Non-universal Roll-off of MOSFET Mobility and V_{DS} Effect in Mobility Measurement

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1. Introduction

The carrier mobility in MOS inversion layer must be modeled accurately in order to correctly simulate electric characteristics of MOSFET's. The mobility data consist of two parts [1]; universal part which is a function of channel effective transverse electric field E_{eff} and is independent of substrate concentration N_A, non-universal part which depends to N_A and rolls off from the universal part. The universal part was incorporated in some device simulators and showed good agreements with measured linear region and I_D vs. V_{DS} characteristics, for example [2]. However, as for subthreshold region or region which depends on mobility in non-universal part, there is no precise report [3].

We report a discrepancy between measured and simulated device characteristics in subthreshold region using the measured mobility in a device simulation. The purpose of this paper is to investigate errors in the non-universal part of measured mobility.

In a device simulator MOS2C [4], we incorporated a mobility model combining universal mobility and Coulomb mobility via Matthiessen's rule. The universal mobility was modeled from the measured value [1]. We described the universal mobility in terms of local transverse electric field [2]. For modeling Coulomb mobility, we at first used the measured non-universal mobility.

Fig. 1 shows calculated and measured I_D vs. V_G characteristics for four different profiles. In order to eliminate ambiguity of device structure, we used conventional n-type MOSFET's with W/L = 100μm/100μm. The profiles were obtained by SIMS analysis. The gate oxide thickness used in the simulation was obtained by ellipsometry, 19.5 nm. The calculated values of I_D in strong inversion region were in good agreement with the measured characteristics. However, in subthreshold region, the measured non-universal mobility gave too small subthreshold swings. Next we adopted the bulk Coulomb mobility model [5] instead of the measured non-universal mobility. As shown in Fig. 1, the bulk Coulomb mobility gave good agreement with the measured characteristics. Next we investigate reasons for measurement errors in the non-universal part of mobility.

2. Diffusion Current Induced Error in Measured Mobility

The non-universal roll-off of measured mobility from the universal curve was ascribed to Coulomb scattering [1]. On the other hand, a suggestion was made that the roll-off may be caused by diffusion current in low gate biases [3]. In order to make data of Coulomb mobility accurate, we investigated the diffusion current contribution.

The measured mobility μ_{eff} was obtained by

$$\mu_{eff} = I_D \cdot (L/W)/(q \cdot N_{inv} \cdot V_{DS}) \tag{1}$$

where L is channel length, W channel width, q elemental charge, N_{inv} inversion layer carrier density (cm^{-2}), and V_{DS} bias applied between source and drain. Mobility is proportional coefficient of current on electric field. Equation (1) supposes that carrier is driven by electric field, V_{DS}/L. However, when diffusion current exists, V_{DS} is not related to electric potential difference of source end and drain end. Instead, V_{DS} is related to quasi-fermi potential difference of source end and drain end [6]. Because of Einstein's relation, the proportional coefficient of current on quasi-fermi potential gradation is also the mobility. Hence, even if diffusion current exists, there may be a region where (1) can be used. We investigated the error of (1) by a numerical experiment using MOS2C.

V_{DS} in the numerical experiment was chosen to be the same as that in the mobility measurement [1], i.e., 50 mV. The mobility in device simulator was made to be a constant. N_{inv} in average of the channel was obtained by directly integrating carrier density in the inversion layer. The calculated I_D and N_{inv} (V_{DS} = 50mV) were used in (1). When (1) is correct the extracted mobility should be the constant. Deviation from the constant represents inapplicability of (1). Fig. 2(a) represents the extracted μ_{eff}. Fig. 2(b) represents N_{inv} which corresponds to Fig. 2(a). In strong inversion region, the extracted mobility was constant. In much lower gate biases, on the other hand, the extracted mobility decreases suddenly. However, at $N_{inv} = 1\times10^{11}$ cm^{-2}, the error was not so large at 10 %. Therefore, near and above threshold voltage, quasi-fermi formulation makes it correct to use (1).

3. Drain Bias Induced Error on Inversion Carrier Concentration

We also examined error in N_{inv} measurement. In [1], N_{inv} was measured by using the gate-channel capacitance, C_{GC}. C_{GC} was measured in V_{DS} = 0 V. Therefore, the V_{DS} condition was different from the condition in which I_D was measured.

