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ALPHA, BORON, SILICON AND IRON ION INDUCED CURRENT TRANSIENTS IN LOW CAPACITANCE SILICON AND GaAs DIODES

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Abstract

High-speed (< 40 ps) current transient and charge collection measurements were made using a wide band 70 GHz, 6 ps rise time sampling oscilloscope, on GaAs and silicon diodes irradiated by 18 MeV Si, 12 MeV B, 12 and 100 MeV Fe ions, and 3 and 5 MeV alpha particles. The results show that the response of a device to a particle strike can be very fast but strongly depends on the LET (Linear Energy Transfer) of the particle. The rise time dependence with different parameters such as the doping density, bias, at different energies with different particles, is also presented. The data are then compared to the predictions of existing models.

ROUGH DRAFT

1 Introduction

The charge collection process that follows the passage of a single energetic ion through the active region of a semiconductor device such as memory cell or latch, can change its state without damage to the device. This occurrence is called Single Event Upset (SEU). The ion generates a track of dense ionization which can extend beyond the active depth of the device down into the substrate. Under certain conditions, the electric field applied across the active region can be strongly distorted and extend down into the substrate causing charge to be collected by drift along the ion track. This is known as the funneling effect and is responsible for large increases in device sensitivity to SEU. Charge collection process can occur on a picosecond time scale (both prompt and funnel components). In addition, a slower component produced by diffusion of the carriers towards the depletion region leads to an additional charge. To improve the SEU hardness of semiconductor devices, it is necessary to measure current transients to improve our knowledge of the physics involved, verify and improve existing models and determine input parameters for device modeling.

Previously, we presented the measurements of funneling-current transients produced by alpha particles on 1, 3, 10 Ω-cm silicon diodes using a 14 GHz sampling system [1,2]. In some cases, the results were limited by the bandwidth of this system. We have since refined and expanded these measurements using a new faster (70 GHz - 6 ps rise time) sampling oscilloscope which uses superconducting Josephson junction technology and includes its own internal superconducting delay line. A new series of experiments has been performed on high-resistivity GaAs devices ($n \sim 10^{16} - 10^{17}$ cm^{-3}) with 18 MeV Si, 12 MeV B and Fe ions and also, on silicon diodes (with resistivities of 1, 3, 10 Ω-cm) with the same ion beams and in addition, 100 MeV Fe ions, and 4 and 5 MeV alpha particles. We present the results of current transients and charge collection measurements.

2 Experimental set-up

The experimental apparatus, presented Fig.1, is similar to the one described previously [2]: the electrical sampling system configuration includes the double-ended diode configuration which allows us to bias the diode on one side and take the signal from the other side, without degradating the response through a bias tee or, for use as a trigger signal.

A 6 ps rise time 70 GHz Hypres sampling oscilloscope with an internal delay-line allowed us to perform the other experiments (Fig.2b).

We found that the operating conditions for the two systems were different. In order to improve these experiments, we studied on both systems, the effects of two experimental parameters on the transient shape: the count rate and the signal amplitude. We found that their influence was critical for the measurement of the rise time with the Tektronix system.

The Tektronix system allows us to sample signals as low as 1 mV and the overall rise time is around 40 ps. However, the measured rise time is strongly dependent on count rate. This was confirmed by a simple experiment. A 3 Ω-cm P type Si diode was bombarded by alpha particles. All the parameters (bias, energy, ...) were fixed and transients have been taken at different count rates in a non-collimated and collimated mode. Table 1 summarizes the results. For 5 MeV alpha particles, the optimum value at 10 - 30 mV signal levels, has been found to be around 1500 – 2000 counts/s. This allows us to take consistent data without serious degradation due to radiation damage.

Jitter and microphonics have a dramatic effect on the shape of the transients. They become more important as the amplitude of the signal decreases. However, if we control the count rate as a function of the signal amplitude, the Tektronix experiments are reliable and reproducible: rise times as fast as 66 ps have been measured on 1 Ω-cm diodes.

Amplitude and count rate measurements have shown the Hypres system to be insensitive to count rate and rise time degradation but, 3 mV signals are required to trigger the oscilloscope and a time window of 500 ps limited our capability to measure long decay time transients. A 3.5 mm diameter semi-rigid microwave coaxial cable of approximately 1 meter, was used to connect the sampling system to the diode. The bandwidth of this cable slowed down the system response. However, the overall rise time was < 30 ps and 30 ps substracted in quadrature have been used to get a more accurate indication of the true transient response.

During our experiments, we found that the data taken near the breakdown voltage were not reliable: the electrical fields applied to the junction are high and the measured rise times slow down due to the onset of avalanche breakdown.

Diode design

Low capacitance Schottky barrier GaAs diode structures have been designed (Fig.3). The diodes are prepared by depositing a 2 μm thick SiO_2 film by low pressure vapor deposition. They are very similar in design to the silicon devices with the exception of the junction type [1,2].

3 Experimental results

Fig.4 displays four current transients obtained respectively from a 1 Ω-cm silicon diode irradiated with 5 MeV alpha particles, 12 MeV B ions, 18 MeV Si ions, 12 and 100 MeV Fe ions and the response of a GaAs device irradiated with 18 MeV Si ions. In all cases, the range of the particles is greater than the depletion width. The total prompt collected charge has been determined by integrating the observed transient, knowing the circuit impedance (50 Ω). The rise time is taken at 10% and 90% of the signal amplitude.

3.1 Silicon devices

Alpha particle experiments

Experimental results obtained with 3 and 5 MeV alpha particles are reported here. The measured transients are faster than the ones reported previously but they exhibit the same trends. Fig.5 compares the present 70 GHz measured rise times versus doping density with the previous 14 GHz data for the same conditions.

For a given beam energy, the higher the doping density, the faster the rise time. Fig.6 displays three transients for three different resistivities under the following experimental conditions: 5 MeV alpha particle energy, 25 V bias voltage.

The measured rise times do not show evidence of a dependency on bias. At low bias, signal amplitudes are low and we are system limited but at higher bias, the rise times do not vary. In a similar way, the experimental rise times measured at 3 MeV are slower than the ones taken at 5 MeV although the difference is around 5 – 10 ps.

We observed that at fixed bias, as the resistivity decreases, the peak amplitude increases since the rise times are getting faster. The amplitude of the current varies with bias and with the energy of the particles: it increases as more charge is deposited in the depletion width. As a consequence, the collected charge increases with bias and is greater in high-resistivity material.

Fig 7 displays two normalized superimposed transients taken at 25 V on two 10 Ω-cm diodes, one being thinned in order to reduce the resistance. They show a discrepancy in the decay time which is shorter for the thinned diode. The possible electrical influence of the diode circuit on the data is being studied.

One of the main interest in the study of SEU is the effect of heavy ions. Heavy particles have a higher LET than alpha particles. Table 1 summarizes the principal characteristics associated with the ions that we used.

Boron ion experiments

12 MeV B ions have a higher LET than 5 MeV alpha particles but lower than 18 MeV Si ions. The diodes did not show signs of radiation damage. As expected, the collection times are slower and doping density dependent: respectively for 1, 3 and 10 Ω-cm diodes biased at 25 V, 56, 60 and 80 ps. The rise times do not vary with bias.

Silicon ion experiments

These experiments showed that the onset of radiation damage was much faster with heavy ions than with alpha particles (Fig.8), although this effect was not obvious with the Boron experiments. A decrease in the peak amplitude occurs with time under the same experimental conditions. As the devices are damaged, a decrease in the rise time occurs. We also found that the 10 Ω-cm devices were radiation damaged much faster than the 1 and 3 Ω-cm devices.

