

Automatic generation of RF compact models from device simulation

Part II: Implementation and applications

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Outline

1. Motivation and principles
2. A simple example: Capacitance modeling
3. Bipolar devices
4. Model extensions: Electromagnetics, thermal coupling, hot-carrier and quantum-mechanical effects
5. Implementation issues

1. MOTIVATION AND PRINCIPLES

Motivation

- Present a coherent methodology for compact model generation
- Allow a higher degree of automation

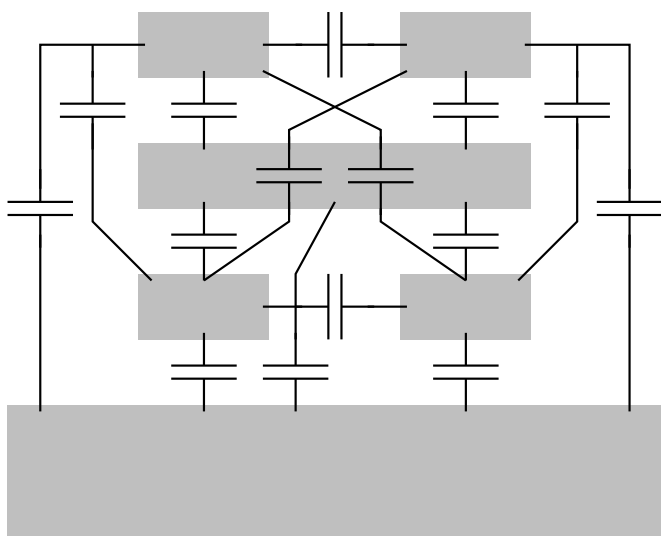
Principles

- Generation of lumped elements by box integration of partial differential equations
- Extraction of element values from exact solutions:
 - Interfacing with numerical simulation
 - Reuse of analytical formulations

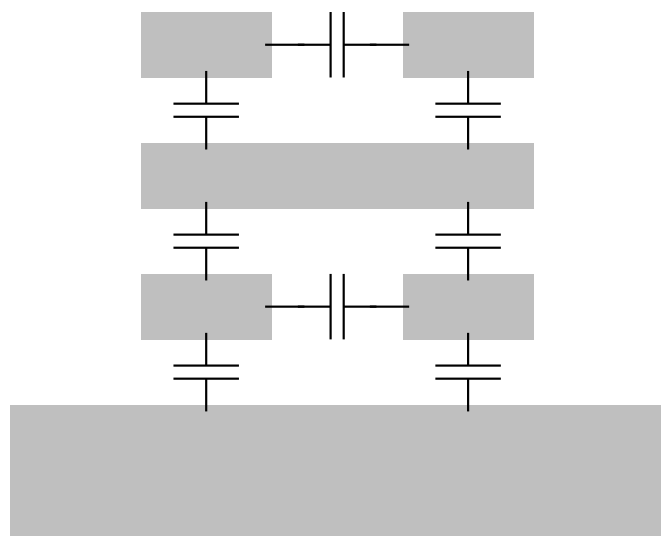
Key properties of generated models

- Local, physically-based circuit topologies
- Recovery of exact solution in significant cases
- Accuracy-complexity tradeoff
- Geometry is the main free variable
- Models can migrate between applications (e.g., thermal to inductance)

