The Role of Parasitic Elements in the Single-Event Transient Response of Linear Circuits

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***Abstract*— Parasitic elements can play an important role in the single-event transient sensitivity of a circuit. This work describes how parasitics can affect the simulation response of linear circuits and shows how parasitics have been identified using a pulsed laser.**

I. INTRODUCTION

THE ability to perform predictive simulations of analog single event transients (ASETs) depends greatly on the accuracy and completeness of the circuit and device models. This includes the identification and simulation of parasitic elements. Without the proper circuit level modeling of these parasitics, sensitive devices can be missed or charge collection can be underestimated. The most familiar examples of these parasitics in digital circuits are the PNPN structure in CMOS devices[1] which can lead to latchup, and the parasitic bipolar junction transistor inherent in SOI MOS transistors[2] which causes enhanced charge collection.

We have found that parasitic elements in analog circuits can drastically affect the simulated ASET response of a circuit [3][4], but often they are difficult to identify *a priori*. Fortunately, there exists an inexpensive method for identifying these parasitics using a pulsed laser. Once the parasitics have been identified, the capability to perform predictive ASET simulations increases considerably.

We present three case studies in which ASET-sensitive parasitic elements were identified using a pulsed laser and then implemented in SPICE. Three types of parasitic elements were found: non-active junctions (such as isolation regions), distributed and spreading resistances, and biasing resistors formed from active elements. We will show the importance of these parasitics in three different linear circuits: two comparators and an operational amplifier.

II. LM119

The first device we will present is the LM119 comparator. The LM119 is a high-speed voltage comparator manufactured by National Semiconductor. ASET tests on the device have been published several times in the literature [4][5][6]. A schematic of the LM119 and a description of its operation is given in [4] and will not be repeated here. In that publication, it was reported that several of the resistors in the LM119 exhibited ASET sensitivity. The sensitivity of each resistor varied as a function of position of the laser strike along its length.

Fig. 1 shows a photomicrograph of the LM119 indicating the resistors and the collector well which is common to several transistors. All the transistors in the LM119 except one are NPN, so the collector region is n-type material and is connected to the positive supply voltage. Thus, the resistors must be diffused p-type material in n-type wells.

Transistor models used for the simulations were extracted directly from the LM119. A focused-ion beam was used to make 4μm deep cuts to isolate several transistors from the rest of the devices. 1.3μm deep cuts were made to generate $10\mu\text{m}\times15\mu$m pads in the passivation layer for making electrical connections to the individual transistors. Contact to the metal pads was made via micromanipulators and 0.6μ probes. Several transistors were probed and families of curves were measured with an HP4156. Junction capacitances were measured also. Utmost[7] from Silvaco, Intl. was used to extract the bipolar transistor parameters from the measured data.

The effect on circuit operation of charge collection at the p-n junction formed between the resistor and the collector region is dependent on the hit location along the length of the resistor structure. From this information and the layout we determined that the most likely cause of the ASET sensitivity was due to charge collection from the junction formed between the resistor and the well in which it was diffused instead of conductivity modulation of the resistor which would not have shown a positional dependence. To model this effect, the resistor was divided into two sections, whose sum equaled the total resistance. A SE-sensitive model of a diode was placed from the junction of the resistors to the positive voltage supply, as shown in Fig. 2. By varying the fraction x from 0 to 1, we were able to model the positional dependence of strikes on the resistor.

Device level 2-D simulations of ion strikes on a simple resistor confirm our modeling technique. Both device and circuit simulations indicate that the fraction of the deposited charge that flows to each end of the resistor is inversely proportional to the distance from that end of the resistor.

The circuit response to ion strikes on these resistors is dependent on the junction capacitance of the diffused resistor struc-

