Gate-to-body tunneling current model for silicon-on-insulator MOSFETs

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A gate-to-body tunneling current model for silicon-on-insulator (SOI) devices is simulated. As verified by the measured data, the model, considering both gate voltage and drain voltage dependence as well as image force-induced barrier low effect, provides a better prediction of the tunneling current and gate-induced floating body effect than the BSIMSOI4 model. A delayed gate-induced floating body effect is also predicted by the model.

Keywords: gate-to-body tunneling, gate-induced floating body effect, image force-induced barrier low effect, silicon-on-insulator

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1. Introduction

As complementary metal–oxide–semiconductor (CMOS) technology continues to aggressively shrink down, the gate oxide becomes thinner and thinner and the associated electrical field becomes much stronger than before. Hereby, electrons or holes can easily tunnel across the gate oxide and the gate current may not be neglected in this case. The gate leakage becomes a big concern in low power circuit design. As a result, it is necessary to carefully analyze the tunneling characteristic.

The gate leakage for devices with an ultra-thin oxide is predominantly formed by the direct tunneling current. Typically, the gate-to-channel and the gate-to-overlap tunneling are the main gate leakage routes. Because of higher tunneling barrier, the gate-to-body tunneling is much smaller than other routes of gate leakage, thus unfortunately, it did not attract enough attention until the gate-induced floating body effect (GIFBE) or the linear kink effect (LKE) was discovered in partially-depleted (PD) SOI metal–oxide–semiconductor field-effect transistors (MOSFETs) without body contacts.[1–3] For PD/SOI technology, the very current can significantly change the body potential and thereby influence the floating body effect or the history effect. Thereby, an accurate gate-to-body tunneling current model is necessary to well predict the GIFBE in device or circuit simulations. It is found that when a device is operating in inversion mode, the gate-to-body tunneling is dominated by electrons tunneling from Si valence-band, known as electron valence band (EVB) tunneling,[4–7] as seen in Fig. 1. Φ_{bv} is the barrier height for electron tunneling, which significantly determines the tunneling probability, and it is used to be treated as a constant in most studies. However, things are now different, owing to the greatly shrinked gate oxide. The resulted barrier height modification, such as the image-force induced barrier low effect, should be included in order to obtain more accurate tunneling predictions.

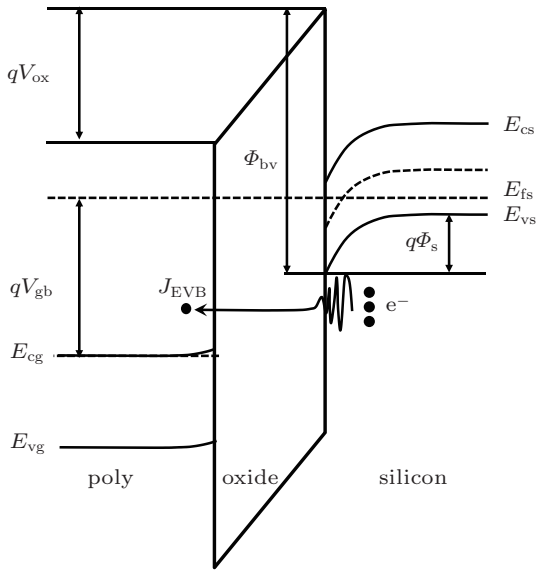


Fig. 1. Schematic plot of energy bands during EVB tunneling.

