SECTION 7. DISCRETE BIPOLAR TRANSISTORS

7.1. INTRODUCTION

Bipolar transistors consist of a pair of closely spaced p-n junctions in a single semiconductor structure. The order can be 'NPN' or 'PNP'.

These devices, in both discrete and integrated form, are essential components in many electronic systems, especially in applications (such as in amplifiers) which require a high current gain or considerable "drive" current. Radiation produces degradation of gain and an increase in leakage. The degradation of gain is well understood and derives from degradation of the transport of minority carriers across the base region. We will discuss the effects of electrons, neutrons and gamma rays on this transport, dividing them into those occurring near the surface of the device and those that occur deeper in the material, i.e. bulk effects. In this chapter, we discuss the basic effects with reference to discrete silicon planar transistors. In this structure (see Fig. 7.1), the silicon substrate forms the collector region. Base and emitter regions are formed by the successive introduction of appropriate dopants by diffusion or ion implantation. The junctions are protected by a passivation layer which usually is thermally grown oxide. In general, this layer is thicker than that of MOS devices and accumulates charge when irradiated.

7.2. EFFECTS OF RADIATION ON DEVICE FUNCTION

7.2.1. Gain

The term "gain" can refer to either of two separate parameters in a bipolar transistor. Common-base current gain (α or h_{FB}) is the ratio between collector current and emitter current and has a value rather less than unity. Common-emitter current gain, β or h_{FE}, is the ratio between collector current and base current; it will have a value, typically, of 50 to 2000. In our discussion of gain degradation, we will use the common-emitter current gain term and, for brevity, use the symbol 'β'.

7.2.2. Degradation of gain

Gain degradation and leakage are the most striking and common effects of radiation on bipolar transistors. One cause of gain degradation is atomic displacement in the bulk of a semiconductor. This bulk damage produces an increase in the number of recombination centres and therefore reduces minority carrier lifetime. The other main cause of gain degradation is ionisation in the oxide passivation layer, particularly that part of the oxide covering the emitter-base junction region (see Fig. 7.1). By a process similar to that in MOS devices, charge-trapping and the generation of new interface states produce degradation of gain. The trapped surface charge and interface states cause an increase in minority carrier surface recombination velocity, reducing gain. Under electron irradiation, such surface-linked degradation often precedes minority carrier effects.

We have seen that two quite distinct processes combine to decrease gain. Thus, degradation can be represented by the equation:-

$$\Delta(1/\beta) = 1/\beta - 1/\beta_0 \qquad \text{..........7(i)}$$

where 'β_0' and 'β' are the gain values before and after irradiation.

Gain degradation is often analysed by plotting the change in reciprocal gain $\Delta(1/\beta)$ versus radiation fluence. The term '$\Delta(1/\beta.)$' is known as the "gain damage figure". The effects of bulk and surface damage can be separated as follows:-

$$\Delta(1/\beta) = \Delta(1/\beta)_b + \Delta(1/\beta)_s$$

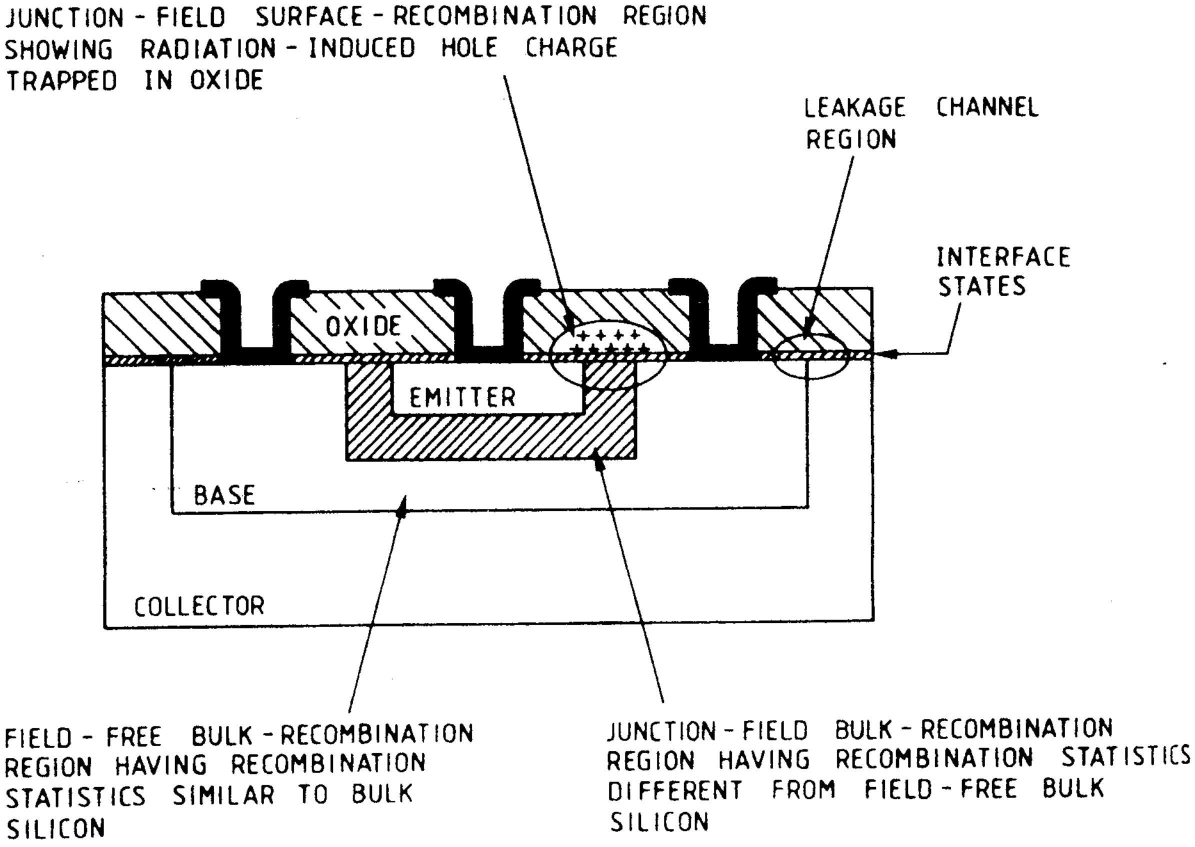
where the suffixes 'b' and 's' indicate the bulk and surface contributions respectively. However, while the bulk contribution may be reasonably predicted from analysis of minority carrier lifetime behaviour, the surface contribution is highly dependent upon process factors (see later Sections).

7.2.3. Other permanent effects

Apart from degradation of gain, irradiation also causes other important effects in bipolar transistors. Increases in the junction leakage currents (e.g. collector-base reverse leakage 'I_{CBO}'), like the surface-linked gain degradation already mentioned, result from ionisation in the surface oxide, particularly the region over the collector-base junction (see Fig. 7.1).

It is also found that heavy atomic displacement damage in the semiconductor causes an increase in the collector-emitter saturation voltage '$V_{CE(SAT)}$'. The rate of this increase with fluence is roughly the same as that with which gain decreases, i.e. the fluences producing a 50% change in either parameter are about the same. This is because '$V_{CE(SAT)}$', the voltage at which both transistor junctions are just forward biased, is an inverse function of transistor gain and is thus affected by changes in minority carrier lifetime.