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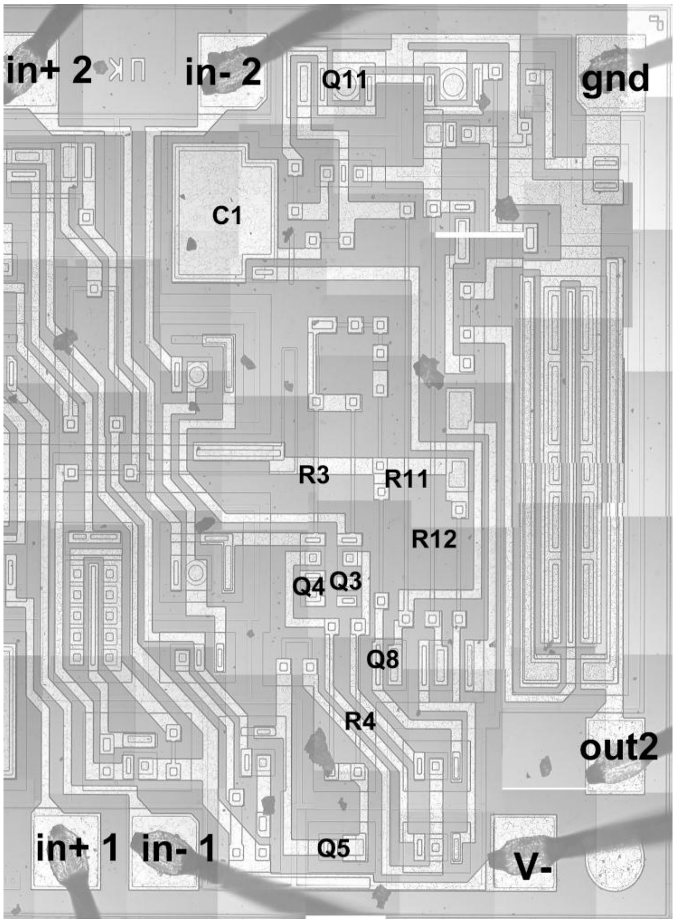

Fig. 1. A portion of the LM119 is shown in this photograph. Resistors have been highlighted. The n-well region the resistors have been diffused in forms the collectors for several transistors which are all connected to Vdd.

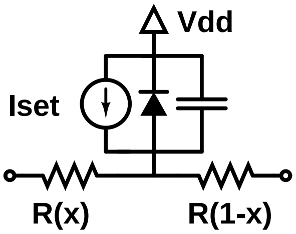

Fig. 2. Distributed resistance model used simulate ion strikes in the resistors of the LM119

ture. Using a single diode to account for the junction capacitance is inadequate, since the photocurrent would change the capacitance of the entire junction. In an actual ion strike, the affected portion of the junction constitutes only a small region of the device. Thus, the capacitance of the junction will remain essentially constant throughout the ion strike. This effect is modeled by lumping the internal capacitances of the diode into a single capacitor placed in parallel with the junction diode, as seen in Fig. 2.

Because the laser data are given in pJ of energy, and the simulations results are given in pC of charge, we must be able to convert between the two units. For a laser with a wavelength of 590nm, 1 pJ of laser energy entering the silicon generates 0.5 pC of charge[3]. Measurements of laser energy were corrected for reflected light.

It is important to distinguish between deposited charge and collected charge. The relationship in the proceeding paragraph deals with the charge deposited by the laser in the silicon. Photocurrents which are placed in the circuit simulator are equivalent to the collected charge. Physical mechanisms such as recombination, funneling, shunting, and bipolar amplification can affect the ratio of collected charge to deposited charge[8]. A detailed discussion of these mechanism is beyond the scope of this paper. Instead, we will focus on the qualitative aspects of parasitic identification and modeling.

Figures 3 and 4 show the simulated sensitivity of the resistor structures R4 and R11, respectively, as a function of relative position. R4 is a 3kΩ resistor sensitive when the ΔV$_{in}$ is positive and R11 is a 13kΩ resistor sensitive when ΔV$_{in}$ is negative. The results are plotted in terms of the amount of collected charge needed to generate a transient of 100mV at the output of the LM119, a quantity we will refer to as critical charge. The deposited charge produced by the laser energy has been appropriately converted to pC and is indicated on the figure. Laser data were only available at the ends of the resistors. The correlation between laser data and the simulation results indicate a charge collection efficiency of approximately 100%.

For reference, on R4, x=0 is the end nearest Q3 and x=1 is the end closest to Q5. On R11, x=0 corresponds to the end of the resistor nearest Q11 and x=1 is the end connected to Q8, all of which are indicated on Fig. 1.

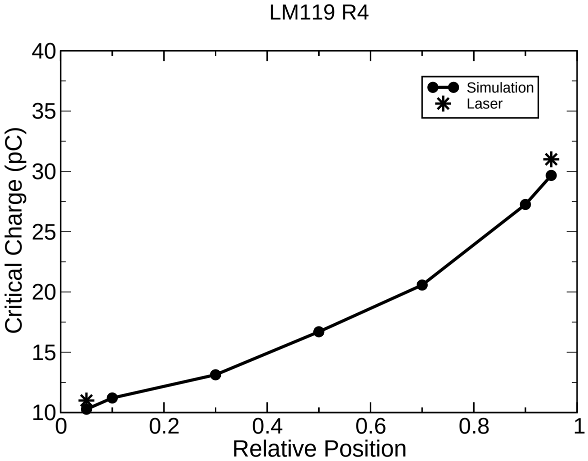

Fig. 3. Positional dependence of R4 in the LM119 to laser strikes.

