Comparison of SETs in Bipolar Linear Circuits Generated with an Ion Microbeam, Laser and Circuit Simulation

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In this paper we present the results of microbeam tests at Sandia Labs on two bipolar linear circuits and compare the results for the most sensitive transistors to the output single event transients (SETs) measured with a laser at NRL and simulated with SPICE at Vanderbilt University. This work was sponsored by the DTRA Radiation Hardened Microelectronics Program. The authors wish to thank Lew Cohn of DTRA for his enthusiastic support.

Outline

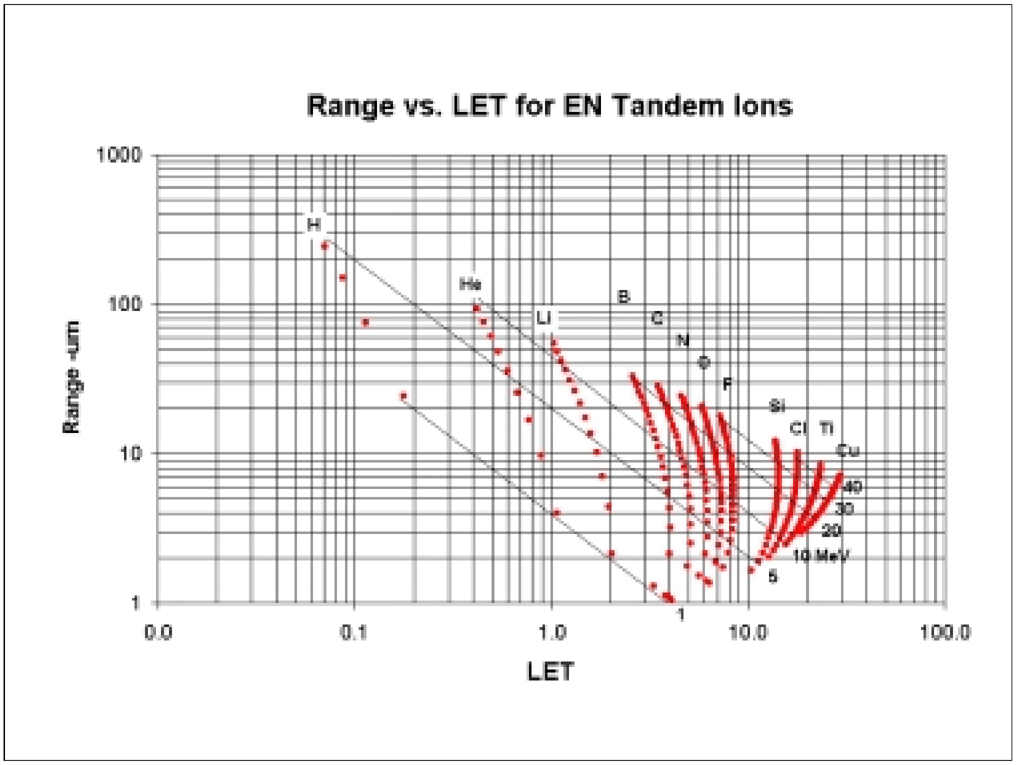
- Ion microbeam facility
- Test circuits and conditions
- Results for LM111
- Results for LM124
- Discussion
- Conclusion

Here is an outline of the presentation. We will start with a description of the Sandia Ion Microbeam facility. We will then describe the bipolar linear circuits that were irradiated along with the irradiation test circuits and test conditions. In the results section we will first describe the results of the microbeam tests then compare the results to the laser tests and the circuit model simulations. We will then present a discussion of the results and finally give some conclusions of the study. The microbeam data discussed in detail here was presented in summary form in the paper “Critical Charge for Single-Event Transients in Bipolar Linear Circuits” by R. L. Pease, et al, IEEE Trans. Nucl. Sci., Vol 48, December 2001, pages 1966-1972. The microbeam data were taken in July of 2001. The laser irradiations and SPICE simulations were performed recently.

