Electro-Thermal SPICE Schottky Diode Model suitable both at room temperature and at high temperature

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Abstract. *Thanks to new developed software, we are able to provide electro-thermal SPICE Schottky diode model starting from raw experimental data. The data taken in account for the electrical model are simply the raw data at room temperature and few points at high temperature (one in the forward direction and two in the reverse one). For the thermal model we use instead the thermal impendence model. The model is available in library format.*

1. Introduction

As it is known, SPICE software contains many electrical models of discrete semiconductor devices to simulate circuit applications [1]. Among these devices, we also have diodes.

Unfortunately, Schottky diodes, obtained by means of deposition of a thin layer of metal on doped silicon, is badly modeled by SPICE.

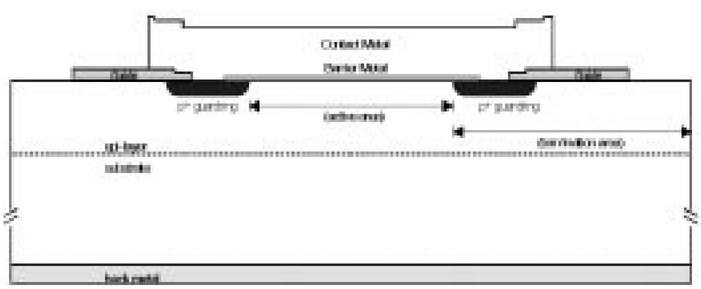

Figure 1. Schottky Diode

In particular, we have that the reverse leakage current should be constant until the voltage reaches the breakdown voltage; in reality Schottky diodes possess a leakage current slowly increasing moving from low reverse voltages to high voltages.

Moreover, at high temperature SPICE is only able to alter accordingly the diode saturation current [1]. There is no way to change the internal diode resistance.

Since this was the problem, we have implemented an original electrical Schottky Diode model adding to the SPICE diode two other components.

We have aimed to achieve a difference between real and *virtual* diode (i.e. that one simulated by SPICE) of less than 2σ, which means roughly $\pm 10\%$.

The result has been very good since we are able to describe correctly the I-V characteristics of the diode both at room temperature and at high temperature.

In addition, we can give the thermal diode model. This is accomplished supposing the diode made up of four layers and imagining every layer composed of a thermal resistance and a thermal capacitance.

Direct experimental data of thermal impedance allow us to extract these eight thermal parameters.

Due to the symmetry of the constituent equation for the thermal impedance, we need to look into the physical meaning of these quantities, relating them to compound.

This association avoids the ambiguity and provides the correct thermal model

The paper is organized in the following way: in section 2, we find the explanation of the electrical model. In section 3, the thermal model is discussed. In section 4, the conclusions are drawn.

2. Electrical Model

In Fig.1, it is represented the original Schottky Diode model we have implemented.

It is composed of a voltage controlled current generator in parallel to the original SPICE diode. The aim of this current generator is to provide a better accuracy in the reverse I-V characteristic.

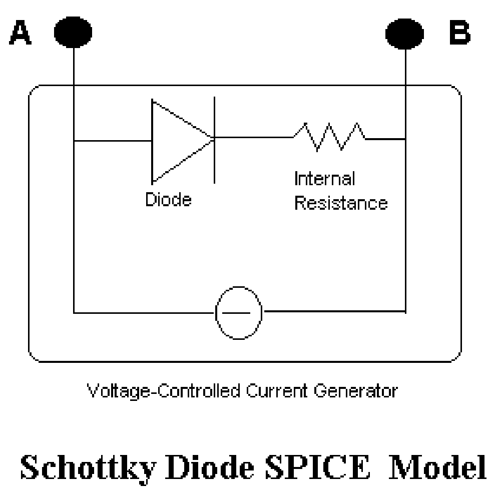

Figure 2. Electric Schottky Diode Model

In addition, we find a resistance depending on the temperature, which simulated the internal diode resistance. As we know [1], SPICE diode has already an internal resistance (i.e. series resistance). Unfortunately, this resistance does not change with temperature. These added one has the target to include this information inside the model.

Since as a final stage we provide the model in library format, the user of the model does not see any of these components save only the cathode and anode, named in Fig. 2 as A and B.

The complete set of raw experimental data is composed of forward and reverse characteristics at room temperature, one point at high temperature (usually the maximum junction temperature) in the forward direction and two points in the reverse direction.

Notwithstanding, the model is able to be accurate at any temperature and range of current as Fig.3 and Fig.4 show.

Using this model we have obtained the following results.

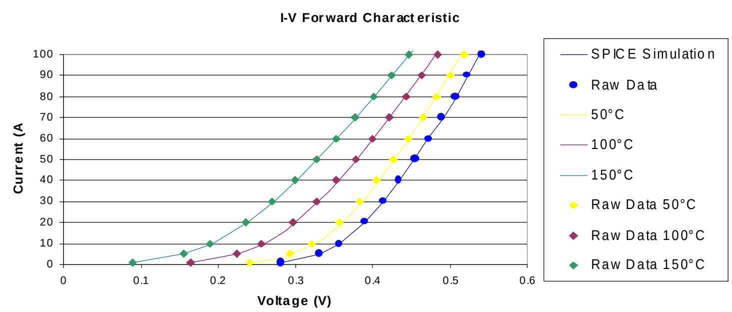

Figure 3. I-V Forward Characteristics-Raw Experimental Data and Simulated Data

In fig.3, we represented the forward I-V characteristics. As we can see directly all the simulated curves lay on the raw experimental data. In particular we present in the following table the values for forward direction at 150°C.

