Improvement of IGBT model to integrate into circuit simulation program

Sergey Kokin, **Sergey Malkov, Evgeniy Osipov, Denis Perminov**

Integrated Solutions LLC

kokinsa@symica.com

WHY IGBT ?

The Insulated Gate Bipolar Transistor (IGBT) is widely used in power electronics where high dynamic range control with low noise is required. When designing power electronics circuits, SPICE simulation is used.

The accuracy and reliability of SPICE simulations determines the quality of the design of such electronic devices. The Hefner model [1] is widely used to simulate IGBTs.

This model is built-in to the simulation programs of the leading CAD vendors [2]. The inability to simulate a device containing an IGBT leads to significant difficulties in the design of circuits.

Disadvantages
of the source code existing

Open source code Verilog-A from QUCS [6] have several problems for use:
- the occurrence of a convergence problem,
- the description of the temperature behavior of the model does not correspond to the experimental data for the range from -55C to +175C.

```
Simulation started:     12.55.00   23/03/2020.

DC analysis started...

Parameter values:
        reltol = 0.001
        abstol(I) = 1e-12
        abstol(V) = 1e-06
        temp = 25 C
        tnom = 25 C
        gmin = 1e-12

Sweep step # 1: value of sweept parameter = 6.
   __error__: convergence problem. Operation Point not calculated.

No DC solution found (no convergence).

Simulation finished:    12.55.00   23/03/2020.
```

Causes of problems

▽ Qgd(x1)
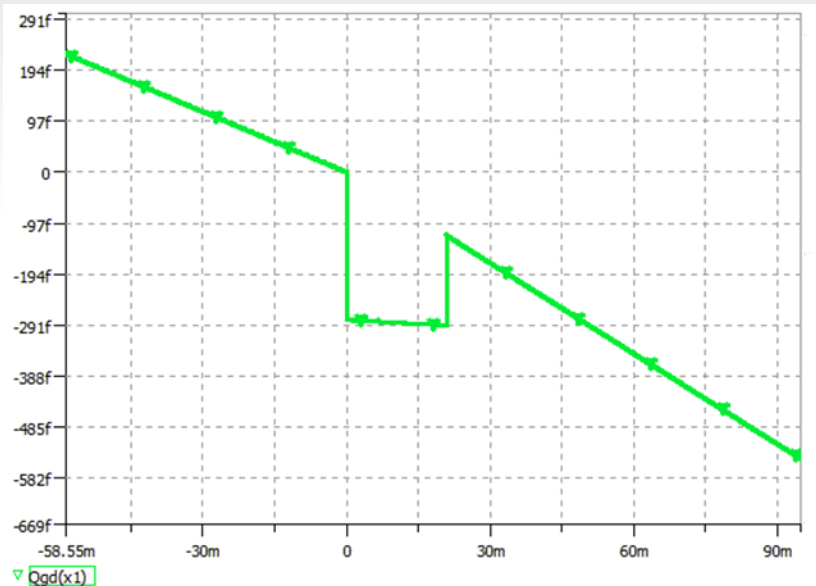
Mathematical algorithms used in SPICE simulations demand continuity and smoothness of mathematical expressions [3]

1. Break of the continuity condition for functions and their first derivatives.

The figure shows the charge behavior function *Qgd*.

2. Calculation of a function of the form:

$$W = 1 - \sqrt{x - 1},$$

provided that W> 0. To get real part positive values of W, you need to limit *x* to values from 1 to 2.

3. Software implementation of a piecewise continuous function of 2 variables

$$F\big(Q_1(x), Q_2(x)\big)$$

is a non-trivial task.

In this function algorithm chooses $Q=\max(Q_1(x), Q_2(x))$ and then uses the numerical value of the maximum variable to calculate the function $F(Q)$.

An incorrect transition between the values of the input variables leads to a discontinuity in the derivative of function. In this case, the continuity of the function itself is preserved.

