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 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.**

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, for every application the corresponding device configuration must be tested - 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?cm^2/mg) and short range (8 µm), 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 µm, iii) some of the SET-sensitive regions were covered with metal and could not be probed 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·cm^2/mg and ranges up to 102 µm, and compare those to SETs generated with a pulsed laser. It is found that each of the different kinds of SETs generated with the broad ion beam can be 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. In addition, plots of pulse amplitude vs. pulse width ($V\Delta t$), 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 wants 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

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laser screening, the design engineer can determine what additional accelerator testing is necessary.

II. Experiment Description

SETs were obtained by exposing the LM124 (from National Semiconductor Corp.) 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 LETs as high as 53.9 MeV?cm^2/mg and ranges up to 102 µm 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. Cable lengths were minimized and two low-capacitance probes were used, one for capturing positive SETs and the other one for negative SETs.

The pulsed laser SET test system at NRL has been described in detail in a previous publication.[5] SET-sensitive transistors were identified by scanning the focused beam (diameter of 1.7 µm and a wavelength of 590 nm) across the chip. By focusing the laser light on the most sensitive location of each transistor and then gradually increasing the laser intensity, a series of SETs could be captured whose amplitudes and widths spanned the entire range observed experimentally.

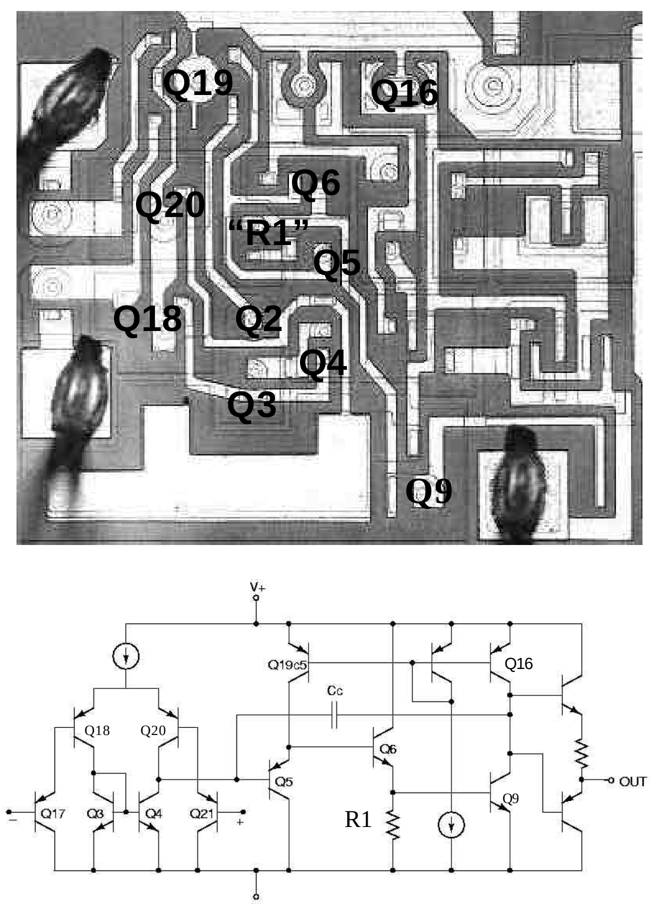

Fig. 1. a) Photomicrograph of LM124 showing all the SET sensitive transistors, b) Simplified circuit diagram.

III. Device Description

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

IV. Results

Fig. 2 shows a comparison of the SETs obtained from irradiating the LM124 with high-energy ions (LET=53.9 MeV?cm^2/mg) and with pulsed laser light. For both experiments, the part was configured as a voltage follower with input 1V and supply of +/- 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 relate SET shapes to specific transistor response using only ion data. 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, their sources could be determined. The excellent agreement between SET shapes obtained by these two methods was achieved by carefully adjusting the intensity of the laser beam until SETs generated by pulsed laser light had the same amplitude as those generated by the ion. In some cases different transistors produced SETs with essentially the same shape. For example, Q2, Q4 and Q5 all produced positive-amplitude SETs that appear to have the same shape, and Q9 and Q19 produced the same negative SETs.

