



IMS

Institute of Microelectronic Systems

University of Hannover

## **A Methodology for Modeling Lateral Parasitic Transistors in Smart Power ICs**

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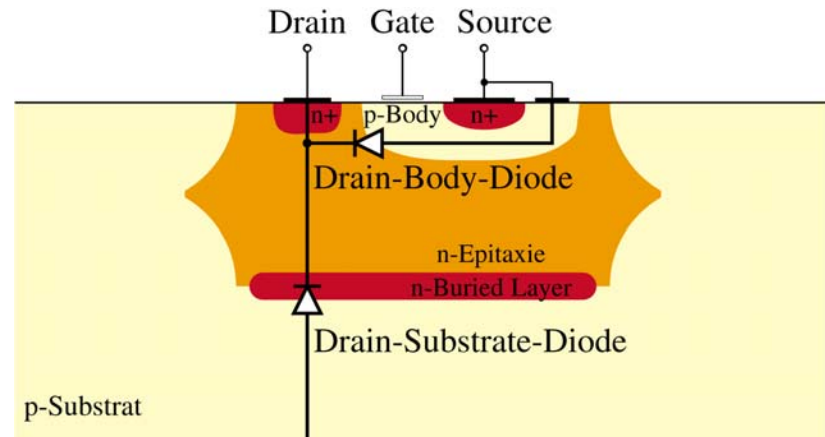
# Overview

- Introduction
  - Substrate currents in smart power ICs
  - Lateral parasitic transistors
  - Why a new model?
- Modeling the parasitic transistor
  - Physical equations
  - Approach for the electron density
- Automated model generation
  - Setup
  - Eliminating linear equations
- Convergence aids
  - Extension of function domains
  - Taylor series
- Results
- Summary

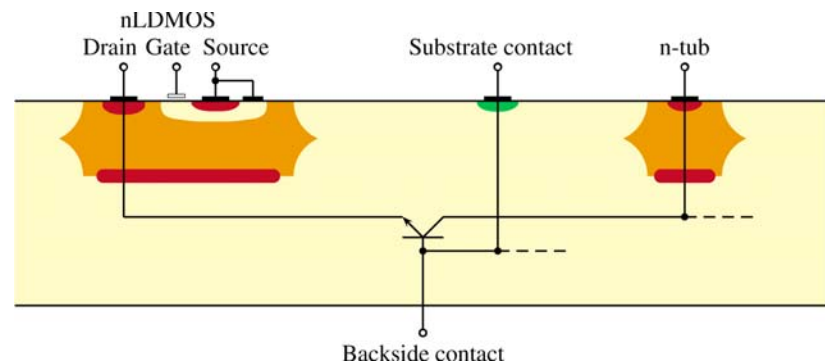


# Substrate Currents in Smart-Power-ICs

- Due to negative voltages
  - e.g. from switching of inductive loads
- Forward biased drain-substrate junction
- Minority carrier injection into the substrate
- Undesired n-tub currents
  - Change logic states
  - Cause latch-up
  - Shift substrate potential



