Automotive Power Semiconductors

Application Note

Behavioural Models for SABER Simulations (MAST)

PROFETs BTS 640 S2, BTS740 S2, BTS840 S2

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A.Introduction

A behavioural model of Sense PROFET devices (highside switch) was implemented into the simulation package SABER. The level of abstraction is suited to support the design of electronic systems.
Dynamic and static characteristics are implemented as well as selfheating effects, protection and feedback features.
With the aid of these models, expensive breadboard experiments can be reduced and critical operation modes can be identified.

B. Overview Types & Characteristics

The three types BTS740S2, BTS740S2, BTS840S2 are similar products (one or two channel highside switches) based on the same silicon design, with different packaging options.

Table 1 summarizes the most important data:

Type	Rdson / Iload	Vbbmax	Package	Rth
BTS 640S2	1x30mOhm 12.6A	34V	TO 220 / TO 263	1.47 K/W
BTS 740S2	2x30mOhm 2x5.5A = 8.5A *	34V	PDSO-20-9	12K/W each ch.
BTS 840S2	2x30mOhm 2x12A = 24A	34V	Power SO 20	1K/W each ch.

Depending on the number of chips on one leadframe and the package type different (ISO-) Current Ratings can be achieved

C. Modular Modelling concept, Interface declarations

The connection points are exclusively of physical nature, i.e electrical and thermal pins were used to describe the interactions with the external system.

Interface declaration (example BTS640.sin):

```
------------------------------------------------------------------------------------------------------------------------
template bts640 vbbx gnd in outx status is Tsens tj tcase  = messages, distribu-
tion

electrical vbbx          battery
electrical gnd           ground
electrical in            input
electrical outx          power output
electrical status        status pin
electrical is    :       current sense pin
thermal_c Tsens          sensor temperature – do not connect!!! (only postproc.)
thermal_c tj             DMOS temp. – do not connect! (to disenable selfheating)
thermal_c tcase          case (leadframe) temperature – always connect !
```

General remarks:

- In case of the two channel devices BTS 740, BTS840 electrical and thermal pins have the suffix „1“ or „2“; Exception: only one tcase – pin for BTS740 (see also section „thermal model“).
- Electrical Pins should never be left disconnected in order to avoid numerical instabilities
- The same applies to the thermal pin **tcase,** which is the only thermal interface from the junction to the heatsink.
- For investigations at a constant chip temperature connect the pin tj directly to a temperature source (eg. to investigate DC behaviour without influence of cooling)
- Don´t connect current sources directly to electrical pins, like in Rdson-„measurements“.

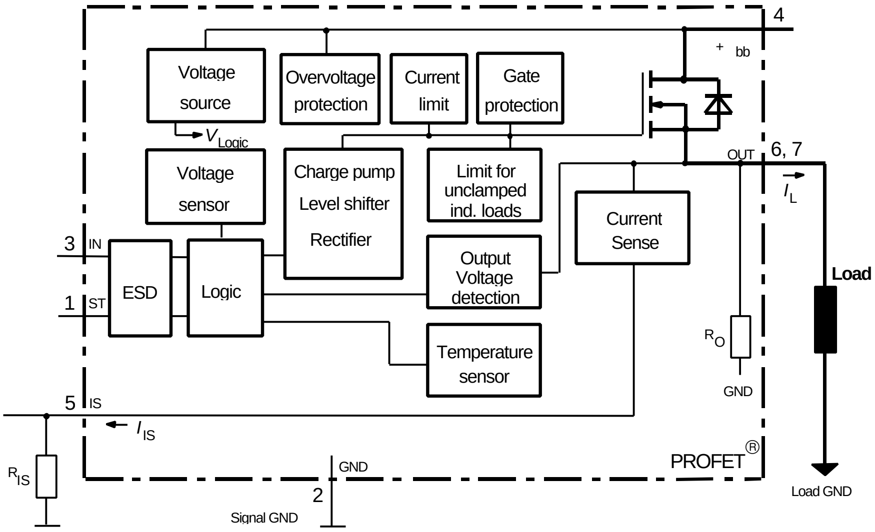


Figure 1 shows the functional concept of one channel which is adopted in the behavioural model as well: The top level model of each channel accordingly consists of a netlist of basic structural elements:

```
-------------------------------------------------------------------------------------------------------------
logic_840.1 inp t usq ov lout ocd en ma st          #logic processing block
ov_protec_l270.1 vbb gnd ov Tsens =mes=messages     #overvoltage detection
undervoltage_l270.1 vbb gnd usq tcase               #undervoltage detection
smt_840.1 inx gnd inp tcase=mes=messages            #Schmitt Trigger input includ-
ing
                                                    #ESD protection
cs.i in inx                                         #current sensor for
                                                    #postprocesing purposes
openload_off.1 out gnd lout tcase                   #openload - detection
open_col.1 st status gnd tcase                      #open collector status output
tempdec.1 vbb gnd t Tsens=mes=messages              #overtemperature detection

ssmart_dmos.1 vbb gate source tj =ns=50900          #output Power DMOS Model
current_sense_840.1 source out vbb out is gnd ma tj #current sense circuit
cs.out out outx                                     #output current sense for
                                                    #postprocessing
chp_840.1 outrec out vbb gnd en tcase               #charge pump&rectifier circuit
gdisch_840.1 outrec out vbb gate en ocd tcase       #gate charge&discharge circuit
t640_tsense.1 tj Tsens tcase                        #thermal network:
                                                    #junction – sensor – case
```

D. Model Parameters:

In general, the setup of parameters is done according to typical data sheet values. In some cases, where only maximum (conservative) values are given in the data sheet, the model represents a realistic, typical value (e.g. the thermal model, see below).
However some selected parameters which are essential for certain investigations can be adapted by the user within the actual statistical range. These are summarized in the MAST – structure ***distribution***.

```
--------------------------------------------------------------------------------
--
struc{
       enum {min,typ,max} cur_sense = typ
       number rdson =27m,  # min:27mOhm        max: 30mOhm,
       slew_rate_on =1.0,  # max:2.0 (1V/us), typ:1.0, min:0.5(0.1V/us)
       slew_rate_off      =1.0,  # max:1.3 (1V/us), typ:1.0, min:0.1(0.1V/us)
       cur_lim      =4.6,  # max:5.0 (58A@RT),typ:4.6 (50A@RT),min:4.2 (40A@RT)
       i_gnd        =1.2m  # max:3.0m (3.0mA), min,typ:1.2m (1.2mA)
       } distribution =()
```

Meaning of parameters in „distribution“:

cur_sense: The nonlinear characteristics of the current sense ratio (=f(Iload, Tj))given in the datasheet is implemented by linear interpolation of current and temperature.
Only distinct values **enum {min,typ,max}** are allowed.

