Transition point consideration for velocity saturating four-terminal DG MOSFET compact model

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1. Introduction: recent topics on DG MOSFETs
2. Modeling: basic equations and carrier velocity saturation
3. Current saturation: modeling of pinch-off
4. Diffusion saturation: formulation and result
5. Summary:

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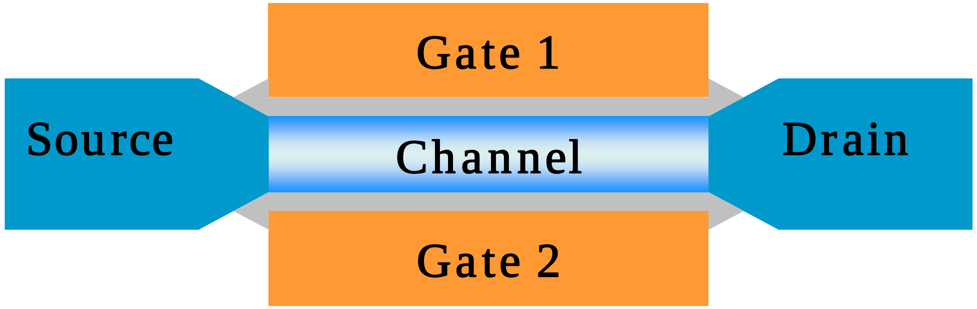
DG MOSFET



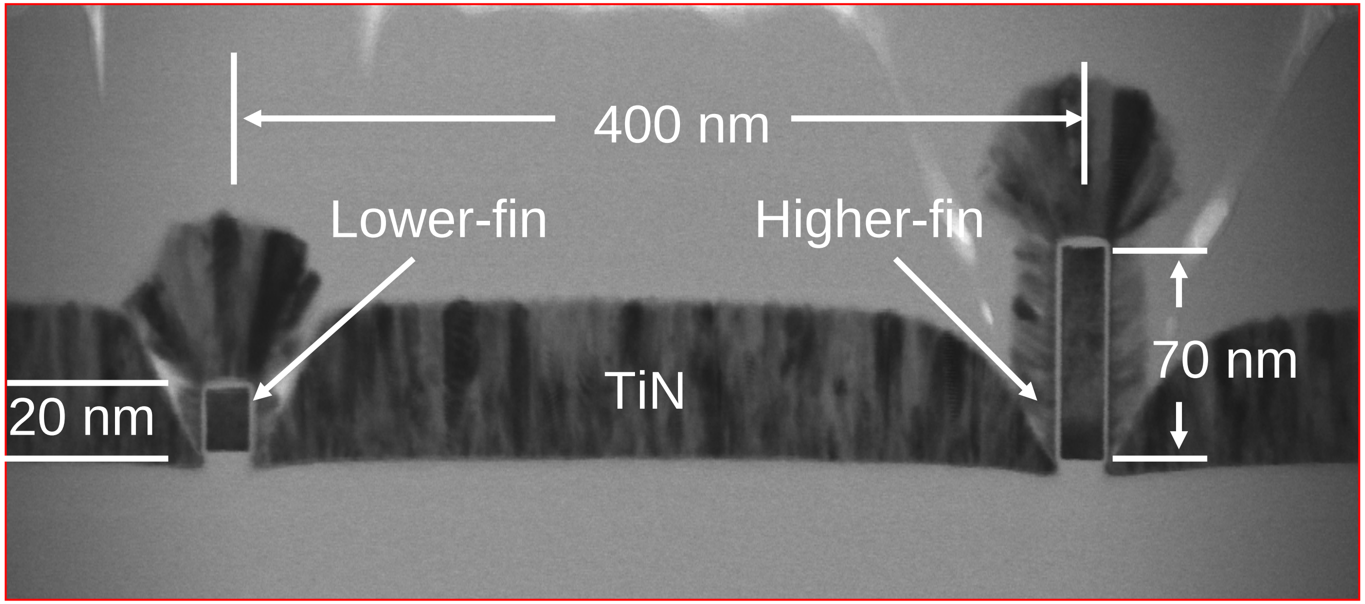
As ITRS2005 stated, DG MOSFETs are not emerging devices;
- they are now on the road.

Many obstacles that prevent DG MOSFETs from production, are now being removed, one by one.

AIST work 1:

Two height coexisting FinFETs

Different Si-fin heights on the same wafer has been confirmed.
That facilitates an easy way to make balanced CMOS circuits.

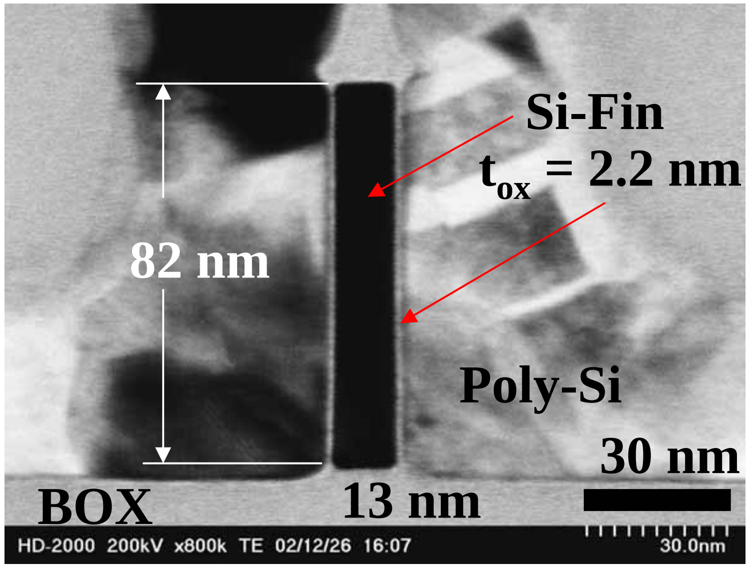


X. Y. Liu et al., Techn. Digest IEDM 2006, pp. 989(2006)

AIST work 2:

