An electro-thermal DMOS model validated on pulsed measurements

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Contents

- *Introduction*
- *Electro-thermal DMOS model*
- *Thermal simulations on floorplan level*
- *Conclusions*

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Introduction

- ***Smart-power technologies:***
  - Large power drivers (voltage ~100V, current ~10A)
  - Sensitive analog circuits: interface to outside world
  - Digital circuitry
- ***High local temperature due to:***
  - High ambient temperature (example: automotive)
  - High power dissipation (drivers)
- ***Importance of (electro-)thermal modelling:***
  - Prediction of reliability issues: electro-migration, TDDB, temp. enhanced BTI, triggering parasitic bipolar, bondwire reliability
  - Device self-heating effects
  - Impact of heating on (sensitive) neighbouring circuits

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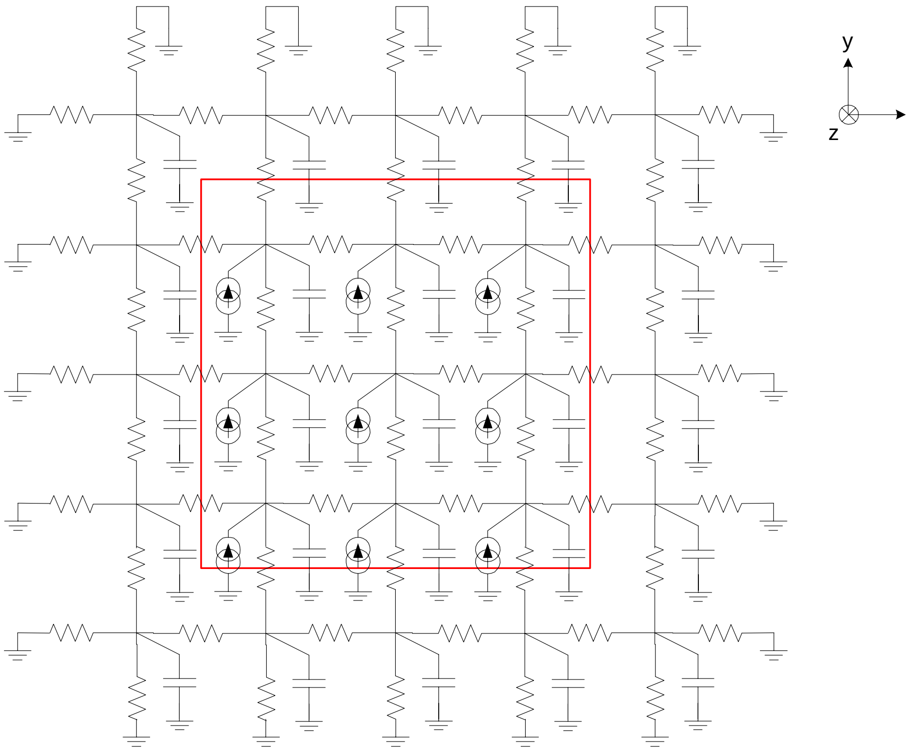
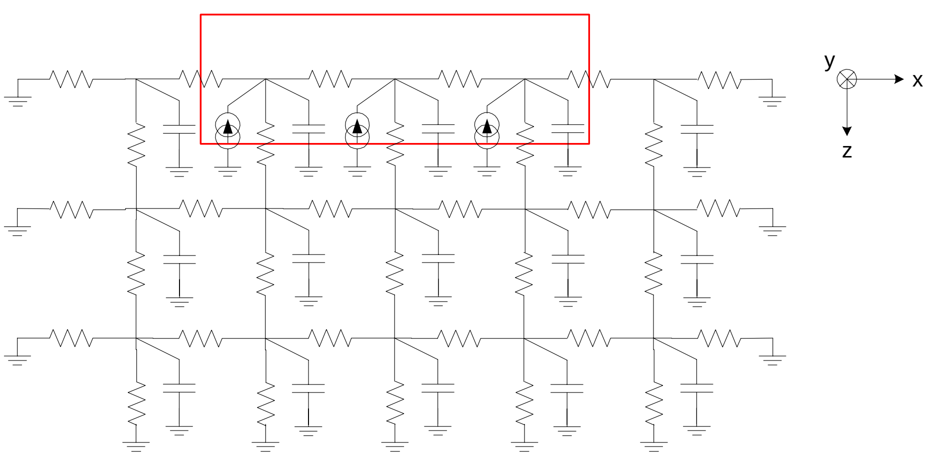
Thermal RC-network

- **Discretisation of space**
- **Modelling of thermal behaviour:**
  - Resistors: heat conduction
  - Capacitors: heat storage
  - Current sources: heat generation