rdson: The onstate resistance @ 5A, 25°C, allowed values 27mOhm...30mOhm.

slew_rate_on: affects the resistance of gate charge path; allowed range:
0.5....2.0 ->covers the data sheet range of 0.1V/us....1V/us

slew_rate_off: affects the resistance of gate discharge path; allowed range:
0.1....1.3 ->covers the data sheet range of 0.1V/us....1V/us

cur_lim: affects the current limitation value by specifiing the corresponding gate voltage
allowed range: 4.2...5.0
! **remark**: Only for fine tuning of the short circuit behaviour to a particular device !
! Data sheet range is covered by temperature variations from –40°C....150°C !

i_gnd: operating current at ground pin
allowed range: 1.2m...3.0m covers the data sheet range of 0.6mA....1.5mA (per channel)

Model parameter ***messages***:
Can be switched either to „***on***“ or „***off***“. Summary of messages see section below.

E. Model Features & validity limits

Dmos (Power Output MOS Transistor):

A physics-based model of a vertical DMOS in the actually used technology „Ssmart“ (self-isolating). On state characteristics are modeled by partitioning the conducting region into distinct areas, the temperature dependence of the mobility is included i.e. the static characteristics are modeled temperature dependent (-40°C to 150°C). This is essential for the simultation of self-heating effects.
Temperature levels from 150°C to 300°C can be simulated (like for short circuit), however only for rough investigations of the peak junction temperature.
Dynamic characteristics (switching behaviour) are accounted for by physical formulations of all relevant capacitances (nonlinear, but independent of temperature).
The temperature dependence of the dynamic characteristics is dominated by the gate charge and discharge path, which is also modeled.
The inverse diode is included by a static model (no reverse recovery) with temperature dependent characteristics.

Thermal Equivalent Network

In Figure 2a the thermal equivalent network of the BTS740 is shown.

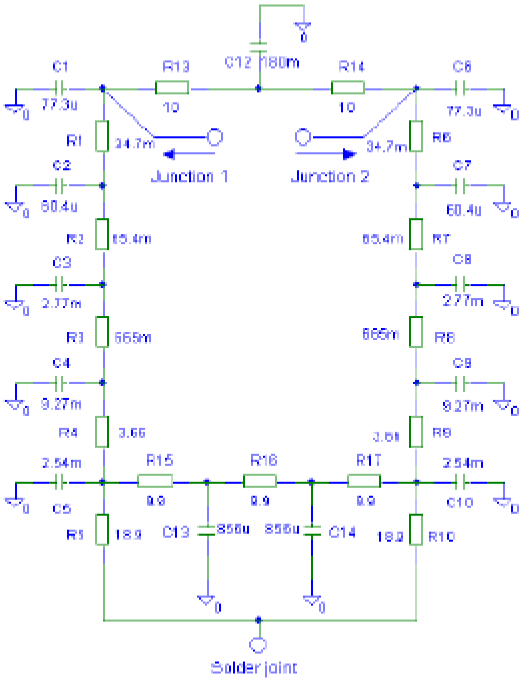


Fig.2a thermal model BTS740

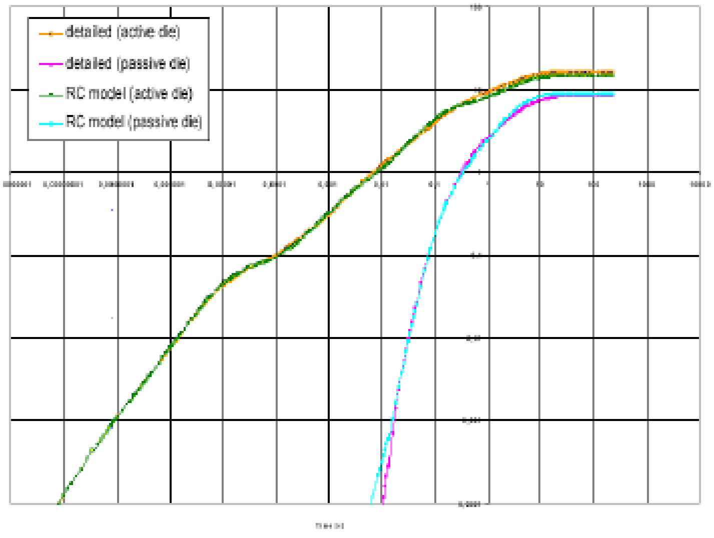


Fig.2b Comparison 3D Simulation <-> lumped model

In order to generate a compact thermal network, at first a transient finite element simulation (fig 2b) was performed which yields the thermal step response at the heat generating junction (self heating, orange line) and at the neighbouring chip (cross-coupling, magenta).

Next, a comprehensive lumped structure of the main heat paths was defined in analogy to electrical RC networks (Fig. 2a), taking into account vertical and lateral components, but leaving the parameter values of each element undefined.
With symbolic algebra software a closed form solution for the step responses can be calculated with arbitrary network parameters. At last, an optimizer with adequate constraints was used to find a reasonable combination of these parameters (Ri and Ci) which has the most similar transient response.
The excellent result of this optimization is shown in Fig 2b (green and blue curves).
When looking at the actual parameter values, one can roughly identify the actual physical layers like silcon, solder, copper and mold.
For a detailed description please refer to *[**noe**]*

Thermal Protection:
Not shown in picture 2a are the additional components necessary for the temperature sensor of each channel, integrated into the active DMOS area. Those are needed to account for the dynamic characteristics of the sensor with a time constant of approximately 200us.
For thermal protection the sensor temperature is monitored and overtemperature turn-off is initiated.
Retriggering via hysteresis is implemented.

Current Sensing:
Nonlinear characteristics of sense ratiois implemented according to datasheet:
K_{ilis} = f(Temperature, I_{load}). The offset current is depending on the switching state (15uA on, 1uA off). The step response is modeled by a low pass behaviour.

Input Characteristic:
Leakage current and input resistance depending on temperature and switching state.

Overvoltage Protection & Shutdown
The protection threshold voltage is decreasing with temperature
The shutdown threshold voltage (with hysteresis) is increasing with temperature.

Undervoltage Protection & Shutdown
The protection threshold voltage is modeled with hysteresis decreasing with temperature

Internal Output Pull Down (Open Drain case):
Temperature dependent resistor

Status output characteristics:
Output resistance and leakage current are modeled dependent on temperatur.

ESD protection
A temperature dependent series resistance is used in the discharge path

Short Circuit Protection / Overcurrent protection
Depencies on Operating Voltage and temperature effects are dominated by DMOS Transistor, gate charge and discharge circuit and dynamic characteristics of temperature sensor.