Transistors with high breakdown voltages have high resistivity (low doping) in the collector region. At very high bulk damage levels, the resistivity may be changed noticeably, causing further changes in '$V_{CE(SAT)}$'. Such effects are of less importance in low power transistors such as logic devices because the switching or amplifying action is not affected by relatively high '$V_{CE(SAT)}$' values. On the other hand, the efficient operation of power transistors, especially switching power transistors, requires low '$V_{CE(SAT)}$' values. Donovan et al (1976) indicate that circuit failure of power transistors can be caused by a 50% increase in '$V_{CE(SAT)}$' or a 100-fold increase in 'I_{CEO}' (a surface-controlled leakage). Table 7(1) shows the change in these and other parameters in a bipolar power transistor.



Essential features of device structure showing regions involved in radiation effects

FIGURE 7.1 - PLANAR BIPOLAR TRANSISTOR

TABLE 7(1) - THE EFFECT OF NEUTRON IRRADIATION UPON THREE SAMPLES OF A FAIRCHILD BIPOLAR TRANSISTOR 1970 era (V_{CE} = 5V, V_{CB} = 30V)

Neutron fluence cm^{-2}	I_m amp.	I_m/I_{mo}	βo at I_{mo}	$\beta/\beta o$ at I_{mo}	β at 1A	V_{CE} (sat)		I_{CEO} at 30V		(a) Approx. equivalent 1-MEV electr.fluence cm^{-2}
						Pre-irrad. V	Post-irrad. V	Pre-irrad. nA	Post-irrad. nA	
$1x10^{14}$	1.05	0.95	35.5	0.75	25.9	0.27	0.38	1.6	6.9	$3x10^{16}$
	0.85	0.88	33.5	0.73	21.1	0.30	0.43	0.5	6.9	
	0.90	0.83	33.7	0.72	22.7	0.29	0.42	0.1	6.0	
$3x10^{14}$	0.90	0.83	34.8	0.57	17.9	0.29	0.54	1.4	17.4	$9x10^{16}$
	1.00	0.90	34.8	0.59	20.0	0.25	0.47	0.4	15.6	
	0.90	0.89	34.3	0.59	19.1	0.25	0.49	0.7	15.3	
$1x10^{15}$	0.90	0.44	34.3	0.31	6.3	0.26	1.19	0.4	35.2	$3x10^{17}$
	0.90	0.44	33.7	0.32	6.4	0.23	1.16	0.8A	1 A	
	0.90	0.34	34.5	0.31	6.6	0.27	1.12	0.5	35.7	
$2x0^{15}$	0.90	0.17	35.3	0.15	–	0.23	1.55	0.4	58.4	
	0.80	0.19	37.1	0.15	–	0.25	2.41	1.1	58.9	
	0.90	0.17	34.7	0.14	–	0.25	1.86	0.4	61.7	

βo = pre-irradiation gain

β = post-irradiation gain

I_{mo} = current at which βo peaks

I_m = current at which β peaks

(a) : 1 n cm^{-2} is equivalent to approximately 300 e cm^{-2} (1 MeV)

7.2.4. Transient effects

The effect of ionisation on the p-n junction of a bipolar transistor may lead to transient photocurrent effects. The radiation dose rates required to produce significant effects are in the region of 10^6 rad $.s^{-1}$, well above the rates produced by either the natural space environment or typical isotope sources. The response of a bipolar transistor to dose rate is usually controlled by the photocurrent generated in the collector-base junction. These currents may be calculated if the dose rate and junction area are known.

7.3. BULK DAMAGE

7.3.1. General

The effect of atomic displacement in bulk silicon is a reduction in conductivity and minority carrier lifetime. The reduction in lifetime may be represented by the following equation:

$$1/\tau - 1/\tau_0 = K_\tau \phi \qquad 7\ (iii)$$

'K_τ ($cm^2.s^{-1}$)' is known as the minority carrier lifetime damage constant for a given type and resistivity of silicon at a given radiation energy, 'ϕ' is the fluence and 'τ_0' and 'τ' are the initial and post-irradiation lifetime values. The value of 'K_τ' is dependent upon material properties, e.g. the value of oxygen-free silicon is significantly less than that of oxygen-rich material.

This picture is complicated by various other factors which depend upon the device geometry, particularly that of the base region. The following are three examples of such complicating factors:-

- The effectiveness of a given recombination centre on lifetime depends upon the charge state of that centre and this, in turn, is controlled by the minority carrier equilibrium pertaining to that point. A diffused junction device contains depletion regions near the junctions. In these regions, the electric fields are high and carriers are swept out rapidly. The material here resembles an intrinsic semiconductor and recombination rates are very low, although the addition of new defects will certainly alter these rates. The actual fields, and hence the carrier equilibria, vary with the bias applied.

- The nature of the production techniques commonly used for transistors is another complicating factor. In a diffused transistor, the base and emitter are regions formed by the diffusion of dopants into the substrate silicon. Thus, the dopant concentration profile (and hence the Fermi level) in the base is far from uniform and varies by orders of magnitude. In an ion-implanted device, different dopant concentration profiles will also be found and, in addition, the implantation itself is likely to cause defects in the silicon.

- When current flows in the transistor, the Fermi level is altered by the presence of excess carriers injected at the emitter-base junction and effectively dependent upon the operating level of the transistor. Therefore, other factors being equal, the value of 'K_τ' in a device carrying a signal current of 1 mA will be different from the 'K_τ' value in a device carrying a current of, say, 10 µA.

Thus, it is a complex task to predict the 'K_τ' value of a device from first principles.

The predicted typical relationship between gain and 1-Mev electron fluence, shown by the dotted lines in Fig. 7.2, derives from equation 7(ii). A change in 'K_τ' is expressed as a translation of the curves along the fluence axis. However, the observed gain degradation in a "planar" (oxide-passivated) bipolar transistor does not follow this predicted course. Instead, many devices are observed to degrade in the manner shown by the solid curve in Fig. 7.2. This is a clear indication that some degrading mechanism other than minority carrier lifetime reduction is affecting gain and this is found to be the surface ionisation effect already discussed.