4. There is a problem with simulating IGBTs over an extended temperature range [4,5]. The use of the temperature dependences of the original model does not correspond to the experimental data for the temperature range from -55 ºC to +175 ºC.

1. The use of the "if" operator requires special attention, because it is the source of the appearance of breaks in the *Qgd* function and its derivative. Comparing code fragments of a piecewise-smooth capacitive model where "if" is used

```
Cgdj = Agd*`EPSSI/(Wgdj+`TINY);
if (Vds < Vgs - Vtd) Cgd = Coxd;
else Cgd = Coxd*Cgdj/(Coxd+Cgdj);
Qgd = Cgd*Vdg;
```
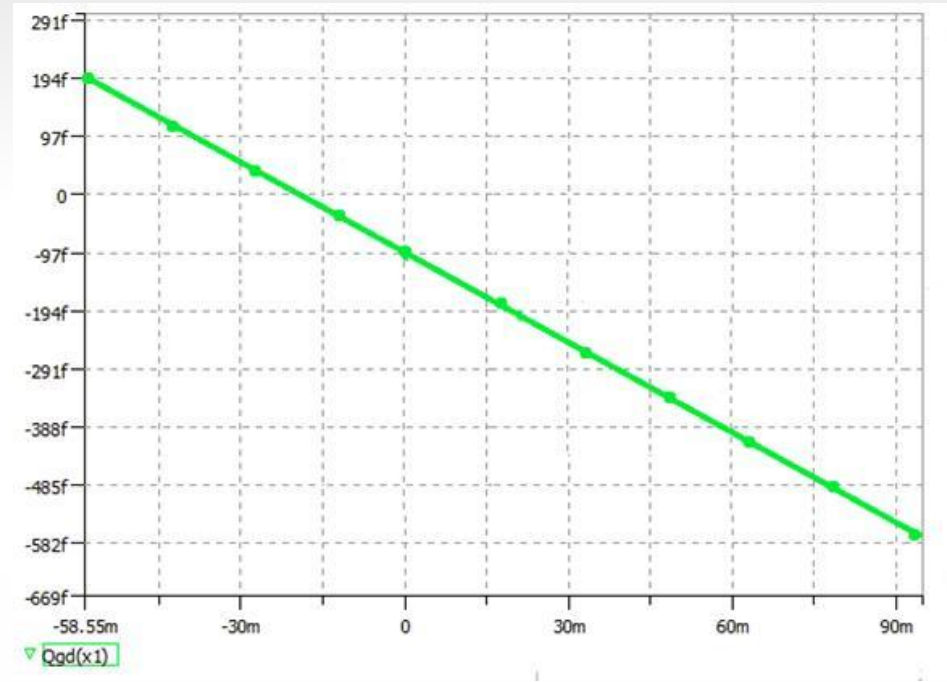

and the charge model, where a single expression for the *Qgr* variable is used (there is no "if" operator)

```
Wdgj = sqrt(2.0*`Esi_spice*(Vdg + vtd)/(`QEL*nb_m));
T1 = COXD*Wdgj/(`Esi_spice*agd);
T2 = `QEL*nb_m*`Esi_spice*agd*agd/COXD;
Qdg = T2*(T1 - ln(1.0 + T1));
Qdg = Qdg - COXD*vtd;
```

without abnormal behavior.

Improving the model

2. To eliminate the problems associated with calculating a function of the form $W = 1 - \sqrt{x-1}$, and to ensure that real part positive values are obtained, it is proposed to use the procedure

