N63-15126

Paper B-4

THE EFFECTS OF PROTONS ON SEMICONDUCTOR DEVICES

William C. Honaker*
NASA Langley Research Center

Abstract

15126

Experimental results are presented covering the data obtained from the bombardment of several transistors with 40 and 440 Mev protons. The data indicated a proton energy as well as a transistor frequency dependence on degradation. Figures are presented showing relative degradation of transistors with integrated flux.

Introduction

The presence of high-energy protons in the earth's radiation belts and in solar flares poses a problem in the design of circuits utilizing transistors for space application. The flux above an energy of 25 Mev in the inner belt is approximately 2.5×10^4 protons/cm^2/sec with the differential energy spectrum varying as $E^{-3.4}$. The proton energy ranges up to approximately 600 Mev (refs. 1 and 2). The proton flux in an extreme solar flare may be as high as 10^6 protons/cm^2/sec. In some high-energy events the proton energies extend into the billion electron volt (Bev) range (ref. 3).

Damage produced in solids by charged-particle bombardment has been considered theoretically in references 4 and 5. Most of the theory for such damage has been arrived at by using pure-element models with no definite correlation existing with a transistor junction; thus, a definite need for experimental data exists. This report presents data obtained during experimental testing of several types of transistors. If transient damage effects such as ionization are neglected, the primary damage produced in pure silicon and germanium is the creation of Frenkel defects (vacancy-interstitial pairs). This is the vacancy created by knocking an atom from its normal lattice site and having it come to rest at an interstitial position within a lattice structure. The defects that are formed affect the electrical characteristics of a semiconductor by providing recombination and trapping sites which can reduce the number of carriers and result in a decrease in carrier lifetime (refs. 6 and 7).

---

*Aerospace Technologist.

Only a limited amount of work has been accomplished with protons in the study of radiation damage on semiconductors (ref. 8). Results of bombardment with 40 and 440 protons presented in the present report show the extent to which transistors are damaged when they are subjected to a total proton flux in the order of 10^{12} protons/cm^2. With a knowledge of the proton spectrum in the radiation belts and in solar flares, an estimate can be made of the lifetime of the various transistors subjected to these environments.

Apparatus and Procedure

University of Minnesota Test

A total of 75 transistors were irradiated with 40 Mev protons by utilizing the linac accelerator at the University of Minnesota. The accelerator is capable of producing a time-average beam current of 10^{-8} amperes (approximately 6×10^{10} protons/sec). The cross-sectional area of the proton beam is approximately 1.25 square centimeters.

The experimental setup used during irradiation tests at the University of Minnesota is shown in figure 1. The transistors were mounted in individual ports on an aluminum disk and were remotely positioned in the proton beam. A cam-controlled electric motor automatically positioned each transistor in the proton beam for 10 minutes at a beam flux rate of 3×10^9 protons/cm^2/sec or a total flux of 1.8×10^{12}. A zinc sulfide phosphor (silver activated) was placed on the aluminum disk in a position corresponding to that of the transistors and was alined with the proton-beam pipe exit. The center of the proton beam was visually located by using a closed-circuit television system to determine the location of the beam-excited portion of the phosphor. By marking the excited portion on the television monitoring screen, each transistor could be properly positioned within the marked area corresponding to the proton beam. During the experiments, the beam flux was monitored by means of a Faraday cup mounted behind the transistors. Periodic checks were made on the beam flux level through a vacant space in the aluminum disk.

During irradiation the transistors were operated in an active circuit. The transistor parameters which were monitored and recorded on a direct-writing oscillograph recorder included collector current, I_C; small-signal current gain, h_{fe}; and leakage current, I_{CBO}. The base current I_B was held constant during the irradiation. Pretest and post-test measurements on each type of transistor were made both at the Langley Research Center (LRC) as well as by the manufacturer, with the exception of the 2N146 and 2N337 transistors for which no manufacturers' data were obtained.

Carnegie Institute of Technology Test

A total of 20 transistors were irradiated by utilizing the 440 Mev proton synchrocyclotron at the Carnegie Institute of Technology. The synchrocyclotron is capable of producing a time-average beam current of 2×10^7 protons/cm^2/sec. The cross-sectional area of the proton beam at the external port is approximately 25 square centimeters.