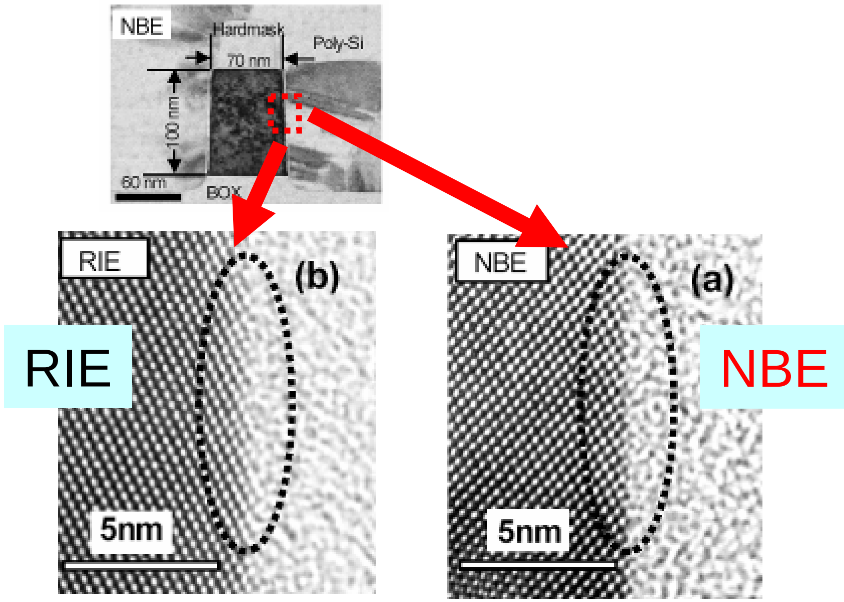
Smooth Si/SiO_2 interface

Orientation dependent wet etching gives atomically flat surface with no resist striation.



X. Y. Liu et al., Techn. Digest IEDM 2003, pp. 986(2003)

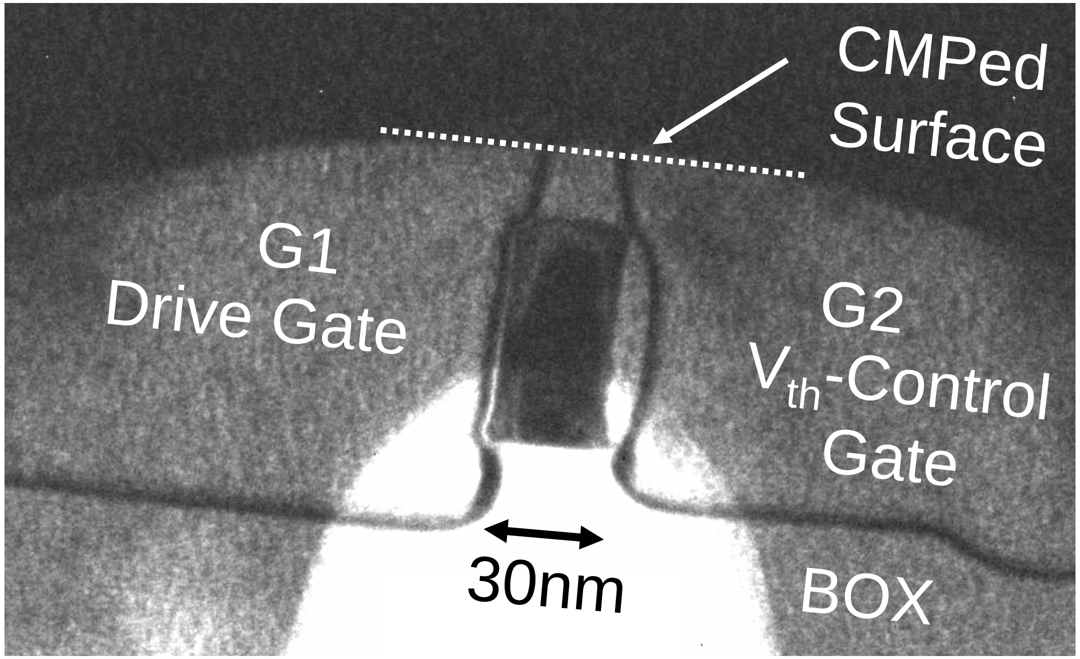
Neutral beam etching (NBE) achieved smooth Si/SiO_2 interface, with no orientation restriction.



K. Endo et al., Techn. Digest IEDM 2005, pp. 859(2005)

IMEC / NXP / AIST work:

Asymmetric-T_{ox} 4T-FinFET



M. Masahara et al., Proc. 2006 IEEE Intern. SOI Conf., pp. 165(2006)

Transport modeling summary

1. Double charge-sheet model
2. Source-end charge calculated by 1-D Poisson equation
3. Gradual channel approximation
4. No current mixing between two charge-sheets
5. Proportional charge profile for the other charge-sheet

Transport of two charge sheets are then solved independently.

Transport equation for one charge-sheet

$$I_i = q\left(\mu_i q \left(\frac{1}{C_{ii}} + \frac{n_j(0)/n_i(0)}{C_{ij}} \right) \frac{\partial n_i(y)}{\partial y} n_i(y) + D_i \frac{\partial n_i(y)}{\partial y} \right)$$

$$C_{11} = C_{\mathrm{OX1}} + \left(C_{\mathrm{Si}}{}^{-1} + C_{\mathrm{OX2}}{}^{-1} \right)^{-1}$$

$$C_{22} = \left(C_{\mathrm{OX1}}{}^{-1} + C_{\mathrm{Si}}{}^{-1} \right)^{-1} + C_{\mathrm{OX2}}$$

$$C_{12} = C_{\mathrm{OX1}} + C_{\mathrm{OX2}} + C_{\mathrm{OX1}} C_{\mathrm{OX2}} C_{\mathrm{Si}}^{-1}$$

