0710, or Fax: (213) 8339658, and I will show them how easy these models are to generate.

I am also enclosing a press release on vendor supplied opamp models. Opamp models supplied by various hardware vendors are becoming very popular. Although we feel that the models are not very good, not well supported, and not computationally efficient, we have decided to support them. It seems that the vendors have no idea what SPICE compatible means. Not one of them have produced their models is a standard SPICE syntax format. This can be very frustrating for SPICE users who have to spend time converting the netlist to the proper SPICE format. We have performed this conversion, and the opamp models from Harris, PMI, Linear Technology, Comlinear, and Texas Instruments are available in true SPICE syntax format (ASCII files). Both Macintosh and PC disk formats are supported."

Sincerely,
Charles Hymowitz
Chief Applications Engineer
Intusoft

In this issue, we also present an article entitled "SPICE Macro Model for the Simulation of Zener Diode Current-Voltage Characteristics," by Silphy Wong and Chenmin Hu, of Valid Logic Systems in San Jose, California. This article shows how the existing SPICE diode model [1] is inadequate to represent the Current-Voltage (I-V) characteristics of the zener diode, and describes a new macro model that yields accurate performance of I-V reverse characteristics, with temperature effects.

SPICE Macro Model for the Simulation of Zener Diode I-V Characteristics

In order to facilitate the growth of the electronics industry, system or IC engineers have come to need increasingly accurate models for an ever larger number of integrated-circuit simulations. It is necessary to provide accurate simulation for voltage reference devices, such as zener diodes. The existing SPICE diode model cannot be used to accurately represent the I-V characteristics of a zener diode in the reverse region. The zener diode macro model

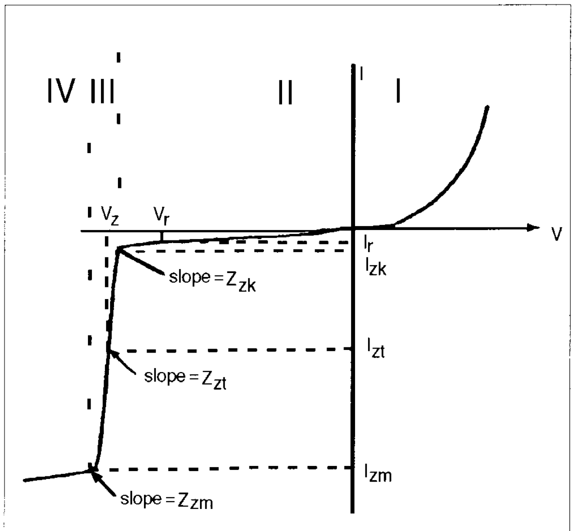


Figure 1

presented here has accurate I-V simulation characteristics, and can be easily made using SPICE provided primitives.

In order to define the I-V characteristic of the zener diode, four regions can be defined in the I-V characteristic curve, as shown in Fig. 1. They are the forward-biased region, reverse-biased before breakdown, reverse-biased after breakdown, and reverse-biased after maximum zener current, I_{zm}, is reached. Obviously, zener diodes are mostly used under reverse bias. The leakage current, I_r, for a reverse-biased zener can be as high as a few tenths of a milliamp. The current is also a non-linear function of the bias voltage, V_r, and the operating temperature. After the breakdown point is reached, there is a specific knee point current I_{zk} where the slope of the I-V curve is defined by $1/Z_{zk}$. Then, nominal voltage V_z is obtained when a test current I_{zt} is applied. Zener impedance Z_{zt} can be measured from the slope of the I-V curve at I_{zt}. The temperature dependence of zener voltage is defined in data-sheets by means of the zener voltage temperature coefficient [2]. A zener diode provides voltage regulating for any currents between I_{zk} and the maximum zener current, I_{zm}. I_{zm} indicates another knee point, after which the zener diode impedance increases, and regulation virtually ceases.