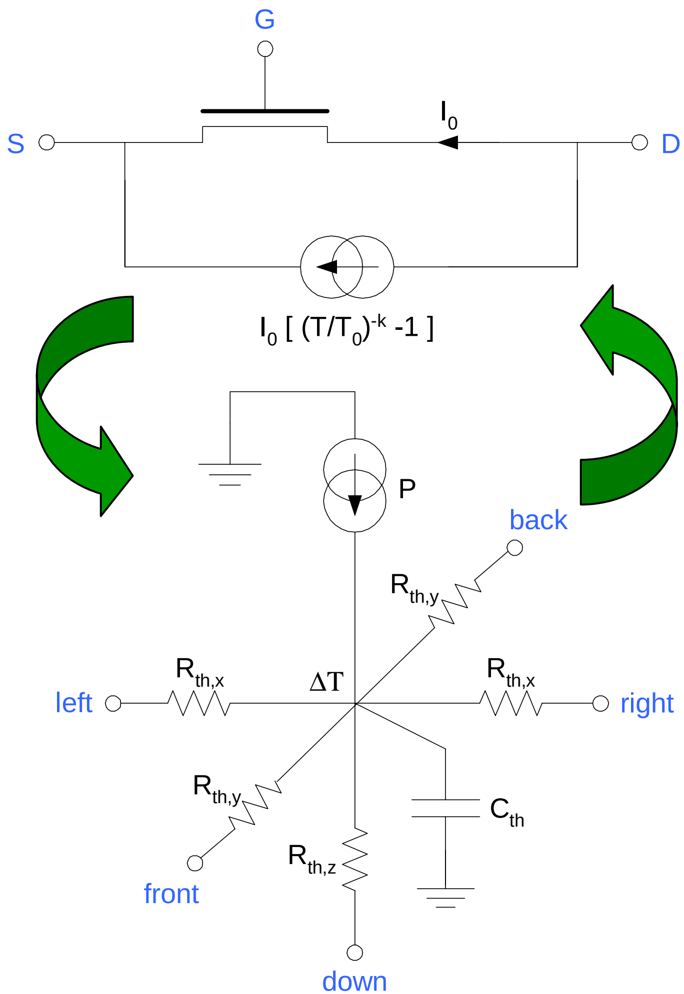
TOP VIEW



SIDE VIEW



Elementary electro-thermal cell



$$\frac{I}{I_0} = \left(\frac{T}{T_0}\right)^{-k}$$

electrical part

coupling

thermal part

Electro-thermal cell in Verilog-A

```
`include "discipline.h"
`include "constants.h"

module electrothermal_cell_3D (el_d, el_s, el_dd,
          th_left, th_right, th_front, th_back, th_up, th_down);

inout el_d, el_s, el_dd,
    th_left, th_right, th_front, th_back, th_down;

electrical el_d, el_s, el_dd;
thermal th_left, th_right, th_front, th_back, th_up, th_down,
        th_center;

parameter real rth_left = 1, rth_right = 1, rth_front = 1, rth_back
        = 1, rth_up = 1, rth_down = 1;
parameter real cth = 1;
parameter real k_exp = 1;

real temp_rise, I0, delta_I, I_tot, P0, P;

analog begin

  temp_rise = Temp (th_center);

  I0 = I (el_d, el_dd);
  delta_I = I0 * (pow (1 + temp_rise / $temperature, - k_exp) - 1);
  I_tot = I0 + delta_I;

  P0 = I0 * V (el_d, el_s);
  P =  I_tot * V (el_d, el_s);

  Pwr (th_center, th_left)  <+ Temp (th_center, th_left)  / rth_left;
  Pwr (th_center, th_right) <+ Temp (th_center, th_right) / rth_right;
  Pwr (th_center, th_front) <+ Temp (th_center, th_front) / rth_front;
  Pwr (th_center, th_back)  <+ Temp (th_center, th_back)  / rth_back;
  Pwr (th_center, th_up)    <+ Temp (th_center, th_up)    / rth_up;
  Pwr (th_center, th_down)  <+ Temp (th_center, th_down)  /
      rth_down;

  Pwr (th_center) <+ cth * ddt (temp_rise);
  Pwr (th_center) <+ - P;

  I (el_d, el_s) <+ delta_I;

end

endmodule
```

self-heating effect

thermal resistors

thermal capacitance

Automatic generation of netlist

- **Full electro-thermal model: typical example:**
  - 15 x 15 lateral grid cells per layer
    (5 x 5 for internal DMOS region)
  - 5 vertical layers
- **Automatic generation of netlist using Matlab program:**
  - Inputs:
    - material properties
    - number of grid cells
  - Output:
    - full generic netlist
    - all parameters in netlist scale with DMOS dimensions

Netlist electro-thermal DMOS model

```
simulator lang = spectre

inline subckt DMOS_self_heating (d g s)
parameters
+ w = 80
+ ns = 2
+ pitch = 8
+ W = w/ns
+ L = ns*pitch
+ rs = 40m
+ rd = 40m
+ k_exp=0.55

   t_1_1_1 (0 1_1_1 0 1_1_1 0 1_1_1) thermal_cell_3D rth_left=2000*W/L
       rth_right=333.333*W/L rth_front=2000*L/W rth_back=333.333*L/W
       rth_up=2.66667e+010/(W*L) rth_down=833333/(W*L) cth=6.524e-013*W*L
   ...
   d_6_6_1 (dd_6_6_1 g s) fnd40b w=w/25 ns=ns rs=rs*25 rd=rd*25
   t_6_6_1 (d s dd_6_6_1 5_6_1 6_6_1 6_5_1 6_6_1 0 6_6_1) electrothermal_cell_3D
       rth_left=333.333*W/L rth_right=333.333*W/L rth_front=333.333*L/W
       rth_back=333.333*L/W rth_up=2.66667e+010/(W*L) rth_down=833333/(W*L)
       cth=6.524e-013*W*L k_exp=k_exp
   ...
   t_15_15_5 (14_15_5 0 15_14_5 0 15_15_4 0) thermal_cell_3D rth_left=20.8333*W/L
       rth_right=125*W/L rth_front=20.8333*L/W rth_back=125*L/W
       rth_up=1.33333e+007/(W*L) rth_down=8e+007/(W*L) cth=1.04384e-011*W*L

ends DMOS_SH
```

