# Comparison of Single-Event Transients Induced in an Operational Amplifier (LM124) by Pulsed Laser Light and a Broad Beam of Heavy Ions

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***Abstract*—A comparison of single-event transients (SETs) from heavy-ion and pulsed-laser irradiation of the LM124 operational amplifier shows good agreement for different voltage configurations. The agreement is illustrated by comparing both individual transient shapes and plots of transient amplitude versus width.**

***Index Terms*—Heavy ions, linear devices, pulse shapes, pulsed laser, single-event transients (SETs).**

## I. Introduction

SINGLE-EVENT transients (SETs) whose characteristics (amplitude, width, cross section, etc.) depend on device configuration (differential input voltage, gain, supply voltage, and output loading) are produced when linear bipolar devices are exposed to ionizing particle radiation [1], [2]. The conventional approach to characterizing the SET sensitivity of a linear bipolar device has been to select a particular device configuration and perform heavy-ion testing at an accelerator facility. However, because the SET sensitivity of a linear device depends on the application configuration, SET testing must be performed for every application—an expensive and time-consuming proposition.

Over the past two years, an effort has been underway to assess whether pulsed lasers and/or circuit level modeling can be used to minimize the amount of ion-beam testing required to qualify linear bipolar parts for space missions. Last year we reported on the excellent agreement between the waveforms obtained from a focused ion-beam, a pulsed laser, and circuit level modeling for the LM124 operational amplifier [3]. Those results provide evidence for the general validity of this approach. However, despite the excellent agreement observed between the ion and laser measurements and the circuit simulations, some issues require further investigation because of the following experimental limitations: i) the Cl ions had low energy (40 MeV), low linear energy transfer (18 MeV $\cdot$ cm$^2$/mg) and short range (8 $\mu$m), resulting in a limited number of transistors exhibiting SETs; ii) the pulsed laser light had a wavelength of 590 nm, corresponding to short 1/e penetration depth of approximately 2 $\mu$m, iii) some of the SET-sensitive regions were covered with metal and could not be probed directly with the laser.

In this paper, we extend the previous results to ions of higher LET and longer penetration depth. We investigate, using a broad-beam heavy-ion accelerator, the SETs produced by a variety of ions with LETs up to 53 MeV $\cdot$ cm$^2$/mg and ranges up to 102 $\mu$m, and compare them to SETs generated with a pulsed laser. It is found that each type of SET generated with the broad ion beam can be matched by SETs reproduced using pulsed laser excitation. This is illustrated in two different ways. First, direct comparison of the SET pulse shapes reveals that the entire range of pulse shapes induced by heavy-ion irradiation can be reproduced with the laser. Second, plots of pulse amplitude versus pulsewidth ($\mathrm{V}\Delta\mathrm{t}$), a powerful method for representing SET data [4], compare favorably for the two different irradiation methods. Furthermore, it is demonstrated that two of the concerns noted above for the pulsed laser, the relatively shallow penetration depth of the 590 nm optical radiation and the issue of metal coverage, are shown to be of little significance in obtaining the results required for this type of investigation.

These results are important because they indicate that the pulsed laser can be used as a first step for screening linear bipolar parts for space missions. Typically, a design engineer needs to know whether specific parts being considered for a space system will produce SETs of sufficient amplitude and duration to affect the system performance. The present results suggest that a 590-nm pulsed laser is suitable for such screening. The pulsed laser experiments can be performed rapidly and at minimal cost. Based on the results of pulsed laser screening, the design engineer can determine what additional accelerator testing is necessary.

