



AIIM

Association for Information and Image Management

1100 Wayne Avenue, Suite 1100

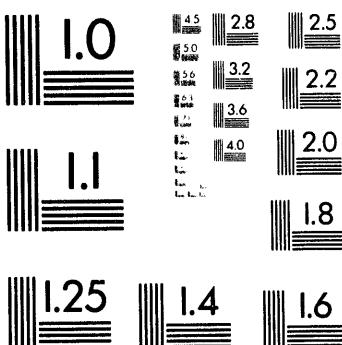
Silver Spring, Maryland 20910

301/587-8202

Centimeter



Inches



MANUFACTURED TO AIIM STANDARDS
BY APPLIED IMAGE, INC.

1 of 1

SPICE Macro Model of a Sprytron with MOSFETs in the Avalanche Mode

Carolyn W. Raney

Component Information and Management Department 2252
Sandia National Laboratories
Albuquerque, NM 87185-1073

Abstract: A SPICE [1] macro model for a triggered vacuum gap, a sprytron, intended for use in rapid discharge circuits such as Exploding Bridge Wire (EBW) applications, is presented. Power MOSFETs in the avalanche mode are utilized as the active switching elements in the model. The macro model is compared for accuracy in predicting the time dependent switching current, switch resistance and voltage drop across the switch using several test circuits. Techniques for extracting model parameters are discussed.

INTRODUCTION

High-power plasma switches are critical components of pulse power devices and electrically activated explosive systems which require high holdoff voltages (1 - 6 kV), large currents (up to 10 kA), and high rates of current rise ($> 10^{11} \text{ A s}^{-1}$). The sprytron, a triggered vacuum gap, intended for use in rapid discharge circuits such as Exploding Bridge Wire (EBW) applications, meets these specifications. It is of rugged ceramic/metal construction to withstand hostile environmental conditions and its vacuum characteristic allows operation in highly radioactive environments. Functionally, they act as normally-open switching elements. This, combined with a low on-state resistance and low forward voltage drop, results in an extremely efficient energy transfer function.

A high power MOSFET when used in the avalanche mode exhibits behavior similar to a sprytron. It is capable of holding off up to 1.2 kV and switching 1 kA in nanoseconds with a very low on-state resistance. For this to occur, the net reactance of the other circuit elements must be sufficiently low (on the order of 0.25Ω to 0.5Ω with 100 nH of inductance). Sprytrons typically have a low inductance (10 nH) and a low on-state resistance ($10 \text{ m}\Omega$ - $30 \text{ m}\Omega$). Due to their similarity in behavior, the approach presented here is to model the sprytron by utilizing a macro model of MOSFETs in an avalanche condition.

Currently no commercial model for the sprytron exists which is for use with present-day, general purpose, circuit analysis programs like SPICE [1] and PSpice [2]. As it is often both expensive and difficult to simply build and test systems, simulation and accurate models are becoming an important activity. To be able to model a non-semiconductor device, such as the sprytron, utilizing an electronic circuit analysis program like SPICE [1], is not only

unique, but affords designers the luxury of implementing design margin analysis on their electrical systems.

The macro model presented in this paper simulates the high power switching characteristics of the sprytron. The techniques for parameter extraction from experimental data will be discussed in detail. A comparison of the bench measurements from several test circuits with the PSpice [2] simulation results will be used to determine the macro model's accuracy in predicting the time dependent switching current, dynamic switch resistance and voltage drop across the switch. The use of this macro model does not require an in-depth understanding of the device characteristics. The macro model is designed to allow the user to easily change sprytron parameters such as trigger probe resistance, capacitance and turn-on voltage.

