Electrothermal HBT modeling

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Outline

- Introduction
- 3D numerical heat flow equation solver (THERMO)
- Green’s function approach
- Test structure for determining thermal coupling
- Summary

Introduction

- Shrinking device dimensions
  - higher electric fields and increased *self-heating*
  - increasing impact on *carrier transport* and *reliability* of the device
- Increased packing density
  - higher thermal *interaction* between neighboring devices (thermal coupling)
  - detect/avoid *hot-spots* in larger devices (e.g. PA-arrays)

=> in-house development

- accurate numerical (discretized) solution (THERMO)
  - highest degree of flexibility (e.g. new material models, boundary conditions, structure, etc.)
  - access on internal quantities and verification of R_{th}/C_{th} extraction methods
  - thermal modeling beyond current materials and models (roadmapping)
- fast solution (Green's function)
  - support of compact model generation and device design, sizing, and optimization
  - fast investigation of temperature distribution across large structures
  - advanced thermal network development (static and transient beyond single R_{th}-C_{th} network)

3D numerical heat flow equation solver (THERMO)

- Numerical solution of the heat flow equation (1D to 3D):

$$div(\kappa(\vec{r}, T_L)grad(T_L)) = \alpha(\vec{r}, T_L)\frac{\partial T_L}{\partial t} - p_{Diss}(\vec{r})$$

- Features:
  - stationary and transient solutions
  - variety of physical models (thermal conductivity κ, thermal diffusivity α)
  - materials covered: Si, SiO_2, SiGe (preliminary model), etc. (parameters from literature)
  - post-processor for determining the most important parameters/quantities (R_{th},...)
  - internal results saved as MAT-Files => can be directly accessed by Matlab/Octave

=> suitable for most applications

discretization and simulation time strongly depend on investigated structure

- Restrictions:
  - only rectangular domains (regular grids) so far => extension to non-regular if demanded

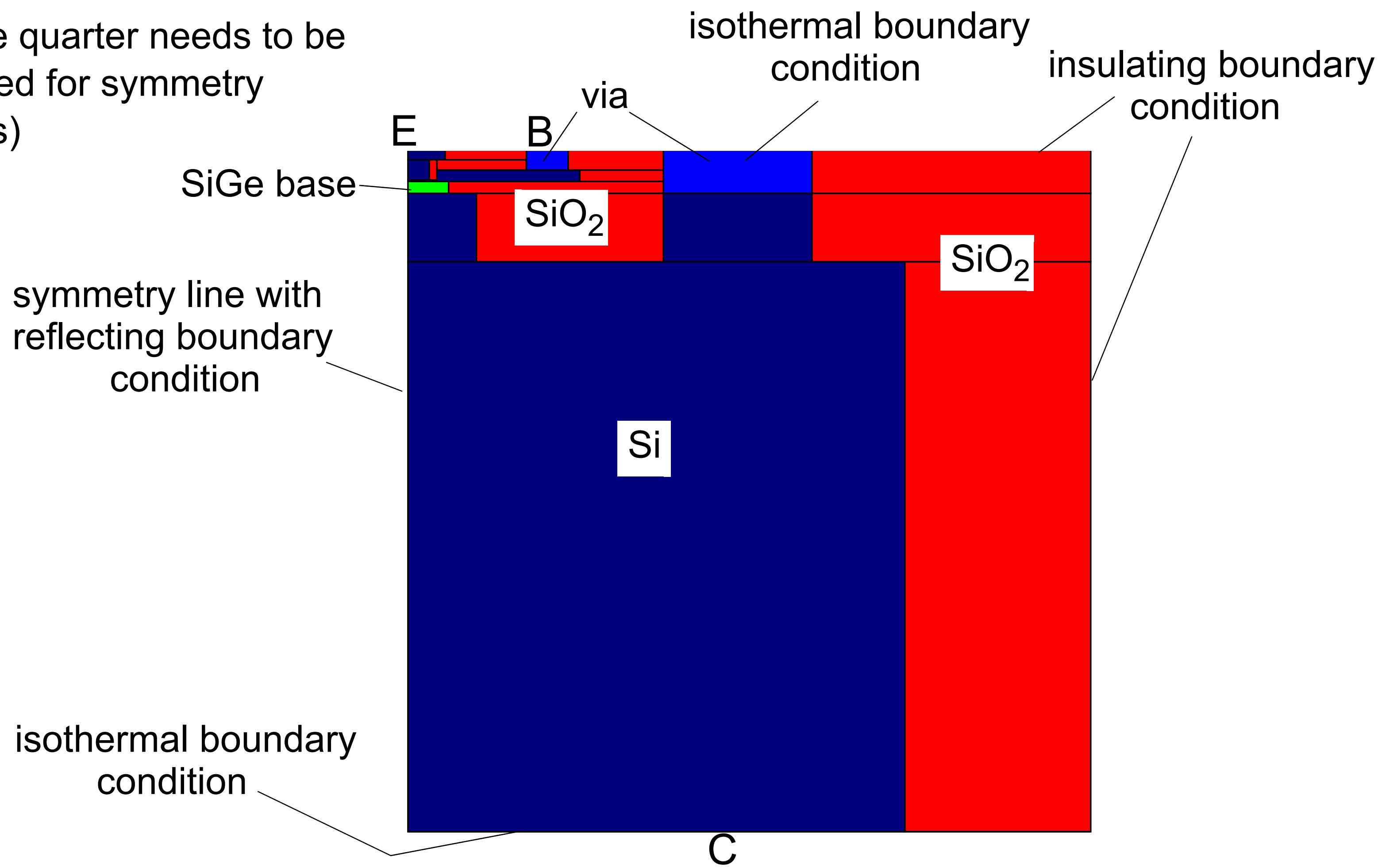
=> tool supports compact modeling and experimental data evaluation