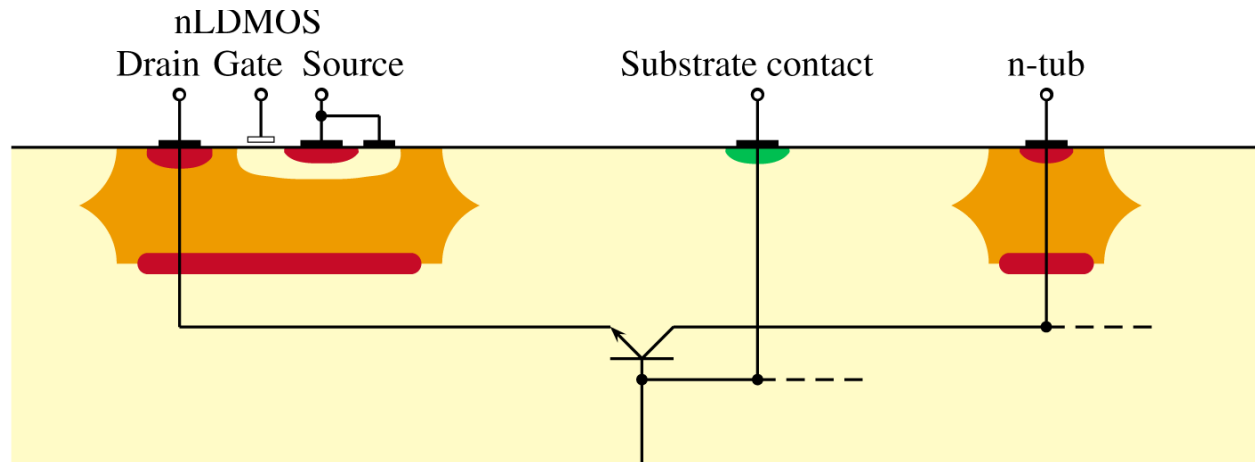
Crosscut of an nLDMOS



Crosscut of a smart power IC



# Physical Behavior



- Electrons are injected into the substrate
  - Most of them recombine
- Substrate contacts provide holes for recombination
  - Holes drift into the substrate
  - An electric field develops
  - Electrons drift to substrate contacts: Accumulation occurs
- Electrons drift and diffuse up to several hundred  $\mu\text{m}$



# Parasitic NPN

- Characterized by
  - Multiple base contacts and collectors
    - Each substrate contact acts as base contact
    - Each n-tub acts as collector
  - Base width of several hundred  $\mu\text{m}$
  - Inhomogeneous current flow
  - High electron densities in the substrate ( $>N_A$ )
- There is no model for such transistors!
  - $\Rightarrow$  No post-layout simulations including the parasitic npn are possible!
  - $\Rightarrow$  A new model is required!
- Changes in the layout might change the structure of the parasitic npn
  - $\Rightarrow$  A methodology for generating models is required!



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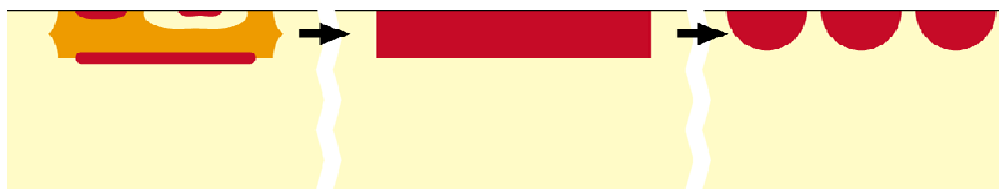


# Approach for the Electron Density

- Electron behavior is described by Shockley equations
  - Cannot be analytically solved in 3d
  - Therefore
    - Neglect influence of the electric field on the electron density
    - Solve the static diffusion equation in spherical coordinates
  - This yields

$$n(x, y, z) = \frac{e^{-\frac{r}{L_n}}}{r}$$

- In order to apply this solution, the geometry of diffusion regions has to be approached by half spheres

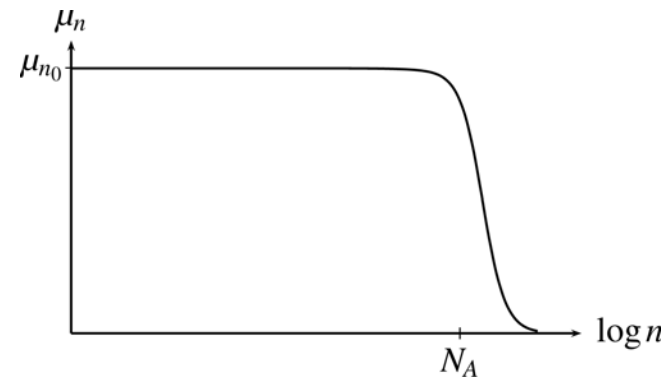


- Then superposition is possible:
 
$$n(x, y, z) = \sum_{i=1}^m N_i \cdot \frac{e^{-\frac{r_i}{L_n}}}{r_i}$$
- Only the  $N_i$  are voltage dependent:
 
$$n(x_0, y_0, z_0) = \sum_{i=1}^m a_i \cdot N_i$$



# Mobility Reduction

- Mobilities strongly decrease
  - For high electron densities ( $n > N_A$ )
  - Due to Carrier-Carrier-Scattering