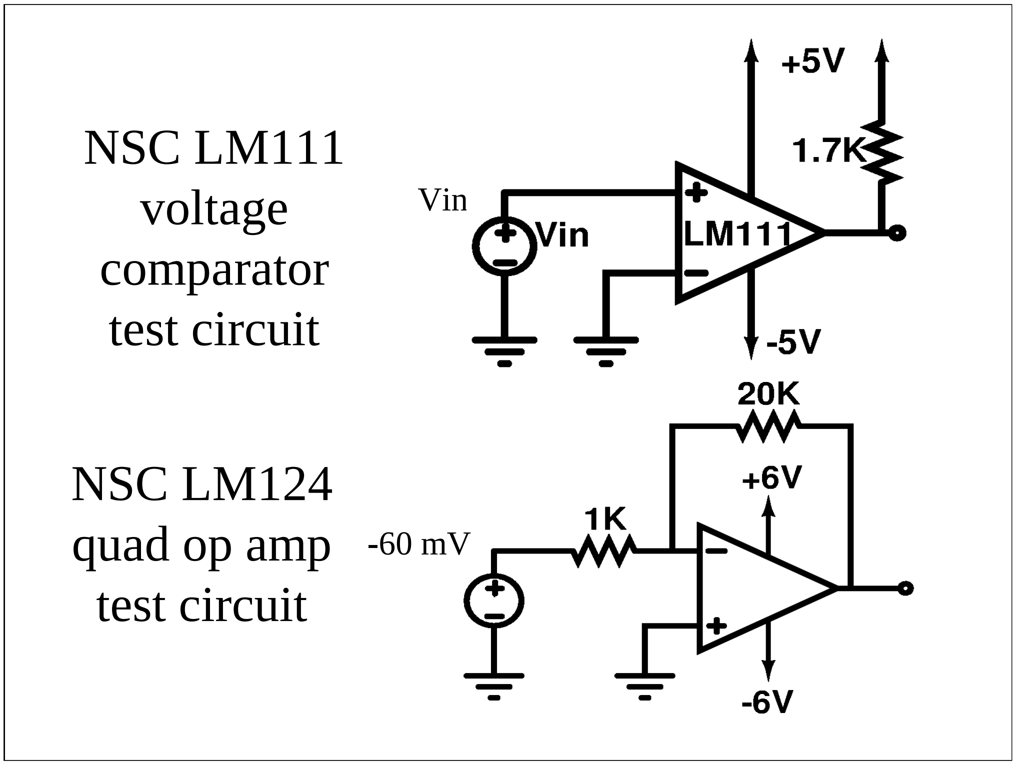
Sandia Ion Microbeam

- Variety of ions available
- Maximum energy about 40 MeV
- Operational modes
  - Vertical or horizontal scan
  - X-Y scan
- Flux of several hundred ions/s
- Part operated in vacuum
- Output to feed through using 1' RG174 cable
- FET probe used on output

The Sandia microbeam facility uses a Tandem Van deGraaff Generator to accelerate the ion beam and magnetic focusing to achieve a spot size of about 1 um. The maximum energy of the ions is about 50 MeV but as a practical matter beams of 40 MeV and below are used. In this study the ion beam was 40 MeV chlorine which has a range of about 11 um in silicon and an initial LET of about 18 MeV-cm^2/mg. The beam can be scanned in several modes. For this study the beam was either scanned horizontally or vertically or was rastered in an x-y pattern. The flux was about one hundred ions/s. In the x-y scan the dwell time at each position was such that only one or two ions hit each "pixel". The part is operated in a vacuum. When these tests were run there was a problem with a slight vacuum leak and it took several hours to pump down to the required vacuum level. Hence we did not attempt to use more than one ion or energy. The circuit under test was placed in a socket on a test board and the output was connected to a one foot RG174 coax cable to the feed through connector. This added several pF capacitance to the output load for the measurement, which was made with a FET probe.



Here we show the ions available at the Sandia microbeam facility. They range from copper to protons. The plot shows the range in um of the ion vs. the LET in MeV-cm^2/mg. The numbers at the bottom of the diagonal lines show the ion energies in MeV from 1 up to 40. As mentioned before 40 MeV Cl has a range in silicon on about 11 um and an LET at the surface of about 18 MeV-cm^2/mg. The overlayers in the bipolar circuits are about 4-5 um including the passivation and metal. We calculated a deposited charge in the silicon of about 1.2 pC accounting for loss in the overlayers.



The two circuits that were characterized were the National Semiconductor LM111 voltage comparator and the National Semiconductor LM124 quad operational amplifier. These are both widely used in space systems and have been characterized for their single event transient (SET) response by several organizations. The test circuits are shown in the figures. The LM111 was operated at +/- 5V with a delta Vin of either +10 mV (causing the output to go high) or –10mV (causing the output to go low). The LM111 is much more sensitive to SETs for small delta Vin. The LM124 was operated at +/-6V with an inverting gain of 20 using a Vin of –60 mV, causing the output to be at 1.2V. These same test conditions were used for the laser tests and the SPICE simulations.

Circuit modeling

- SPICE circuit extracted from photomicrograph to assure accurate representation
- Transistor models obtained from test chip I-V curves
- "Hit" simulated with double exponential current pulse across junction
  - Nanosecond rise and fall times
  - Charge derived from area under curve
- Collector substrate junctions included
- Many parasitics included to increase accuracy

The circuit modeling was performed at Vanderbilt University. Talks by Andrew Sternberg and Younes Boulghassoul at his symposium describe the technique in detail. The SPICE model was derived from the photomicrograph of the die and includes many of the parasitic elements. These parasitics (e.g. base resistance term, collector to substrate junctions, distributed diffused resistors with isolation junctions, etc.) were added as a result of the microbeam and laser testing in order to achieve better correlation to the experimental results. The transistor models in the SPICE circuit were parameterized using measured I-V curves from test coupon transistors supplied by National. Instead of using mixed mode simulation with a 2-d device physics code such as ATLAS, it was shown that the same SET waveforms could be obtained with a current source in the junction. A double exponential current source was used with varying pulse width and amplitude to simulate the charge deposited in the junction.

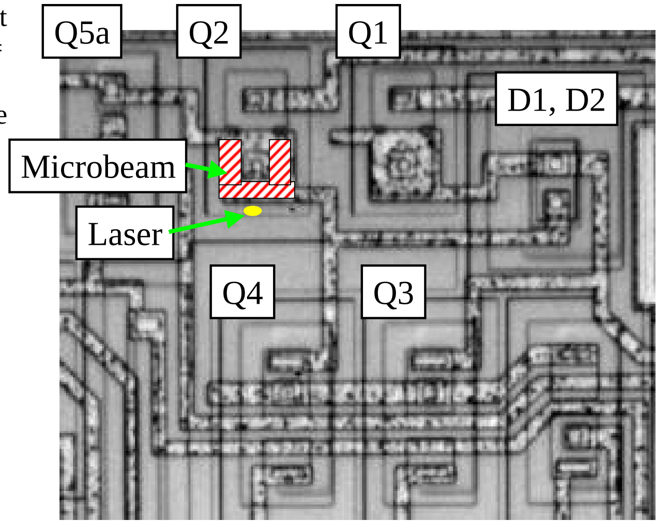
LASER tests

- NRL laser facility
- 590 nm laser
- Top side irradiation
- 2 μm 1/e depth
- 1.2 μm spot size
- FET probe on output through 2” RG174 cable

The laser tests were performed using the NRL laser test facility. This facility has been described in several publications. The laser wavelength is 590 nm with a 1/e depth in silicon of about 2 um. The spot size is about 1.2 um and the circuits are irradiated from the top. This means that junctions under metal cannot be reached directly with the laser. However they can be reached indirectly by irradiating as close as possible to the edge of the metal and diffusing charge to the junction. The test circuits are the same as used for the microbeam tests and a FET probe was used to sense the output transient. The laser energy deposited in the silicon was calculated and converted to a deposited charge. It was assumed that all of this charge was collected from junctions that are within 2 um of the interface. The charge was varied to reproduce the SET waveforms measured with the microbeam.

