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Influence of structural parameters on the immunity of short-channel effects in grooved-gate nMOSFET

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This paper presents the influences of structural parameters on the immunity of short-channel effects in grooved-gate n-channel metal–oxide–semiconductor field effect transistor (nMOSFET) using the simulator PISCES-II. The zero or negative groove-junction depth is beneficial to the improvement of the threshold characters, but there exists a limited range. The doping concentration of both substrate and channel has a significant influence on the threshold characters as well as on the device transconductance. Thus, the variation in these adjustable parameters may help to optimize the device design.

Keywords: grooved-gate MOSFET, threshold voltage, short channel effect, junction depth
PACC: 0750, 6170T, 7340Q

1. Introduction

With the development of metal–oxide–semiconductor field effect transistor (MOSFET) technology towards sub-micron and even deep sub-micron range, some limitations, for example, short-channel effects, hot-carrier effects, etc, deteriorate the operating performance of the devices.[1] The strong electric field of the channel near the drain junction is regarded as the origin of the deterioration. Thus, the most effective method to avoid the potential extension is to separate the two regions by grooves filled with gate materials. Several studies[2−6] have already verified the usefulness of grooved-gate structure for suppressing the short-channel and hot-carrier effects. Compared with planar structure devices, the variation in device design may help to develop transistors for the next technology nodes.

The main advantage of the grooved-gate MOSFET is the presence of a large number of structural parameters, such as the corner angle, junction depth, the channel doping concentration and the substrate doping concentration, which can be used to suppress the short-channel effects. These need to be studied more thoroughly. Our work is focused on the specific variation of device characters influenced by the change of structural parameters. which consist of the channel length L, the groove-junction depth $X_{\rm Gj}$, substrate doping concentration $N_{\rm sub}$ and channel doping concentration $N_{\rm channel}$. Subjects studied include the electric field profiles, threshold voltages, subthreshold characteristics and drain current. It is expected that this study can provide some useful information for the design of new MOSFETs.

The simulations of grooved-gate nMOSFET are carried out by using a two-dimensional device simulator, PISCES. The variations of the groove are formed by adjusting the intrinsic function of PISCES, 'SPREADS'. The simulated structure parameters include the groove-junction depth, the substrate doping concentration and the channel doping concentration. The simulation results reveal that the grooved-gate device can effectively adjust the characteristics of the device including surface potential, threshold voltage roll-off, sub-threshold swing and drain-induced barrier lowering (DIBL), etc.

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2. Device structure and model

Figure 1 is a cross-section of a grooved-gate nMOSFET based on the charge sharing model of MOSFET.[7] The labels in the figure are the depletion width at the strong inversion (X_{dm}), the inversion layer charges controlled by gate (Q_b), the channel length (L), the groove-junction depth (X_{Gj}), the decrements of charges controlled by gate (ΔQ) and the spread length of depletion layer to inversion layer (X_c). As the channel area drops, the corners are formed on the interface between channel and drain or source. The electric fields of the channel near corners become distorted by the interaction between the horizontal electric field (controlled by drain) and the vertical electric field (controlled by gate).

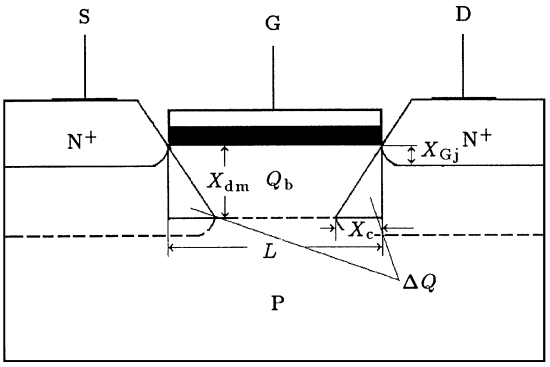


Fig.1. Cross-section of a grooved-gate nMOSFET.

The charges of the channel depletion are shared by the gate and the p–n junction of source-substrate or drain-substrate in the view of the charge sharing model. The decrements of charges controlled by gate may cause the shift of threshold voltage. It affects the device electrical characteristics, including threshold voltage V_{th}, linear region transconductance g_m, the subthreshold slope S and the saturation region current, etc. The $I_{ds} - V_{gs}$ relation of the device may remarkably decrease due to the channel damage caused by the stress.