Application example

3D simulation of a fabricated SiGe HBT (CBEBC)

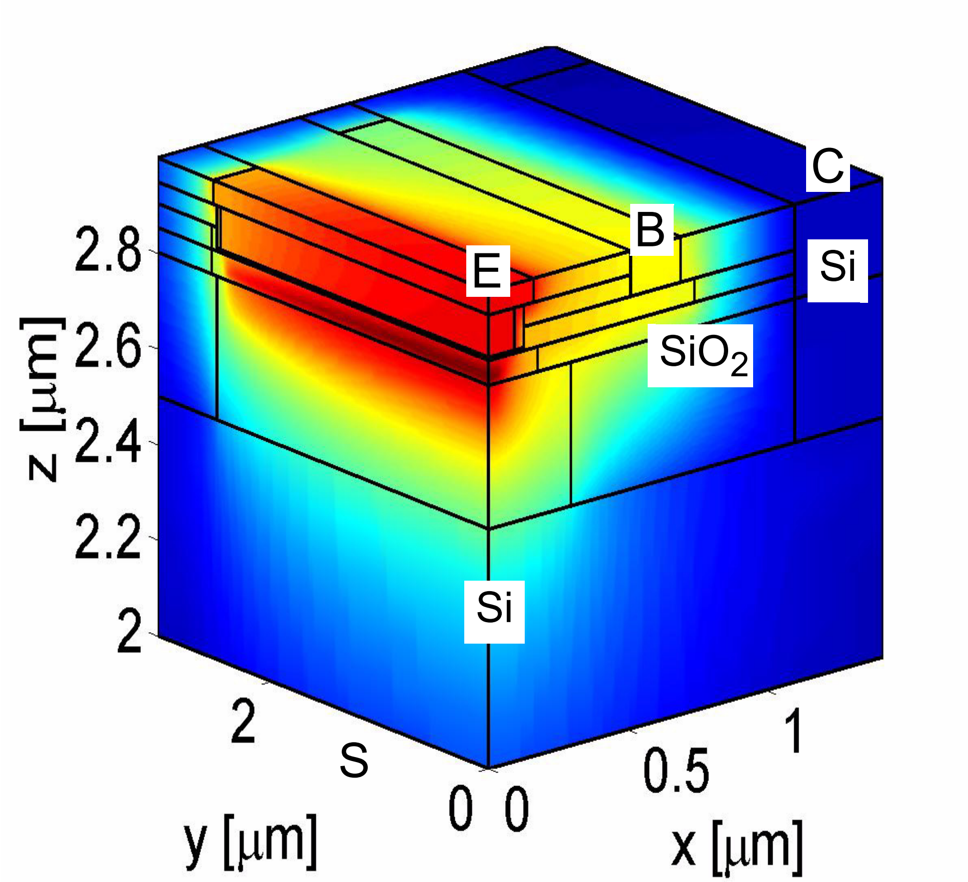
2D cross section of a 3D structure

(only one quarter needs to be simulated for symmetry reasons)