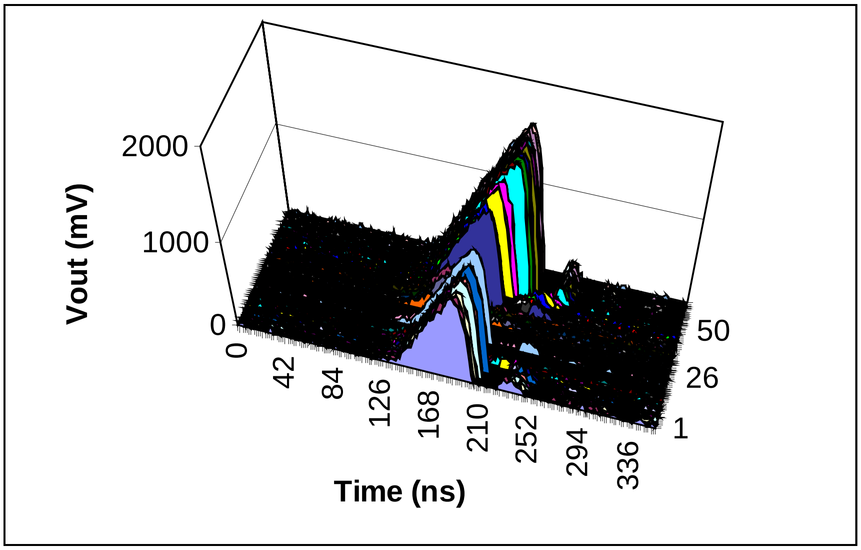
LM111 input circuit showing SET sensitive region for ΔVin = -10 mV

- Most sensitive test condition- ΔVin = -10mV
- Only one sensitive region- Q2-eb depletion region on three of four sides under field plate outside the emitter diffusion shown at right
- For ΔVin = +10mV, Q1-eb was sensitive, but sensitive area narrower



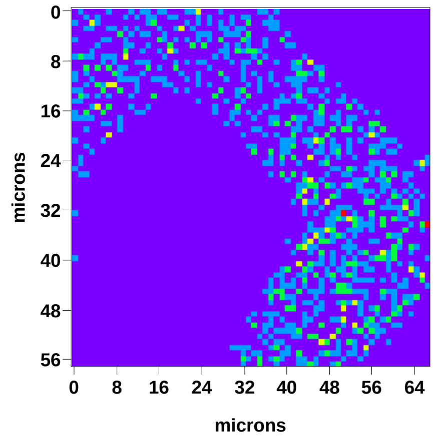
Here we show a photomicrograph of the LM111 input circuit. The only transistors on the entire circuit that we could get to initiate SETs were the input pnp transistors Q1 and Q2. These transistors are composite structures consisting of both a vertical substrate transistor (no buried layer) and a field plated lateral transistor from emitter to the isolation region that contacts the substrate. Q1 was sensitive for delta Vin of +10 mV and Q2 was sensitive for delta Vin of -10 mV. For the condition with delta Vin = -10 mV the region of Q2 that was sensitive is shown with the red stripes. This is just the region under metal over the base. This region is not directly accessible to the laser. However by irradiating just outside the metal field plate, shown by the dot, sufficient charge diffused to the sensitive region to cause an output transient.

LM111 Q2 horizontal scan of emitter for ΔVin = -10 mV



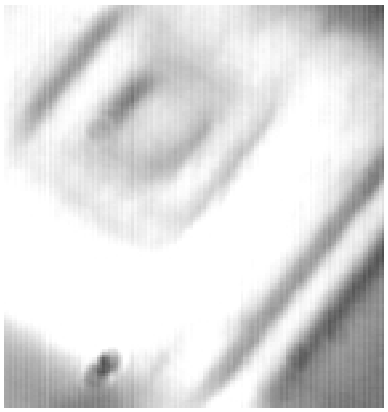
In this graph we show a 3 dimensional plot of the SETs as a function of position along a scan line across the emitter-base region of transistor Q2. You can see that we get SETs on either side of the emitter but not directly across the emitter. The amplitude of the SETs is about 1.5V and the duration is about 100 ns.

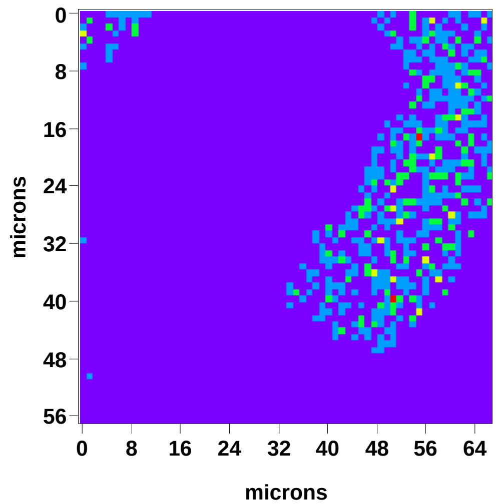
X-Y map of SET sensitive region of LM111 Q2 for ΔVin = -10 mV



In this slide we show on the left an optical photomicrograph of the emitter base region of Q2 that was scanned and on the right we show the part that is SET sensitive. Each contrasting “dot” is a region that produced an SET using a threshold detection level of about 0.2V. Again we see that the only region that is sensitive is the base region under the metal field plate on three sides of the emitter but not on the fourth side near the base contact.