150 ºC			
I_F	V_{SPICE}	V_{TEST}	*Err(%)*
1	0.089	0.090	1%
5	0.156	0.155	-1%
10	0.193	0.190	-2%
20	0.239	0.236	-1%
30	0.274	0.270	-1%
40	0.305	0.299	-2%
50	0.333	0.327	-2%
60	0.359	0.353	-2%
70	0.385	0.377	-2%
80	0.409	0.401	-2%
90	0.434	0.424	-2%
100	0.457	0.447	-2%

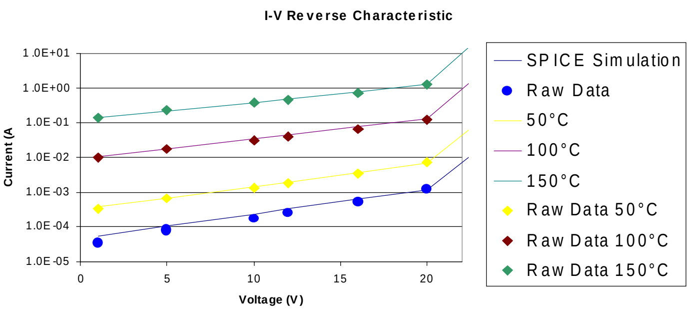

Figure 4. I-V Reverse Characteristics-Raw Experimental Data and Simulated Data

In fig.4, we see that even in the reverse I-V characteristics case, the accuracy of the model is very good. Again we show for the reverse direction the values of the simulated and tested data.

150 ºC

V_R	I_{SPICE}	I_{TEST}	Err(%)
1	1.39E-01	1.39E-01	0%
5	2.20E-01	2.38E-01	8%
10	3.91E-01	3.80E-01	-3%
12	4.91E-01	4.62E-01	-6%
16	7.76E-01	7.35E-01	-6%
20	1.23E+00	1.23E+00	0%

Moreover we have to say that the extension of the dot, indicating raw experimental data, is related to the statistical standard deviation σ.

3. Thermal Model

We need to start from the diode depicted in Fig.1 and to implement a model, which is able to describe the thermal response of the diode to heat pulses.

Thermally speaking, a diode is modeled by a 4-layer structure: junction-silicon, silicon-solder, solder-base and base-heatsink. A thermal resistance and a thermal capacitance describe every layer.

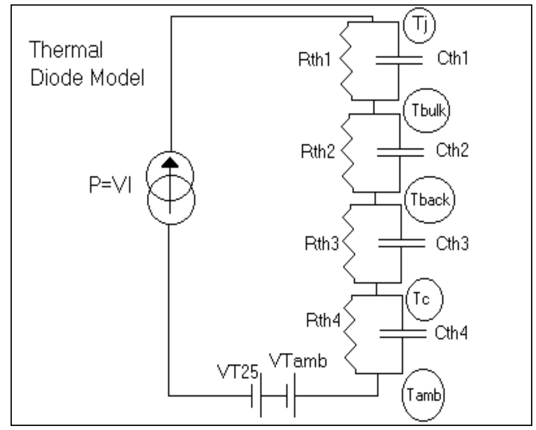

Figure 5. Thermal Schottky Diode Model

The formula that describes the parametric relation is

$$Z_{th} = \sum_{i=1}^{n} R_{thn}\left[1-\exp\left(-\frac{t}{R_{thn}C_{thn}}\right)\right] \quad (1)$$

In our case, n is equal to 4 but it can be any value greater than 1 depending on the complexity of the model.

From the data representing the thermal impedance vs. time of a diode, we try to extract these 8 thermal parameters.

As we can immediately see, this formula does not allow us to distinguish the different layers, since it is completely symmetric.

How can we assign properly to these constants their right layers?

3.1 Physical Model

We start remembering the definitions of the thermal resistance and thermal capacitance

$$R_{th} = \frac{w}{KA} \qquad (2)$$
$$C_{th} = p_s c_s A w = p_s c_s V$$

where w is the thickness of the layer, A is the area of the layer, K is the material thermal constant, p_S is the specific weight and finally c_S means the specific heat.

The table reports the values of these constants for Si (silicon), PbSn (alloy 60/40) and Cu (copper).

	K J/(s m K)	p_S Kg/m^3	c_S J/(Kg K)
Si	125.52	2330	702.91
Cu	29.29	8900	376.56
Al[1]	225.94	2698	920.48
PbSn	47.27	9200	230.12

From these constants, defining the dimensions of the layer is possible to evaluate the thermal resistance and capacitance of the layer.

With this information and the values listed in the precedent table, we can evaluate the thermal capacitance of the silicon using formula (2). The same applies to the thermal resistance.