F. Errors, warnings and messages

Warnings associated with overvoltage protection and shutdown

Battery voltage is exeeding max value ~43V:

warning("\n Maximum allowed value for Vbb is out of spec at t=%s in %. Actual value: Vin=%(Volt) , Maximum values: %(Volt) < Vin > %(Volt). \n ",time,instance(),vbb_gnd,ovt)

Drain source voltage is exceeding max value

warning("\n Over Voltage Protection is activated at t=%s in %. Actual value: Vin=%(Volt) \n ",time,instance(),vbb_gnd)

Input voltage exceed maximum level

warning("\n Maximum allowed value for Vin is out of spec %s in %. Actual value: Vin=%(Volt), Maximum values: %(Volt) < Vin > %(Volt).\n ",time,instance(),vpn,limit_esd)

Short circuit protection

warning("\n shortcircuit or over current detected at t=%s in % \n ",time,instance())

Warnings associated with overtemperature

Sensor temperature exceeds trigger level (170°C)

warning("\n Overtemperature Protection activated a T=%s in % actual sensor temperature: %degC \n ",time,instance(),tc(Tic))

Active DMOS area ist heated above 175°C

warning("\n You are leaving maximum specified temperature range channel2 at t=%s in % actual junction temperature: %degC \n ",time,instance(),tc(tj2))

warning("\n You are leaving maximum specified temperature range channel1 at t=%s in % actual junction temperature: %degC \n ",time,instance(),tc(tj1))

Active DMOS area is approaching destruction temperature limit:

message("Warning !!!!: Overtemperature >300degC in % :",instance())

message("Model is leaving intended area of operation")

message("Please check your thermal network and/or operating conditions")

Status output

warning("\n Maximum allowed current at status pin is out of spec at t=%s in %. Actual value: ist=%(Amp), Maximum values: 5mAmp \n ",time,instance(),ist)

Current through reverse diode

warning("\n reverse current at t=%s in % a ",time,instance())

Warnings associated with wrong input parameters or simulation domains

error("analysis type is not supported by the model in % ", instance())

error("statistical analysis is not supported by the model in % ", instance())

error("argument setting for slew_rate_on out ouf range: \n valid range: 0.5...2.0 in model % ", instance())

error("argument setting for slew_rate_off out ouf range: \n valid range: 0.1...1.3 in model % ", instance())

error("argument setting for rdson out ouf range:\n valid range: 27m...30m in model % ", instance())

error("argument setting for cur_lim out ouf range:\n valid range: 4.2...5.0 in model % ", instance())

error("argument setting for i_gnd out ouf range:\n valid range: 1.2m...3.0m in model % ", instance())

G. Postprocessing Quantities&Signals

Analog variables of interest are collected by the group definition „post_info“ (see declarations section)

```
##############################################################
#### analog postprocessing variables
##############################################################
#
# possible syntax of signal list:   sigl /.../post_info
##############################################################
#
group {it1, it2, power1, power2, tmos1,tmos2,ibb, iin1, iin2, iout1, iout2, isen-
se1, isense2, irev1, irev2, vcp1, vcp2} post_info

values{
      ibb=isense(cs.vbbsense)         # current into the voltage supply pin
      it1=idmos(current_sense_840.1)  # dmos current (channel + rev. diode)
      it2=idmos(current_sense_840.2)
      power1=it1*v(vbb,source1)       # total powerdissipation dmos1 + rev.diode1
      power2=it2*v(vbb,source2)
      tmos1=tc(tj1)                   # junction temperature dmos1
      tmos2=tc(tj2)
      iin1=isense(cs.i1)              # current into input pin channel 1
      iin2=isense(cs.i2)
      iout1=isense(cs.out1)           # current out of output pin channel 1
      iout2=isense(cs.out2)
      isense1=iso(current_sense_840.1)# current out of sense output 1
      isense2=iso(current_sense_840.1)
      irev1=-irev(ssmart_dmos.1)      # current through reverse diode 1
      irev2=-irev(ssmart_dmos.2)      #   (polarity: positive in reverse dir.
      vcp1=vcp(chp_840.1)             # voltage of charge pump (static model)
      vcp2=vcp(chp_840.2)
}

#################################################################################
```

digital postprocessing variables (which could not be grouped)

```
#################################################################################
# type:    state logic_4

# signalname       meaning                                    convention

# lout1, lout2     openload status "raw"signals               l4_1 = Vds>3V
# ocd1, ocd2       current limitation status                  l4_1 = active
# t1, t2           overtemperature detection status           l4_1 = active
# usq1, usq2       undervoltage detection status    !!!  !!l4_0 = active !!!!
# ov1, ov2         overvoltage de/Pro-tection status           l4_1 = active
#
##################################################################################
```

H. Example Simulation circuits

In order get a quick insight into the functionalities of the models, simulation test circuits have been attached to the model files:

BTS640_test.sin, BTS740_test.sin, BTS840_test.sin

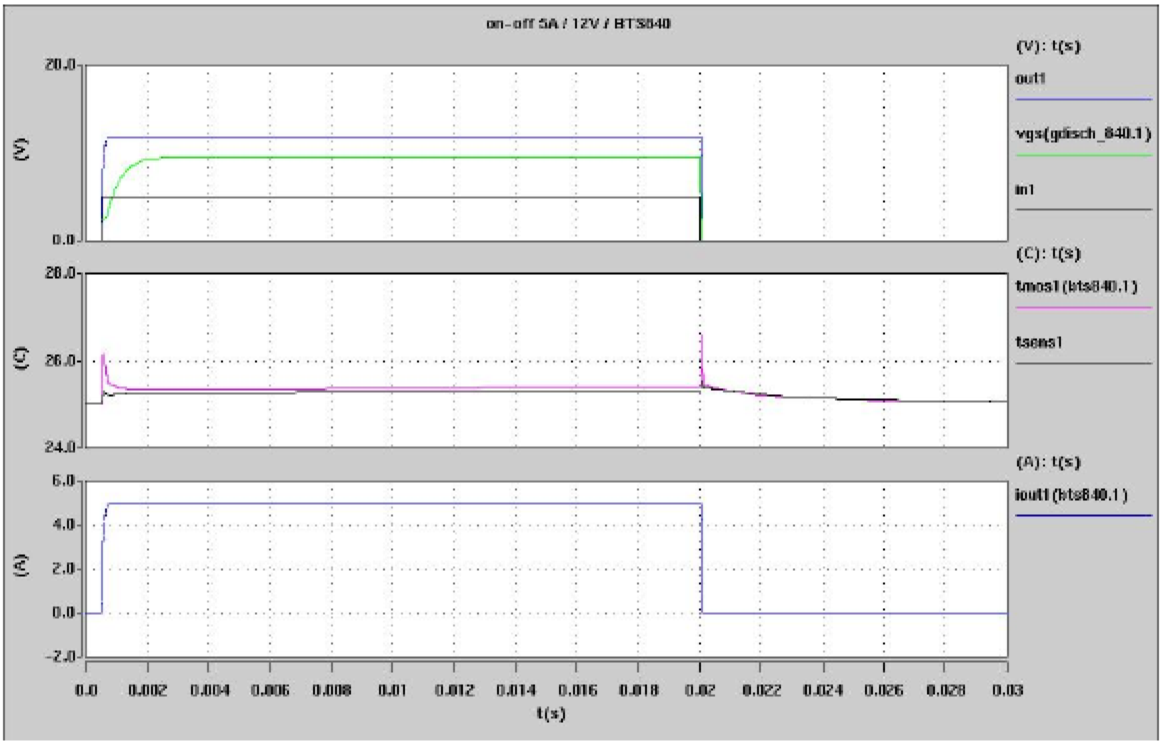
In Principle they consist of battery, wire inductances, a PROFET (single or double channel), ohmic, inductive loads, sense and status terminations, a heatsink and pulsed voltage sources as input signals.

