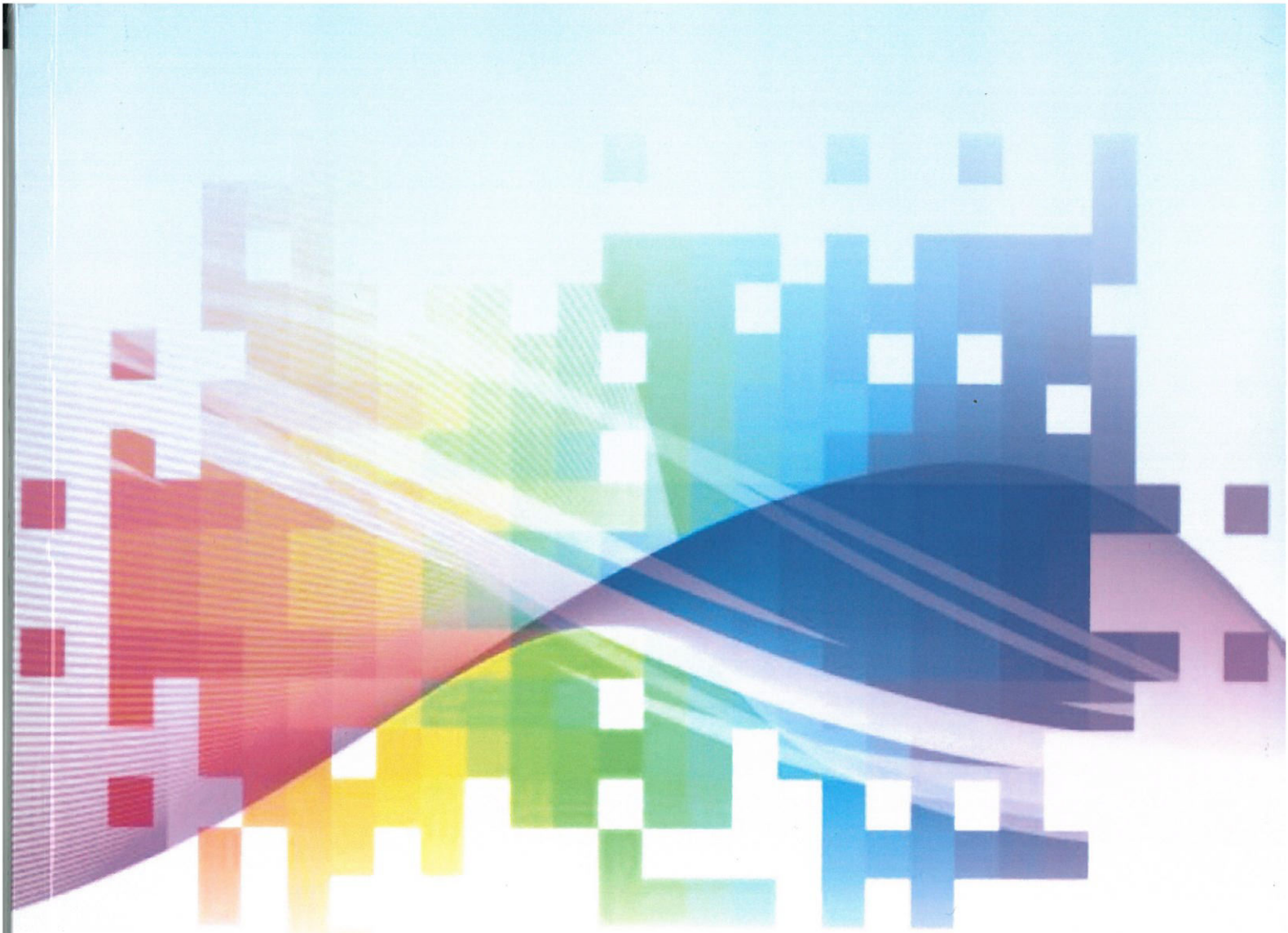

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High-k Gate Stacks Influence on Characteristics of Nano-scale MOSFET Structures

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***Abstract*—The models of electro-physical effects built-into Sentaurus TCAD have been tested. The models providing an adequate modeling of deep submicron high-k MOSFETs have been selected. The gate and drain leakage currents for 45 nm MOSFET with PolySi gate and SiO_2, SiO_2/HfO_2 and HfO_2 gate dielectrics have been calculated using TCAD. It has been shown that the replacement of traditional SiO_2 by an equivalent HfO_2 dielectric considerably reduces the gate leakage current by several orders due to elimination of the tunneling effect influence. Besides, the threshold voltage, saturation drain current, mobility, transconductance, etc. degrade within 10-20% range.**

Keywords-component: MOSFET; high-k materials; TCAD; physical models.