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## II. Experiment Description

SETs were obtained by exposing the LM124 (from National Semiconductor Corporation) to a variety of ion beams at Texas A&M University (TAMU) Cyclotron Facility. The ion energies available at TAMU were considerably greater than the energy of the Cl ions used in the ion microprobe studies previously reported [3]. Having available a broad beam of ions with LET's as high as 53.9 MeV $\cdot$ cm$^2$/mg and ranges up to 102 $\mu$m made it possible to excite SETs in all SET-sensitive areas. At each LET, many different kinds of SETs were generated, some with positive amplitudes, some with negative amplitudes and some bipolar. All SETs were captured on a digital oscilloscope and immediately stored on a computer for later analysis. Both positive and negative SETs were captured on the oscilloscope by connecting two low-capacitance probes to the device output, and setting channel 1 of the oscilloscope to trigger on positive SETs and channel 2 on negative SETs.

The pulsed laser SET test system at NRL has been described in detail in a previous publication [5]. For these experiments the laser beam had a diameter of 1.7 $\mu$m, a wavelength of 590 nm, and a penetration depth of 2 $\mu$m. SET-sensitive transistors were identified by scanning the laser beam across the chip while checking for SETs on the oscilloscope. The laser light was then focused on the most sensitive SET location of each transistor and the laser intensity gradually increased. In this way a complete set of SETs could be captured whose amplitudes and widths spanned the entire range observed during heavy ion experiments. By searching through all the different types of SETs generated with the pulsed laser light it was possible to find a SET that perfectly matched one generated by heavy ions.

## III. Device Description

Fig. 1 is a photomicrograph of one of the amplifiers in the LM124. The ten transistors and one resistor labeled in the figure were all identified as SET sensitive by irradiating them with a focused laser beam. Fig. 2 is a circuit diagram showing the location in the circuit of all the SET sensitive transistors identified in the photomicrograph.

## IV. Results

Fig. 3 shows a comparison of the SET waveforms obtained by irradiating the LM124 with high-energy ions (LET $= 53.9$ MeV $\cdot$ cm$^2$/mg) and with pulsed laser light. For both experiments, the part was configured as a voltage follower with input 1 V and supply of $\pm 15$ V. SETs representative of each type were selected from the multitude of SETs obtained with heavy ions. Because the part was exposed to a broad beam of ions, it was impossible to assign a specific SET to a specific transistor. However, by probing each of the SET-sensitive transistors with pulsed laser light and comparing the shapes of the SETs with those obtained with heavy ions, the location of an ion strike producing a particular SET could be determined. The excellent agreement between SET shapes obtained by these two methods was achieved by carefully adjusting the intensity of the laser light until the SET matched the one generated by the ion.

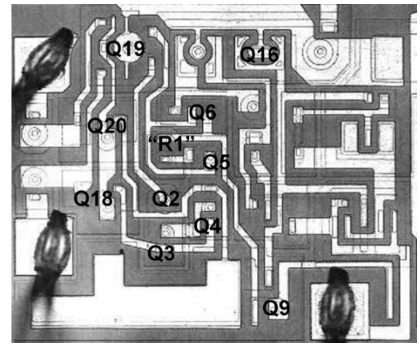


Fig. 1. Photomicrograph of LM124 showing all the SET sensitive transistors.

SET's with similar, but not identical, shapes were generated in more than one transistor. For example, SETs generated at transistors Q2, Q3, Q4, and Q5 all have approximately the same shape. The excellent agreement shown in Fig. 3 was obtained by inspecting laser-light induced SET's from all four transistors and selecting the one that most closely matched the SET produced by the ion; in this case the match was achieved with an SET generated at Q2. The second graph in Fig. 3 shows an ion-induced SET and one generated at transistor Q9. Because SETs from Q19 are similar, but not identical to, those from Q9, (see Fig. 12 of [3], we searched both sets of SETs to find the one that most closely matched the one generated by an ion. Fig. 3 shows the excellent match that can be obtained between SETs obtained from heavy-ion and pulsed-laser irradiation. The fact that all SETs generated in the LM124 by heavy ions could be matched with SET's generated by pulsed laser light confirms the useful role played by the pulsed laser in simulating SETs.

