Modeling Bidirectional Thyristors Using *ATLAS*

Part 1: The Steady-State

Introduction

Thyristors are semiconductor devices that exhibit multi-stable or bi-stable electrical characteristics, and can be switched between a high-impedance OFF state and a low-impedance ON state. Bidirectional thyristors are particularly useful for ac applications because they operate in the first and third quadrants of the I-V curve, depending on the anode and cathode polarities. It is useful to simulate and predict the important electrical characteristics of these devices, so they can be optimized for figures-of-merit such as breakover voltage, holding current, and switching speed.

In Part 1, we examine the principal voltage-current characteristics of two diac (diode ac switch) structures: the *ac trigger diode* and the *p-n-p-n diode switch*. In the next issue of the *Simulation Standard*, we will examine the transient electrical behavior of the *p-n-p-n diode switch* for large current pulses typically associated with ESD and other discharge phenomena. This characterization typically requires 3-D simulation of z-plane effects due to asymmetry of the electric fields in the device.

AC Trigger Diode

Figure 1 shows a typical ac trigger diode structure, constructed like a bipolar transistor with no base contact and equally doped emitter and collector regions. When either bias is applied to a contact, one junction is forward-biased and the other is reverse-biased. The current is limited initially by the reverse-biased junction leakage at lower voltages, and the device eventually breaks down at $V_{br} = BV_{CBO}\,(1-\alpha)^{1/n}$, where α is the common-base current gain, BV_{CBO} is the avalanche breakdown voltage of the reverse-biased *p-n* junction, and n is an empirical constant [1]. As the current increases after breakdown, α increases, causing a drop in contact voltage and negative-resistance region shown in Figure 2.

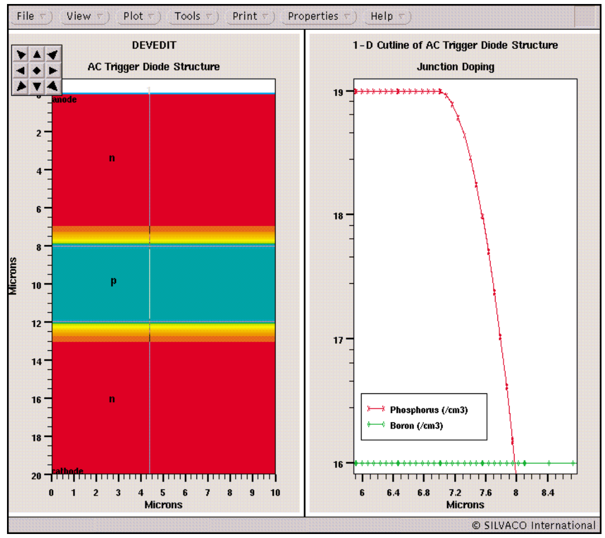

Figure 1. AC trigger diode structure created in ***DevEdit***.

The data of Figure 2 was simulated in ***ATLAS*** from a device created analytically using the ***DevEdit*** device editor in 2-D mode. The solution was obtained in one sweep using the ***Curvetrace*** automatic curve tracing routine in ***ATLAS***. The sweep ends when the controlling current contact reaches a current compliance limit of 20 μA/μm.

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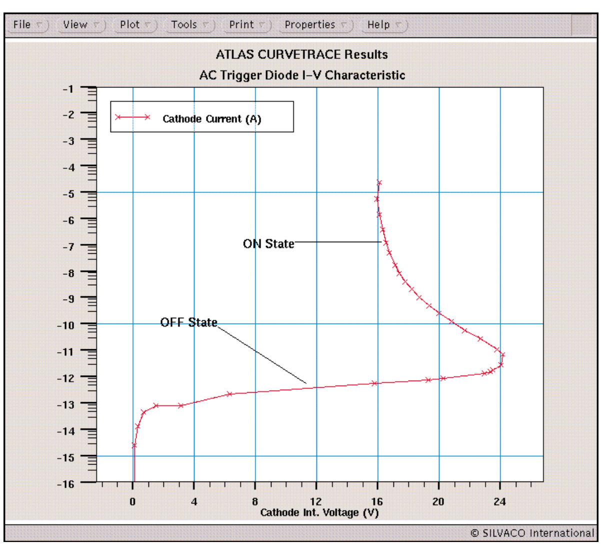

Figure 2. Simulated I-V characteristic of AC trigger diode structure from ***ATLAS*** Curvetrace routine.

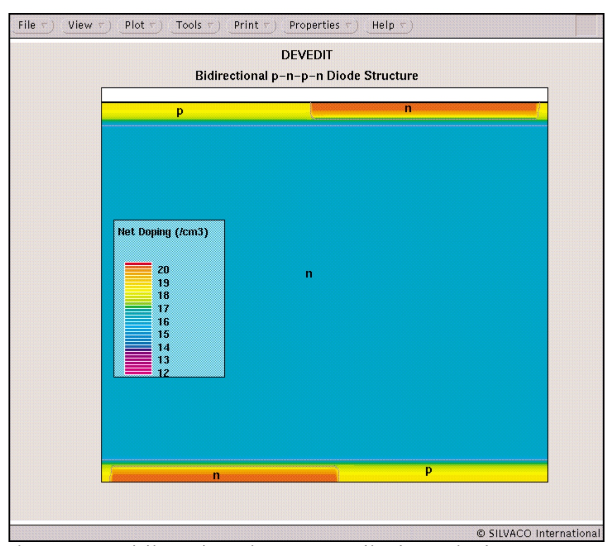

Figure 3. Bidirectional p-n-p-n diode switch structure created in ***DevEdit***.

