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A Continuous and Analytical Surface Potential Model for SOI LDMOS

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Abstract: A continuous and analytical surface potential model for SOI LDMOS, which accounts for automatic transitions between fully and partially-depleted statuses, is presented. The surface potential equation of the SOI device is solved by using the PSP's accurate algorithm of surface potential, and the front and back surface potentials are obtained analytically as a function of gate and drain voltage. The formulations of inversion charge and body charge under the fully-depleted state have been modified. The continuous and analytical DC model for SOI LDMOS is given based on PSP. The comparisons between simulation and measurements indicate that this model can predict the DC characteristics of SOI LDMOS accurately.

Key words: SOI; LDMOS; body contact; surface potential; PSP

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1 Introduction

Silicon-on-insulator (SOI) devices become more and more important for power integrated circuit design with the development of SOI technology. SOI devices have ideal isolation and less parasitic effects, and do not suffer from latch-up[1,2]. SOI devices have many advantages over bulk devices and they are used widely in RF applications[3,4]. SOI LDMOS is a high-voltage device, which is attractive for automotive and consumer applications. SOI devices can operate in two conditions, including fully-depleted (FD) and partially-depleted (PD), which are decided by the film thickness, applied bias, and channel doping concentration. But in practice, the device may go through transitions between these two conditions, restricting the device characteristics. Thus, an SOI model that can predict the device characteristics accurately must consider the transition, and a good model used in power circuit design should have a wide voltage range.

At present, existing models can be subdivided into threshold-voltage based, inversion charge (q_i) based, and ϕ_s-based models. Threshold-voltage based models such as BISM3/4 are widely used, but inadequate for sub-100nm and RF designs due to their defects. There is a general consensus that these models should be replaced by q_i-based or ϕ_s-based models. q_i-based models can describe the moderate inversion regions physically, but have some disadvantages such as the inability to model the accumulation region[5,6]. ϕ_s-based models can describe all regions physically without increasing the model complexity and parameters, while many physical effects are modeled well[7]. The PSP model is a representative ϕ_s-based model.

There are some papers have reported on SOI device models, but few of them are based on surface potential. The current model in Ref. [8] is continuous and has considered the automatic transitions between FD and PD. But the surface potential is calculated iteratively, which decreases the computational efficiency. Reference [9] has proposed an SOI model based on an SP model, but the surface equation has not considered the FD state. The SOI model in Ref. [2] is all-analytical, but it has many complex smooth functions, the current is not a single piece, and the range of voltage is small.

In this paper, a continuous and analytical current model for the SOI LDMOS is proposed based on PSP, which accounts for automatic transitions between FD and PD. This model has been verified by experiments, and it can characterize the current, transconductance, and output conductance.

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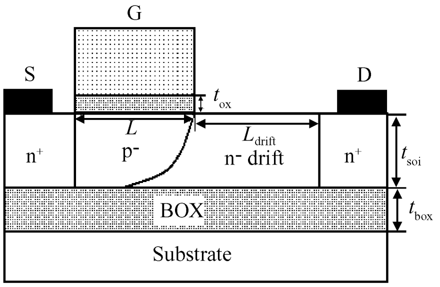

Fig.1　Cross-section of SOI LDMOS

2　DC characteristic model of SOI-LDMOS

Figure 1 shows the cross-section of SOI-LDMOS. The channel doping concentration N_a is $9\times10^{16}\mathrm{cm}^{-3}$, the thickness of the gate oxide t_{ox} = 30nm, the thickness of the SOI t_{soi} = 200nm, the length of the channel $L = 1\mu$m, the length of the drift region $L_{drift} = 3\mu$m, and the thickness of the BOX t_{box} = 100nm. This device is body contacted through the source side, which restricts the floating effect and the operation of the parasitic BJT.

