Extraction of Diode Parameters from I-V characteristics for SPICE Simulations

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Abstract— The paper discusses a precise method for evaluation of Diode Parameters N, IS and RS by solving the Schottky Diode equation. The Exponential model of diode has been considered for evaluating the DC characteristics. The procedure involves three stages; solving an approximated closed form equation, taking a feedback from the SPICE simulator and then optimizing the parameter values by solving the model's Current Equation by Numerical Methods.

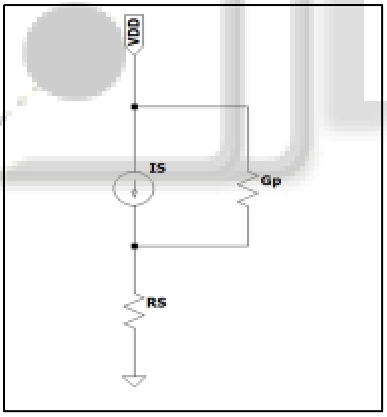
Keywords: Schottky Diodes, Rectifiers, LEDs, Diode Parameters, Dark Saturation Current (IS), Thermal Voltage (VT), Ideality Factor (N), Series Resistance (RS), SPICE, Large Signal Analysis

I. INTRODUCTION

The general Schottky Current Equation of Diodes is

$$ID = IS.\left(e^{\frac{VD}{N.VT}} - 1\right) \qquad [1.1]$$

where VD is the voltage across diode, ID is the diode current, N is the Ideality factor, IS is the Dark Saturation Current, and VT = (k.T)/q is the Thermal Voltage of diode at T° temperature (k=Boltzmann Constant and q=Charge of Electron.) The exponential model takes into consideration the Series and the Parallel Resistances of diode model.



$$ID = IS.\left(e^{\frac{VD - ID.RS}{N.VT}} - 1\right) + Gp.(VD - ID.RS) \qquad [1.2]$$

Here, RS is the Series Resistance and Gp is the Parallel Resistance which is also often stated as Shunt Conductance of diode. The ideal values of RS is 0 and Gp is ∞, these are also the default values in Spice Model of diode. The parameters N, IS and RS can model the diode's forward I-V characteristics over the operating voltage range. The other parameters required in the DC analysis of diodes are Breakdown Voltage (BV) and Current at Breakdown Voltage (IBV), which define the Reverse Bias Characteristics of the diode. Considering the three parameters N, IS and RS to model the diode's forward characteristics, the Schottky Current Equation becomes

$$ID = IS.\left(e^{\frac{VD - ID.RS}{N.VT}} - 1\right) \qquad [1.3]$$

II. APPROXIMATING THE CURRENT EQUATION AS A CLOSED FORM FUNCTION

The product of IS*$e^{\frac{VD - ID.RS}{N.VT}}$ in the Equation 1.3 is greater than the value of IS, especially in the case of Small Signal Schottky diodes where IS is of the order e-12 to e-18. So, the term -IS can be ignored to approximate Equation 1.3 to a Closed Form Function. The solutions to N, IS and RS are given by the equations below. A constant CR is defined to simplify calculations.

$$CR = \frac{\ln\left(\frac{ID1}{ID2}\right)}{\ln\left(\frac{ID3}{ID4}\right)} \qquad [2.1]$$

A. Series Resistance

$$RS = \frac{CR.(VD3 - VD4) - (VD1 - VD2)}{CR.(ID3 - ID4) - (ID1 - ID2)} \qquad [2.2]$$

B. Ideality Factor: N

$$N = \frac{(VD1 - VD2) - RS(ID1 - ID2)}{VT.\ln\left(\frac{ID1}{ID2}\right)} \qquad [2.3]$$

C. Dark Saturation Current: IS

$$IS = \frac{ID}{\left(e^{\frac{VD - ID*RS}{N*VT}} - 1\right)} \qquad [2.4]$$

The points (VDi, IDi) are voltages and current at different points on the I-V curve. These values can also be obtained from an experimental setup to determine the current through the diode over the operating voltage range.