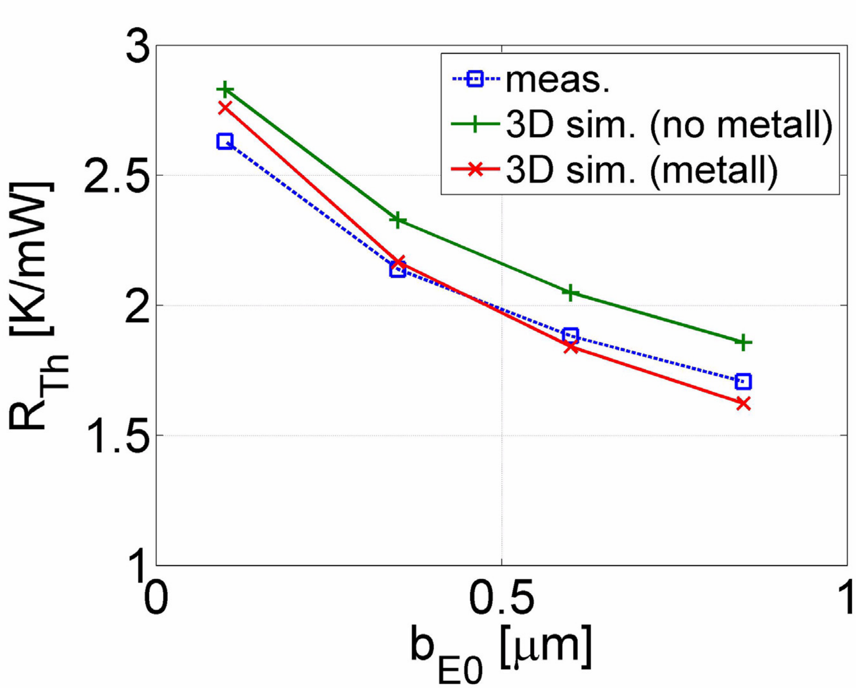
Results

3D temperature distribution



thermal resistance

simulated vs. measured geometry dependence



=> impact of including surface metallization still approximate

=> Simulation and measured results agree with each other within range of uncertainty margin (structure, physical models and parameters)!

Green's function approach

... for 3D heat equation

- Semi-analytical solution of linear heat flow equation (1D to 3D):