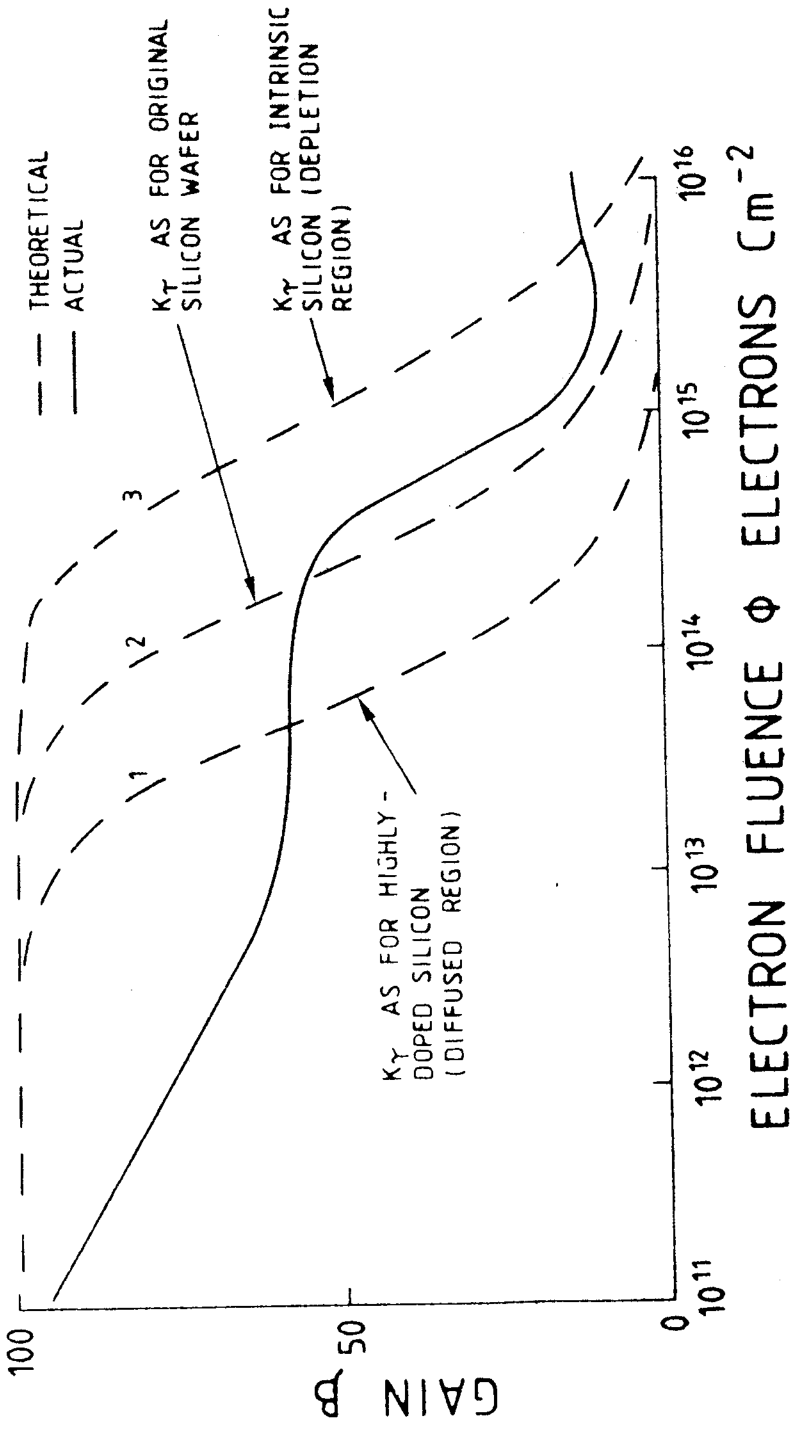
7.3.2. The influence of base width

In MOS transistors, the oxide thickness is an important device parameter; in bipolar devices, base width is an equally important factor and - as described below - has a significant influence upon gain degradation by bulk damage.

The Webster equation for the gain of a bipolar transistor uses the following term for relating gain 'β' to minority carrier lifetime 'τ':

$$\frac{1}{\beta} = \frac{W_b^2}{2D} + \ldots \qquad \text{......7(iv)}$$

where 'W_b" is the base width and 'D' is the minority carrier diffusion constant. Other terms in this equation account for the contributions of surface recombination (the surface effect) and emitter efficiency. The base width term is the controlling one for reduction in 'β' (i.e. bulk damage).



Common emitter current gain as a function of electron fluence. Solid curve shows typical behaviour of a real device indicating the early effects of ionisation in the surface oxide passivating layer.

FIGURE 7.2 - BIPOLAR TRANSISTOR DEGRADATION

Assuming that the surface recombination and emitter efficiency terms remain constant, a combination of the Webster equation and equations 7(i) and 7(iii) produces the following equation for the figure of gain damage caused by bulk damage:

$$\Delta(1/\beta) = \frac{W_b^2}{2D} . K_\tau . \phi \qquad \text{......7(v)}$$

This equation demonstrates the strong dependence of the gain damage figure upon base width. Thus, it is necessary to measure or calculate this term for devices under consideration. The value of 'W_b' itself cannot be measured easily; however, the cut-off frequency 'f_α' (the frequency at which common-base current gain 'α' falls to one-half of its low-frequency value, say at 1 kHz) bears a close relation to 'W_b'. By using this dependence, Messenger and others (1965) derived the following prediction for the effect of bulk damage on transistors:

$$\Delta(1/\beta) = \frac{K_\tau \phi}{2\pi f_\alpha} \qquad \text{......7(vi)}$$

Here, gain degradation has been related to more easily measurable parameters. For the purpose of the prediction, 'K_τ' must be determined at least one type of particle for any given bipolar transistor technology.

Typical figures for 'K_τ', measured for diffused NPN and PNP transistors under 1 MeV electron irradiation, are 1×10^{-8} and 3×10^{-8} $cm^2.s^{-1}$ respectively and, for reactor neutrons, 1×10^{-6} and 3×10^{-6} $cm^2.s^{-1}$ respectively.

As might be expected from solar cell investigation ('P' diffusion on N- type base is more sensitive than 'N' on 'P'), PNP transistors are more sensitive than the NPN-type by a factor of about 3 (the fluence required to yield a given degradation value is three times lower).

Although the cut-off frequency 'f_α' is included in the equation for gain prediction, an alternative parameter 'f_T' (the gain bandwidth product) is more easily measured and also most commonly quoted for transistors. It is the product of common-emitter gain 'β' and the frequency of measurement when the frequency lies on the descending part of the gain frequency curve.

The value of f_T is also the frequency at which 'β' falls to unity. Table 7(2) gives examples of the relationship between 'f_T' and base width 'W_b'.

The frequencies 'f_α' and 'f_T' are not exactly equal, 'f_T' being slightly lower. The ratio between them depends on the doping profile. For ideal step junctions, 'f_α' = $\sqrt{1.22\, f_T}$; for diffused junctions, the ratio is 1.33. thus, in practice, the error introduced by using 'f_T' in the prediction of $\Delta(1/\beta)$ is not often significant and, in any case, errs on the side of safety. In recent publications, 'f_T' is used in place of 'f_α' for diffused transistors, without any correction factor (Cooper et al, 1979; Berger et al, 1978).

It is often convenient to express transistor damage as "a gain damage factor" ('K_b') without normalising for base width, 'f_T', etc. Thus:

$$1/\beta - 1/\beta_O = 1/\beta = K_b\phi \qquad ......7(vii)$$

TABLE 7(2) - CALCULATION OF BASEWIDTH FROM BASE TRANSIT TIME OR APPROXIMATE GAIN-BANDWIDTH PRODUCT (GBP)

Approx. GBW Product (1) f_T (MHz)	Base transit time (2) t_b (ns)	$\sqrt{33.2\, t_b}$ (s)	33.2 t_b (cm)	Base width NPN (2) W_b (µm)	Base width PNP W_b (µm)
1000	0.16	5.28x10^{-9}	7.26x10^{-5}	0.73	0.63
500	0.32	1.05x10^{-8}	1.02x10^{-4}	1.02	
200	0.80	2.63x10^{-8}	1.62x10^{-4}	1.62	
100	1.59	5.28x10^{-8}	2.30x10^{-4}	2.29	2.0
50	3.18	10.5x10^{-8}	3.24x10^{-4}	3.24	
20	7.95	26.3x10^{-8}	5.13x10^{-4}	5.12	
10	15.9	52.8x10^{-8}	7.26x10^{-4}	7.26	6.3
1	1.59	5.28x10^{-6}	22.9x10^{-4}	22.9	20

(1) Ignoring t_e, t_c, etc.; GBW = gain bandwidth;

(2) using relations: $t_b \simeq \dfrac{2\pi ft}{1}$

$$W_b = \sqrt{2D_n t_b} = \sqrt{33.2\, t_b}$$

$$D_n = 16.6\ \text{cm}^2\ \text{s}^{-1}\ (D_p = 12.5\ \text{cm}^2\ \text{s}^{-1})$$

See F. Larin, "Radiation Effects in Semiconductor Devices" (pp. 18, 67, 04); Wiley, 1968

Gain after a given irradiation can be calculated:

$$\beta = \frac{\beta_0}{1 + \beta_0 k_b \phi} \qquad \text{......7(viii)}$$

A simple relation between 'K_b' and K_τ' is derived from equation 7(vi):-

$K = 2\pi\ K_b.\ f_T = 6.28\ K_b.\ f_T$ ......7(ix)

7.3.3. The influence of type and energy of radiation

The atomic displacement process which causes bulk damage is, unlike the process causing surface damage, quantitatively dependent upon the momentum of the radiation. It is useful to consider briefly the effects of energy and particle type because this enables the test results of a large range of particle types and energies, including many results for reactor neutrons, to be found. Moreover, the particle spectrum in space is very broad.