The collection times vary with doping density: measured rise times are faster on heavily doped material, respectively for 1, 3 and 10 Ω-cm diodes biased at 50 V, 48, 84 and 120 ps, higher than what have been measured with alpha particles. In contrast to the alpha and boron ions results, we note a dependency of rise time with bias: it gets slower as the bias is reduced although the system resolution is limited with decreasing amplitude: respectively for 1, 3 and 10 Ω-cm diodes biased at 25 V, 76, 104 and 144 ps (Fig.9). We will comment this behaviour further.

Iron ion experiments

Two different energies have been used for these transient measurements: Fig.10 displays two superposed transients at 12 and 100 MeV for a 1 Ω-cm diode.

- 12 MeV experiments: results were only obtained for 1 Ω-cm devices: the particles were stopped in the depletion width of the 3 and 10 Ω-cm diodes. The same trends for Si ions are observed with Fe ions: fast degradation of the diode characterized by a decrease of rise time and a dependency of rise time with bias.

- 100 MeV experiments: these experiments increased the problem of radiation damage. A compromise had to be found between count rate and the preservation of the diode. It was determined empirically that a count rate of 100 counts/s was sufficient to get good system resolution. However, at this count rate, radiation damage could be detected by a decrease in the amplitude of the signal in less than 2 minutes and was doping density dependent. The amplitude of the signal into the 50 Ω circuit impedance was just under 500 mV. Experiments were made on 1, 3 and 10 Ω-cm diodes. Initial measurements were made uncollimated on 10 Ω-cm devices at a dose > 10o ions/s. Radiation damage reduced the amplitude by a factor of 10 in approximately 1 minute: no useful data were collected on these devices.

The transient taken at 100 MeV shown on Fig.10, exhibits two features: a slow rise time component of 238 ps and a tail with a decay time of ~ 500 ps. When the bias on the diode was changed from 50 to 10 V, the rise time increased to 360 ps and the decay time to 600 ps. The results obtained at different bias for different substrates, show all a bias dependent rise time. They range in the 200 – 450 ps, increasing with lower bias.

3.2 GaAs devices

Experiments have been made on GaAs with 12 MeV B ions, 18 MeV Si ions and 12 MeV Fe ions. Because of the very short lifetime of the minority carriers and the higher electron mobility, one can expect some differences in the behaviour of this material under irradiation.

Boron ion experiments

The diodes did not get radiation damaged at this energy with these ions. The measured rise times are ~ 36 ps.

Silicon ion experiments

The GaAs devices were highly sensitive to radiation damage, causing the signal height and the rise time to decrease with successive transients. A 40% reduction in the signal was observed for an estimated dose of $4 \cdot 10^9$ ions/cm^2. For this reason it is hard to say if the results display a dependency of rise time with bias. Fig.11 shows a current transient produced by 18 MeV Si ions in a GaAs Schottky barrier diode biased at 5 V. The measured rise time was 34 ps.

Iron ion experiments

Similar behaviour has been found when a GaAs diode is exposed to 12 MeV Fe ion beam. The measured rise times are also in the range of the 35 ps.

4 Discussion

The results of these different measurements are presented in Fig.12–15. A first difference to what have been previously published [2], is the use of heavy ions. The signals obtained with higher LET particles are different in shape from those obtained with alpha particles (Fig.4). In the late case, the transients display a fast component (40 ps for a 1 Ω-cm diode biased at 45 V) and a slow diffusion tail with a total decay time of ~ 400 ps which is composed by a fast component of ~ 170ps and a slower one extending over 230 ps. However, with Si or Fe ions, the rise time is slower (48 ps for a 1 Ω-cm diode irradiated with 18 MeV Si ions) and the transients tend to be broader on the descending edge with a less sharp transition. In most of cases, the decay times have been estimated because the time window of the Hypres system did not allow us to record long decay times. This suggests that the electrical field is able to remove most of the carriers in the case of light particles and then, a slow diffusion process can take place. With heavy ions, because the amount of carriers created in the sensitive area is so large and because the collection process has been delayed by the plasma, the final carriers are removed slowly.

The data presented on Fig.12a clearly show the rise time dependency with both doping density, whatever the incident particle is, and the LET of the particle. There is a significant difference between the results obtained for alpha particles, B, Si or Fe ions. The measured rise times vary with the LET of the particle, and consequently with particle type. The heavy ions have a higher LET than the alpha particles: a dense plasma of electrons and holes is created along the track and may delay the start of the charge collection process. The higher the LET, the denser the plasma, possibly the stronger the shielding effect and the slower the rise time [3,7]. The energy lost by a light particle along its path creates a high density of electron-hole pairs. After thermalization, these carriers are confined in a column at a density higher than the substrate doping density. Inside the depletion width and near the outer edge of the column, the holes created neutralize the acceptors of the P type area while the electrons are attracted by the positive electrode. The potential across the depletion area drops and the field is redistributed along the track. During the same time, the plasma column expands radially by ambipolar diffusion. When the density on the outer edge of the column reaches the background density, charge separation occurs: the electrons drift towards the positive potentials and the holes the negative ones. The electric field continues to collapse into the substrate: additional carriers can be collected by drift. When the generated carriers density inside the track is comparable to the substrate doping density, the junction reestablishes itself, the electric field relaxes back to its original position. The remainder of the charge is slowly collected by diffusion.

In the case of heavy ions with high LET, the charge collected is less than what is expected and the collection time is longer. The electric field could be reduced and the consequent potential drop would not be as high as with small LET or long range particles. This can occur if the plasma density is very high. Moreover, because the stopping-power of heavy ions decreases with energy, the charge density will be higher at the beginning of the track than at the end. This density could be high enough to prevent the charges down in the track from seing the electric field when charge separation occurs. As collection gradually occurs, the plasma is eroded and the junction is reestablished. The slow diffusion process can take place.

This increase in the collection time may have an influence on the amount of collected charge as follow. The diodes are severely radiation damaged under heavy ion beams. Crystalline defects are created and act as recombination centers for the carriers. In addition, in some materials such as GaAs, the carrier lifetime is very short and recombination can occur. In consequence, this charge is not collected.

The GaAs transients are different in shape and time characteristics from the Silicon transients (Fig.4). The measured rise times are very fast ($\sim$ 30 ps), a kind of shoulder is observed on the back edge of some transients and the diffusion tail extends to only $\sim$ 140 ps. These discrepancies come from the fact that in GaAs the mobility of the carriers is higher than in Silicon and that, due to their very short lifetime, recombination can occur. However, the GaAs data presented Fig.12b show the same trend as far as the dependency of rise time with LET is concerned.

5 Conclusion

These measurements with alpha particles, Si, Fe and B ions at different energies were used to determine the effects of particles with differing LET. The rise time and decay time of the current transients were shown to depend on the electrical field range and the LET of the ionizing particle: the rise time of the transient increased with LET.

This work represents the fastest charge collection measurements made to date. The results will potentially have a large impact on the modeling of SEU phenomena and the physical processes therein.

References

[1] R. S. Wagner, J. M. Bradley, C. J. Maggiore, J. G. Beery, R. B. Hammond, "An Approach to Measure Ultra-Fast Funneling Current Transients"; IEEE Transactions on Nuclear Science, Vol. N5-33, 1651-1655 (December 1986).