2. A SIMPLE EXAMPLE: CAPACITANCE MODELING

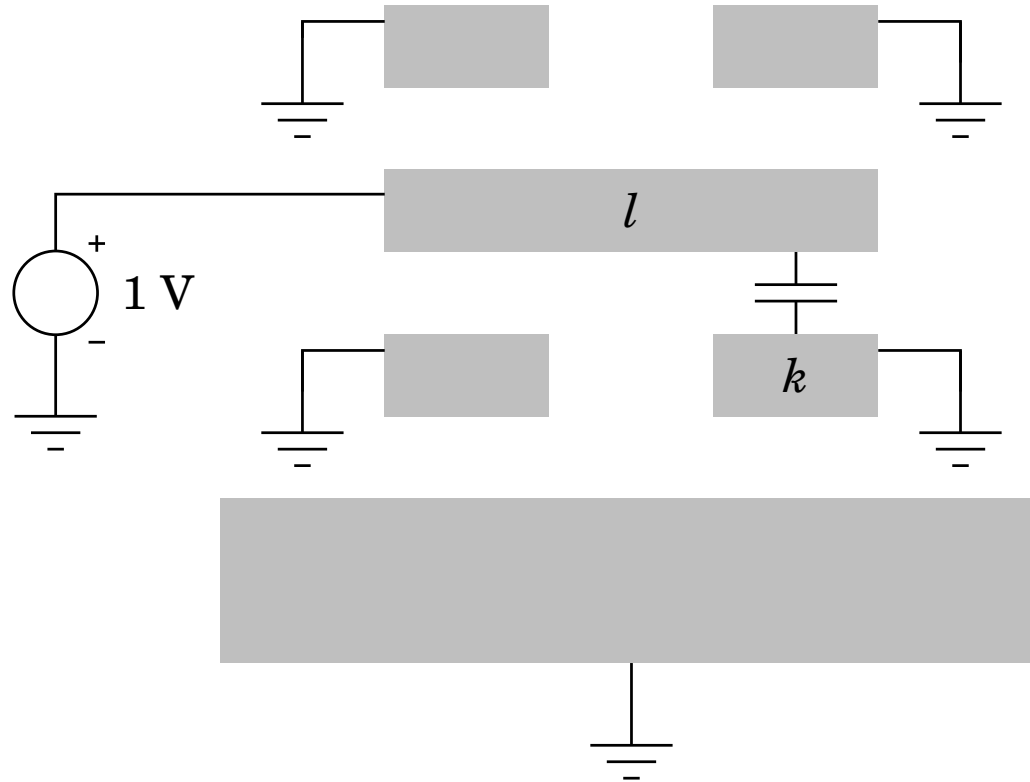


Capacitance matrix



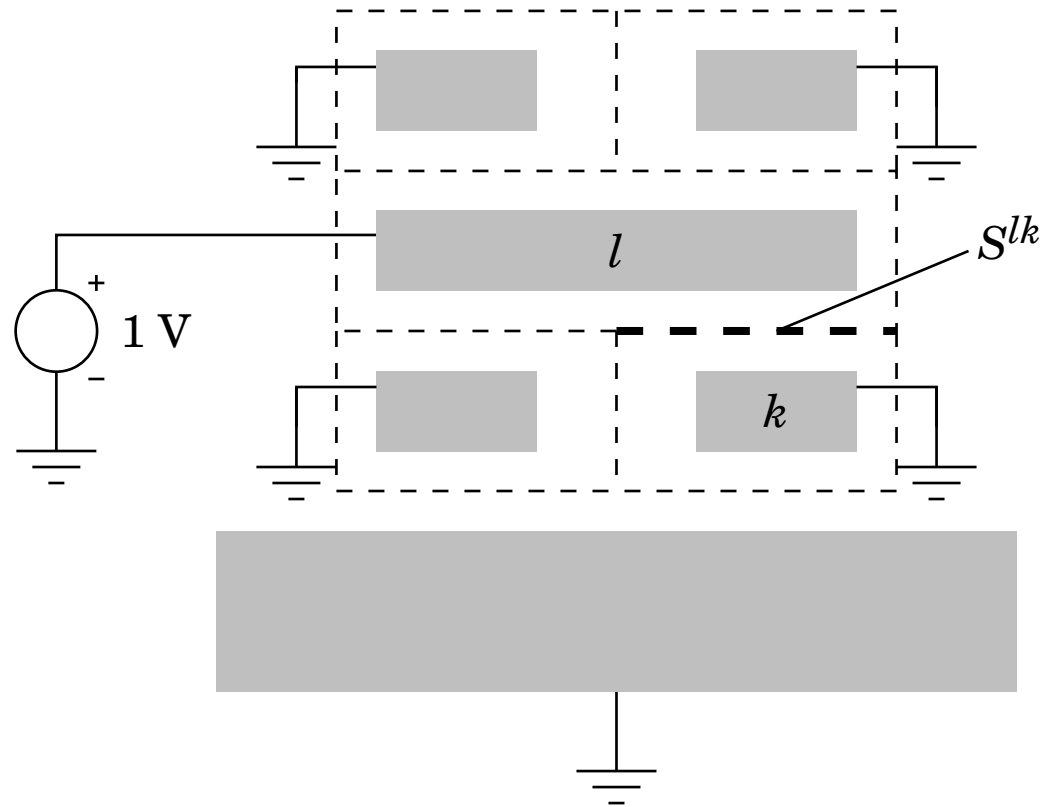
Local model

Capacitance matrix:



$$C^{kl} = C^{lk} = -\frac{\delta Q_k}{\delta V_l}$$

Nearest-neighbor capacitance:



$$C_d^{lk} = \frac{1}{\delta V^l} \int_{S^{lk}} d\mathbf{S} \cdot \boldsymbol{\varepsilon},$$

Key properties:

- The capacitance-matrix **sparseness** is built into the model
- The model self-capacitance is **exact**:

$$\sum_l C_d^{kl} = \sum_{l \neq k} C^{kl} = -C^{kk},$$

- **Accuracy** increases with the number of elements
- Well-behaved **boundaries** between conductors must be found
- The same scheme works for **any** boundary-value Laplace problem

The model is **not unique**:

- The result depends on the choice of **trial solutions**
- The matrix is **not symmetric**: $C_d^{kl} \neq C_d^{lk}$

The trial potential distribution $\psi(x, y, z)$ can be a

full numerical simulation: Expensive but accurate

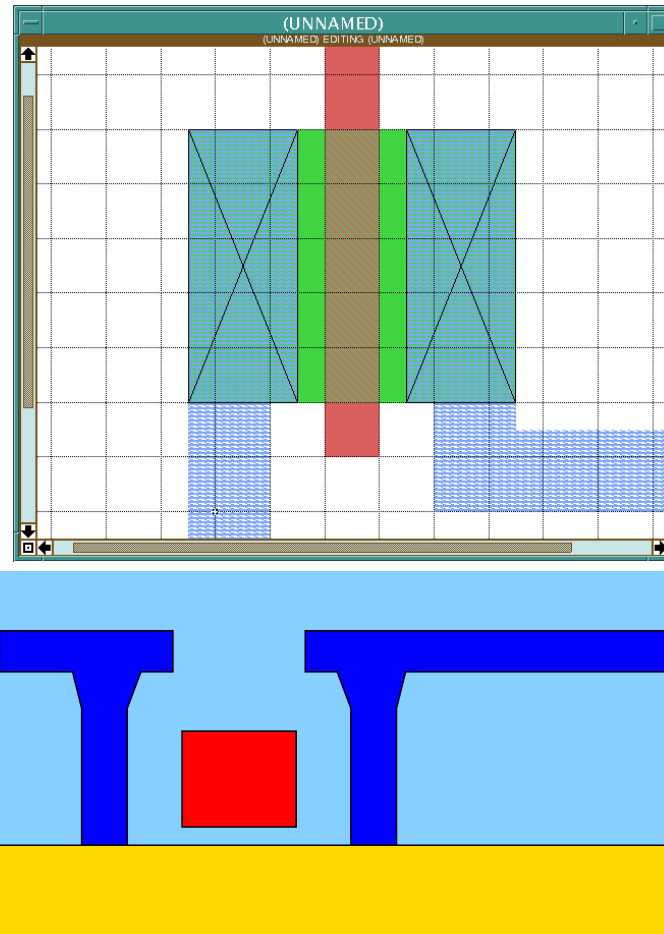
analytical approximation: Suitable for rule-based extraction

What about accuracy?