SETs generated by ions and pulsed laser light were also compared on a more global scale by plotting their amplitudes as a function of width (V?t).[4] Results for laser light irradiation are presented first. The approach involved focusing the laser light on the most sensitive area of a transistor and gradually increasing the light’s intensity while, simultaneously, capturing SETs on a digital oscilloscope. A software program was used to extract pulse amplitude and width for all captured SETs. Fig. 3 contains four plots of V?t for SETs obtained by irradiating nine different transistors (Q2, Q3, Q4, Q5, Q9, Q16, Q19 and Q20). Fig. 4 shows similar plots for transistors R1 and Q6. Data for transients having similar shapes are combined together on the same V?t plot, even though they originate on different transistors. Thus, the first plot in figure 2 contains data points from transistors Q2, Q3, Q4 and Q5, all of which give positive-going transients with similar shapes, as shown in figure 2. Careful examination of the first plot in figure 3 shows that, although all the SETs have shapes similar to that shown in figure 2, they do not have the same dependence of amplitude on width over the entire energy range. At low laser light intensities the V?t points all lie along a common line, thus making it possible to fit all the laser-induced SETs to the ion induced SET.

However, they deviate significantly from one another at higher intensities. The fact that the V?t points for Q2 lie along a straight line indicates that the SETs do not change shape with increasing laser intensity. In contrast, the plot for Q5 indicates that the shape does changes significantly with

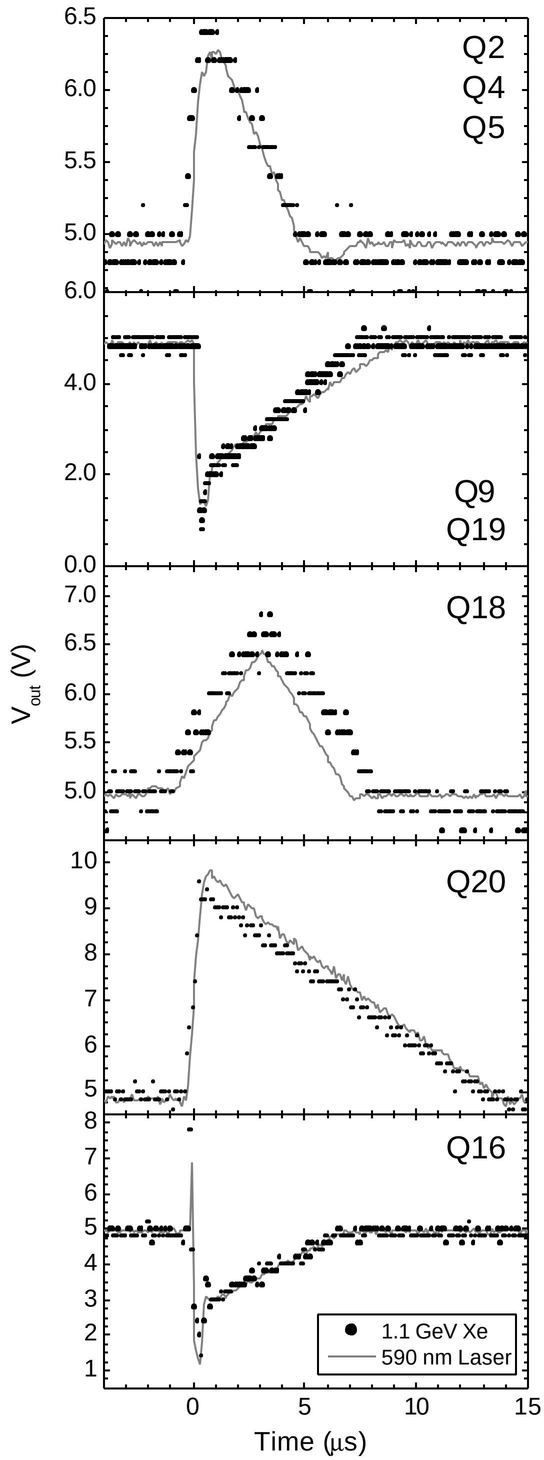

Fig. 2. Comparison of Xe-ion and pulsed-laser induced SETs.

laser intensity. The V?t points for Q3 show that the SETs 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. SETs from Q9, Q16 and Q19 all have similar shapes that do not change with increasing laser intensity. However, there is a second branch for Q16, consistent with