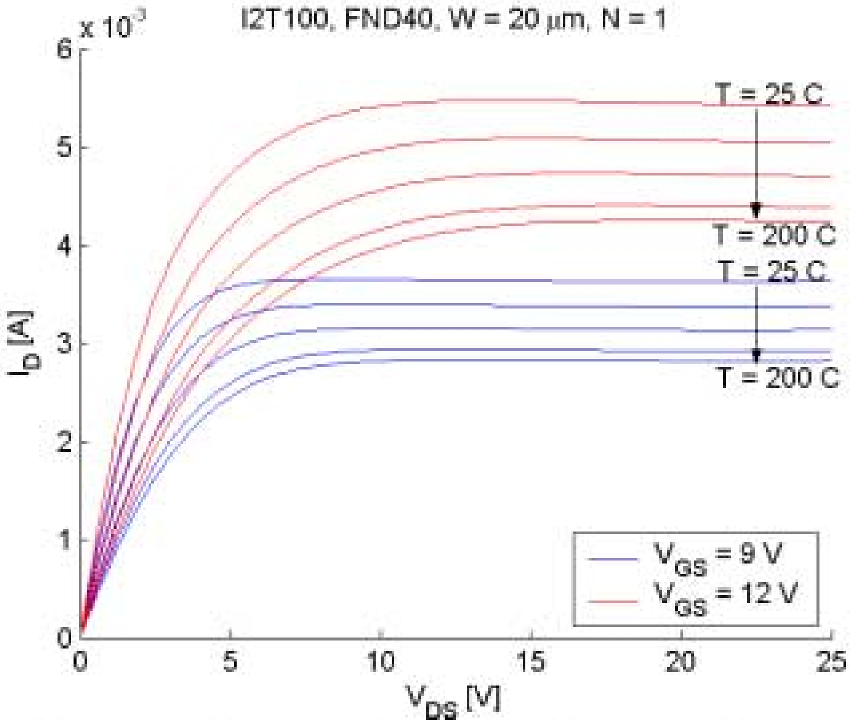
standard DMOS model

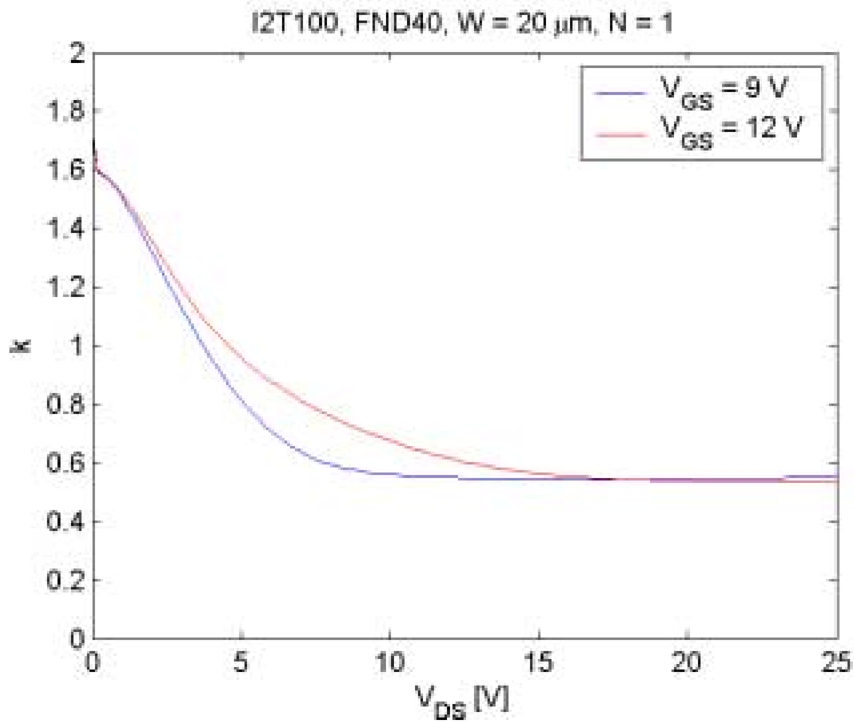
electro-thermal cell model

Extraction of exponent k

- **Assumption: temperature dependence mainly attributed to mobility decrease**
- **Power law model**
- **Extraction of *k* on small devices**