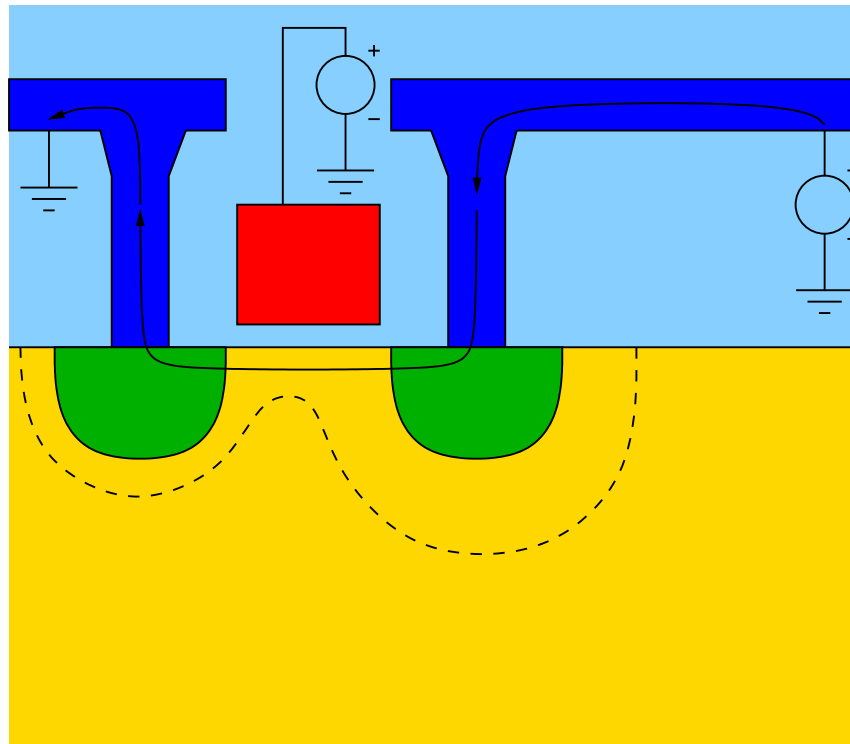
- Multiple trial solutions probe different operation modes
- For a large number of elements the Laplace equation is recovered
- The model can be further optimized on simulation and/or experimental data
- The topology can be used as a template for order reduction of another model (the “smart mesh”)