[2] R. S. Wagner, J. M. Bradley, Nicole Bordes, D. N. Sinha, C. J. Maggiore, R. B. Hammond, "Transient Measurements of Ultra-Fast Charge Collection in Semiconductor Diodes"; IEEE Transactions on Nuclear Science, Vol. N5-34, N . 6, 1640-1245 (December 1987).

[3] W. Seibt, K.E. Sundstrom, P. A. Tove, "Charge Collection in Silicon Detectors for Strongly Ionizing Particles"; Nuclear Instruments and Methods 113 (1973) 317-324.

[4] R. N. Williams, E. M. Lawson, "The Plasma Effect in Silicon Semiconductor Radiation Detectors"; Nuclear Instruments and Methods 120 (1974) 261-268.

[5] E. C. Finch, "Charge Plasma Erosion for Short-Range Partially and Totally Stripped Ions Stopped in Silicon Radiation Detectors"; Nuclear Instruments and Methods 121 (1974) 431-437.

[6] E. C. Finch, A. A. Cafolla, M. Asghar, "The Plasma Decay Time in Semiconductor Detectors for Energetic Heavy Ions"; Nuclear Instruments and Methods 198 (1982) 547-556.

[7] C. F. G. Delaney, E. C. Finch, "Rise and Plasma Times in Semiconductor Detectors"; Nuclear Instruments and Methods 215 (1983) 219-223.