From the structure of this SOI-LDMOS, it is obvious that the drain-source current I_{ds}, channel current I_{ch}, and drift region current I_{drift} have the same value, and I_{ch} can be characterized by surface potential at the drain and source sides. The drift region is very important and it is used to bear the voltage. Thus, it can be treated as a resistance that has been incorporated in drain resistance. The current I_{ds} is modeled basing on surface potential from the surface potential equation in the channel.

2.1　Calculation of surface potential

A surface potential equation concerning the bulk was proposed first by Pao and Sa in 1966[10], and the model based on surface potential describes the device accurately and physically. But the problem of solving the equation has limited the development of the surface potential model. Recently, Gildenblat[11], van Langevelde[12], and He[13] obtained accurate approximate analytical solutions in different ways. Sleight *et al*. proposed an SOI surface potential equation based on two boundary conditions of an SOI device from the Poisson equation[8]:

$$(x_g - x)^2 - R^2(x_{gb} - x_b)^2 = G^2(\Delta(e^x - e^{x_b}) + e^{-x} - e^{-x_b} + x - x_b) \qquad (1)$$

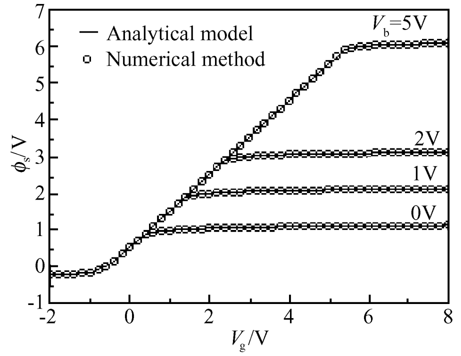

Fig.2　Comparison of analytical solution of the surface potential to the numerical result　t_{ox} = 2nm, $N_a = 9\times10^{16}\mathrm{cm}^{-3}$, t_{soi} = 100nm

where $x_g = (V_{gb} - V_{fb})/V_t$, $x_{gb} = (V_{sub,b} - V_{fbb})/V_t$, $\Delta = \exp[-(2\phi_f - V_b)/V_t]$, $G = \sqrt{2\varepsilon_{si} qN_a/V_t}/C_{ox}$, and $R = t_{ox}/t_{box}$. $x = \phi_s/V_t$ and $x_b = \phi_b/V_t$ are normalized front and back surface potentials, V_{fb} and V_{fbb} are front and back flat voltage, V_b is the body potential, and C_{ox} is the oxide capacitance per unit. In general, the thickness of the gate oxide is much smaller than that of BOX, so we get:

$$(x_g - x)^2 = G^2(\Delta(e^x - e^{x_b}) + e^{-x} - e^{-x_b} + x - x_b) \qquad (2)$$

From Eq. (2), the relation between x and x_b is needed. When the device operates in FD condition, x_b does not equal zero. Thus the relationship can be constructed through the body charge density under FD condition[8]:

$$x_b = \begin{cases} 0, & x < x_0 \\ x - x_0, & x > x_0 \end{cases} \qquad (3)$$

where $x_0 = qN_a t_{soi}^2/(2\varepsilon_{si}V_t)$. Because this device is body contacted, the hole produced from impact ionization in the depleted region will not accumulate in the body. There is no floating effect and Equation (2) can accurately describe the surface potential of this device. A continuous, analytical, and accurate surface potential has been obtained from this equation by using the algorithm in PSP, as shown in Fig. 2. Compared to iterative method, it saves computational time while not decreasing accuracy[8]. The analytical front and back surface potentials with different thicknesses of Si film are shown in Fig. 3.