The following equations summarise four important "damage constants" ('K') which relate the relevant "damage figure" to particle fluence. Minority carrier lifetime damage constant, 'K' (cm 2 .s^{-1}):

$\Delta(1/\tau) = K_\tau\phi$ ......7(x)
(see also 7(iii))

Gain damage constant, 'K_b'. (cm^2):

$\Delta(1/\beta) = K_b\phi$ ......7(xi)
(see also 7(vii))

Diffusion length damage constant (for solar cells), 'K_L' (cm^2 per cm^2):

$\Delta(1/L^2) = K_L\phi$ ......7(xii)

Carrier removal rate, '$\Delta n/\Delta\phi$ (or Δ p/$\Delta\phi$' (cm^{-1}))

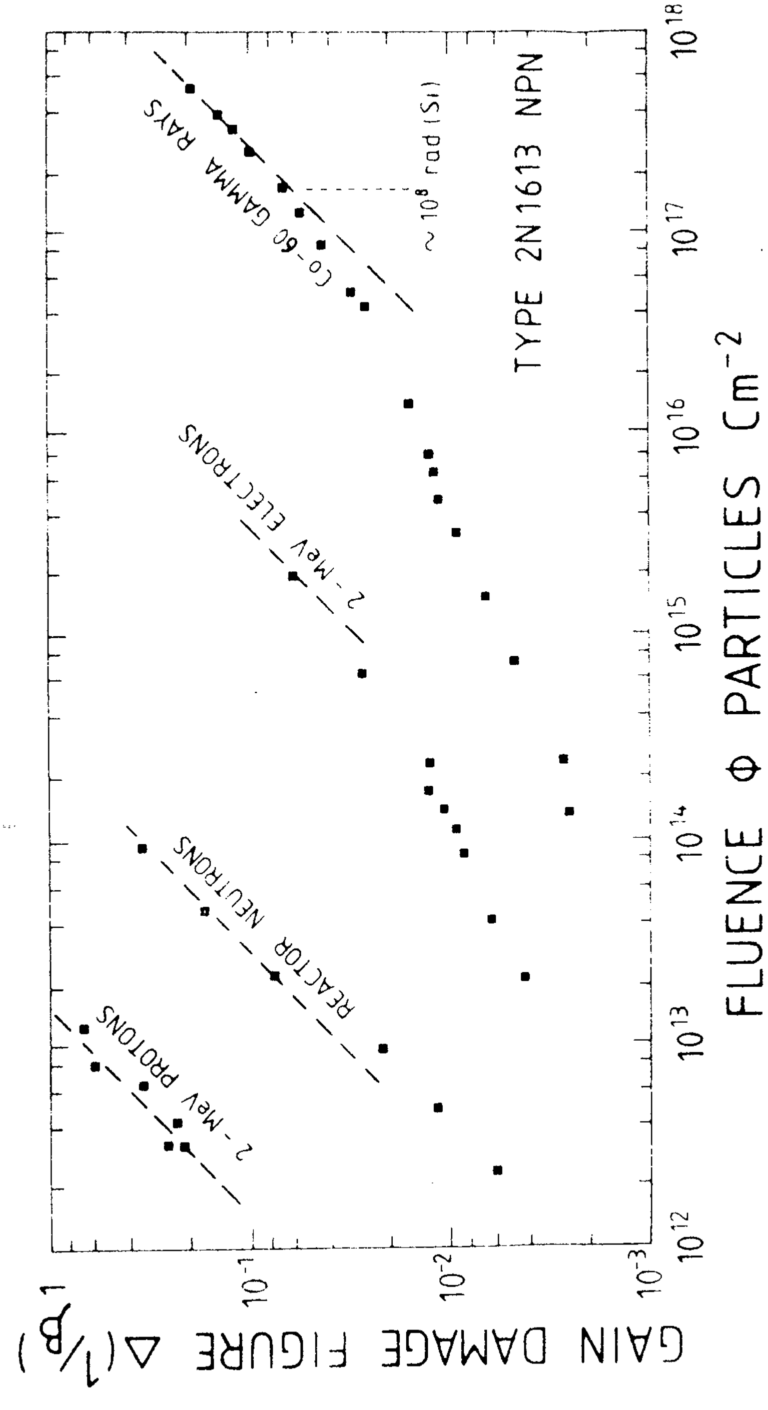
$$n(\phi) = n_0 \frac{\Delta n}{V\phi}$$ ......7(xiii)

These constants all change with particle type and energy and this section will discuss mainly the variation of the lifetime and gain damage constants in bipolar transistors. Figure 7.3 shows the experimental results of exposing a 2N1613 transistor to several different types of radiation. The form of degradation is the same for each type of radiation except that ($1/\phi$) is displaced along the flux scale (i.e. 'K_b' is different). Thus, it may often be possible to employ test results using one particle type or energy to predict the effects expected under irradiation by another particle type or energy.

Figure 7.3 also shows that in all cases some slowly developing non-linear degradation takes place well before a linear growth of gain damage with fluence (indicated by a dotted line) is observed to occur. This early degradation is the "surface effect" due to the ionising component of the radiation.

The constant 'K_b' can be measured from the linear portion of Figure 7.4. 'K_b' for reactor neutrons is seen to be over 100 times greater than for electrons. It is fortunate that low-energy protons are filtered out by normal device packaging as otherwise the high 'K_b' value shown for 2 MeV protons would cause a serious effect in space. The long "tail" of the ^{60}Co gamma-radiation curve indicates that ionisation (surface effect) is the major effect of this radiation although bulk damage from Compton electrons is evident at very high doses (10^8 rad (Si)).

Table 7(3) lists a more complete set of results by Brown and colleagues (1964, 1967), giving 'K_b' for a number of bipolar transistors and six different radiation sources. To normalise for base width, 'K_b' has been converted to 'K_τ' with the aid of equation 7(ix).