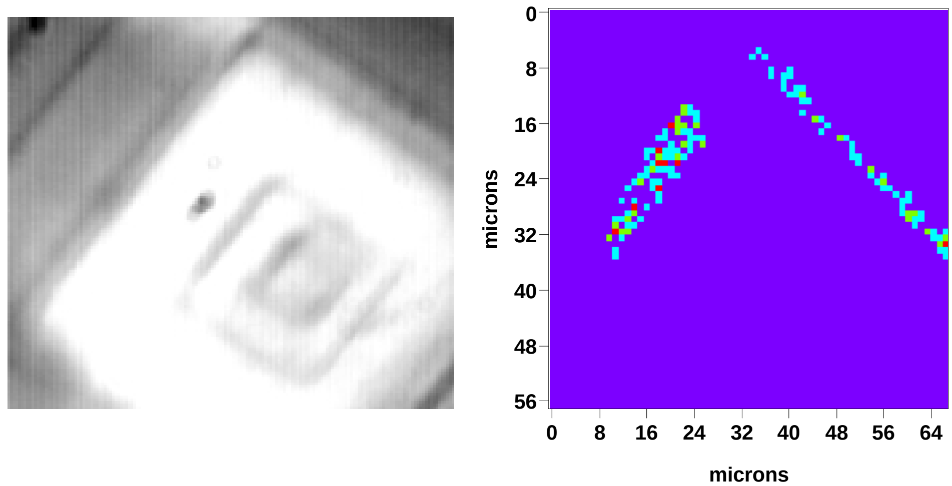
X-Y map of SET sensitive region of LM111 Q2 for ΔVin = -10 mV



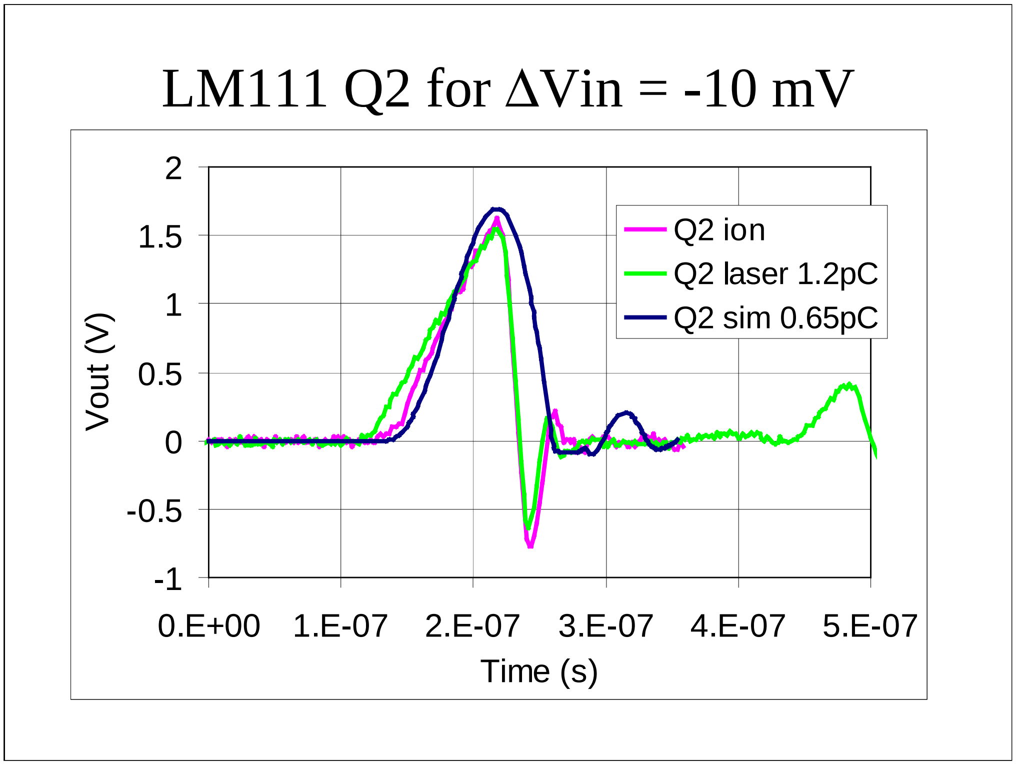


This figure is just another scan that was moved down slightly to show that no SETs occur on the fourth side of the emitter.

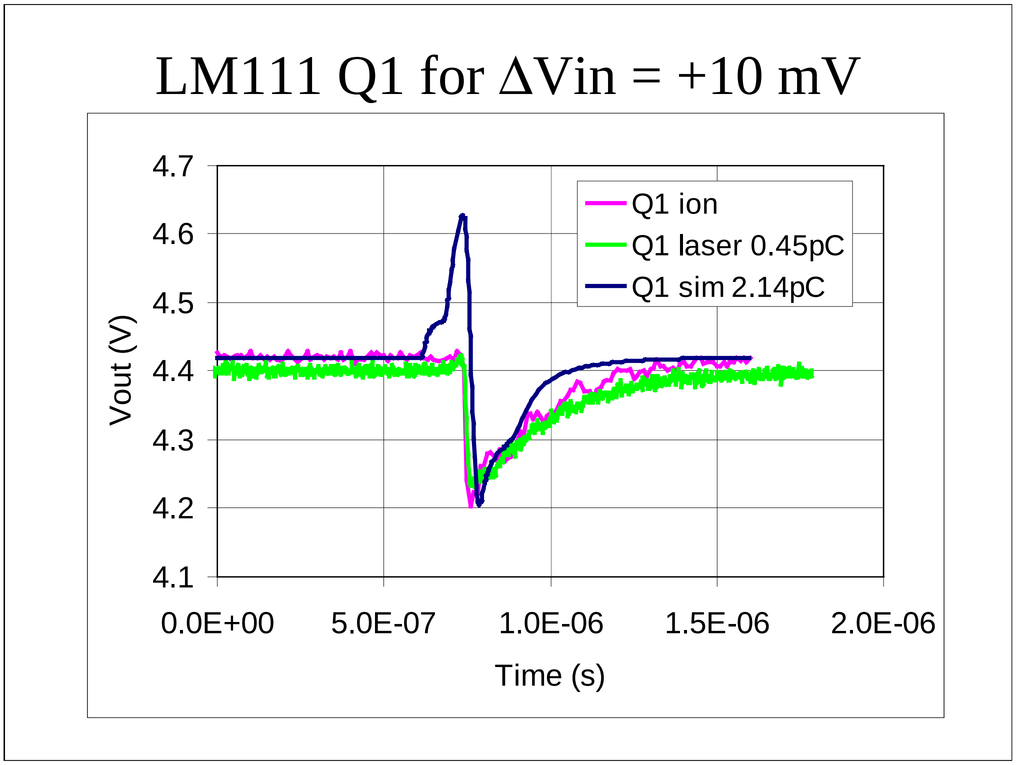
X-Y map of SET sensitive region of LM111 Q1 for ΔVin = +10 mV