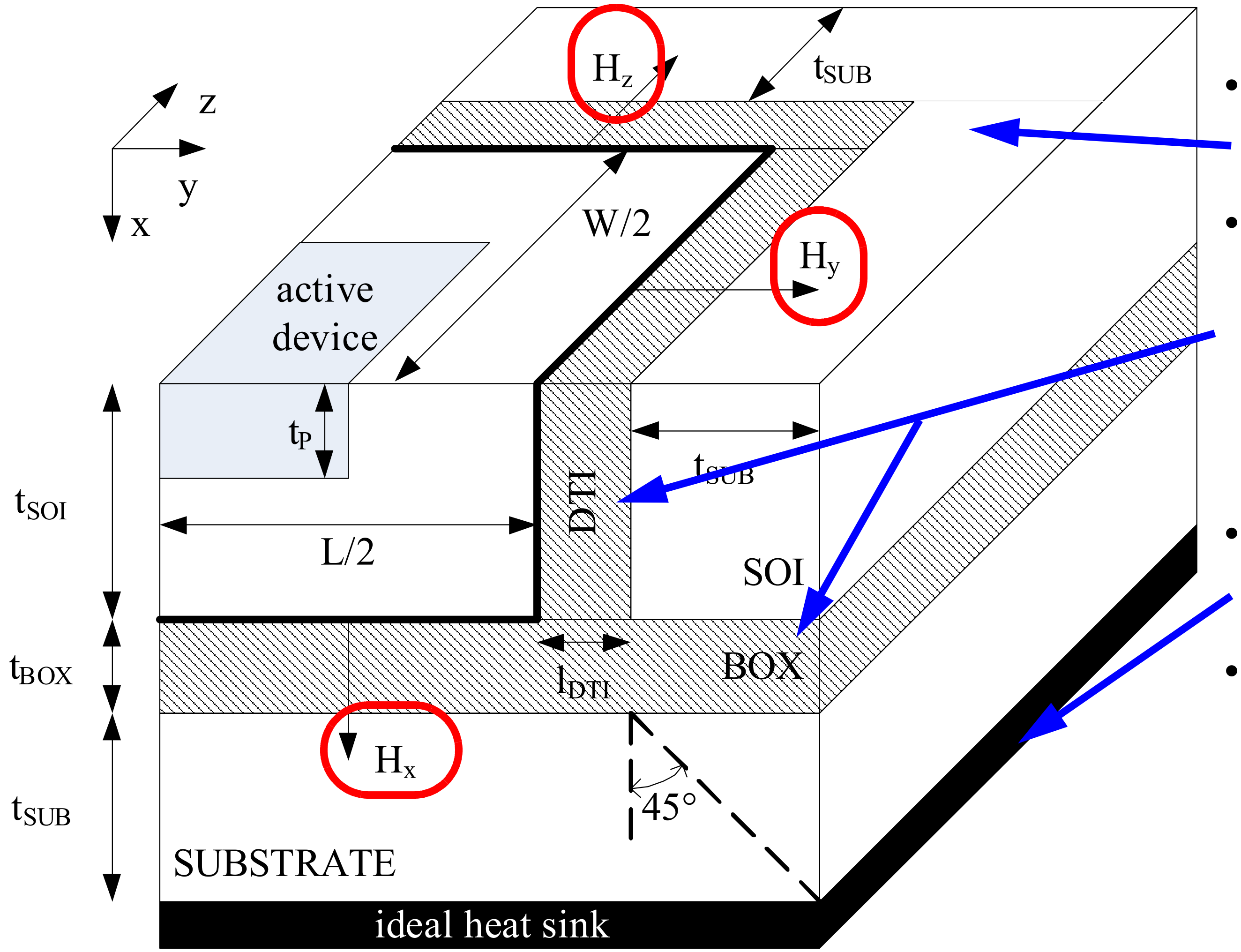
$$div(\kappa grad(T_L)) = \alpha\frac{\partial T_L}{\partial t} - p_{Diss}(\vec{r})$$

- Features
  - *stationary* and *transient* solutions for *small* AND *large* homogeneous domains, either (semi-) infinite (e.g. lateral substrate extension) or with laterally bounding regions (e.g. trench)
  - possible boundary conditions:
    - at surfaces: spatially variable temperature $T_L = f(\vec{r})$ or heat flux $\kappa\frac{\partial T_L}{\partial n} = f(\vec{r})$
    - at interfaces convection boundary condition $\kappa\frac{\partial T_L}{\partial n} + hT_L = 0$

      with heat transfer coefficient *h* for, e.g., reduced heat flow into trench-walls or buried oxide with different thermal conductivity
  - *temperature dependent non-linear thermal conductivity* can be included through *Kirchhoff transformation* (=> e.g. $R_{th}(T_L)$)

Example

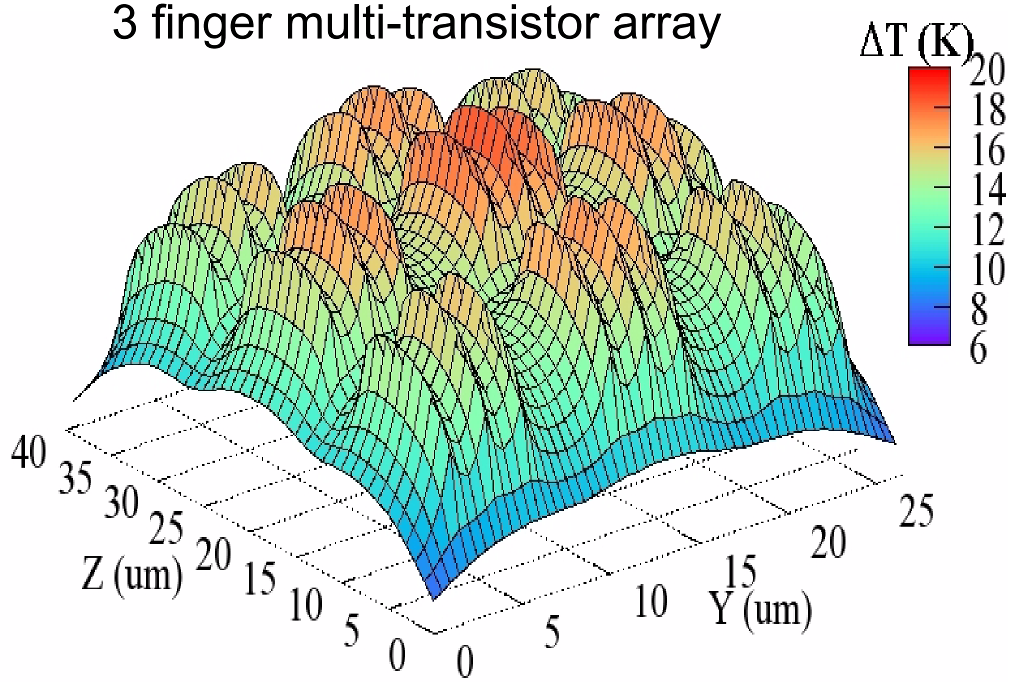
Thermal characterization of active devices fabricated in a SOI technology