Gain damage figure for 2N1613 devices as a function of radiation fluence, showing the effect of radiation-type (data from Brown, 1964)

FIGURE 7.3 - THE INFLUENCE OF RADIATION TYPE (FROM BROWN 1964)

TABLE 7(3) - BROWN'S DAMAGE CONSTANTS FOR A NUMBER OF TRANSISTORS SUBJECTED TO VARIOUS TYPES OF IRRADIATION

<table>
<tr><th rowspan="2">Device type</th><th rowspan="2">f_T MHz (nom)</th><th colspan="2">Protons[a]</th><th>Reactor neutrons</th><th colspan="2">Electrons</th><th>Gamma rays</th></tr>
<tr><th>2-MeV</th><th>10-MeV</th><th>>10KeV</th><th>2-MeV</th><th>5-MeV</th><th>Co-60</th></tr>
<tr><td colspan="8">A. Transistor gain damage constant K_b(cm^2) for various types of radiation (after Brown et al (11, 12); Collector current 2mA</td></tr>
<tr><td>2N336 NPN</td><td>7</td><td>–</td><td>70E-15</td><td>2.5E-15</td><td>4.0E-17</td><td>2.5E-17</td><td>9.0E-19</td></tr>
<tr><td>2N1132A NPN</td><td>60</td><td>5.5E-14</td><td>–</td><td>–</td><td>2.5E-17</td><td>–</td><td>7.0E-19</td></tr>
<tr><td>2N1613 NPN</td><td>60</td><td>7.0E-14</td><td>5.0E-15</td><td>2.5E-15</td><td>4.0E-17</td><td>7.0E-15</td><td>4.0E-19</td></tr>
<tr><td>2N2107 NPN</td><td>150</td><td>–</td><td>–</td><td>–</td><td>4.50E-17</td><td>–</td><td>3.5E-19</td></tr>
<tr><td>2N2217 NPN</td><td>100</td><td>–</td><td>–</td><td>8.0-16</td><td>1.5E-17</td><td>1.7E-17</td><td>1.0E-19</td></tr>
<tr><td colspan="8">B. Nominal minority-carrier lifetime damage constant K_τ (cm^2 s.$^{-1}$) calculated from the values of K_b above[b]</td></tr>
<tr><td>2N336 NPN</td><td>7</td><td>–</td><td>2.5E-7</td><td>9.0E-8</td><td>1.4E-9</td><td>9.0-10</td><td>3.2E-11</td></tr>
<tr><td>2N1132A PNP</td><td>60</td><td>1.7E-5</td><td>–</td><td>–</td><td>7.7E-9</td><td>–</td><td>2.2E-10</td></tr>
<tr><td>2N1613 NPN</td><td>60</td><td>2.2E-5</td><td>1.6E-6</td><td>7.8E-7</td><td>1.2E-8</td><td>2.1E-8</td><td>1.3E-10</td></tr>
<tr><td>2N2107 NPN</td><td>150</td><td>–</td><td>–</td><td>–</td><td>3.5E-9</td><td>–</td><td>2.7E-10</td></tr>
<tr><td>2N2217 NPN</td><td>100</td><td>–</td><td>–</td><td>4.1E-7</td><td>7.6E-9</td><td>8.7E-9</td><td>5.1E-11</td></tr>
</table>

a. Proton irradiation with cans removed.

b. Calculated from equation 5(ix) assuming f_T equal to f_α.

The uncertainty ascribed by Brown to his K_b values is typically ± 30%.

The notation "E-14" indicates "10^{-14}" (etc.).

TABLE 7(4) - BRUCKER'S DAMAGE CONSTANTS FOR A NUMBER OF TRANSISTORS SUBJECTED TO VARIOUS TYPES OF IRRADIATION

(with pre-irradiation to saturate surface effects - see text)

Device type	f_T MHz (nom)	Protons 16.8 MeV	Reactor neutrons >10 keV	Electrons 1 MeV	Collector current mA
A. Gain damage constant, Kb (cm^2) for various types of radiation (after Brucker ([13]))					
2N2102 NPN	100	1.5E-14 8.0E-15 –	4.6E-15 2.9E-15 4.9E-15	1.9E-17 1.8E-17 4.1E-17	1 10 100
2N1132 PNP	100	1.8E-14 1.2E-14 –	4.5E-15 2.4E-15 3.4E-15	7.4E-17 6.2E-17 6.8E-17	1 10 100
B. Nominal minority-carrier lifetime damage constant, K_τ ($cm^2.s^{-1}$) calculated from the values of K_b above					
2N2102 NPN	100	7.7E-6 4.1E-6 –	2.4E-6 1.5E-6 2.5E-6	9.7E-9 9.2E-9 2.1E-8	1 10 100
2N1132 PNP	100	9.2E-6 6.2E-6 –	2.3E-6 1.2E-6 1.7E-6	3.8E-8 3.2E-8 3.5E-8	1 10 100

a. Calculated from equation 5 (ix) with f_T assumed equal to f_α.

Damage efficiency of protons and neutrons compared with 1 MeV electrons at collector current of 1mA (energies as above).

Device	$K_\tau (p,n) / K_\tau (e)$	
	Protons	Neutrons
2N2102 NPN	790	240
2N1132 PNP	240	60

Brucker ascribes an uncertainty to Kp values of typically ± 20%.
The notation 'E-14' indicates 'x 10^{-14}' (etc.).

The 'K_τ' values of three of the NPN devices fall within the range given by Van Lint and co-workers (1975) for 3 MeV electrons in 1 ohm/cm silicon, namely 2 to 8×10^{-9} $cm^2.s^{-1}$.

It is not clear whether the variations from type to type are due to variations in resistivity in the base region, different impurities or other dissimilarities between experiments. The data quoted by Van Lint (1975) are largely for the base regions of solar cells or other uniformly doped silicon. In the circumstances, the correlation is quite good.

Brucker (1965, 1967) performed a set of irradiation tests similar to those carried out by Brown, but added a preliminary heavy irradiation with 125 keV electrons. This caused no displacement damage, but virtually saturated the surface damage. As a result, 'K_b'could be determined over a wider range of fluence because the obscuring influence of surface effects had been removed. The Brucker 'K_b' values, which have again been converted into 'K_τ', are shown in Table 7(4). The electron result for an NPN transistor at 1 mA again lies near Van Lint's figure. Both protons and neutrons yield 'K_τ' values higher than those of Brown's devices. Brucker also studied the effect of varying electron energy over the range 0.275 to 1 MeV and found that the energy dependence of 'K_τ' in solar cells was similar to that found by other workers.

The influence of displacement defects on 'τ' is well known to be affected by the concentration of minority carriers ("injection level") in the device. This can be explained by the Shockley-Hall-Read recombination theory. Irradiation results from mesa and wide-base power transistors at 1 MeV and 8 MeV suggest that damage constants of the order given above can be used for these devices despite their very different structures. In Europe, Lambert et al (1975) report the testing of a wide range of discrete and integrated devices (including operational amplifiers) under neutrons, high-energy protons and ^{60}Co gamma radiation, but do not apply the analytical treatments discussed here.

7.3.4. Irradiation results

Table 7(5) lists the results of an extensive series of nuclear reactor exposures performed in the U.K. under the sponsorship of the U.K. Government. Listed in the first group are the maximum values of 'K_b' for the fluence range 10^{12} to 10^{13} reactor neutrons.cm^{-2} ($E >$ 10 keV). Where possible, we have selected an 'I_c' value of 1 mA. 'K_b' is the experimental value and we have calculated the "apparent K_τ" value from 'K_b' as in equation 7(ix). The variations in this value are unlikely to be due to a true difference in lifetime degradation. The high values probably contain a contribution to

$\Delta 1/\beta$ from effects at the surface and in the emitter-base depletion region. The quoted value of 'f_T' is not a measured value, but the minimum value quoted in the manufacturer's data sheet. It is quite likely that some of the samples tested had a higher value than that specified. Hence, both high values of apparent 'K_τ' and some variability are to be expected.