SET's generated by ions and pulsed laser light were also compared on a more global scale by plotting their amplitudes as a function of width $(\mathrm{V}\Delta\mathrm{t})$, where the width is defined as the full width at half-maximum (FWHM) amplitude [4]. Results for laser light irradiation are presented first. The approach involved capturing the SETs as described above and then using a software program to extract pulse amplitude and width for all captured SETs. Fig. 4 contains four $\mathrm{V}\Delta\mathrm{t}$ plots for SETs obtained by irradiating nine different transistors (Q2, Q3, Q4, Q5, Q9, Q16, Q18, Q19, and Q20) with the pulsed laser. Fig. 5 shows similar plots for resistor R1 and transistor Q6. Data for transients having similar shapes are combined together on the same $\mathrm{V}\Delta\mathrm{t}$ in Fig. 4 even though they originate in different transistors. Thus, the first plot in Fig. 4 contains data points from transistors Q2, Q3, Q4, and Q5, all of which give positive-going transients with similar, though not identical, shapes. Since the SET amplitudes for Q3, Q4, and Q5 are not a linear function of pulse width, their shapes change with increasing laser pulse energy. In contrast, the $\mathrm{V}\Delta\mathrm{t}$ points for Q2 lie along a straight line, a clear indication that the SETs originating at Q2 do not change shape with increasing laser intensity. The $\mathrm{V}\Delta\mathrm{t}$ points for Q3 show that the SET's are small ($<1$ V) even for the highest laser intensities. For the most part, Q18 shows little change in shape with increase in laser intensity, except for a region where the pulse broadens while the amplitude stays constant. At higher intensities the shape is once again unchanged with increasing intensity. The linear plots for SETs from Q9, Q16, and Q19 demonstrate that the shape for

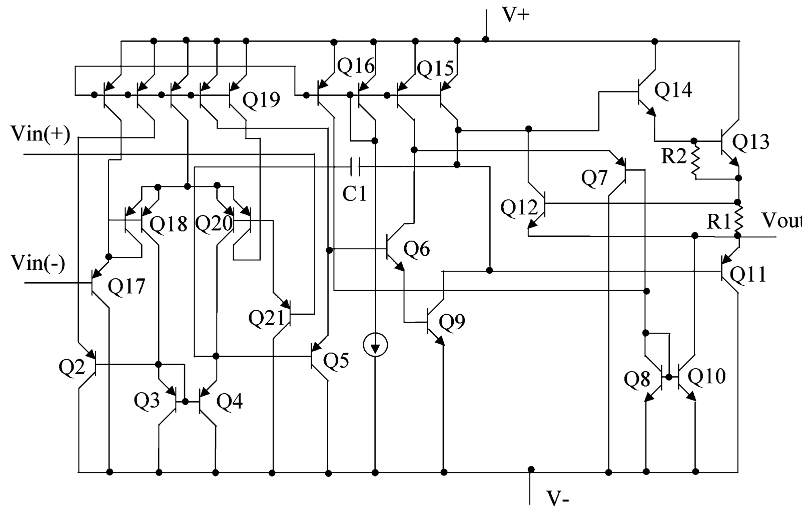


Fig. 2. Circuit diagram showing Q19 with five collectors, Q15, Q16, Q18, and Q20 with 2 collectors each.

those SETs also do not change significantly with laser intensity. However, there is a second branch for Q16, consistent with very short SETs having large amplitudes. Inspection of the SET for Q16 in Fig. 3 shows it is bipolar with an initial large narrow positive component that precedes the much broader negative component. It is that initial fast component that constitutes the second branch.