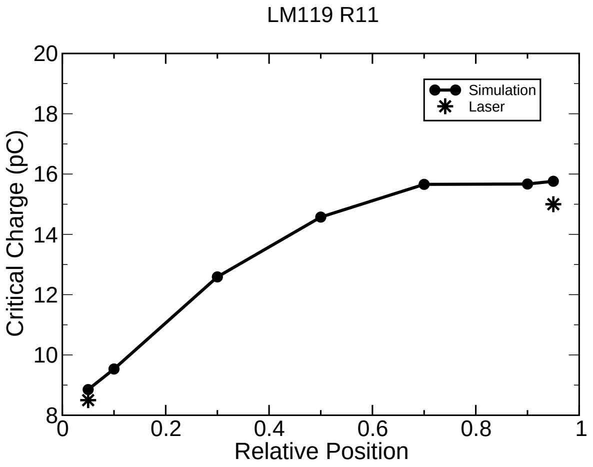

Fig. 4. Positional dependence of the R11 in the LM119 to laser strikes.

III. LM111

The next device we will look at is the LM111. Similar to the LM119, the LM111 is also a voltage comparator from National Semiconductor which has been frequently studied [3][6][9][10][11]. In comparing simulation results to laser tests, an important factor was observed in the sensitivity of the input transistors. Fig. 5 shows a simplified schematic of the input stage of the LM111. The laser found the collector-base junction of Q2 to be the most sensitive region when the inverting input was grounded and the non-inverting input was negative.

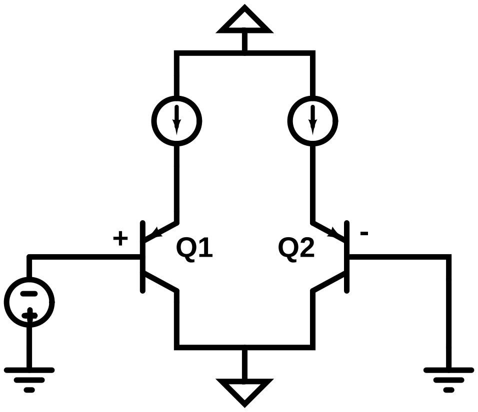

Fig. 5. Simplified schematic of the input stage to the LM111 showing biasing sources.

Our analysis of laser data and simulation results demonstrated the critical importance of the base spreading resistance for ASET simulations. Fig. 6 shows how current sources are used in SPICE to simulate single-events[12]. They are placed across the junctions such that the current flows from n-type material to p-type material.

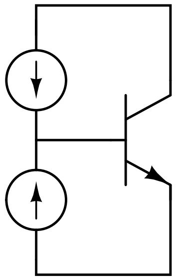

Fig. 6. Method for simulating single-events in bipolar transistors. Current sources are directed from collector to base or emitter to base. The directions of the current sources are reversed in PNP devices.

In a typical Gummel-Poon model[13] as shown in Fig. 7, the collector, base, and emitter resistances are included inside the model. These internal nodes are not accessible in SPICE. Simulated photocurrents placed on the external junctions must flow through these resistances, causing a voltage drop. In reality, these photocurrents exist at the junctions and do not flow directly through these resistances. Improper modeling of these junctions can have two main effects on the circuit.

The first is that the critical charge needed to cause a given transient is greater when the photocurrent sources are placed on the leads of the transistor external to the resistances. This is due to the voltage drop across the internal model resistors.

The second effect is a result of the use of ideal sources. In the case of the input transistors of the LM111, simulated photocurrents on the collector-base junctions would show no response under the biasing arrangement of Fig. 5. The reason for this is that an ideal DC biasing source is connected directly across the collector-base junction of both transistors. If the ASET photocurrent is in parallel with the ideal source, it will see a zero impedance path through the DC source, and no current would flow through the transistor, rendering the junction insensitive to ASETs.

