SPICE Implementation of Lossy Transmission Line and Schottky Diode Models

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Abstract — Models for the lossy transmission line and the Schottky diode have been incorporated into the source code of the circuit simulation program SPICE (version 2G.6). This work is a continuation of our recent SPICE modeling efforts involving enhancement- and depletion-mode GaAs FET's. As before, the line-by-line modifications to SPICE to include the new models will be made available to interested researchers.

I. Introduction

The SPICE program [1] for transient and frequency-domain analysis of linear and nonlinear circuits continues to be of great importance to designers, even as the technology evolves to include more and more sophisticated silicon and gallium-arsenide based devices. This motivated our recent work [2] in which we installed a model for the enhancement- and depletion-mode GaAs FET into the source code of SPICE version 2G.6. This was an update of our earlier effort [3] which dealt with depletion-mode GaAs FET's only.

The present project is a continuation of our endeavors to augment SPICE's modeling capabilities. We have included both a lossy transmission line model and a Schottky diode model directly into the source code of SPICE 2G.6. In both cases, the models themselves were developed by others; our contribution has been to include these models into SPICE and to make the updated code available to interested researchers.

Sometime after the commencement of our modeling work, a new release of SPICE (version 3A7) was made available from the University of California at Berkeley. The program now contains a GaAs FET model which is similar, but not identical, to our previously installed model. It also contains a lossy transmission line model which is different from the one described here. (The distinction between the two lossy-line models is described in Section II. For brevity we omit the comparison between the two GaAs FET models; the details are available in [2] and the latest version of the SPICE user's guide.) However, the consensus of circuit simulation experts present at the authors' recent talk [4] is that SPICE 3A7 needs a considerable amount of debugging before that version of the program will be usable. Consequently we expect that SPICE 2G.6 will remain in use at least for the immediate future, and our models—with aspects that may make them better for certain applications anyway—will continue to be of interest.

II. The Lossy Transmission Line Model

A. The Basic Model

The model used for the lossy transmission line was derived by Gruodis in 1979 [5]. While the model is not the most recent one available (e.g. [6]), it was shown to agree with experiment and to be amenable to installation into a computer program. (Gruodis installed the model into ASTAP, an IBM proprietary transient analysis program.) Hence our decision to select this model.

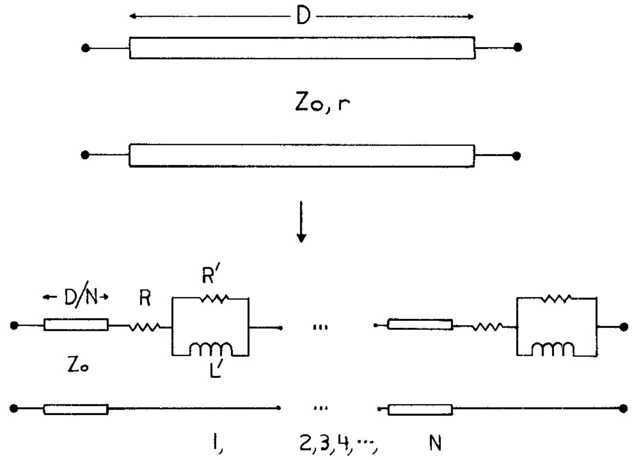

Fig 1. Equivalent circuit of lossy transmission line

The basic idea is to model a lossy line of length D as a cascade of N two-port sections, each consisting of an ideal, lossless line of length $d = D/N$ and a resistor of value $R = r^*(D/N)$, where r is the loss per unit length of line. This is illustrated in Fig. 1. The elements R' and L' take into account the skin effect, which is discussed in the next section.

The reference [5] discusses how the present model was evolved from previous lumped models and how the new distributed model more accurately portrays the true electrical behavior of a lossy transmission line. In particular, [7] and [8] discuss a lossy transmission line model consisting of LCR T-sections in cascade. It normally took up to 100 such sections to approximate a line, and even with this, spurious oscillations appeared in the calculated response. Gruodis's approach solved this problem and furthermore achieved accurate results with fewer sections.

The lossy transmission line that is now available in SPICE 3A7 models a uniform distributed RC line as a cascade of lumped RC sections. The capacitors of this model may be replaced, optionally, by reversed-biased diodes, thereby providing a nonlinear capacitance. While we have not had the opportunity to compare this with Gruodis's model, our intuitive feeling is that the latter is probably more accurate for transmission lines suspended within or deposited upon standard dielectric substrates, while the SPICE 3A7 model may be superior for modeling interconnect on semiconductor substrates.

B. The Inclusion of the Skin Effect

The idea of modeling the skin effect by the parallel RL network section shown in Fig. 1 is due to Brennan and Ruehli [9]. A typical skin-effect response can be achieved by setting R' equal to R, the elemental resistance described above. The inductor L' models a length of transmission line which is much shorter than the length of lossless line in each section of the overall model. The derivation of an expression for L' proceeds as follows.

