IMS
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A Methodology for Modeling Lateral Parasitic Transistors in Smart Power ICs

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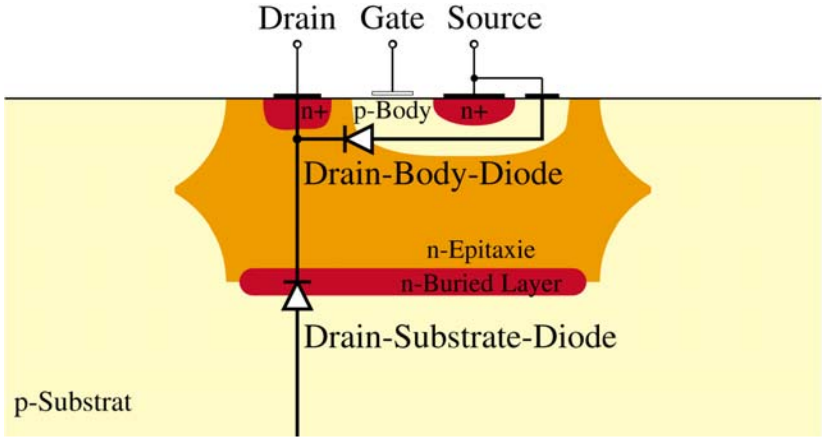
Overview

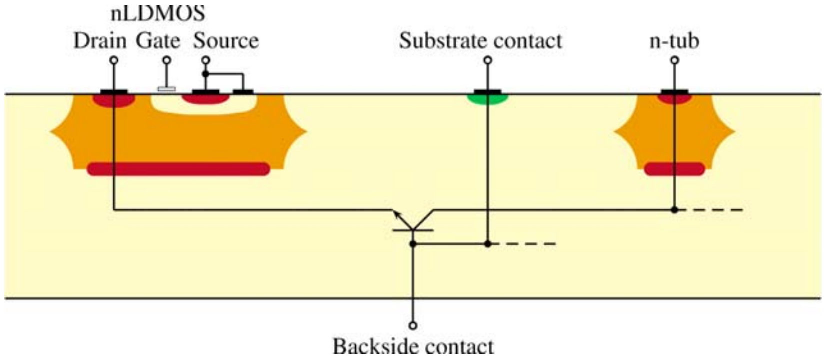
- Introduction
  - Substrate currents in smart power ICs
  - Lateral parasitic transistors
  - Why a new model?
- Modeling the parasitic transistor
  - Physical equations
  - Approach for the electron density
- Automated model generation
  - Setup
  - Eliminating linear equations
- Convergence aids
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

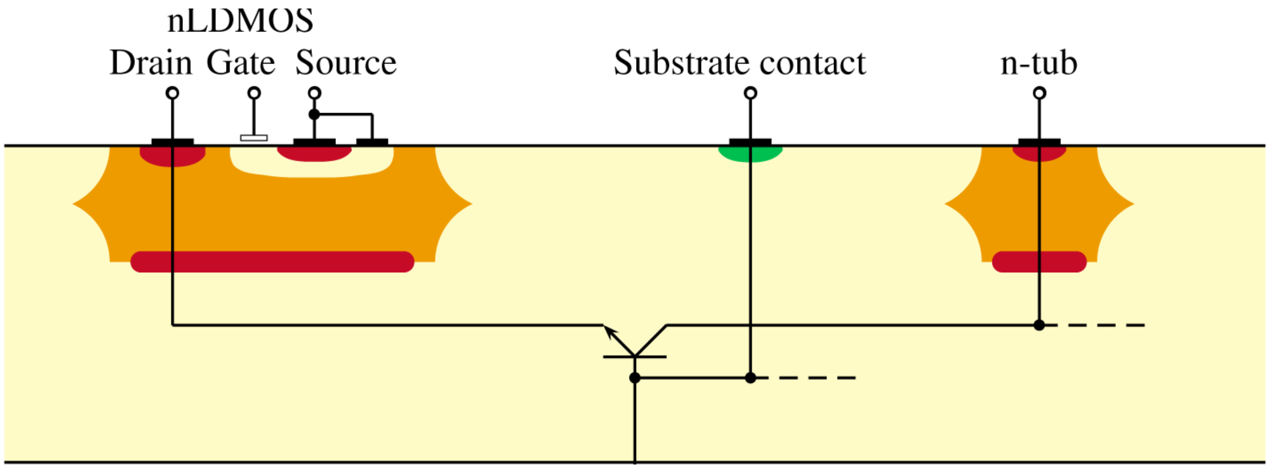


Crosscut of an nLDMOS



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 µm

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 µm
  - Inhomogeneous current flow
  - High electron densities in the substrate (>N_A)

- There is no model for such transistors!