FIGURE CAPTIONS

Figure 1 Single Event Upset (SEU) experimental configuration

Figure 2 Sampling system configurations

a- 14 GHz Tektronix sampling system

b- Hypres sampling system

Figure 3 GaAs Schottky barrier diode

Figure 4 Response of a 1 Ω-cm Silicon and high-resistivity GaAs diode

Figure 5 5 MeV alpha particles Silicon diode – 25 V bias

Figure 6 5 MeV alpha particles in Silicon diodes

Figure 7 Response of 10 Ω-cm Silicon thinned and unthinned diodes

Figure 8 1 Ω-cm Silicon diode before and after radiation damage

Figure 9 18 MeV Si ions in Silicon diodes

Figure 10 12 and 100 MeV Fe ions in 1 Ω-cm Silicon diodes

Figure 11 18 MeV Si ions in GaAs diodes

Figure 12 Rise times as a function of doping density for different particles

a- Silicon diodes

b- GaAs diodes

Table 1 Experimental parameters with the Tektronix sampling system

Table 2 Range of alpha, Fe, B and Si ions at different energies in Si and GaAs

Tom Wagner
15 June 88

SINGLE EVENT UPSET (SEU) EXPERIMENTAL CONFIGURATION

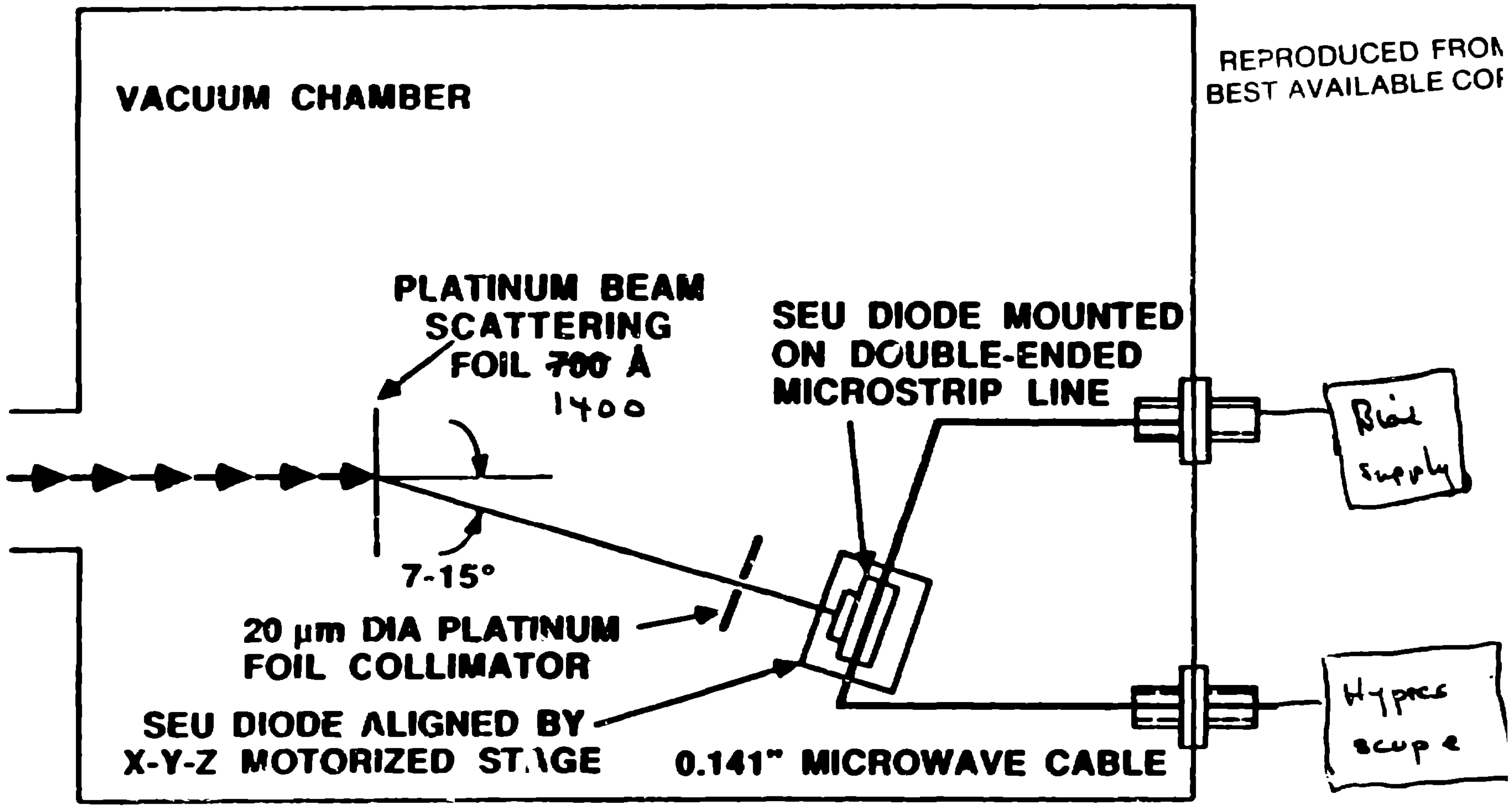

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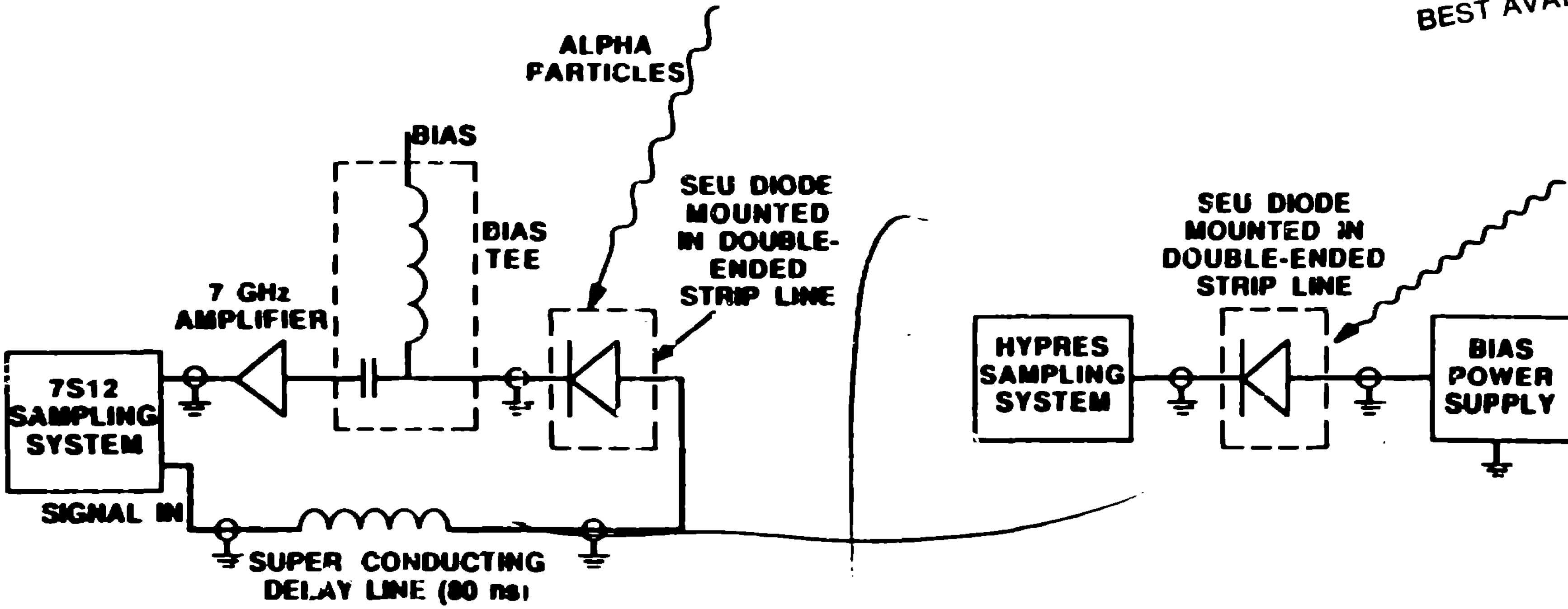
Fig 1

SAMPLING SYSTEM CONFIGURATIONS



(a)

14 GHz TEKTRONIX SAMPLING SYSTEM

(b)

HYPRES SAMPLING SYSTEM

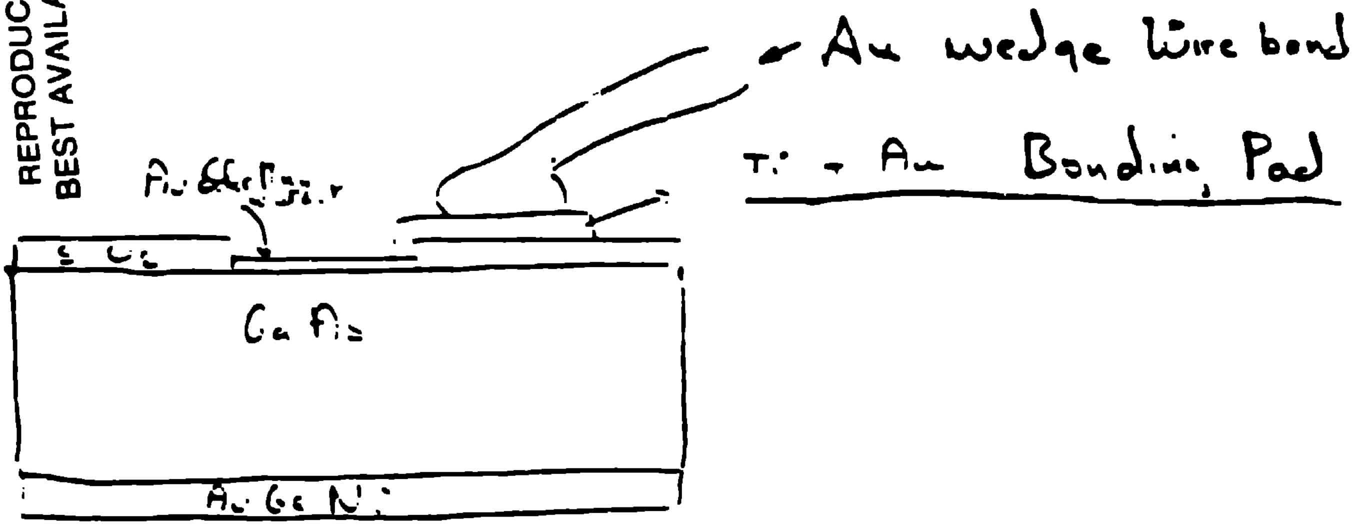


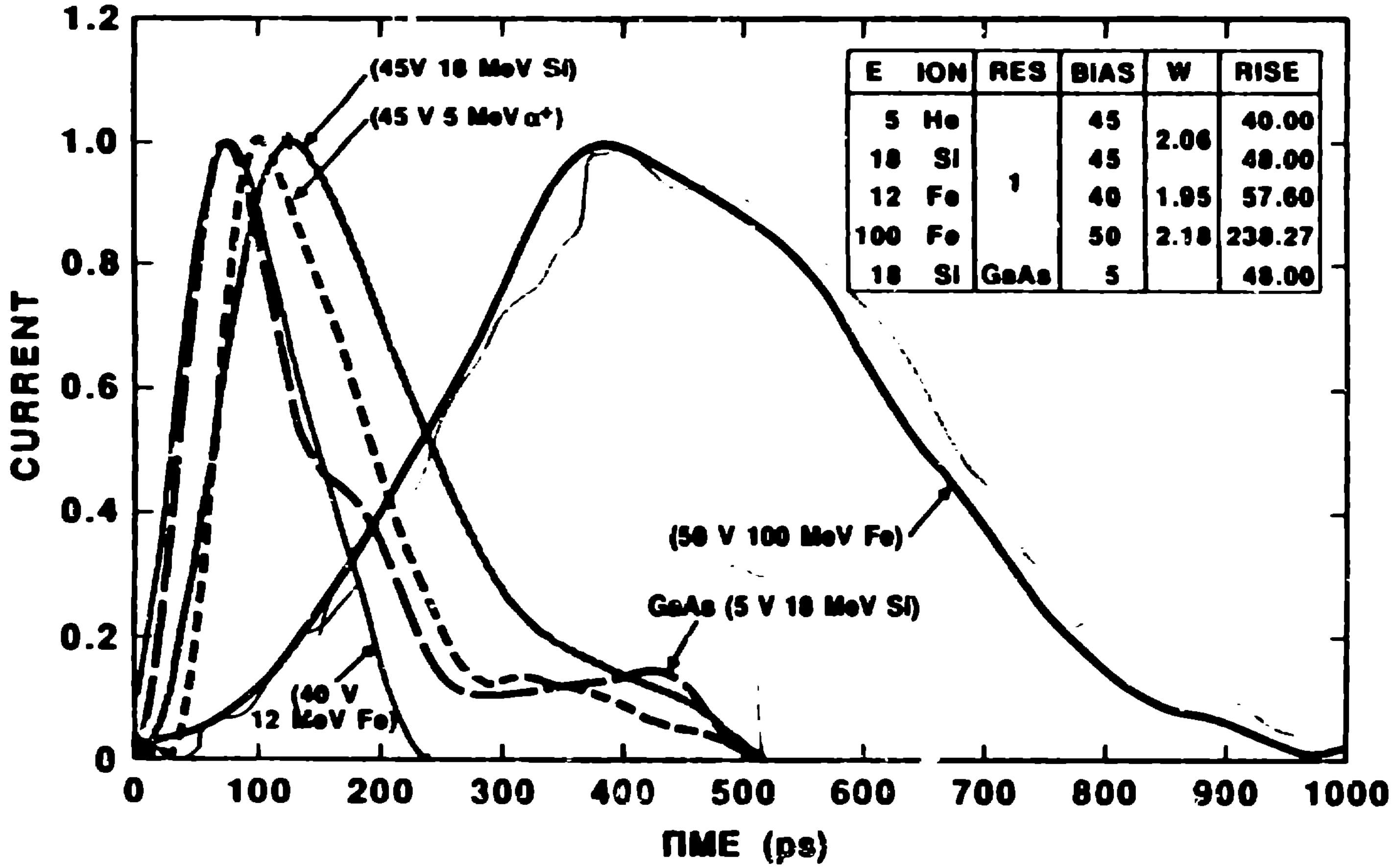
fig 3

Combine with microstrip diagram.

