Compact Model for Multiple Independent Gates Ambipolar Devices

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Motivation: Ambipolarity is often suppressed by processing steps; It can be exploited to enhance logic functionality Natural evolution of FinFE

Novel approach is needed to takle complex structures

Multiple Gates vs Multi-Gates

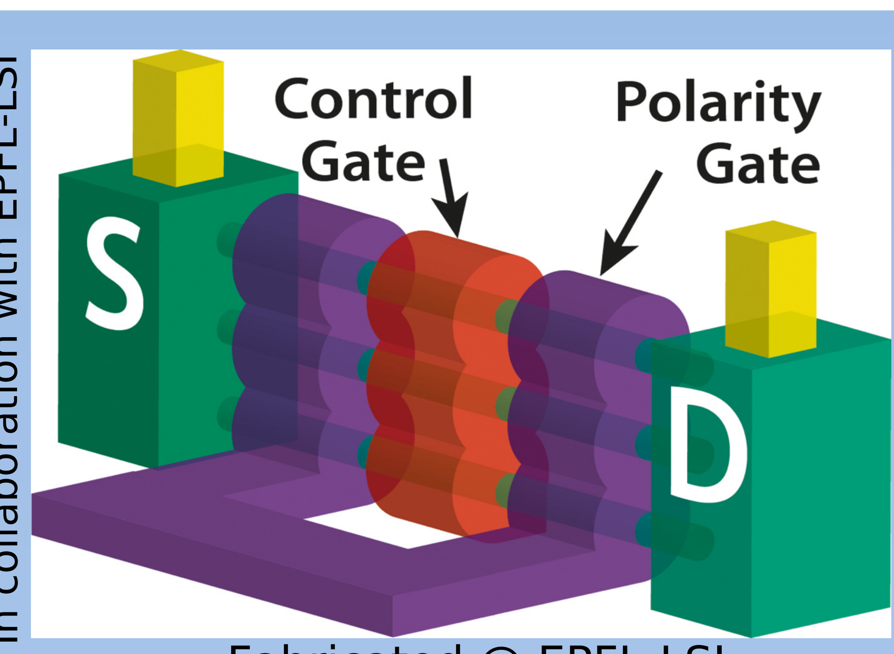
In this context, Multiple Gates ≠ Multi-Gate

GAA are Multi-Gate devices, but do not necessarily feature MultipleGates

Present work is about Multiple Independent Multi-Gate devices

Nanoarray-based structures can benefit, as well, of this approach

Model developed In collaboration with EPFL-LSI



Fabricated @ EPFL-LSI

Device section modeling

Idea: to study such devices with these free parameters:

L1, L2, L3 (different length of the sections)
VG1, VG2, VG3 (different applied voltages to the gates)
R (radius of the nanowire) **tox** (oxide thickness)
I_{di} independently calculated in sections S_i exploiting a charge-based model

Hypothesis: no voltage drop at S_i and $S_{(i+1)}$ contacts

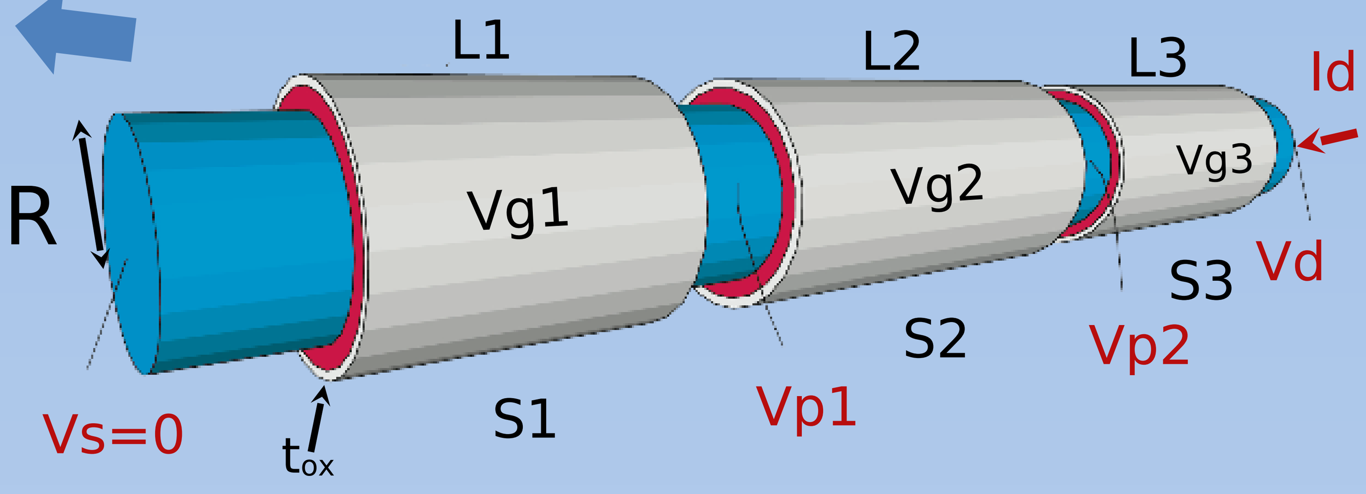
The approach: a collective strategy.