2.2　Current model

The PSP model has many attractive advantages over other models. In PSP, all operating regions, including the accumulation region have

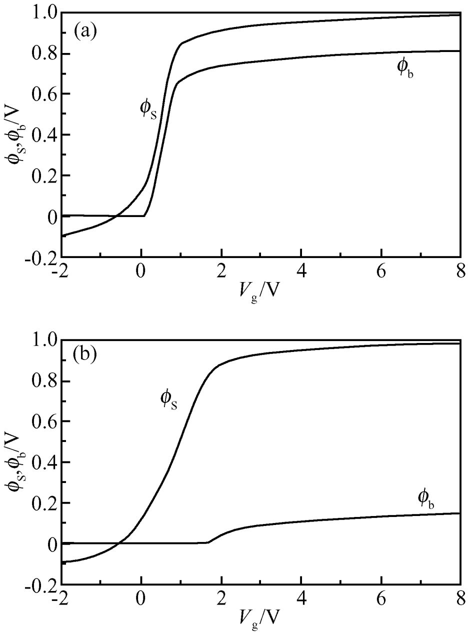

Fig.3 Front, ϕ_s, and back, ϕ_b, surface potentials $V_{ds} = 0\mathrm{V}$, $t_{ox} = 30\mathrm{nm}$, $N_a = 9 \times 10^{16}\,\mathrm{cm}^{-3}$ (a) $t_{soi} = 50\mathrm{nm}$; (b) $t_{soi} = 110\mathrm{nm}$

been modeled, and many physical effects such as Coulomb scattering, quantum mechanical effects and the polysilicon depletion region have been considered. The nonsingular velocity saturation model and symmetric linearization make PSP models free from some defects that exist in other models. This model satisfies the Gummel symmetry condition, and the current and its high derivatives do not have singularity at $V_{ds} = 0$. We adopted PSP to model our device. But when the device operates in the FD regime, the body charge density and inversion charge density expressions should be modified. Some of them have been changed as follows:

$$D_d = \Delta_{nd}(1 - e^{-x_0})\frac{1}{E_d} \tag{4}$$

$$D_s = \Delta_{ns}(1 - e^{-x_0})\frac{1}{E_s} \tag{5}$$

$$P_m = x_0 + (1 - e^{x_0})E_m \tag{6}$$

$$D_m = \frac{D_s + D_d}{2} + \frac{(x_d - x_s)^2}{8}\left(E_m - \frac{2}{G^2}\right) \tag{7}$$

$$x_{gm} = G\sqrt{D_m + P_m} \tag{8}$$

$$q_{im} = \frac{G^2 V_t D_m}{x_{gm} + G\sqrt{P_m}} \tag{9}$$

$$q_{bm} = V_t G\sqrt{P_m} \tag{10}$$

$$\alpha = 1 + \frac{G(1 - E_m)}{2\sqrt{P_m}} \tag{11}$$

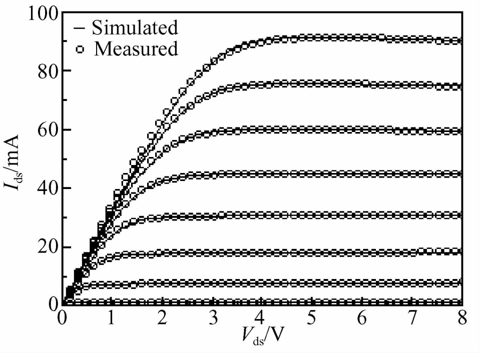

Fig.4 Simulated and measured I_{ds}-V_{ds} characteristics

where $E_s = e^{-x_s}$, $E_d = e^{-x_d}$, $E_m = \sqrt{E_s E_d}$, and x_d and x_s are the surface potentials on the drain and source sides respectively. We adopt the following current expression[7]:

$$I_{ds} = \mu_{eff} W q_{im}^{*} \Delta\Psi / G_{vsat} L \tag{12}$$

where $G_{vsat} = \frac{1}{2}\left[1 + \sqrt{1 + 2(\theta_{sat}\Delta\Psi)^2}\right]$, $\theta_{sat} = \mu_{eff}/(v_{sat}L)$, $q_{im}^{*} = q_{im} + \alpha V_t$, and $\Delta\Psi = V_t(x_d - x_s)$. q_{im} is the charge density at the midpoint of the surface potential, μ_{eff} is the effective mobility, and v_{sat} is the saturation velocity. The variables above are all the functions of x_s and x_d.