Most relevant cases can be simulated with one netlist by using alter commands.
Some suggestions can be found in the command-scripts

tut_640.scs, tut_740.scs, tut_840.scs,

Example 1: Normal switching cycle on-off @ 5A/12V/ambient temperature

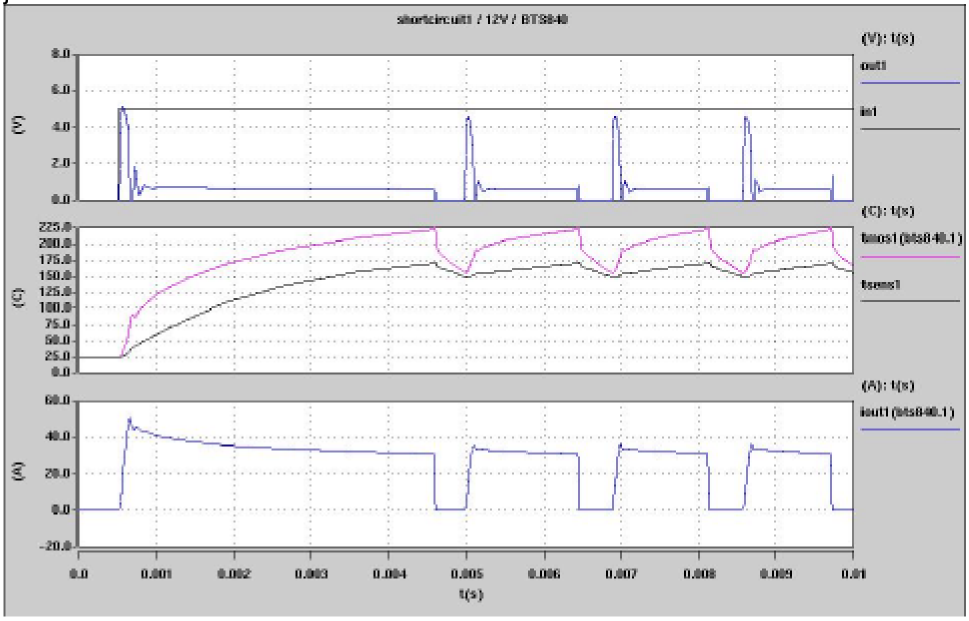
In addition to the measurable signals out1 (load voltage), in1 (input voltage) and iout1 (load output current) some internal signals are displayed:
Vgs (green, gate source voltage of the output DMOS Transistor), tmos1, tsens1 (temperature at the DMOS junction and the sensor)



Example 2: Shortcircuit1@ 25°C, 12V, 20mOhm: Thermal shut down with auto restart

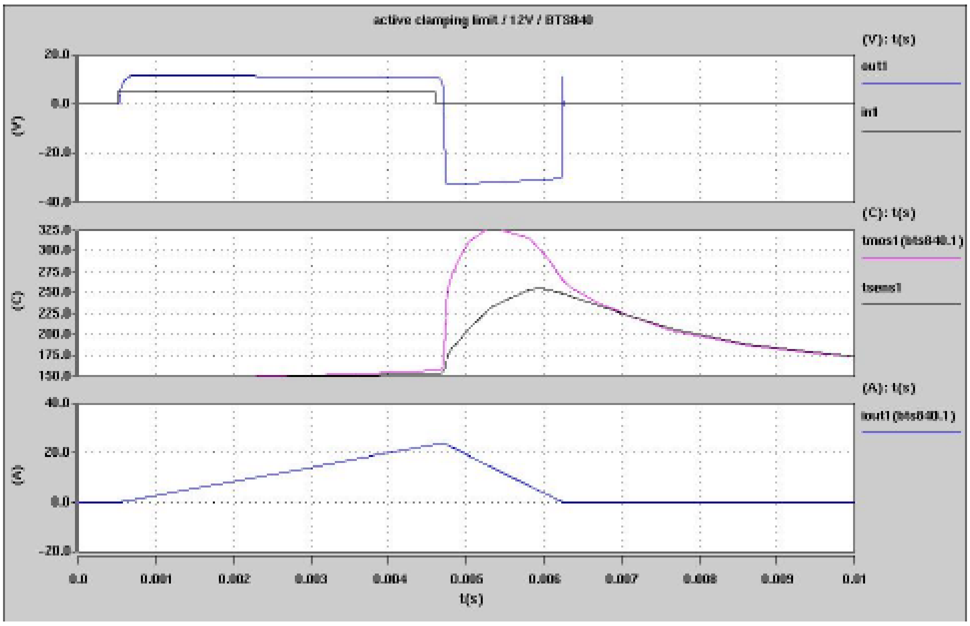
The device is turned on into an existing short circuit, and turned off by its overtemperature protection feature. Thermal toggling is initiated due to the hysteresis of the temperature protection. Self heating of the device can be observed by the decreasing short circuit current. The actual junction temperature can be considerably higher than the sensor temperature.

Although save turn-off is guaranteed under such conditions, the simulation example reveals the reason for lifetime degradation, if the device is repeatedly switched into the short circuit: The maximum junction temperature exceeds the specified value and temperature cycles of up to 70K occur at the junction.