The definition of threshold voltage V_{th} is the gate voltage needed to initiate the surface inversion:

$$V_{th} = V_{fb} + \phi_{Si} - \frac{Q_b(\phi_{Si})}{C_{ox}}, \qquad (1)$$

where V_{fb} is flat band voltage, ϕ_{Si} is surface potential, C_{ox} is gate capacitance, Q_b is gate depletion charge. From Fig.1 Q_b is the area of the rectangle under the gate, i.e.

$$Q_b = qN_bX_{dm}\left\{1 - \frac{X_{Gj}}{L}\left[\sqrt{1 + \frac{2X_{dm}}{X_{Gj}}} - 1\right]\right\}, \qquad (2)$$

where N_b is the doping concentration in the substrate. We can use F as the charge sharing factor which is defined as

$$F = 1 - \frac{X_{Gj}}{L}\left[\sqrt{1 + \frac{2X_{dm}}{X_{Gj}}} - 1\right], \qquad (3)$$

then we have

$$Q_b = qN_bX_{dm}LF. \qquad (4)$$

F represents the influence of the potential extension from the source and drain regions to the channel. The reduction of F represents the decrease of charges controlled by the gate, so the short-channel effects result. In long-channel devices, F is approximately equal to 1 owing to large L, i.e. little or nothing changes in Q_b, while in a conventional device F is less than 1 and decreases with decreasing L. The decrease of X_{Gj} means the formation of grooves and enhances F. The simulation of the variation F with X_{Gj} shows that the maximum of F is obtained at X_{Gj}=0, as shown in Fig.2. Therefore, compared with planar-structured devices, grooved-gate structures will restrain the short-channel effects, and this tendency will enhance with the junction depth going to zero. X_{Gj} is determined by the doping density. Thus, all the parameters that we discuss here are correlative.

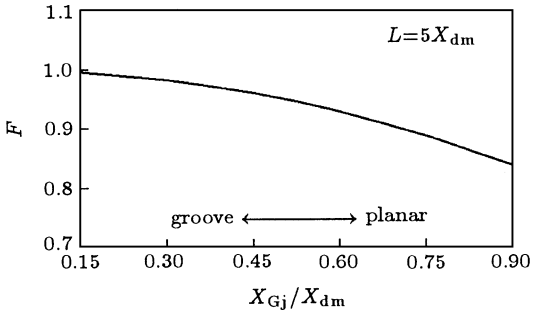


Fig.2. Simulations of the relation of F with X_{Gj}.

The two-dimensional (2D) device simulators are necessary for accurate simulation of grooved-gate structures. PISCES-II can simulate the port properties and the internal physical quantity profile of a MOSFET as a classical 2D device simulator. The properties of grooved-gate nMOSFETs with different corner angles, such as the electric fields, currents and threshold voltages, are compared with those of the planar structure.

The following parameters for the simulated grooved-gate nMOSFET are chosen in the simulation: the channel length L ranges from 0.03 to 0.9 μm, the $X_{\rm Gj}$ value lies between 0.03 and –0.015μm, the $N_{\rm sub}$ and $N_{\rm channel}$ are 5.0×10^{16} cm^{-3} and 5.0×10^{18}cm^{-3} respectively, the gate oxide thickness $t_{\rm ox}$ is 4 nm and the maximum doping concentration at the surface $N_{\rm SD}$ is 5.0×10^{18}cm^{-3} in the source/drain region.

3. Results and discussion

The simulation results of the grooved-gate nMOSFET comprise the potential contours in the channel, the substrate currents, the threshold voltages, the subthreshold currents and subthreshold slopes, as well as the drain currents. The change of threshold voltages and the subthreshold characters comes from the short channel effect. Therefore, the simulation results can be used to optimize the structural parameters of the grooved-gate nMOSFET.

3.1. The simulations of electric potential contours

Figure 3 shows the 2D simulations of potential contours in a grooved-gate nMOSFET. The potential barrier is observed at the concave corners. The punch-through in the conventional MOSFET is found to be caused by the effect of the drain potential approaching the source potential, and the corner of grooved-gate at the drain limits the extension of the drain potential. The threshold voltage of the grooved-gate MOSFET is higher than that of the planar MOSFET. The potential barrier profile at the concave corner alters with the corner angle, the groove-junction depth and the doping concentration.