H Si

H Si

RESPONSE OF 1 Ωcm SILICON AND HIGH RESTIVITY GaAs DIODES



E	ION	RES	BIAS	W	RISE
5	He	1	45	2.06	40.00
18	Si		45		48.00
12	Fe		40	1.95	57.60
100	Fe		50	2.18	238.27
18	Si	GaAs	5		48.00

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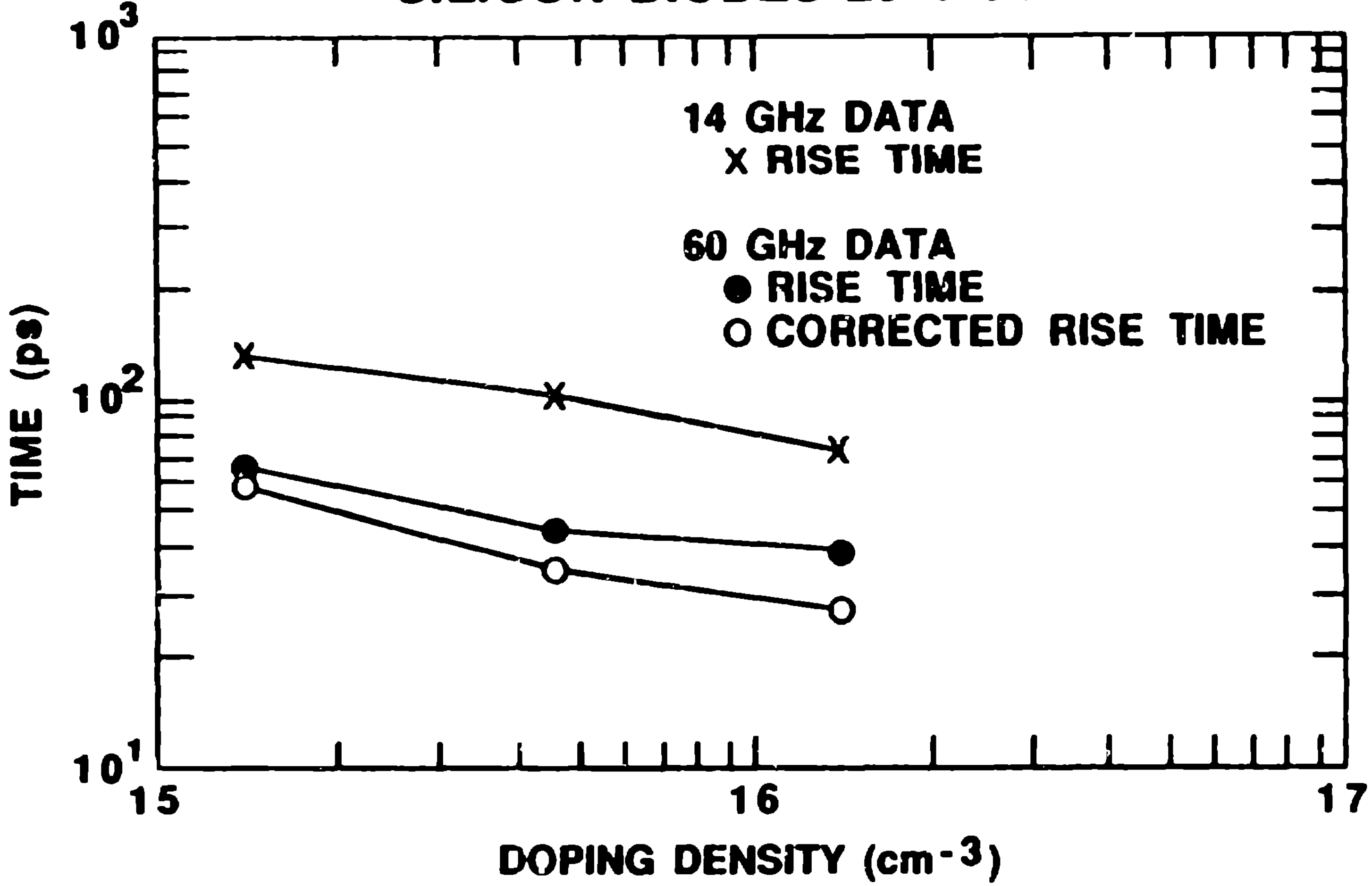
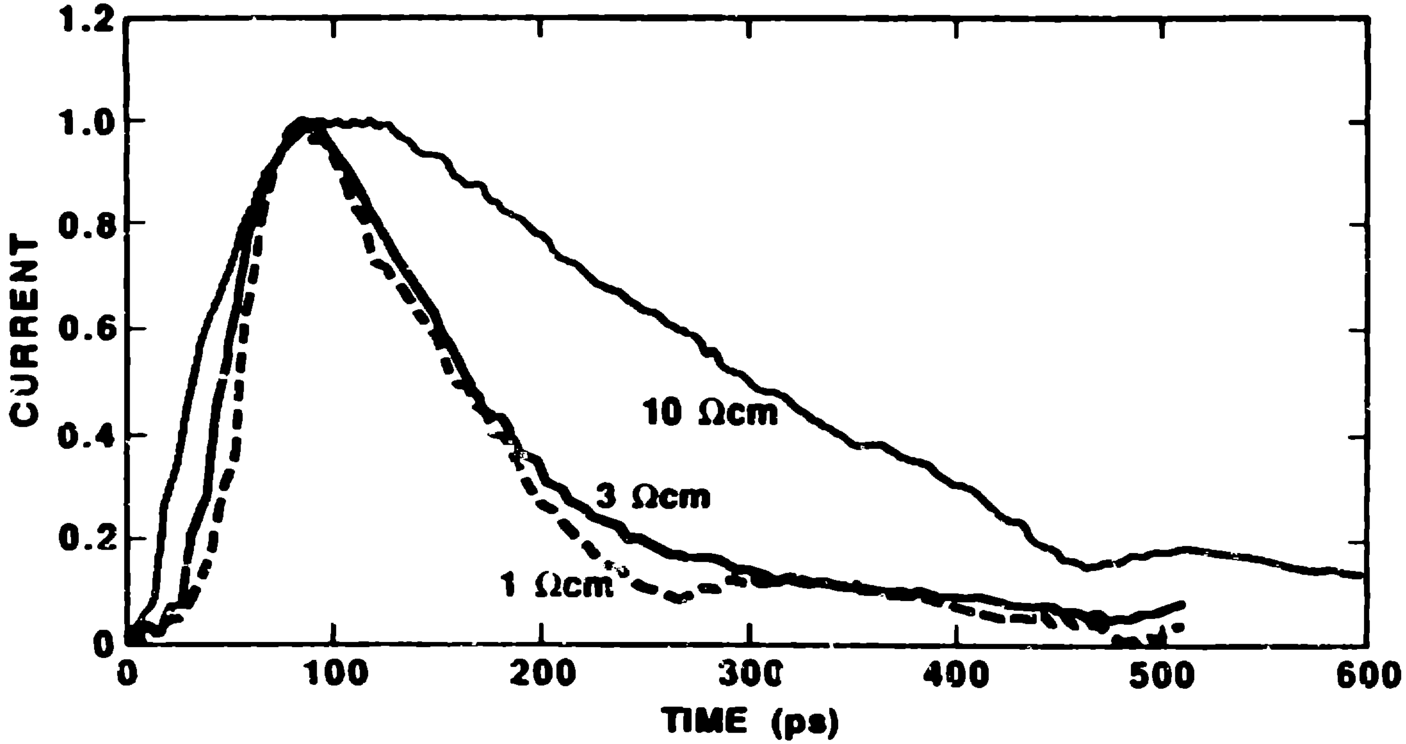
5 MeV ALPHA PARTICLES, SILICON DIODES 25 V BIAS