2. Model derivations

When a device is in strong inversion, the valence band in the body is higher than that in the poly gate. Electrons in the valence-band of body region could then directly tunnel across the gate oxide, resulting in current flowing from gate to body. The electron state of interest here is between E_{cg} and E_{vs}. Therefore, the general electron tunneling current density

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can be modeled by[4]

$$J_{\rm EVB}=\frac{4\pi q m_{\rm v}^*}{h^3}\int_{E_{\rm cg}}^{E_{\rm vs}}(E_{\rm vs}-E_{\rm v})P\cdot{\rm d}E_{\rm v}. \tag{1}$$

The tunneling transmission coefficient P is obtained based on the WKB approximation, and given as

$$\begin{aligned}P &= \exp\left[-2\int_0^{t_{\rm ox}}\sqrt{\frac{2m_{\rm ox}^*}{\hbar^2}(E_{\rm vs}+\Phi_{\rm bv}-qE_{\rm ox}x-E_{\rm v})}\,{\rm d}x\right]\\ &= \exp\left\{-\frac{4t_{\rm ox}\sqrt{2m_{\rm ox}^*(E_{\rm vs}+\Phi_{\rm bv}-E_{\rm v})}}{3h}\frac{E_{\rm vs}+\Phi_{\rm bv}-E_{\rm v}}{qV_{\rm ox}}\right.\\ &\quad\left.\times\left[1-\left(1-\frac{qV_{\rm ox}}{E_{\rm vs}+\Phi_{\rm bv}-E_{\rm v}}\right)^{3/2}\right]\right\},\end{aligned} \tag{2}$$

where $m_{\rm v}^*$ and $m_{\rm ox}^*$ are the effective mass in body valence band and that in oxide, respectively; $E_{\rm v}$ denotes the tunneling energy of electrons, and $V_{\rm ox}$ is the voltage across the gate oxide (with thickness of $t_{\rm ox}$); $\Phi_{\rm bv}$ is the barrier height for EVB tunneling and is about 4.22 eV. To account for image-force induced barrier low effect that may not be ignored in state-of-the-art device with ultra-thin oxide, $\Phi_{\rm bv}$ is replaced by $\Phi_{\rm bveff}$ as follows:[8]

$$\Phi_{\rm bveff}=\Phi_{\rm bv}-\Delta\Phi=\Phi_{\rm bv}-\sqrt{\frac{qV_{\rm ox}}{4\pi\varepsilon_{\rm ox}t_{\rm ox}}}. \tag{3}$$

Unluckily, the integration in Eq. (1) can only be resolved numerically without any approximation. In order to obtain an analytical equation for device and circuit simulation, the tunneling transmission coefficient is assumed to be a constant and then Taylor expanded as follows:

$$\begin{aligned}P &= \exp\left\{-\frac{4t_{\rm ox}\sqrt{2m_{\rm ox}^*\Phi_{\rm bveff}}}{3h}\frac{\Phi_{\rm bveff}}{qV_{\rm ox}}\right.\\ &\quad\left.\times\left[1-\left(1-\frac{qV_{\rm ox}}{\Phi_{\rm bveff}}^{3/2}\right)\right]\right\}\\ &= \exp\left\{-\frac{4t_{\rm ox}\sqrt{2m_{\rm ox}^*\Phi_{\rm bveff}}}{3h}\right.\\ &\quad\left.\times\left[a_0+a_1\frac{qV_{\rm ox}}{\Phi_{\rm bveff}}+a_2\left(\frac{qV_{\rm ox}}{\Phi_{\rm bveff}}\right)^2+o\left(\frac{qV_{\rm ox}}{\Phi_{\rm bveff}}\right)^3\right]\right\},\end{aligned} \tag{4}$$

where a_0, a_1, and a_2 are treated as fitting parameters to compensate for the errors introduced by both the WKB approximation and the constant tunneling transmission coefficient approximation. Thus, the gate-to-body current density can be simplified into

$$\begin{aligned}J_{\rm EVB} &= \frac{4\pi q m_{\rm v}^*}{h^3}\exp\left\{-\frac{4t_{\rm ox}\sqrt{2m_{\rm ox}^*\Phi_{\rm bveff}}}{3h}\right.\\ &\quad\left.\times\left[a_0+a_1\frac{qV_{\rm ox}}{\Phi_{\rm bveff}}+a_2\left(\frac{qV_{\rm ox}}{\Phi_{\rm bveff}}\right)^2\right]\right\}\\ &\quad\times\frac{(E_{\rm vs}-E_{\rm cg})^2}{2}.\end{aligned} \tag{5}$$