1) Define λ as wavelength, ω as radian frequency, f as frequency in Hz, $\tau = 1/f$ as delay, and θ as electrical length.
2) Recall that $d = D/N$ is the physical length of one section of the lossy transmission line model.

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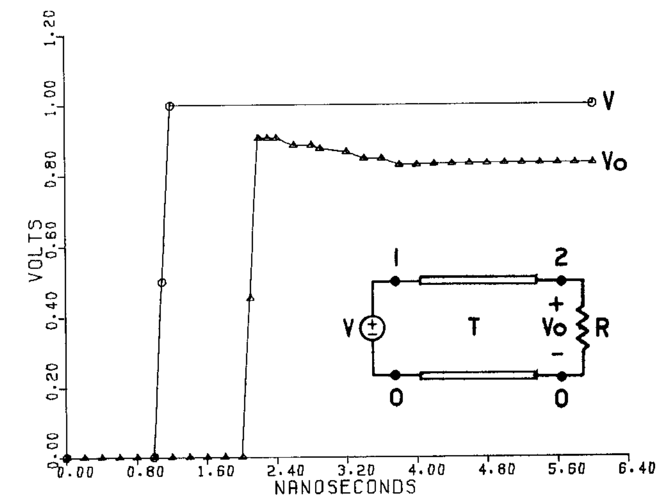

Fig. 2. Response of lossy transmission line.

3) Note the relationship $\theta = (2*\pi/\lambda)*d$.
4) Use the approximate equivalence [10]

$$L = Z_0 \sin\theta/\omega$$

between an inductor L and a transmission line of electrical length θ.
5) Set $d' = 0.1d$ to obtain a "short" line, and then use the small angle approximation $\sin\theta = \theta$ to arrive at the following formula for L':

$$L' = Z_0*(\tau)*(d'/\lambda).$$

To obtain a fixed value for L', the midband quantities for delay and wavelength are assumed.

C. An Example

To verify the model (with no skin effect), we simulated a lossy transmission line operating between a step-function voltage source and a 50-Ω termination. This example is the same as the (experimentally verified) one given in [5, fig. 6, case D]. The SPICE data file for this is given below.

```
Lossy Transmission Line, No Skin Effect
V 1 0 Pulse (0 1 1ns .2ns .2ns 9.4ns 10ns)
T 1 0 2 0 Z0 = 50 Td = 1ns NL = 1 NorLc = 10 Nr = 10
R 2 0 50
.Tran .1ns 6ns
.Print Tran V(1) V(2)
.Plot Tran V(1) (0.0, 1.0) V(2) (0.0, 1.0)
.Options Limpts = 500
.End
```

The circuit, along with a plot of the response, is shown in Fig. 2. Our results were identical to those of [5]. We used ten sections rather than 50 as in [5] with no noticeable difference in the calculated results. We tried to determine the minimum number of sections needed; we found that we could use as few as five sections before our results diverged from those of [5]. In an arbitrary problem one would have to experiment a bit to determine the fewest sections needed. Based upon our own observations, ten sections would seem to suffice in most cases. With the skin effect accounted for in this particular simulation, the output voltage changed by less than 1 percent from the values displayed in the plot of Fig. 2.

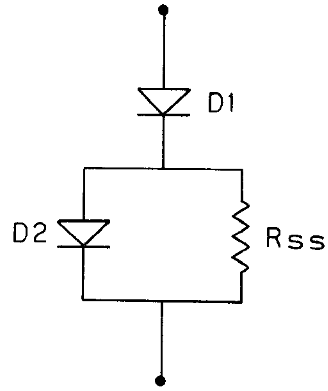

Fig. 3. Equivalent circuit of Schottky diode.

III. The SCHOTTKY Diode Model

A. The Basic Model

The dc model for the Schottky barrier diode as shown in Fig. 3 was formulated by Estreich [11] and consists of elements $D1$, $D2$, and R_{ss}.

$D1$ and $D2$ are described by the standard pn-junction diode equations contained within SPICE. The essential parameters that need to be specified for these diodes are as follows:

For $D1$:	N	emission coefficient
	I_s	saturation current
	R_s	ohmic + bulk resistance
For $D2$:	N_s	emission coefficient
	I_{ss}	saturation current.

The Schottky spreading resistance is modeled by the resistor R_{ss}. For the principal diode, $D1$, values may be assigned to *any* of the parameters that normally are associated with the standard SPICE pn-junction diode model. Any parameters that are not assigned revert, as usual, to their respective default values as given in the SPICE manual for pn-junction diodes. For the auxiliary diode, $D2$, only N_s and I_{ss} may be assigned. The other parameters of $D2$ are fixed at their defaults.