A minimum of three points are required to determine an approximate value of these parameters. For more than three points, the program can solve these equations for all combinations of data points and select the approximated values that fall within acceptable parameter limits. These values to N, IS and RS provide with a seed values for the next steps to further Optimize the parameter values.

III. FEEDBACK FROM SPICE SIMULATOR

One of the significant steps that optimzes the values of these parameters much closer to the roots of the Current Equation is to get a feedback from the SPICE simulation.

This is necessary because of the various factors that affect the voltage-current relations that this paper does not consider. When the solution to the current equation is used to create a SPICE model for simulation, it shows a certain deviation in I-V characteristics from what is expected. So, the Voltage values are scaled by a Scaling Factor.

The Voltage Scaling Factor makes up for this difference by adjusting the voltages to be higher or lower than what the SPICE would calculate internally, accounting for all other diode effects. So, the data matrix becomes,

$$[\,(VDi, IDi)\,] \rightarrow [\,(VDi * FACTOR, IDi)\,] \qquad [3.1]$$

where the constant FACTOR can range from 0.8 to 1.2 depending upon the % change of voltage.

A simple parameter-sweep inside the SPICE script, and an error feedback for the sweep from the SPICE program makes the values of N, IS and RS closer to its roots.

Similarly, if the Voltages are again scaled during Optimization by Numerical Methods, they reduce the I-V curve fitting errors.

As a result, there exists two voltage scaling variables, one for scaling the voltages for computation of seed values, and another one for scaling the voltages for the Optimization by Numerical Methods.

IV. NUMERICAL METHODS TO SOLVE CURRENT EQUATION

The actual values of N, IS and RS that solve the Schottky Current Equation 1.3 for all the data points (VDi, IDi) on the I-V curve are computed by a very common approach of Numerical Methods. To solve the Equation 1.3, we have considered the Newton-Raphson method for this paper because it has a simple algorithm and converges quicker. The Current Equation 1.3 becomes

$$f(N, IS, RS) = N.VT.\ln(\frac{ID}{IS} + 1) + ID.RS - VD = 0 \quad [4.1]$$

The general equation to represent the Iterative Step in Newton Raphson for Multi-Variate Equation is

$$[x_{n+1}] = [x_n] + J^{-1}.[\, f(x_n)\,] \quad [4.2]$$

The method here requires to solve the Equation 4.1 by Equation 4.2, for many datapoints, and thus the J matrix computed in the Newton-Raphson method becomes a non-square matrix. The term f1, f2,…fn corresponds to the function for the number of data points or the number of (VDi, IDi) values.

$$J = \begin{bmatrix} \frac{df1}{dN} & \frac{df1}{dIS} & \frac{df1}{dRS} \\ \frac{df2}{dN} & \frac{df2}{dIS} & \frac{df2}{dRS} \\ \frac{df2}{dN} & \frac{df2}{dIS} & \frac{df2}{dRS} \\ & \vdots & \end{bmatrix} \quad [4.3]$$

To overcome this problem, a modified version of Equation 4.1 becomes

$$[x_{n+1}] = [x_n] + (J^T.J^{-1}).J^T.[\, f(x_n)\,] \quad [4.4]$$

where the term $[x_n]$ represents the matrix of the values of N, IS and RS in the present Iteration, and the term $[x_{n+1}]$ is the matrix of values that Equation 4.4 computes, which would then become the term $[x_n]$ in the next iteration. The starting values of N, IS and RS in $[x_n]$ for the first iteration are provided by the Equations 2.2, 2.3 and 2.4.

The term $J^T.J^{-1}$ becomes a Square Matrix. The derivatives of function in Equation 4.1 for J matrix are

$$\frac{df}{dN} = VT.\ln(\frac{ID}{IS} + 1) \quad [4.5]$$

$$\frac{df}{dIS} = \frac{-N.VT}{IS.(1+\frac{IS}{ID})} \quad [4.6]$$

$$\frac{df}{dRS} = ID \quad [4.7]$$

The system is solved for number of iterations that are required to make the function in Equation 4.1 nearly 0 and constant for a couple of iterations.