From the doping and geometry, the value of the base spreading resistance was found to be on the order of 1-2kΩ. Once this resistance was added in series between the voltage source and the base of the transistor, the simulations agreed well with the laser data. When the base spreading resistance was 2kΩ, the amount of collected charge needed to produce a transient with an amplitude of 100mV was 1pC. The estimated collected charge required to generate a similar transient was 1.1pC from the laser data[3].

Simulating ASETs with resistors included in the compact model may not always be appropriate. Fig. 8 is a modified model used for all transistors, not just the input devices. It shows a more accurate way to model photocurrents in bipolar transistors, where Rc, Re, and Rb are the internal model resistances, and have been taken outside the compact model and placed in series with the terminals. Inspection of Fig. 7 reveals that this modification can be made without altering the electrical characteristics of the model. In practice, a small base resistance needs to be included inside the model to prevent di-

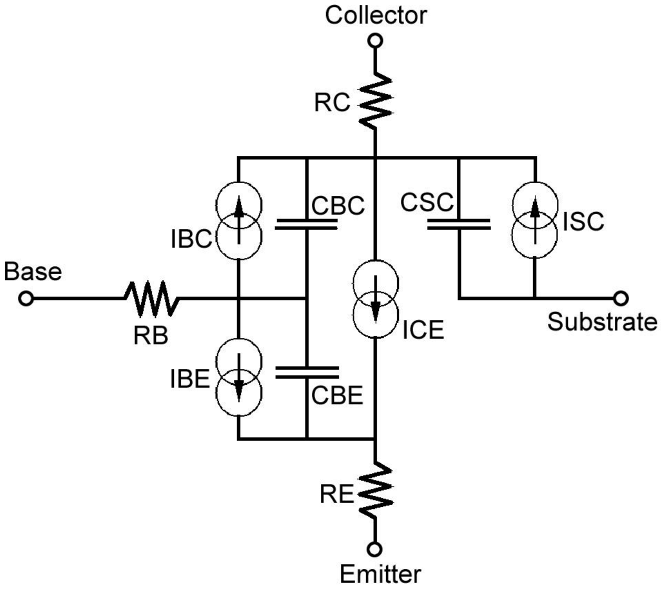

Fig. 7. Gummel-Poon compact spice model showing the emitter, base, and collector resistances.

vergence of the simulator. It should be small enough so that the voltage drop across it is negligible.

This modification of the Gummel-Poon model has minimal effect on the shape of the generated transients. It can affect the charge needed to produce the same transient on the unmodified model.

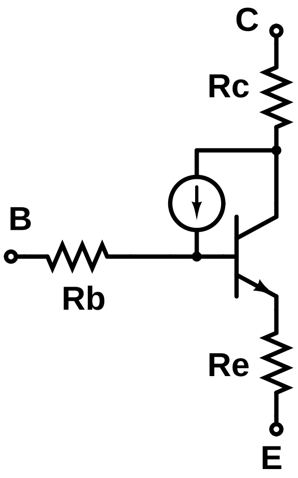

Fig. 8. Improved modeling technique for ASETs. Internal resistances are moved to the outside leads, preventing the voltage drop occurring in the resistances. Sensitivity is enhanced and improves agreement with measured data.

IV. LM124

The final device we will discuss is the LM124. The LM124 is a general purpose operational amplifier from National Semiconductor. Extensive modeling and calibration has been performed on the LM124[14]. A good correlation was found between circuit simulations, laser tests, and broadbeam data, except for one point. When the broadbeam data were plotted as duration verses amplitude (Fig. 9)[14], three distinct trends were seen. Each trend represents a class of transient shapes: slower, positive-going transients, slower, negative-going transients, and a class of faster, large amplitude transients (R1 transients in Fig. 9). The durations of the pulses were measured at the full width, half maximum (FWHM).

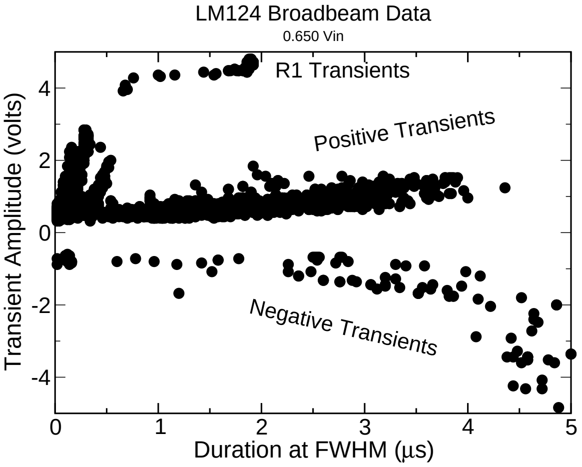

Fig. 9. Amplitude vs. duration for broadbeam ions in the LM124 in a non-inverting configuration with a gain of 2.

