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An Analytical Device Model Including Velocity Overshoot for Subquartermicrometer MOSFET

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Abstract

A semi-empirical device model including velocity overshoot for subquartermicrometer MOSFET's is presented, in which the velocity overshoot near source is attributed to the strong field here instead of the field gradient. Key features include successful modeling of the dependence of velocity overshoot on both channel length and doping, and closed form expressions for both drain current and transconductance. The proposed model is verified in comparison with experiments.

1. Introduction

Velocity overshoot was proved to enhance the drain current of subquartermicrometer MOSFETs(SQM) by both experiments[1,2] and Monte Carlo simulation[3]. Now, analytical device models[4,5] including velocity overshoot have been developed to provide engineering tools for the development of SQM. In previous studies, the velocity overshoot near source, which is responsible for the current enhancement, is attributed to the gradient of chordal field, and the field at the source end of channel E(0) is neglected. In fact, the channel of SQM is so short that E(0) is comparable to the critical field E_S[6], and the value of E(0) derived from the equations in previous work[4,5] shows the same result. Therefore, the neglect of E(0) not only results in overestimation of the field gradient near source, but also leads to inconsistent modeling. In addition, the dependence of overshoot on channel doping cannot be modeled.
In this work, the velocity overshoot near source is attributed to the strong field here instead of its gradient, a semi-empirical overshoot factor model is proposed to incorporate drain current enhancement due to overshoot into compact device modeling.

2. Modeling

2.1. A simple model of the effect of overshoot on drain current

Although overshoot exists in the pinched-off region of even "long channel"(e.g. 2um) MOSFET, only when the channel length is down to below quartermicrometer , is the current enhancement observable, since drain current is determined mainly by the velocity near source[7]. It is also well known that the major reason for the overshoot in the pinched-off region is the great field gradient here. However, as for the overshoot near source in the case of SQM, the field near source is quite gradual, as opposed to that in the pinched-off region, because the field E(0) increases correspondingly with the reduction of channel length, partly compensating for the increase of field gradient due to channel length reduction, the verification of this point is given later.

It is argued that the strong field near source is the very reason instead of the field gradient. The electrons are in equilibrium with lattice inside the source, then are injected cold into the channel existing strong field, the electrons gain energy from the field and the electron temperature rises. As a direct consequence of the rise of electron temperature, velocity overshoot occurs, which is very similar to the electron movement from a "cold" source into a constant field studied in [8]. The overshoot factor, defined as the average overshoot compared to the drift-diffusion value υ_{dd} near source that is responsible for the enhancement of drain current[5], is supposed to be directly proportional to the rise of electron temperature in the case of "cold" electron injection into a constant high field E(0), which is representative of the field near source as

$$r=1+\frac{\upsilon-\upsilon_{dd}}{\upsilon_{dd}}=1+\alpha\frac{T'-T_L}{T_L} \quad (1)$$

where r is overshoot factor, T_L is lattice temperature, T' is the final electron temperature after achieving balance with the field E(0), α is a coefficient determined by data fitting. With the fact that the diffusivity of electron is nearly independent of its temperature[9], T' can be obtained from the generalized Einstein relation as

$$\frac{kT_L}{q}\mu_{eff}=\frac{kT'}{q}\frac{\upsilon_{dd}(E(0))}{E(0)} \quad T'=T_L(1+\frac{E(0)}{E_s}) \quad (2)$$

where μ_{eff} is low field effective mobility, and the following drift-diffusion velocity model is used[10]

$$\upsilon_{dd}=\frac{\mu_{eff}E}{1+E/E_s} \text{ for } E<E_s \quad \upsilon_{dd}=\upsilon_s \text{ for } E>E_s \quad (E_s=2\upsilon_s/\mu_{eff}) \quad (3)$$

where υ_s is the saturation velocity in silicon inversion layer, which is chosen as $7.0\text{x}10^6$cm/s[6], and the low field mobility model proposed in [10] is used. Substituting (2) and (3) into (1), one obtains

$$r=1+\frac{\alpha}{2}\frac{E(0)\mu_{eff}}{\upsilon_s} \quad (4)$$

The overshoot factor model proposed here is just for the modeling of enhancement of drain current due to the overshoot near source, in which the overshoot in the pinched-off region is neglected because of little contribution to drain current, as discussed above.

2.2. Drain current and transconductance model

With the proposed overshoot factor model, conventional charge control analysis in linear region, and the pseudo-two-dimensional analysis in saturation region[4], an analytical expression for drain current is obtained. An analytical expression for transconductance is obtained following the treatment in [10].

3. Results and discussions

The calculated drain current and transconductance are verified in comparison with Sai-Halasz et al.'s experiments[1,2](Fig.1 and Fig.2), where the determined coefficient α in (1) is 0.50.