$$\frac{I}{I_0} = \left(\frac{T}{T_0}\right)^{-k}$$

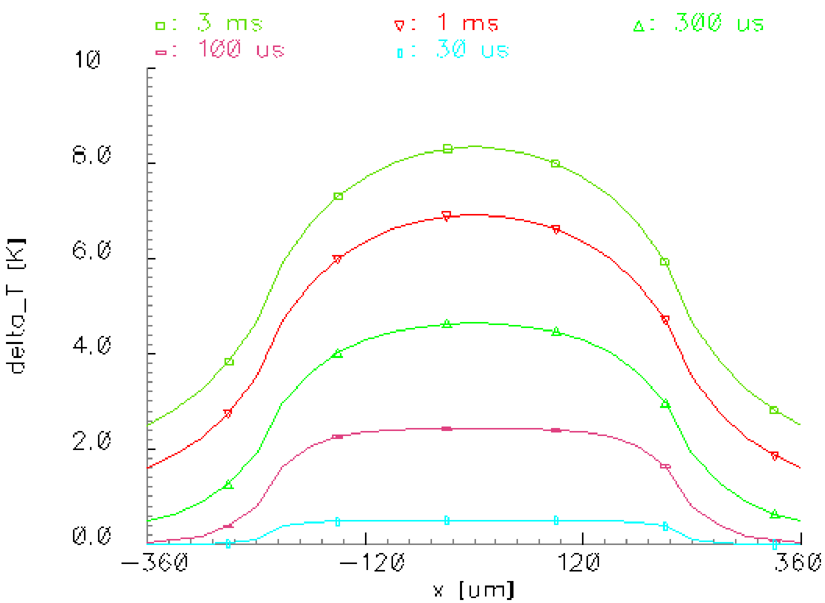




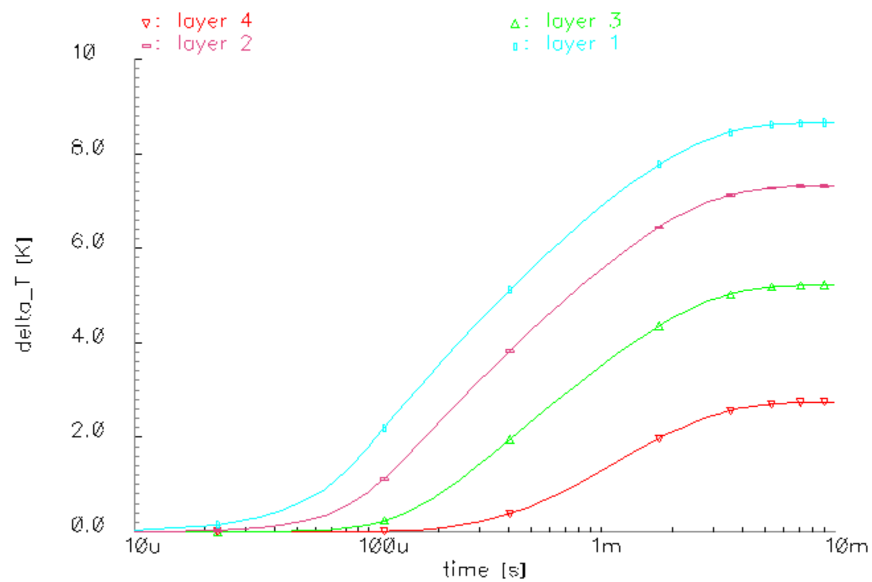
Results from Spectre simulation (1)

- **Typical output from Spectre simulation for large driver (W=450µm, L=450µm, P=1W):**

temperature through cross-section



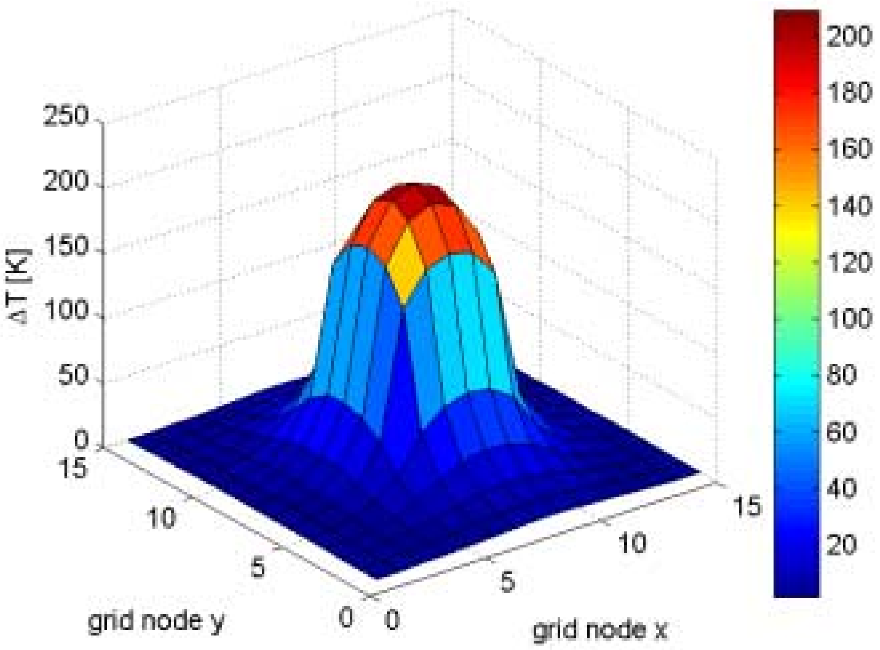
temperature versus time



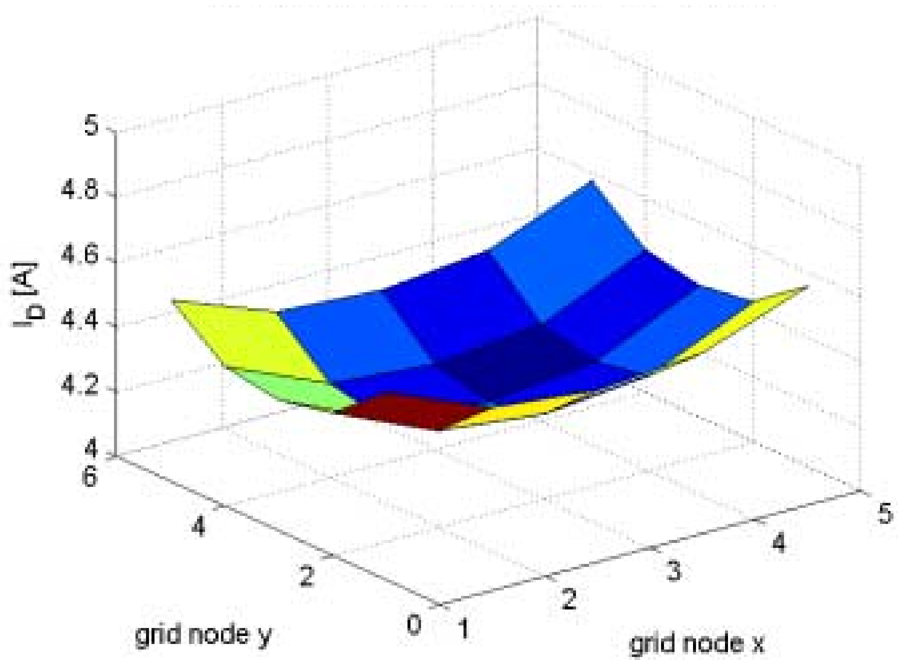
Results from Spectre simulation (2)