$$\text{MINA\_MAXA(val, min, max, a),}$$

where, *val* - is the current value of the variable x, min - is the minimum x limit, max - is the maximum x limit, a - is the smoothing factor that controls the smoothness of the transition to min and max values. The use of this procedure for smoothing the *Wbcj* function is shown in the figures below.

```
`define MINA_MAXA(val,min,max,a) \
0.5*((0.5*(val + min + sqrt((val - min)*(val - min) + a) ) + max)\
-sqrt((0.5*(val + min + sqrt((val - min)*(val - min) + a)) - max)\
*(0.5*(val + min + sqrt((val - min)*(val - min) + a)) - max) + a))
```
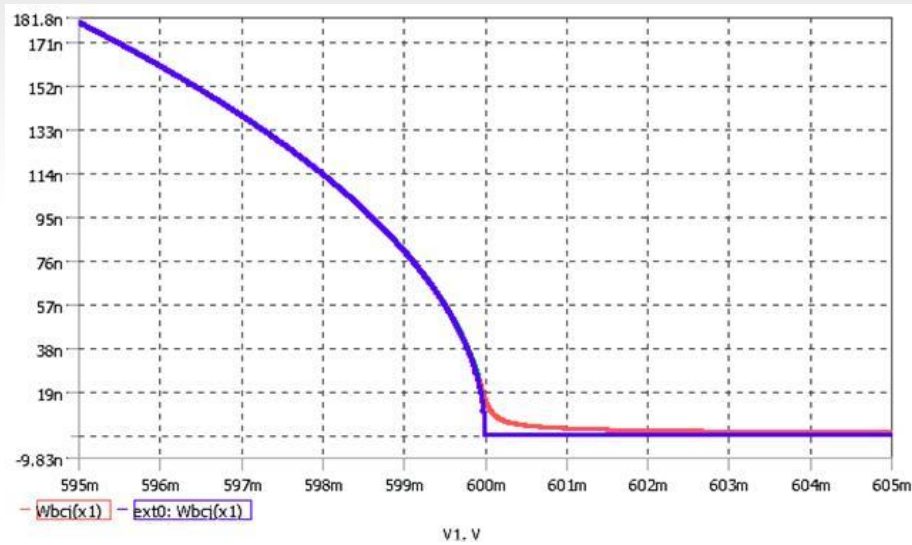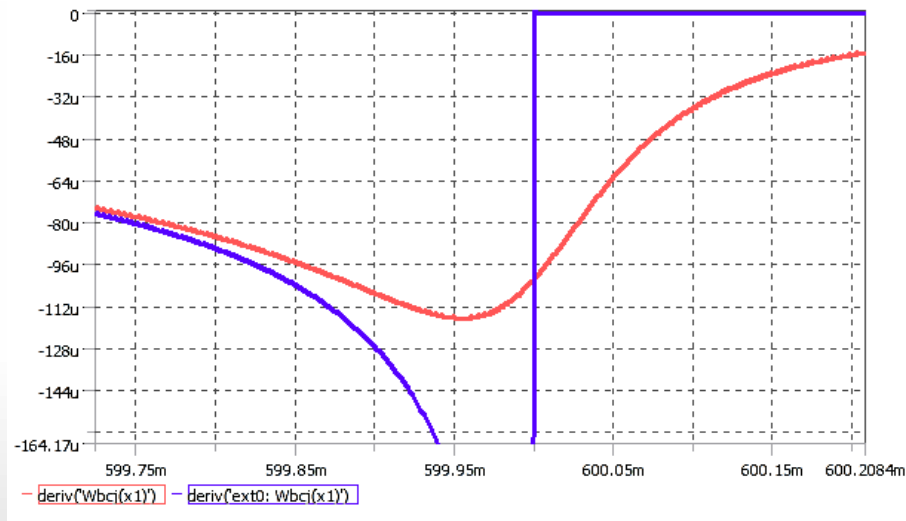
Function *Wbcj*.

Derivative *Wbcj*

Smoothing the function

3. The problem of obtaining the continuous derivative of a piecewise linear function has been known for a long time. Its solution is based on the condition of equality of the function and its derivative to the left and right at the transition point x_o:

$$F_1\left(x\big|_{x<x_0}\right) = F_2\left(x\big|_{x\geq x_0}\right), \qquad F_1{'}\left(x\big|_{x<x_0}\right) = F_2{'}\left(x\big|_{x\geq x_0}\right).$$

In our case, when programming a piecewise continuous function of 2-variables, the transition point must be determined dynamically at runtime (the position of the point x_0 is not predefined).