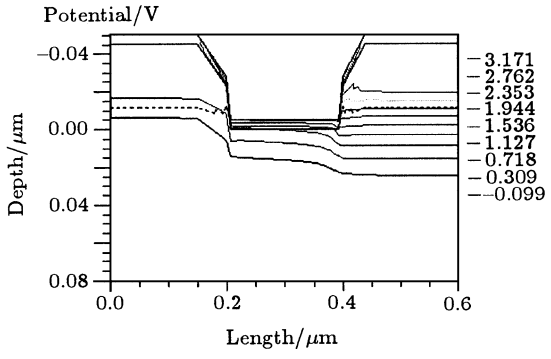


Fig.3. The 2D simulations of potential contours in a grooved-gate and planar nMOSFET.

3.2. The simulations of threshold voltages

$V_{\rm th}$ is defined as the gate voltage ($V_{\rm gs}$) at the drain current ($I_{\rm ds}$) of (W/L) 10^{-7} A. It is expected that this technique yields very precise evaluations of $V_{\rm th}$ in MOSFET. We have simulated the threshold voltages controlled by the groove-junction depth $X_{\rm Gj}$. When $X_{\rm Gj}$ changes from 0.03 to –0.015μm, i.e. from a planar gate device to a grooved-gate device, the $V_{\rm th}$ of the simulated device rises from 0.58 to 0.7V. The curve of $V_{\rm th} - X_{\rm Gj}$ is shown in Fig.4 with the channel length L being 0.15μm. The smaller the $X_{\rm Gj}$, the larger the $V_{\rm th}$. When L changes from 0.9 to 0.03μm, the $V_{\rm th}$ of the planar device ($X_{\rm Gj}$=0.03μm) drops rapidly and the variation of $V_{\rm th}$ of the grooved-gate device ($X_{\rm Gj}$=–0.015μm) is basically a smooth line, as shown in $V_{\rm th} - L$ of Fig.4. This indicates that the threshold voltage variation with L in a grooved-gate MOSFET is much less than that in a planar structured MOSFET. In other words, the grooved-gate is more immune to the short-channel-induced threshold voltage degradation.

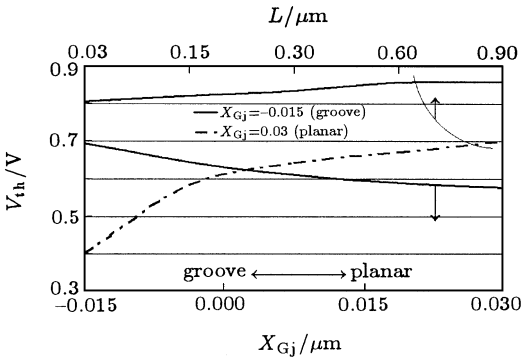


Fig.4. Simulations of the threshold voltages for the device as a function of the groove-junction depth.

It is a consistent tendency that the threshold voltage increases with the increase of doping concentration of both channel and substrate. High substrate doping concentration can shorten the groove-junction depth ($X_{\rm Gj}$) and high channel doping concentration can increase the channel charge density directly. The impact of the latter is stronger than that of the former. Figure 5 shows the simulations of the variation of threshold voltage with doping concentration. For the curve of $V_{\rm th} - N_{\rm sub}$, the values of $N_{\rm channel}$, $X_{\rm Gj}$ and L are respectively 5.0×10^{16}cm^{-3}, –0.015μm and 0.15μm. For the curve of $V_{\rm th} - N_{\rm channel}$, the values of $N_{\rm sub}$, $X_{\rm Gj}$ and L are respectively 5.0×10^{16}cm^{-3}, –0.015μm and 0.15μm.

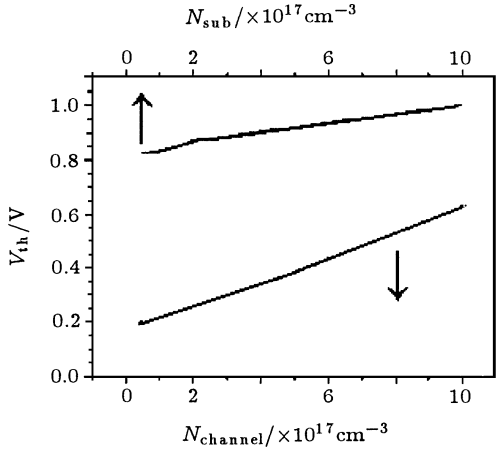


Fig.5. Simulations of the variation of threshold voltages with doping concentrations.

3.3. The simulations of subthreshold characteristics

The minimum surface potential occurs at the concave corner of the groove-gate. It reflects the degradation of subthreshold characteristics in a groove-gate MOSFET.