The method used for exposing the transistors to the beam in this experiment differed from the method used at the University of Minnesota in that the larger cross-sectional area of the beam permitted the irradiation of several transistors at the same time with each bombardment lasting approximately 6 hours. Due to the nonuniformity of the cross-sectional area of the proton beam, a profile survey was made with a scintillation counter. The positions of the various transistors in the beam were carefully determined, and total dosages were arrived at by using the beam-profile plots. The beam current was measured before and during irradiation by using a helium-filled ionization chamber mounted between the beam exit port and the specimen and operated at 2 lb/sq in. above atmospheric pressure. The transistors exposed to the beam were mounted on a bracket supported by a junction box attached to a tripod. The transistor parameters measured before, during, and after irradiation were the same as those of the University of Minnesota experiments except that no manufacturer's data were obtained. Also, the number of transistors irradiated was fewer because of the lower beam flux and the longer irradiation time.

Discussion and Results

Figure 2 shows seven 2N146 (NPN) germanium, low-frequency transistors which were irradiated with 40 Mev protons. The average change in gain was a decrease of 70 percent at a total flux of 1.8×10^{12} p/cm^2, which was found to be typical for low-frequency germanium devices. Figure 3 is a plot of six, 2N743, NPN, high-frequency silicon transistors with small signal current gain plotted against integrated proton flux. The change was about a 12-percent decrease at a total flux of 1.8×10^{12} p/cm^2 or approximately one-sixth the damage sustained by the low-frequency transistor in figure 2. In figure 4 a plot is shown of a 2N337, NPN, silicon low-frequency transistor. This device was damaged by about 85 percent of its original value after a dose of 1.8×10^{12} p/cm^2. The extent of damage was about the same as for the low-frequency germanium device.

To give an idea of the frequency dependence on transistor damage figure 5 shows a 2N1302 transistor having an alpha cutoff frequency of 0.5 megacycle and a 2N224 transistor with an alpha cutoff frequency of 4.5 megacycles. The difference in frequencies here is approximately an order of magnitude and the difference in change in gain is 20 percent. The change would be approximately the same for other orders of magnitude change in frequency but this can also vary with materials and type of junction.

The 2N1302 shown in figure 5 was one of the devices irradiated at both 40 and 440 Mev. Figure 6 shows the relative damage at these two energies for a medium frequency transistor. The relative change at the two energies at 3×10^{11} p/cm^2 was approximately a factor of 3 for this transistor. A comparison can be made between this NPN germanium device and a PNP germanium device shown in figure 7. Figure 7 is basically the same type of plot as figure 6 except that a 2N224, PNP, germanium transistor is irradiated in figure 7. The relative change in the 40 and 440 Mev bombardment again is approximately a factor of 3 at identical fluxes. Note the initial increase in gain and then a decrease. This phenomenon is noticed in PNP germanium junctions but not in NPN germanium junctions.

Table I gives a complete list of transistors bombarded with 40 Mev protons and shows the type junction, material, alpha cutoff frequency and the average change in each transistor gain at a total flux of 1.82×10^{12} protons/cm^2. The averages were arrived at using six or seven transistors at the same proton dose and the changes noted ranged from an increase of 10 percent for the 2N128 PNP germanium transistor to a decrease of 85 percent for the 2N337 NPN silicon device.

For a good comparison between NPN and PNP junction, the second transistor the 2N1302 which changes by 65 percent and the sixth a 2N1303 which changed by 23 percent are nearly the same device except for the type junction; here it is evident that the PNP junction is more resistant to proton irradiation.

In table II, if one can assume a tolerable operating level of 0.7, the original gain of a transistor and a flux of 5×10^4 p/cm^2/sec in the space environment, then the lifetime of the various transistors irradiated is given in the right-hand column which extends from 30 to 418 days.