Very significant deficiencies exist when using the SPICE diode model to simulate a zener. Although the I-V characteristics of a zener diode in the forward-biased region can be easily modeled using the SPICE diode model, the model is unable to simulate the dynamic impedance accurately in both the forward and reverse regions. One may use the diode model just for the simulation of the reverse region. Even in this case, there are still a few noticeable problems.

(1) The reverse leakage current Ir cannot be modeled properly. In the region of reverse-bias before breakdown, the current I_r from SPICE diode model is [3]:

$$I_r = I_s + V_d G_{min}$$

where I_s is the reverse saturation current, and G_{min} is a very small conductance (equal to 10^{-12} in default [1]), which makes the second term small enough to be neglected. However, a large I_s in the µA range is needed to model zener leakage current, which will easily cause convergence problems in simulation at high temperatures. Additionally, I_r appears as a constant instead of a function of V_d.

(2) It is possible by using the parameter BV (the breakdown voltage) to simulate a nominal zener voltage V_z, and using the parameter RS (the ohmic resistance) to simulate zener impedance Z_{zt}, both at the given I_{zt}. If V_z and V_d assume positive values, the following two equations can be easily derived from the SPICE diode model equations [3]:

$$I_{zt} = I_s(e^{(V_z - BV - I_{zt} RS)} - 1 + BV/V_t)$$

where V_t is the thermal voltage, N is the emission coefficient, and

$$Z_{zt} = (I_d/V_d)^{-1} + RS = V_t/I_d + RS$$

at $I_G = I_{zt}$, where

$$I_d = I_s(e^{(V_d - BV)}/V_t - 1 + BV/V_t)$$

As a consequence, the parameter I_{BV} (current at breakdown) is fixed as

$$I_{BV} \geq I_s(BV/V_t)$$

which can be much different from the required value of I_{zk}. One may assume that I_{BV} matches I_{zk}, but there will still be no way to model Z_{zk} at the given I_{zk}.

(3) The temperature dependence of the zener voltage and, more importantly, the second knee point I_{zm} cannot be simulated by the diode model.

(4) The parameters I_s and N are used for the modeling of the forward region. But, the parameter RS obtained from the simulation of Z_{zt} is usually not acceptable in the forward region, because different values of RS are usually required for the modeling of the forward and reverse regions.

Macro Model Description

The schematic, as shown in Fig. 2, describes the design of the proposed zener-diode macro model.

A. Static I-V Characteristics

The zener diode static behavior is represented by the curve of Fig. 1, which can be considered as the four distinct regions shown in the figure.

(1) Forward bias region: Since a zener diode is nearly identical to an ordinary semiconductor diode in this region, the model I-V characteristic is determined by the forward-biased diode D_1 in Fig. 2.

The terminal current of the model is

$$I_d = I_{d1} + I_{d2} + I_R$$

When the applied voltage V_d is greater than zero, I_R and I_{d2} can be ignored in comparison with I_{d1}. In fact, I_{d2} is equal to I_{s2}, which is the reverse saturation current of D_2. The current through the resistor R is also small, since R is very large in value for the simulation of the zener leakage current in the reverse-bias region before breakdown. Then, we have $I_d = I_{d1}$. Therefore, region I of the I-V curve in Fig. 1 can be simulated by properly picking the parameters I_{s1}, N_1, and R_s for diode D_1.