In this figure we show the results of a similar scan of Q1 for the condition with delta Vin = + 10 mV. For this case the output is high and the transient is negative going. Here we see a much narrower region that is sensitive.

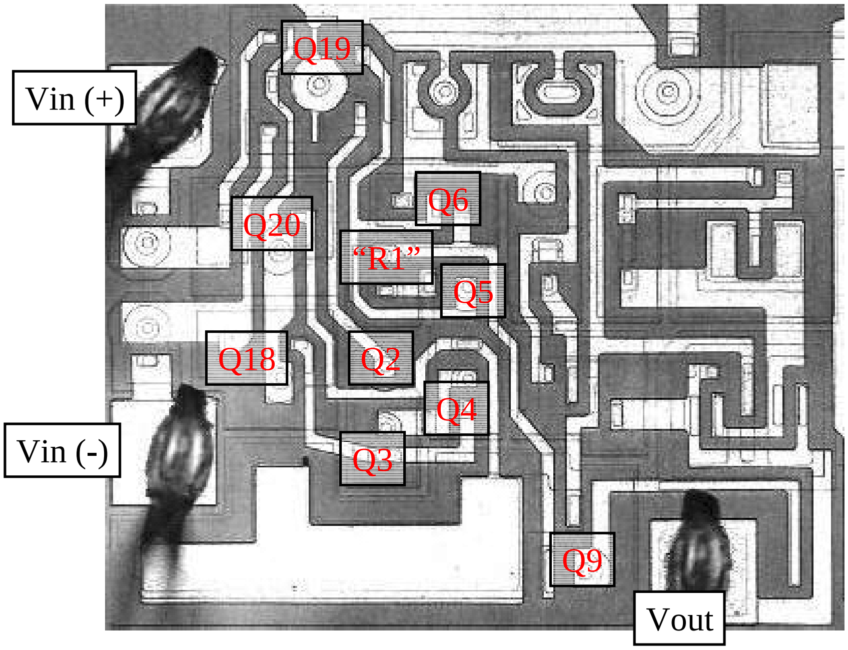


Here we show a comparison of the SET waveform for the microbeam, the laser and the simulations. The simulation is for a collector to emitter strike in Q2. For the same collected charge the SPICE simulation over predicts the amplitude of the SET. However, by adjusting the collected charge to 0.65 pC, about half of that deposited by the microbeam, we get a close match. The laser waveform is also shown for comparison. However in the case of the laser a different region of the transistor was exposed since the portion of the transistor sensitive to the microbeam is under metal. For the laser the most sensitive region was just outside the metal field plate. Also the laser deposited charge required to match the microbeam trace was 1.2 pC, an extremely good match to the microbeam. In the simulation the c-e junction was most sensitive. The simulation included a 1 kohm base spreading resistance. By adjusting the value of spreading resistance the SET waveform could be matched at the same collected charge as occurred for the microbeam exposure.



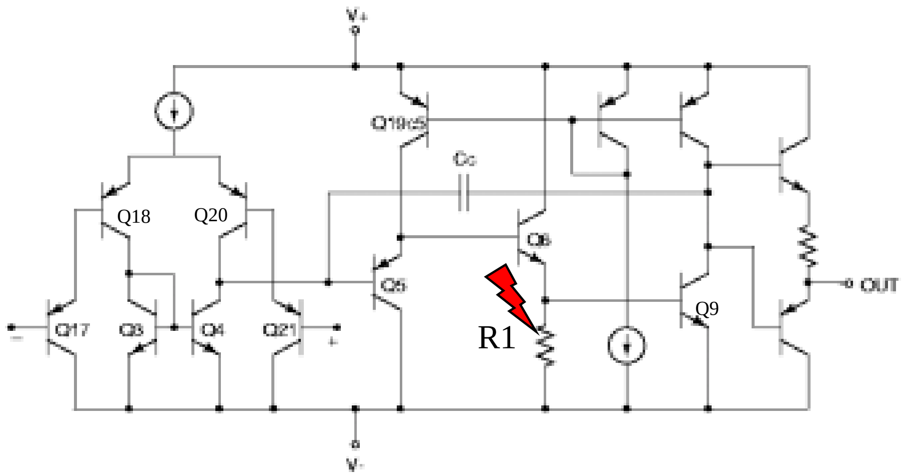
Here we show the results for the case of delta Vin = +10 mV and the output high. The transient is negative going for the microbeam and is much smaller than for the output low condition shown in the previous viewgraph (200 mV compared to 1.5V for the output low condition). The simulated pulse is first positive going then negative going. In order to match the (negative going) amplitude of the microbeam pulse the required collected charge for the SPICE simulation is about twice that for the microbeam test. For the laser irradiation the match is very close but the required charge is only 0.45 pC, about 2.5 times smaller than for the microbeam.