With mathematical smoothing, it is necessary to perform a smooth transition from the maximum value on the "right" to another maximum value on the "left". To do this, select a function so that the following conditions are met:

$$F\big(Q_1(x), Q_2(x)\big) = \begin{cases} \lim\limits_{x>x_0} F\big(Q_1(x), Q_2(x)\big) = Q_2(x) \\ \lim\limits_{x<x_0} F\big(Q_1(x), Q_2(x)\big) = Q_1(x) \\ F\big(Q_1(x), Q_2(x)\big) = Q, \quad when\ Q_1(x_0) = Q_2(x_0) = Q \end{cases}$$

Smoothing the function

To smooth the function of 2 variables, it is proposed to use the expression below:

$$F(x) = F\big(Q_1(x), Q_2(x)\big) = \frac{Q_1^{n+1}(x) + Q_2^{n+1}(x)}{Q_1^n(x) + Q_2^n(x)},$$

where n – even. If the values of the function $Q_1(x)$ on the $(-\infty, x_o)$ are greater than the function $Q_2(x)$, on the $(x_o, +\infty)$ or vice versa $Q_2(x) > Q_1(x)$, then we obtain the desired result satisfying conditions above. The function is applicable if $Q_2(x)$ and $Q_1(x)$ both have either positive or negative values at the same time:

$$\lim_{x \to +\infty} \frac{Q_1^3(x) + Q_2^3(x)}{Q_1^2(x) + Q_2^2(x)} = Q_2(x), \qquad x > x_0,$$

$$\lim_{x \to -\infty} \frac{Q_1^3(x) + Q_2^3(x)}{Q_1^2(x) + Q_2^2(x)} = Q_1(x), \qquad x < x_0.$$

If the values of the function $Q_2(x)$ or $Q_1(x)$ reverse the sign, then the expression requires additional modification.
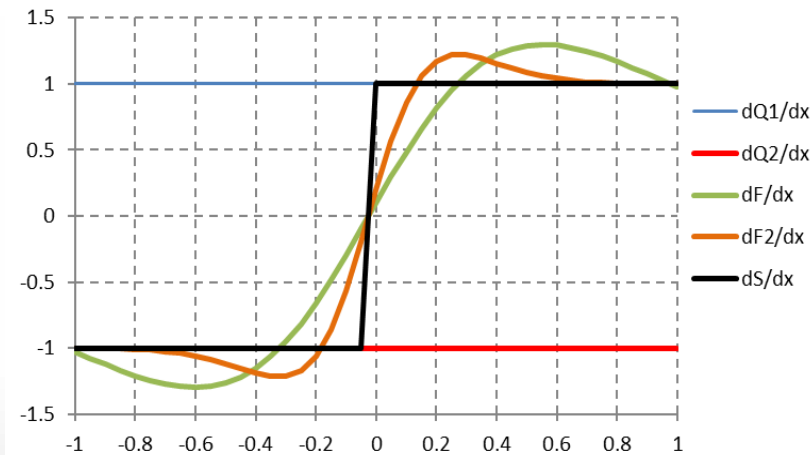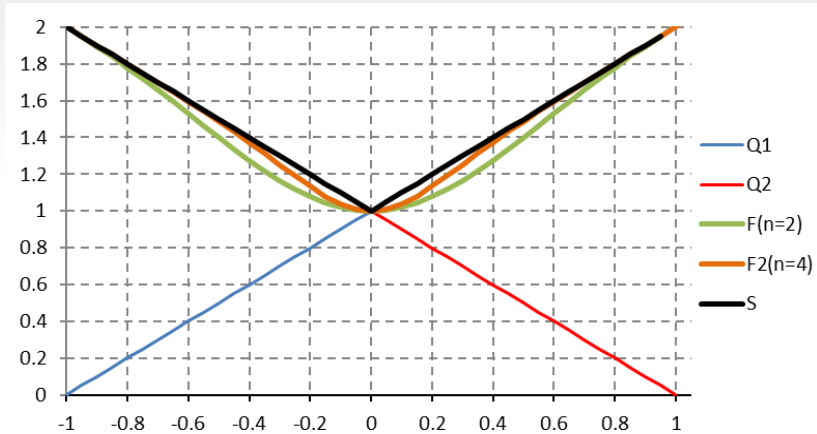
Let $Q_1(x) = 1 + x$, $Q_2(x) = 1 - x$, $x = [-1, 1]$. The program implements the following algorithm:

$$S = S(x) = \begin{cases} Q_2(x), & x < 0 \\ Q_1(x), & x \geq 0 \end{cases}$$

The plot of $S(x)$ (black line) – is a piecewise continuous function that always has a discontinuity in the derivative at the point $x=0$. The derivative value changes from -1 to +1. When replacing the original function $S(x)$ with $F(x)$, we obtain a smooth derivative with a slight deviation of the values of the function near the break point. The deviation is regulated by the exponent n. In the figures, the green line corresponds to $n = 2$, the orange line corresponds to $n = 4$.
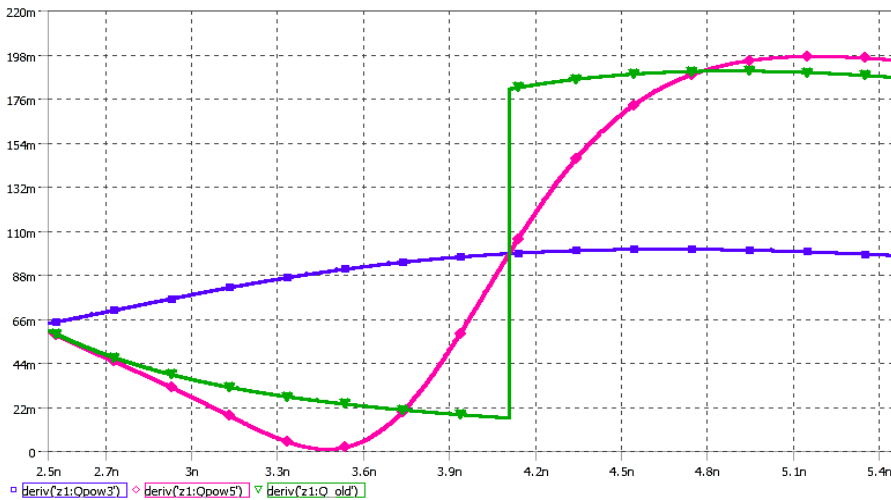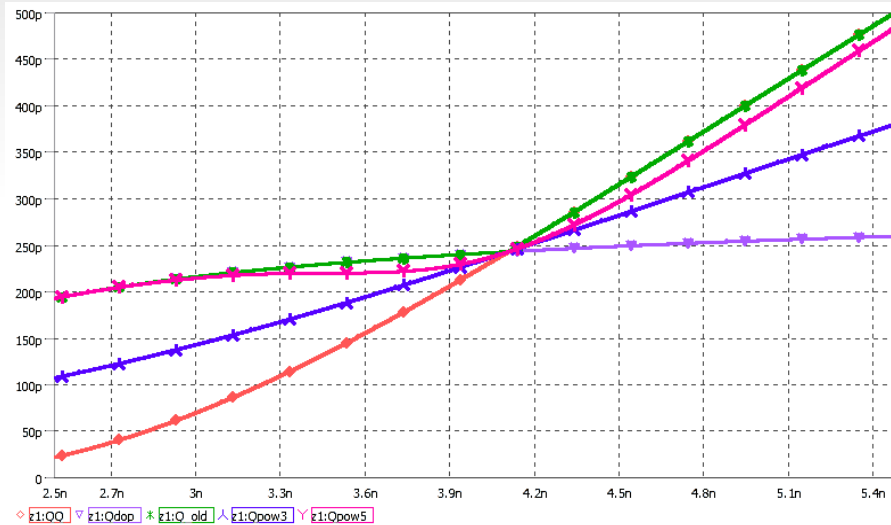
Consider the behavior of the model variables QQ, Q_{dop}, Q_old, Q.