References

1. Smith, R. V., Fisher, P. C., Imhof, W. L., and Reagan, J. B.: Midas IV Proton Measurement in the Inner Van Allen Belt. [Rep.] 3-77-62-6 (Contract AF 19(604)-8028) Nuclear Phys. Dept., Lockheed Missiles and Space Corp., Feb. 1962.

2. Freden, Stanley C., and White, R. Stephen: Protons in the Earth Magnetic Field. Phys. Rev. Letters, vol. 3, no. 1, July 1, 1959, pp. 9-11.

3. Foelsche, Trutz: Current Estimates of Radiation Doses in Space. NASA TN D-1267, 1962.

4. Seitz, Frederick, and Koehler, J. S.: Displacement of Atoms During Irradiation. Solid State Physics, Vol. 2, Frederick Seitz and David Turnbull, eds., Academic Press, Inc. (New York), 1956, pp. 305-448.

5. Mitchell, E. W. J.: The Effect of Radiation Damage on the Electronic Properties of Solids. British Jour. Appl. Phys., vol. 8, no. 5, May 1957, pp. 179-189.

6. Denny, J. M., and Pomeroy, D.: Radiation Damage and Transistor Life in Satellites. Proc. IRE, vol. 48, no. 5, May 1960, pp. 950-952.

7. Billington, Douglas S., and Crawford, James H., Jr.: Radiation Damage in Solids. Princeton University Press, 1961.

8. Hulten, W. C., Honaker, W. C., and Patterson, John L.: Irradiation Effects of 22 and 240 Mev Protons on Several Transistors and Solar Cells. NASA TN D-718, 1961.

TABLE I

RELATIVE DAMAGE TO Si AND Ge TYPE TRANSISTORS

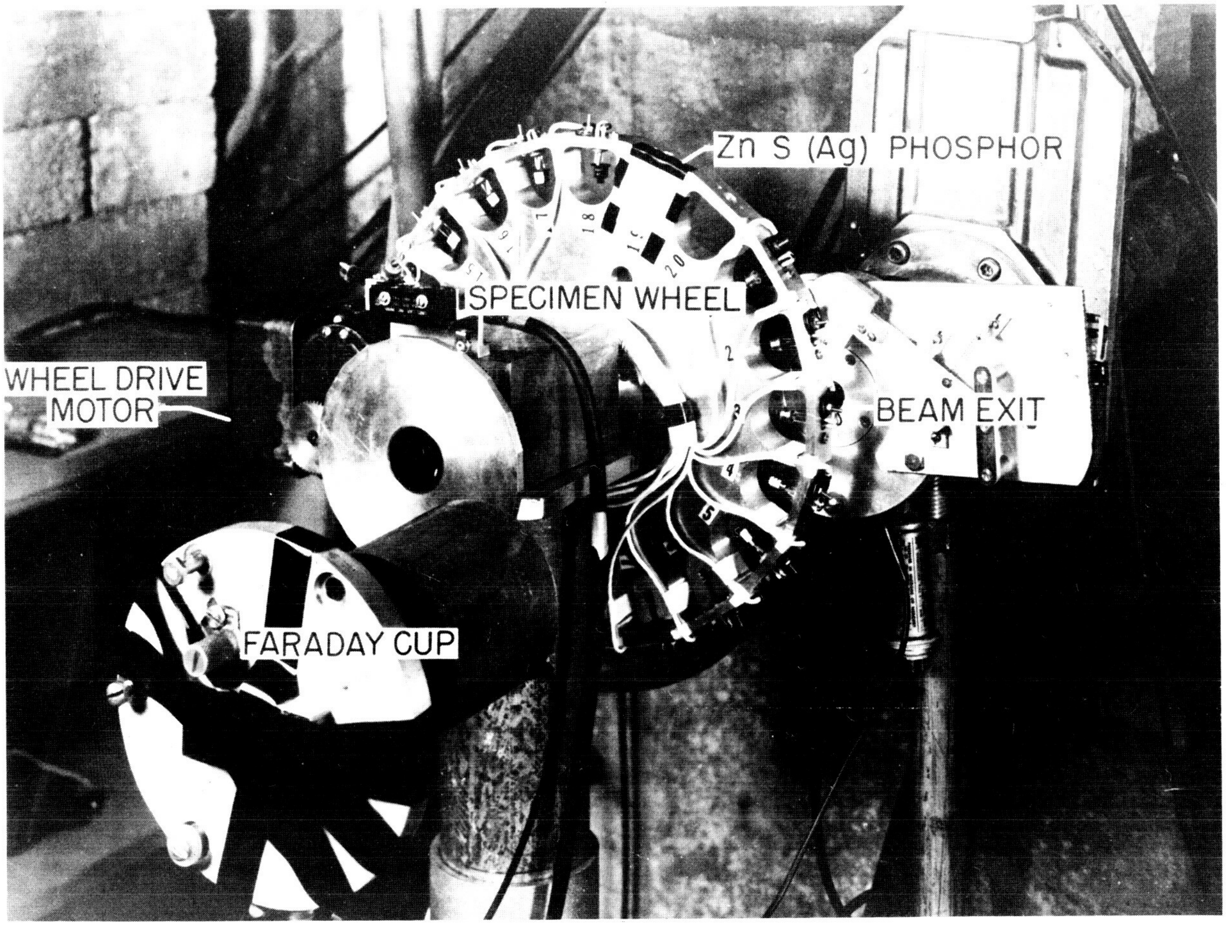
40 MEV PROTONS - TOTAL FLUX 1.82×10^{12} CM^{-2}