The pulsed laser reveals that SETs generated by irradiating Q20 are significantly more complicated. As reported in a previous publication, the shape changes dramatically with laser intensity, but it also depends on where the light is focused relative to the two collectors [3]. SETs originating near collector C1 of Q20 start out with a small negative pulse that becomes more negative with increasing laser intensity. At some intermediate laser intensity the amplitude starts to decrease and the SET takes on a bipolar character with an initial positive going segment. With further increases in laser intensity, the negative component of the bipolar SET disappears, and it becomes purely positive, increasing in amplitude with increasing laser light intensity. SETs originating near collector C2 start out bipolar with an initial negative component. With increasing laser intensity, the SET amplitude and width both become very large. The SET then evolves into a more complex shape with three components, and finally at the highest laser intensities the SET is entirely positive.

Fig. 5 shows the $V\Delta t$ plots for resistor R1 and transistor Q6. The time axis has been expanded to reveal the complex nature of the short duration transients. In both cases there are positive and negative branches resulting from the transient undergoing dramatic changes with increasing laser light intensity. At low intensities, the SETs have positive amplitudes, but with increasing intensity they assume a bipolar shape with a negative component following the initial positive component. With further increases in intensity, the negative component grows at the expense of the positive one. Therefore, the positive branch in Fig. 5 is for low laser intensities and the negative branch for high intensities.

Fig. 6 combines all the data points shown in the previous figures into one plot. Although there are numerous branches of $V\Delta t$ points that originate in different transistors, giving the impression of a very complicated figure, all the information is needed in order to make comparisons with SETs produced by heavy ions. Note that, because the laser is able to deposit significantly more charge into the silicon than heavy ions can, $V\Delta t$ branches obtained from laser-induced SETs are typically much longer than branches obtained from heavy ion irradiation.

These types of plots are also useful for studying how changing the device configuration affects the shapes of the SETs. Fig. 7 presents $V\Delta t$ plots for two different configurations for the LM124—one a noninverting amplifier with gain of 11 and the other a voltage follower. The figure clearly shows that there are differences in the dependence of the SET shapes on laser light intensity for the two configurations. When configured as a noninverting amplifier, the $V\Delta t$ branches indicate that the largest positive SETs have much longer durations than for the case of the voltage follower. Also, there are clear differences in the $V\Delta t$ plots for negative amplitudes—two negative branches are well separated from one another for the case of the voltage follower, but not for the amplifier with noninverting gain.

The acid test for validating this approach is to compare plots of $V\Delta t$ obtained for laser-induced SETs with those obtained for heavy-ions. Of the many different sets of data we analyzed, the results for only three will be presented here. The first condition is for the LM124 configured as a voltage follower with an input of 5 V exposed to a beam of ions having low LETs. Fig. 8 shows the comparison between the ion data (solid triangles) and the pulsed laser data (solid circles). By selecting data points obtained with the laser that match those of the low-LET ions, it is possible to identify the two transistors with the lowest SET thresholds—R1 and Q20. All the branches obtained with the laser over the full energy spectrum are included. The $V\Delta t$ points obtained from the ion-induced SETs overlap those obtained with the laser from Q20 over a very small range due to the fact that near threshold the amplitudes and widths of the SETs are small. However, the positive SETs generated at R1 reach their maximum amplitudes at very low laser energies and low ion LET's. This can be seen in the steeply rising positive branch where the ions and laser data points overlap.

Fig. 9 shows a comparison of $V\Delta t$ data obtained from pulsed laser (solid circles) and heavy ion (solid triangles) irradiation for the same configuration as in Fig. 8, but with ions having a much higher LET (53 MeV $\cdot$ cm$^2$/mg). All $V\Delta t$ points from ion-in-