Mobility modeling summary

Bulk mobility
μ_0

→

Surface mobility μ

$$\mu^{-1} = \mu_0^{-1} + \mu_{PH}^{-1} + \mu_{SR}^{-1}$$

$$\mu_{PH} = A_{PH} \times 3.5 \times 10^4 \times E_\perp^{-1/3}$$

$$\mu_{SR} = A_{SR} \times 8 \times 10^{14} \left(E_\perp + kT/qT_{Si}\right)^{-2}$$

A_{PH}, A_{SR}: Fitting parameters

→

Velocity saturation

$$\mu \rightarrow \mu \frac{1}{\sqrt{1 + \left|\frac{E}{E_c}\right|^2}}$$

Transport equation

$$-q\mu\left(\frac{q}{C}\frac{dn}{dy}n + \frac{kT}{q}\frac{dn}{dy}\right) = I_i$$

+

Velocity saturation

$$\mu \rightarrow \mu\left(1 + \left|\frac{E}{E_c}\right|^2\right)^{-1/2}$$

=

Transport equation with velocity saturation

$$-q\mu\left(\frac{q}{C}\frac{dn}{dy}n + \frac{kT}{q}\frac{dn}{dy}\right) = I_i\left(1 + \left|\frac{E}{E_c}\right|^2\right)^{1/2}$$

Transition point: definition

The drain potential permeates into the channel. Its profile is exponential:

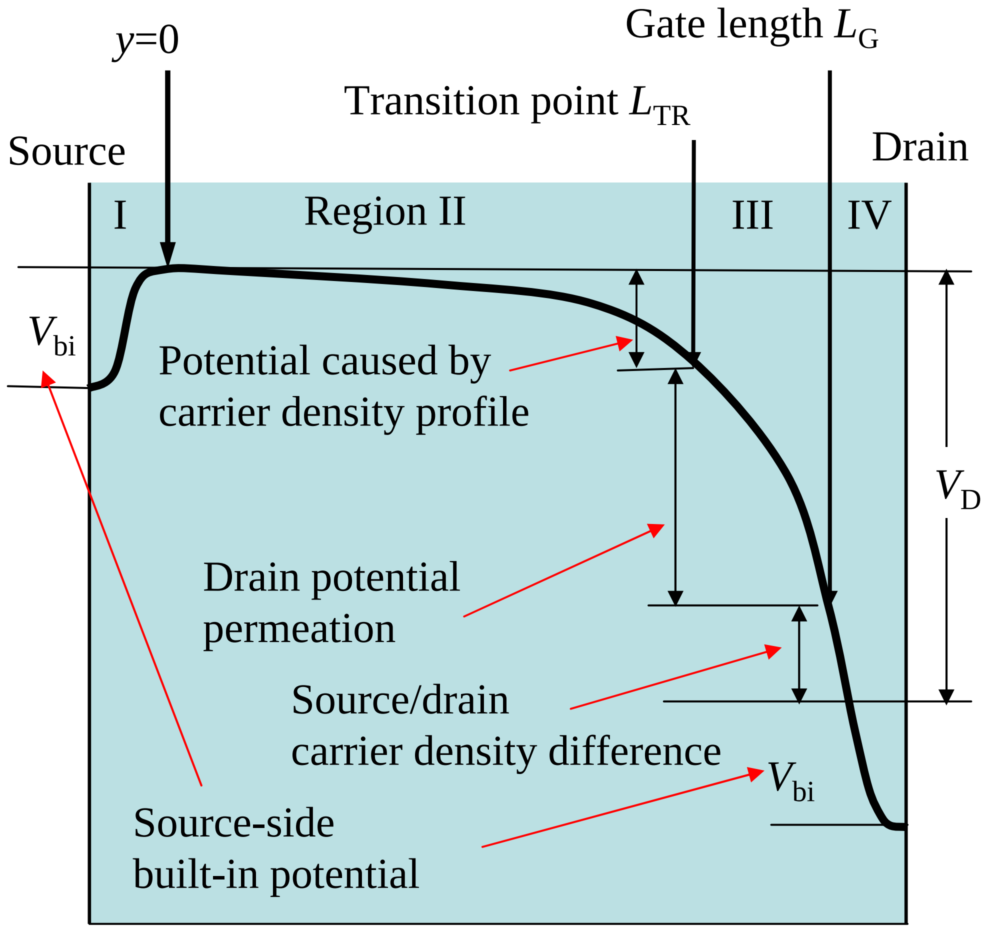
$$\psi_{drain} = \psi_0 \exp((y - L_G)/\lambda)$$

At the point where the drain electric field becomes dominant, we assume the condition for the carrier profile

$$\frac{d^2 n}{dy^2} \bigg/ \frac{dn}{dy} = \frac{1}{\lambda}$$

This condition guarantees most smooth transition across the point. We call the point 'transition point.' L is the endpoint of the model, and is not necessarily the gate length.

Potential profile in a charge-sheet



Transition point: calculation

Determine the carrier density at the transition point using: $\frac{d^2n}{dy^2} \Big/ \frac{dn}{dy} = \frac{1}{\lambda}$

If the carrier density is too small or negative, replace it to: $n = \frac{I_D}{qv_{sat}}$

This replacement is necessary because unphysical negative carrier density occurs when drain current is low enough.

Calculate the transition point L_{TR} using the integral of the transport equation.

If the L_{TR} is outside of the channel, recalculate drain-end carrier density.