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Bidirectional p-n-p-n Diode Switch

Figure 3 shows a bidirectional p-n-p-n diode, or 5-layer diode structure, as created in ***DevEdit***, based on an actual device (thus no direct geometric information is shown). If we consider a vertical axis of symmetry dividing the structure in to left and right halves, we can see two conventional Shockley diodes connected in anti-parallel. The structure can therefore be triggered into conduction by dV/dt, by exceeding the breakover voltage, or by increasing the temperature and saturation current until the common-base current gains sum to one. Also, due to the common-base current gains, the 5-layer thyristor will have carrier generation features, a larger range of negative resistance, and a smaller forward drop than the ac trigger diode. Figure 4 illustrates the simulated current-voltage characteristics of the p-n-p-n diode switch structure. Figure 5 shows the simulated impact ionization rate just before breakdown, and the current density at turn-on.

Another important feature of the p-n-p-n diode is the emitter overlap, evident in Figure 3. This overlap creates a lateral current path, increasing the lateral voltage drop for a given current density, and helping to trigger the device at a lower current density. In Part 2 of this series, we will consider the operation of the p-n-p-n diode in greater detail, and also examine the introduction of emitter shunts, which break the monolithic emitter into curved areas, decreasing the associated electric fields and allowing greater control of critical voltages and currents [2].

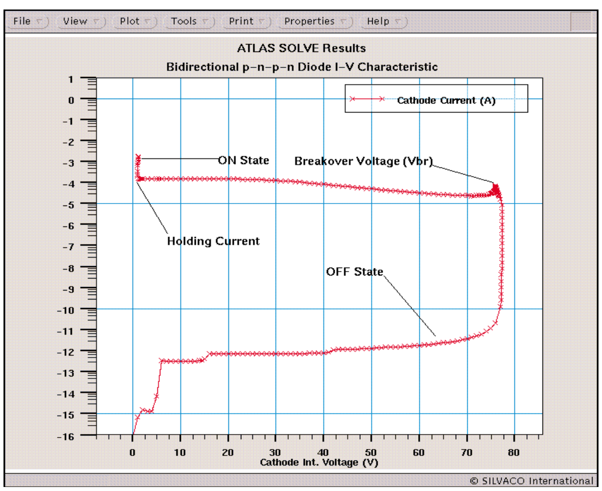

Figure 4. Simulated I-V characteristic of p-n-p-n diode from ***ATLAS***.

Summary

The current-voltage characteristics of two classes of bidirectional thyristor structures is described theoretically and simulated using the ***ATLAS 2-D*** device simulator in automatic curve trace mode and in standard voltage/current driven solution modes. Simulated results of steady-state I-V curves for the ac trigger diode and for the p-n-p-n diode are typical for these devices. Physical models used in the simulation solutions are standard drift-diffusion with Boltzmann carrier statistics, Shockley-Read-Hall recombination, concentration-dependent low-field mobility and parallel electric field-dependent high-field mobility, bandgap narrowing, and the Selberherr impact ionization models.

In Part 2 we analyze temporal behavior of the bidirectional p-n-p-n diode switch in three dimensions, based on more complex thermal and impact ionization models. This analysis will allow us to understand the mechanisms and geometries of the device that may be optimized using simulation.

Rerences

[1] S.M. Sze, Physics of Semiconductor Devices, 2nd Edition, John Wiley & Sons, New York, 1981.

[2] A. Blicher, Thyristor Physics, Springer-Verlag, New York, 1976.

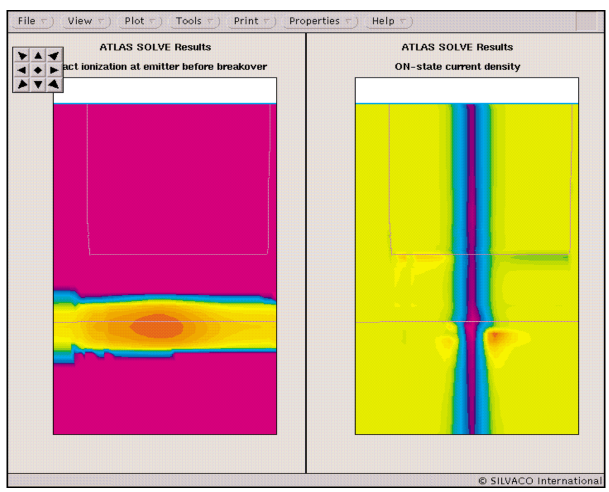

Figure 5. Simulated impact ionization rate at breakdown and total current density after device turn-on.