3. SEMICONDUCTOR DEVICES

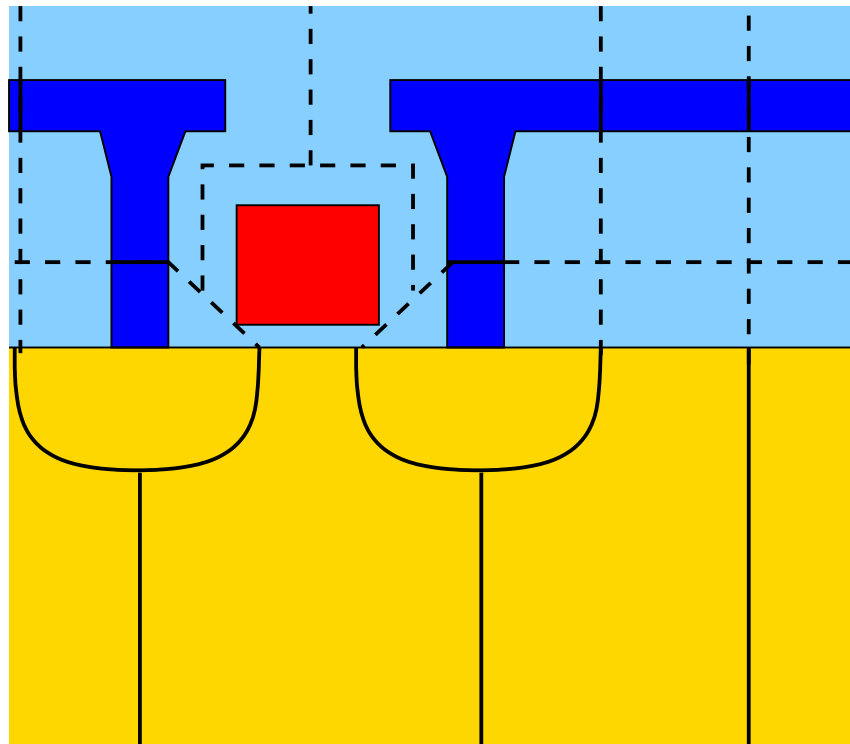
Phase 1: Geometry generation



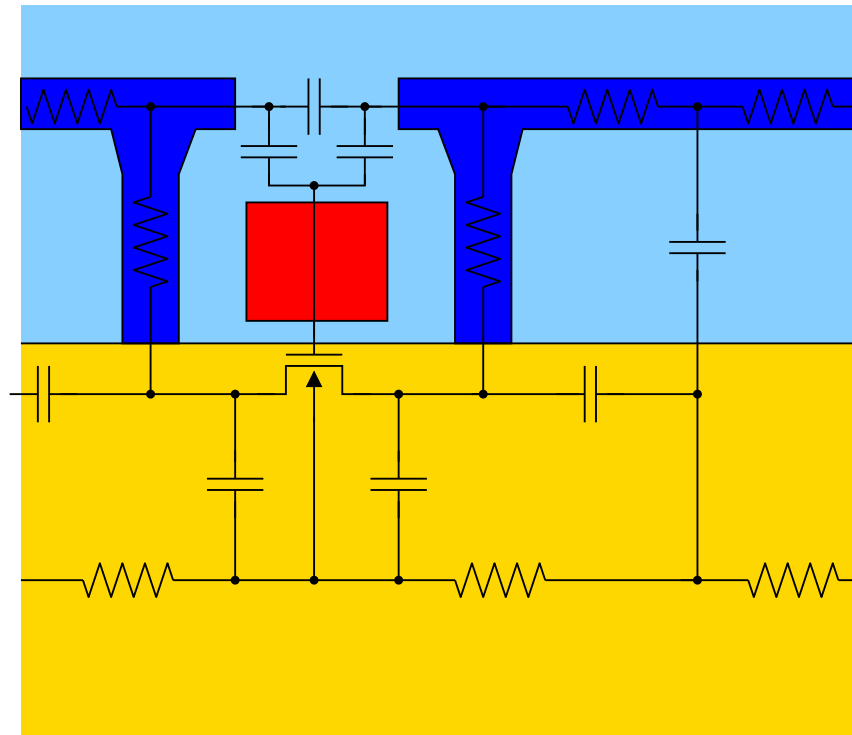
Phase 2: Simulation



Phase 3: Partitioning



Phase 4: Extraction

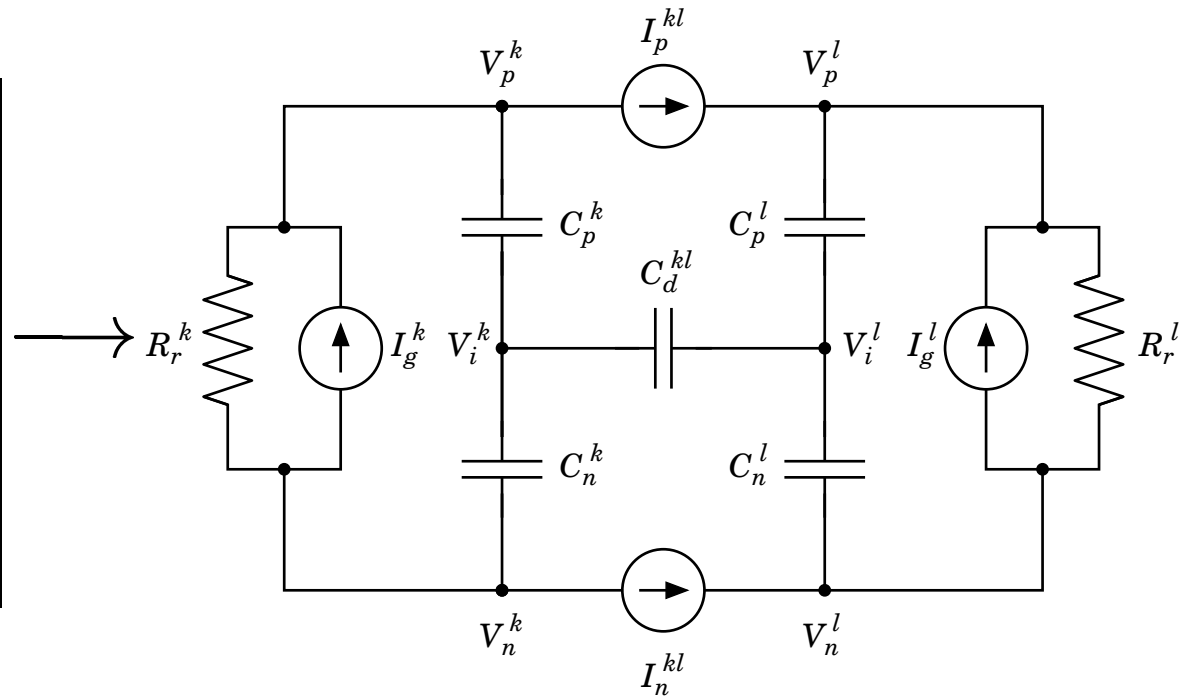


The circuit building block

$$e \frac{\partial p}{\partial t} = -\nabla J_p - eR$$

$$\nabla(\epsilon \nabla \phi) = e(n - p)$$

$$e \frac{\partial n}{\partial t} = \nabla J_n - eR$$

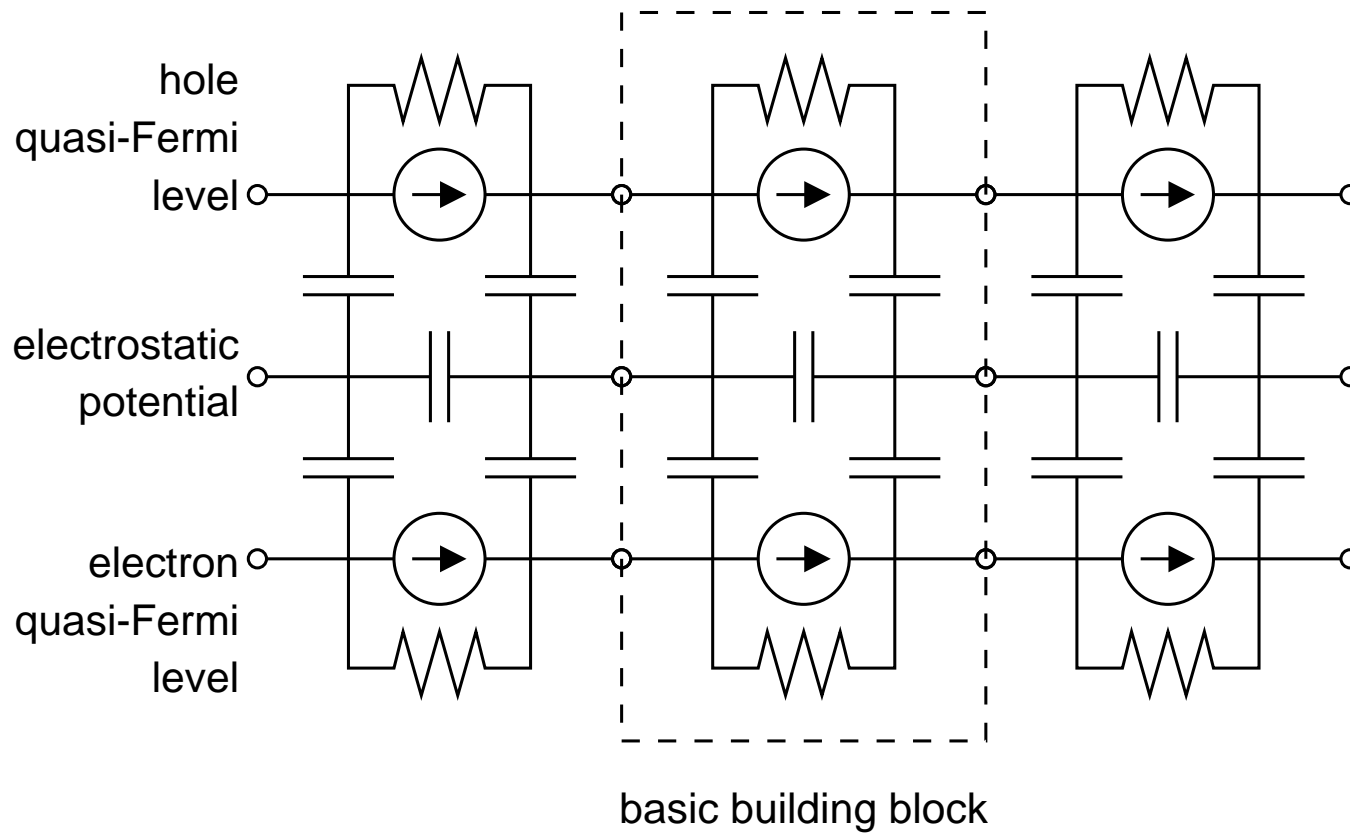


Circuit elements are extracted from device simulations

$$C_n = \frac{\delta Q_n}{\delta(V_i - V_n)}$$
$$R_n = \frac{\delta(V'_n - V_n)}{\delta J_{vn}}$$
$$G_n = \frac{\delta J_{dn}}{\delta(V_i - V_n)}$$