- **Typical output from Spectre simulation for large driver (W=450µm, L=450µm, V_{GS}=10V, V_{DS}=10V, t=500µs):**

temperature distribution



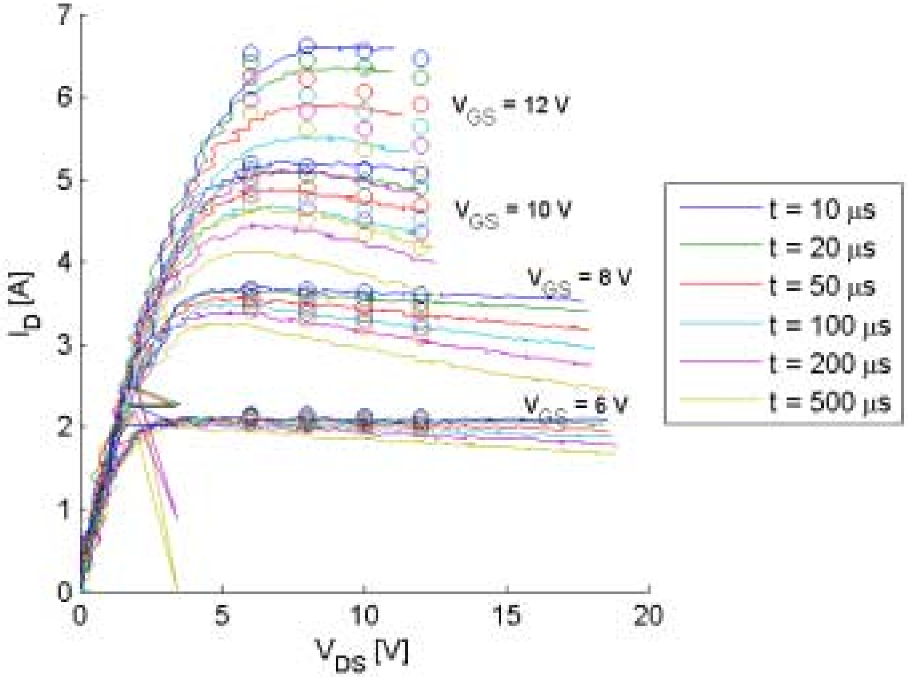
drain current distribution



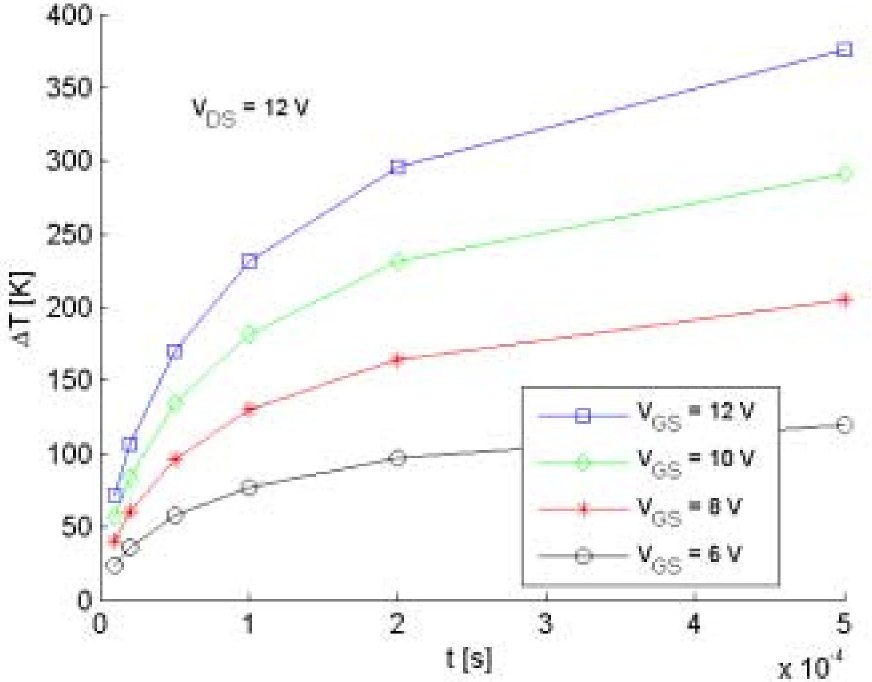
Comparison to measurements

- Pulsed measurements on home-made energy capability set-up
- Used to characterise large devices

model (circles) versus measurements (lines)



model



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Thermal modelling approach (1)

- **Assumptions:**
  - rectangular, infinitely thin, homogeneous power source at top surface
  - perfectly isolated top surface
  - constant thermal conductivity (independent of temperature)
- **Exact analytical solution (based on Green's function):**

$$\Delta T(x,y,z,t) = \frac{\sqrt{\alpha}}{4kWL\sqrt{\pi}} \int_{t'=0}^{t} \left[erf\left(\frac{W/2+x}{\sqrt{4\alpha(t-t')}} \right) + erf\left(\frac{W/2-x}{\sqrt{4\alpha(t-t')}} \right) \right]$$

$$\cdot \left[erf\left(\frac{L/2+y}{\sqrt{4\alpha(t-t')}} \right) + erf\left(\frac{L/2-y}{\sqrt{4\alpha(t-t')}} \right) \right]$$

$$\cdot \frac{1}{\sqrt{t-t'}} \cdot \exp\left(-\frac{z^2}{4\alpha(t-t')} \right) \cdot P(t') \cdot dt'$$