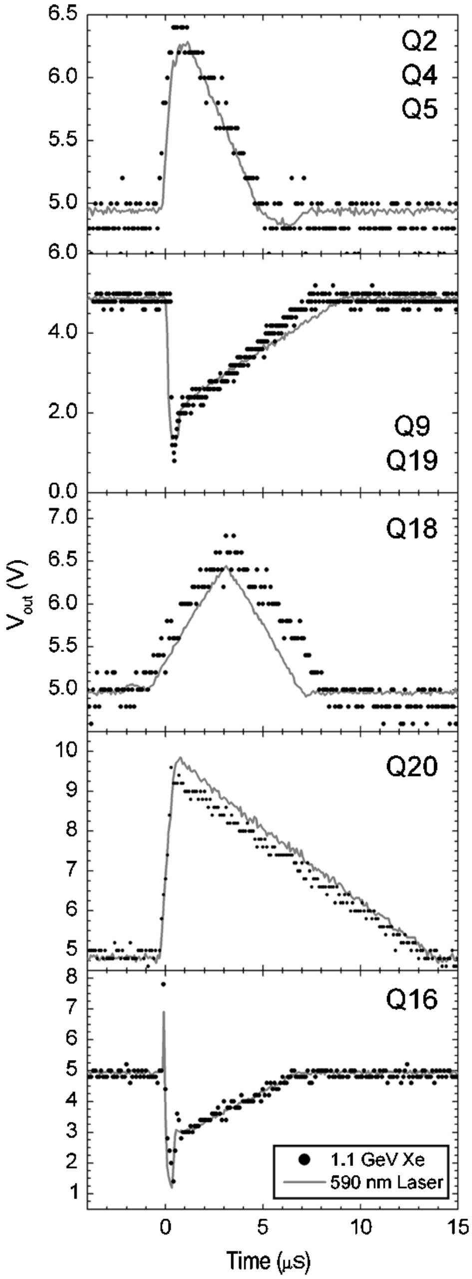


Fig. 3. Comparison of Xe-ion and pulsed-laser induced SETs.

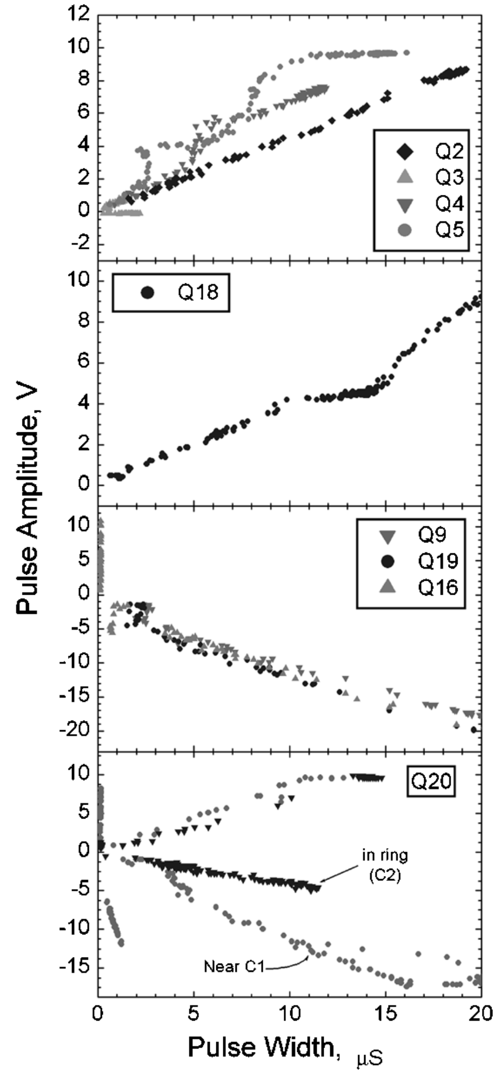


Fig. 4. Pulse amplitude as a function of width for SETs generated by irradiating all the sensitive transistors of the LM124.

duced SETs fall on branches of $V\Delta t$ points generated by the laser. This clearly demonstrates that the laser and ions produce the same SETs. The plot contains a single data point describing a SET with negative amplitude of $-20$ V and FWHM of 30 $\mu$s. We should also point out that the number of data points from heavy ions is much smaller than for the laser. Many transients are captured for each transistor because the laser light is focused on a single location and, no matter how small the cross section, the full energy range may be scanned without damaging the device. In contrast, the ion beam arrives at random locations, and transistors that have small cross sections or high LET thresholds will contribute relatively few points.

