Body Bias Dependence of Substrate Current and Its Modeling for SOI Devices

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ABSTRACT

Two competing factors affect the body bias dependence of substrate current in SOI devices. One is through drain current. The other is through electric field in channel near drain side. It is shown that with the increase of body voltage, threshold voltage of the device decreases, so the total drain current is increased. Therefore, substrate current caused by impact ionization is also increased. This causes negative resistance of body current with respect with body voltage, which is a potential issue during circuit simulation to cause convergence problem with BsimSOI model. On the other hand, increased body bias also decreases the electric field near drain region, which causes the decreasing of substrate current. The current available model in BsimSOI is used to demonstrate the two competing factors. It is concluded that a good modeling approach including both factors and model parameter extraction methodology are important to accurately characterize substrate current body bias dependence.

Keywords: SOI, substrate current, body bias dependent

1 INTRODUCTION

Accurate modeling of substrate current is important in SOI devices to predict correctly floating body behavior [1,2]. Recent research shows that due to self-heating effect, substrate current is enhanced in SOI devices than bulk MOSFET devices [3, 4].

One important factor to be considered in SOI substrate current model is the body bias dependence. For floating body SOI devices, the body bias could be positive and negative dependending on device working condision and circuit behavior. Regarding the body bias dependence of substrate currents, two factors should be considered. First one is the effect of body bias on drain current through body bias dependent of threshold voltage. The other is the effect of body bias dependent of the electric field near drain end. Both are necessary for a substrate current model to accurately describe the body bias dependence.

It is well known that as body bias increase, threshold voltage of the devices decrease and thus drain current increase. It is very likely that the increased drain current can cause higher substrate current. Since the increased substrate current flows into the substrate which has an increasing bias, negative conductance is produced during circuit simulation. This negative conductance very often causes convergence problem during circuit simulation. Special handling in model or simulator are needed to avoid the convergence problem caused by the negative conductance associated with substrate current.

On the other hand, when body bias increase, the voltage drop between drain and substrate decrease provided the drain bias is fixed. Thus the electric field near drain region decreases, which results decreased substrate current. So the two factors regarding body bias dependence of substrate current are competing, and the final behavior of substrate current depends on which factor dominates the changes.

In this paper, the body bias dependent of substrate current are investigated through circuit simulation. And the effects of the two competing factors on substrate current are demonstrated.

2 BODY BIAS DEPENDENCE OF SUBSGTRATE CURRENT

It is believed that substrate current in MOSFETs (including SOI devices) caused by impact ionization is proportional to drain currents. It is straightforward since the mobile carriers who are responsible to drain current cause the impact ionization and thus substrate current. The higher the drain current, the higher density of carriers in the high field region and then the higher of the substrate current. So, usually the substrate current is expressed as:

$$Isub = \alpha \cdot Ids \tag{1}$$

In which α is a bias dependent item counting for electric field dependence of substrate current.

As discussed above, due to body bias effect on threshold voltage and then on drain current, it is expected that Isub can increase as body voltage as the increasing of Ids. Figure 1 and 2 give a typical example to illustrate this. As shown in both figure 1 and 2, drain current and substrate current increase as body voltage increase. It is necessary to note that the substrate current plotted here is solely the impact ionization current without other components.