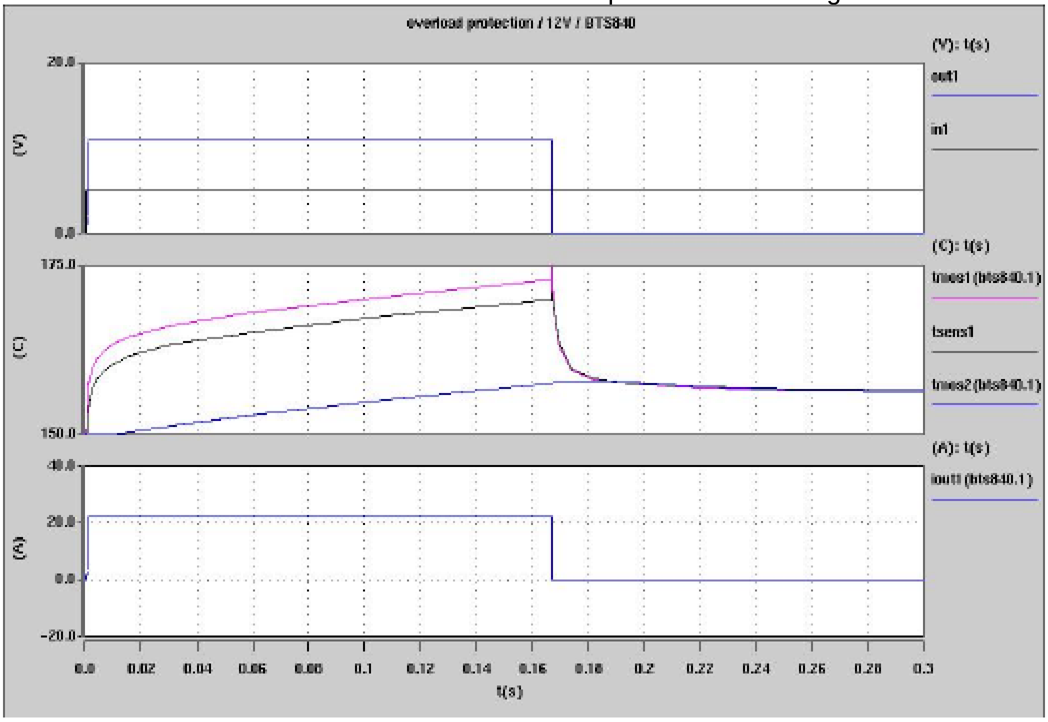
Example3: maximum switchable inductance according data sheet: 24A/2.0mH
active zehner clamping, junction is heated to 300degC

This simulation corresponds to the maximum specified energy dissipation at inductive load turn-off. The junction temperature approaches the physical limit where the device loses its blocking capability.



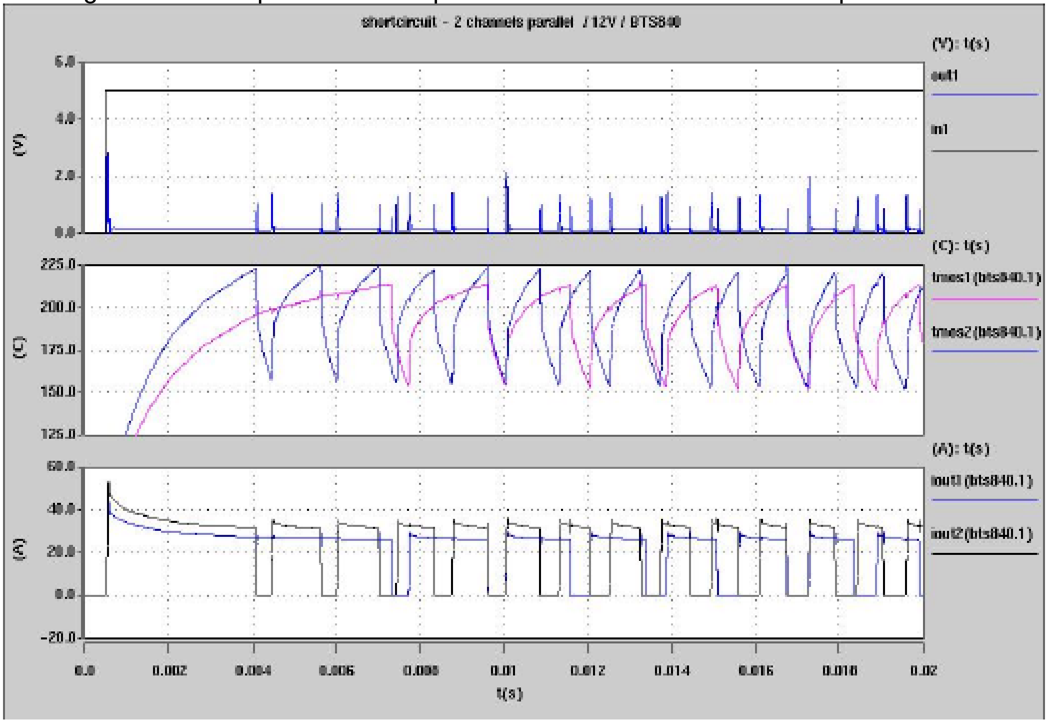
Example 4: overload channel 1; onstate 24A, rth ca =100K/W
slow self heating, turnoff at tmos1=170degC