W, L: dimensions power source

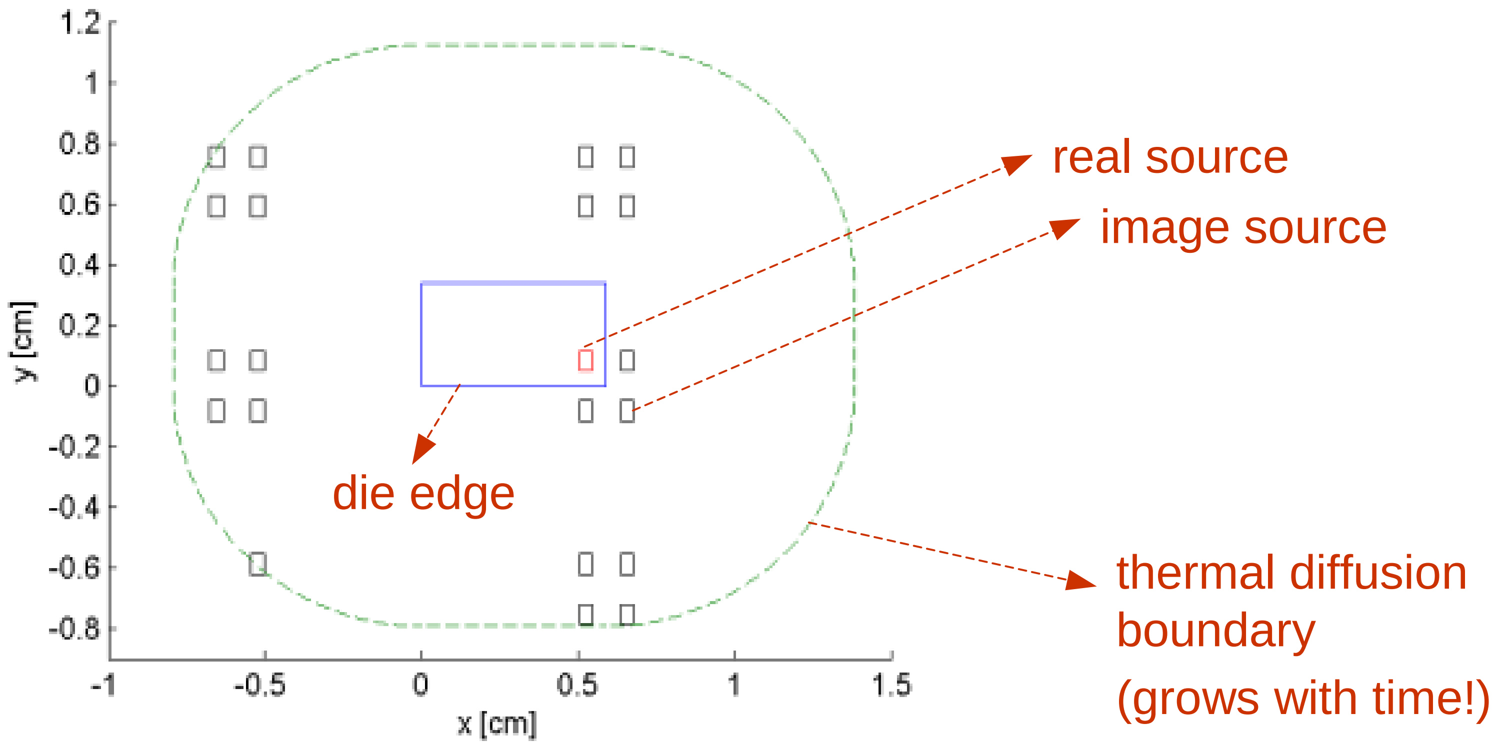
k: thermal conductivity

α: thermal diffusivity

P: power (<u>any</u> function of time)

Thermal modelling approach (2)

