Physics-based compact model for the Surrounding-Gate MOSFET

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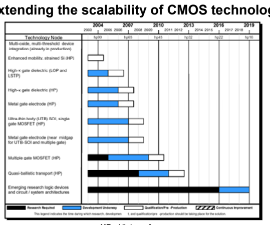
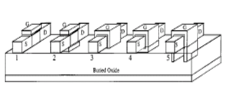
Abstract:- **We present a continuous analytic current-voltage model for cylindrical undoped (lightly doped) surrounding-gate (SGT) MOSFETs. It is based on the exact solution of the Poisson's equation, and the current continuity equation without the charge-sheet approximation, allowing the inversion charge distribution in the silicon film to be adequately described. It is valid for all the operation regions (linear, saturation, subthreshold) and traces the transition between them without fitting-parameters, being ideal for the kernel of SGT-MOSFETs compact models. We have demonstrated that the current-voltage characteristics obtained by this model agree with three-dimensional numerical simulations for all ranges of gate and drain voltages.**

Extending the scalability of CMOS technology



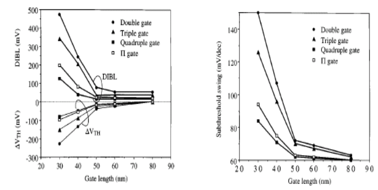
HP= High performance
LOP=Low operating power
LSTP=Low stand-by power

Multiple-gate MOSFETs



Gate configurations for SOI devices

1 single gate
2 double gate (DG)
3 triple gate
4 quadruple gate: Gate-all-around (GAA) + Surrounding-gate transistor (SGT)
5 pi-gate



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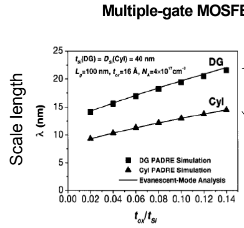
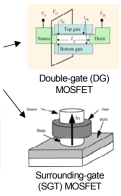
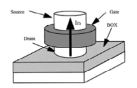
Multiple-gate MOSFETs





The Surrounding-gate (SGT) MOSFET



Excellent device for continuing scalability of the CMOS technology

Advantages

- Maximum control of Short-Channel Effects ⇒ best scaling potential
- Higher channel mobility than the bulk-MOSFET

Problems to be solved

- Difficult to fabricate
- Threshold voltage control difficult by conventional means: gate electrode workfunction engineering

Physics-based model for the SGT-MOSFET

1D Poisson's equation for undoped/lightly doped channels

$$\frac{d^2\psi}{dr^2}+\frac{1}{r}\frac{d\psi}{dr}=\frac{qn_i}{\varepsilon_{Si}}e^{\frac{q(\psi-V)}{kT}}$$

(Mobile charge)

Boundary conditions:

Symmetry	$\frac{d\psi}{dr}(r=0)=0$
Surface potential	$\psi(r=R)=\psi_s$

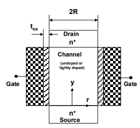
Gradual channel approximation: V=V(y)

Potential	$\psi(r)=V+\frac{kT}{q}\ln\left(\frac{-8B}{\frac{q\eta}{\varepsilon_{Si}}\left(1+Br^2\right)^2}\right)$ (1)

B is a constant related with the surface potential

From **Gauss's law** the following relation must hold:

$$C_{ox}(V_{GS}-\Delta\varphi-\psi_s)=\varepsilon_{Si}\left.\frac{d\psi}{dr}\right|_{r=R}=Q \quad (2)$$



Substituting the analytical solution for the potential (1) into (2) yields:

$$\frac{q(V_{GS}-\Delta\varphi-V)}{kT}-\ln\left(\frac{8}{\delta R^2}\right)=\ln(1-\beta)-\ln\beta^2+\eta\left(\frac{1-\beta}{\beta}\right) \quad (3)$$

where $\beta\equiv 1+BR^2$ is a constant (of *r*) to be determined from (3), and $\eta=4\varepsilon_{Si}/C_{ox}R$ is a structural parameter.

For a given V_{GS}, β can be solved from (3) as a function of *V*.

V(*y*) and β(*y*) is determined by the **current continuity equation**, which requires the (drift-diffussion) current $I_{DS}=\mu(2\pi R)Q\,dV/dy$=constant, independent of *V* or *y*.

Integrating $I_{DS}dy$ from the source to the drain, the current can be written as:

$$I_{DS}=\mu\frac{2\pi R}{L}\int_0^{V_{DS}}Q(V)dV=\mu\frac{2\pi R}{L}\int_{\beta_S}^{\beta_D}Q(\beta)\frac{dV}{d\beta}d\beta \quad (4)$$

where β_S, β_D are solutions to (3) corresponding to V=0 and V=V_{DS} respectively.