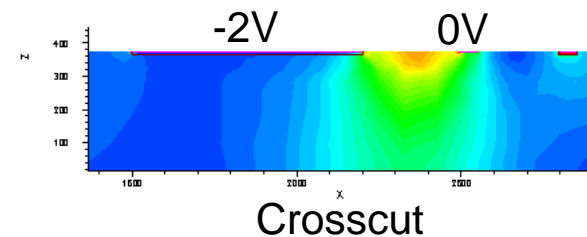
- We model this according to the Conwell-Weisskopf screening theory:

$$\mu_{n,p} = \frac{1}{\frac{1}{\mu_{n,p0}} + \frac{1}{\frac{1}{1.0410^{21} \frac{1}{cmVs}} \sqrt{n(n+N_A)} \ln \left( 1 + 7.45210^{13} cm^{-2} (n(n+N_A))^{-\frac{1}{3}} \right)}}$$



# Voltage Drop in the Substrate

- Electric field causes a significant voltage drop
  - For high injection levels
  - Between injecting LDMOS and the nearest substrate contact
  - $V_{Bi} = \int E \cdot dl$
  - But:  $E(x,y,z)$  unknown
- Therefore we assume
  - For low injections:  $E \sim \frac{1}{r}, E \sim \frac{1}{r^2}$ 
    - according to  $\text{Div } E=0$
  - For high injection:  $E \approx \text{const.}$ 
    - see the paper for more details
  - An empiric equation models the transition from low to high injection



# Boundary Conditions

- Fletcher boundary conditions

- For forward biased pn and pp<sup>+</sup> junctions:
- Valid for high electron densities on both sides of the junction

$$V_{PN} = U_T \ln \left( \frac{\left( -1 + \sqrt{1 + 4 \frac{n_E^2}{N_D^2} + \frac{4n_E N_A}{N_D^2}} \right) N_D^2 N_A}{2 (n_E + N_A) n_i^2} \right)$$

- Electron density increases due to finite velocities

- At reverse biased pn junctions:  $v_D$   $j_{n_C} = q \cdot v_D \cdot n_C$
- At the Schottky-like back contact:  $v_e$   $j_{n_{BS}} = q \cdot v_e \cdot n_{BS}$
- At pp<sup>+</sup> junctions: S

$$j_{n_B} = q \cdot S \cdot \left( \frac{n_B \cdot (n_B + N_A)}{N_A} - n_0 \right)$$



# Recombination Currents in the Substrate

- Substrate contacts provide holes for recombination
  - Hole current through a substrate contact equals the recombination current for a corresponding volume

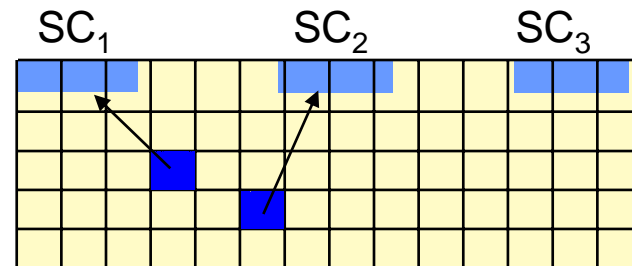
$$I_{rec} = \int R dV$$

- Calculation of the recombination current is simplified by a substrate discretization:

- Each volume element is assigned to the nearest substrate contact

$$I_{rec_i} = \frac{q}{\tau_n + \tau_p} \cdot n_{center} \cdot \Delta x \cdot \Delta y \cdot \Delta z$$

$$\rightarrow I_{SC_p} = \sum I_{rec_i}$$



- Required for calculating the electric field beneath substrate contacts



# Terminal Currents

- Current densities 
$$j_n = \mu_n \cdot V_T \cdot \nabla n + \mu_n \cdot n \cdot E$$
$$j_p = -\mu_p \cdot V_T \cdot \nabla n + \mu_p \cdot (n + N_A) \cdot E$$
- Applying the approach for the electron density at point k results in

$$j_{nk} = \mu_{nk} \cdot \left( \sum_{i=1}^m a_i \cdot N_i + \sum_{i=1}^m b_i \cdot N_i \cdot E_k \right)$$
$$j_{pk} = \mu_{pk} \cdot \left( \sum_{i=1}^m c_i \cdot N_i + \sum_{i=1}^m d_i \cdot N_i \cdot E_k \right)$$