TABLE 7(5) - COLLECTED VALUES OF DAMAGE CONSTANTS FOR COMMERCIAL PLANAR SILICON TRANSISTORS AND REACTOR NEUTRONS

1 Device type nr. (d)	2 Manufacturer (d)	3 Polarity	4 Nominal cutoff Frequency(a) f_T (MHz)	5 IC Value for Meas. I_C (mA)	6 Exptl. Beta-damage Const. (b) K_b $(10^{-15}cm^2n^{-1})$	7 $K_b \times f_T$ $(10^{-9}cm^2n^{-1}s^{-1})$	8 Lifetime damage constant (low I_C) (c) K col 7 x 2 $(10^{-6}cm^2n^{-1}s^{-1})$
2N720A	TEX	NPN	50	1	9.8	490	3.27
2N918	TEX	NPN	900	1	0.71	639	4.26
2N930	TEX	NPN	45	1	1.9	86	1.84
2N1486	RCA	NPN	1.2	10	110.0	132	0.88
2N1613	TEX	NPN	60	1	6.7	402	2.68
2N2219	TEX	NPN	250	1	0.99	248	1.65
2N2219	SGS	NPN	250	1	1.1	275	1.83
2N2219A	FAI	NPN	250	3	0.67	168	1.12
2N2222A	FER	NPN	250	1	1.6	400	2.67
2N2223A	TEX	NPN	50	1	6.6	330	2.20
2N3055	FER	NPN	20	100	44.0	880	5.87
2N3055	MUL	NPN	20	100	69.0	1380	9.20
2N2905	NAT	PNP	200	3	0.95	190	1.27
2N2905A	TEX	PNP	200	3	0.57	114	0.76
2N2906	TEX	PNP	200	3	2.1	420	2.80
2N2906	TEX	PNP	200	1	3.2	640	4.26
2N2907A	TEX	PNP	200	1	3.4	680	4.53
2N4901	TEX	PNP	4	100	8.7	34.8	0.23
2N4904	MOT	PNP	4	100	10.13	0.52	0.003
2N1132	TEX	PNP	90	3	4.0	360	2.40
2N2303	FAI	PNP	60	1	2.7	162	1.08
2N2412	TEX	PNP	200	1	1.7	340	2.27
2N2894	FAI	PNP	370	1	0.51	189	1.26
2N4028	FAI	PNP	150	3	2.2	330	2.20
2N5883	MOT	PNP	4	30	35.0	140	0.93
Cooper, Retzler and Messenger 1979, (e)							
2N222A	–	NPN	300	0.51	1.4	467	3.11
2N2907A	–	PNP	200	1	0.54	108	0.72
2N2369A	–	NPN	500	10	0.20	100	0.67
2N4150	–	NPN	15	1000	3.68	55	0.37
2N5666	–	NPN	20	1000	5.75	115	0.77

See next page.

a) Quoted on data sheets: Specified minimum, not actual

(b) $K_b = \left[\frac{1}{\beta} \frac{1}{\beta_0} \right] - \phi_n$

(c) $K = 2\pi K_b f_T$

(d) Herald reactor, UK; maximum K_b observed:
$\phi_n = 10^{12}$ to $2 \times 10^{13}\ \text{cm}^{-2}$;
isotope γ-rays: 3000 to 30 000 rad (Si).

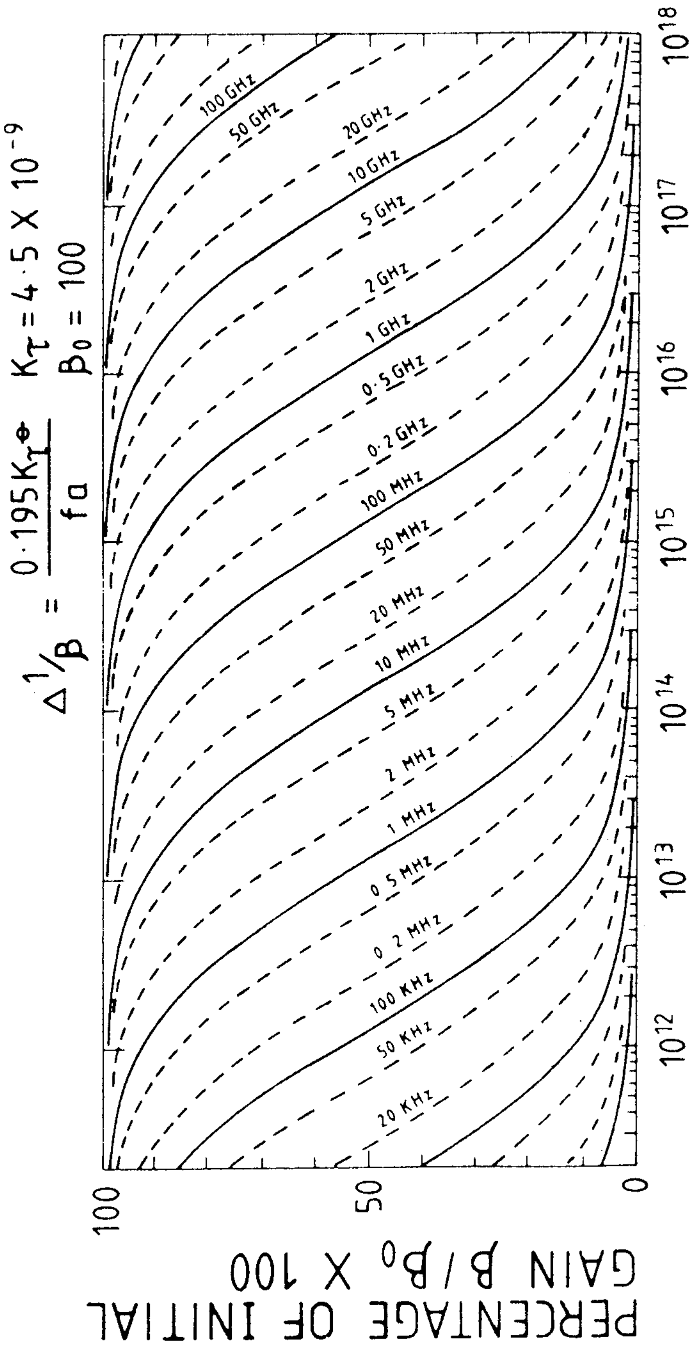
(e) Equiv. 1 MeV neutrons quoted. $\phi_n = 2$ to $5 \times 10^{13}\ \text{cm}^{-2}$.

7.3.5. Prediction of degradation

Once decided, lifetime damage constants can be turned into a master set of prediction curves. For example, those shown in Fig. 7.4 are for an NPN device, having an original gain 'β_0' of 100, exposed to 1 MeV electrons. These curves apply to that one value of gain only, but the trends are the same for all values of gain.

To predict the degradation of a given device numerically, the value of $\Delta(1/\beta)$ may be calculated from equations given earlier. This value of $\Delta(1/\beta)$ may then be converted by calculation to the final value of 'β'. A convenient ready reckoner for this conversion is given in Table 7(6).

Table 7(7) shows some calculations of degradation in space, using three values of electron fluence such as might be calculated for a spacecraft in a high-radiation orbit.



Degradation of gain as a function of electron fluence showing variation with alpha cut-off frequency Fα (a function of base width).