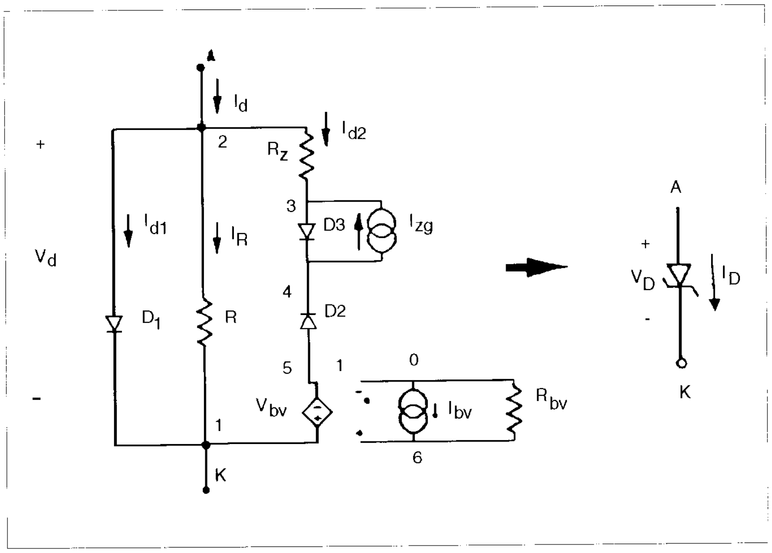


Figure 2

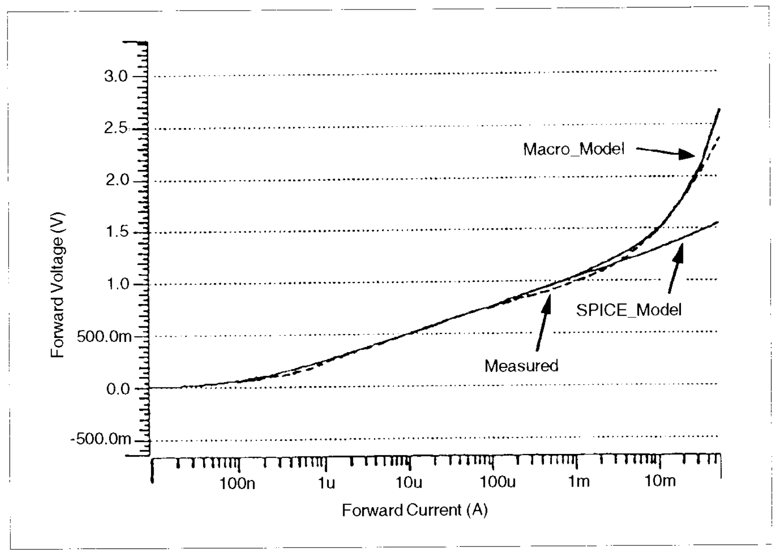


Figure 3

(2) Reverse bias before breakdown: For an applied reverse-biased voltage smaller than the breakdown voltage, the model I-V characteristic behaves linearly with a slope of 1/R, where R is the resistor connected in parallel with D_1. The two diodes in the model are both reverse biased. Then, the zener leakage current Ir is modeled as

$$I_d = V_d/R - I_{s2} + I_{s1}$$

The leakage current is approximated by V_d/R. In physical devices, the leakage currents vary almost exponentially with the reverse biased voltages, as shown in region II of Fig. 1. The linear approximation in this region is a limitation of the proposed model.