A less extreme overload simulation with the assumption of bad cooling conditions

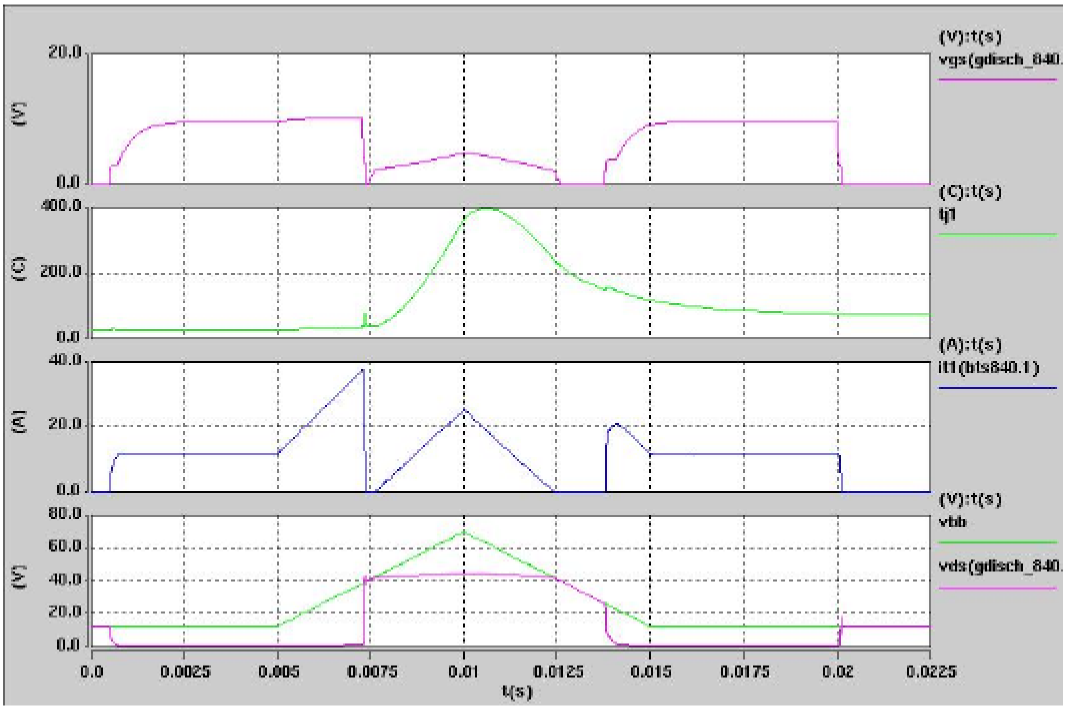


Example 5: paralleling of channel 1 and 2, effective load:1uH 10mOhm shortcircuit
asymmetrical current limitation assumed, thermal toggling

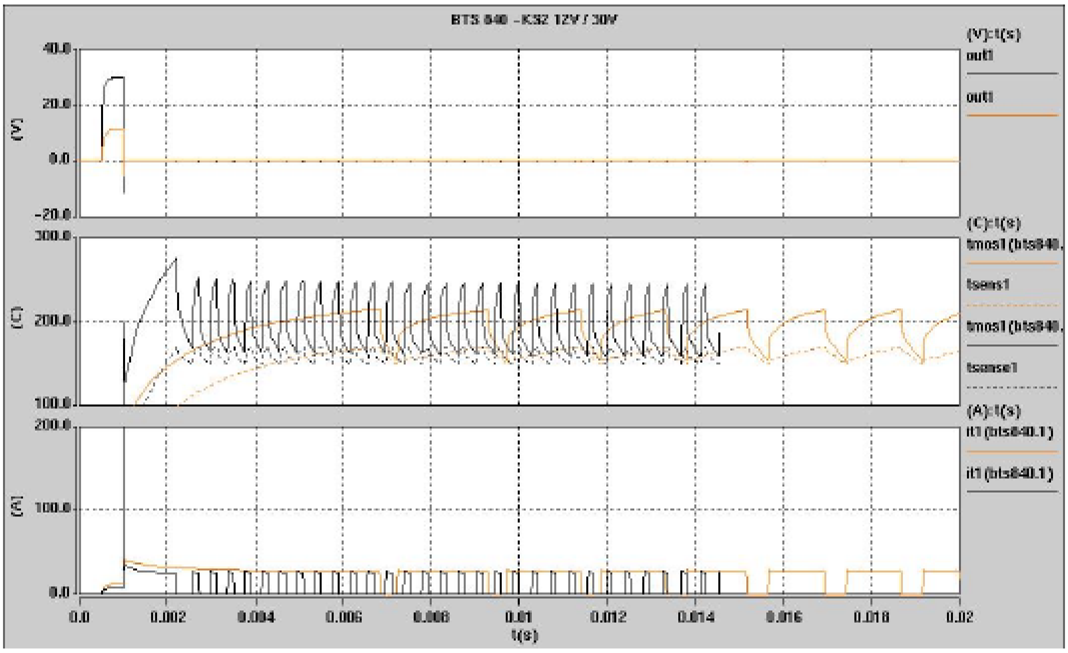
The purpose of this simulation is to demonstrate the independent protection features of each channel
It also gives an example how to adapt the current limitation value to a particular device.



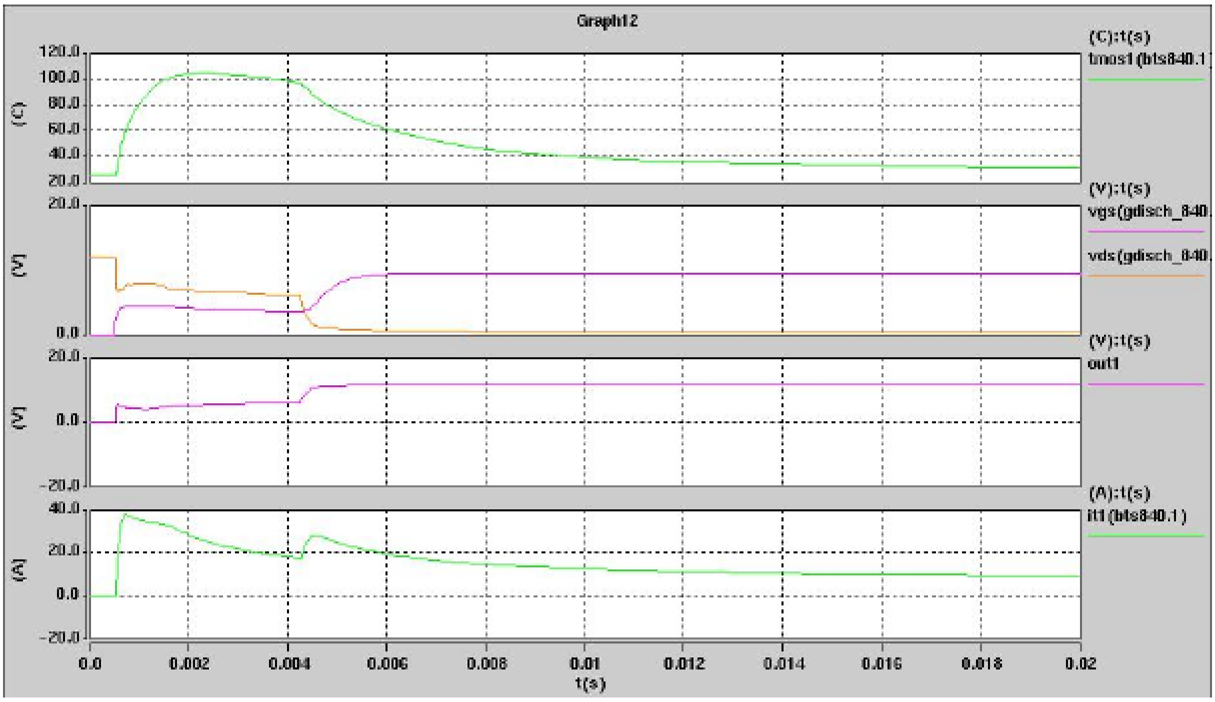
Example 6: Battery voltage ramped from 12V to 70V and back
Overvoltage turn-off when shut down voltage is reached, active zehnerclamping when the protection level is reached, stress at the load is reduced. Self heating to Tjmax=400°C =>Destructive operation mode !!!