The tunneling energy window ($E_{\rm vs}-E_{\rm cg}=qV_{\rm ox}-E_{\rm g}$) is recalculated by a smooth function to ensure an almost zero value in Eq. (5) when $V_{\rm ox}$ is lower than $E_{\rm g}/q$.

$$\begin{aligned}E_{\rm vs}-E_{\rm cg} &= qNv_t\ln\left[1+\exp\left(\frac{(V_{\rm fb}+\Phi_{\rm f}+V_{\rm ox})-E_{\rm g}/2q}{Nv_t}\right)\right]\\ &= qNv_t\ln\left[1+\exp\left(\frac{V_{\rm ox}-E_{\rm g}/q}{Nv_t}\right)\right].\end{aligned} \tag{6}$$

Actually, electrons may still tunnel into the gate when $E_{\rm vs}<E_{\rm cg}$, known as trap assisted tunneling or thermally assisted tunneling.[9,10] With the introduced smooth function, we can also give an acceptable prediction of this current by fine tuning the fitting parameter N.

The TCAD simulated energy band is shown in Fig. 2. The valence band energy ($E_{\rm vs}$) of the body surface varies with the location along the channel. The tunneling energy window is narrowed towards the drain, as a result, tunneling becomes less severe. In addition, the narrowing of the tunneling energy window will be even more significant when drain voltage is higher. Hence, voltage across the gate oxide ($V_{\rm ox}$) should be treated as a function of location as follows:

$$V_{\rm ox}=(V_{\rm gb}-\Delta V_{\rm poly})-V_{\rm fb}-(\Phi_{\rm s}+V), \tag{7}$$

where $\Delta V_{\rm poly}$ and $V_{\rm fb}$ denote the poly gate depletion effect and the flat-band voltage, respectively, and V is the local quasi-Fermi potential for the channel inversion electrons, depending on drain voltage. Therefore, the total EVB tunneling current could be calculated by integrating $J_{\rm EVB}$ along the channel as

$$\begin{aligned}I_{\rm EVB} &= W\int_0^L J_{\rm EVB}(y)\,{\rm d}y=W\int_0^{V_{\rm ds}}J_{\rm EVB}(V)\frac{{\rm d}y}{{\rm d}V}\,{\rm d}V\\ &= W\cdot P(V_{\rm ox0})\int_0^{V_{\rm ds}}\frac{(E_{\rm vs}-E_{\rm cg})^2}{2}\frac{{\rm d}y}{{\rm d}V}\,{\rm d}V,\end{aligned} \tag{8}$$

$$V_{\rm ox0} = (V_{\rm gb}-\Delta V_{\rm poly})-V_{\rm fb}-(\Phi_{\rm s}+\theta\cdot V_{\rm ds}). \tag{9}$$

According to mean value theorem of integrals, the average tunneling transmission coefficient $P(V_{\rm ox0})$ is determined for a simple integration process, and $\theta\cdot V_{\rm ds}$ term accounts for the corresponding local quasi-Fermi potential, where θ is less than 1. Based on the BSIMSOI4 drain current equation,[11] the location derivative with respect to quasi-Fermi potential can be written in the form of

$$\frac{{\rm d}y}{{\rm d}V}=(V_{\rm gsteff}-A_{\rm bulk}V)f(V_{\rm ds})-\frac{1}{E_{\rm sat}}, \tag{10}$$

$$f(V_{\rm ds})=\frac{L+V_{\rm ds}/E_{\rm sat}}{(V_{\rm gsteff}-A_{\rm bulk}V_{\rm ds}/2)V_{\rm ds}}, \tag{11}$$

where $V_{\rm ds}$ tends to be saturated as $V_{\rm dsat_evb}$, implying that the tunneling window is totally closed

$$V_{\rm dsat_evb}=(V_{\rm gb}-\Delta V_{\rm gb})-V_{\rm fb}-(\Phi_{\rm s}+E_{\rm g}/q). \tag{12}$$