MACRO MODEL DEVELOPMENT

An example of the drain-source voltage (V_{DS}) and current (I_{DS}) characteristics of a power MOSFET conducting in the avalanche breakdown mode is presented in Figure 1. Figure 2 shows the anode-cathode voltage (V_{AC}) and current (I_{AC}) characteristics of a sprytron. Due to the similarity in the voltage and current characteristic curves it was decided that an avalanche mode MOSFET macro model [3] could be utilized as the basis for a sprytron macro model. A schematic of the sprytron macro model is presented in Figure 3, while a netlist of the macro model is presented in Table 1.

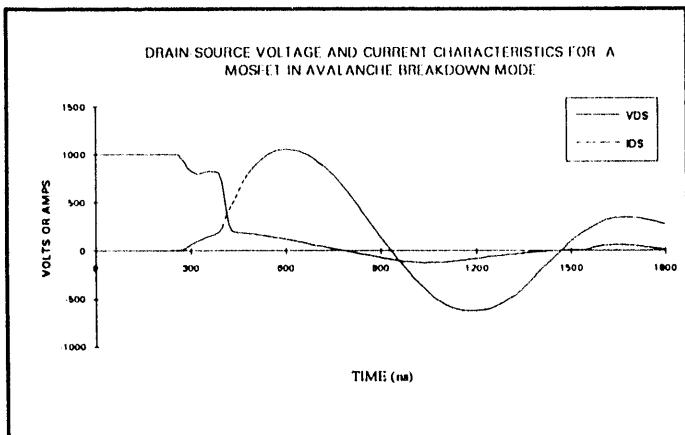
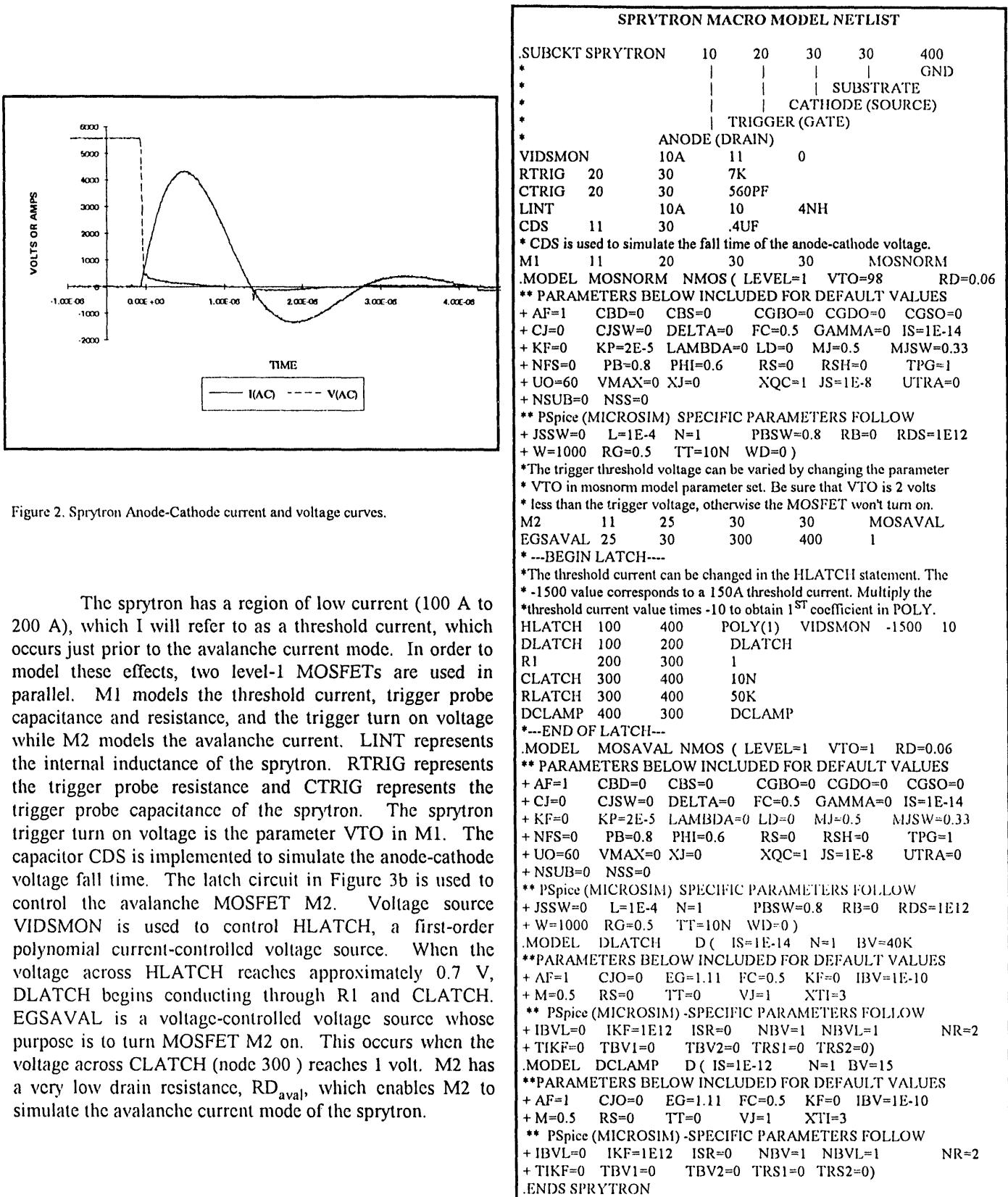