By using (1) and replacing it into $Q/\varepsilon_{Si}=d\psi(R)/dr$: $Q(\beta)=(2\varepsilon_{Si})(2kT/q)(1/\beta R)(1-\beta)$. Note that $dV/d\beta$ can also be expressed as a function of β by differentiating (3).

Substituting these factors in (4), integration can be performed analytically to yield:

$$I_{DS}=\mu\frac{4\pi\varepsilon_{Si}}{L}\left(\frac{2kT}{q}\right)^2\left[\frac{\eta}{4\beta^2}+\frac{1-\eta/2}{\beta}+\frac{1}{2}\ln\beta\right]_{\beta_D}^{\beta_S} \quad (5)$$

To compute I_{DS} we define the following two functions representing the RHS of (3) and (5):

$$f(\beta)=\ln(1-\beta)-\ln\beta^2+\eta\left(\frac{1-\beta}{\beta}\right) \quad (6)$$

$$g(\beta)=\frac{\eta}{4\beta^2}+\frac{1-\eta/2}{\beta}+\frac{1}{2}\ln\beta \quad (7)$$

Note that the range of β is 0<β<1

For given V_{GS} and V_{DS} ⇒ β_S and β_D are calculated from the conditions $f(\beta_S)=(q/kT)(V_{GS}-V_0)$ and $f(\beta_D)=(q/kT)(V_{GS}-V_0-V_{DS})$

where

$$V_0=\Delta\varphi+\frac{kT}{q}\ln\left(\frac{8}{\delta R^2}\right) \quad (8)$$

From (7), the drain current $I_{DS}\propto g(\beta_S)-g(\beta_D)$ can be easily computed

Operation regions

1) *Linear region above threshold*: $f(\beta_S)$, $f(\beta_D)$>>1, so β_S, β_D ~0.

$$I_{DS}=2\mu C_{ox}\frac{\pi R}{L}\left(V_{GS}-V_t-\frac{V_{DS}}{2}\right)V_{DS}$$

where $V_t=V_0-\eta(kT/q)$ is the **threshold voltage**. V_t shifts more than 120 mV per decade of variation on R (at room temperature), being this shift more important for higher t_{ox}/R ratios.

2) *Saturation region*: $f(\beta_S)$>>1 and $f(\beta_D)$<<-1, so β_S~0 and β_D~1.

$$I_{DS}=\mu C_{ox}\frac{\pi R}{L}\left\{(V_{GS}-V_t)^2-\left(\frac{kT}{q}\right)^2\left[\frac{\eta^2}{\left(1-e^{\frac{q(V_{GS}-V_0-V_{DS})}{kT}}\right)^2}+\frac{4\eta(1-\eta/2)}{\left(1-e^{\frac{q(V_{GS}-V_0-V_{DS})}{kT}}\right)}\right]\right\}$$

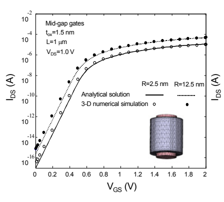
The saturation current depends on $(V_{GS}-V_t)^2$, as expected for a MOSFET

3) *Subthreshold region*: $f(\beta_S)$, $f(\beta_D)$<<-1, so β_S, β_D~1.

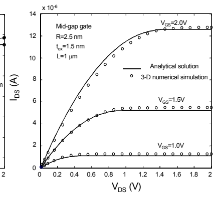
$$I_{DS}=\mu\frac{\pi R^2}{L}n_i kT e^{\frac{q(V_{GS}-\Delta\varphi)}{kT}}\left(1-e^{\frac{-qV_{DS}}{kT}}\right)$$

The subthreshold current is proportional to the cross-sectional area of the SGT-MOSFET and independent of t_{ox}. This is a characteristic of the **volume inversion** phenomenom that cannot be captured by standard charge-sheet based models.

Model validation



Transfer characteristics obtained from the analytical model compared with numerical simulations from DESSIS-ISE®.



Output characteristics obtained from the analytical model compared with numerical simulations from DESSIS-ISE®.

Conclusions

We have presented a simple analytical I-V model suitable for compact modeling of undoped (lightly doped) SGT-MOSFETs. All the regions of operation and the transitions are correctly described by preserving the physics. In particular, the **volume inversion**, that cannot be captured by using the charge-sheet approximation, is well accounted for in this model.

The presented **long-channel model** is ideally suited for being the kernel of a SGT-MOSFET compact model. In order to complete the model, SCE, quantum effects, low and high field transport, noise, and more, should be added.

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