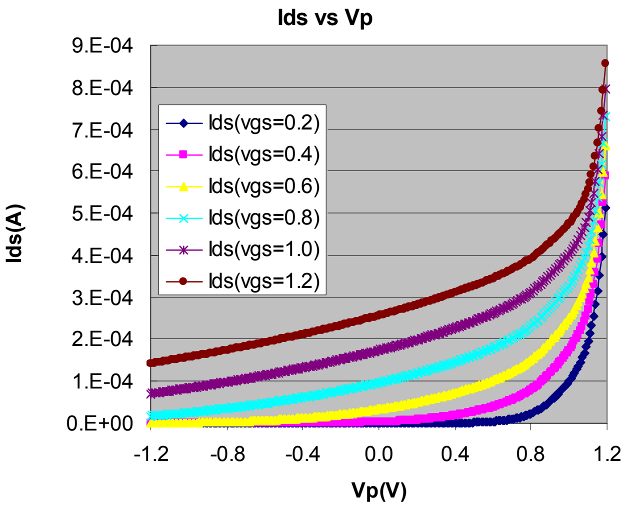

Figure 1: Drain current dependence on body voltage

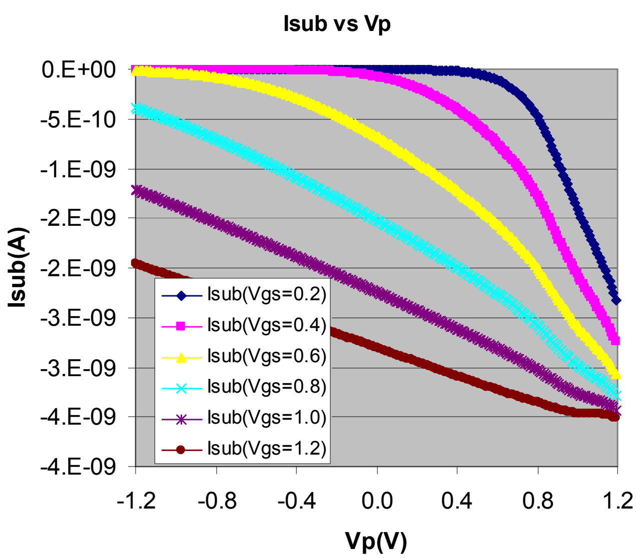

Figure 2: Substrate current dependence on body voltage

Since the substrate current is flowing into substrate node, it gives negative values here. As shown in figure 3, the derivative of substrate current with respect to body voltage gives negative values as well. That is negative conductance is produced during circuit simulation. Since this item is in diagonal position in matrix, it is very likely to cause convergence problem during circuit simulation. Special handling in the model or in the circuit simulator has to be incoporated to avoid the problem.

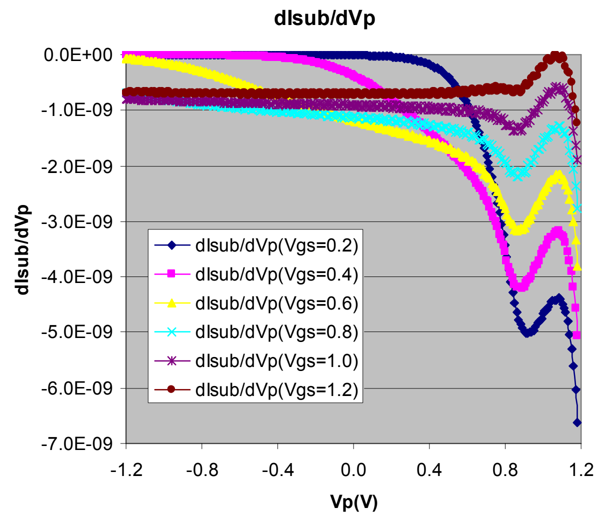

Figure 3: Negative conductance caused by substrate current body bias dependence

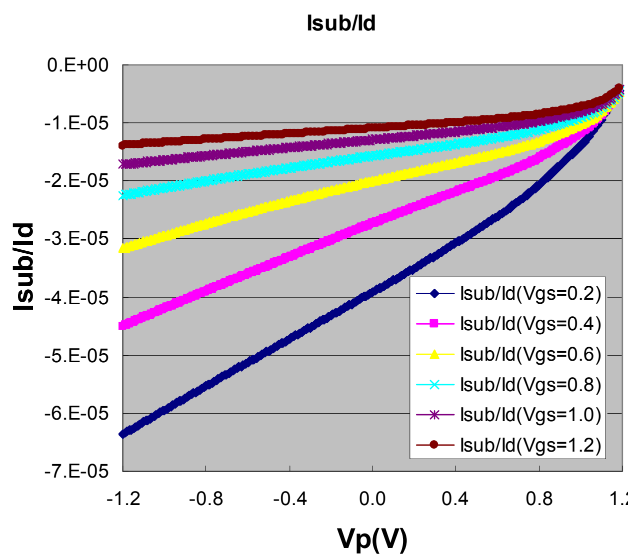

Figure 4: Ratio of substrate current with drain current

It is also shown in figure 3 that the conductance is not monotonic. This shows the competing factors affecting substrate current from body bias. They have different strength in different bias region. In negative or small positive body bias region, Ids factor dominates while in higher body bias region, the electric field factor dominates. Thus wriggles happen in the plot of conductance versus body bias.