Example 7: Shortcircuit 2 at t=1msec: Drain Current rises to 200A, Tj~200°C
A crtitical stress for any power switch, when the short circuit occurs during the conducting state. Two cases are shown Vbat=12V and Vbat = 30V. When the overcurrent is detected, it is limited and thermal toggling begins with a maximum junction temperature of 270°C.



Example 8: Turn-on of a 100W – lamp:
When a lamp is turned on, the initial current exceeds the stationary value by a factor of 10. The current limiting feature of the PROFET is activated and reset when the load voltage is sufficiently high. A physical lamp model was used in combination with the PROFET model.



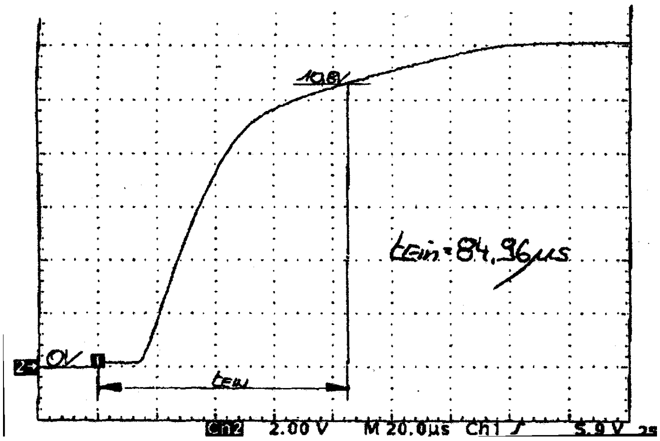
I. Validation Results, Range of Validity

In general, the concept of an electronic datasheet was introduced into the simulation model Although this does not imply that simulation results guarantee device properties, most of the data sheet values are represented in the model. Validation should therefore related to typical data sheet values rather than to application measurements of a particular device.

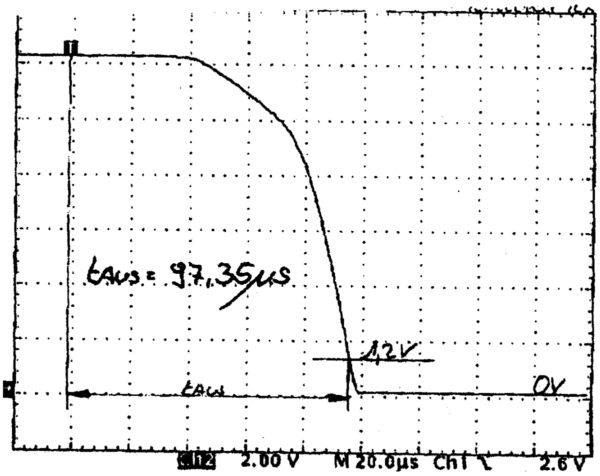
However, especially in the thermal characteristics, conservative values are given in the datasheet which would lead to too pessimistic simulation results. Therefore, electrothermal characteristics have been modeled with more realistic assumtions and must therefore be validated seperately.
A good method is to apply short circuit conditions because the load current level and the toggling frequency is an excellent criteria for electrothermal validation.

Similar considerations apply to the dV/dt characteristics if EMI investigations have to be performed.

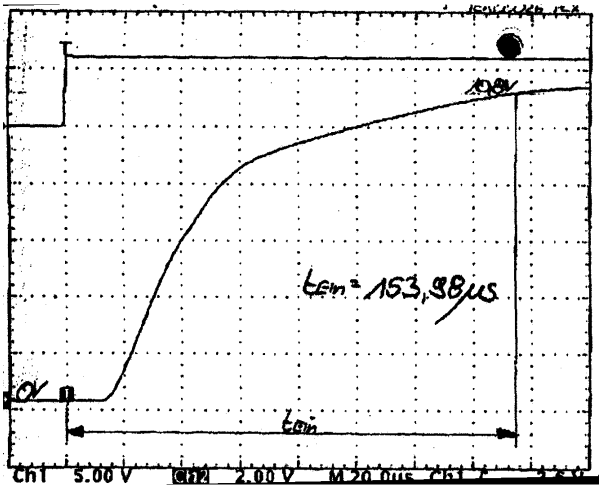
Measurement 1A/12V @25°C 20µs/div, 2V/div
Turn-On



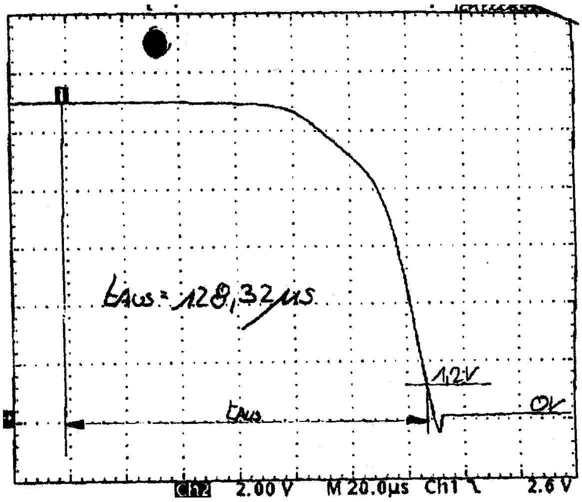
Measurement 1A/12V @25°C 20µs/div, 2V/div
Turn-Off



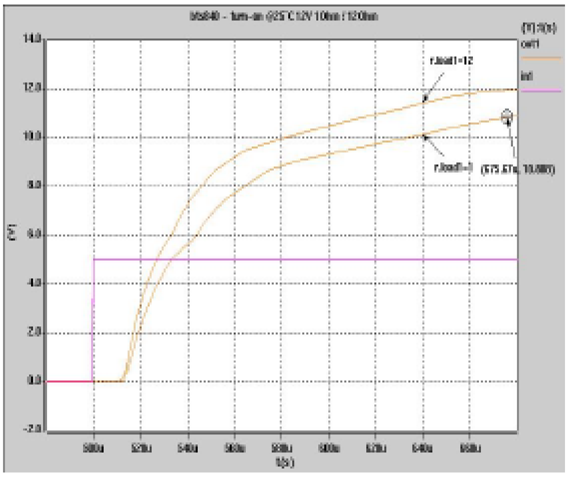
Measurement 12A/12V @25°C
20µs/div,2V/div
Turn-On