Figure 1. Power MOSFET Conducting in Avalanche Breakdown Mode.



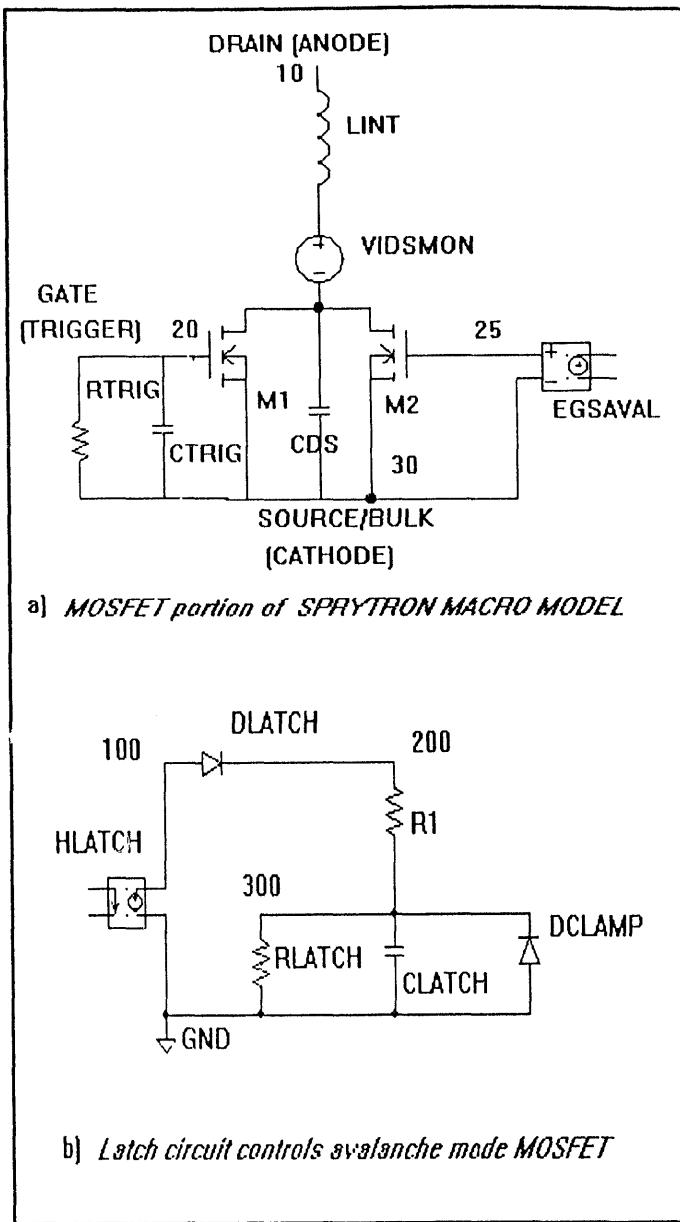


Figure 3. Sprytron Macro Model

Parameter Extraction

Figure 4 shows the test circuit used for parameter extraction and model verification. Parameter extraction for the model requires known values of the external circuit elements, measurements from laboratory data (I_{AC} as a function of time), and a series of simple calculations from the characteristic equations [4] for an under damped series RLC circuit. Model parameter values are initially calculated using the method outlined in Table 2. The I_{AC} wave forms provide the timing values needed for the calculation of the

total resistance and inductance in the circuit. Once the source values of resistance and inductance have been measured for the external circuit elements, including parasitics from wires, leads, and connections, the sprytron model parameters can be calculated. All but two parameters (VTO and RD) in the MOSFET model statements use the default values.

SPRYTRON MACRO MODEL PARAMETER CALCULATIONS

$$\begin{aligned}\omega_0 &= \text{IDEAL RADIAN FREQUENCY} = \\ &= \text{NATURAL FREQUENCY OF AN L-C CIRCUIT} = \\ &= 2 * \pi * f = 2 * \pi * (1 / T) = (L * C)^{(-1/2)} \\ f &= \text{FREQUENCY OF } I_{AC} \text{ CURRENT WAVE FORM} = 1 / T \\ T &= \text{PERIOD OF } I_{AC} \text{ CURRENT WAVE FORM} \\ \omega_d &= \text{REAL RADIAN FREQUENCY} = (\omega_0^2 - \alpha^2)^{1/2} \\ \alpha &= R_{\text{total}} / (2 * L_{\text{total}})\end{aligned}$$