Original value of Q_old (green line) calculate like maximum value between the input variables QQ(red line) and Q_{dop} (lilac line). The new variable Q was calculated at two values of the exponent n = 2 and n = 4. It can be seen from the Figures 6a that at n = 2 the plot of the variable Q (blue line) deviates more strongly near the transition point from the line Q_old than the line Q for case n = 4 (magenta line). Analyzing the behavior of the derivatives, it can be noted that dQ/dt at n = 2 (blue line) smoother than at n = 4 (magenta line).

symica
custom IC design toolkit
IGBT in temperature range

4. The Hefner model uses the following physical characteristics to describe the thermal properties of silicon [8].

$$\varphi_{t_0} = \frac{k \cdot T_0}{q}$$
Thermal voltage at $T_0=27°C$,

$$\varphi_t = \frac{k \cdot T}{q}$$
Thermal voltage,

$$Eg(T_0) = 1.16 - \frac{7.02 \times 10^{-4} \cdot T_0^2}{T_0 + 1108}$$
Band gap at $T_0=27°C$,

$$Eg(T) = 1.16 - \frac{7.02 \times 10^{-4} \cdot T^2}{T + 1108}$$
Band gap,

$$n_i = 1.45 \times 10^{10} \cdot \left(\frac{T}{T_0}\right)^{1.5} \cdot e^{(Eg_{t_0}/\varphi_{t_0} - Eg_t/\varphi_t)}$$
Intrinsic carrier concentration,

$$\mu_n(T) = \mu_n \cdot \left(\frac{T_0}{T}\right)^{2.5}$$
Electron mobility,

$$\mu_p(T) = \mu_p \cdot \left(\frac{T_0}{T}\right)^{2.5}$$
Hole mobility,

$$BVk_t = 5.34 \times 10^{13} \cdot \left(\frac{T}{T_0}\right)^{0.35}$$
Break-down voltage coefficien,

$$\tau(T) = \tau \cdot \left(\frac{T}{T_0}\right)^{\tau_1}$$
Lifetime,

.

IGBT in temperature range

To describe the temperature behavior of the I-V characteristic of a transistor, expressions are used:

$$J_{sne}(T) = \frac{J_{sne} \cdot A \cdot \left(\frac{T}{T_0}\right)^{J_{sne1}}}{e^{14000 \cdot \left(\frac{1}{T} - \frac{1}{T_0}\right)}}$$
Emitter saturation current for electrons,

$$V_T(T) = V_T + V_{T1} \cdot (T - T_0)$$
Threshold voltage,

$$Kp(T) = Kp \cdot \left(\frac{T_0}{T}\right)^{Kp1}$$
Transconductance,

where τ_1, J_{sne1}, V_{T1}, $Kp1$ – temperature coefficients.