LM124 showing transistors hit with microbeam

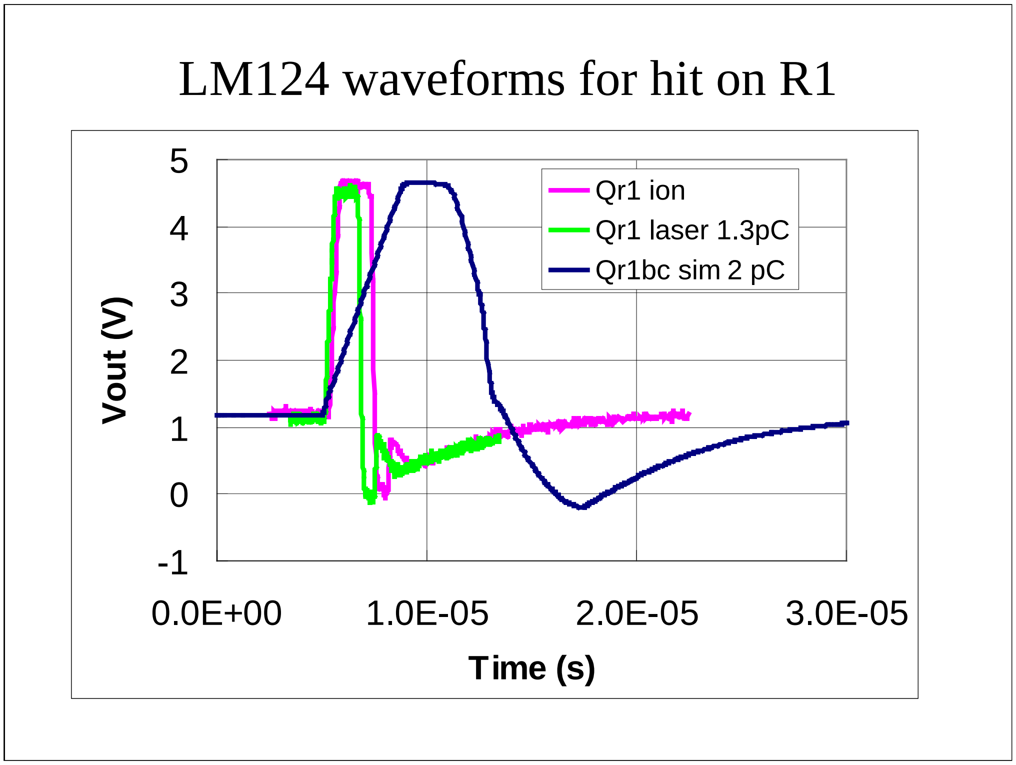


The LM124 was much more sensitive than the LM111. At least 10 transistors produced output transients for the 40 MeV Cl ions. The sensitive transistors are shown in the photomicrograph here, which is one of the four op amps in the LM124. The most sensitive transistor is a floating base npn transistor labeled "R1", since it is a two terminal device identified as a resistor in the circuit diagram. This structure is discussed in more detail in the presentation by Andrew Sternberg, et. al. at this symposium.