B. An Example

To verify the model, we simulated the $I-V$ curve of a typical Schottky diode. This example is the same as that given in [11, fig. 6], which considers a GaAs Schottky diode with a 3×15 μm rectangular anode. The parameter extraction problem for this device is solved in [11] and the results for the parameters I_s, R_s, N, R_{ss}, I_{ss}, and N_s are given in the SPICE data file below.

```
Diode Model
Vin 1 0
D1 2 0 Schottky
Vid 1 2
.Model Schottky Sd(Is = .3p Rs = 70.0 N = 1.05 Rss = 90
Iss = 14.4u Ns = .389)
.DC Vin .5 1.2 .05
.Print DC I(Vid) V(1)
.Plot DC I(Vid)
.End
```

Our results, shown in Fig. 4, are indistinguishable from those of [11].

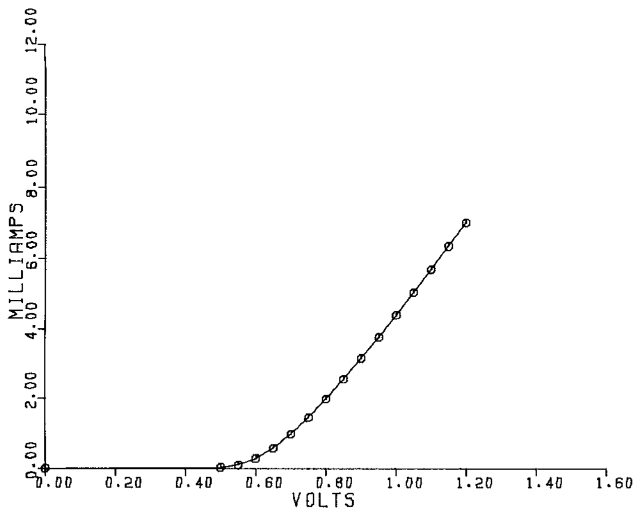

Fig. 4. $I-V$ characteristic of Schottky diode

IV. Conclusions

Models for lossy transmission lines and Schottky diodes have been installed into SPICE 2G.6. The models offer capabilities not previously available in the public domain. Although these models can (and have been) implemented into SPICE as subcircuit models, our installation directly into the source code of SPICE yields execution times typically five times faster, according to numerical experiments performed by us.

Interested readers should contact the authors concerning arrangements for distributing the modified SPICE source code (which also includes our previous released models for enhancement- and depletion-mode GaAs FET's [2]). It should be noted that the models described here are not directly compatible with SPICE 3A7. One reason for this is that version 3A7 is written in the C programming language, while SPICE 2G.6 is written in Fortran.

Appendix I
User's Guide for the Lossy Transmission Line Model

Model Usage:

Txxx n1 n2 n3 n4 param1 = val1, param2 = val2, ..., Skin

Notes:

n1 n2: Nodes at port 1 of the transmission line

n3 n4: Nodes at port 2

Skin: If this word is present, then skin effect calculations are performed.

Example:

T1 1 0 2 0 Z0 = 50 Td = 1ns NL = 1 NorLc = 10 Nr = 10 Skin

Parameter Variable	*Parameter Description*	*Default Value*
Z0 (a Z and a zero)	Characteristic impedance (ohms)	—
Td	Transmission delay (seconds)	—
NL	Electrical length of Line in number of wavelengths	0.25
F	Frequency at which line is NL wavelengths long (Hz)	—
Nr	Resistance per unit wavelength of line (ohms/wavelength)	0.0
NorLc	Number of elemental sections used within SPICE to model lossy line	10

Note. 1 At most 2 of the parameters Td, NL, and F should be specified since the relation Td = NL/F is enforced in SPICE.

2 NorLc need be specified only if Nr is not equal to zero.

Appendix II
User's Guide for the Schottky Diode

Model Usage:

Dxxx n1 n2 Your_Model_Name

.Model Your_Model_Name Sd(param1 = val1, param2 = val2, ...)

Notes:

n1: Anode

n2: Cathode

Example:

D1 2 0 Schottky

.Model Schottky Sd(Is = 0.3p Rs = 70.0 N = 1.05 Rss = 90 Iss = 14.4u Ns = 0.389)

Parameter Variable	*Parameter Description*	*Default Value*
Is	Saturation current for principal diode (D1 in Fig. 3)	1e-14
Iss	Saturation current for auxiliary diode (D2 in Fig. 3)	1e-14
Rs	Ohmic + bulk resistance of principal diode	0.0
Rss	Schottky spreading resistance	36.0
N	Emission coefficient of principal diode	1.0
Ns	Emission coefficient of auxiliary diode	1.0

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Propagation Losses in Dielectric Image Guides

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***Abstract*—To evaluate low-loss transmission lines for integrated circuits operating at millimeter wavelengths, we have calculated the propagation**

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