FIGURE 7.4 - THE INFLUENCE OF BASE WIDTH.

TABLE 7(6) - FINAL VALUES OF TRANSISTOR GAIN 'β', GIVEN INITIAL GAIN 'βo' AND DAMAGE FIGURE 'Δ1/β' (BASED ON Δ1/β = 1/β-1/βo)

← Original values of gain, βo →

Δ1/β	10	12	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100	110	120	130	140	150	170	200	250	300	350	400
.0005	9.95	11.9	14.9	19.8	24.7	29.6	34.4	39.2	44.1	48.8	55.3	58.1	62.9	67.6	72.5	76.9	81.3	86.2	90.9	95.2	104	114	122	132	139	156	182	222	263	294	333
.0007	9.93	11.9	14.9	19.7	24.6	29.4	34.1	38.9	43.7	48.3	55.3	57.5	61.7	66.7	71.4	75.8	80.0	84.8	89.3	93.5	102	111	119	128	135	152	175	212	250	278	313
.001	9.90	11.9	14.8	19.6	24.4	29.2	33.8	38.5	43.1	47.6	52.1	56.6	61.0	65.4	69.9	74.1	78.1	82.6	87.0	90.9	99.0	107	115	124	130	145	167	200	233	256	286
.0015	9.85	11.8	14.7	19.4	24.1	28.7	33.2	37.7	42.2	46.5	51.8	55.0	59.2	63.4	67.6	71.4	75.2	79.4	83.3	87.0	94.3	102	109	116	122	135	154	182	208	227	250
.002	9.80	11.7	14.6	19.2	23.8	28.3	32.7	37.0	41.3	45.5	49.5	53.6	57.5	61.4	65.4	69.0	72.5	76.3	80.0	83.3	90.1	96.8	103	110	115	127	143	167	189	204	222
.0025	9.76	11.7	14.5	19.0	23.5	27.9	32.2	36.4	40.5	44.4	48.3	52.2	55.9	59.6	63.3	66.7	69.9	73.5	76.9	80.0	86.2	92.3	98.0	104	109	119	133	154	172	185	200
.003	9.71	11.6	14.3	18.9	23.3	27.5	31.7	35.7	39.7	43.5	47.2	50.8	54.4	57.9	61.4	64.5	67.6	70.9	74.1	76.9	82.6	88.2	93.5	99.0	103	112	125	143	159	170	182
.0035	9.66	11.5	14.3	18.7	23.0	27.2	31.2	35.1	38.9	42.6	46.1	49.5	52.9	56.2	59.5	62.5	65.4	68.5	71.4	74.1	79.4	84.8	89.3	94.3	98.0	106	118	133	147	156	167
.004	9.62	11.5	14.1	18.5	22.7	26.8	30.7	34.5	38.2	41.7	45.1	48.4	51.6	54.7	57.8	60.6	63.3	66.2	69.0	71.4	76.3	81.1	85.5	90.1	93.8	101	111	125	137	145	154
.005	9.52	11.3	13.9	18.2	22.2	26.1	29.9	33.3	36.8	40.0	43.1	46.2	49.0	51.9	54.6	57.1	59.5	62.1	64.5	66.7	70.9	75.0	78.7	82.6	85.7	91.7	100	111	121	127	133
.006	9.43	11.2	13.8	17.9	21.7	25.4	28.9	32.3	35.5	38.5	41.3	44.1	46.7	49.3	51.8	54.1	56.2	58.5	60.6	62.5	66.2	69.8	73.0	76.3	79.0	84.0	90.9	100	108	112	118
.007	9.35	11.1	13.6	17.5	21.3	24.8	28.1	31.3	34.3	37.0	39.7	42.3	44.6	47.0	49.3	51.3	53.2	55.2	57.1	58.8	62.1	65.2	68.0	70.9	73.2	77.5	83.3	90.9	97.1	101	105
.008	9.26	11.0	13.4	17.2	20.8	24.2	27.4	30.3	33.1	35.7	38.2	40.5	42.7	44.9	47.0	48.8	50.5	52.4	54.1	55.6	58.5	61.2	63.7	66.2	68.2	71.9	76.9	83.3	88.5	91.7	95.2
.009	9.17	10.8	13.2	16.9	20.4	23.6	26.6	29.4	32.1	34.5	36.8	39.0	41.0	42.9	44.8	46.5	48.1	49.8	51.3	52.6	55.3	57.7	60.0	62.1	63.8	67.1	71.4	76.9	81.3	84.0	87.0
.010	9.09	10.7	13.0	16.7	20.0	23.1	26.0	28.6	31.1	33.3	35.5	37.5	39.4	41.2	42.9	44.4	45.9	47.4	48.8	50.0	52.4	54.5	56.5	58.5	60.0	62.9	66.7	71.4	75.2	77.5	80.0
.011	9.01	10.6	12.9	16.4	19.6	22.6	25.3	27.7	30.1	32.3	34.3	36.1	37.4	39.5	41.1	42.6	43.4	45.3	46.5	47.6	49.7	51.2	53.5	55.3	56.5	59.2	62.5	66.7	69.9	71.9	74.1
.012	8.93	10.5	12.7	16.1	19.2	22.1	24.7	27.0	29.2	31.3	33.1	34.9	36.5	38.1	39.5	40.8	42.0	43.3	44.4	45.5	47.4	49.2	50.8	52.4	53.6	55.9	58.8	62.5	65.4	67.1	69.0
.013	8.85	10.4	12.6	15.9	18.9	21.6	24.1	26.3	28.4	30.3	32.1	33.7	35.2	36.6	38.0	39.2	40.3	42.5	42.6	43.5	45.3	47.0	48.3	49.8	50.8	52.9	55.6	58.8	61.4	62.9	64.5
.014	8.77	10.3	12.4	15.6	18.5	21.1	23.5	25.6	27.6	29.4	31.1	32.6	34.0	35.1	36.6	37.7	38.8	39.8	40.8	41.7	43.3	44.8	46.1	47.4	48.3	50.3	52.6	55.6	57.8	59.2	60.6
.015	8.70	10.1	12.2	15.4	18.2	20.7	23.0	25.0	26.9	28.6	30.1	31.6	32.9	34.1	35.3	36.4	37.3	38.3	39.2	40.0	41.5	42.9	44.1	45.3	46.2	47.9	50.0	52.6	54.6	55.9	57.1
.017	8.62	10.0	12.0	14.9	17.5	19.9	21.9	23.8	25.5	27.0	28.4	29.7	30.9	32.0	33.0	33.9	34.7	35.6	36.4	37.0	38.3	39.5	40.5	41.5	42.2	43.7	45.5	47.6	49.3	50.3	51.3
.020	8.33	9.67	11.5	14.3	16.7	18.8	20.6	22.2	23.7	25.0	26.2	27.3	28.3	29.2	30.0	30.8	31.5	32.2	32.8	33.3	34.4	35.3	36.1	36.9	37.5	38.6	40.0	41.7	42.9	43.7	44.4
.025	8.00	9.23	10.9	13.3	15.4	17.2	18.7	20.0	23.4	22.2	25.8	24.0	27.9	25.5	29.6	26.7	27.2	27.7	28.2	28.6	29.3	30.0	30.6	31.2	31.6	32.4	33.3	34.5	35.3	35.8	36.4
.030	7.69	8.82	10.3	12.5	14.3	15.8	17.1	18.2	21.9	20.0	20.8	21.4	22.0	22.6	23.1	23.5	23.9	24.3	24.7	25.0	25.6	26.1	26.5	27.0	27.3	27.9	28.6	29.4	29.9	30.4	30.8
.035	7.41	8.48	9.83	11.8	13.3	14.6	15.8	16.7	21.7	18.2	20.5	19.3	19.8	20.3	22.8	21.0	21.4	21.7	22.0	22.2	22.7	23.0	23.4	23.8	24.0	24.5	25.0	25.6	26.1	26.4	26.7
.040	7.14	8.11	9.38	11.1	12.5	13.6	14.6	15.4	21.4	16.7	17.2	17.6	18.0	18.4	18.8	19.0	19.3	19.6	19.8	20.0	20.4	20.7	21.0	21.2	21.4	21.8	22.2	22.7	23.1	23.3	23.5
.050	6.67	7.50	8.57	10.0	11.1	12.0	12.7	13.3	21.2	14.3	14.7	15.0	15.3	15.6	15.8	16.0	16.2	16.4	16.5	16.7	16.9	17.2	17.3	17.8	17.6	17.9	18.2	18.5	18.8	18.9	19.1
.060	6.25	6.98	7.89	9.09	10.0	10.7	11.3	11.8	21.0	12.5	12.8	13.0	13.3	13.5	13.6	13.8	13.9	14.1	14.2	14.3	14.5	14.6	14.8	14.9	15.0	15.2	15.4	15.6	15.8	15.9	16.0
.070	5.88	6.52	7.32	8.33	9.09	9.71	10.1	10.5	20.8	11.1	11.3	11.5	11.7	11.8	12.0	12.1	12.2	12.3	12.4	12.5	12.6	12.8	12.9	13.0	13.0	13.2	13.3	13.5	13.6	13.7	13.8
.080	5.56	6.12	6.82	7.69	8.33	8.85	9.21	9.52	20.5	10.0	10.2	10.3	10.5	10.6	10.7	10.8	10.9	11.0	11.1	11.1	11.2	11.3	11.4	11.5	11.5	11.6	11.8	11.9	12.0	12.1	12.1
.090	5.26	5.77	6.38	7.14	7.69	8.13	8.42	8.70	20.3	9.09	9.25	9.38	9.49	9.59	9.68	9.76	9.68	9.89	9.95	10.0	10.1	10.2	10.2	10.3	10.3	10.4	10.5	10.6	10.7	10.8	10.8
.100	5.00	5.45	6.00	6.67	7.14	7.52	7.81	8.00	20.1	8.33	8.46	8.57	8.67	8.75	8.83	8.89	8.95	9.00	9.05	9.09	9.17	9.23	9.29	9.34	9.28	9.44	9.52	9.62	9.68	9.72	9.76