- Current through a half sphere
    - Use of average values
- $$I_{HS} = \int (j_n + j_p) dA = (j_{nk} + j_{pk}) A$$
- Terminal current
    - Sum of all currents through corresponding half spheres

$$I_T = \sum I_{HS}$$



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- **Automated model generation**
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# Setting up the Equations (1/2)

## 1. Equations for the electron density at diffusion region

- We assume constant electron density at all half spheres of a diffusion region

$$n(x_k, y_k, z_k) = \sum_{i=1}^m a_i \cdot N_i$$

## 2. Mobility equations for each diffusion region

$$\mu_{n,p} = \frac{1}{\mu_{n,p0} + \frac{1}{\frac{1.04 \cdot 10^{21} \frac{1}{\text{cm}^3 \text{Vs}}}{\sqrt{n(n+N_A)} \ln \left( 1 + 7.45210^{13} \text{cm}^{-2} (n(n+N_A))^{-\frac{1}{3}} \right)}}}$$

## 3. Recombination current equations for each substrate contact

## 4. Kirchhoffs voltage law

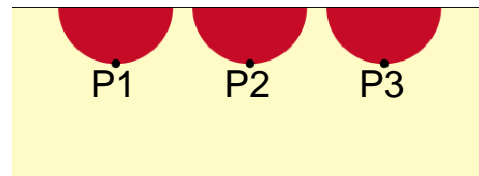
- Only once
- Including the junction voltages of the injecting LDMOS and the nearest substrate contact



# Setting up the Equations (2/2)

## 5. Boundary conditions

- For each half sphere
- Nonlinear boundary conditions only for one half sphere of a diffusion region
- For the other half spheres applies  $n(P1) = n(P2)$
- This reduces the number of nonlinear expressions
- For example:
  - 3 half spheres belonging to one diffusion region



$$j_n(P1) = q \cdot S \cdot \left( \frac{n(P1) \cdot (n(P1) + N_A)}{N_A} - n_0 \right)$$

$$n(P2) = n(P1)$$

$$n(P3) = n(P2)$$

## 6. Terminal current equations



# Elimination of Linear Equations

- Purpose:

- Reduce number of equations
  - Up to now there are a few hundred
- As less as possible simultaneous equations
- Keep some procedural equations
  - Allow the user to see, whether the results are reasonable or not
  - Calculate large, nonlinear expressions only once

- Eliminate linear equations:  $\sum_{i=1}^m a_i \cdot N_i = \sum_{i=1}^m b_i \cdot N_i \Rightarrow N_j = \sum_{\substack{i=1 \\ i \neq j}}^m c_i \cdot N_i$

- Isolate a variable
- Substitute this variable
  - Replace  $N_j$  by  $\sum_{\substack{i=1 \\ i \neq j}}^m c_i \cdot N_i$  in all other equations
- Remove equation from the equation system



# Verilog-A Model

- Implemented in Verilog-A for Spectre-Simulations
- Mostly procedural equations
  - For the electron densities and mobilities
  - Serve as intermediate variables
  - Shorten the equation system
  - Allow the user to see, whether the results are reasonable or not
- A few simultaneous equations remain
  - Boundary conditions of pp+ junctions
  - Kirchhoffs voltage law
  - As less as possible we could figure out
  - # simultaneous equations depends on # substrate contacts
- Model size independent of:
  - # n-tubs
  - # half spheres per diffusion region