For a more accurate IGBT simulation over a temperature range from -55^{0}C to +175^{0}C the above system of equations has been improved. So the expressions for n_i, $\mu_n(T)$, $\mu_p(T)$ и $\tau(T)$ replaced with:

$$n_i = 1.45 \times 10^{10} \cdot \left(\frac{T}{T_0}\right)^{n_{i1}} \cdot e^{(Eg_{t_0}/\varphi_{t_0} - Eg_t/\varphi_t)n_{i2}},$$
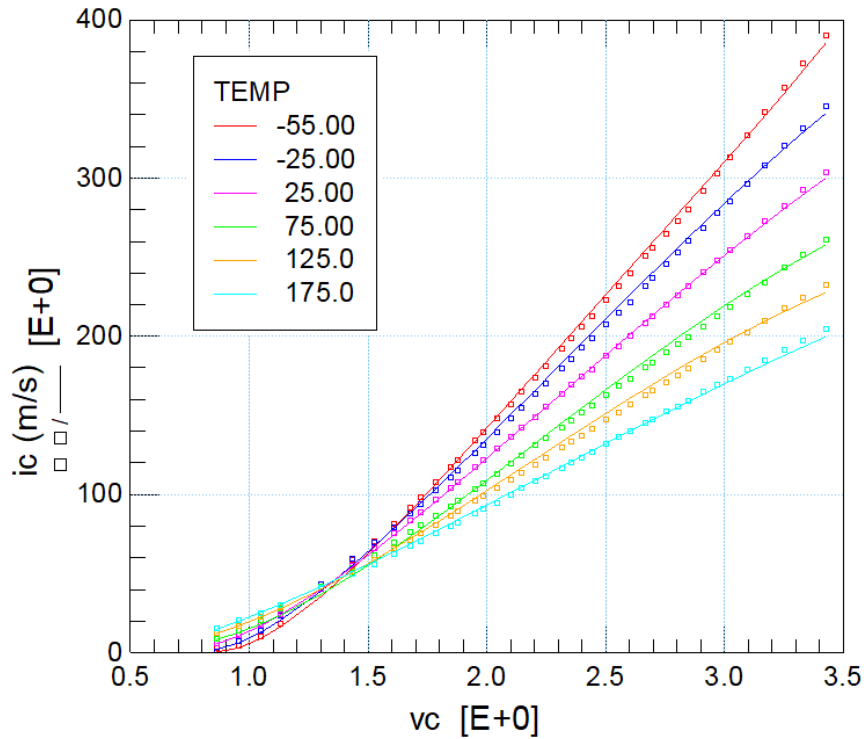
$$\mu_n(T) = \mu_n \cdot (1 + \mu_{n1} \cdot (T - T_0) + \mu_{n2} \cdot (T - T_0)^2),$$

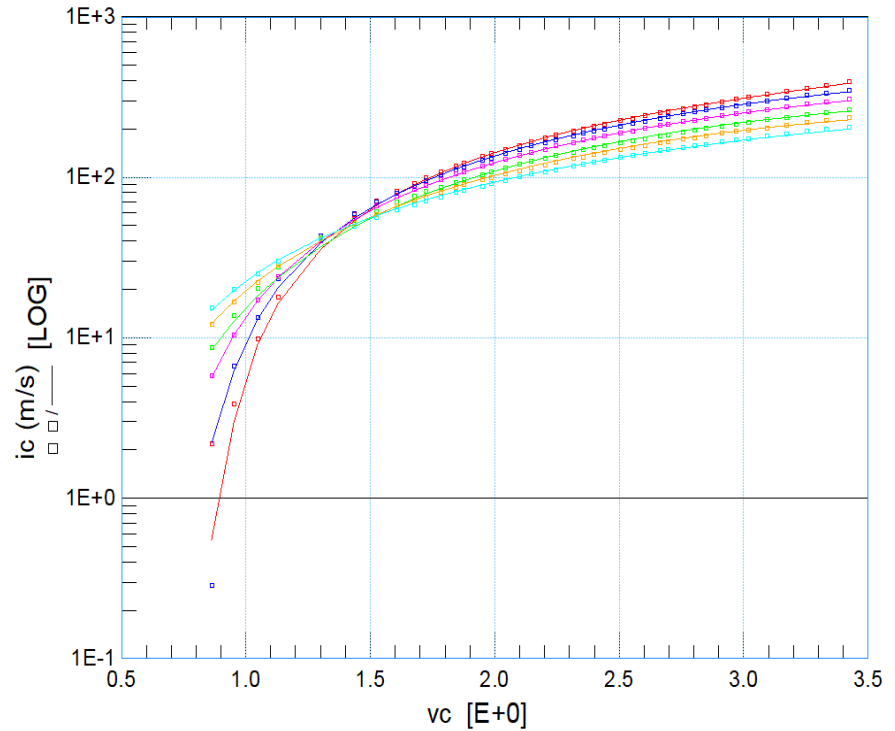$$\mu_p(T) = \mu_p \cdot \cdot \left(1 + \mu_{p1} \cdot (T - T_0) + \mu_{p2} \cdot (T - T_0)^2\right),$$