Device is seen as composed by a series of Sections.
How to **decompose** it:

Define appropriate sections (S_i) in the overallstructure.

Sections need not feature the same parameter set

The study of the complete device is reduced to the study of simpler parts



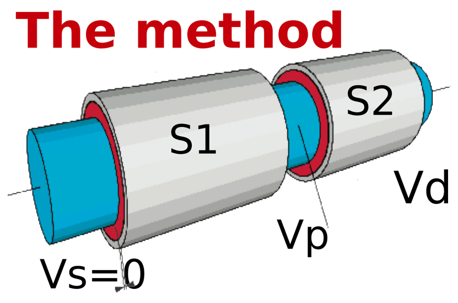
Current in sections

I_{di} can be calculated independently in each Section S_i, provided we know V_{Di} and V_{Si} of all sections $V_{Di} = Vs_{(i+1)}$ $Ids_i = Ids_{(i+1)}$

Potential ⟶ charge density

Charge density ⟶ current

The method



$$I_{ds1} = I_{ds2}$$

$$\mu\frac{2\pi R}{L_1}\left[2\frac{kT}{q}(Q_{s1}-Q_{d1})+\frac{Q_{s1}^2-Q_{d1}^2}{2C_{OX}}+\frac{kT}{q}Q_0\log\left[\frac{Q_{d1}+Q_0}{Q_{S1}+Q_0}\right]\right]=$$
$$=\mu\frac{2\pi R}{L_2}\left[2\frac{kT}{q}(Q_{s2}-Q_{d2})+\frac{Q_{s2}^2-Q_{d2}^2}{2C_{OX}}+\frac{kT}{q}Q_0\log\left[\frac{Q_{d2}+Q_0}{Q_{S2}+Q_0}\right]\right]$$

Q_{d1} and Q_{d2} are linked with V_P and V_{DS} through the charge control eq:

$$V_{GS}-\Delta\varphi-V-\frac{kT}{q}\log\left(\frac{8}{\delta R^2}\right)=\frac{Q}{C_{ox}}+\frac{kT}{q}\log\left(\frac{Q}{Q_0}\right)+\frac{kT}{q}\log\left(\frac{Q+Q_0}{Q_0}\right)$$

$V_{s1} < V_{d1} \equiv V_P$ $V_{s2} \equiv V_P < V_{ds}$
$Q_{d1} < Q_{s1}$ and $Q_{d2} < Q_{s2}$

Qd1 and Qd2 can be neglected in calculating $I_{ds1} = I_{ds2}$

Q_{s20} can be calculated as solution of:

$$\frac{1}{2C_{OX}L_2}Q_{s2}^2+\frac{2V_{th}}{L_2}Q_{s2}-\frac{Q_{s1}^2}{2C_{OX}L_1}-\frac{2V_{th}Q_{s1}}{L_1}=0$$

V_P can be calculated substituting Q_{s20} in the charge control equation:

$$V_{G2}-\Delta\varphi-V_P-\frac{kT}{q}\log\left(\frac{8}{\delta R^2}\right)=\frac{Q_{s20}}{C_{ox}}+\frac{kT}{q}\log\left(\frac{Q_{S20}}{Q_0}\right)+\frac{kT}{q}\log\left(\frac{Q_{s20}+Q_0}{Q_0}\right)$$