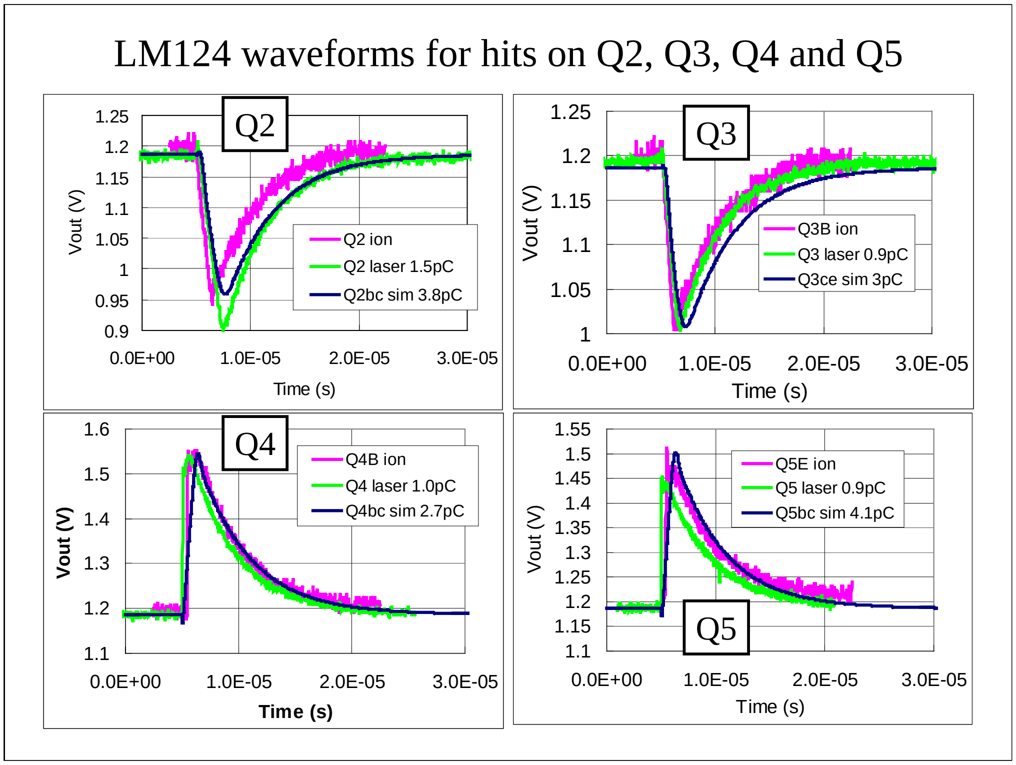
LM124 simplified circuit diagram



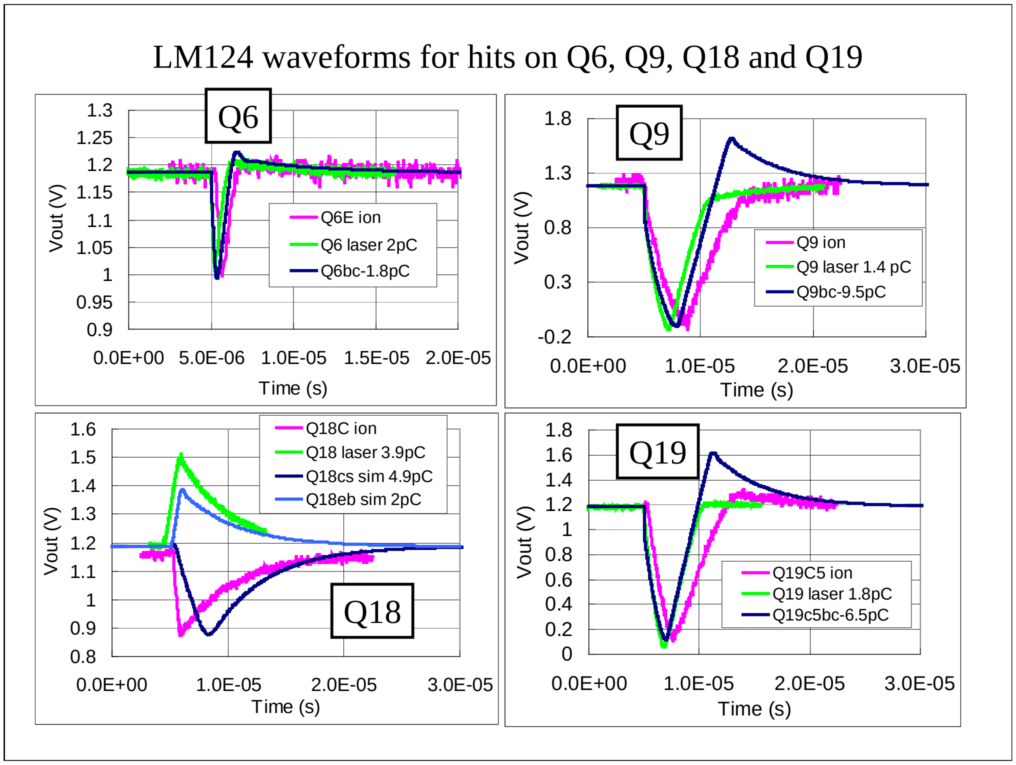
Here we show a simplified circuit diagram of the LM124. Most of the sensitive transistors are shown here including the floating base npn transistor labeled “R1”. The identification of the “resistor” element as a floating base npn transistor required extensive analysis by the failure analysis group at NAVSEA Crane and resulted in much discussion among the co-authors since it was unclear why the manufacturer would choose this type of circuit element for such an application. However, its identification was verified by the manufacturer. When this element is hit with an ion the transistor is turned “on” pulling the base of Q9 low and and turning Q9 “off”. This causes the pnp transistor above Q9 to turn “on” pulling the output high. However, the output only goes to Vcc (6V) minus two diodes drops or 4.7V. Since the output is at 1.2V the output transient saturates with a swing of 3.5V as observed in the microbeam and laser tests and simulated by SPICE.



In the next several viewgraphs we show the comparison of the microbeam induced SET waveforms to the laser induced waveforms and the SPICE simulations for the most sensitive transistors. The most sensitive, as mentioned, is the floating base transistor "R1" also denoted as Qr1 in the plot. The microbeam trace shows saturation at 4.7V for the 1.2 pC of deposited charge. For the simulation the charge required to get the same saturated pulse width is 2 pC. The simulated waveform shows much slower rise and fall times than the experimental waveforms. In the case of the laser, the charge required to match the microbeam ranges from 0.5 to >2 pC. As the charge is increased the pulse does not widen appreciably. Here we show the results for 1.3 pC which is nearly the same as for the microbeam. The undershoot is a function of the capacitive load. In the laser tests the capacitive load was matched to the load used in the microbeam tests using a FET probe connected to 1 foot of RG174 cable. Without the cable the undershoot would not have been matched.



Here we show the comparison of the microbeam SETs to the laser induced SETs and the simulations for Q2, Q3, Q4 and Q5. In all cases the laser and simulated waveforms could be matched to the microbeam induced waveforms by merely adjusting the collected or deposited charge. However the amount of charge required to match the microbeam result varied for both the laser and simulation among the different transistors. In the case of the laser measurements the range of charge for these transistors was 0.9 to 1.5 pC, whereas the range of charge for the simulations was 2.7 to 3.8 pC. Once the adjustments in charge were made the correlation of the laser and simulated waveforms to the waveform for the microbeam was nearly perfect.



Here we show the results for transistors Q6, Q9, Q18 and Q19C5. For Q6, Q9 and Q19C5 the correlation of the laser and simulation to the microbeam waveform is quite good after adjusting the charge. However, in the case of Q18 the laser waveform is of opposite polarity to that of the microbeam. If we look at the simulations for Q18 we see why this is the case. In the simulations if the eb junction is hit, the waveform is of the opposite polarity to the microbeam and if the cs junction is hit the simulated waveform correlates with the microbeam. It would seem reasonable that the laser is hitting the eb junction which is near the surface and is not able to penetrate deep enough to reach the cs junction. Apparently the ion beam deposited charge is preferentially collected by the cs junction. A similar result was seen for Q20 but is not shown in the figure.