$$R_{\text{total}} = \text{EFFECTIVE TOTAL RESISTANCE OF TEST CIRCUIT} = R_{\text{EXT}} + R_{\text{para}} + R_{\text{CVR}}$$

R_{EXT} = EXTERNAL LOAD RESISTANCE

(USE $R_{\text{total}} - R_{\text{para}} - R_{\text{CVR}}$ IN SIMULATIONS)

$$R_{\text{para}} = R_{\text{D, norm}} // R_{\text{D, aval}}$$

$R_{\text{D, norm}}$ = DRAIN RESISTANCE VALUE OF MOSFET M1 =

$$R_{\text{D, aval}} = 2 * R_{\text{para}}$$

$R_{\text{D, aval}}$ = DRAIN RESISTANCE VALUE OF MOSFET M2 =

$$R_{\text{D, norm}} = 2 * R_{\text{para}}$$

C_{EXT} = TOTAL EXTERNAL CAPACITANCE IN TEST CIRCUIT

$$L_{\text{total}} = \text{EFFECTIVE TOTAL INDUCTANCE OF TEST CIRCUIT} = L_{\text{EXT}} + L_{\text{int}}$$

L_{int} = SPRYTRON MACRO MODEL INDUCTANCE

L_{EXT} = EXTERNAL CIRCUIT INDUCTANCE

(USE $L_{\text{total}} - L_{\text{int}}$ IN SIMULATIONS)

Calculations for determining:

$$R_{\text{total}}, L_{\text{total}}, R_{\text{para}}, R_{\text{D, aval}}, R_{\text{D, norm}}, \alpha, \text{ and } \omega_0$$

$$\begin{aligned}i(t) &= A e^{-\alpha t} \cos(\omega_d t) + B e^{-\alpha t} \sin(\omega_d t) \\ i(0) &= A = 0\end{aligned}$$

$$\therefore i(t) = B e^{-\alpha t} \sin(\omega_d t)$$

$$di/dt = \omega_d B e^{-\alpha t} \cos(\omega_d t) - B e^{-\alpha t} \sin(\omega_d t)$$