TRANSISTOR	TYPE	DESCRIPTION	$f_{\alpha b}$ MC	Δh_{fe} PERCENT
2 N 859	PNP Si	ALLOY JUNCTION	17	78
2 N 1302	NPN Ge	ALLOY JUNCTION	4.5	65
2 N 224	PNP Ge	ALLOY JUNCTION	0.5	85
2 N 1305	PNP Ge	ALLOY JUNCTION	8	65
2 N 1303	PNP Ge	ALLOY JUNCTION	4.5	23
2 N 526	PNP Ge	ALLOY JUNCTION	3	65
2 N 337	NPN Si	GROWN JUNCTION	30	85
2 N 146	NPN Ge	GROWN JUNCTION	13	70
2 N 169A	NPN Ge	RATE GROWN	9	50
2 N 743	NPN Si	DIFFUSED MESA	500	12
2 N 128	PNP Ge	SURFACE BARRIER	60	+10

TABLE II

FLUX TOLERANCE $\frac{h_{fe}(\phi)}{h_{fe}(o)} = 0.7$

TRANSISTOR TYPE	MAXIMUM PROTON FLUX $(10^{11}/CM^2)$	PROTON ENERGY	SIMULATED TIME IN DAYS IN A PROTON FLUX OF 5×10^4 P/cm²/SEC
2N 337	1.3	40 MEV	30
2N 224	1.5		35
2N 146	2		46.5
2N 859	2.5		58.1
2N 1305	5		116.3
2N 1302	5		116.3
2N 526	6.5		151.2
2N 169A	7		162.8
2N 1303	18		418.6
2N 743	>18		>418.6
2N 128	>18	↓	>418.6



NASA
L-62-1017

Figure 1.- Transistor positioning device in the 40 Mev beam.