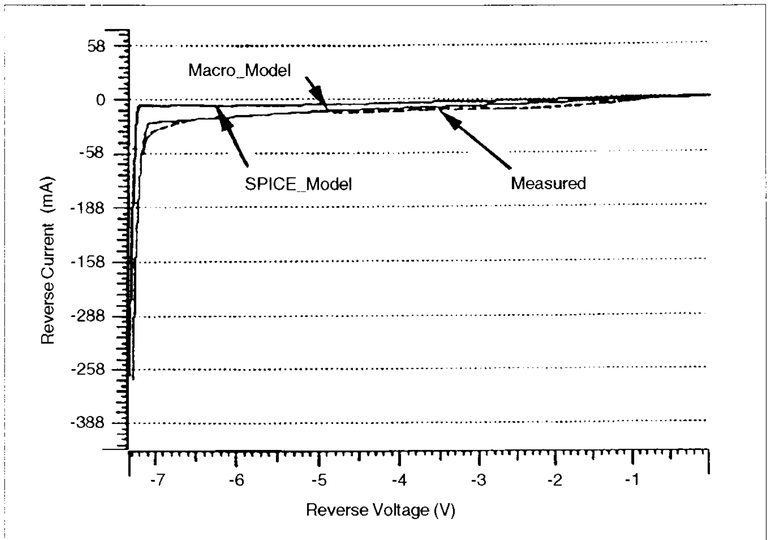


Figure 4

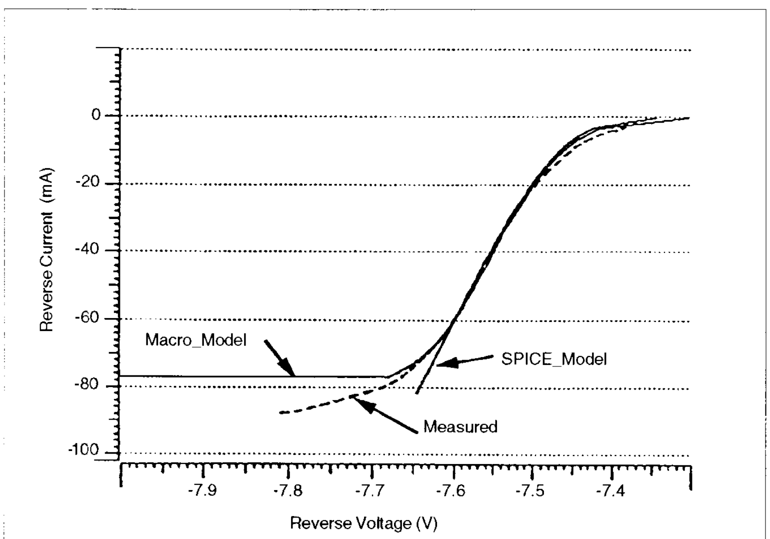


Figure 5

(3) Reverse bias after breakdown: The branch which contains diode D_2 is used to model the I-V characteristics in regions III and IV of Fig. 1. If the reverse-biased voltage is higher than V_{bv}, the product of R_{bv} and I_{bv}, D_2 begins to turn on. The value of V_{bv} is chosen for the model to yield a nominal zener voltage, V_z, at a given test current I_{zt} as

$$V_{bv} = V_z - V_{d2} - V_{Rz} + V_{d3}$$

$$V_z - N_2 V_t \ln(I_{zt} - I_{s2}) - R_z I_{zt} + N_3 V_t \ln((I_{zg} - I_{zt})/I_{s3})$$

The two reverse saturation currents, I_{s2} and I_{s3}, are set equal to 2.5 fA for simplicity. With the diode D_3 and current source I_{zg}, the branch current I_{d2} will never exceed the value of I_{zg}. Thus, the second knee point defined by I_{zm} can be simulated. The current through D_3 is expressed as $I_{d3} = I_{zg} - I_{d2}$.

When the magnitude I_{d2} increases to the value of I_{zg}, D_3 is reverse-biased and allows no further current increase in the branch. In order to avoid a possible negative voltage for V_{bv}, V_{d2} and V_{d3} are set equal at I_{zt}, which requires that

$$N_3 = N_2/\ln((I_{zg} - I_{zt})/I_{zt}).$$

The parameters R_z and N_2 will be calculated from the derivation of zener impedance. By neglecting the parallel connected large resistor R, the total zener impedance in this region can be expressed as

$$Z_z = R_z + Z_{d2} + Z_{d3}$$

The forward-biased diode impedance at a low frequency is $Z_d = \delta V_d/\delta I_d = NV_t/I_d$

where the small junction capacitance which is required for modeling the reverse-biased terminal capacitance is ignored. Hence, we have

$$Z_z = R_z + N_2 V_t/I_{d2} + N_3 V_t/(I_{zg} - I_{d2})$$

By substituting the two most important points of the zener impedance, Z_{zt} and Z_{zk}, two equations are generated as follows:

$$Z_{zt} = R_z + N_2 V_t/I_{zt} + N_3 V_t/(I_{zg} - I_{zt})$$
$$Z_{zk} = R_z + N_2 V_t/I_{zk} + N_3 V_t/(I_{zg} - I_{zk})$$