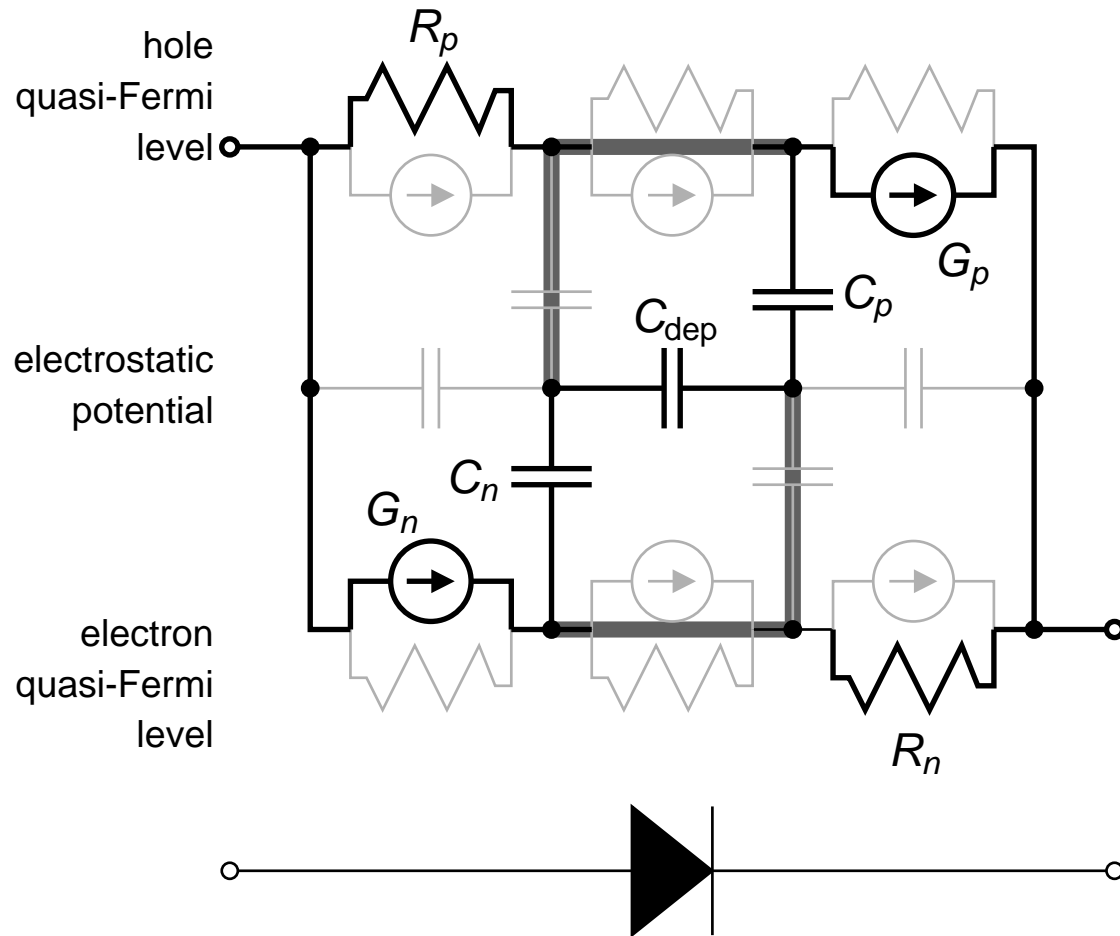
Only **dc** solutions are needed

One-dimensional implementation

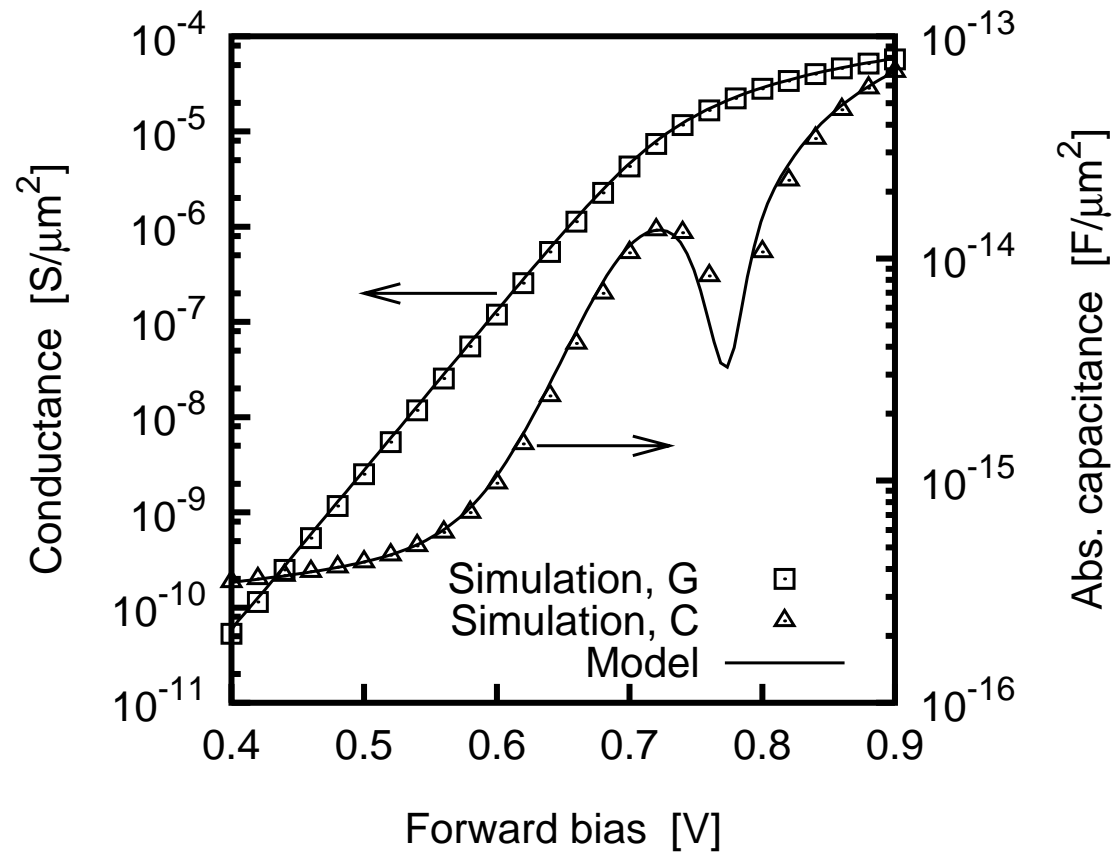


- 1D drift-diffusion simulations performed with PADRE (Bell Labs)
- Extracted quantities: Potential, electron and hole concentrations
- Small-signal quantities obtained from numerical differentiation or ac analysis
- Large-signal behavior obtained as combination of bias-dependent small-signal models