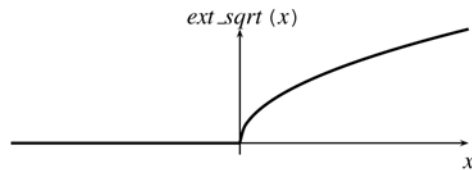
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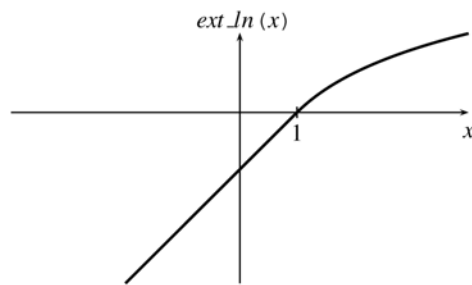


# Extension of Function Domains

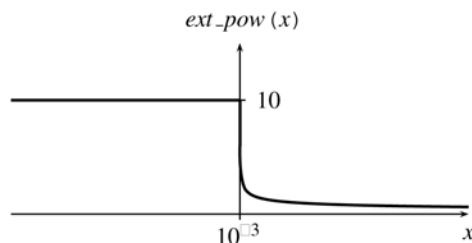
- Negative electron density values
  - Occur for very low injection levels due to simplifications
  - Aborts the simulation as e.g.  $\text{sqrt}(-K)$  is not defined
- Therefore, some domains have to be extended



$$\sqrt{x} \Rightarrow \begin{cases} \sqrt{x} & \text{for } x \geq 0 \\ 0 & \text{for } x < 0. \end{cases} \quad \begin{array}{l} * \text{ smooth extension} \\ \text{slows down} \\ \text{simulation time} \end{array}$$



$$\ln x \Rightarrow \begin{cases} \ln(x) & \text{for } x \geq 1 \\ x - 1 & \text{for } x < 1. \end{cases}$$



$$x^{-\frac{1}{3}} \Rightarrow \begin{cases} x^{-\frac{1}{3}} & \text{for } x \geq 10^{-3} \\ 10 & \text{for } x < 10^{-3}. \end{cases}$$



# Taylor Series

- Problem: Numerical imprecision
  - Sum of numbers of different orders of magnitude
  - e.g.

$$-1 + \sqrt{1+x} = 0 \text{ for } x=10^{-30} ?$$

- Results in a not defined expression in the Fletcher boundary conditions:

$$\ln(k \cdot (-1 + \sqrt{1+x})) \Rightarrow \ln(0)!$$

- Solution: Taylor series

$$-1 + \sqrt{1+x} = \frac{1}{2} \cdot x - \frac{1}{8} \cdot x^2 + \dots$$

- For a continuous transition we adjust the 2<sup>nd</sup> coefficient and apply:

$$-1 + \sqrt{1+x} \Rightarrow \begin{cases} -1 + \sqrt{1+x} & \text{for } x \geq 10^{-3} \\ 0.5 \cdot x - 0.12493754 \cdot x^2 & \text{for } x < 10^{-3} \end{cases}$$