  ⇒No post-layout simulations including the parasitic npn are possible!

  ⇒A new model is required!

- Changes in the layout might change the structure of the parasitic npn

  ⇒A methodology for generating models is required!

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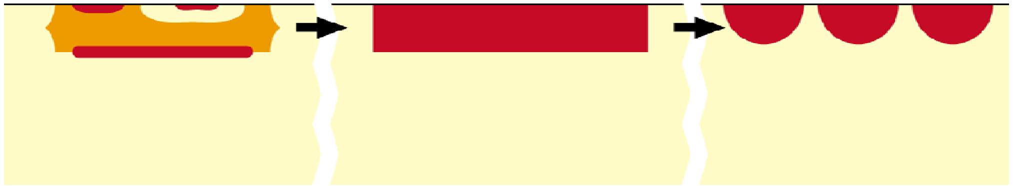
Approach for the Electron Density

- 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

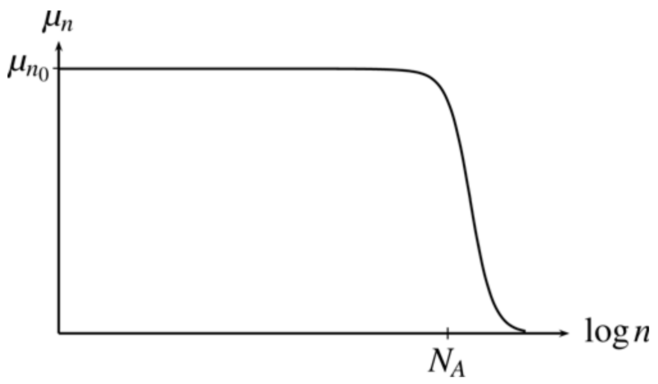


- Then superposition is possible: $$n(x,y,z) = \sum_{i=1}^{m} N_i \cdot \frac{e^{-\frac{r_i}{Ln}}}{r_i}$$

- 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



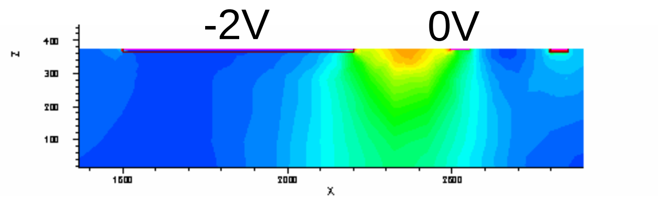
- We model this according to the Conwell-Weisskopf screening theory:

$$\mu_{n,p} = \frac{1}{\frac{1}{\mu_{n,p_0}} + \frac{1}{\frac{1.0410^{21}\frac{1}{cmVs}}{\sqrt{n(n+N_A)}\ \mathrm{ln}\left(1+7.45210^{13}cm^{-2}(n(n+N_A))^{-\frac{1}{3}}\right)}}}$$

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 Div E=0
  - For high injection: $E \approx const.$
    - see the paper
      for more details



Crosscut

  - An empiric equation models the transition
    from low to high injection

Boundary Conditions

- Fletcher boundary conditions
  - For forward biased pn and pp$^+$ junctions:
  - Valid for high electron densities on both sides of the junction