Since N_3 has previously been defined, the two unknowns R_z and N_2 can be solved by these last two equations. If the calculated R_z is smaller than zero, R_z is set to zero, and N_2 can then be calculated from Z_{zt}. Some error in Z_{zk} may be introduced as a result. The value of I_{zg} will define the zener impedance at the second knee point I_{zm}. That is,

$$Z_{zm} = R_z + N_2 V_t/I_{zm} + N_3 V_t/(I_{zg} - I_{zm}).$$

Z_{zm} is generally not an important characteristic, and setting $I_{zt} = 1.1(I_{zm})$ will usually be sufficient. After I_{d2} reaches I_{zg}, the slope of the I-V curve is determined by 1/R again.

B. Temperature Response

By taking the advantage of the SPICE provided resistor temperature coefficients [3], the proposed model simulates the temperature response of the zener voltage and the zener leakage current.

Table 1: Zener 1N5236 Macro-Model Spice List

```
Zener 1N5236 macromodel analysis
*
*
.option TNOM = 27
*
.SUBCKT M1N5236 2 1
*          : :
*          : cathode
*          anode
*
D2 5 4 MD2
.MODEL MD2D I=2.5F  N=1.444
   XTI=1
D3 4 MD3
.MODEL MD2 D  IS=2.5 F  N=1.3
IZG 4 3 80M
R 1 2 1.9MEG TC=-7.5M
D1 2 1 MD1
.MODEL MD1 D IS=0.1229U  N=4.423
   XTI= 1 RS=20
RZ 3 2 578M
EV1 1 5 6 0 1
*    EV1(=VBV)
IBV 0 6 1M
RBV 6 0 7.415K TC=5.8U
*
.ENDS M1N5326
```

Table II: SPICE Diode Parameters for 1N5236

Parameters	Description	Value
N	Emission coefficient	4.423
IS	Saturation current	0.1229e-6
XTI	Temperature coefficient of I_s	1
RS	Ohmic resistance	1.71
BV	Reverse breakdown voltage	7.29
IBV	Current at V-Breakdown	0.06e-3

(1) The temperature response of zener voltage: The temperature response of a nominal zener voltage is usually defined in the manufacturer's data Book [2], as a linear temperature coefficient T_{vz} (μV/C). This can be easily achieved by providing the temperature coefficients of R_{bv} in the model, as follows:

$$V_{bv}(T_2) - V_{bv}(T_1)[\Delta T^*Tvz/100+1]$$

where T_1 is the room temperature (27 C), and ΔT is equal to T_2 - T_1. From Figure 2, $V_{bv}(T_2) = I_{bv}\, R_{bv}(T_2)$
$= I_{bv}\, R_{bv}(T_1)\, [1+\text{lin}\, \Delta T]$

where lin is the linear temperature coefficient for resistor R_{bv}, and lin = $T_{vz}/100$.

(2) The Temperature Response of the Reverse Leakage Current: The leakage current of a zener diode, I_r, is a nonlinear function of temperature. This temperature-dependent function can be approximated as a second-order nonlinear function, which could be represented by the temperature behavior of a resistor. As a result, resistor R can be set to model the temperature characteristic of I_r as

$$R(T_2) = R(T_1)\, [1+\text{lin}\, \Delta T + \text{quad}\, \Delta T]$$

where quad is the second-order temperature coefficient. Since I_r is equal to V_r/R, the leakage current will change with temperature.

