Electrical Characterization and Design Optimization of Finfets with TiN/HfO_2 Gate Stack

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Triple-gate field-effect transistors like FinFETs have been recognized as the best candidates for sub-100 nm scaling of MOSFETs due to their immunity to short channel effects (SCEs) and proximity to standard bulk planar CMOS processing [1-7]. Multi-channel FinFETs have been reported demonstrating their feasibility for digital/analogue circuit applications [6], [8, 9], as well as applications in equipments requiring extremely low power consumption [10-12]. In most of the recent studies, device optimization was studied with simulations using graded doping profile in the source/drain underlap regions [13, 14]. However, as the FinFETs scale down, the fins need to be thinner for better control of the short-channel effects, resulting in difficulties for experimental realization of a specific doping profile in such thin fins [15].

FinFETs with extensions under the spacers between gate and source/drain contacts of constant doping concentration have been demonstrated, which show higher subthreshold leakage current as they are scaled down [16]. This finding suggests that the extensions under the spacers need to be optimized in these devices. In this work, based on experimental and simulation data, we report electrical characteristics of lightly doped n-channel FinFETs with TiN/HfO_2 gate stack and provide the optimized technological parameters of the source/drain extension under the spacers needed to improve the performance of 60 nm gate length FinFETs.

The n-channel triple-gate FinFETs were fabricated at IMEC (Leuven) on SOI wafers with 145 nm buried oxide thickness, following the process described elsewhere [6]. The measured devices were 5-fin FETs with a structure schematically represented in Fig. 1. The channel of the transistors is silicon with background boron doping concentration of about 10^{15} cm^{-3}. As gate insulator, HfO_2 was deposited with equivalent gate oxide thickness 1.7 nm, whereas a 5 nm TiN film was deposited for gate metallization. The length and the doping concentration of the extensions under the spacers between gate and source/drain pads are L_{ext} = 50 nm and N_{ext} = 5×10^{19} cm^{-3}, respectively. The doping concentration of the source/drain contacts is about 2×10^{20} cm^{-3}, the fin height is H_{fin} = 65 nm, the fin width W_{fin} is varying from 25 to 875 nm and the gate length L_g is varying from 60 to 910 nm. Details of the fabrication processes are described in [17].

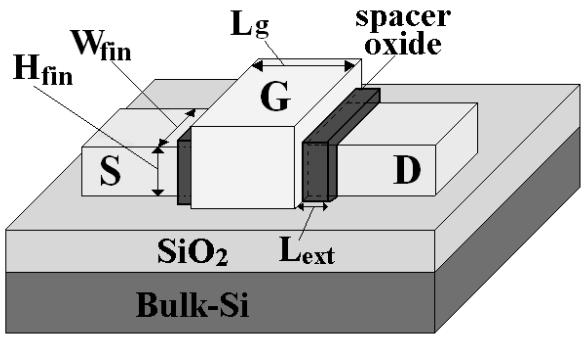

Figure 1. 3-D configuration of the FinFET device.

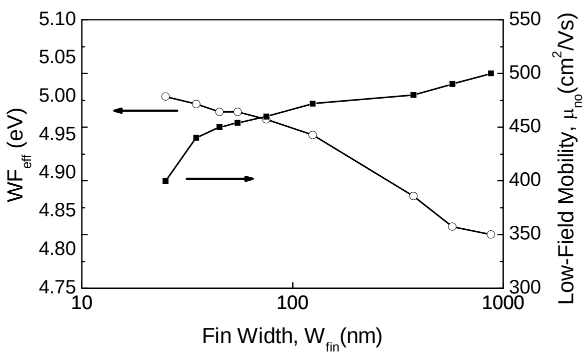

Figure 2. Effective work function WF_{eff} and low field mobility μ_{no} as a function of the fin width.

The experimental transfer characteristics of FinFETs with W_{fin} lying within the range of 875-25 nm and with gate length L_g varying from 910 to 60 nm have been analyzed and reproduced with simulations, using a 3-D commercial software tool (SILVACO-ATLAS). For the simulations, we used as fitting parameters the effective gate work function WF_{eff} for the HfO_2/TiN gate stack and the low field mobility μ_{no} in Shirahata's mobility model. The behavior of WF_{eff} and μ_{no} versus W_{fin} is presented in Fig. 2 (for FinFETs with L_g=910 nm). It is worth to notice that decrease of the fin width from 875 to 25 nm shifts the effective gate work function from 4.82 to 5.00 eV, i.e. shifts WF_{eff} by ~200 mV. The lower value of the WF_{eff} = 4.82 eV characterizes mainly the TiN/HfO_2 stack of the top-gate since W_{fin} >> H_{fin}, whereas the higher value of WF_{eff} = 5.00 eV characterizes the gate stack of the side-gates of the device since $W_{fin} < H_{fin}$. This finding can be explained with the results of a recent work obtained from calculations of the TiN/HfO_2 valence band offset, which depends on the interface dipoles; it is shown that the effective work function of the TiN/HfO_2 gate stack depends on the TiN and HfO_2 interface stoichiometry and the species inter-diffusion [18]. In oxygen/nitrogen rich interfaces the effective work function is high (5.1 eV), reducing to 4.7 eV when oxygen is mixed in TiN or oxygen vacancies exist at the TiN/dielectric interface [18]. Therefore, the obtained experimental values of WF_{eff} indicate a different stoichiometry of the top and side gates interfaces.

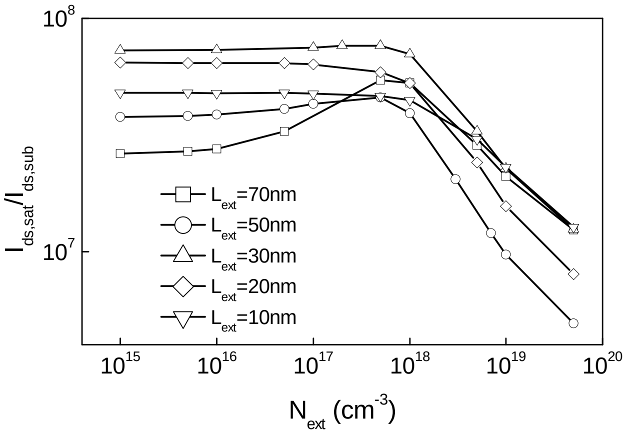

Figure 3. Dependence of the current ratio $I_{d,sat}/I_{d,sub}$ on the extension doping concentration N_{ext} and length L_{ext}, for finFETs with L_g = 60 nm.

Optimization of the extension regions under the spacers, characterized by the two parameters of extension doping concentration N_{ext} and length L_{ext} was performed for the FinFET with the shorter gate length of L_g = 60 nm and fin width W_{fin} = 25 nm (using the aforementioned values of WF_{eff} and μ_{no}). In order to develop guidelines for optimal device performance in terms of both N_{exts} and length L_{ext}, we evaluated their influence on the current ratio $I_{d,sat}/I_{d,sub}$. Fig. 3 shows that an extension length smaller than 50 nm and extension doping concentration lower than 5×10^{19} cm^{-3} are required to achieve improved device performance with maximum saturation drain current to subthreshold leakage current ratio ($I_{d,sat}/I_{d,sub}$). In fact, optimum current ratio $I_{d,sat}/I_{d,sub}$ is obtained (for the 60 nm gate length FinFETs), when L_{ext} = 30 nm and $N_{ext} \approx 5\times10^{17}$ cm^{-3}.

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