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

- Electron density increases due to finite velocities
  - At reverse biased pn junctions: v_D
  - At the Schottky-like back contact: v_e
  - At pp$^+$ junctions: S

$$j_{n_C} = q \cdot v_D \cdot n_C$$

$$j_{n_{BS}} = q \cdot v_e \cdot n_{BS}$$

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

Recombination Currents in the Substrate

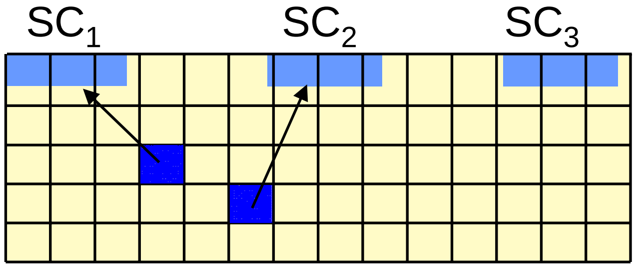
- Substrate contacts provide holes for recombination
  - Hole current through a substrate contact equals the recombination current for a corresponding volume

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

- 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

$$j_n = \mu_n \cdot V_T \cdot \nabla n + \mu_n \cdot n \cdot E$$

$$j_p = -\mu_p \cdot V_T \cdot \nabla n + \mu_p \cdot \left(n + N_A\right) \cdot E$$

- 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

$$I_{HS} = \int \left(j_n + j_p\right) \, dA = \left(j_{nk} + j_{pk}\right) \, A$$

- Terminal current
  - Sum of all currents through corresponding half spheres

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

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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

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

2. Mobility equations for each diffusion region

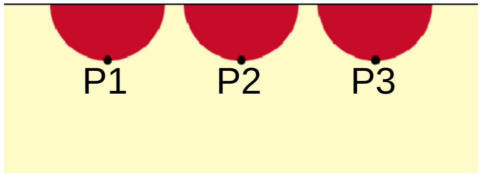
$$\mu_{n,p} = \frac{1}{\frac{1}{\mu_{n,p_0}} + \frac{1}{\frac{1.0410^{21}\frac{1}{cmVs}}{\sqrt{n(n+N_A)}\,\ln\left(1+7.45210^{13}cm^{-2}\left(n(n+N_A)\right)^{-\frac{1}{3}}\right)}}}$$

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



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

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

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

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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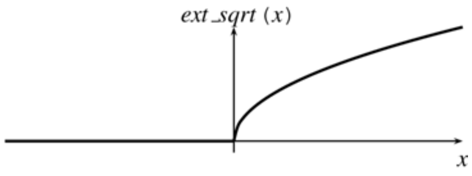
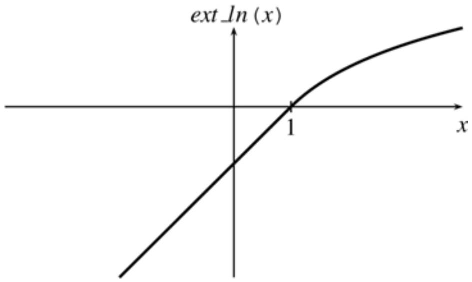
Extension of Function Domains

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

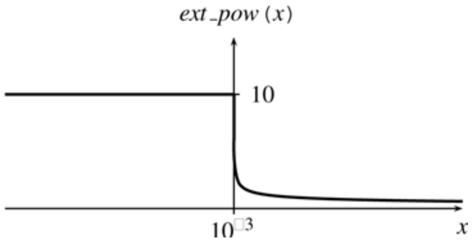


$$\sqrt{x} \Rightarrow \begin{cases} \sqrt{x} & \text{for } x \geq 0 \\ 0 & \text{for } x < 0. \end{cases}$$

* smooth extension slows down simulation time



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



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

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:

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

- Solution: Taylor series

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

  - For a continuous transition we adjust the 2nd 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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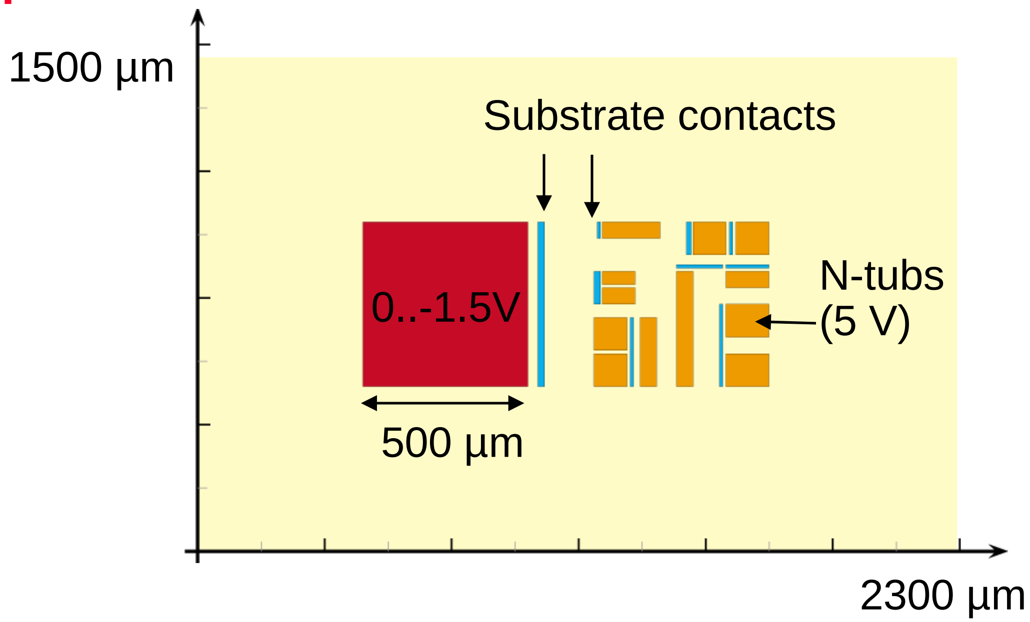
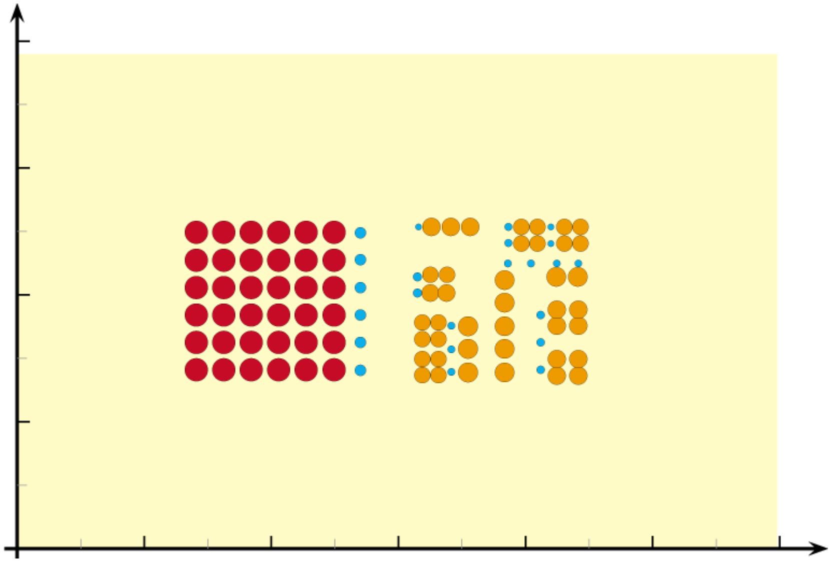
Example