The estimate of V_P can be used to calculate Q_{d1} :

$$Q_{d1}=C_{OX}\left(-\frac{2C_{OX}V_{th}^2}{Q_0}+\sqrt{\left(\frac{2C_{OX}V_{th}^2}{Q_0}\right)^2+4V_{th}^2\log^2\left(1+\exp\left(\frac{V_{G1}-V_T+\Delta V_T-V_P}{2V_{th}}\right)\right)}\right)$$

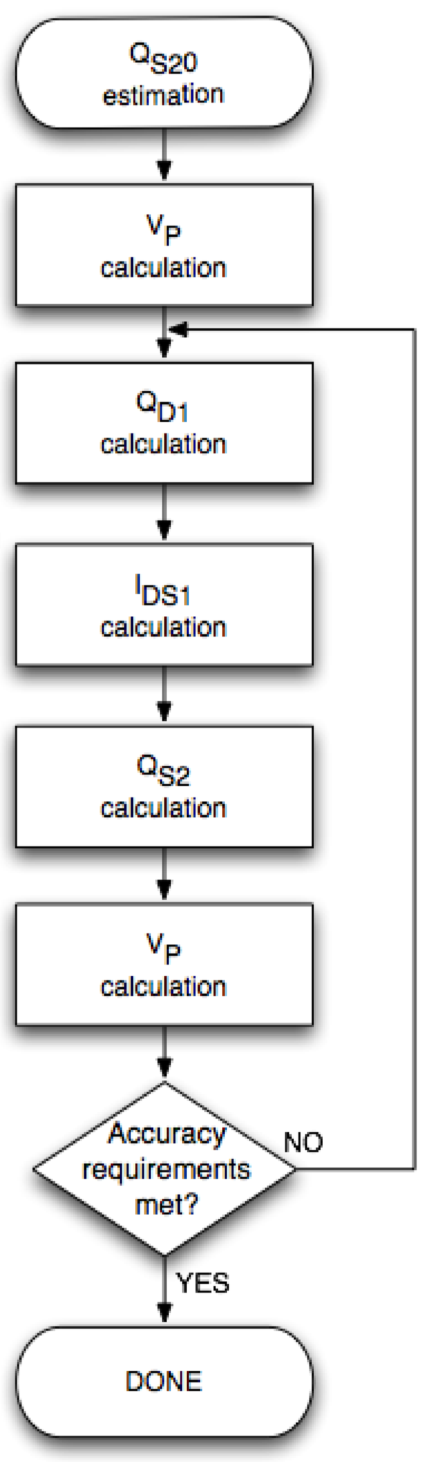
Knowing Q_{d1} it is possible to calculate the current:

$$I_{DS1}=\mu\frac{2\pi R}{L_1}\left[2\frac{kT}{q}(Q_{s1}-Q_{d1})+\frac{Q_{s1}^2-Q_{d1}^2}{2C_{OX}}+\frac{kT}{q}Q_0\log\left[\frac{Q_{d1}+Q_0}{Q_{S1}+Q_0}\right]\right]$$

$$I_{ds1} = I_{ds2} \quad \frac{1}{2C_{OX}}Q_{s2}^2+2V_{th}Q_{s2}-\frac{I_{ds1}L_2}{2\pi\mu R}\frac{Q_{s1}^2}{2C_{OX}L_1}-2V_{th}Q_{d2}-\frac{Q_{d2}^2}{2C_{OX}}+V_{th}Q_0\log\left(\frac{Q_{d2}^2+Q_0}{Q_{s20}+Q_0}\right)=0$$

V_P can now be calculated through the charge control equation:

$$V_P=V_{G2}-\Delta\varphi-\frac{kT}{q}\log\left(\frac{8}{\delta R^2}\right)-\frac{Q_{s2}}{C_{ox}}-\frac{kT}{q}\log\left(\frac{Q_{S2}}{Q_0}\right)-\frac{kT}{q}\log\left(\frac{Q_{s2}+Q_0}{Q_0}\right)$$

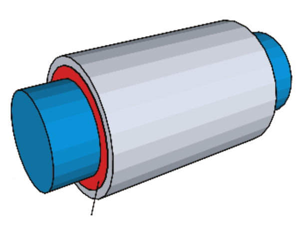


If requirements are not met it is possible to iterate the process. As a rule of thumb, the more the gates, the more iterations.
Up to three gates one iteration is enough, as will be shown in the results section.
Else the process ends.