Solve for max/min $\Rightarrow di/dt = 0 \Rightarrow$

$$\omega_d = \alpha (\sin(\omega_d t) / \cos(\omega_d t))$$

$$\text{or } \alpha = \omega_d (\cos(\omega_d t) / \sin(\omega_d t))$$

Use the lab data peaks to solve for several values of α and average them.

$$\text{Solve for } \omega_0 = (\omega_d^2 + \alpha^2)^{1/2}$$

$$L_{\text{total}} = (1 / (\omega_0^2 * C))$$

$$R_{\text{total}} = \alpha * 2 * L_{\text{total}}$$

$$R_{\text{para}} = R_{\text{total}} - R_{\text{EXT}}$$

$$R_{\text{D, aval}} = R_{\text{D, norm}} = 2 * R_{\text{para}}$$

Table 2. Details of Sprytron Macro Model Parameter Calculations

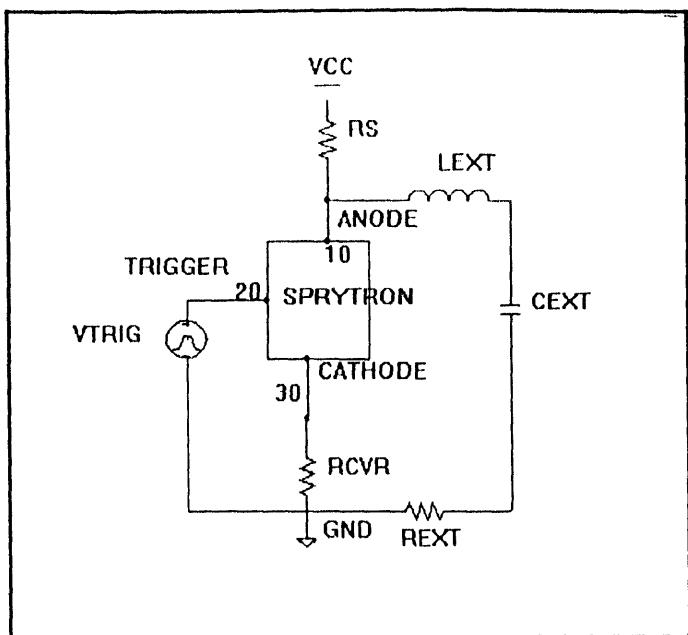


Figure 4. Test circuit for parameter extraction and model verification.

MODEL EVALUATION

Actual applications rely on the anode-cathode current supplied to the load. Data was taken using a Tektronix DSA602A digitizing oscilloscope. Although the voltages are displayed in the figures, there was not a requirement to match these. The voltage measurements were extremely difficult to obtain. The 1000X Tektronix 6015A voltage divider probe which was used to take the voltage measurements only had an accuracy of approximately 10%. In addition, the measurements had to be obtained at 100 MHz bandwidth which introduced noise. We obtained measurements at a 20 MHz bandwidth which resulted in less noise, but altered the fall time of the voltage waveform. Therefore, we had to use 100 MHz bandwidth measurements. Figures 5 and 6 display the voltage and current data for 5 shots using the same sprytron and load circuit. The voltage peak values vary as much as 67% (excluding the -1000 V spikes). There is variation in current peak values of as much as 6% on the second and third peaks. The customer's requirements for the macro model were that the first current peak for I_{AC} be within 5 % of the measured value and that the second and third peaks be within 10 %. The timing parameter requirements for the I_{AC} wave form were that the first three peaks and pulse widths be within 8 % of the measured values. The macro model met or exceeded these requirements. We verified the macro model against measured values for several different loads, capacitors, and anode voltages using the circuit in Figure 4.