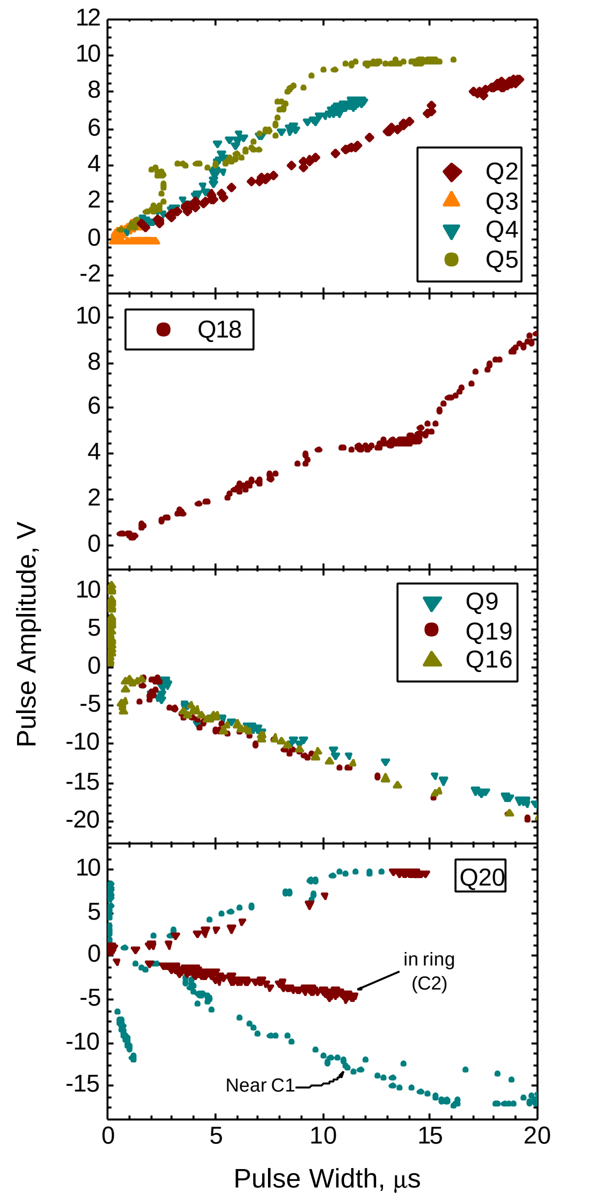

Fig. 3. Plots of pulse amplitude vs width for SETs generated by irradiating all the sensitive transistors of the LM124.

very short SETs having large amplitudes. Inspection of the SET for Q16 in Fig. 2 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

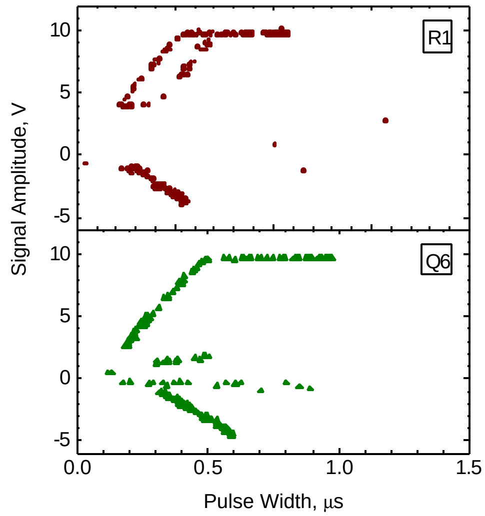

Fig. 4. Amplitude versus width for pulsed laser irradiation of transistors R1 and Q6.

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. 4 shows the V?t plots for R1 and 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 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. 4 is for low laser intensities and the negative branch for high intensities.

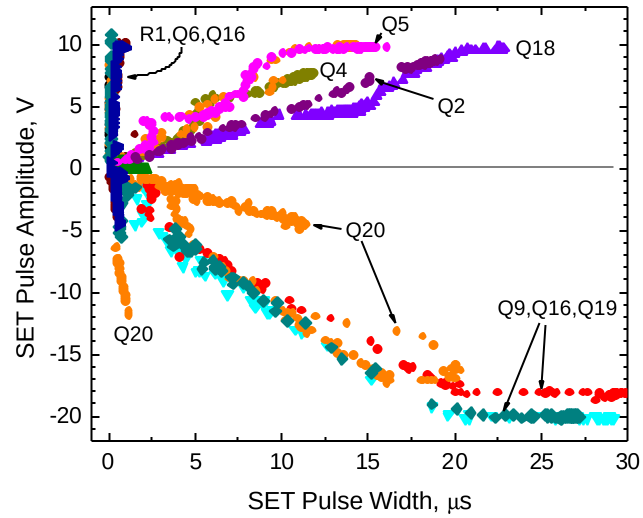

Fig. 5. V?t points for all the transistors combined in one plot.