Single selection modeling

Charge-based model is used at Single Section level to obtain current information .Drain current calculated as:

$$I_{DS_i}=\mu\frac{2\pi R}{L}\int_0^{V_{DS_i}}Q(V_i)\,dV$$

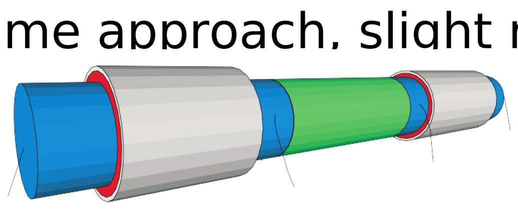


Extensions

Same nature of the problem, same approach, slight modifications

Gateless section

$$V_{P1}=V_{P2}-RI_{DS_2}$$



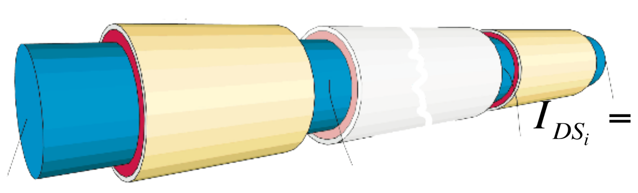
$$R=\rho\frac{L}{A}=\frac{1}{q\mu N_D}\frac{L_R}{2\pi R^2}$$

Doped channel

$$Q^*=Q-\alpha$$

$$\psi(r)=-\delta\frac{N_A}{4n_i}\frac{kT}{q}R^2+\delta\frac{N_A}{4n_i}\frac{kT}{q}r^2+V+\frac{kT}{q}\log\left(\frac{-8B}{\delta(1+Br^2)^2}\right)$$

$$\delta^*=\frac{e^{\alpha/(C_{ox}Vt)}}{N_A/n_i}\qquad V_{GS}-\Delta\varphi-V-\frac{kT}{q}\log\left(\frac{8e^{\alpha/(VtC_{ox})}}{\delta\frac{N_A}{n_i}R^2}\right)=\frac{Q-\alpha}{C_{ox}}+\frac{kT}{q}\log\left(\frac{Q-\alpha}{Q_0}\right)+\frac{kT}{q}\log\left(\frac{Q-\alpha+Q_0}{Q_0}\right)$$



$$I_{DS_i}=I_{DS_1}\quad i=2,\ldots,n$$

$$\frac{1}{2C_{OX}L_i}Q_{si0}^2+\frac{2V_{th}}{L_i}Q_{si0}-\frac{Q_{s1}^2}{2C_{OX}L_1}-\frac{2V_{th}Q_{s1}}{L_1}=0$$

Arbitrary Num. of gates

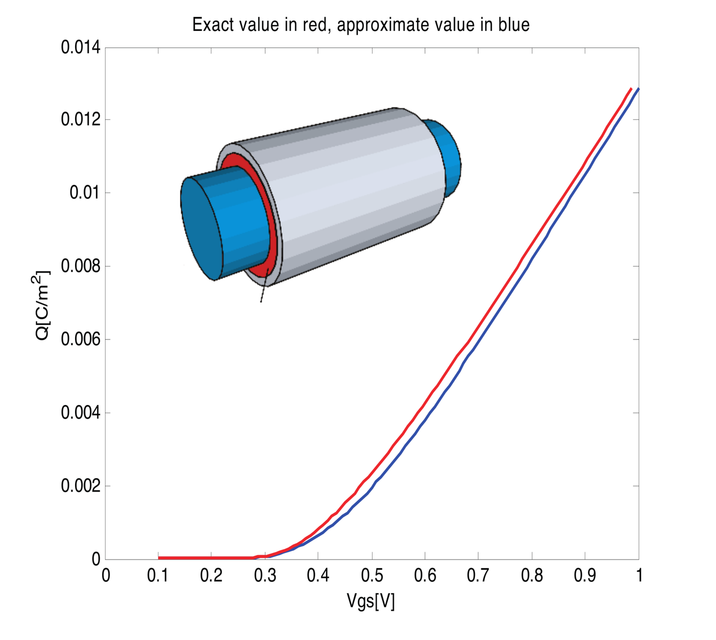
Q_{si0} can be determined as positive root of:

V_{Pi} obtained through the charge control equation:

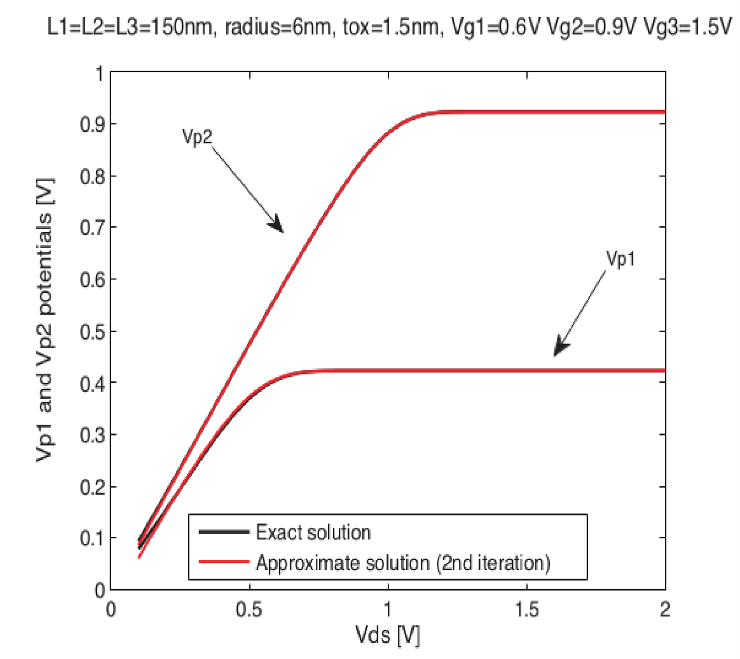
$$V_{Gi}-\Delta\varphi-V_{Pi}-\frac{kT}{q}\log\left(\frac{8}{\delta R^2}\right)=\frac{Q_{si0}}{C_{ox}}+\frac{kT}{q}\log\left(\frac{Q_{Si0}}{Q_0}\right)+\frac{kT}{q}\log\left(\frac{Q_{si0}+Q_0}{Q_0}\right)$$

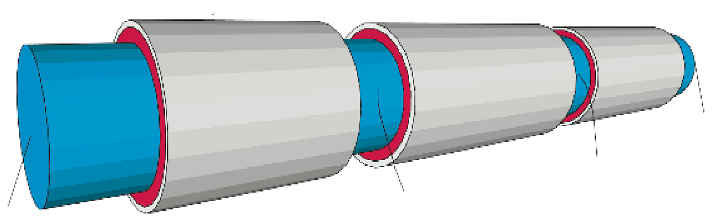
$$\underset{i=1,\ldots,n-1}{Q_{di}}=C_{OX}\left(-\frac{2C_{OX}V_{th}^2}{Q_0}+\sqrt{\left(\frac{2C_{OX}V_{th}^2}{Q_0}\right)^2+4V_{th}^2\log^2\left(1+\exp\left(\frac{V_{Gi}-V_T+\Delta V_T-V_{Pi}}{2V_{th}}\right)\right)}\right)$$