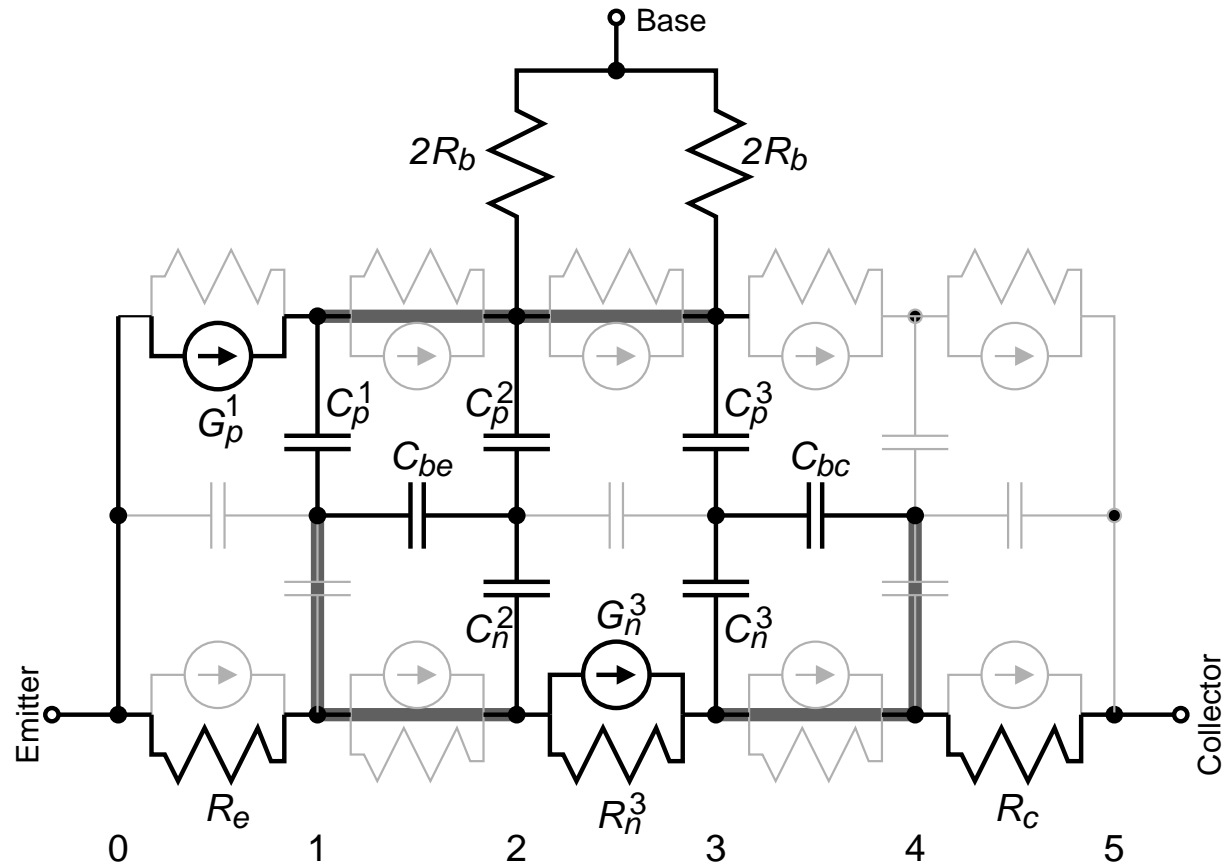
PN junction



Negative capacitance at high forward bias



0.25 μm bipolar transistor



4. EXTENSIONS

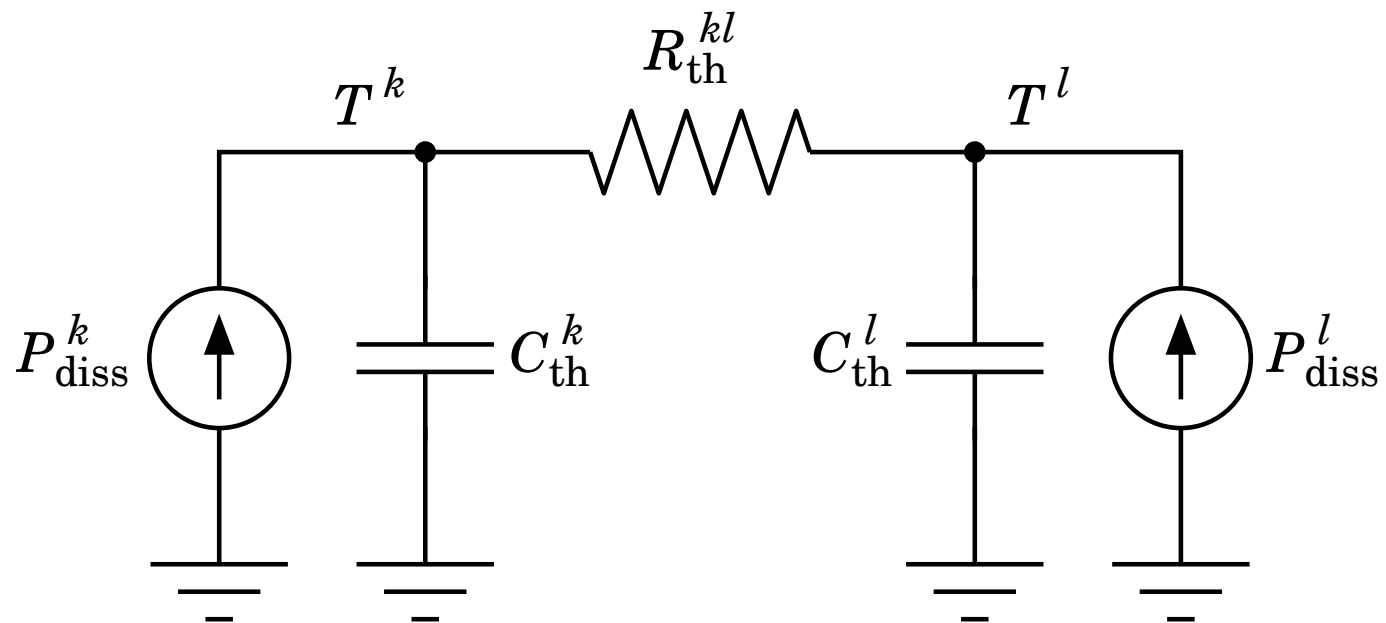
Electromagnetic effects

- A circuit can be formulated for both magnetostatics (inductance) and wave propagation (speed-of-light effects)
- Circuit topology based on vector potential
- The model is local and provably stable
- Full layout extraction implementation in progress