5 MeV ALPHA PARTICLES IN SILICON DIODES



E	ION	RES	BIAS	W	RISE	Q COLL	I	T PEAK	DECAY
		1		1.54	36.00	38.07	292.00	88.00	152.00
5	He	3	25	2.67	40.00	46.12	299.49	92.00	244.00
		10		4.86	56.00	73.95	269.02	104.00	375.00

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Fig. 6

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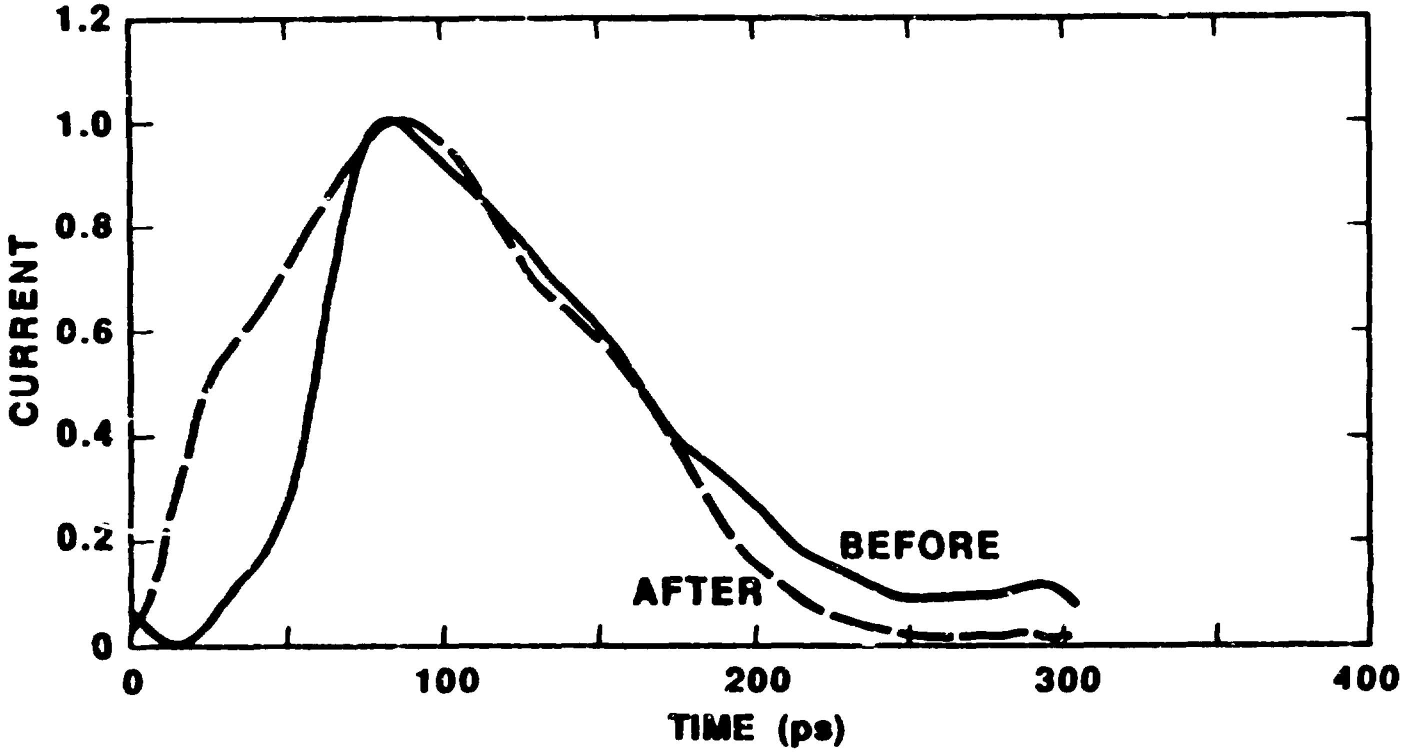
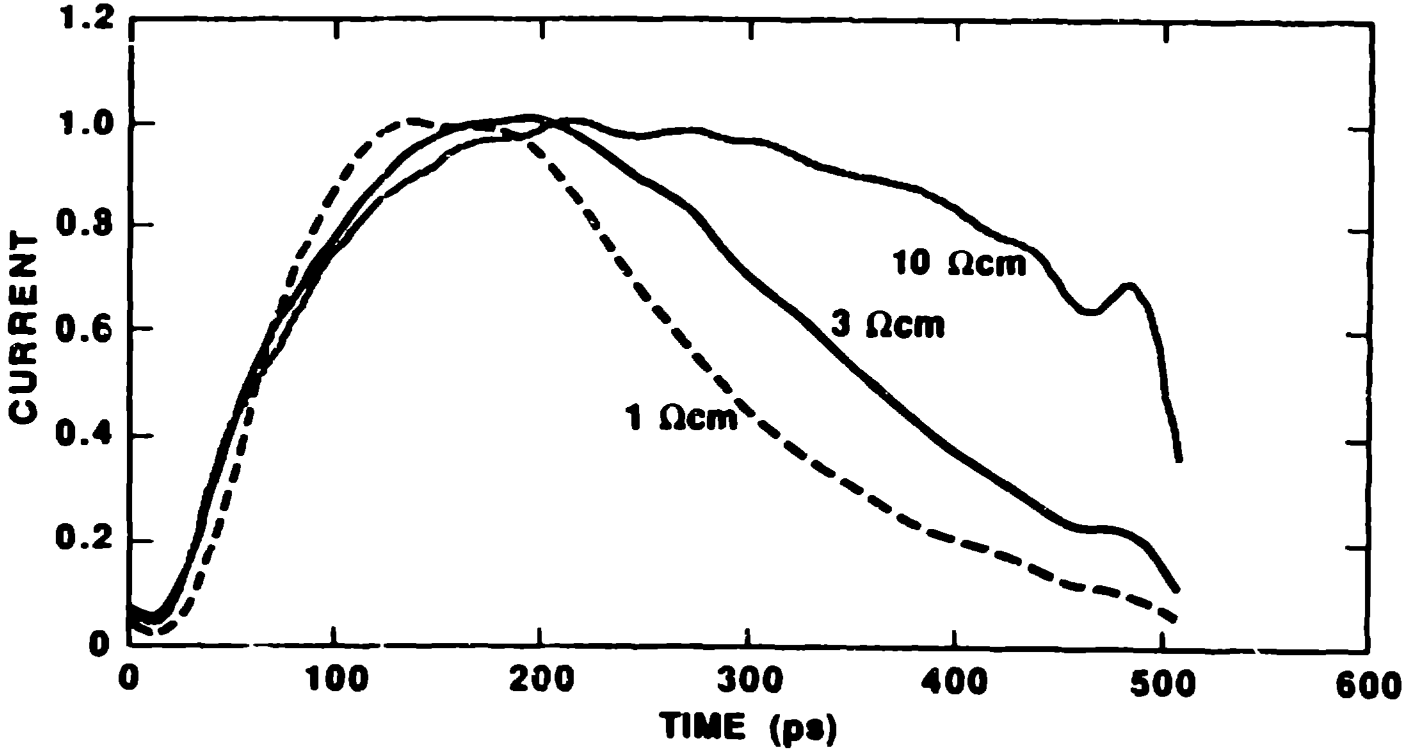
1 Ωcm SILICON BEFORE AND AFTER RADIATION DAMAGE



