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Measurement and Modeling of the n-channel and p-channel MOSFET's Inversion Layer Mobility at Room and Low Temperature Operation

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Abstract: A new semi-empirical model for the electron and hole mobilities of the MOSFET inversion layers is proposed. This model takes into account the dependence of Coulombic, phonon, and surface roughness scattering on temperature and transverse field over a wide range of values ($77\text{ K} \leq T \leq 343\text{ K}$ and transverse fields up to 1.36 MV/cm). For the first time, the magnitude of the key parameter η in defining the effective transverse field is found to be a continuous function of temperature for both electrons and holes. The E_{eff} dependences of the universal curves are observed to differ between the electrons and holes, particularly at low temperatures. The proposed model, verified by comparison of experimental data and simulated MOSFET I-V characteristics at different temperatures, can be easily incorporated into 2-D device simulators for device and circuit simulation.

1. INTRODUCTION

The mobility of carriers in the MOSFET inversion layer has been studied extensively due to its importance in device and VLSI circuit design [1][2]. The previous mobility models are limited to a low transverse electric field and are only useful over a limited temperature range. It is important to have a mobility model valid over a wide temperature range, even down to 77 K , due to recent interest in low temperature CMOS operation.

It has been reported that the electron and hole mobilities in the inversion layer follow universal curves at room temperature, independent of the substrate impurity, oxide thickness, and substrate bias when plotted as a function of effective transverse electric field, E_{eff} , defined by following equation:

$$E_{\text{eff}} = \frac{1}{\epsilon_{\text{si}}} (Q_{\text{dpl}} + \eta Q_{\text{inv}}), \quad (1)$$

where Q_{dpl} is the surface depletion charge density, Q_{inv} is the surface inversion charge density, and ϵ_{si} is the permittivity of silicon. Here, η is an empirical parameter in defining E_{eff} and was reported to be equal to $1/2$ in order to provide the universal relationship. Recent studies show that η is not $1/2$ for electrons or $1/3$ for holes at all temperatures [3]-[5]. The value of η directly affects the precise of mobility modeling. However, the relationship between the η and temperature is still not clear. In this work, we propose a new semi-empirical mobility model for the electrons and holes in the MOSFET inversion layer, which is applicable over a wide range of values ($77\text{ K} \leq T \leq 343\text{ K}$ and transverse fields up to 1.36 MV/cm). For the first time, the magnitude of the key parameter, η , in defining the electric field is found to be a continuous function of temperature for both electrons and holes. The proposed model is verified by comparison of the experimental I-V curves and those simulated by MEDICI [6] including the new model at different temperatures.

2. DEVICE DETAILS AND EXPERIMENTAL TECHNIQUES

The n-channel enhancement-mode MOS transistors were fabricated using n+ poly gate on (100) substrate while p-channel transistors were fabricated using p+ poly gate. To minimize the effects of extrinsic series resistance on the mobility measurements, large area devices ($W/L=100\text{ }\mu\text{m}\times 100\text{ }\mu\text{m}$) were measured for both NMOS and PMOS. The n-channel devices have 96 Å gate oxide with two surface channel doping concentrations of $3\times 10^{15}\text{ cm}^{-3}$ and $1\times 10^{17}\text{ cm}^{-3}$, respectively. The p-channel devices have 130 Å gate oxide and one doping concentration of $5\times 10^{16}\text{ cm}^{-3}$.

The effective inversion layer mobility, μ_{eff} , was experimentally extracted from the measured differential drain conductance, g_d (with $V_{ds}=\pm 5\text{ mV}$):

$$\mu_{\text{eff}} = \frac{g_d}{\frac{W}{L} Q_{\text{inv}}} \quad , \quad (2)$$

where Q_{inv} is the inversion layer charge per unit area. To avoid the ambiguity in the definition and determination of the threshold voltage, a high frequency split C-V method at 10 kHz, as shown in Fig. 1, is used to extract Q_{inv} from the measured gate-channel capacitance, C_{gc} [7]. The inversion layer charge is defined as

$$Q_{\text{inv}} = \int_{-\infty}^{V_{gs}'} C_{gc}(V_{gs}') dV_{gs}' \quad , \quad (3)$$

Similarly, the bulk charge density in Eq. 1, Q_{dpl} , is determined by integrating the gate-substrate capacitance, C_{gb} :

$$Q_{\text{dpl}} = \int_{V_{FB}}^{V_{gs}'} C_{gb}(V_{gs}') dV_{gs}' \quad , \quad (4)$$

where V_{FB} is the flatband voltage. The temperature dependence of the flatband voltage V_{FB} in Fig. 2 was determined by comparing the experimental and simulated C-V curves for the MOS transistors at different temperatures [8].

Figure 1. Split C-V measurements of n-channel transistor at 77 K and 300 K. C_{gb} is the gate-channel capacitance and C_{gc} is the gate-substrate capacitance.

Figure 2. Temperature dependence of the flatband voltage for two different n-channel doping devices.

3. RESULTS AND DISCUSSION

It has been found that the universal mobility-field curves, as shown in Figs. 3 and 4, result only if the effective field in Eq. 1 is defined differently for electrons and holes. The parameter η in the definition of E_{eff} was chosen so that the experimental data for μ_{eff} (E_{eff} , N_a , V_{sub}) fall on a single curve for sufficiently

Figure 3. Transverse effective electric field (E_{eff}) dependence of the inversion layer mobility for n-channel devices at temperatures 77 K, 125 K, 250 K, 300 K, and 343 K. Symbols correspond to experimental data, while solid line represent the mobility given by Eq. 6.