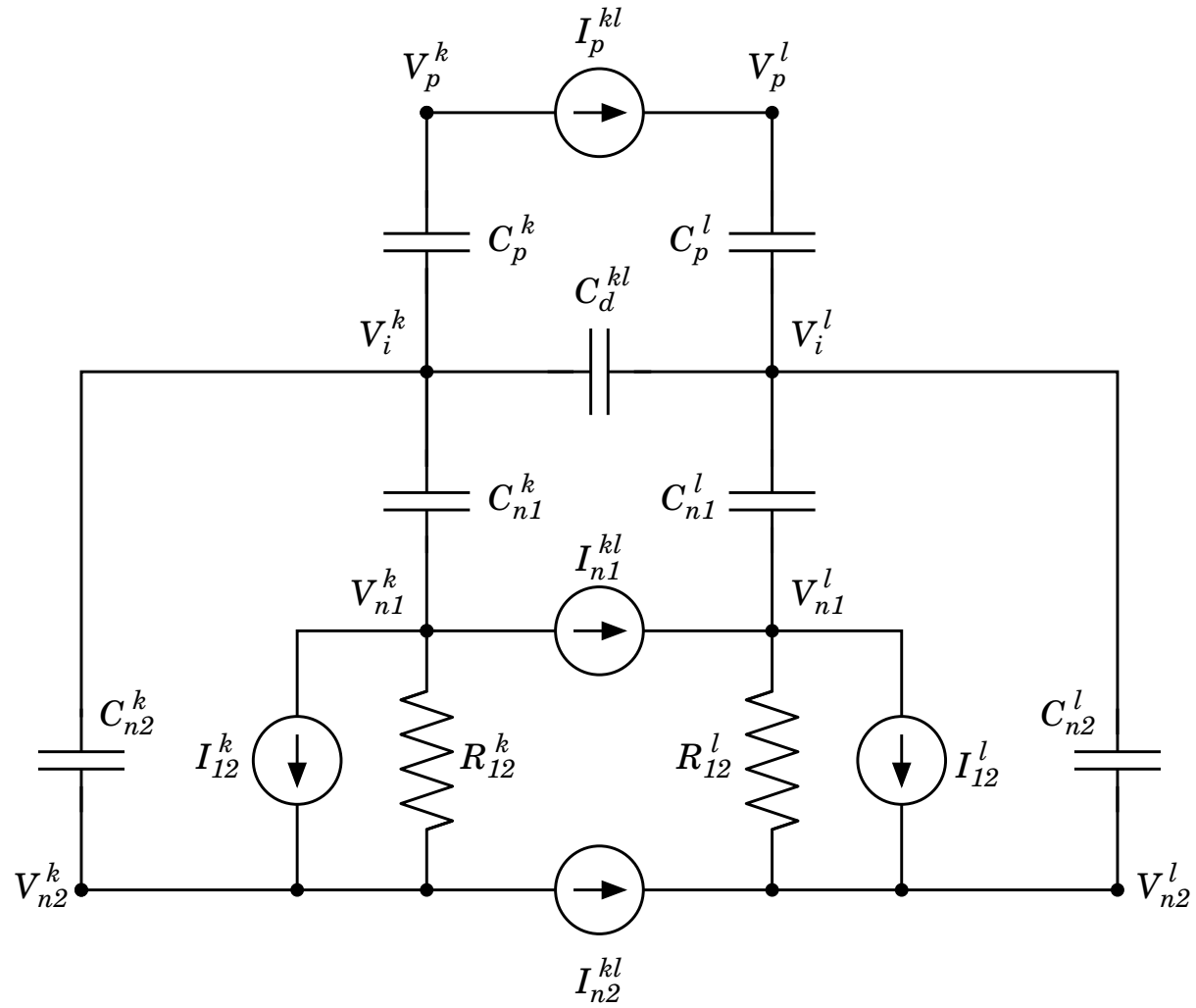
Substrate coupling

- Smart mesh versus Green's functions
- Must couple long-range and short-range propagation (similar to hierarchical models)
- High potential for handling full-chip simulation

