The necessary majority carriers are supplied primarily by the gate tunneling current. Again, for large pulses (1.2 V), the tunneling current increases exponentially, thus being able to rapidly adjust the body charge and suppress the undershoot transient effect.

The dimensional effects are explained by the increase of the recombination rate (in narrow channels) and by the role of leakage current (in short channels). In small-geometry MOSFETs, the removal of the majority carriers from the body is more effective, which in turn renders the role of the gate tunneling current less pronounced. Note that for shorter gates, the gate-to-body current is reduced whereas the junction currents are not, leading to a lower steady-state body voltage.

4. Conclusion

We have introduced and analyzed a novel floating-body effect (GIFBE) which is a surprising consequence of progress in CMOS technology. The gate tunneling current can charge the floating body of partially-depleted SOI MOSFETs. Most relevant implications (hump in drain current, second peak in transconductance, suppression of transient effects) have been investigated and explained. When undesirable, GIFBE can be combated by using fully-depleted transistors and/or thicker high-K dielectrics.

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