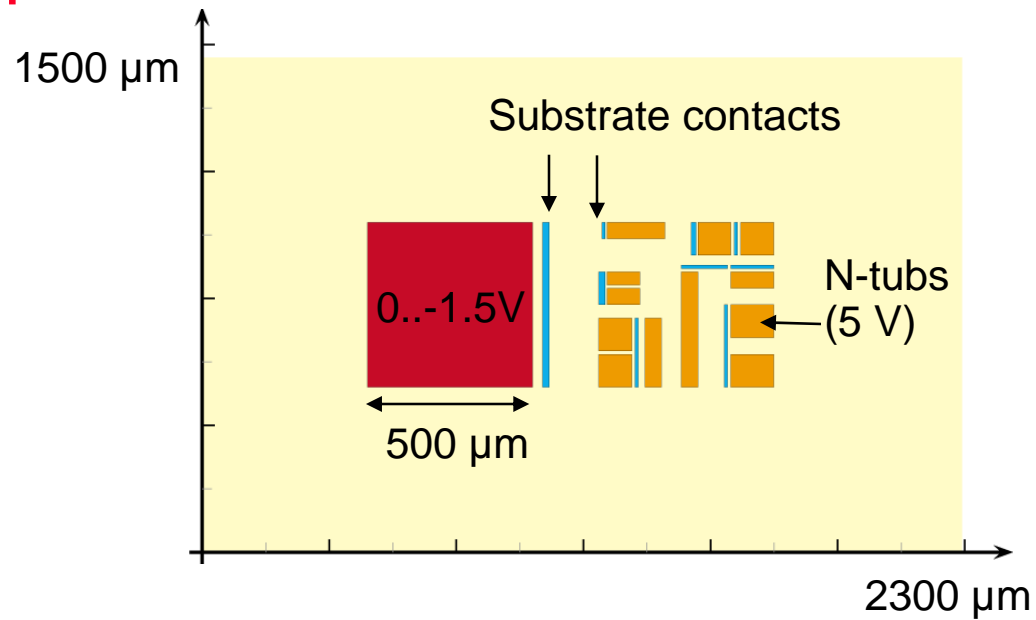


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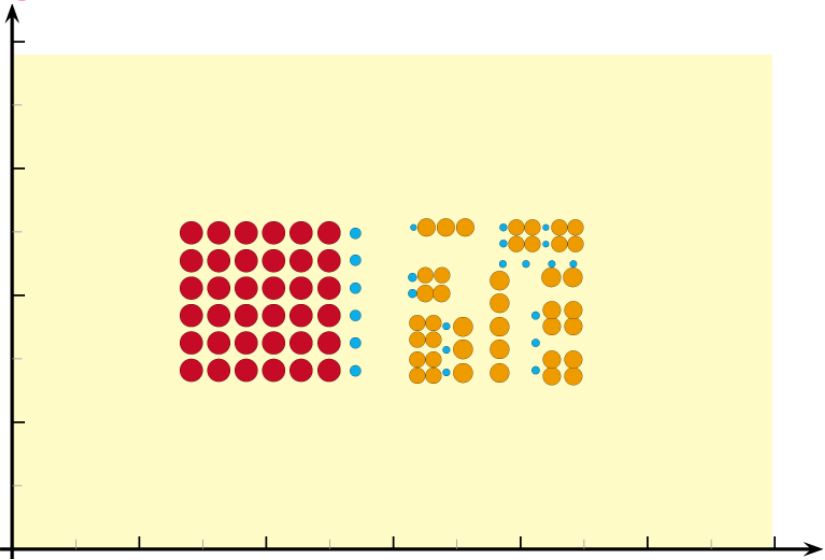
# Example



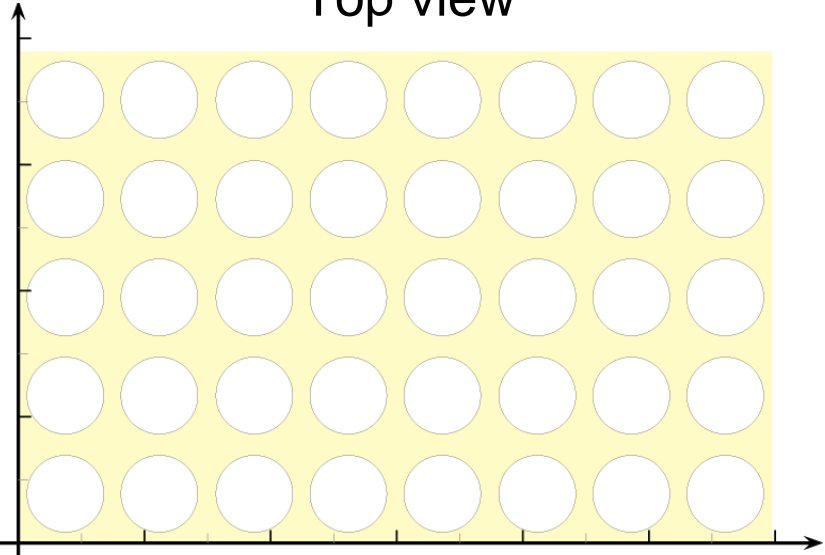
- 1 large n-region (red), representing the drain regions of a LDMOST
  - Injects electrons ( $V = 0.. -1.5 \text{ V}$ )
- 9 substrate contacts @ 0 V (blue)
- 12 n-tubs @ 5 V (orange)