E	ION	RES	BIAS	W	RISE	Q COLL	I	T PEAK	DECAY
12	Fe	1	30	1.69	64.80 40.00	113.48 50.40	909.15 441.95	88.80 84.00	100.80 134.40

18 MeV SI IONS IN SILICON DIODES



E	ION	RES	BIAS	W	RISE	Q COLL	I	T PEAK	DECAY
		1		1.54	76.00	297.95	1239.67	140.00	248.00
18	Si	3	25	2.67	104.00	332.28	1157.81	196.00	264.00
		10		4.86	144.00	>230.00	599.30	216.00	>152.00

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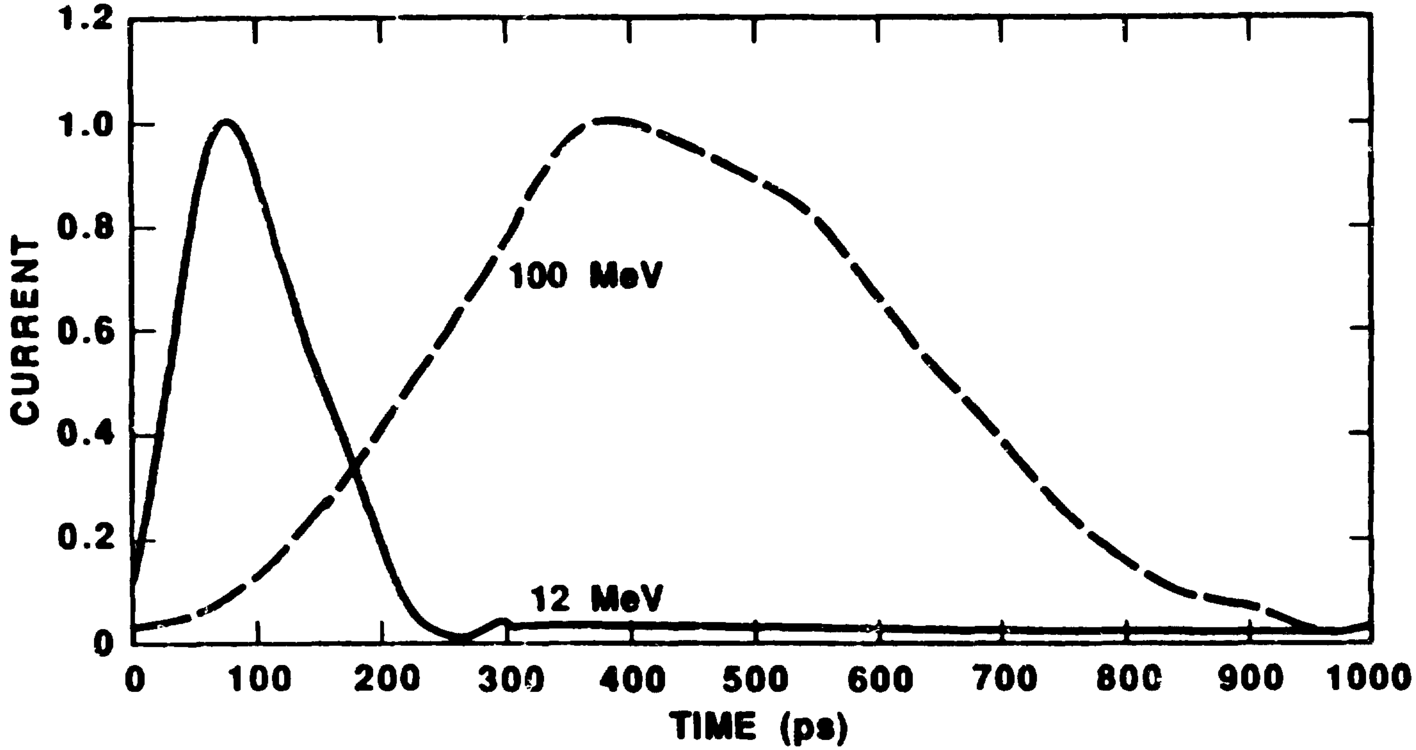
12 AND 100 MeV Fe IONS IN 1 Ωcm SILICON DIODES



E	ION	RES	BIAS	W	RISE	Q COLL	I	T PEAK	DECAY
18	Fe	1	40	1.95	60.00	127.80	1081.57	76.80	115.20
100	Fe		50	2.18	238.27	4151.20	9497.94	386.69	341.77

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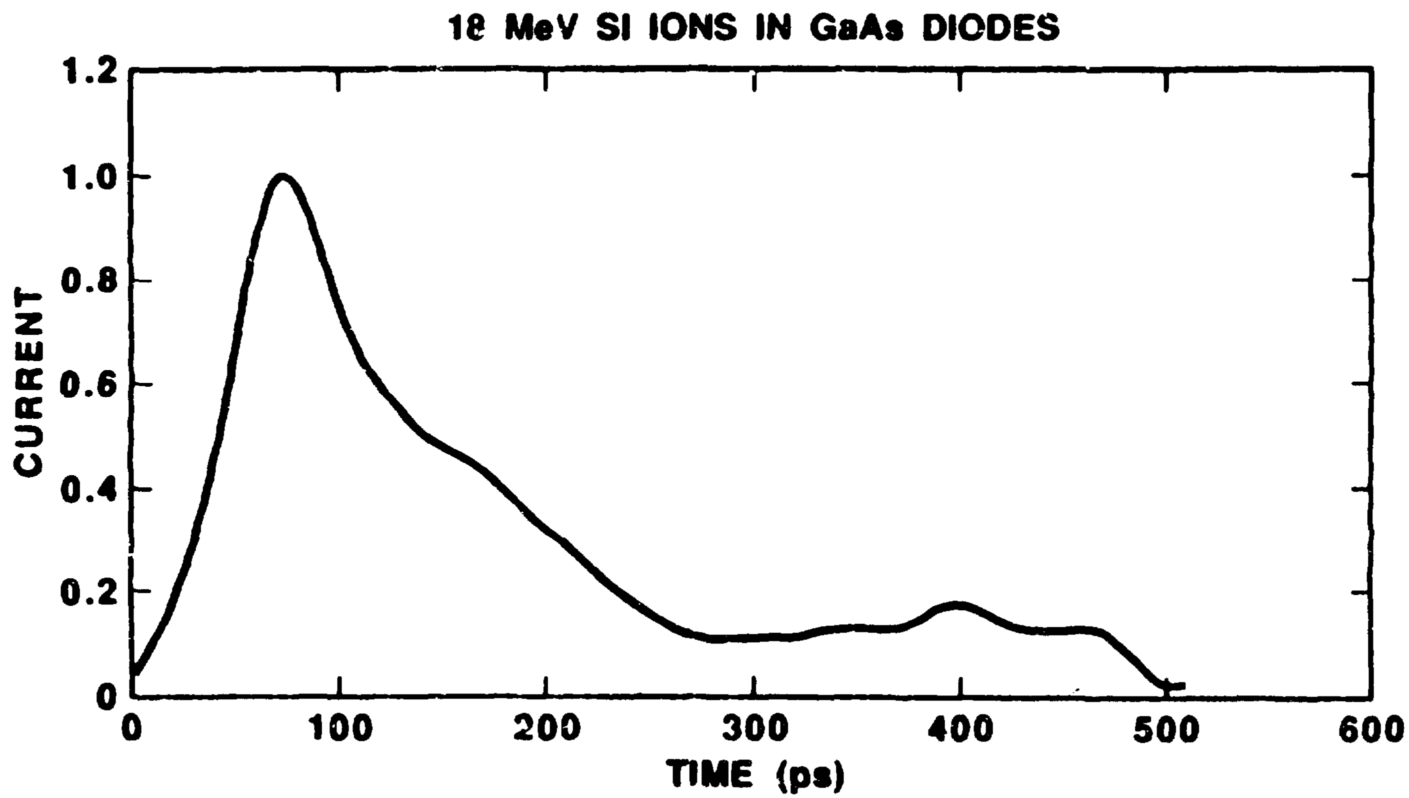