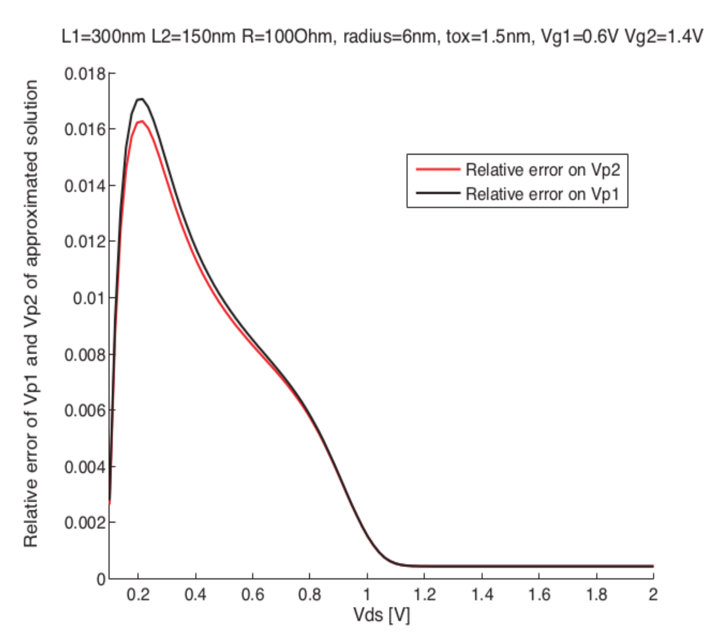
Results: single section



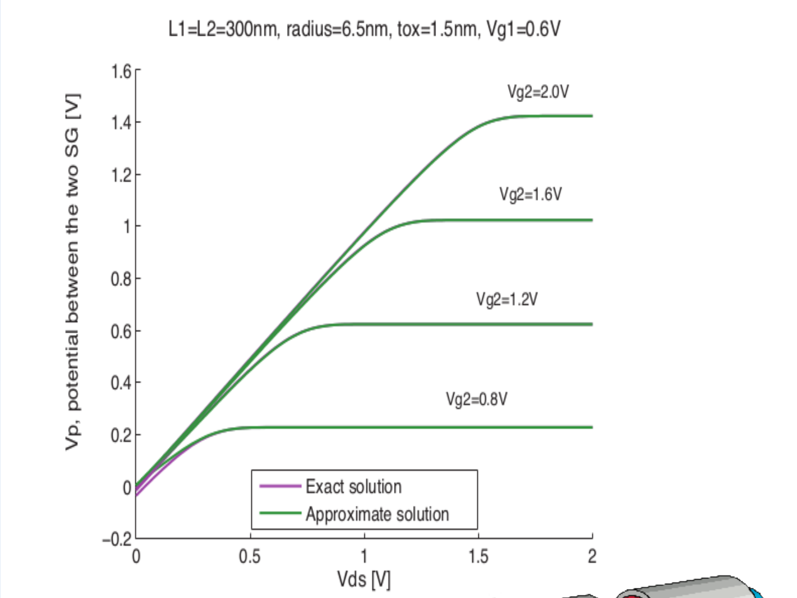
Results: triple section

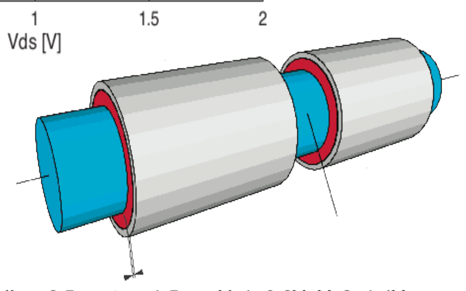


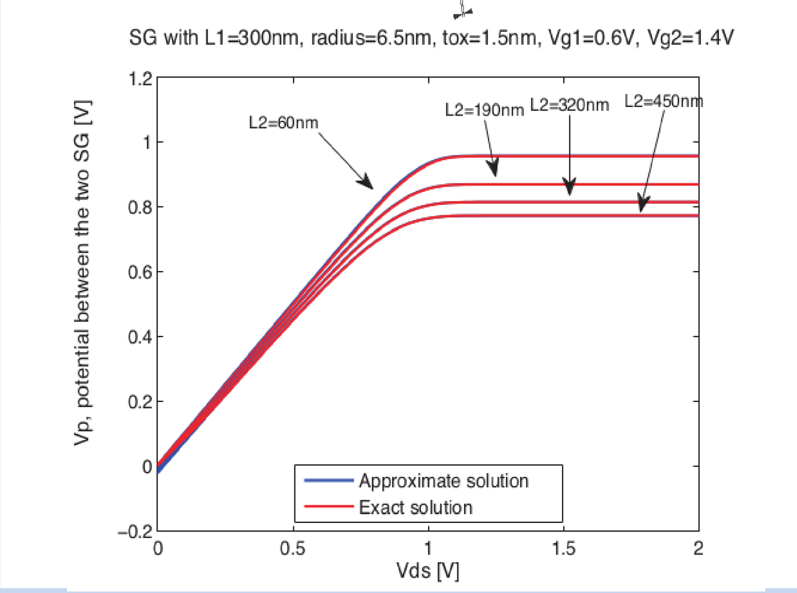




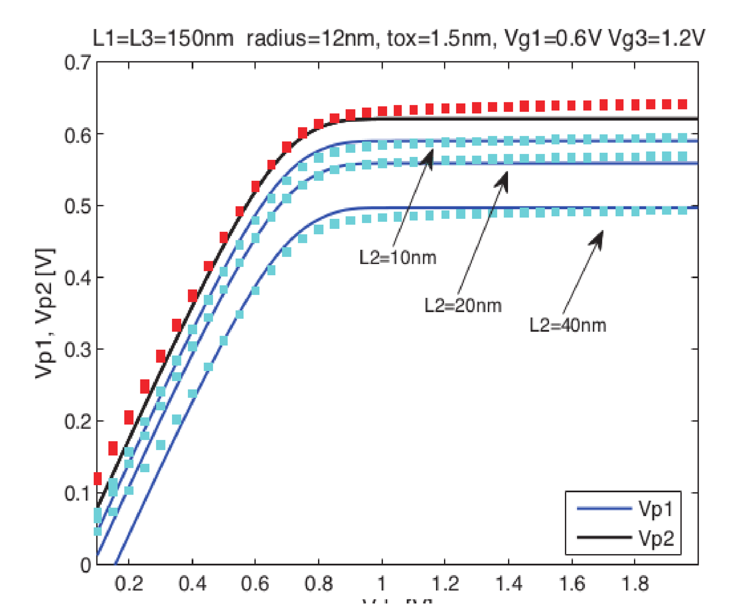
Results: double section

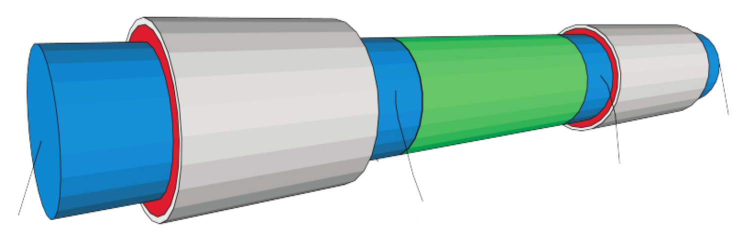