I. INTRODUCTION

In novel microprocessors produces by Intel, AMD, Apple, Samsung, NEC Electronics high-k gate CMOS devices are used. In recent years high-k gate nano-scale MOSFETs became to real candidates to reduce standby power consumption of CMOS VLSIs due to their possibility in reduction of gate leakage current in comparison with conventional silicon dioxide gate structures. In previous works the electro-physical behavior of unirradiated high-k gate MOSFETs using Sentaurus [1]-[4] and ATLAS [5], [6] device modeling tools was analyzed. However, the use of high-k gate dielectric also effects the rest characteristics of MOSFETs which need to be studied in detail.

In our work according to the modeling and design strategy for nanoelectronics devices supported by European Nanoelectronics Initiative Advisory Council we have realized the TCAD modeling procedure to achieve close match between TCAD modeling results and experimental characteristics.

II. PHYSICAL TCAD MODELS

All the physical models of mobility, scattering, carrier transport, tunneling, quantization, generation–recombination, hot-carrier injection implemented in Sentaurus version J-2014.09 were examined. The set of adequate models was selected and recommended for high-k gate MOSFET design (see Table I).

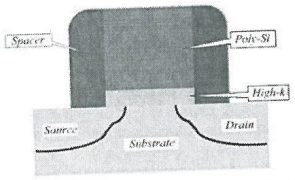

Figure 1. MOSFET structure withhigh-k gate insulator.

TABLE I. SET OF TCAD PHYSICAL MODELS FOR HIGH-K SIMULATION

Models	Gate Oxide		
	SiO_2	*SiO_2/HfO_2*	*HfO_2*
Transport Model	Hydrodynamic		
Carrier–Carrier Scattering	CarrierCarrierScattering(BrooksHerring)		
Mobility Degradation	Enormal		Enormal (Lombardi_highk)
Generation–Recombination	SRH(DopingDep), Auger		
Quantization	Density Gradient Quantization Model		
Tunneling	DirectTunneling		
Hot-Carrier Injection	Lucky		

The experimental works [7]-[16]where the main physical parameters describing the silicon-dioxide surface discrete trapped charges; device doping profiles; electron and hole mobilities of conversional and SOI FETs with different gate stack and others were analyzed. The real input data for the physical parameters used in Sentaurus tool for different high-k gate FET structures simulation were established.

In [6]-[8] have shown that the carriers capture more intense at HfO_2/Si interface than at SiO_2/Si interface. The values of the surface states charge (Q_{int}) for SiO_2, HfO_2 and SiO_2/HfO_2 dielectrics assumed to be $5\cdot10^{10}$, $5\cdot10^{11}$ and $1\cdot10^{12}$ cm^{-2} respectively. Similar Q_{int} values are used in [5] and [6].

Direct Tunneling model parameters were modified with using [9].

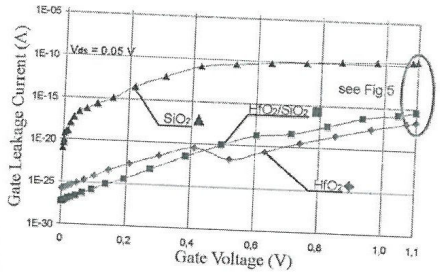

Figure 2. Gate leakage current for high-k MOSFETs with different gate oxide.

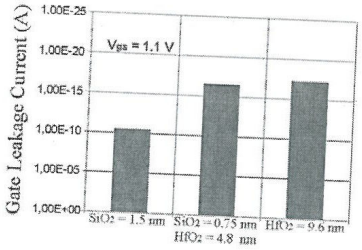

Figure 3. Comparison of Gate leakage current for high-k MOSFETs with different gate oxide.

III. 45NM MOSFET MODELING

The calibration of electrical characteristics for different high-k gate MOSFETs was carried out comparing I-V characteristics obtained from TCAD simulations and those from measurements.