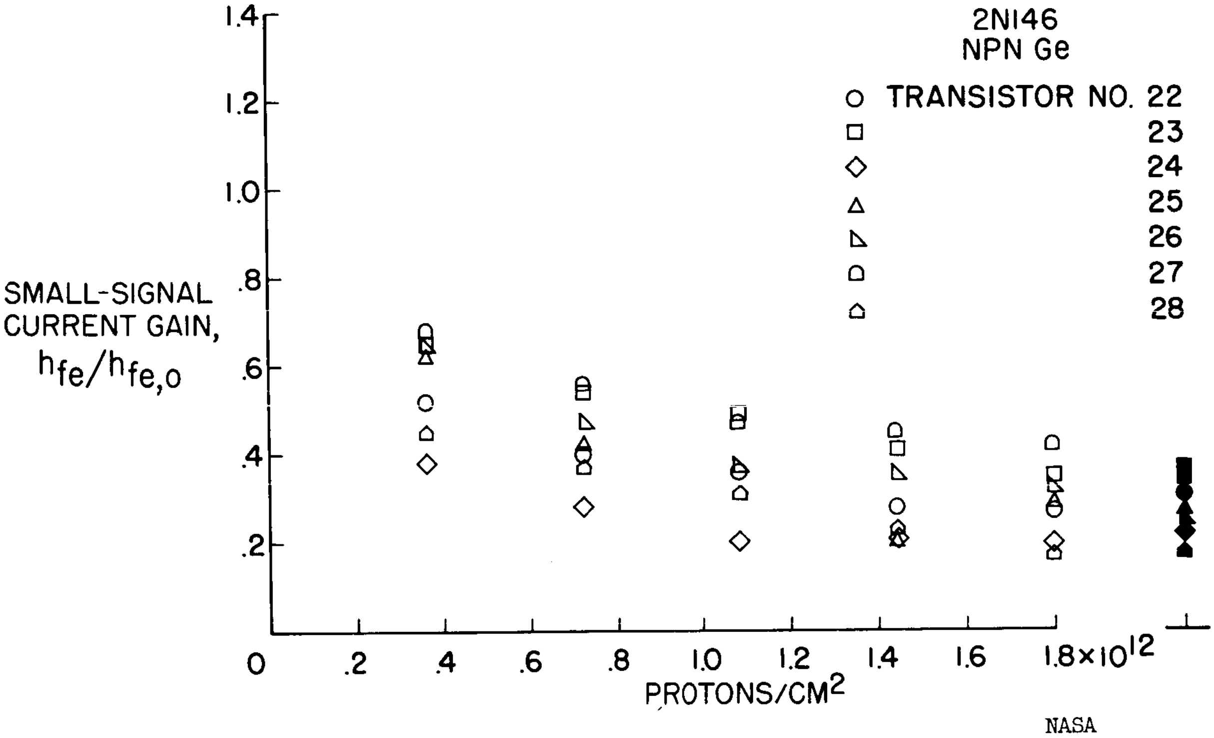


Figure 2.- 40 Mev proton damage.