Notwithstanding it is important to highlight that this represents an approximation of the reality (nowadays a large use of computer simulations is adopted to handle the issue of estimating the thermal parameters).

For our purposes, it is enough to define the different layers using the orders of magnitude of these parameters. They are represented in the following table.

A thumb's rule is that the thermal capacitance is such that

Heatsink>Base>Silicon>Solder

When this rule does not work properly, one has to look at the τ constant.

3.2 Example: IR80CPQ20

Let us see how this technique works for a real example.

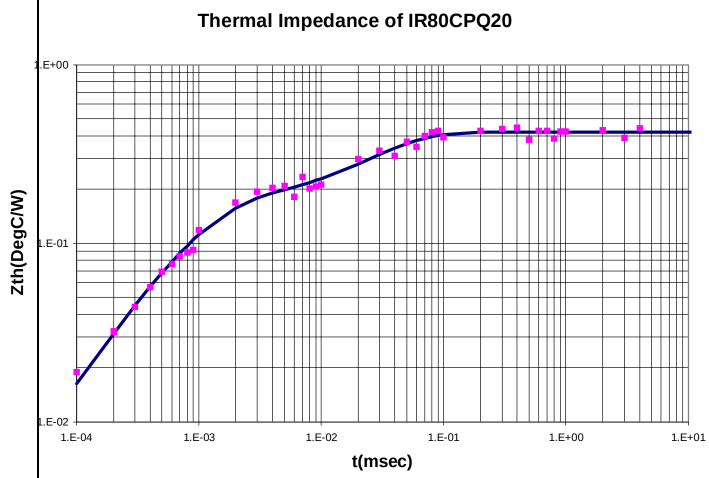

Figure 6. Thermal Impedance of IR80CPQ20

Fitting the thermal impedance data, referring to the Schottky diode IR80CPQ20, we have the following values.

	#1	#2	#3	#4
Rth	$1.1\ 10^{-5}$	$2.5\ 10^{-1}$	$7.4\ 10^{-2}$	$9.3\ 10^{-2}$
Cth	$1.9\ 10^{2}$	$1.4\ 10^{-1}$	$1.4\ 10^{-2}$	$1.1\ 10^{-2}$
τ	10^{-3}	10^{-2}	10^{-3}	10^{-3}

Applying the thermal capacitance rule,

	Junction Silicon	Silicon Solder	Solder Base	Base Heatsink
Rth	10^{-1}	$10^{-2}\div10^{-1}$	10^{-1}	$10^{-5}\div1$
Cth	$10^{-2}\div10^{-1}$	$10^{-3}\div10^{-2}$	$10^{-1}\div1$	$10^{1}\div10^{3}$
τ	$10^{-3}\div10^{-2}$	$10^{-5}\div10^{-3}$	$10^{-2}\div1$	$10^{-4}\div10^{3}$

we see immediately that #1 is base-heatsink and that #2 is evidently solder-base contact.

What is more complicated is distinguish between #3 and #4 since they are very close both in the thermal capacitance and in τ constant.

We decide to follow the thermal capacitance rule and assign #3 to junction-silicon and #4 to silicon-solder contact.

[1] Al is reported but since it is very similar to Si, it is quite undistinguishable using raw data fit.

This undefined situation has arisen since we have few points for time less than 10^{-4}s.

4. Conclusions

In this paper we presented how to improve SPICE diode model to solve the baffling problems of reverse leakage current and high temperature characteristics.

A thermal model is also developed. We give this model a physical explanation, which clearly depicts the diode features.

All this information about the diode is included in a SPICE model provided in library format.

```
demo
.SUBCKT 80CPQ20 ANO CAT
D1 ANO 1 DMOD (0.24359)
*Define diode model
.MODEL DMOD D(IS=1.94886077425861E-04A,N=1.08257328308576,BV=24V,
+ IBV=0.180833785355525A,RS= 0.0002874362,CJO=7.13176859874403E-08,
+ VJ=0.647017772282121,XTI=2, EG=0.69645788462863)
********************************************
*Implementation of VCG2T
VX 1 2 DC 0V
R1 2 CAT TRES 1E-6
.MODEL TRES RES(R=1,TC1=5.05442614166 69)
GP1 ANO CAT VALUE={-ABS(I(VX))*(EXP((((-2.336086E-03/5.054426)*((V(2,CAT)*1E6)/(I(VX)+1E-
6)-1))+1)*0.1610795*ABS(V(ANO,CAT)))-1)}
********************************************
.ENDS 80CPQ20

*Thermal Model Subcircuit
.SUBCKT 80CPQ20T 5 1

CTHERM1 5  4 1.10E-2
CTHERM2 4  3 1.38E-2
CTHERM3 3  2 1.36E-1
CTHERM4 2  1 1.86E+2

RTHERM1 5  4 9.27E-2
RTHERM2 4  3 7.39E-2
RTHERM3 3  2 2.54E-1
RTHERM4 2  1 1.12e-5

.ENDS 80CPQ20T
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Acknowledgements

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References

[1] P.Antognetti and G.Massobrio, *Semiconductor Devices Modeling with SPICE*, New York, McGraw-Hill, 1988.