To further demonstrate the electric field factor influence of body bias to substrate current, the ratio between substrate current and drain current is given in figure 4. As can be seen, the ratio decreases monotonically with increasing of body bias. This means the electric field decreasing monotonically with increased body bias.

3 ADVANCED SUBSTRATE CURRENT MODEL FOR SOI DEVICES

To accurately model both the effects of body bias dependence of substrate current through drain current and through electric field, advanced substrate current model is necessary. BsimSOI model [2,5] provided such a choise. In addition to explicly Ids dependence in the substrate current model in BsimSOI, new model parameters dedicated to substrate current are added to model the body bias dependence of electric field part for the substrate current. So, α in Eq. 1 explicty includes body bias dependency through Vgst term. So, the model provided has flexibility of independently adjust the substrate current at different body voltage biases.

Figure 5 and 6 give the drain current and substrate current using the advanced substrate current model. Compared with the results in previous section, drain current has no obvious changes, while the substrate current does. Substrate current, especially at higher Vgs biases, decrease as body voltage increase after a certain point. This means the effect of electric field reduction due to bocy voltage increase exceeds the effect of drain current effect on substrate current. In lower Vgs biases, substrate current still increases as body voltage increases. This is because in this bias region, threshold voltage modulation by body voltage has significant effect on drain current, then on substrate current.

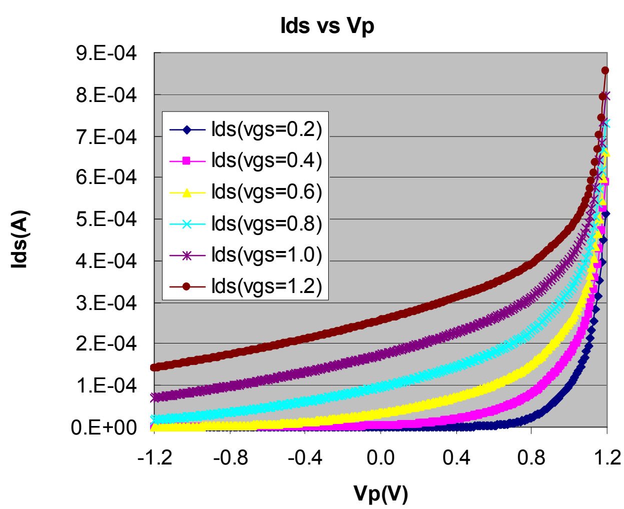

Figure 5: Drain current body bias dependence using advanced substrate current model

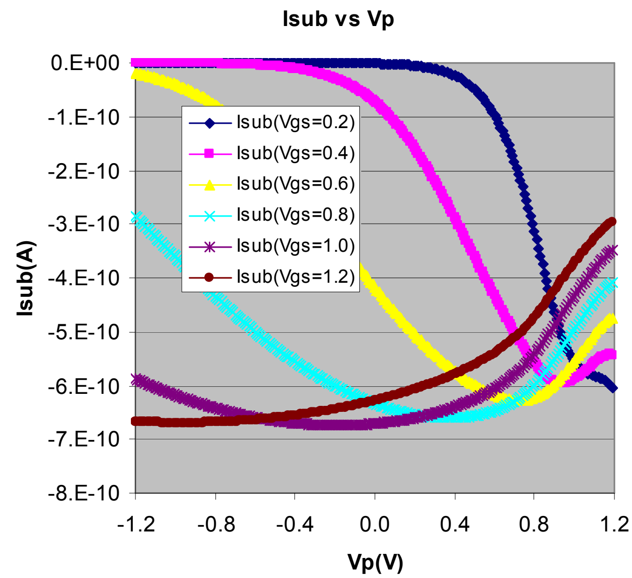

Figure 6: Substrate current body bias dependence using advanced substrate current model