V. RESULTS OF THE PROGRAM

A program was developed to extract values of N, IS and RS from the I-V characteristics of the diode was tested on four categories which are Small Signal Schottky, Rectifiers, LEDs and Pin diodes. The program ran on I-V data from a total of 28 diodes from different manufacturers, and the results are represented in a tabular format.

To make the SPICE model exhibit I-V behavior closer to the actual I-V characteristic, consider more I-V points along the curve.

To check the correctness of the program, the program created necessary SPICE files and ran the simulation. The model evaluates voltages at different currents.

The error used to measure the accuracy of the model's characteristics is Square Root Error. In the paper, Square Root Error is calculated for a total of around 15 points taken over the operating range of forward voltage.

TYPE OF DIODE	VOLTAGE RANGE (Vmin, Vmax) (V)	CURRENT RANGE (Imin, Imax) (A)	N	IS (A)	RS (ohm)	SQUARE ROOT ERROR IN VOLTAGE (V)
LED	1.7, 2.7	0, 50m	1.630	2.500E-23	9.520E+00	10.76m
	1.5, 2.5	0, 50m	2.000	1.410E-18	1.886E+00	16.94m
	1.5, 2.5	0, 50m	3.256	5.765E-13	3.309E+00	15.80m
	1.5, 2.5	0, 50m	2.000	1.410E-18	1.886E+00	16.94m
	2.0, 4.0	0, 50m	4.427	2.239E-13	2.107E+01	31.05m
	2.0, 4.5	0, 50m	4.427	2.243E-13	2.107E+01	31.05m
	1.5, 2.5	0, 50m	1.542	1.970E-23	4.479E+00	14.22m
PIN	0, 1.2	0.01m, 100m	2.190	4.900E-09	4.136E-01	7.416m
	0, 1.2	0.01m, 100m	1.428	1.208E-12	5.766E-01	6.423m
	0.4, 1.0	0.01m, 100m	1.828	7.205E-11	5.600E+00	4.432m
	0.001, 1	10n, 10	1.650	7.660E-09	5.845E-03	47.36m
	0, 1.3	1u, 100m	2.000	7.074E-13	4.426E-01	22.15m
	0.5, 1.2	0.01m, 100m	1.080	1.704E-16	1.386E+00	7.818m
	0, 1.2	10u, 1	1.936	9.324E-10	3.653E-02	9.490m
RECTIFIERS	0, 0.9	0.01m, 100m	2.132	2.461E-06	3.251E-03	14.4m
	0, 1.2	0.1, 10	3.803	2.035E-03	1.912E-02	7.093m
	0, 1.6	0.01, 100	1.366	2.760E-05	2.135E-02	30.82m
	0, 1	10m, 100	2.451	1.199E-04	1.475E-02	7.496m

	0, 1	10m, 100	1.000	5.347E-06	1.040E-02	2.751m
	0.2, 1.6	0.1, 100	1.950	8.423E-07	4.986E-03	22.73m
	0, 1.4	0.001, 10	1.930	7.517E-08	4.695E-02	7.266m
SCHOTTKY	0, 0.9	0, 50m	1.400	2.137E-07	1.026E+01	5.675m
	0, 0.9	0, 50m	1.133	2.108E-08	1.061E+01	2.541m
	0.75, 1.20	10m, 1	1.789	5.328E-10	2.545E-01	5.565m
	0, 0.5	0.001, 1	1.000	6.759E-07	6.910E-02	8.112m
	0, 1	10m, 100	1.129	2.335E-07	2.298E+00	10.41m
	0, 0.6	0.001, 1000	1.056	4.580E-08	6.540E-01	3.368m
	0, 2	100u, 100m	1.150	2.650E-09	3.155E+01	20.27m

Table 1: Values of N, IS, RS for different diodes under four diode categories and their corresponsing Square Root error in voltage, obtained from SPICE simulation.

The extracted diode parameters produce I-V characteristics well within the error limit and replicate the I-V curve precisely over the operating voltage range. The extracted parameters are within the range of their respective orders.

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