In a similar plot of circuit simulation results only the lower two trends were seen, as shown in Fig. 10. The fast, large amplitude transients were not observed.

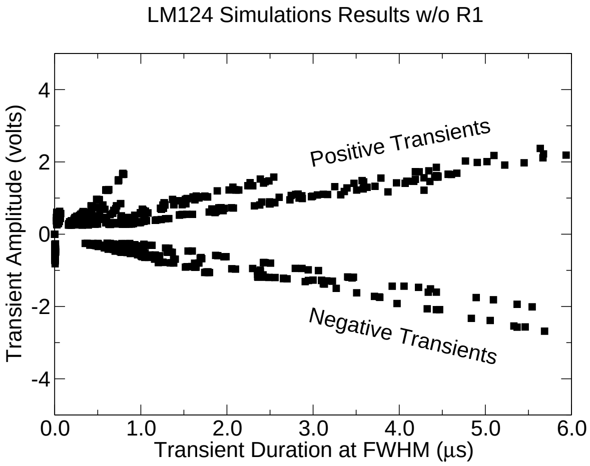

Fig. 10. Simulation results of broadbeam configuration. R1 model has not been included.

We probed the circuit with a pulsed laser and found a point on the circuit which was far more sensitive than any other location on the die: it was a biasing element in the gain stage in the amplifier. Fig. 11 shows a schematic of the gain stage with the biasing element modeled as resistor R1. Fig. 12 is a photomicrograph of the biasing element.

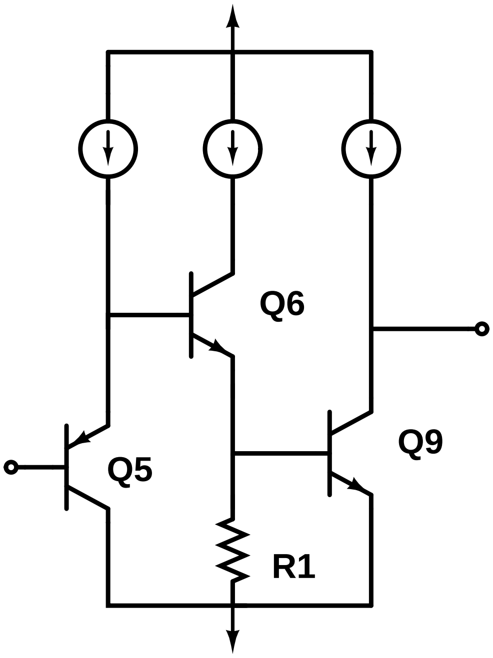

Fig. 11. Schematic of the LM124 gain stage. The biasing element in question is labeled R1.

Considerable destructive analysis and characterization went into the determination of the composition of this “resistor”. In the end it was revealed to be fabricated as a floating-base transistor[15], which explains its extreme sensitivity. Since the base is floating, it is very sensitive to any change in potential, such as that seen with a heavy-ion or laser strike. Inclusion of this parasitic element in the LM124 circuit model corrected the discrepancy seen between the data and simulations. The results of the added model are seen in Fig. 13.

The simulated events due to the floating-base biasing element are approximately 2μs longer than the measured events. We believe that this is probably a result of slew-rate limiting in the output stage. Despite this minor discrepancy, the simulations correctly show that it is the most sensitive portion of the circuit, producing a large transient at much lower values of collected charge than any of the other junctions.

The LM124 is a good example of how collaboration between simulations and lasers can help uncover, understand, and quantify an important SET response. Broadbeam data by itself reveals nothing about the identity of the transistors causing the trends seen in Fig. 9. Performing simulation tests on all the different junctions and plotting the results in a similar manner revealed good agreement to the lower two trends. An important difference is that the simulations also recorded the junctions associated with each point.