Fig. 5 combines all the data points shown in the previous figures into one plot. Although there are numerous branches of VΔt 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. In fact, because the laser is able to deposit significantly more charge into the silicon than heavy ions can, VΔt branches obtained from laser-induced SETs should typically be 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. Figure 6 presents plots of VΔt for two different configurations for the LM124 – one where it was configured as a non-inverting amplifier with gain of 11 and the other as 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 non-inverting amplifier, the VΔt 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 VΔt 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 non-inverting gain.

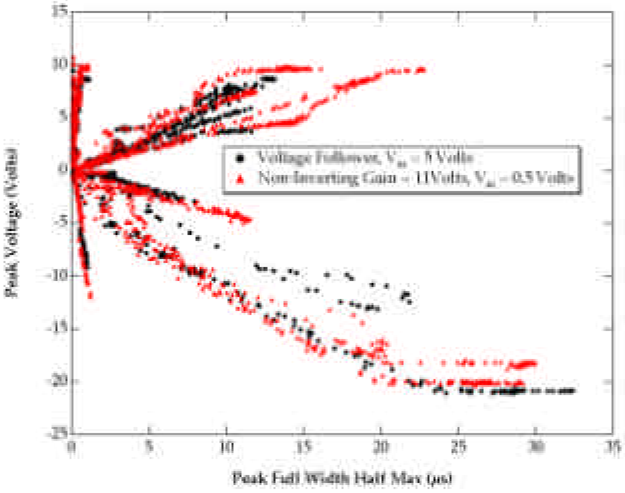

Fig. 6. Plot of amplitude versus width obtained by irradiating all the transistors in the LM124 for two different configurations.

The acid test for this approach is to compare plots of VΔt 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 volts exposed to a beam of ions having low LETs. Figure 7 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 VΔt 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 LETs. This can be seen in the steeply rising positive branch where the ions and laser data points overlap.

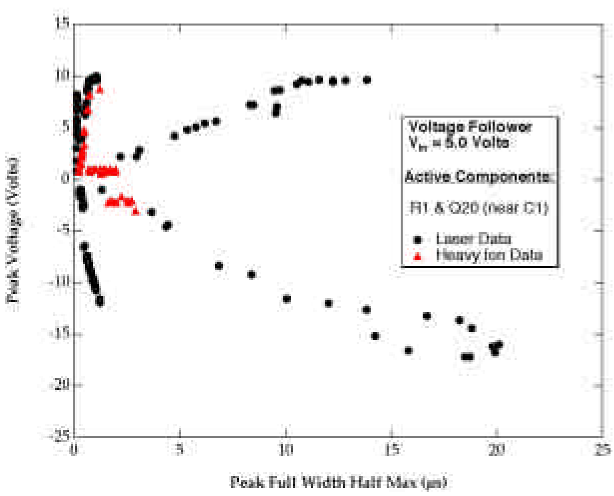

Fig. 7. Peak voltage as a function of full width at half maximum for SETs produced by low LET (2.8 MeV.cm^2/mg) ions and pulsed laser light.

Fig. 8 shows a comparison of V?t data obtained from pulsed laser (solid circles) and heavy ion (solid triangles) irradiation for the same configuration as in Fig. 7, but with ions having much higher LET (53 MeV.cm^2/mg). All V?t points from ion-induced SETs fall on branches of V?t points generated by the laser. This clearly demonstrates that the laser produces the same SETs as do heavy ions. The plot contains a single data point describing a SET with a negative amplitude of –20 V and FWHM of 30 µs. We should also point out that because of statistics the number of data points from heavy