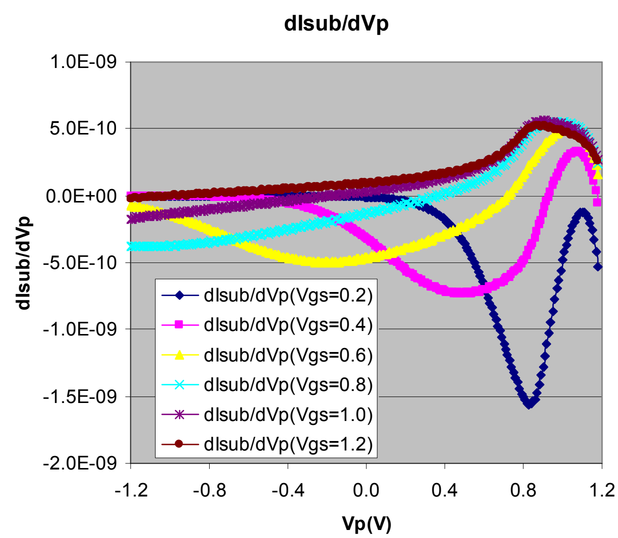

Figure 7: Negative conductance caused by substrate current body bias dependence using advanced model

Figure 7 gives the derivative of substrate current with respect to body voltage using the advanced model. As expected, at higher Vgs biases, after certain body bias point, the conductance becomes positive. It is worth to mention that although the advanced model provides the flexibility of modeling body bias dependence of substrate current independently, at certain bias region, the negative conductance is still the case. This continues to be a convergence problem during circuit simulation. It is worth to investigate by either experiments, or by device simulation to confirm the negative conductance presented in substrate current model in SOI devices.

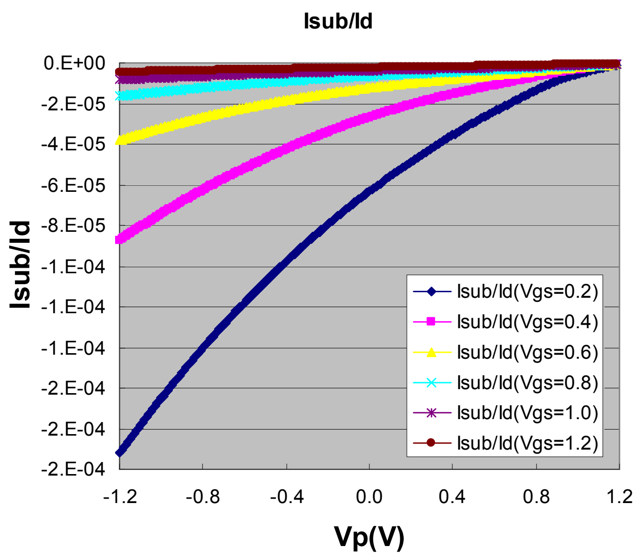

Figure 8: Ratio of substrate current with drain current using advanced substrate current model

As a comparison, the ratio of substrate current and drain current using advanced model is also given in figure 8. Although the trend is the same as the results shown in figure 4, the range of the ratio is much higher in the advanced model. This is due to the enhanced body bias dependence of electric field effect on substrate current in the advanced model.

It is worth to mention that the effect of electric field changes due to body voltage on substrate current is actually included implicitly in conventional substrate current model as that in Bsim3 and Bim4. The effect is included through Vdseff item. However, explicitly including independent parameters for this effect is necessary in SOI device modeling in order to accurately modeling the substrate current body bias dependent which is important for floating body device.

4 SUMMARY

Body bias dependency of substrate current in SOI devices is discussed. It is shown that with the increase of body voltage, threshold voltage of the device decreased, so the total drain current is increased. Therefore, substrate current caused by impact ionization is also increased. This causes negative resistance of body current with respect with body voltage, which is a potential issue during circuit simulation to cause convergence problem with BsimSOI model. On the other hand, increased body bias also decreases the electric field near drain region, which causes the decreasing of substrate current. The current available model in BsimSOI is used to demonstrate the two competing factors in body bias dependence of substrate current. It is shown that a good modeling approach including both factors and model parameter extraction methodology are important to accurately characterize substrate current body bias dependence.

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