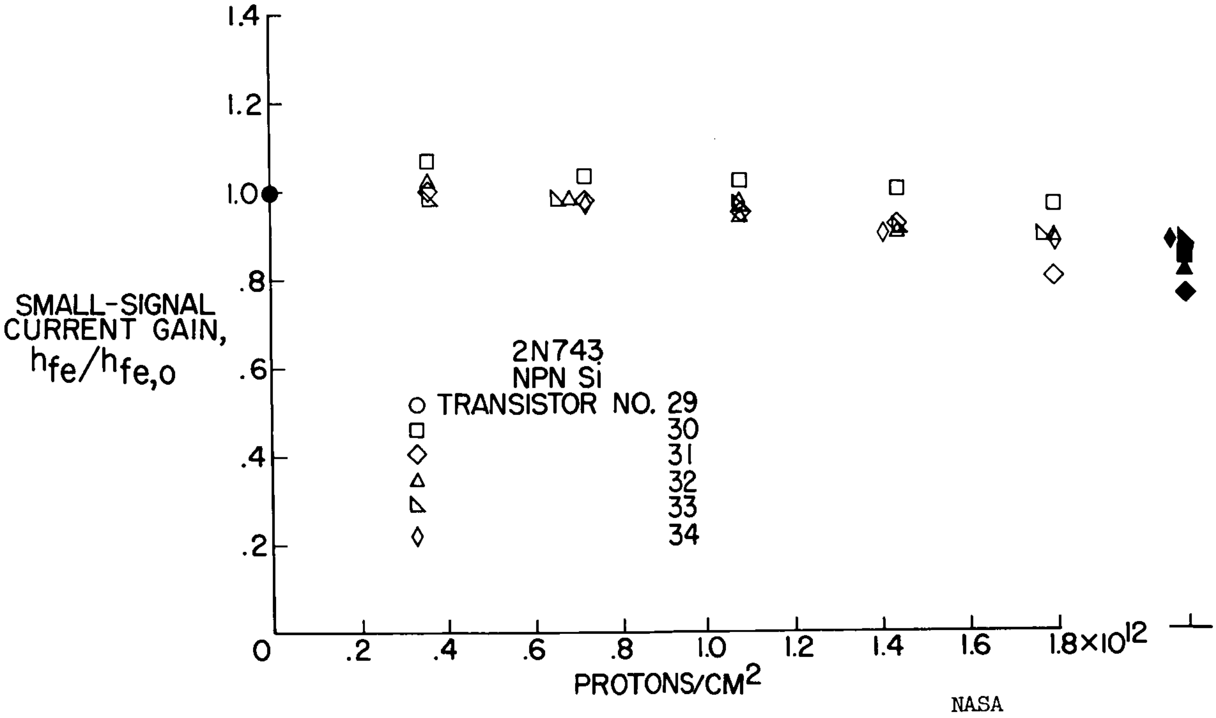


Figure 3.- 40 Mev proton damage.

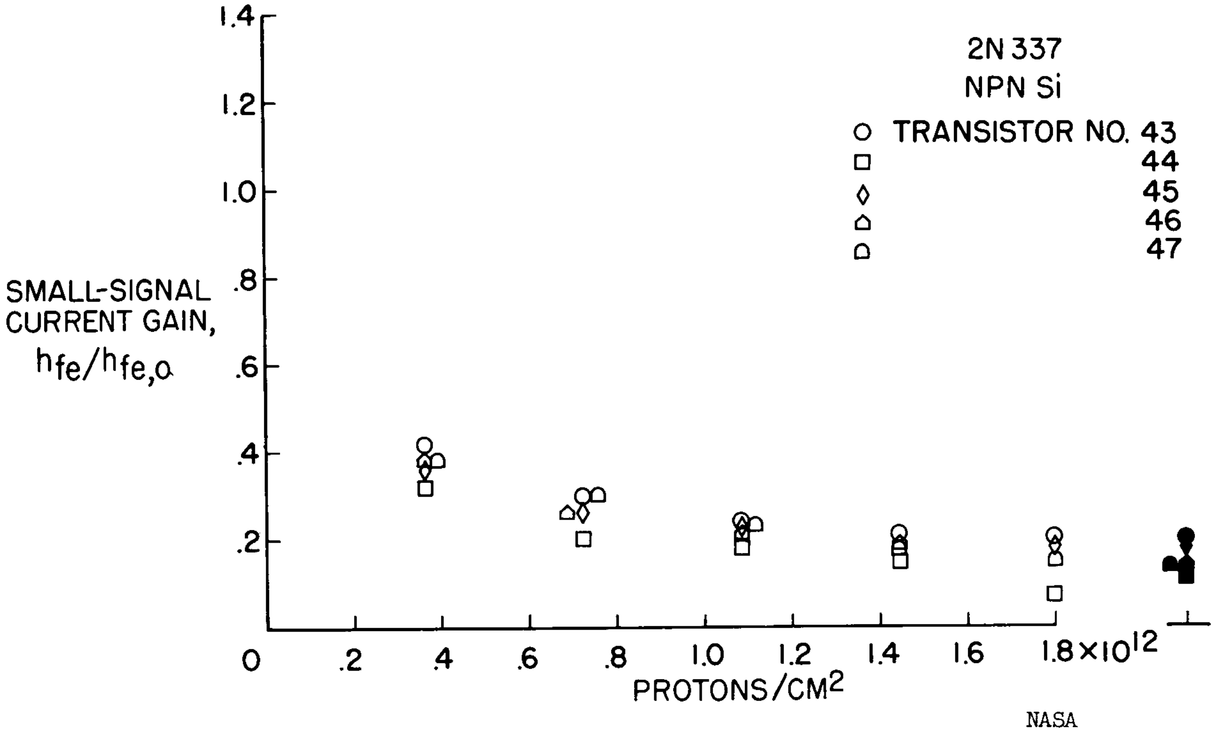


Figure 4.- 40 Mev proton damage.