The sprytron which we measured had a minimum holdoff voltage of 10 kV, a trigger probe resistance of $1\text{ k}\Omega$, a minimum trigger voltage of 100 V, and a trigger capacitance of 650 pF. Measured laboratory data and simulated PSpice [2] data are shown in Figure 7 for test conditions of $V_{CC} = 5575\text{ V}$, $C_{EXT} = 0.5\text{ }\mu\text{F}$, $L_{EXT} = 321\text{ nH}$, $R_{EXT} = 543\text{ m}\Omega$, and $R_{CVR} = 5\text{ m}\Omega$. Figure 8 displays the measured and simulated voltage and current data for a different load condition ($V_{CC} = 5575\text{ V}$, $C_{EXT} = 0.06\text{ }\mu\text{F}$, $L_{EXT} = 401\text{ nH}$, $R_{EXT} = 269\text{ m}\Omega$ and $R_{CVR} = 5\text{ m}\Omega$). The macro model accurately simulates the peak values, decay characteristics, and ring down frequency of I_{AC} . The macro model accurately simulates the decay characteristics of V_{AC} , however better measurement techniques need to be explored in order to obtain accurate V_{AC} waveform data.

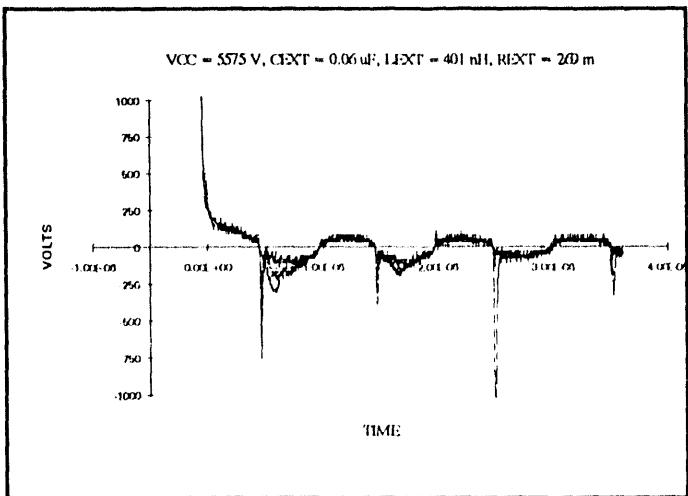


Figure 5. Measured anode-cathode voltage for 5 shots.

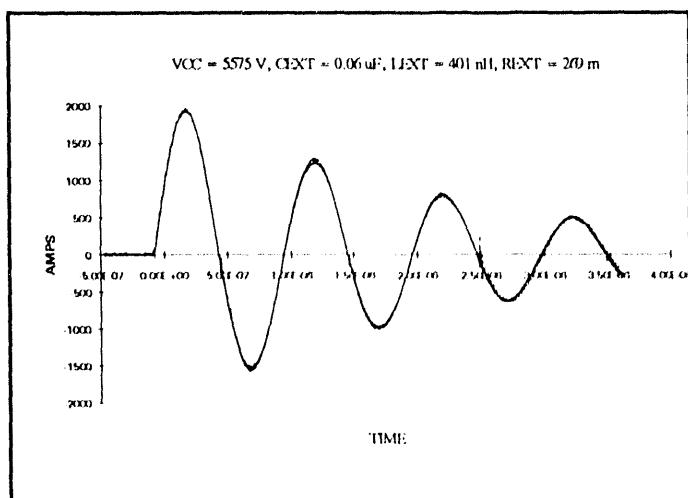


Figure 6. Measured anode-cathode current data for 5 shots.