Fig. 10 shows the same type of plot for the LM124 configured as a voltage follower but with an input of 10 V. A comparison of Figs. 9 and 10 shows that the shapes of the SETs change when the input voltage changes from 5 V to 10 V. Fig. 10 demonstrates that SETs generated by the pulsed laser-light have the same shapes as those generated by heavy ions for this configuration as well.

## V. Discussion

In [3] we chose for comparison the largest transients measured for both laser excitation and the focused ion beam. As such, those results correspond to the most sensitive location of each SET sensitive element. In contrast, the precise location of individual ion strikes is unknown when a broad beam of heavy ions is used for irradiation. In general, with pulsed laser excitation, we observe a tradeoff between deposited charge (LET) and position (distance from the most sensitive location). As such, a given pulse shape may be obtained for a range of pulse energies simply by adjusting the position of the laser spot. Similarly, at a single location we may obtain the full range of pulse shapes and amplitudes for a given sensitive element simply by changing the laser pulse energy (deposited charge). Similar behavior is expected for heavy ion irradiation as a function of ion LET and po-

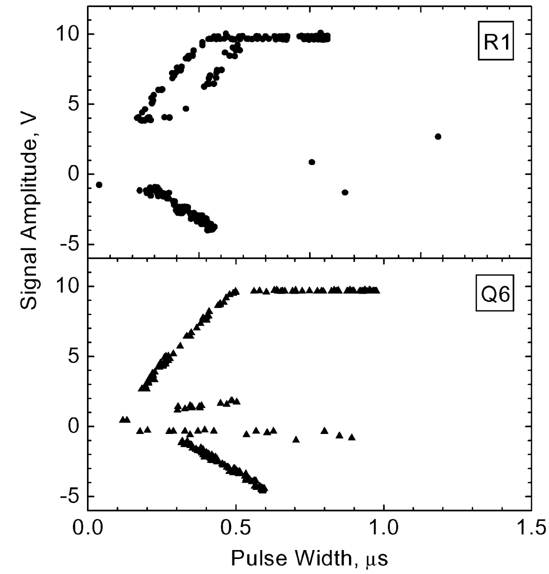


Fig. 5. Amplitude versus width for pulsed laser irradiation of resistor R1 and transistor Q6.

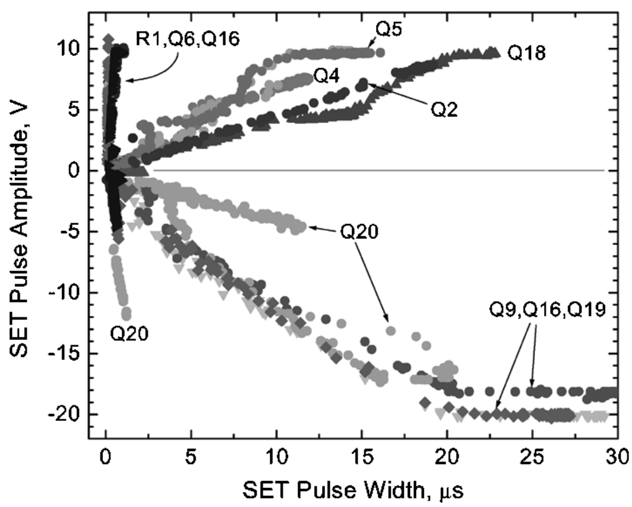


Fig. 6. $V\Delta t$ points for all the transistors combined in one plot.