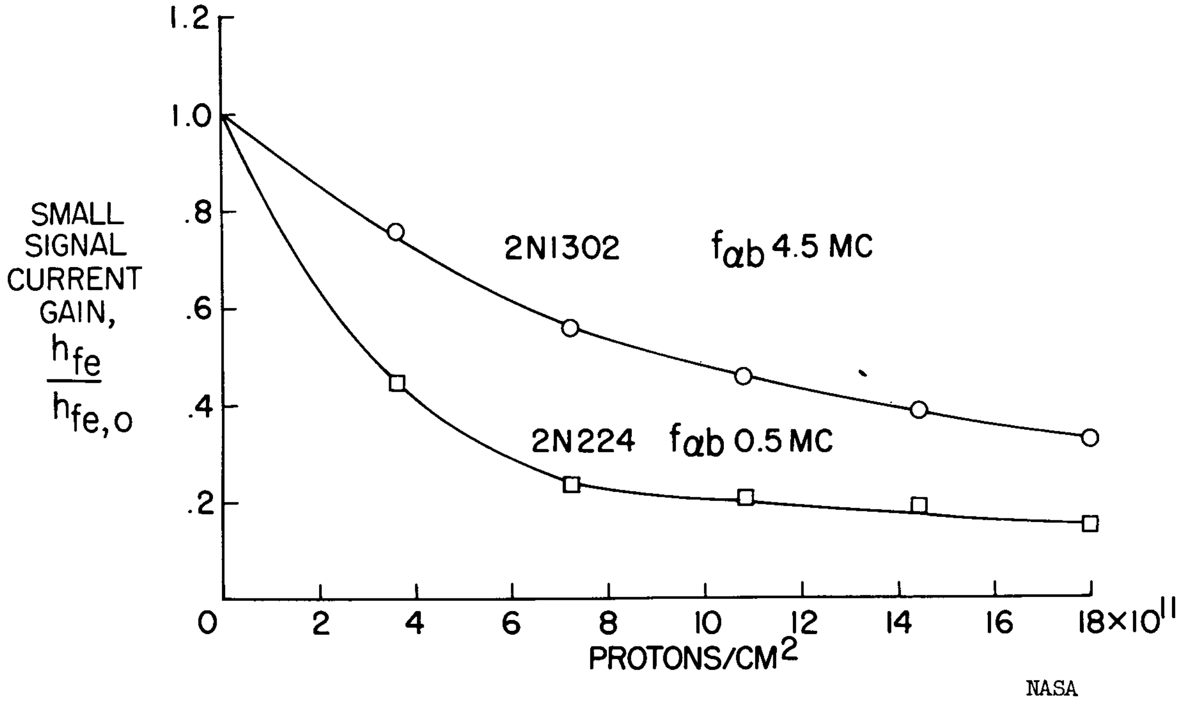
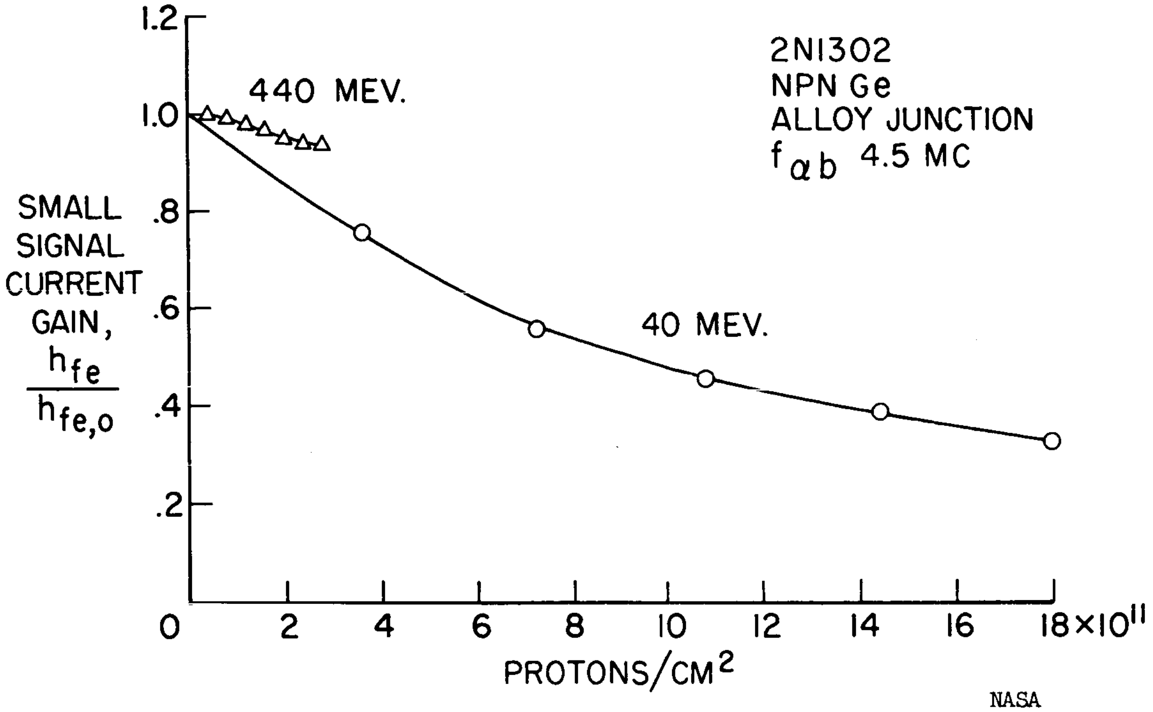
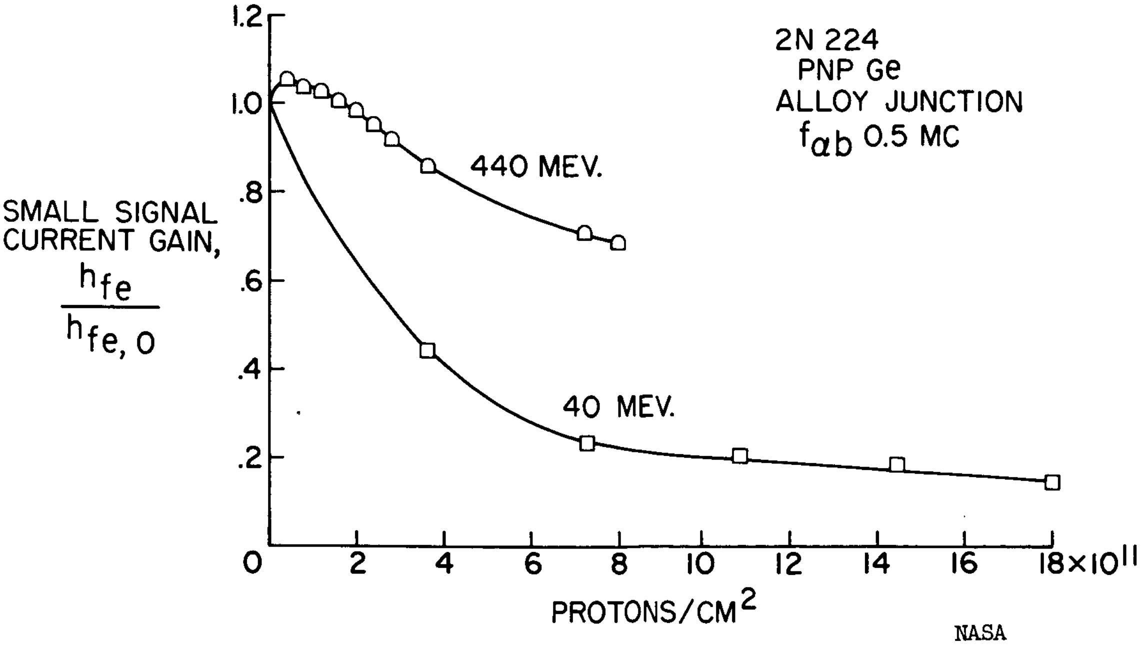


Figure 5.- Proton damage versus alpha cutoff.



NASA

Figure 6.- Proton damage versus energy.



NASA

Figure 7.- Proton damage versus energy.