According to the charge-sheet model [6], V_{DS} contribution on threshold voltage V_{th} is extracted at strong inversion region.

$$V_{th} = -\psi_{S0} + (Q_{B0}/C_{OX}) + V_{DS}/2 + (Q_{B0}/C_{OX})(V_{DS}/2\psi_{S0}) \tag{2}$$

where ψ_{S0} is surface electric potential at source end, Q_{B0} substrate bulk space charge at source end, C_{OX} gate oxide capacitance. Equation (2) shows that V_{th} increases when V_{DS} is applied. Hence,

$$N_{inv}(V_{DS} = 50\ \text{mV}) < N_{inv}(V_{DS} = 0). \tag{3}$$

This discrepancy reduces the measured μ_{eff}. In accordance with the last two terms of (2), the higher the substrate concentration and/or the thinner the gate oxide thickness, V_{DS} dependence of V_{th} becomes stronger, and hence, the larger the error.

We estimated the error caused by this N_{inv} difference. By using device simulation, we calculated N_{inv} (V_{DS} = 0) and N_{inv} (V_{DS} = 50 mV), and corrected the measured μ_{eff}. Fig. 3 represents the measured and the corrected μ_{eff} dependence on E_{eff}. In very low substrate concentration ($N_A = 3.9\times10^{15}\text{cm}^{-3}$), the corrected measured mobility does not show non-universal roll-off. In this substrate concentration, Coulomb scattering is very weak and it does not affect mobility. In higher substrate concentration, the corrected measured mobility showed non-universal roll-off.

In conclusion, V_{DS} effect on measured N_{inv} caused a larger error in μ_{eff} than the diffusion current induced error. V_{DS} effect gave spurious non-universal roll-off of measured μ_{eff} and too small subthreshold swings in the simulated device characteristics. Smaller V_{DS} will give more accurate mobility data. We also comment that for accurate modeling of mobility, correct N_A estimation in measuring mobility is also important.

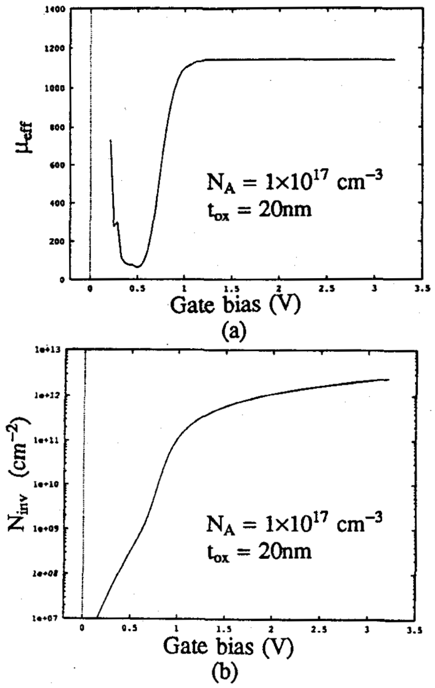

Fig. 2. Result of the simulation experiment. (a) Extracted mobility where input mobility in the simulator was constant. (b) Inversion layer carrier density which corresponds to (a).

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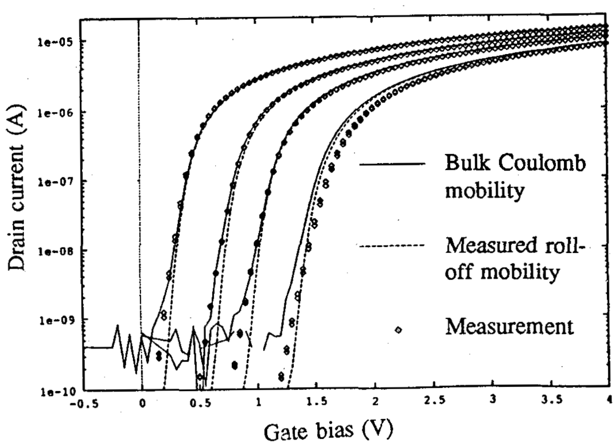

Fig. 1. Simulations using measured roll-off mobility or bulk Coulomb mobility. In both simulations, measured universal mobility is used.

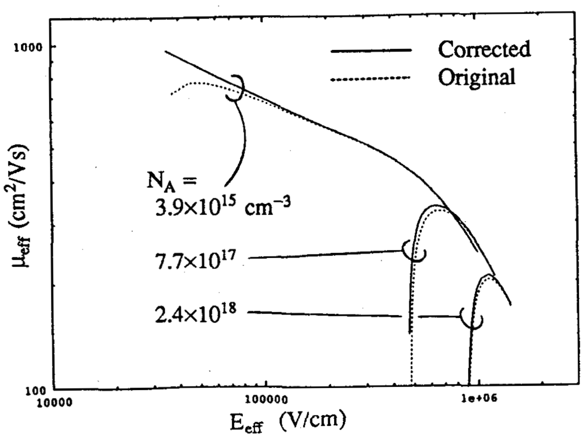

Fig. 3. Original measured mobility and corrected mobility respecting N_{inv} error caused by V_{DS}.