When the transistor is ON, L_{TR} is usually outside of the cannel even former calculated carrier density at L_{TR} is negative, and the replacement does not affect the result. But in sub-threshold region, the replacement causes anomaly in drain current,

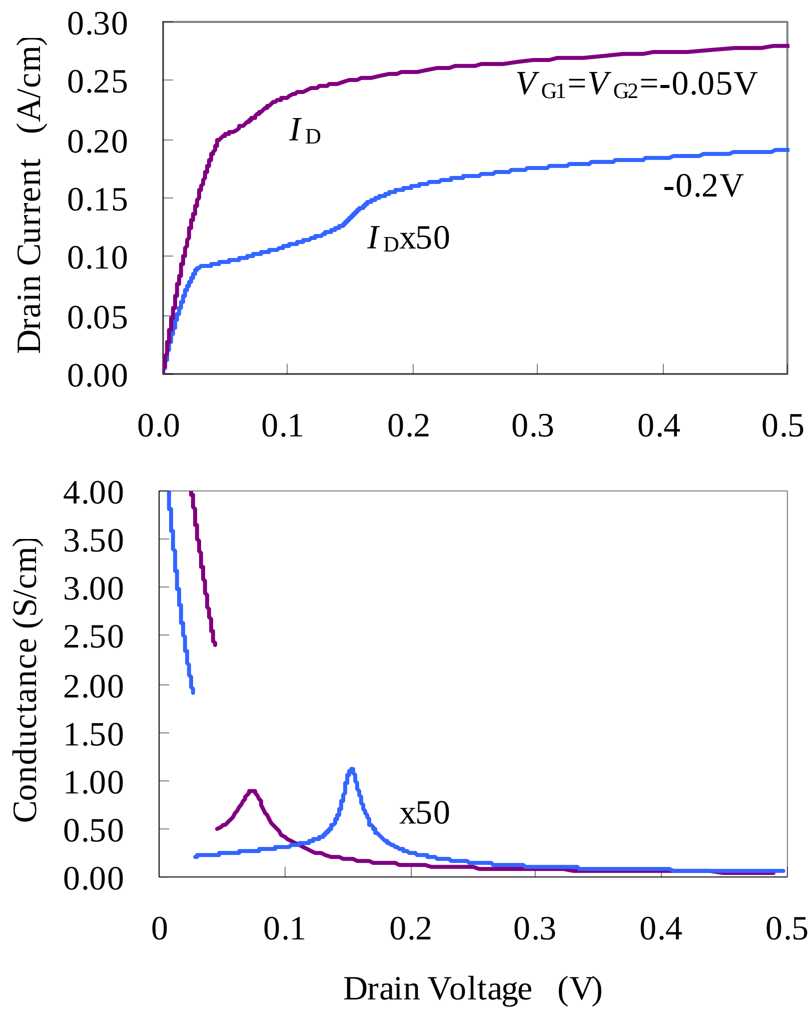
Anomaly in subthreshold region

Distinct kink is observed. It becomes more eminent for lower gate voltages.

The cause of this anomaly comes from the improper definition for the transition point. But another cause is the fact that the diffusion current

$$I_D\Big|_{n=0} = -qD\frac{dn}{dy}\Big|_{n=0} \neq 0$$

becomes nonzero even carrier density is zero.



Redefinition of transition point

Conventional approach → New approach

	Conventional approach		New approach
Smoothness target :	surface electrical potential	→	quasi-Fermi level
Transition point definition:	$\left(\frac{\partial^2 \psi_S}{\partial y^2}\right) \Big/ \left(\frac{\partial \psi_S}{\partial y}\right) = \frac{1}{\lambda}$	→	$\left(\frac{\partial^2 \psi_f}{\partial y^2}\right) \Big/ \left(\frac{\partial \psi_f}{\partial y}\right) = \frac{1}{\lambda}$
Transition point expression:	$1 = \frac{\lambda \beta E_c n_{aL} n_b}{\left(n_{aL}^2 - n_b^2\right)^{3/2}}$	→	$1 = \frac{\lambda \beta E_c n_b \left(n_{aL}^3 - n_b^2\right)}{n_{aL}\left(n_{aL} - 1\right)\left(n_{aL}^2 - n_b^2\right)^{3/2}}$
In subthreshold and $I_D \to 0$:	carriers at L_{TR} becomes negative	→	carriers at L_{TR} tends to $\lambda \beta E_c n_b$

$$n_{aL} = n_a(L_{TR})$$
$$n_{a0} = n_a(0)$$
$$n_a = \frac{n}{n_{th}} + 1$$
$$n_b = \frac{I_D}{q\mu E_C} \frac{1}{n_{th}}$$
$$n_{th} = \frac{CkT}{q^2}$$

In the new approach, carrier densities always stay positive.

Subthreshold current with revised L_{TR}

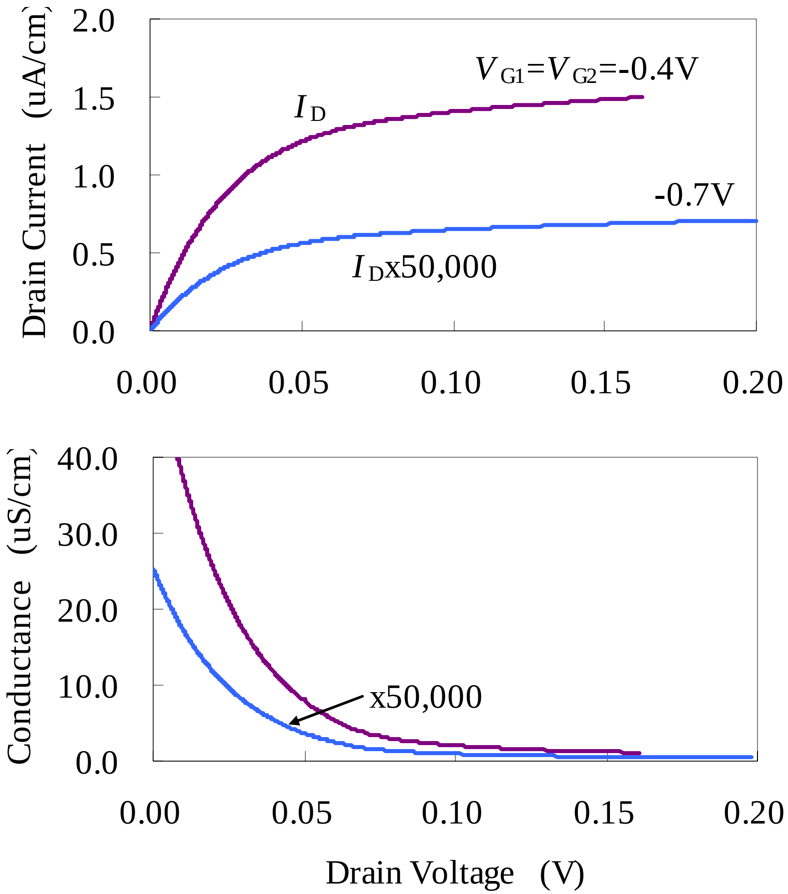
Based on the new approach for transition point determination, no kink is observed.