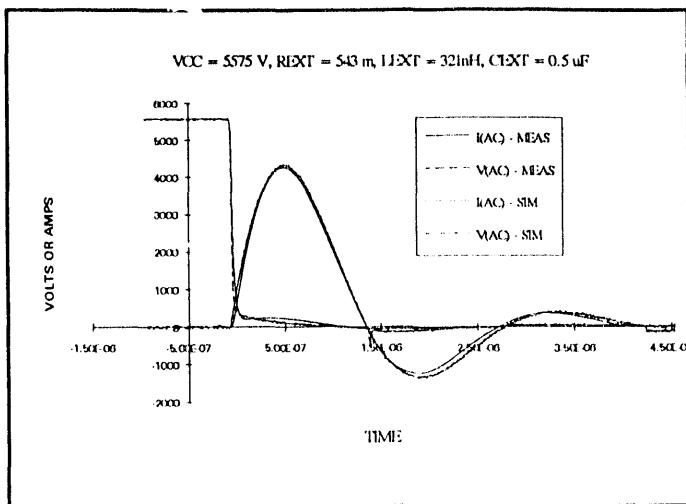


Figure 7. Anode-Cathode voltage and current characteristics (measured and simulated).

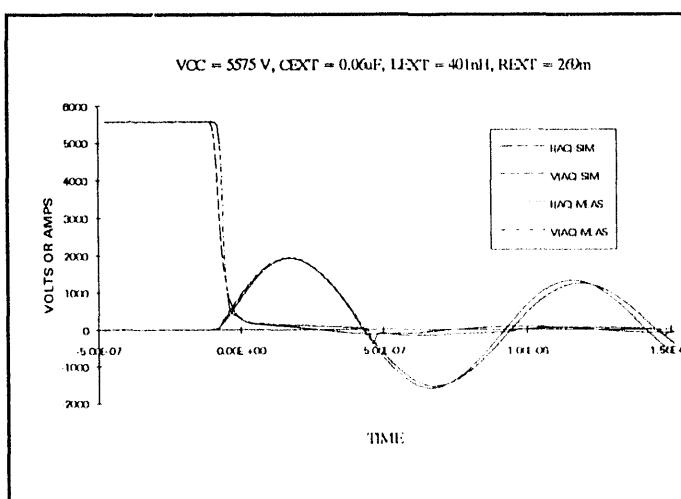


Figure 8. Anode-Cathode voltage and current characteristics (measured and simulated).

SUMMARY and CONCLUSIONS

A macro model of a high energy switch, a sprytron, has been presented. The model is SPICE2G.6 compatible which allows it to be used in the broadest range of circuit simulators. The model accurately simulates the firing characteristics of the anode-cathode current. The model is unique because it utilizes an electronic circuit analysis program to model a non-semiconductor device. The model parameters are relatively easy to extract from measured data. The use of this macro model does not require an in-depth understanding of the device characteristics. The macro model is designed to allow the user to easily change sprytron parameters such as trigger probe resistance, capacitance and turn-on voltage. Future work could be done to improve the V_{AC} phase and amplitude characteristics. However, the model allows a designer to explore variations in circuit loads, thus enabling the designer to optimize his circuit design analytically without having to resort to the more expensive method of laboratory bench testing.

ACKNOWLEDGMENTS

The author wishes to thank Gordon Boettcher, Ronald Brooks, Roger Roberts, Roger Edwards, Alan Vigil, Wallace Newman, Fred Anderson, John Rosborough and Michael Devaney of Sandia National Laboratories for providing information and data for the initial design of the model. This work was supported by the United States Department of Energy under Contract DE-AC04-94AL85000.

REFERENCES

- [1] SPICE2G.6, Department of Electrical Engineering and Computer Sciences, University of California.
- [2] PSpice Circuit Analysis Version 6.0, MicroSim Corporation, January 1994.
- [3] C. Helms, M. Ackermann, T. Fischer, and M. Devaney, "SPICE Macromodel for a 1-Megawatt Power MOSFET Switch," Proceedings of the 36th Midwest Symposium on Circuit and Systems, Vol. 2, 1994.
- [4] J. W. Nilsson, "Electric Circuits," pp. 229-234, Addison-Wesley Inc., 1983.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

100
2
3
4

DATE
FILED
9/8/96
b