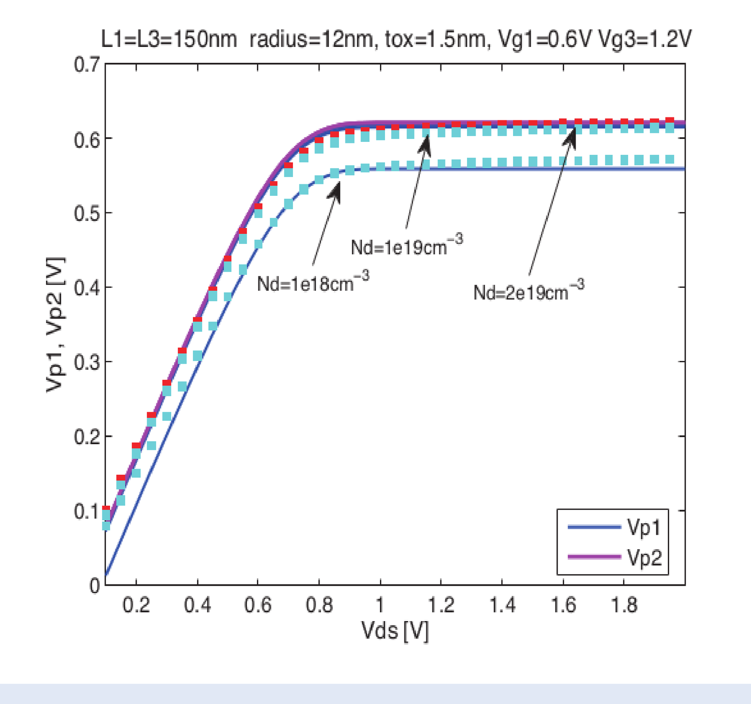




Results: triple section, one gateless







Validation

Theoretical: numerical simulations TCAD (Silvaco Atlas)

Experimental: at this stage of development, we still did not perform this kind of verification

Conclusions

Fast (second vs. hours) and accurate (max err negligible) simulation