Self-heating and thermal coupling

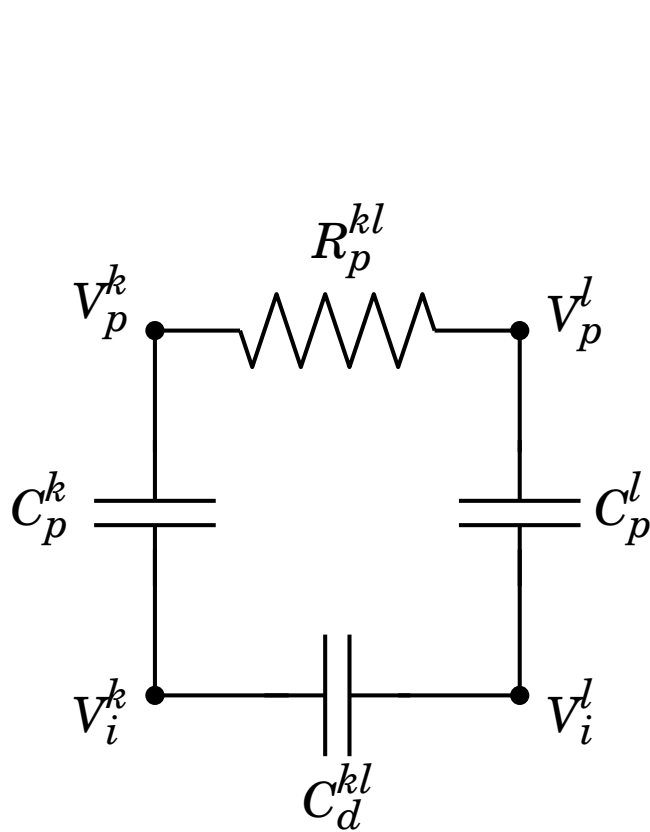


Hot-carrier and quantum-mechanical effects

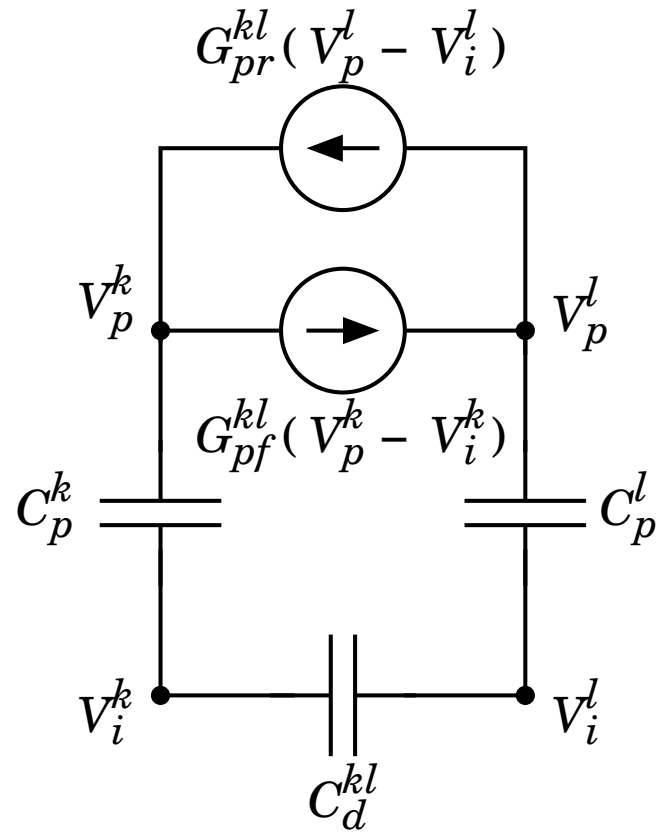


5. IMPLEMENTATION ISSUES

Choice of circuit topology

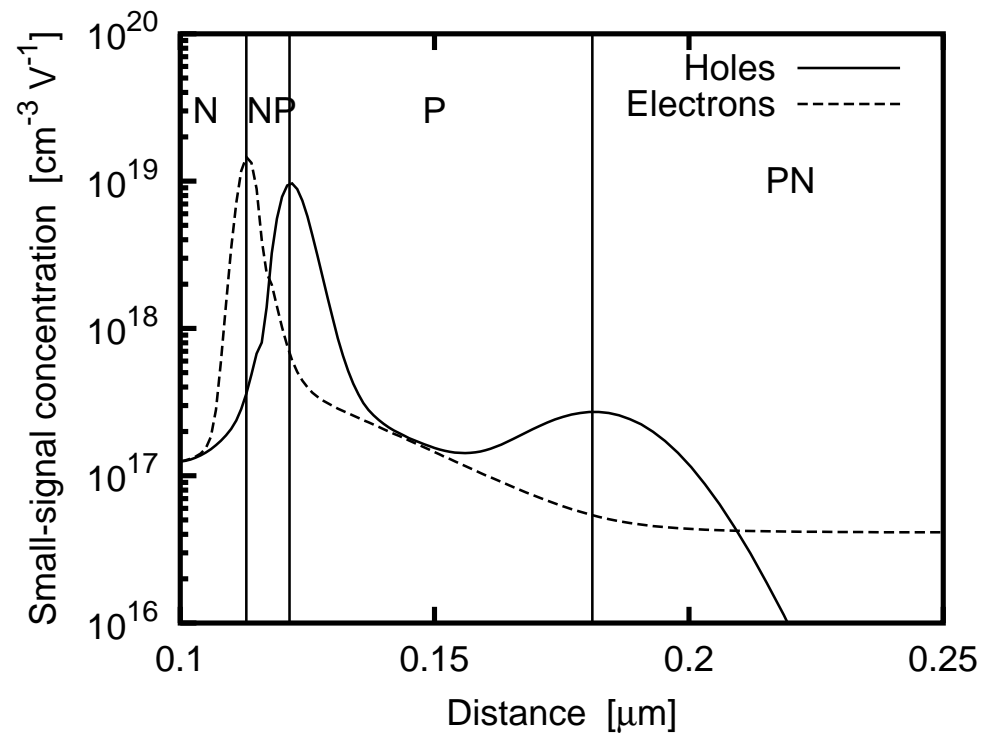


Simple, general topology

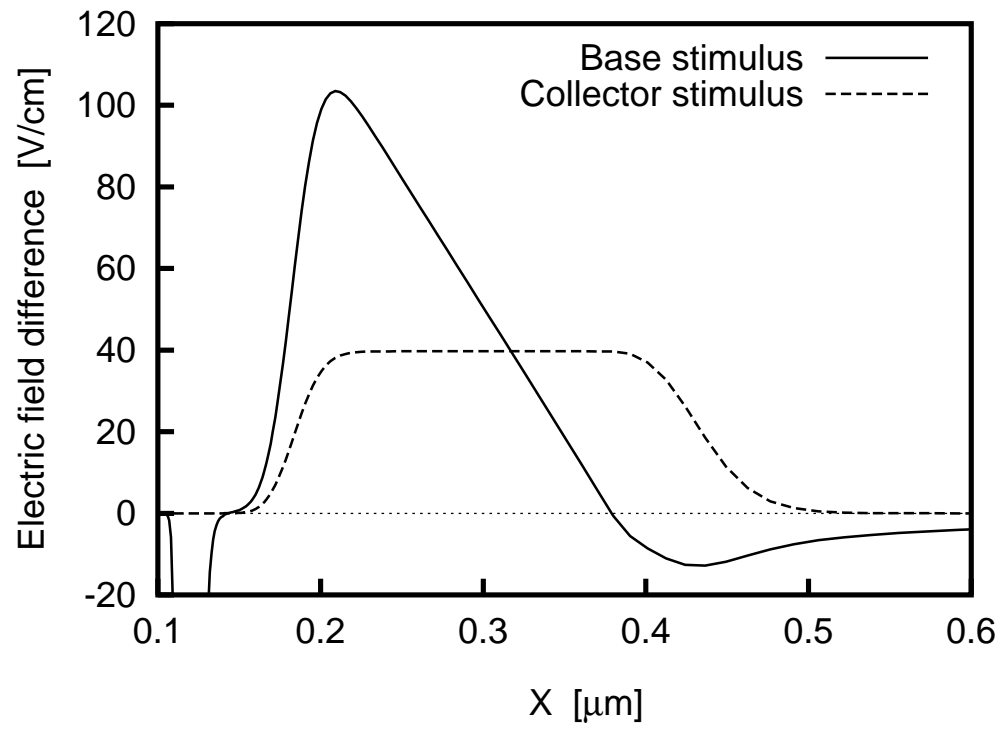


Diffusion-specific topology

Partitioning



Choice of stimuli



Conclusions

- Models can be generated in a consistent fashion for a number of physical effects, from electromagnetics to quantum mechanics
- Using a combination of numerical simulation and well-known analytical results, a high degree of automation can be achieved