After integrating Eq. (8), a whole analytical gate-to-body current model is obtained as

$$I_{\rm EVB} = W\cdot L\cdot P(V_{\rm ox0})\frac{(E_{\rm vs}-E_{\rm cg})^2}{2}$$

$$\times\left[1+\frac{A_{\rm bulk}(1+V_{\rm ds}/E_{\rm sat}L)V_{\rm ds}^2}{6\left(V_{\rm gsteff}-A_{\rm bulk}V_{\rm ds}/2\right)V_{\rm ox0}}+\frac{1}{12}\left(\frac{V_{\rm ds}}{V_{\rm ox0}}\right)^2\right]. \quad (13)$$

The current $I_{\rm EVB}$ given by Eq. (13) is smooth under all bias conditions. Note that the tunneling current will decrease with the increase of drain voltage, which is implied by the model. We show in the next section that the negative dependence on drain voltage affects the GIFBE characteristics of SOI transistor a great deal.

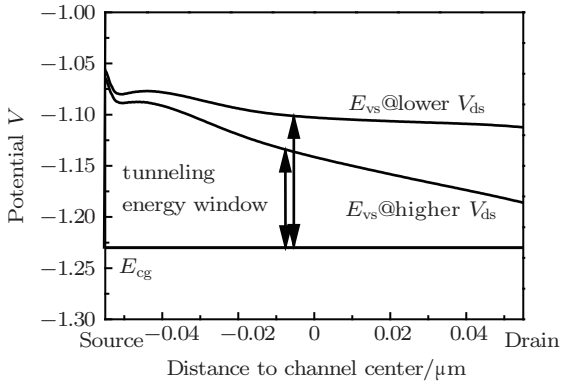


Fig. 2. TCAD simulated energy bands at a given gate voltage. The valence band energy ($E_{\rm vs}$) of the body surface varies with the location along the channel.

3. Results and discussion

To check our model, a PD SOI transistor on a 130-nm technology node is chosen for verification, since the gate oxide is thin enough to create an obvious linear kink effect. The gate-to-body tunneling current is measured with a body-contacted SOI MOSFET, e.g., a T-gate device, by using an Agilent B1500A semiconductor parameter analyzer at room temperature. The tunneling current, shown in Figs. 3 and 4, leads to an exponential growth with gate voltage increasing, while falling with drain voltage increasing before becoming saturated. The proposed model well demonstrates the voltage dependences of the tunneling current, and they are in good agreement with the measured data within all bias conditions. As indicated in Eq. (3), barrier height is reduced because of the large image force in the device with a thin gate oxide. Therefore, EVB tunneling could be much greater than expected (see Fig. 3). The effective onset bias appears ~ 60 mV earlier in the low $V_{\rm GB}$ region for our device. However, in the BSIMSOI4 model, there is no correction term to account for the low barrier effect, and modeling engineers have to always try to make some intentional over-tuned parameters so as to obtain the correct relationship between tunneling current and gate voltage. Although right value is obtained, it is not so physical.

The negative dependence on drain voltage is illustrated in Fig. 4. When channel potential arises as drain voltage increases, as discussed above, the voltage drop in the gate oxide reduces correspondingly, causing a narrower tunneling energy window ($E_{\rm vs}-E_{\rm cg}=qV_{\rm ox}-E_g$), hence, the tunneling efficiency becomes less weakened. Once the pinch-off point at the channel is fixed, the gate-to-body current then remains constant and unchangeable.

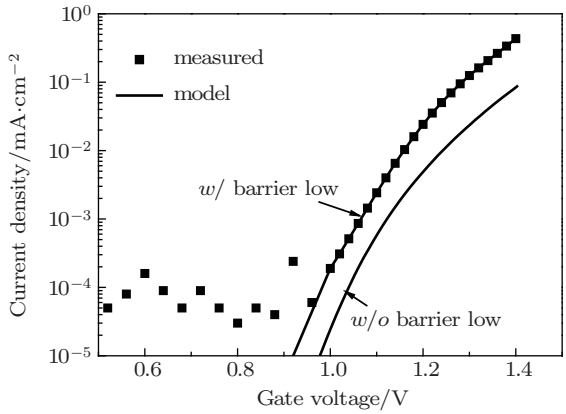


Fig. 3. Gate voltage dependence of the gate-to-body tunneling current. $t_{\rm ox}=1.8$ nm. Symbol: measurement, solid line: simulation by proposed model. The tunneling current is much larger with the consideration of the barrier lower effect while keeping other parameters the same.

