Optimizing MOS-Gated Thyristor using Voltage-based Equivalent Circuit Model for Designing Steep Subthreshold Slope PN-Body Tied SOI FET

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Abstract

We proposed a new circuit model that provides a guide on designing MOS-Gated Thyristor (MGT). The impact of design parameters on MGT is examined to find out how to regulate the voltage response of MGT. The model will be useful for designing an SOI MOSFET merged with MGT (i.e., PN-Body Tied SOI FET [1-3]), which shows extremely steep subthreshold slope with very low supply voltage.

1. Introduction

PN-Body Tied SOI FET (PNBTFET) is an SOI MOSFET whose body is attached to the body terminal via a PNP diode (Fig. 1). It shows extremely steep subthreshold slope (SS) less than 6 mV/decade even with a very low drain voltage of 0.1 V [1-3]. Between the source and body terminals is a PNPN structure with a MOS gate, i.e., MOS-Gated Thyristor (MGT) [4] (Fig. 2), whose cathode and anode correspond to the source and body terminals, respectively. It is believed that, when MGT turns on, holes suddenly accumulate in the P body region, causing abrupt increase of the drain current, and steep SS. Therefore, to achieve a PNBTFET with low on and off gate voltages (Von and Voff) with small hysteresis, proper designing of the inherent MGT switching behavior is essential. It should also be noted that, to achieve low power CMOS using PNBTFETs, reduction of the on-state body current ION is important; the current flowing to the source terminal cannot be blocked by the series off-state complementary FET, and causes additional standby power dissipation.

Recently, we proposed a new equivalent circuit model of MGT (Fig. 3) [5], which explains the switching mechanism of MGT, and would be useful for exploring such design goals. In this paper, it is demonstrated that the model shows good correlation with the MGT operation, and can be conveniently used for designing PNBTFETs with suitable threshold voltages and low body current.

2. Voltage-based Equivalent Circuit Model

The circuit model in Fig. 3 consists of two cross-coupled voltage inverters, namely, Electron Current Inverter (ECI) and Hole Current Inverter (HCI) [5], Von, Voff, and Vg correspond to P region potential, N region potential, and gate voltage, respectively. ECI has input VF and VG and output VN, and HCI has input VN and output VF. ECI input VF follows HCI output, and HCI input VN follows ECI output. In this model, the operating point of VF and VN settles at one of the stable points, which are located at the intersection of ECI and HCI transfer curves on VF-VN diagram (Fig. 4). Note that upper left stable point indicates off-state, and lower right one on-state. When an off-state stable point disappears as ECI curve is modulated by raising VN, the operating point in off-state is forced to move instantly to the on-state stable point. In this way, the proposed model can explain the abrupt switching behavior. ECI and HCI transfer curves were simulated independently using 2D TCAD models shown in Fig. 5. The N region length LN in ECI model is extended to eliminate the impact of PNP bipolar action. In the same way, HCI model has the P region length LP extended and the MOS gate removed.

3. Results and Discussion

In order to obtain desired threshold voltages in the proposed model, it is needed to know how design parameters affect ECI and HCI transfer characteristics. In this study, the impact of P region length LP, P region acceptor concentration NA, and anode voltage Vg on the proposed model and MGT is examined by TCAD simulations.

Fig. 6(a) shows LP dependence of ECI transfer curves. Extending LP decreases the inherent NPN transistor gain and shifts ECI transfer curve upward in high VF (> 0.5 V) so that when VG is decreasing, ECI curve in high FP detaches from HCI curve at higher VG. As a result, Voff of the circuit model rises and the hysteresis width decreases as LP is extended. While the circuit model predicts that the hysteresis width is decreased from 0.55 V to 0.40 V by changing LP from 0.5 µm to 2.0 µm, the actual hysteresis width in MGT is decreased from 0.52 V to 0.34 V.

Fig. 8 shows Von dependence of ECI transfer curves. Decreasing Von not only enhances the inherent NPN transistor gain but also lowers the threshold voltage of the inherent MOSFET so that ECI transfer curve starts being modulated at lower VO (Fig. 8(a)). Consequently, both Von and Voff of the circuit model are lowered by decreasing Von (Fig. 8(b)). Fig. 9 shows Voff-Von characteristics of MGT corresponding to the circuit model in Fig. 6. MGT also shows tendency that Voff rises and the hysteresis width decreases as LP is extended. While the circuit model predicts that the hysteresis width is decreased from 0.77 V to 0.38 V, and Voff from 0.77 V to 0.19 V, thus, MGT with low threshold voltages and small hysteresis is achieved by tuning ECI parameters.

When Von is reduced, ECI and HCI transfer curves shift keeping their shapes (Fig. 10(a)) so that Von and Voff of the circuit model hardly change (Fig. 10(b)). In the same way, MGT keeps its threshold voltages as VO varies (Fig. 11(a)). The benefit of Von reduction for MGT is that on-current is reduced exponentially to VO (Fig. 11(b)). This means that in PNBTFET, the body terminal voltage and the body current can be suppressed at once, and therefore, the constant power consumption can be greatly reduced.

When VO in MGT rises, the operating point of VO-VF stays at the point (Fig. 12). This shows that in PNBTFET, the body terminal voltage and the body current can be suppressed at once, and therefore, the constant power consumption can be greatly reduced.

4. Conclusions

It was confirmed that the voltage-based equivalent circuit model of MGT shows good correlation with MGT characteristics and their response to design parameters LP, NA, and VO. This model will help properly designing steep SS PNBTFETs with low power consumption, by providing insight into the MGT operation mechanism.

References
Fig. 1 Bird-eye view of PN-Body Tied SOI FET (PNBTFET).

Fig. 2 Schematic cross-section of MOS-Gated Thyristor (MGT) [5].

Fig. 3 Voltage-based equivalent circuit model of MGT [5].

Fig. 4 Schematic transfer curves of HCl and ECI. Stable points indicated by circles may move, appear, or disappear when ECI curve is modulated by $V_G$.

Fig. 5 Schematic 2-dimensional TCAD models of (a) ECI and (b) HCl [5]. Both $L_N'$ and $L_P'$ are fixed at 10 $\mu m$.

Fig. 6 Impact of $L_P$ variation on (a) transfer curves of ECI and (b) $V_P-V_G$ characteristics decided by ECI and HCl transfer curves. $V_A = 1.0 \text{ V}$, $N_P = 2 \times 10^{18} \text{ cm}^{-3}$.

Fig. 7 Impact of $L_P$ variation on $V_P-V_G$ characteristics of MGT corresponding to the model in Fig. 6.

Fig. 8 Impact of $N_P$ variation on (a) transfer curves of ECI and (b) $V_P-V_G$ characteristics decided by ECI and HCl transfer curves. $V_A = 1.0 \text{ V}$, $L_P = 2.0 \mu m$.

Fig. 9 Impact of $N_P$ variation on $V_P-V_G$ characteristics of MGT corresponding to the model in Fig. 8.

Fig. 10 Impact of $V_A$ variation on (a) ECI and HCl transfer curves, and (b) $V_P-V_G$ characteristics decided by ECI and HCl transfer curves. $N_P = 7 \times 10^{17} \text{ cm}^{-3}$, $L_P = 2.0 \mu m$.

Fig. 11 Impact of $V_A$ variation on (a) $V_P-V_G$ characteristics and (b) $L_P-V_G$ characteristics of MGT. $N_P = 7 \times 10^{17} \text{ cm}^{-3}$, $L_P = 2.0 \mu m$. 

- 244 -