Still unphysical behavior of the transport equation, i. e.

$$I_D\Big|_{n=0} = -qD\frac{dn}{dy}\Big|_{n=0} \neq 0$$

remains: it is only outside of the modeling coverage.

To eliminate this behavior, diffusion saturation independent of electric field is necessary.



Revisiting diffusion saturation

Two possible formulations for the diffusion saturation

Diffusion saturation is caused by the electric field
-- the formula used the above transport equation

$$I_{\text{diff}} = q\beta n D_0 \frac{1}{\sqrt{1+\left|E/E_{\text{c}}\right|^2}} E$$

Diffusion saturation is caused by the carrier density gradient

$$I_{\text{diff}} = q\beta n D_0 \frac{1}{\sqrt{1+\left(\frac{1}{\beta E_{\text{c}}}\frac{1}{n}\frac{dn}{dy}\right)^2}} E$$

When carrier population is in equilibrium, these two are equivalent.
In non-equilibrium condition, these two do not match each other.
The latter formulation gives decent diffusion current when carrier density gradient becomes large, removing unphysical large diffusion current.

$$\text{when } \left|\frac{dn}{dy}\right| \to \infty, \qquad I \approx \operatorname{sgn}\left(\frac{dn}{dy}\right) q\mu_0 E_{\text{C}} n = \operatorname{sgn}\left(\frac{dn}{dy}\right) q v_{\text{sat}} n$$

New transport equation

With new diffusion saturation:
-- too complex to solve

$$-q\mu\left(\left(1+\left|\frac{E}{E_c}\right|^2\right)^{-1/2}\frac{q}{C}\frac{dn}{dy}n+\left(1+\left(\frac{1}{\beta E_c}\frac{1}{n}\frac{dn}{dy}\right)^2\right)^{-1/2}\frac{kT}{q}\frac{dn}{dy}\right)=I_i$$

An alternate approximate formula:
-- integration possible

$$-q\mu\left(1+\left(\frac{q\beta n}{C}+1\right)^2\left(\frac{1}{\beta E_c n}\frac{dn}{dy}\right)^2\right)^{-1/2}\left(\frac{q}{C}\frac{dn}{dy}n+\frac{kT}{q}\frac{dn}{dy}\right)=I_i$$

Drift-only limit:

when $n\to\infty$, $$-q\mu\left(1+\left(\frac{E}{E_c}\right)^2\right)^{-1/2}\frac{q}{C}\frac{dn}{dy}n=I_i \qquad \left(E=\frac{q}{C}\frac{dn}{dy}\right)$$

Diffusion-only limit:

when $n\to 0$, $$-q\mu\left(1+\left(\frac{1}{\beta E_c n}\frac{dn}{dy}\right)^2\right)^{-1/2}\frac{kT}{q}\frac{dn}{dy}=I_i$$

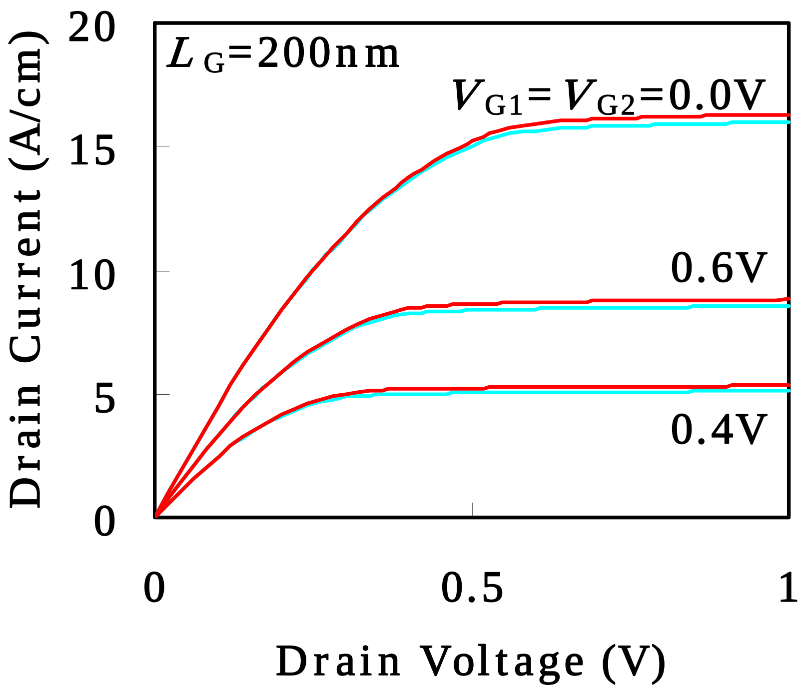
This is equivalent to the replacement in the conventional transport equation: $E\equiv\frac{d\psi_S}{dy}\to\frac{d\psi_f}{dy}$