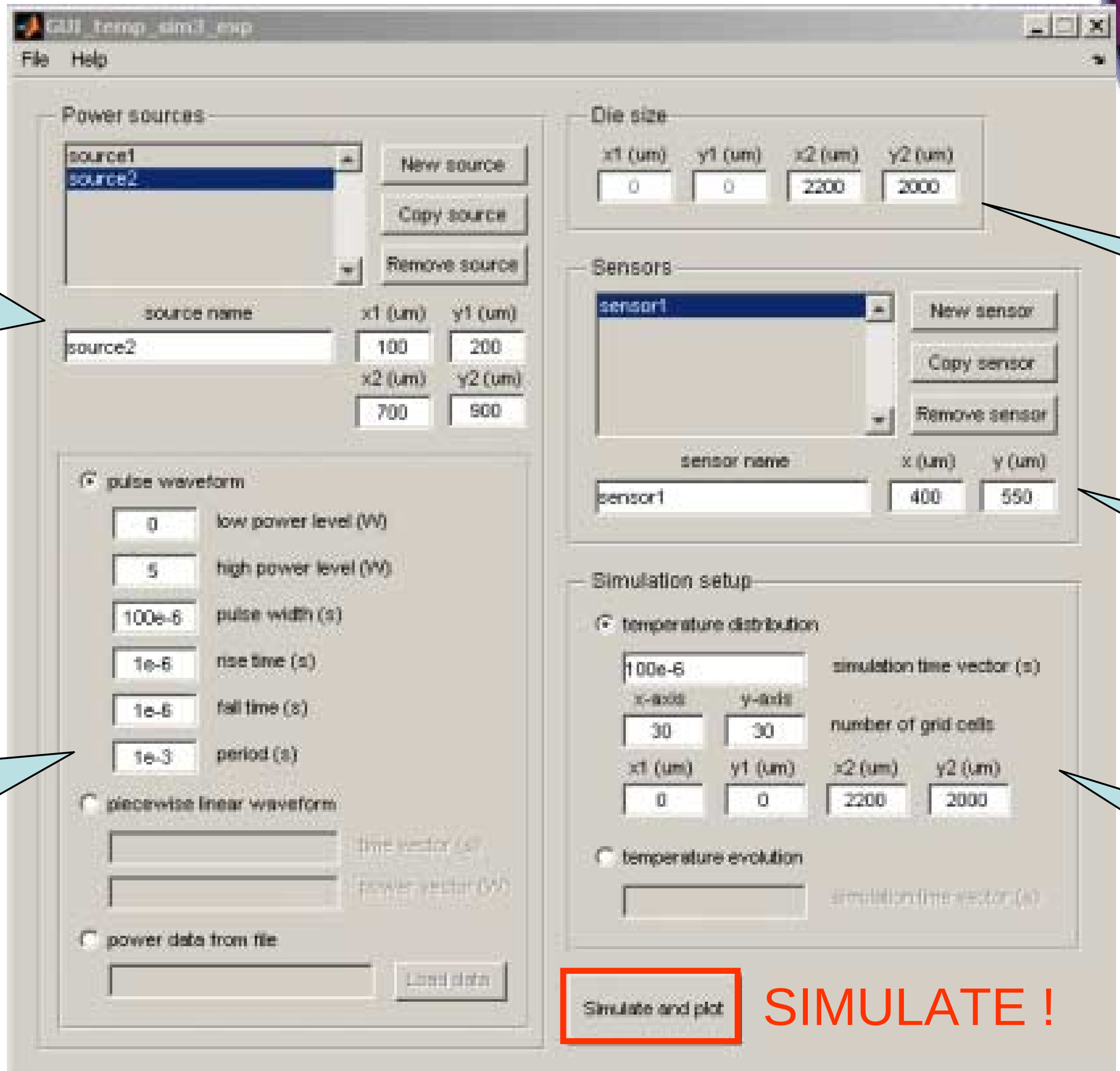
- **Introduction of adiabatic die edges by superposition of solutions for array of real and image sources**
- **Only images within thermal diffusion boundary (limits simulation time)**



User interface of thermal tool

power source positions

power waveforms



SIMULATE !