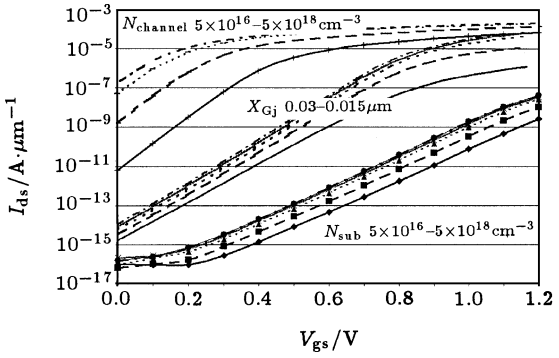


Fig.6. Simulations of the variation of subthreshold characteristics with doping concentrations and groove-junction depths.

Figure 6 shows the simulations of subthreshold characteristics of the grooved-gate nMOSFET. The basic structural parameters in each group of curves are $N_{channel}$=$5.0\times10^{16}cm^{-3}$, N_{sub}=$5.0\times10^{16}cm^{-3}$, X_{Gj}=–0.015μm and L=0.15μm. The three groups of curves are the results of the simulations with various parameter values including channel doping concentration, groove-junction depth and substrate doping concentration respectively. Threshold voltages increase with the increase of doping concentration and the decrease of groove-junction depth. The subthreshold slope S is nearly unchanged with the change of groove-junction depth and substrate doping, which means that the effects of these variations are the same or similar. In fact, the groove-junction depth can be determined by substrate doping concentration. Channel doping concentration can strongly affect the changes of both threshold voltage and subthreshold slope, so the effect of channel doping concentration on a MOSFET is the largest.

3.4. The simulations of drain characteristics

Drain output characteristics can represent the stress effect on the drain-driving of a MOSFET and the channel charge modulated by the drain voltage.

Figure 7 shows the simulations of drain currents versus doping concentration and groove-junction depth for the applied bias of V_{gs}=1.0V and V_{ds}= 0.1V. Other structural parameters are $N_{channel}$= $5.0\times10^{16}cm^{-3}$, N_{sub}=$5.0\times10^{16}cm^{-3}$, X_{Gj}=–0.015μm and L=0.15μm. In the curve of I_{ds} – X_{Gj}, the drain currents decreases as the groove-junction depth decreases from 0.03 to –0.01μm, and then increases remarkably. There exists a critical junction depth. Under the normal condition the drain-driving is weakened as the groove-junction depth decreases. Beyond this scope the MOSFET is noneffective.

The variation of drain currents with doping concentration is smaller than that of groove-junction depth. The drain currents are nearly unchanged as the doping concentration decreases from 5×10^{16} to $5\times10^{17}cm^{-3}$ both in the substrate and channel. When the doping concentration increases, the drain current will decrease because the transconductance of the channel becomes lower. The variation of the drain current with the channel doping concentration is larger than that with the substrate doping concentration. This indicates that the influence of channel doping is larger than that of substrate doping.

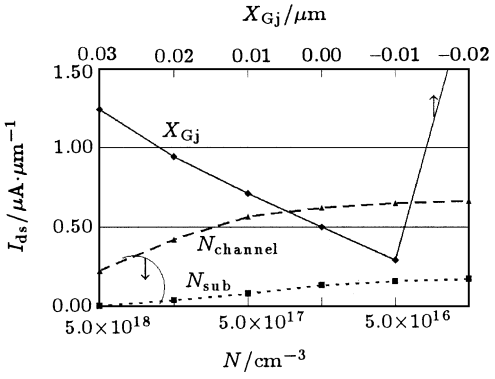


Fig.7. Simulations of drain-current characteristics of the grooved-gate device.

4. Conclusion

Short-channel effects in the grooved-gate nMOSFET have been studied by simulation of the effects of geometric structural parameters, including groove-junction depth, substrate doping concentration and channel doping concentration, using PISCES-II. The short-channel effect immunity of the grooved-gate MOSFET is better than that of the planar MOSFET, and can be affected by the geometric structural parameters significantly.

Zero or negative groove-junction depth can improve the threshold characters of MOSFET expediently, but there exists a limited range. Doping concentrations of both substrate and channel can adjust the channel parameters. The increase of doping concentration enhances the restrain ability to short channel effects and lowers the transconductance. These results may help to improve the grooved-gate MOSFET structure for the next technology nodes.

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