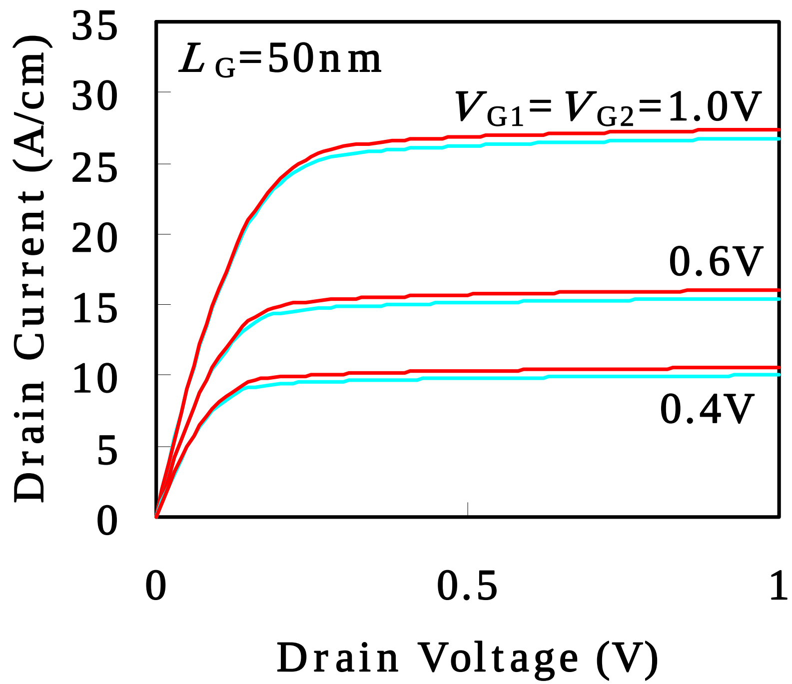
ON-state current

Same mobility parameters.

$T_{OX1} = T_{OX2} = 2nm$, $T_{Si} = 5nm$

Transport equation: old / new





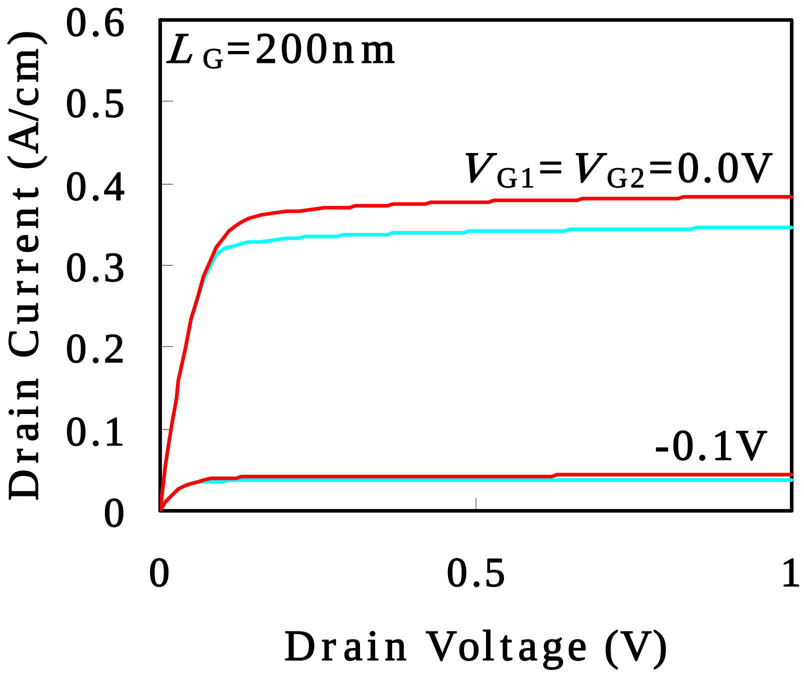
New transport equation gives similar results for long and short channel, as far as the transistor is ON state.

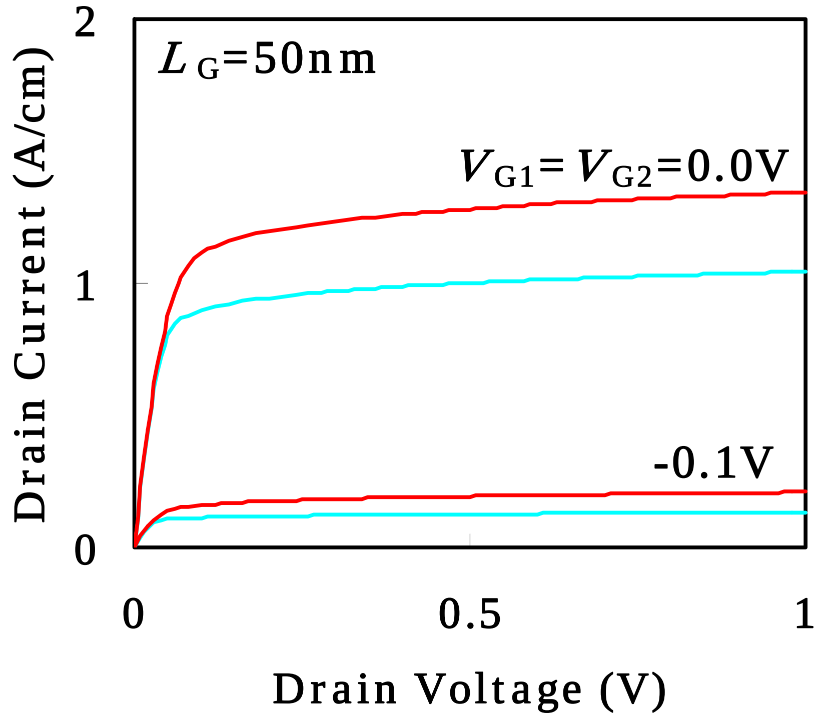
Near-threshold current

Same mobility parameters.