- insulating boundary at substrate surface
- reduced heat flux into DTI and BOX modeled by convection b.c. (use of heat transfer coefficients H_x, H_y, H_z)
- isothermal b.c. at chip backside (heat sink)
- exploiting symmetry through use of insulating b.c.

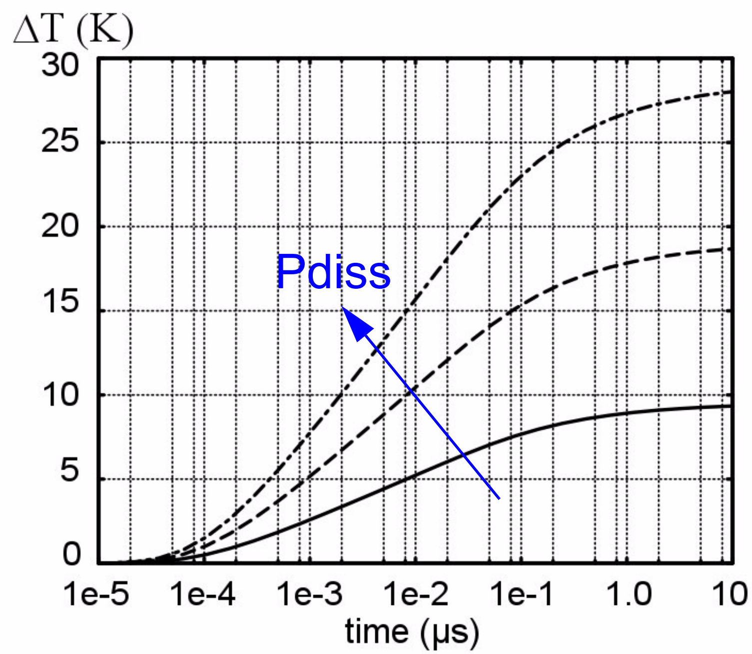
Applications

3D temperature distribution in a 3 finger multi-transistor array



=> detect peak temperature & reliability issues

time dependence of temperature increase during dynamic operation



=> dynamic thermal network

- fast investigation/generation (seconds) of temperature distributions also over large structures (e.g. transistor arrays)
- easily tunable through use of results from measurements/extraction and numerical simulations

Application to circuit design and simulation

- supports efficient generation of thermal models (self-heating, thermal coupling)
- thermal models available in SPICE and VERILOG-A format

```
.SUBCKT THNET_L4 TN001 TN002 TN003 TNAMBIENT
simulator lang=spectre
simulator lang=spice
RTH001       Tn001     Tn001001                     412.98
 ETH001002   Tn001001  Tn001002 Tn002 Tn002001    0.3676
 ETH001003   Tn001002 TNAMBIENT Tn003 Tn003001    0.2585
RTH002       Tn002     Tn002001                     412.98
 ETH002001   Tn002001  Tn002002 Tn001 Tn001001    0.3676
....
```