$$\tau(T) = \tau \cdot (1 + \tau_1 \cdot (T - T_0) + \tau_2 \cdot (T - T_0)^2),$$

where $n_{i1}, n_{i2}, \mu_{n1}, \mu_{n2}, \mu_{p1}, \mu_{p2}$ and τ_2 – additional temperature coefficients.

IGBT in temperature range

a)   b)

Results of comparison of experimental [7] and model characteristics in a wide temperature range. a) linear, b) semilogarithmic scales.

Summary

The improved IGBT model is based on the well-known Hefner model. It is suitable for both transient (.TRAN) simulation and .DC circuit design. The identified convergence problem was eliminated in the model. The model allows for circuit simulation of electronic circuits containing IGBTs in a wide temperature range from −55°C to +175°C.

New points are:

- The use of a specially developed function of smoothing of 2 variables. This function meets the requirement of dynamically determining the inflection point and allows you to control the amount of smoothing by changing the exponent.

- The use of temperature dependences that differ from the known expressions makes it possible to increase the accuracy of modeling circuits in a wide temperature range.

- The use of a charge model allows one to describe a single continuous function Qgd for the entire range of input values.

The improved model embedded into the SymSpice circuit simulation program. The study was supported by The Foundation for Assistance to Small Innovative Enterprises (FASIE).

References

1. A. R. Hefner. INSTANT – IGBT Network Simulation and Transient Analysis Tool / Semiconductor Electronics Division Electronics and Electrical Engineering Laboratory National Institute of Standards and Technology 400-88, Gaithersburg, MD 20899 -June, -1992, -159p.

2. PSpice A/D Reference Guide / Cadence, Product Version 10.2, -June, -2004, -426p.

3. Leon O. Chua, Pen-Min Lin. Computer aided analysis of electronic circuits, algorithms and computational techniques / Prentice-Hall, Englewood Cliffs, N.J., -1975, -737 p.

4. H. Wang, M. Liserre, F. Blaabjerg. Toward reliable power electronics: challenges, design tools and opportunities / IEEE Industrial Electronics Magazine, Volume 7, Issue 2, -June, -2013, pp.17-26

5. R. Wu, F. Blaabjerg, H. Wang, M. Liserre, F. Iannuzzo. Catastrophic failure and fault-tolerant design of IGBT power electronic converters - An overview / 39th Annual Conference of the IEEE Industrial Electronics Society IECON 2013, 10-13 November, -2013, pp.505-511.

6. https://sourceforge.net/projects/qucs/files/qucs/0.0.20/qucs-0.0.20-rc2.tar.gz/download.

7. J. L. Fock-Sui-Too, B. Chauchat, S. Nicolau, F. Madrid, P. Austin1,2, P. Tounsi, M. Mermet-Guyennet. Experimental study of power IGBT technologies at large range temperature / Mixed Design of Integrated Circuits and Systems MIXDES 2008, 15th International Conference, Poznan, -June, -2008, pp.519-524.

8. A. Hefner. A dynamic electro-thermal model for the IGBT / IEEE Transactions on Industry Applications, vol. 30, Issue 2, -Apr., -1994, pp.394-405.

Thank you for attention!

www.symica.com