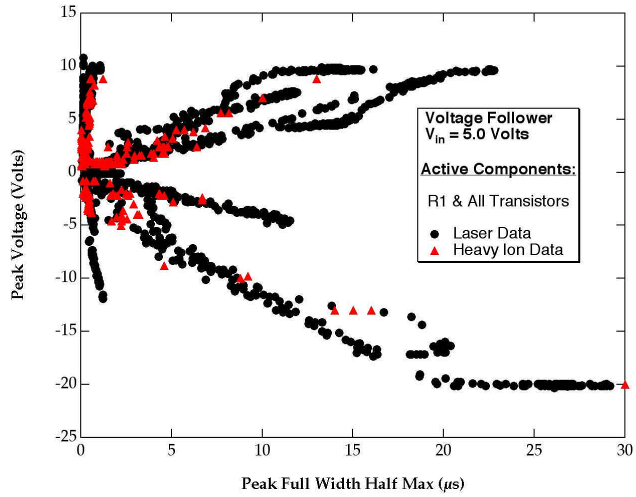

Fig. 8. Peak voltage as a function of full width at half maximum at the highest LET for an input of 5V.

ions is much smaller than for the laser and the maximum energies that may be deposited by the laser are significantly larger than by the heavy ions available at TAMU. Many transients are captured for each transistor because the pulsed laser light is focused on a single location and, no matter how small in 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.

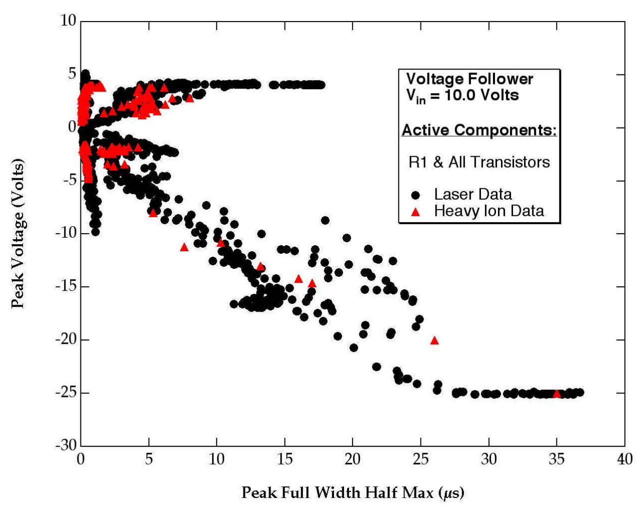

Fig. 9. Peak voltage as a function of full width at half maximum for laser light and ion irradiation for maximum LET with an input of 10 volts.

Fig. 9 shows the same type of plot for the LM124 configured as a voltage follower but with an input of 10 volts. Comparing Figs. 8 and 9 shows that increasing the input voltage from 5 V to 10 V drastically changes the shapes of the pulses. In fact the change is greater when the input voltage is increased from 5 V to 10 V than when the configuration of the amplifier is changed from voltage follower to amplifier with non-inverting gain of 11. Figure 9 shows that, for the changes in the shapes of SETs brought about by an increase in the input voltage from 5 V to 10 V, the pulse shape of the SETs generated by pulsed laser are still in excellent agreement.

V. Discusssion

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 sensitive element. In contrast, with broad-beam heavy-ion irradiation, the precise location of individual ion strikes is unknown. 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 often 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 position. 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]. A thorough examination of all the SETs obtained by ion irradiation revealed that, despite metal covering some SET-sensitive transistor areas and despite the small 1/e penetration depth, all of them could be matched with SETs generated by pulsed-laser excitation at some location in the device. Therefore, concerns about metal coverage and limited penetration depth appear to be of no consequence for pulsed-laser testing of this device and other similar linear bipolar devices.

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 expoenentially with distance from the Si surface, the amount of energy deposited at a particular depth can be increased merely by increasing the light intensity. 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.

The plots containing V?t from only the laser do not provide any information about the relative sensitivities of the various transistors. Therefore, the fact that one branch is long and another short cannot be used to infer that the long branch is more SET sensitive. Relative sensitivities can only be determined by measuring the laser energies for which the minimum SETs are generated.

VI. Summary and Conclusions

The results reported here provide the first pulse-to-pulse comparison of pulsed laser and high-LET heavy ion single-event transients for a linear bipolar part. These results confirm that the pulsed laser may be used to identify SETs that might 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 SET width. The good agreement reported here suggests that the apparent shortcomings of the pulsed laser, i.e., small 1/e penetration depth and metal covering some sensitive areas are of no consequence for this type of investigation.

VII. REFERENCES

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