$T_{OX1} = T_{OX2} = 2\text{nm}, \ T_{Si} = 5\text{nm}$

Transport equation: old (red), new (cyan)





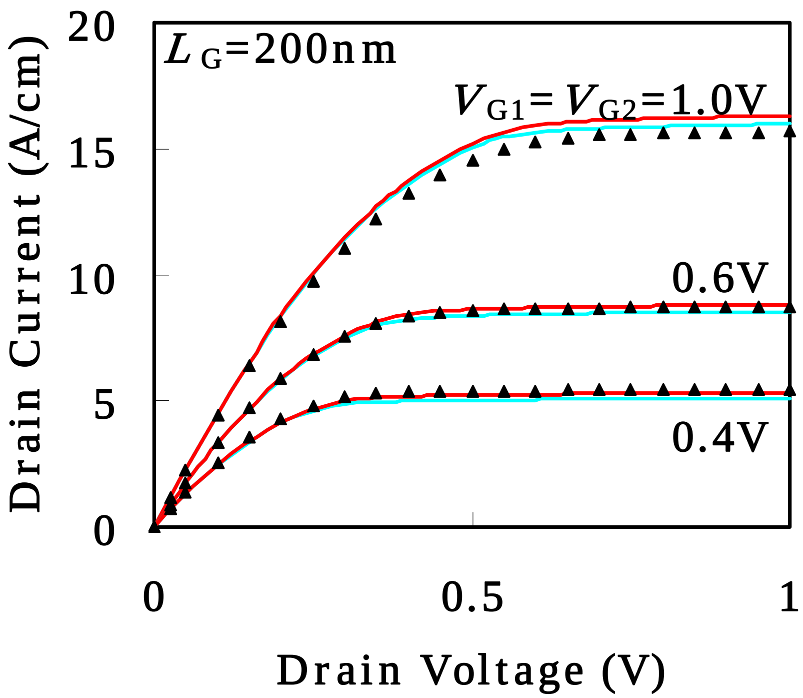
New transport equation gives lower values near threshold voltage, in particular, for short channel devices.

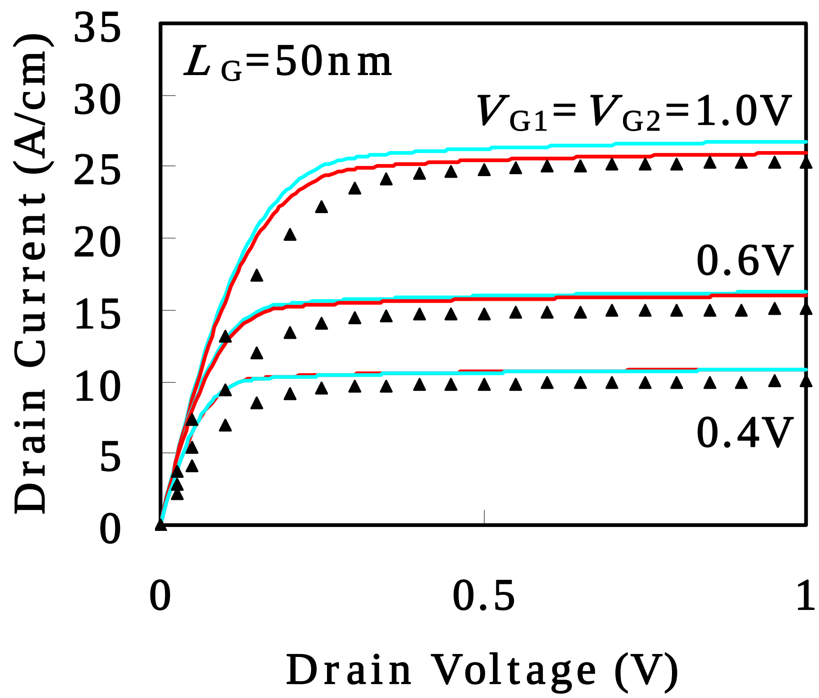
Comparison with device simulator

Mobility parameters tuned independently .

Transport equation: old / new

T_{OX1}= T_{OX2}= 2nm, T_{Si}= 5nm





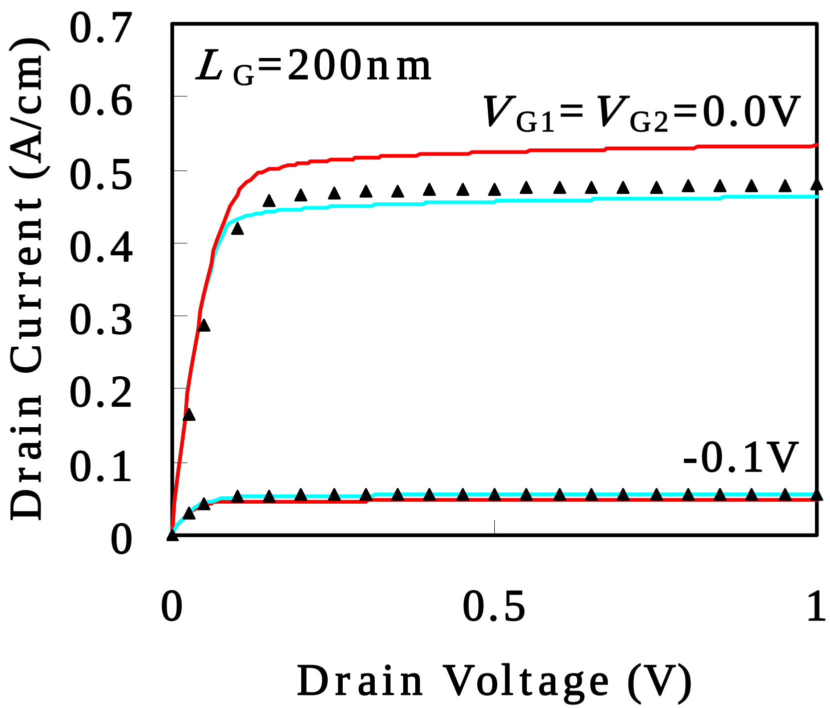
Both are in good agreement with ATLAS results, except too sharp transition from linear to saturation region, in particular, for a short channel device.