E ION	RES	BIAS	W	RISE	Q COLL	I	T PEAK	DECAY
18 SI	GaAs	5		48.00	136.25	958.11	76.00	180.00

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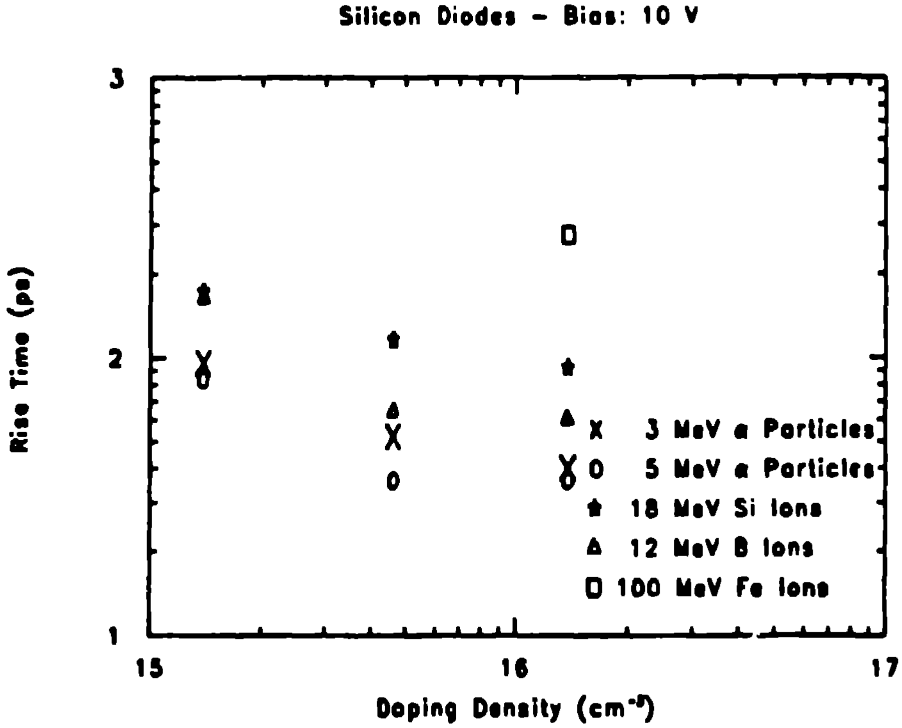
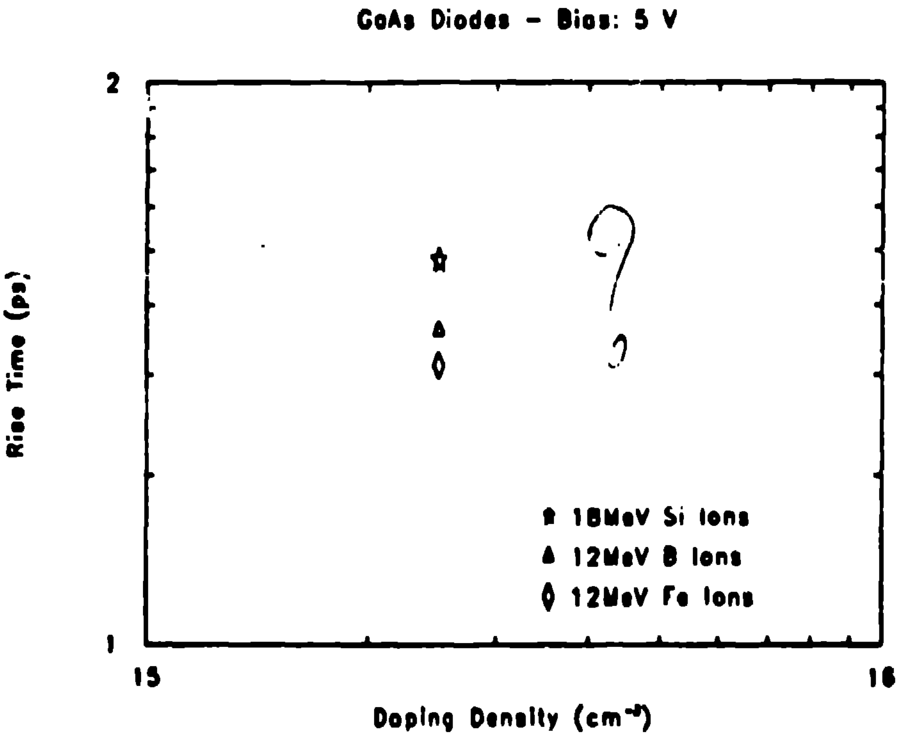

Silicon Diodes - Bias: 10 V
3
2
1
Rise Time (ps)
15
16
17
Doping Density (cm⁻³)
X 3 MeV α Particles
O 5 MeV α Particles
18 MeV Si Ions
Δ 12 MeV B Ions
□ 100 MeV Fe Ions


GaAs Diodes - Bias: 5 V
2
1
Rise Time (ps)
15
16
Doping Density (cm⁻³)
18MeV Si Ions
12MeV B Ions
◊ 12MeV Fe Ions

	Uncollimated		Collimated	
Count Rate (cts/s)	300	2000	300	1000
Rise Time (ps)	255	120.8	178	78
Amplitude (mV)	19	18.65	14	13.64

		(MeV)	(MeV)	(microns)	(MeV/(mg/cm2))
SILICON	Alpha	3	2.92	11	0.86
		5	4.93	23	0.63
	Boron	12			3.40
	Silicon	18	16.2	6.3	13.74
	Iron	12	9.75	3.6	13.43
		100	95.6	17	30.04
GaAs	Boron	12			
	Silicon	18	16.2	5.5	
	Iron	12	9.75	3.3	