Charge required for best fit to microbeam data

Circuit	Transistor	Charge for best fit (pC) Simulation	Laser
LM111	Q1 (ΔVin+)	2.14	0.45
	Q2 (ΔVin-)	0.65	1.2
LM124	Q2bc	3.8	1.5
	Q3ce	3.0	0.9
	Q4bc	2.7	1.0
	Q5bc	4.1	0.9
	Q6bc	1.8	1.95
	Q9bc	9.5	1.4
	Q18c-sub	4.9	diff polarity
	Q19C5bc	6.5	1.8
	Q20c-sub	3.5	diff polarity
	"R1"bc	2.0	1.3

In this table we summarize the results of the collected charge required to fit the microbeam waveforms for the most sensitive transistors (as observed in the microbeam testing) for both the simulations and the laser tests. As mentioned earlier, for the LM111 there was only one sensitive transistor for each test condition. For output high the charge to fit the data was about twice that of the microbeam and for output low it was one half. For the laser the charge for output low was the same as for the microbeam and for output high it was about 2.5X lower. For the LM124 the simulated charge to fit the microbeam waveforms was greater than 1.2 pC in all cases, ranging from 1.8 to 9.5 pC. However, for the laser the range of charges required to fit the microbeam data was 0.9 to 1.95 pC, which is very close to the charge for the microbeam. For Q18 and 20 the laser waveform had the opposite polarity, as discussed previously.

Discussion

- Microbeam
  - Can probe any region
  - Limited on range and total deposited charge
  - Can map sensitive area of individual transistor
- Laser
  - Cannot probe regions under metal
  - Limited penetration depth for laser used here
  - Can easily vary energy to determine threshold
- Modeling
  - Can explore SET sensitivity of any junctions in any transistor with variable charge
  - Requires iteration with experimental data to assure accuracy of circuit model

In this slide we discuss some of the features of the three methods for generating SETs by striking individual transistors or circuit elements of a bipolar linear circuit. The microbeam is a heavy ion source capable of being focused on a very small region of a transistor. Hence it can penetrate any region and be used to identify the most sensitive parts of an individual transistor. However, the energy of the ions is limited to about 40 MeV and, since the parts are run in vacuum, it takes a long time to change either the energy or type of ion to vary range and LET. The total deposited charge is limited to 1-2 pC and for higher LETs the range is not great enough to penetrate the epitaxial layer in many bipolar linear circuits. The laser is an extremely useful tool since it causes no damage, is easily focused to a small spot size (~1.5 um), is operated in air and the energy can be varied over orders of magnitude. However, it usually has a fixed wavelength and, for the one used here, the 1/e depth is only 2 um, which is not optimum for bipolar linear circuits. Also, it cannot penetrate metal, which restricts the regions that can be hit, except indirectly. With a SPICE simulation any pn junction in the circuit can be hit and the collected charge can be changed at will. The only limitations are in the accuracy of the circuit representation and the parameterization of the circuit element models. Much work is required to develop a good model, as the presentation by Boulghassoul shows, and the model must be calibrated and verified with experimental data. In addition, as shown by Sternberg, many parasitic elements are sensitive must be included.

Discussion (cont.)

- LM111
  - Microbeam results limited by deposited charge of ~1.2 pC
  - Laser results limited by metal but good results anyway
  - Modeling gave good results for two most sensitive transistors
- LM124
  - Many transistors characterized by microbeam
  - Correlation with laser excellent except on Q18 and Q20
  - Modeling results somewhat mixed
    - Excellent correlation on waveforms
    - The charge to fit microbeam data was up to 8X

In the case of the LM111 the microbeam results were limited by the total deposited charge. Only one region was sensitive for the worst case circuit bias condition, which is very small delta Vin. The region most sensitive to the microbeam was only accessible to the laser indirectly by hitting at the edge of the metal. The simulation required the inclusion of a base spreading resistance to reproduce the SETs in the sensitive transistors. For both the laser tests and simulations several other transistors were shown to be sensitive at slightly higher collected charges including Q3, Q4, Q5a and Q5b. For the LM124, on the other hand, 10 transistors were shown be be sensitive for the 1.2 pC deposited charge with the microbeam, whereas, for simulations the collected charge was much greater to get the same SET response. For the laser the amount of charge to get good matching varied from about 25% below to 60% above the charge deposited by the microbeam ions, which is quite good correlation. For transistor Q18 and Q20 the polarity of the laser SET was opposite to that of the microbeam. The reason for the apparent discrepancy between the microbeam and laser for these transistors is probably explained by the difference in the charge vs depth profile. Whereas the laser deposits charge near the surface affecting the eb junctions, the microbeam charge deposition is much deeper affecting the cb and cs junctions. The simulations show that the SET from and eb strike is of the opposite polarity to that for a cs strike for Q18 and Q20. The differences between the microbeam and simulations, with respect to the charge required for the same transient, may be due to the transistor model parameterization.

Conclusions

- Detailed understanding of SET response requires combination of modeling and several experimental "tools"
- Both the microbeam and laser are very useful but each has limitations
- Circuit simulations require very accurate circuit model with parasitics
- Circuit modeling requires iteration with experimental data for calibration and validation
- Mixed mode simulator not required for generation of transistor SET waveforms for these circuits

In conclusion we can say that, while the broadbeam data is necessary to characterize the overall circuit response in terms of LET vs. cross section, the techniques discussed here, microbeam and laser testing and circuit simulations, are required to understand the SET mechanisms in terms of the details of the individual transistor sensitivity. We have also demonstrated that because of various limitations of each technique, a combination of these techniques is necessary to fully understand the SET response. Excellent correlation was shown between the SET waveforms from the microbeam and laser and by adjusting the collected charge the simulations can be matched to the experimental waveforms.

While we claim that mixed mode simulation is not required to simulate the SET response of these older slower circuits, the details of the frequency response is affected by the injected charge waveform, as shown by Boulghassoul in another presentation at this symposium. Also for the much higher speed, modern bipolar linear circuits the characteristics of the injected charge waveform may be more important.