thermal network

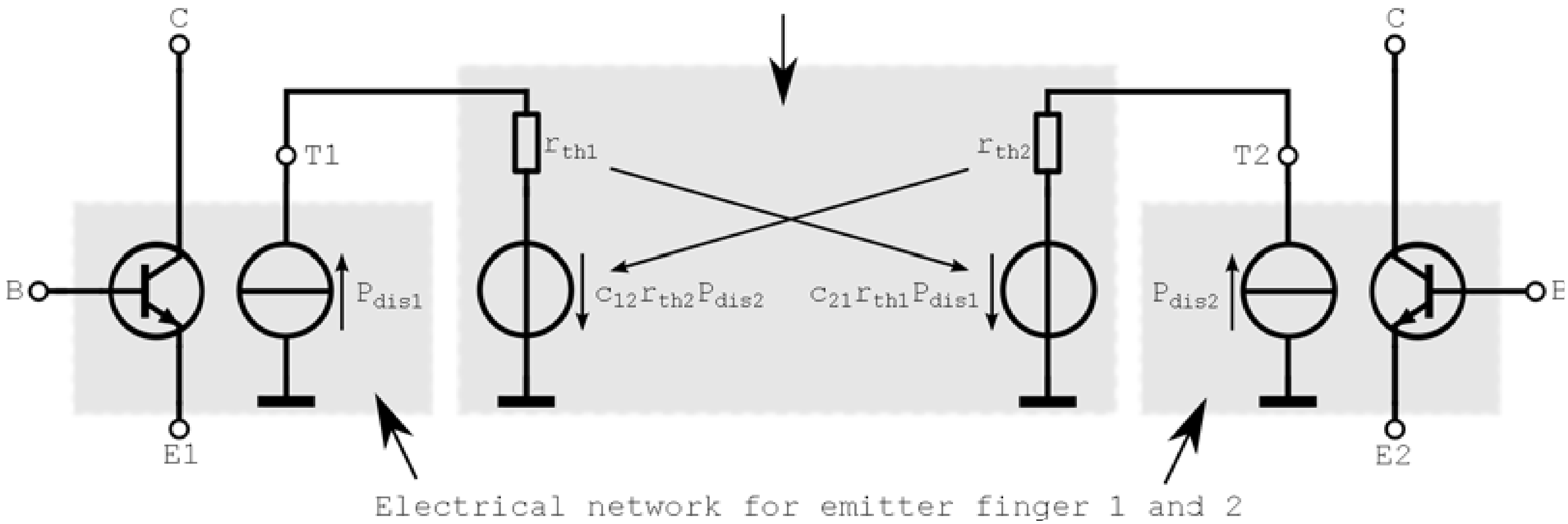
```
analog
  begin
   Tnom = tnom+`P_CELSIUS0;
//=== self-heating source  1
   rth001   =   412.98;
   rth001_t = rth001 * exp(zetarth * ln(($temperature + V(Tn001)) / Tnom)
    V(Tn001,Tn001001)     <+ I(Tn001,Tn001001) * rth001_t;
//--- coupling source   1
   c001002  = 0.367593;
   c001003  = 0.258534;
    V(Tn001001,Tn001002)  <+ V(Tn002,Tn002001) * c001002;
    V(Tn001002,THGND) <+ V(Tn003,Tn003001) * c001003;
```

models

=> well-suited for device sizing and layout optimization w.r.t. thermal constraints

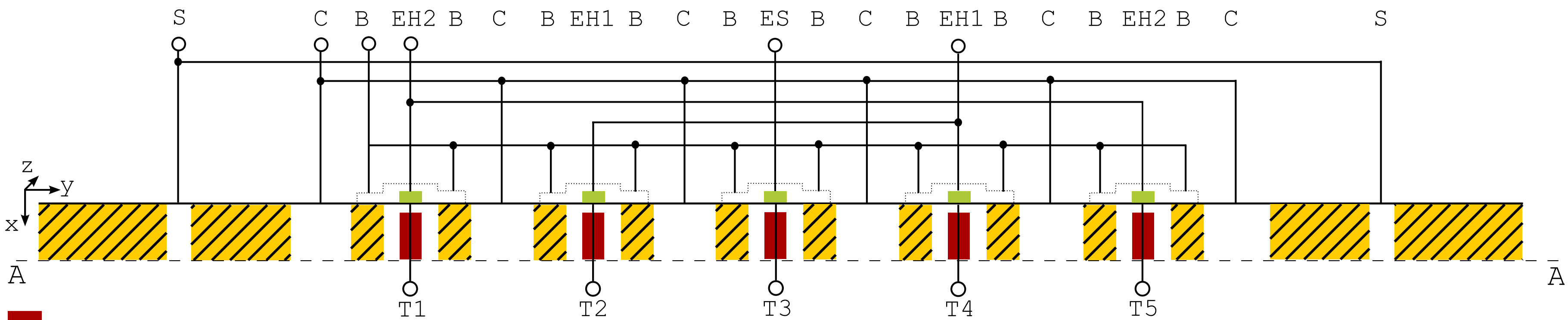
Modeling of static thermal coupling

thermal subcircuit for two-finger transistor or two transistor cells (example)