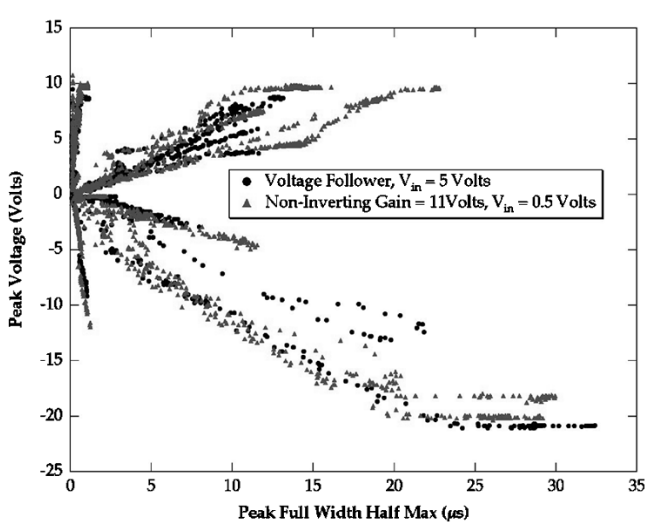


Fig. 7. Plot of amplitude versus width obtained by irradiating all the transistors in the LM124 for two different configurations.

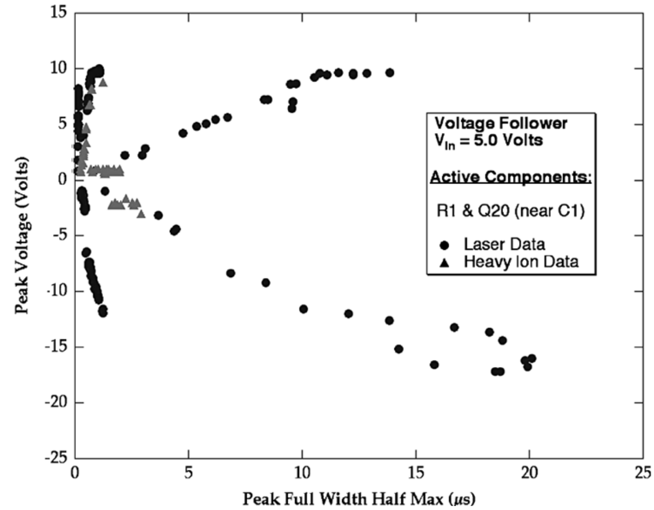


Fig. 8. Peak voltage as a function of FWHM for SETs produced by low LET (2.8 MeV · $cm^2$/mg) ions and pulsed laser light.

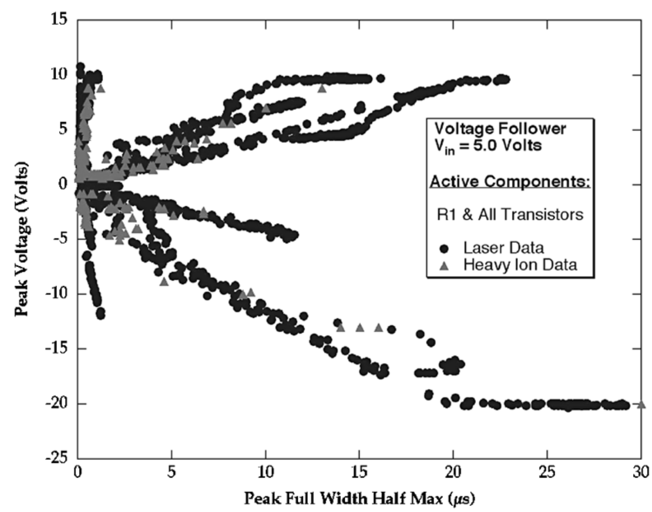


Fig. 9. Peak voltage as a function of FWHM for ions with $\mathrm{LET} = 53.9$ MeV · $cm^2$/mg and laser light for an input of 5 V.

sition. However, the position is not an experimental parameter over which we have control. Therefore, using the pulsed laser probe, we are able to reproduce the vast majority of pulse shapes observed with heavy ion irradiation by adjusting the laser pulse energy using a finite number of spot locations. We must note, however, that the simple picture described here is not always valid. Due to the complexity of the devices under investigation, unique pulse shapes are sometimes observed at very precise locations. This appears to be the case within Q20, for example [6], for which competition between different charge collection pathways gives rise to a complex dependence of SET pulse shape on position.