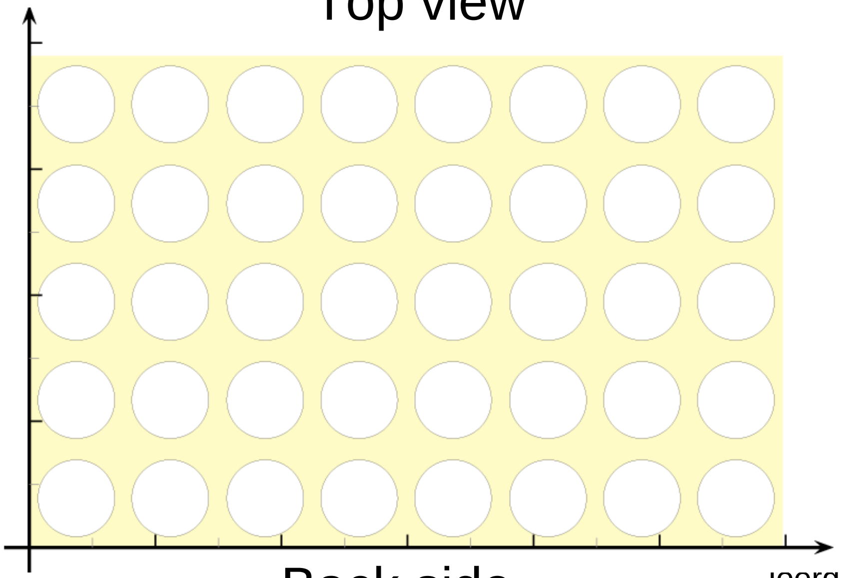


- 1 large n-region (red), representing the drain regions of a LDMOST
    - Injects electrons (V = 0.. –1.5 V)
- 9 substrate contacts @ 0 V (blue)
- 12 n-tubs @ 5 V (orange)

Approaching the Geometry with Half Spheres



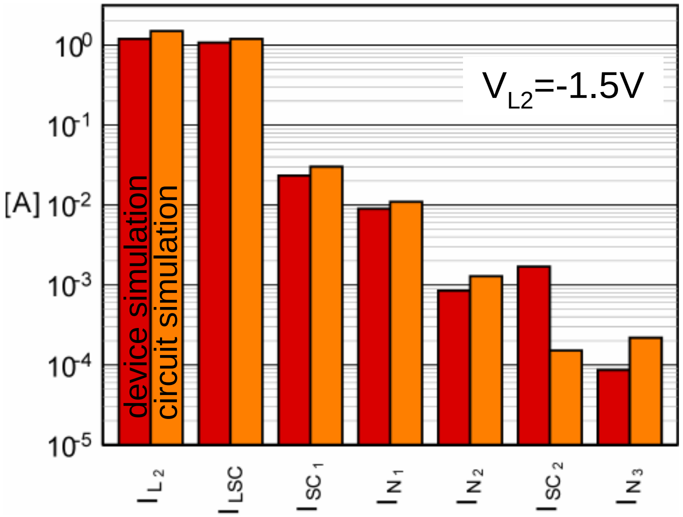
Top view

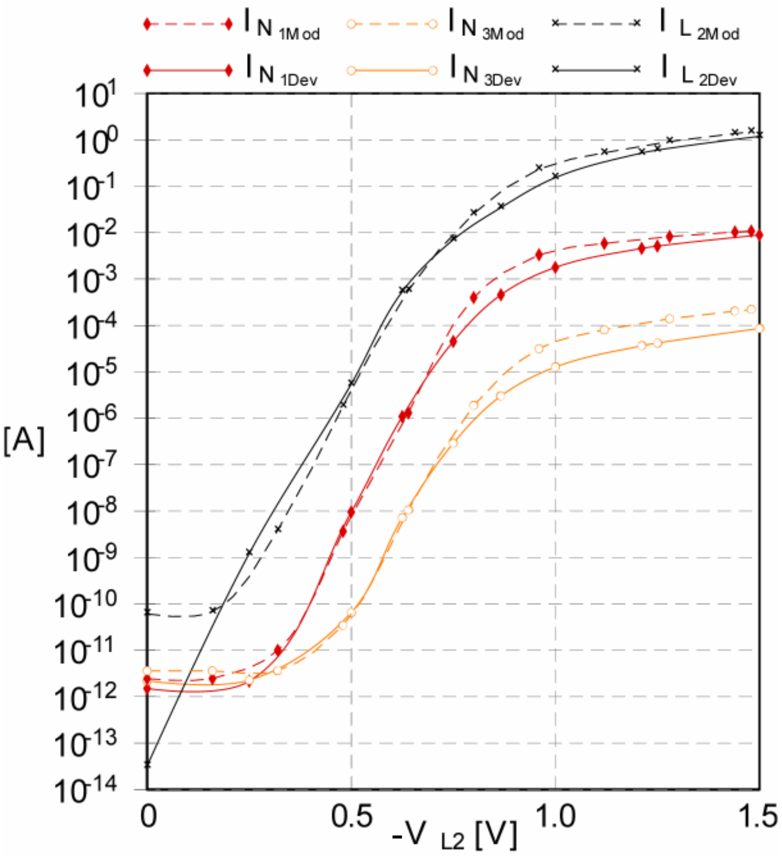


Back side

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