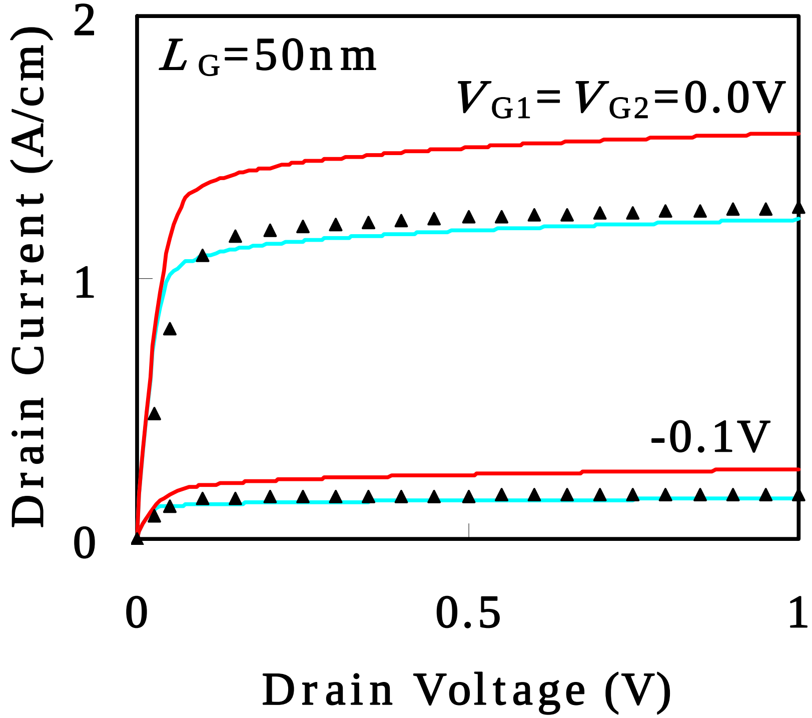
Comparison with device simulator

Mobility parameters tuned independently .

$T_{OX1} = T_{OX2} = 2\text{nm}, \ T_{Si} = 5\text{nm}$

Transport equation: old / new

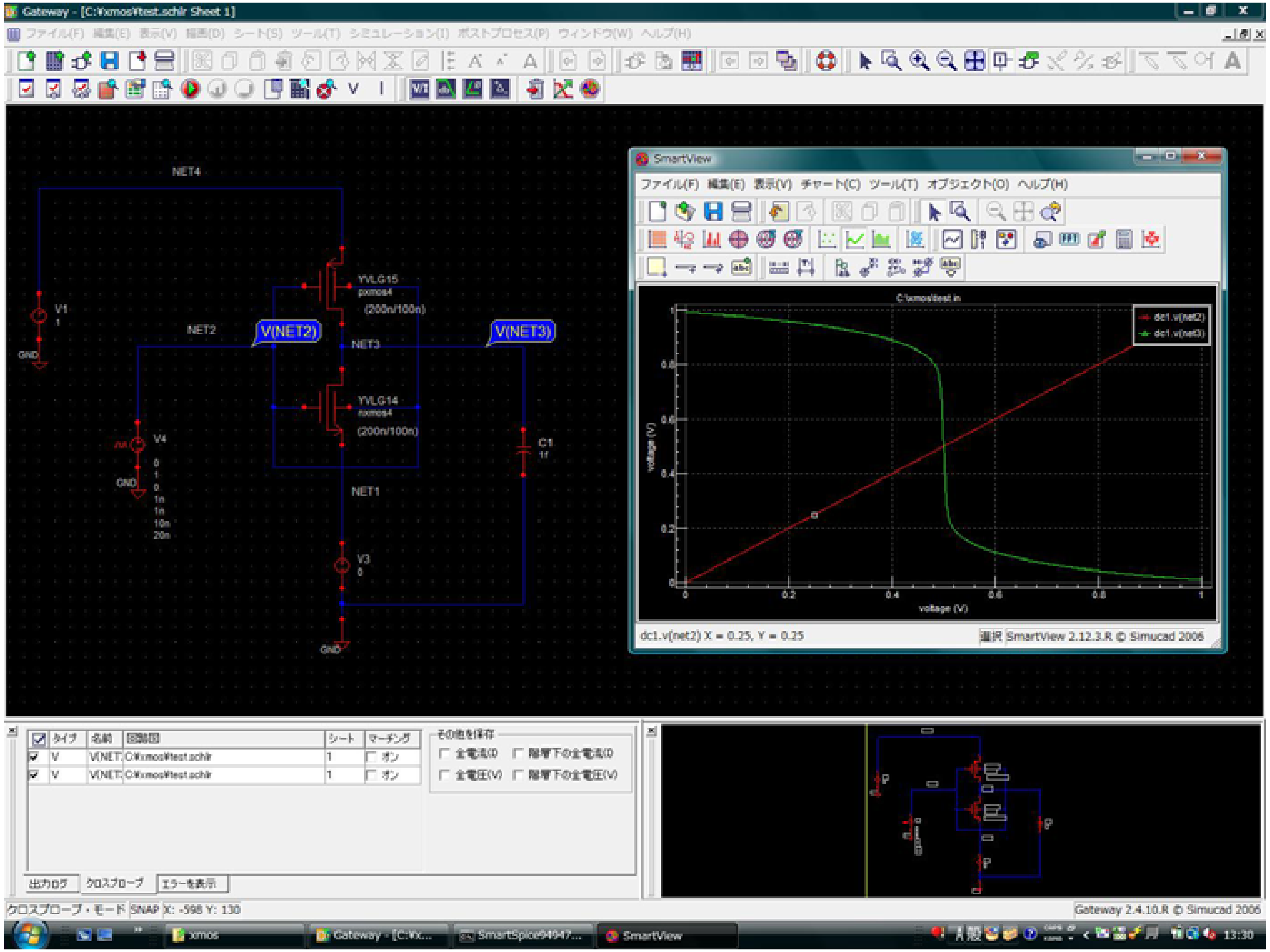




New transport equation is apparently better, but too sharp transition from linear to saturation region, becomes more prominent.

written in Verilog-A

Editing
Cicuit
And
Simulating
it.



Summary

The equation to determine the transition point has been discussed.

It was found that the smooth connection of the quasi-Fermi level produces the better results, compared to the smooth connection of the electric potential.

As for the velocity saturation, the model of identical degradation for m and D causes too high diffusion current in deep sub-threshold region.

Modified transport which includes diffusion saturation caused by the steep carrier profile, was tested.

Although it gave good result by retuning the mobility parameters, too sharp transition from linear to saturation region, becomes more prominent.

The model is now running in SmartSpice with Verilog-A language.