Also noteworthy is the transient measured for Q16. This node was not sensitive with the lower LET ion microprobe used in our previous test [3].

The fact that all the SETs obtained by ion irradiation could be matched with SETs generated by pulsed-laser excitation at some location in the device suggests that the presence of metal over some of the transistor junctions was not a limitation. This is due to the fact that every SET-sensitive junction in the LM124

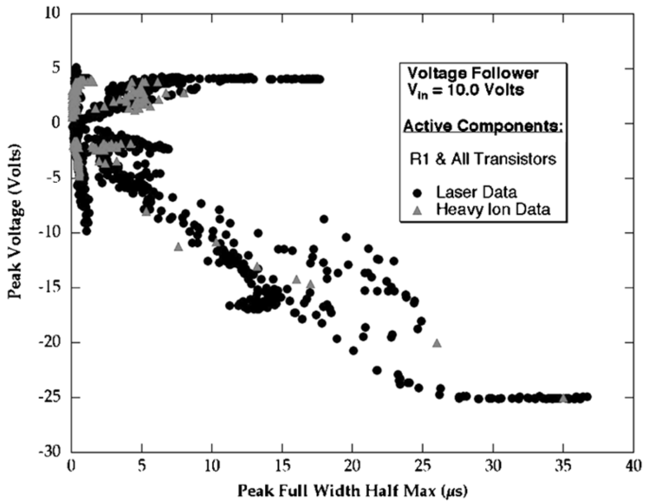


Fig. 10. Peak voltage as a function of FWHM for laser light and ion irradiation for maximum LET with an input of 10 V.

had some area not covered by metal. Even when a sensitive junction is completely covered with metal, SETs can still be generated with laser light. For example, there are two junctions in the LM111 voltage comparator that are very sensitive to SETs and are completely covered with metal. Nevertheless, focusing the laser light on areas adjacent to the sensitive junction could generate SETs, whose shapes matched those of ion-induced SETs. Sufficient charge to generate SETs could diffuse under the metal to the sensitive junction. It also appears that the limited penetration depth of the light does not modify the SET shapes, as demonstrated by the excellent agreements shown in Fig. 2.

A point worth noting is that the pulsed laser is capable of depositing significantly more charge than any of the ions can. Because the intensity decreases exponentially with distance from the Si surface, the amount of energy deposited at a particular depth can be increased merely by increasing the light intensity, and is limited only by thermal damage to the material. Therefore, traces produced by pulsed-laser light can cover a much larger effective LET range than those produced by any particular set of heavy ions.

We note that $V\Delta t$ plots using only laser data provide no information about the relative sensitivities of the various transistors. Therefore, the fact that one branch is longer than another cannot be used to infer that the long branch is more SET sensitive. Comparison of ion and pulsed-laser SET's may be used to determine which transistors are the most SET sensitive. For instance, Fig. 8 clearly shows that R1 and Q20 are the most sensitive for the configuration being tested. In contrast, essentially all the SET-sensitive transitors identified with the pulsed laser produce SET's when irradiated with heavy ions having an LET of 53.9 MeV $\cdot$ $cm^2$/mg.

## VI. Summary and Conclusion

The results reported here provide the first pulse-to-pulse comparison of pulsed laser and high-LET heavy ion SETs for a linear bipolar part. These results confirm that the pulsed laser may be used to identify SETs that occur when the part is irradiated with heavy ions. By capturing the SETs, comparison can be made either directly between pulse shape or indirectly through inspection of plots of SET amplitude versus width. The good agreement reported here suggests that the small $1/e$ penetration depth and metal covering some sensitive areas are not a limitation for the pulsed laser, and because it can be determine whether SETs will propagate through circuitry connected to the output of the device, it is a useful tool for reducing the amount of SET testing.

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