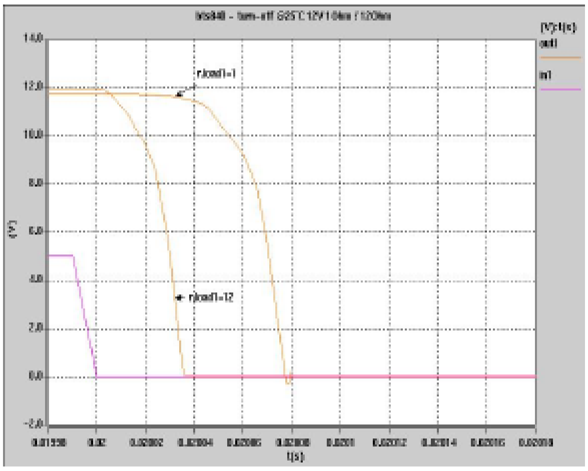
Measurement 12A/12V @25°C
20µs/div,2V/div
Turn-Off



Simulation 12A+1A /12V @25°C
Turn-On

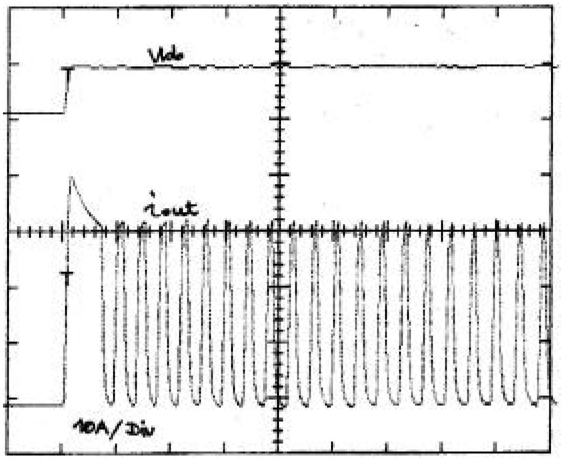


Simulation 12A+1A /12V @25°C
Turn-Off

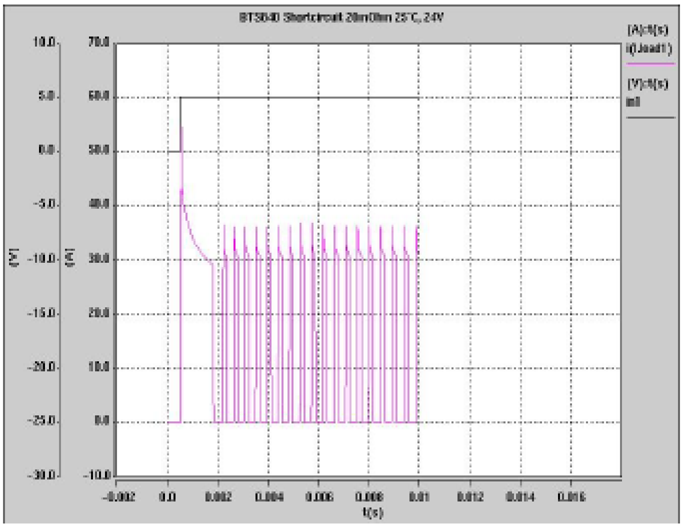


Turn_On into short circuit @25°C, Vbat=24V (20mOhm)

Measurement: 10A/div, 2msec/div



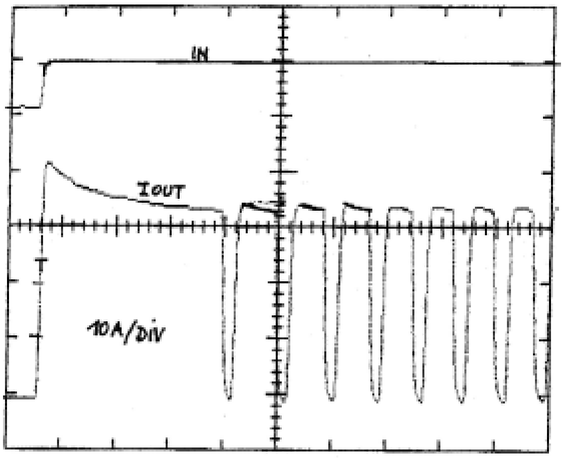
Simulation

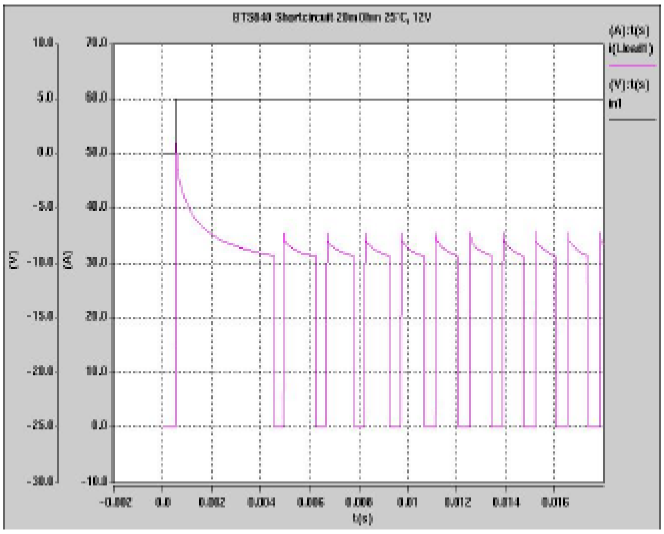


Turn_On into short circuit @25°C, Vbat=24V (20mOhm)

Measurement: 10A/div, 2msec/div

Simulation





K. Installation hints, Simulator settings.

The selfextracting ZIP file „bts840.exe“ contains the following files:

- This application note: *bts840_readme.pdf*
- The include-file „*components_l270.sin*“:(encrypted) functional components of integrated fuctions
- The include-file „*dmos_comp_l270.sin*“:(encrypted) functional components of DMOS Transistor
- The include-file „*sthermal.sin*“: (not encrypted) mainly thermal components
- The model files (templates) „*bts640.sin“, „bts740.sin“and „bts840.sin*“ which use the previously mentioned components
- Three test circuits „*bts640_test.sin“, „bts740_test.sin“and „bts840_test.sin*“
- Three saber command scripts „*tut_640.scs“, „tut_740.scs“, and „tut_840.scs*“.

For installation, copy all files into the simulation directory or into the saber data path

The **recommended simulator settings** are different from default only for transient analysis:
Saber> tr (tn 10...... „target newton iterations“
This is necessary because of the highly nonlinear nature of the model. Ignoring this advice will lead extremely small timesteps, long simulation time and convergence problems.

For technical support please contact: simulate@infineon.com

References:

*[**noe**]:*
Noebauer, G., “Creating Compact Models Using Standard Spreadsheet Software“*, Proc. of 17th IEEE Semiconductor Thermal Measurement & Management Symp.*, 2001