- need external access to thermal node in compact model
- set thermal resistance of compact model to infinity
- temperature dependence of thermal resistance in thermal subcircuit included through Verilog-A code

Test structure for determining thermal coupling

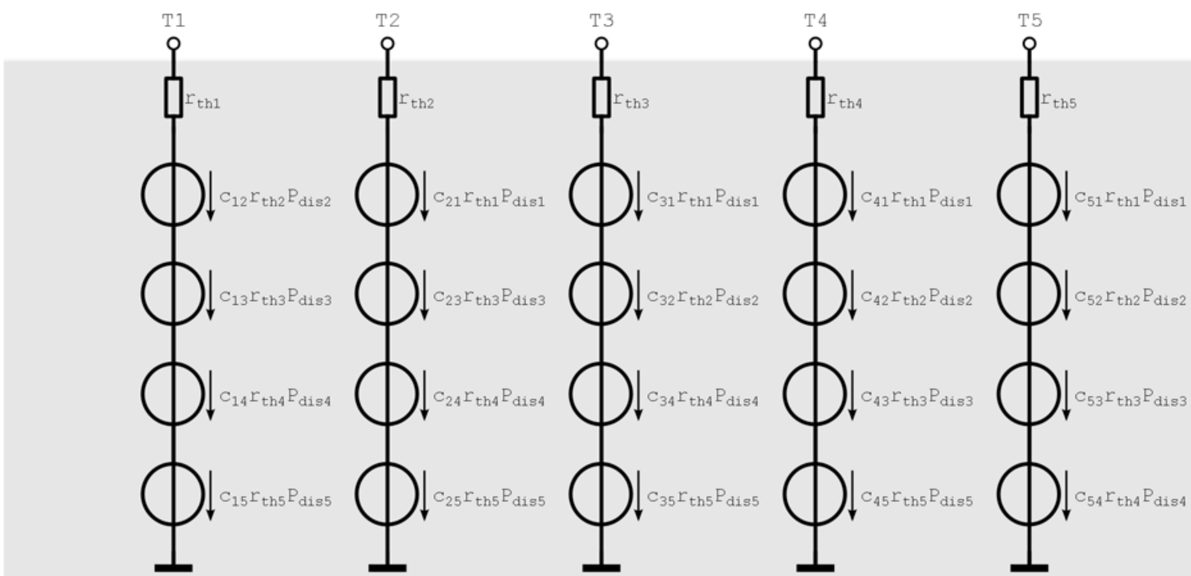


Heat source domain

Shallow trench

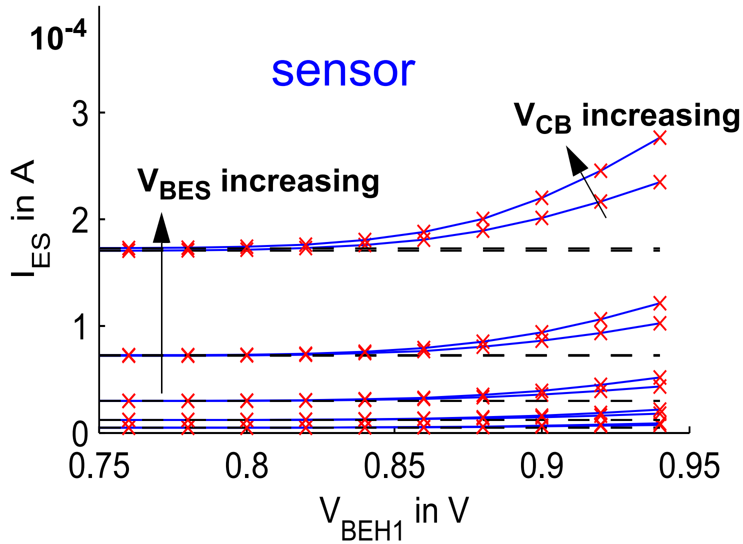
Emitter

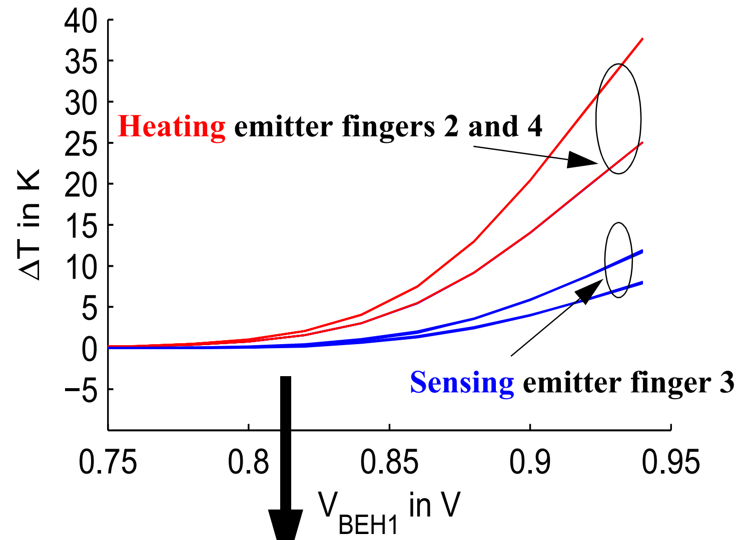
common S, B, C => use E as sensor and for adjusting power

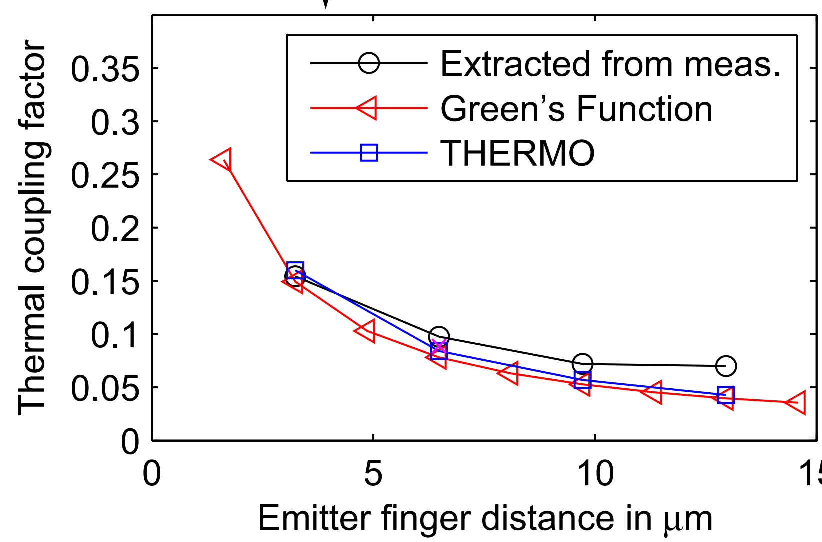


=> fabricated in Si and investigated with THERMO, GF

Extraction of static thermal coupling







- extraction of (temperature) coupling from heating emitter fingers 2 and 4 to emitter finger 3

$$I_{ES} = I_{ESS}(T_{amb} + \Delta T)\exp\left(\frac{qV_{BES}}{mk_B(T+\Delta T)}\right)$$

$$\Delta T = r_{th,EH1}P_{EH1}$$

- Note: finger symmetry to be considered!

Summary

- Numerical thermal solver
  - captures complicated structures without simplifications
  - good agreement with measured R_{th} of state-of-the art devices
  - aid in tuning of GF-based method (e.g. determination of heat transfer coefficients)
  - highly valuable for (HBT) roadmapping

- GF-method
  - can be adjusted to model realistic structures (including DTI, SOI)
  - well-suited for large *and* small structures (i.e. including arrays of transistors)
  - fast but still accurate results for model generation and circuit design related applications (sizing, optimization)

- Accuracy depends on material models and parameters!!!

=> test structures and measurements needed for development/verification of material models for advanced devices

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- IHP, Frakfurt/Oder, Germany
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