Figure 4. Transverse effective electric field (E_{eff}) dependence of the inversion layer mobility for p-channel devices at temperatures 77 K, 150 K, 218 K, and 300 K. Symbols correspond to experimental data, while solid line represent the mobility given by Eq. 6.

Figure 5. Temperature dependence of the electric field parameter for electrons and holes at temperature range from 77 K to 343 K.

Figure 6. NMOS linear-region transconductances g_m versus gate voltage at 77 K, 100 K, 150 K, 218 K, 250 K, and 300 K. Negative transconductances are observed at $T < 218$ K.

Figure 7. Simulated NMOS linear-region drain currents versus gate voltage with different gate oxide thicknesses including the new mobility model at 77 K.

Figure 8. Measured and simulated subthreshold and linear characteristics of a $100 \mu\text{m} \times 100 \mu\text{m}$ NMOS devices at 77 K and 300 K.

Figure 9. Measured and simulated saturation characteristics of 100 $\mu\text{m} \times 100 \mu\text{m}$ NMOS devices at 300 K.

Figure 10. Measured and simulated saturation characteristics of 100 $\mu\text{m} \times 100 \mu\text{m}$ NMOS devices at 77 K.

high transverse field at different substrate doping concentrations or substrate bias. The magnitude of extracted η is shown in Fig. 5. We found that the η values for both electrons and holes are not a constant but have a linear temperature dependence given by $\eta(T) = 0.86 - 1.23 \times 10^{-3}T$ for electrons and $\eta(T) = 0.42 - 2.9 \times 10^{-4}T$ for holes. The η value increases from 0.5 to 0.75 for electrons and from 0.33 to 0.40 for holes as the temperature is reduced from 300 K to 77 K.

Effective mobility is limited by three scattering mechanisms: phonon scattering (μ_{ph}), surface roughness scattering (μ_{sr}), and Coulombic scattering (μ_c). To model these scattering mechanisms, we used a formula similar to that proposed by Watt, et al. [9]:

$$\frac{1}{\mu_{eff}} = \frac{1}{\mu_{ph}} + \frac{1}{\mu_{sr}} + \frac{1}{\mu_c} \quad (5)$$

$$\frac{1}{\mu_{eff}} = \frac{1}{\mu_1} \left(\frac{10^6}{E_{eff}} \right)^{\alpha_1} + \frac{1}{\mu_2} \left(\frac{10^6}{E_{eff}} \right)^{\alpha_2} + \frac{1}{\mu_3} \left(\frac{10^{18}}{N_B + Q_f/z} \right)^{-1} \left(\frac{10^{12}}{Q_{inv}} \right)^{\alpha_3} \quad (6)$$

where N_B is substrate doping concentration, Q_f is interface state density, and z is the width of the inversion layer given by [10]. The parameters in the proposed mobility model (Eq. 6) can be extracted from the mobility measurements (Figs. 3, 4) and are summarized in Table 1. The E_{eff} dependence of the universal curves is

Table 1: Parameters of electron and hole mobility model

	α_1	μ_1	α_2	μ_2	α_3	μ_3
Electrons	-0.22	$7.25 \times 10^6 T^{-1.71}$	-2.6	$2.63 \times 10^3 - 6.59T$	1	$1.63 \times 10^2 + 1.31T$
Holes	-0.32	$5.80 \times 10^5 T^{-1.5}$	-1.02	125	1	$263.5 - 0.46T$

observed to differ between electrons and holes, particularly at low temperature. At 77 K, the mobility is dominated by surface roughness scattering. The electron mobility is proportional to $E_{eff}^{-2.6}$ while the hole mobility is proportional to $E_{eff}^{-1.02}$. This is believed to be due to the different occupancy statistics associated with the lowest subband, where the surface roughness scattering is dominant [11]. At room temperature, the mobility is dominated by the phonon scattering. The phonon limited mobility μ_{ph} is proportional

to $E_{\text{eff}}^{-0.22}$ for electrons and $E_{\text{eff}}^{-0.32}$ for holes, respectively, which is very close to the theoretical calculations [12]. The phonon limited mobility exhibits a temperature dependence of $T^{-1.71}$ for electrons and T^{-} for holes, which can be seen to be very similar for both electrons and holes. Weak temperature dependence is observed for the Coulombic scattering and surface roughness scattering terms, especially for the hole mobility. The values of μ_{eff} vs. E_{eff} for electrons and holes obtained from this model are also plotted in Figs. 3, 4, respectively.

In order to concentrate on the effective mobility model, we have limited ourselves to the case of long-channel MOSFET's, where the saturation velocity does not play a significant part in the computation of the I-V characteristics. Good agreement between the experimental I-V curves and those simulated by MEDICI including the new mobility model is obtained for NMOS devices at 77 K and 300 K, which is shown in Figs. 8, 9, 10. Negative transconductance was observed due to strong surface roughness scattering at high E_{eff} and 77 K (Figs. 6, 7).

4. CONCLUSION

A new semi-empirical universal mobility model is presented. The definition of effective electric field was revised with a temperature dependent parameter. This model takes into account the dependence of different scattering mechanisms on temperature and transverse electric field over a wide range. The proposed model can be easily incorporated into 2-D simulators for device and circuit simulation over a temperature range from 77 K to 70 °C.

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