One of the main disadvantages of SOI devices is self-heating, which appears in the measurements. This self-heating must be considered, and the current expression thus is modified to:

$$I'_{ds} = \frac{I_{ds}}{1 + I_{ds} V_{ds} E_{beta}} \tag{13}$$

where E_{beta} is a heat effect parameter.

3 Results

The model equations have been executed with the Agilent ICCAP, and ICCAP will call the ADS simulator automatically to simulate our model. The simulation results are fitted with measurements of SOI LDMOS to verify their accuracy. Figures 4 and 5 demonstrate that this model can

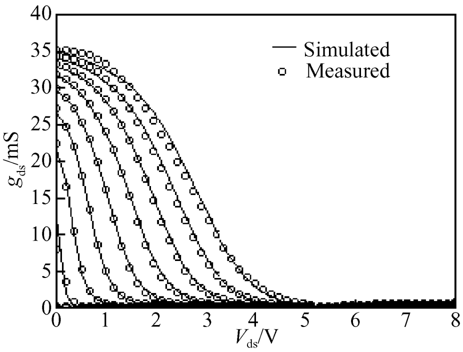

Fig.5 Simulated and measured g_{ds}-V_{ds} characteristics

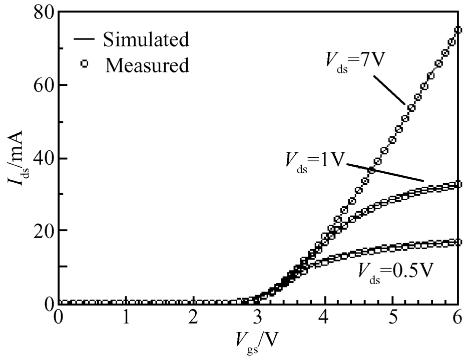

Fig. 6　Simulated and measured I_{ds}-V_{gs} characteristics

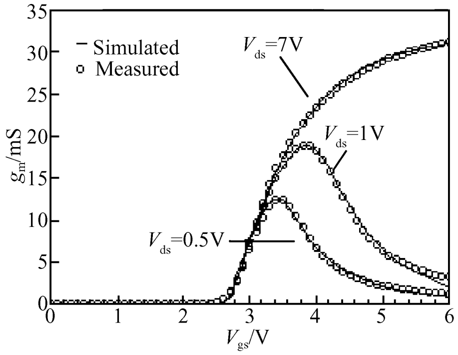

Fig. 7　Simulated and measured g_m-V_{gs} characteristics

accurately predict the characteristics of the device for a wide range of the gate voltage and drain voltage. Figures 6 and 7 show good agreement between the transfer characteristics and the corresponding measurements. This model predicts the DC characteristics of the SOI LDMOS accurately.

4 Conclusions

The surface potentials at front and back Si-SiO_2 interfaces under its operating conditions have been calculated from the SOI surface potential equation by adopting the algorithms in PSP. A continuous and analytical DC model that can predict SOI LDMOS characteristics accurately is proposed based on PSP, modifying some physical variables such as inversion charge and body charge in the FD regime and considering the self-heating effect.

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一个连续且解析的SOI LDMOS表面势模型

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摘要： 提出了一个实现全耗尽与部分耗尽自动转换的体接触SOI LDMOS连续解析表面势模型.采用PSP的精确表面势算法求解SOI器件的表面势方程，得到了解析的以栅压和漏压为变量的SOI器件正、背硅/氧化层界面的表面势.修正了全耗尽状态下的反型层电荷和体电荷表达式，结合PSP的模型方程，给出连续解析的体接触SOI LDMOS直流模型.仿真结果与实验数据比较，二者吻合得很好，表明该模型能精确表征SOI LDMOS直流特性.

关键词： SOI；LDMOS；体接触；表面势；PSP

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