The dependence of overshoot on channel doping is given in Fig.3. It can be seen that the current enhancement due to overshoot increases with the lowering of channel doping, because of improved low field mobility, which results from reduced bulk charge.

Transconductance and overshoot factor for different channel length as a function of gate voltage V_g are given in Fig.4 and Fig.5 respectively. Both of the two parameters increase with V_g first because of increased E(0), and then decrease gradually or saturate because of high gate voltage induced enhancement of surface roughness scattering and phonon scattering, which reduces the low field mobility.

For devices in Fig.2, as the channel length decreases from 0.3 to 0.1um, the field at the source end of channel E(0) increases from $0.1E_S$ to $0.7E_S$. Using the term $(E_S-E(0))/L$ as an approximation of the field gradient near source, where $E<E_S$, we see that there is little increase of the field gradient in the channel region near source. It follows that the increase of the field gradient near source is not the major reason for the increase of overshoot factor with the reduction of channel length, as discussed in the second part.

Another advantage of the proposed model is that the dependence of overshoot on both channel length and doping are accounted for. According to (4), the shorter the channel, the larger is E(0) and, therefore, the bigger is overshoot factor; similarly, lower channel doping gives less bulk charge, which in turn results in bigger overshoot factor.

4. Conclusions

The velocity overshoot near source, which is responsible for drain current enhancement, is attributed to the strong field near source instead of the field gradient. A semi-empirical model of overshoot factor is proposed and used in compact device modeling. The dependence of overshoot on both channel length and doping are successfully accounted for. Good agreement with experiments is obtained.

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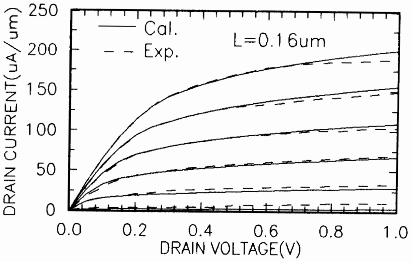

Fig.1 Calculated and measured drain current as function of drain voltage at 300K. Channel length 0.16um, acceptor concentration $3.0x10^{17}cm^{-3}$, gate oxide thickness 4.5nm, junction depth 65nm, substrate bias 0.0V, gate voltage minimum 0.3V, gate voltage increment 0.1V.

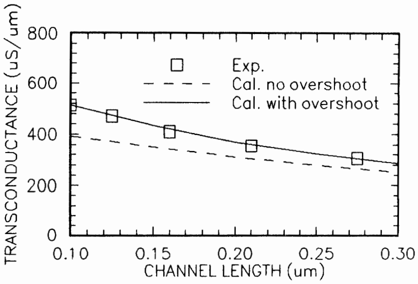

Fig.2 Calculated and measured transconductance as function of channel length at 300K. Solid curve and dashed curve are calculated results with and without velocity overshoot respectively. Transconductance are chosen at the gate voltage for maximum value at V_d=0.8V. Substrate bias is 0.0V. Device parameters are the same as that in Fig.1.

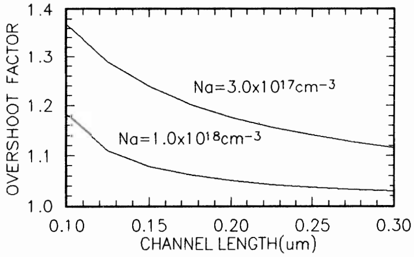

Fig.3 Current enhancement in terms of velocity overshoot factor as a function of channel length at the gate voltage for maximum transconductance with different channel doping level N_a. Device parameters and bias are the same as that in Fig.1.

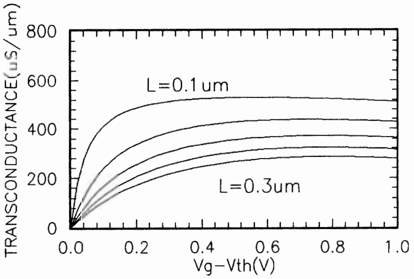

Fig.4 Transconductance as a function of gate voltage V_g-V_{th} for different channel length. Channel length minimum 0.1um, channel length increment 0.05um. Device parameters are the same as that in Fig.1. Substrate bias is 0.0V, drain bias is 0.5 V.

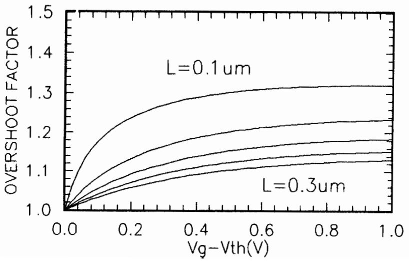

Fig.5 Overshoot factor r as a function of gate voltage V_g-V_{th} for different channel length. Channel length minimum 0.1um, channel length increment 0.05um. Device parameters and bias are the same as that in Fig.4.