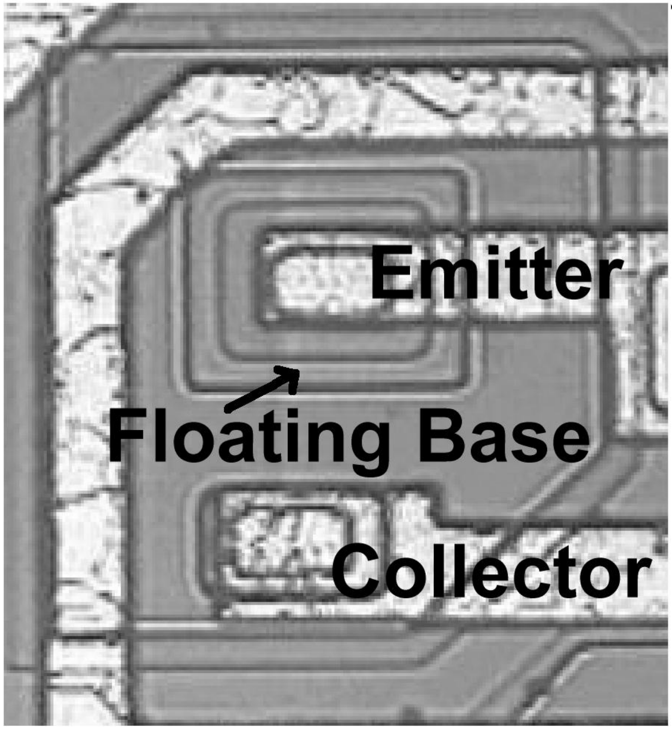

Fig. 12. photomicrograph of the biasing element in the gain stage of the LM124.

By comparing the sensitivity of the different devices between the laser and simulations, R1 was found to be very sensitive, but no counterpart existed in the simulations. Investigation of R1, simulation, and comparison with laser tests allowed us to develop a model of this biasing element which showed similar response and sensitivity.

When the model of R1 was included in the simulations of broadbeam tests, we were able to generate all three trends. By using an iterative test and simulation methodology, we were able to reproduce the heavy-ion data, identify the junctions associated with each portion of the data, and improve the predictive capabilities of our model.

V. CONCLUSION

The modeling of parasitic elements in analog circuits can be very important to determining their response to heavy ions. Three case studies on different linear circuits revealed three different types of parasitic elements which must be modeled to increase the ability of the circuit simulations to produce predictive results.

In the LM119, although the resistors proved to be less sensitive than the transistors in the circuit, they represent a frequently overlooked aspect of the circuit simulation of ASETs. It may be the case that in other circuits, similar resistors may be the most sensitive devices due to the circuit topology. Proper modeling

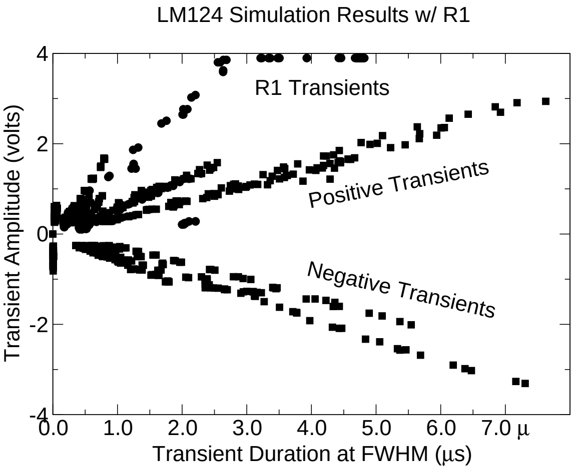

Fig. 13. Simulation results of LM124 broadbeam configuration. The model for R1 as a floating base transistor has been included in the circuit. The upper trend is clearly due to R1, although the transients are slightly slower in the simulations.

of these junctions should be considered when determining the sensitivity of a device.

In the LM111 we discovered that modeling the base spreading resistance can significantly impact the simulated response to single-event strikes. These impacts include incorrectly identifying the critical charge for the circuit and even having situations where a junction is rendered insensitive due to the nodes being shorted by ideal sources. Circuit topology ultimately determines the necessity of modeling these internal resistances externally to the model in order to avoid having an over-constrained circuit.

In our investigation of the LM124 we found that a biasing resistor fabricated utilizing a floating-base transistor was the most sensitive portion of the LM124 to single-events. The proper modeling of this biasing element allowed the simulations to reproduce all three different trends of pulse shapes which are seen from broadbeam data. We were also able to agree with the laser and microbeam data on the sensitivity of this junction.

The pulsed laser has proved to be an invaluable tool in identifying elements of analog circuits which are sensitive to single-events. It has shown the ability to locate additional junctions and resistance which must be simulated to more fully model the ASET response of analog circuits. The iterative procedure between simulations and laser tests is an effective method for evaluating and investigating the ASET response of circuits.

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