Model Performance

A silicon zener diode 1N5326 (pp. 4-54 to 4-59 of [2]) is selected as an example to illustrate the model performance for the simulation of the zener I-V characteristics. The SPICE net-list of the 1N5236 macro model is shown in Table 1. A SPICE diode model for 1N5236 is also derived for the purpose of comparison. The diode model parameters are listed in Table 2. Both simulations were done using Valid Logic System's AWBII. The performance of the two models are summarized in Table 3. The I-V curves in the forward region are shown in Fig. 3. The I-V Curves shown in Fig.4 are for reverse current from 0 to I_{zk}. The I-V curves in the reverse-biased region after breakdown are shown in Fig. 5. The second knee point I_{zm} cannot be modeled by the SPICE diode model as shown in Fig. 5. However, there is a noticeable error for the macro model in the region where the current is greater than I_{zm}.

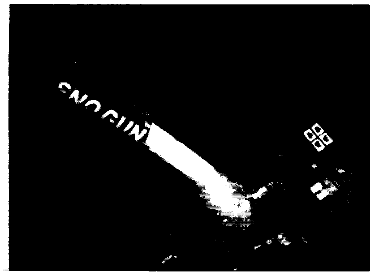
If the junction capacitance were modeled, zener impedance would be different at high frequencies. If desired, junction capacitance could be added to D_1 to model this characteristic. Due to the existence of DC sources V_{bv} and I_{zg}, a voltage drop of -12 μV appears across the macro model when it is connected in high impedance situation.To summarize, the main enhancements for the zener diode macro model, as compared to the SPICE diode model, are listed as follows:

(1) By using three circuit branches, the model separates the simulation of three bias regions, forward, reverse before breakdown, and reverse after breakdown, in a zener I-V characteristics. The performance, therefore, in each of the regions is modeled much more accurately comparing with the SPICE diode model.

(2) The voltage regulation range of a zener I-V characteristics can be precisely modeled including the nominal zener voltage V_z at test current I_{zt}, the zener impedance at the two knee points I_{zk} and I_{zm}, and the zener impedance at V_z and I_{zt}.

(3) The temperature variations of zener voltage V_z and reverse leakage current I_r are

(continued on page 52)



and other delicate components inevitably gather dust, particulate matter, even fingerprints, thus requiring cleaning. Most cleaning systems contained hazardous agents such as CFC's. Va-Tran Systems, Inc. has introduced the Sno Gun™ Dry Ice Snow Cleaning System, an environmentally sound alternative to CFC-based cleaning agents. The hand-held Sno Gun utilizes a non-toxic, non-hazardous cleaning process, using CO_2. Employee exposure to hazardous cleaning agents is eliminated. Cleaning with dry ice snow is more thorough and gentle than nitrogen. Submicron particles and even fingerprints are removed with leaving residue and without scratching delicate surfaces. The Sno Gun cleaner is non-conductive allowing electrical and electronic components to be cleaned safely even while energized. For more information contact: Va-Tran Systems, inc., 677-A Anita Street, Chula Vista, CA 91911-4661. Tel: (619) 423-4604. Fax: (619) 423-4555. **Circle Number 74**

Laser Direct-Write System

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Simulation and Modeling
(continued from page 12)

also modeled by the SPICE provided resistor temperature coefficients.

(4) Simulation convergence problems associated with conventional diode breakdown are avoided with this macro model.

With all the design equations derived in this article, a model can be readily generated for a zener diode from measurement or from manufacturer data sheet information. The simplicity and accuracy together with the use of the most popular circuit simulation program SPICE enables design engineers to apply the model in all general purpose CAE applications.

Table III: Summary of Model Performance Schemes

Parameter	Unit	Measured	Mcro Model	SPICE Diode	Test Cond.
I_r	µA	3	3.07	0.11464	V_r = 5.7 V
Z_{zk}	ohm	300	300	519	I_{zk} = 0.25 mA
V_z	V	7.5	7.5	7.5	I_{zt} = 20 mA
Z_{zt}	ohm	3	2.995	3	I_{zt} = 20 mA
T_{vz}	µV/C	0.058	0.058	2.091	I_{zt} = 20 mA
T_{Ir}	µA/X	300	312	1314.69	V_r = 5.7

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