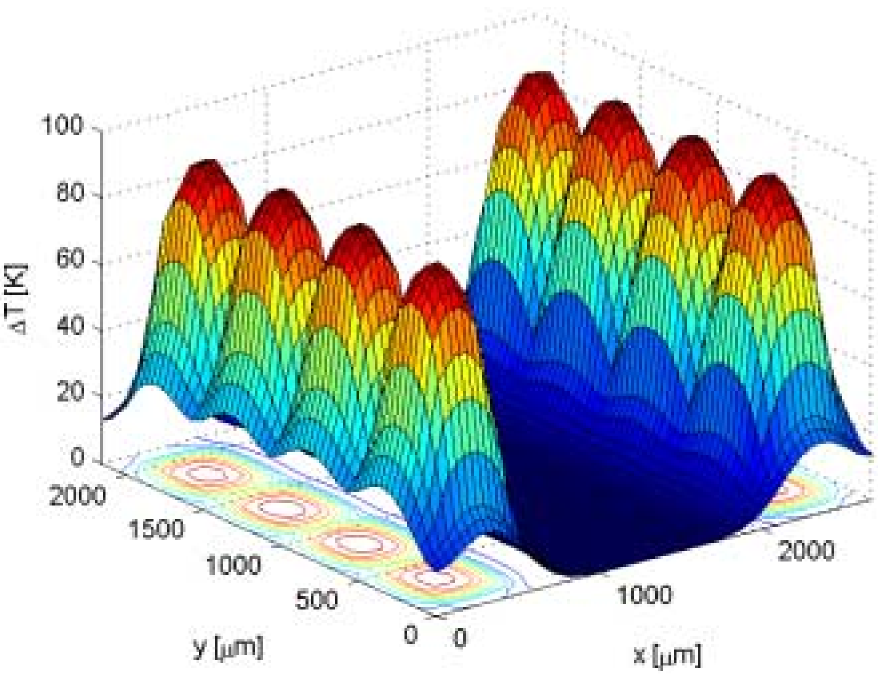
die size

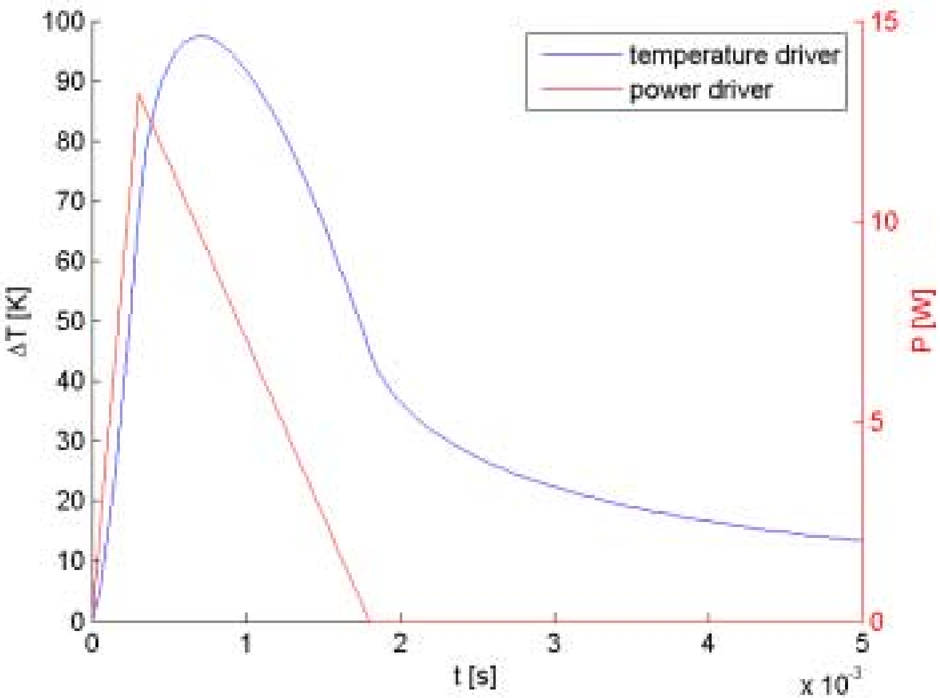
sensor positions

simulation grid and time

Typical application

- **Simultaneous application of triangular power pulse to 8 large drivers:**

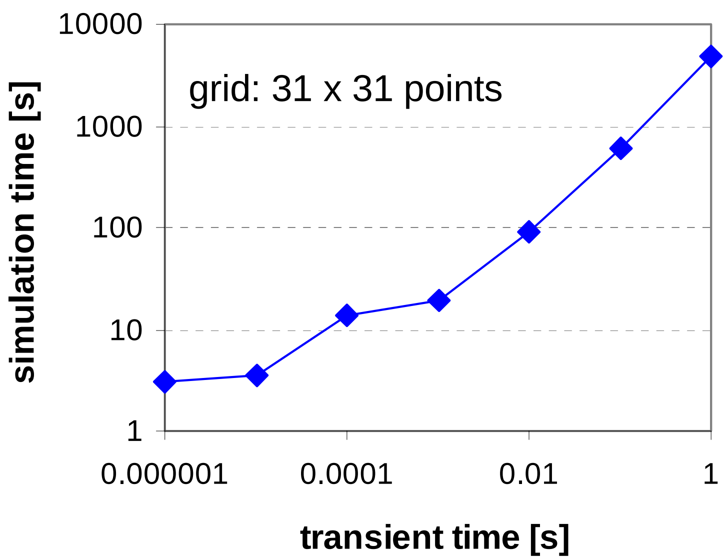




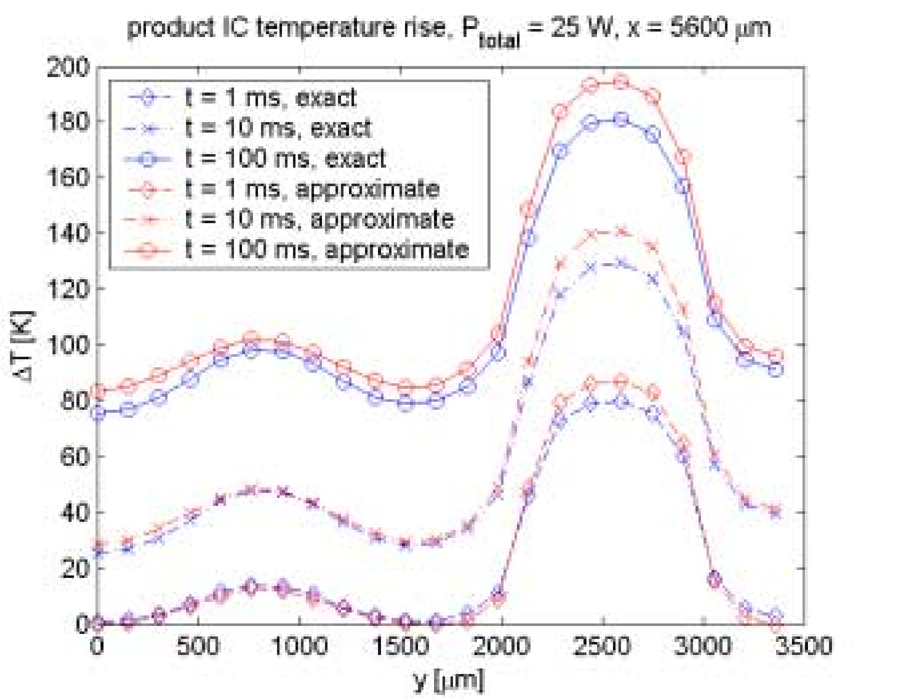
Speed / accuracy trade-off

- **Simulation time increase: due to increase of images**
- **Using approx. solution (only for power step function):**
  - error: within 5%
  - speed increase: factor 30 !

simulation time exact solution



deviation approximate solution



Contents

Conclusions

- ***Electro-thermal DMOS model:***
  - Automatic generation of full netlist with RC-network
  - Electro-thermal coupling using Verilog-A modules
  - Model is scalable versus geometry
  - Standard DMOS model is simply linked using a subcircuit
  - Good correspondence with pulsed measurements
- ***Thermal simulations on floorplan level:***
  - Fast and flexible Matlab tool with GUI
  - Arbitrary number of arbitrary power waveforms
  - Allows temperature evaluation on system level
  - Results have been verified on products