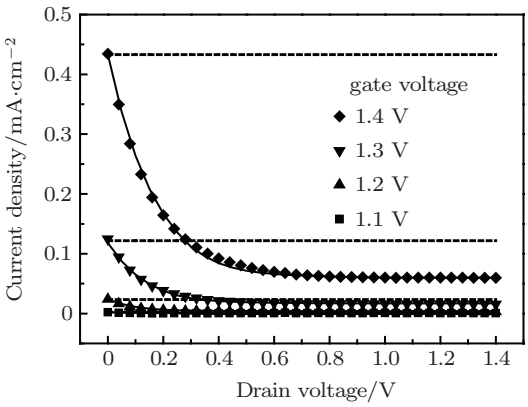


Fig. 4. Drain voltage dependence of the gate-to-body tunneling current. $t_{\rm ox}=1.8$ nm. Symbol: measurement, dotted line: simulation by BSIMSOI4, solid line: simulation by using the proposed model. The tunneling current decreases substantially as drain voltage increases, which fails in BSIMSOI4.

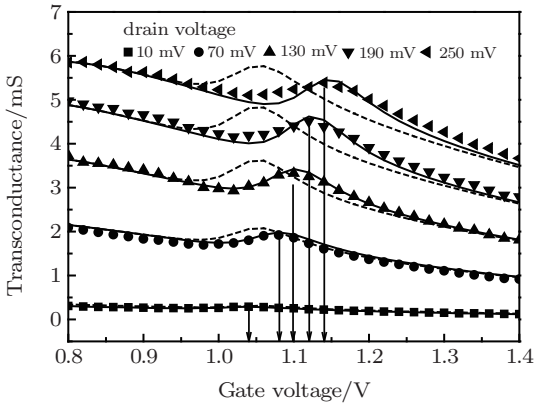


Fig. 5. Gate-induced floating body effect on transconductance with variable drain voltage in a floating body PD/SOI device. The kink occurs later as drain voltage increases. $W/L=10$ μm/0.13 μm. Symbol: measurement, dotted line: simulation by BSIMSOI4 model, solid line: simulation by using the proposed model.

When the tunneling current flows from the gate into the floating body in SOI devices without a body contact, the body potential is raised, causing a second transconductance peak (e.g., kink) in the linear region. This is similar to the impact ionizing-induced conductance kink. The kink in linear region transconductance is known as evidence for the GIFBE in floating body PD SOI devices. Actually, it would will even occur in a fully depleted (FD) SOI device when its substrate is in accumulation mode. The transconductance under variable drain voltage is plotted versus applied gate voltage in Fig. 5. According to what has been mentioned above, when drain voltage rises, the gate-to-body tunneling current degrades correspondingly. As a result, the body potential arises less and the GIFBE becomes slightly weakened. In other words, the kink in transconductance occurs later than that in the circumstance with near-zero drain voltage. One can see the good correlation between the experimental data and the modeling results in Fig. 3. In our case, the kink in transconductance is delayed by about 100 mV when drain voltage is 250 mV. Unfortunately, there is no evidence of this weakened GIFBE in the BSIMSOI4 model since no drain voltage dependence for EVB tunneling is included.

4. Conclusion

The gate-to-body tunneling current in an SOI MOSFET is discussed. The image force-induced barrier low effect would make the tunneling stronger than expected. In addition, both gate voltage and drain voltage have great influence on the magnitude of the certain current. When larger drain voltage is applied, the GIFBE becomes a little weaker and the kink in linear region transconductance occurs later.

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