# Approaching the Geometry with Half Spheres



Top view

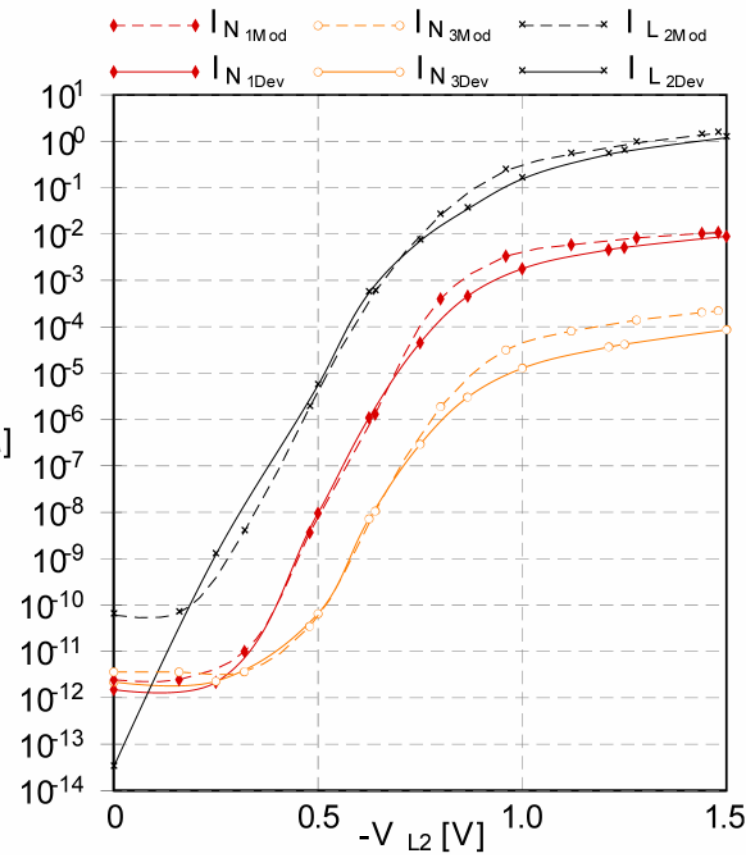
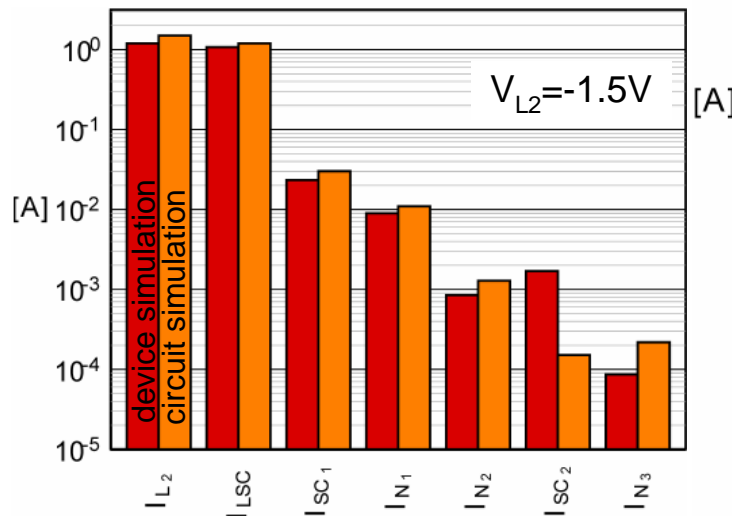


Back side



# Results

- Comparison device- with circuit simulation
  - DESSIS (3 weeks) vs. Spectre (30s CPU, 1s DC sweep)
- Accuracy:
  - Factor 2.5 for n-tub currents
  - Larger error for currents through distant substrate contacts
    - Does not affect the accuracy of n-tub currents



# Summary

- Methodology for generating Verilog-A models for parasitic transistors
  - For post-layout simulation
  - Including minority charge carrier injection and collection
- Short simulation times
  - A few 100 ms in contrast to several days for device simulations
- Accuracy: factor of 3
  - Sufficient for detecting inadmissible substrate currents
  - Much better than experience values
- Limitation:
  - No active protection measures