45nm MOSFET structure with polysilicon gate (W_{poly} = 500 nm, L_{poly} = 45nm) was simulated. Different gate dielectric: SiO_2, HfO_2 and composite (stack) of SiO_2 and HfO_2 were used. For all modeled MOSFET structures EOT was set at 1.5 nm (see. Fig.1).

$$EOT = t_{high\text{-}k} \cdot \left(\frac{k_{SiO\,2}}{k_{high\text{-}k}}\right).$$

The doping of the silicon source/drain region is assumed to be $1\cdot10^{20}$ cm^{-3}. The peak value of doping concentration in silicon channel region is assumed to be $1\cdot10^{18}$ cm^{-3}.

The doping concentration in polysilicon gate is $1\cdot10^{22}$ cm^{-3} at the top and $1\cdot10^{20}$ cm^{-3} at bottom of the polysilicon gate.

Threshold voltage (V_{th}), drain leakage current (I_{off}) and gate leakage current (I_{gate}) were calculated at a lower voltage (V_{ds}=0.1 V, V_{gs} from 0 to 1.0 V). Saturation drain current (I_{on}), mobility (μ) and transconductance (S) were calculated at a high voltage (V_{ds}=1.0 V, V_{gs} from 0 to 1.0 V). The values of the basic parameters for 45nm MOSFET with the three types of gate dielectric are collected in Table II.

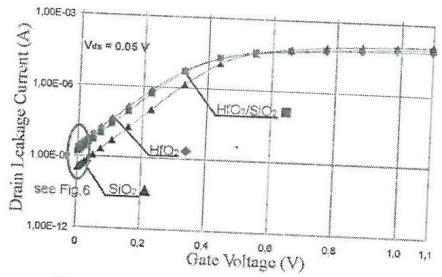

Figure 4. Id-Vg characteristics for high-k MOSFETs with different gate oxide.

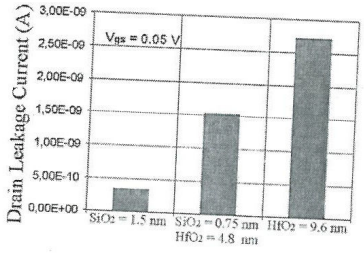

Figure 5. Comparison of Drain leakage current for high-k MOSFETs with different gate oxide.

TABLE II. PARAMETERS OF 45NM HIGH-K MOSFET WITH DIFFERENT GATE OXIDE

Parameters	Gate Oxide		
	SiO_2 1.5 nm	*SiO_2 0.75 nm / HfO_2 4.8 nm*	*HfO_2 9.6 nm*
I_{gate}, A	2.82E-10	3.26E-16	2.10E-17
V_{th}, V	0.42	0.38	0.37
I_{off}, A	3.35E-10	1.53E-09	2.72E-09
I_{on}, mA	1.12	1.0	0.84
μ, m/(V·s)	168	133	125
S, uA/V	330	290	210

Table II and Fig. 2 and Fig. 3 show that the gate carrier tunneling effect could be pressed and gate leakage current could be considerably 6-7 orders reduced by replacement traditional SiO_2 gate dielectric of equivalent HfO_2 dielectric.

The rest of important MOSFET parameters: threshold voltage, saturation drain current, mobility, transconductance etc. degrade after replacing SiO_2 with HfO_2 in MOSFETs with polysilicon gate (see Fig.3-Fig.6).

The presented TCAD simulation results agree with experimental I-V characteristics investigations [1], [4] and [13].

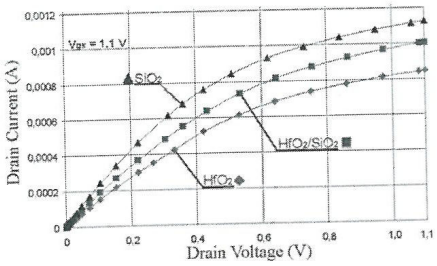

Figure 6. Id-Vd characteristics for high-k MOSFETs with different gate oxide.

IV. CONCLUSION

The physical TCAD models providing an adequate modeling of deep submicron high-k MOSFETs have been selected. I-V characteristics of 45 nm high-k gate MOSFET on bulk substrate were simulation with selected models for confirm their adequacy.

ACKNOWLEDGMENT

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The Density of Gaps in the Seal Joint in Elastic Contact of Microasperities

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***Abstract*—Initially, a contact between a rigid rough surface and a homogeneous elastic half-space without taking into account the mutual influence of microasperities is considered. To determine the dependence of the density of gaps in the joint on dimensionless the force elastic geometrical parameter, the discrete roughness model presented by microasperities in the form of equal spherical segments with the height distribution corresponding to the bearing profile curve of the real surface is used. To determine the volume of intercontact space, the volumes of gaps attributable to the single contacting or noncontacting asperities are determined. In this case the equations describing the sections of surfaces of contacting or noncontacting asperities and the half-space under load are used. Then we consider a contact between a rigid rough surface and a layered half-space consisted of the coating with thickness δ1 and the substrate. By using the stiffness model of a layered half-space, the elastic characteristic are determined for every contacting asperity. The system of transcendental equations which allow to determine the dependence of the density of gaps in case of contact through coating layer on the roughness parameters, material properties, coating thickness and applied load is given. The characteristic curves showing the dependence of the density of gaps in the joint for different coating thickness are given.**

Keywords- rough surface, spherical asperity, elastic contact of asperities, volume of gaps, density of joint, thin-layer coatings, layered elastic half-space.

I. INTRODUCTION

A promising way to increase seals and friction joints' operational factors is the surfacing polymeric covering on their work surfaces anti-frictional films. Operation experiment has shown that the sealing ability anti-friction properties are determined not only by the properties, but also the thickness of the coating material [1]. Long experience of the authors in improving the methods of calculation of tightness of joints show that the density of gaps and in the seal junction and the relative contact area are the critical characteristics. The influence of coating thickness on the relative area for different types of contact is considered in [2, 3]. At the same time, there are no data of the influence of coating thickness on the density of gaps in the joint. It has defined the purpose of the present paper.

II. CONTACT BETWEEN A ROUGH SURFACE AND A HOMOGENEOUS ELASTIC HALF-SPACE

We use the discrete model of a rough surface, in which microasperities are presented by identical spherical segments with the distribution of segments' peaks on height corresponds to the bearing profile curve of the real surface [4]. To describe the distribution of the reference curve is used incomplete beta function:

$$\eta(\varepsilon)=\frac{B_\varepsilon(\alpha,\beta)}{B(\alpha,\beta)}. \quad (1)$$

Where $B_\varepsilon(\alpha,\beta)$ and $B(\alpha,\beta)$ are incomplete and complete beta functions;

$$\alpha=\left(\frac{R_p}{R_q}\right)^2\left(\frac{R_{\max}-R_p}{R_{\max}}\right)-\frac{R_p}{R_{\max}},\ \beta=\alpha\left(\frac{R_{\max}}{R_p}-1\right); \quad (2)$$

Where R_p, R_q, $R_{\max}$ are height roughness parameters according to ISO 4281/1–1997.

In this case, the density of the asperities distribution on height function is

$$\varphi_n'(u)=\frac{u^{\alpha-2}(1-u)^{\beta-2}[(\alpha-1)(1-u)-(\beta-1)u]}{\varepsilon_s^{\alpha-1}(1-\varepsilon_s)^{\beta-1}}, \quad (3)$$

Where ε_s is determined from the condition $\varphi_n(\varepsilon_s)=1$, $\omega R_{\max}$ is the height of a spherical segment, $\omega=1-\varepsilon_s$.

The radius of the spherical segment is

$$r=\frac{a_c^2}{2\omega R_{\max}}, \quad (4)$$

Where a_c is the radius of the base of the spherical segment.

The problem of the density of gaps upon contact between a rigid rough surface and a half-space was considered in [5]. As it follows from [5], to find the volume of intercontact space it is necessary to determine the volume of gaps attributable to the single contacting or noncontacting asperities as

$$V_c=\begin{cases}V_{ri}=2\pi\int_{a_{ri}}^{a_c}[z_{10}(\rho)-z_{20}(\rho)]\rho d\rho,\\ V_{oi}=2\pi\int_{0}^{a_{oi}}[z_{1r}(\rho)-z_{2r}(\rho)]\rho d\rho,\end{cases} \quad (5)$$

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