← Final values of gain, βo →

TABLE 7(7) - PREDICTED DEGRADATION OF BIPOLAR TRANSISTORS IN SPACE RADIATION

Device type	Damage constants		Gain (β) after given 1-MeV electron fluence (cm^{-2})		
	K $cm^2.s^{-1}$	K cm^2	10^{13}	10^{14}	10^{15}
60 MHz transistor					
NPN (e.g. 2N1613	5.84E-9	1.0 E-17a	98.6	87.3	40.7
PNP (e.g. 2N1132)	2.27E-8	7.4 E-17a	93.1	57.5	11.9
200 MHz transistor					
NPN (e4.g. 2N2222A)	5.84E-9	5.71E-18	99.4	94.6	63.7
PNP (e.g. 2N2907A)	2.27E-8	2.22E-17	97.8	82.0	31.3
1.2 MHz power transistor					
NPN (e.g. 2N1485)	4.2E-9	6.6E-16	58.8	12.5	1.5

NOTE that "E-9" signifies "x10-9", etc.

$$(1/\beta) = \frac{0.195K}{f}\,\phi = K_b\phi$$

7.3.6. Selection rules for bipolar transistors

In general, the longest survival time of a transistor will be achieved if the following selection rules are applied:

- Where possible, use low-gain transistors at fairly high collector current levels;
- When heavy particle irradiation is involved (near a space nuclear power system), employ - where possible - high-frequency NPN devices.

7.4. SURFACE-LINKED DEGRADATION IN GAIN

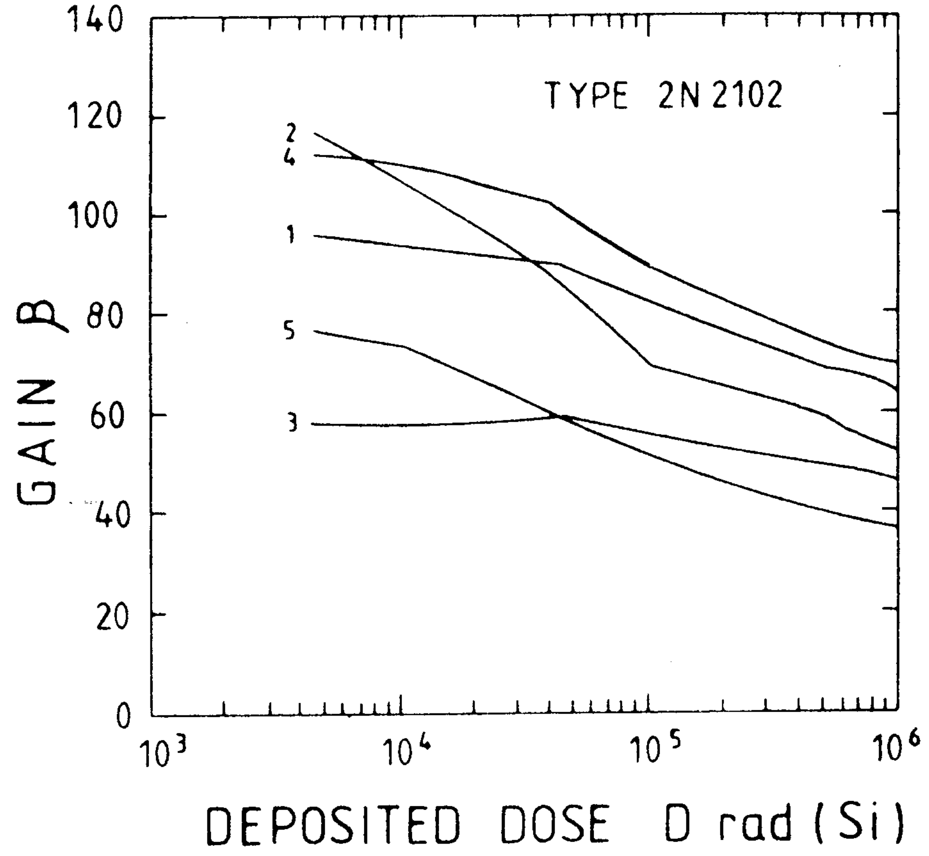
7.4.1. Introduction

In previous sections, it has been shown how gain degradation is made up of surface and bulk contributions. While the bulk damage figure $\Delta(1/\beta)_b$ can be predicted fairly well by means of the analytical techniques described, the value of the surface damage figure

$\Delta(1/\beta)_S$ produced by a given radiation dose is much less easily predicted for a given transistor design. The latter value is highly dependent upon the surface preparation used, which usually consists of the growth of a passivating oxide in steam. Each manufacturer tends to use a slightly different process and, even when meeting ultra-high reliability specifications, is liable to vary the process significantly from time to time.

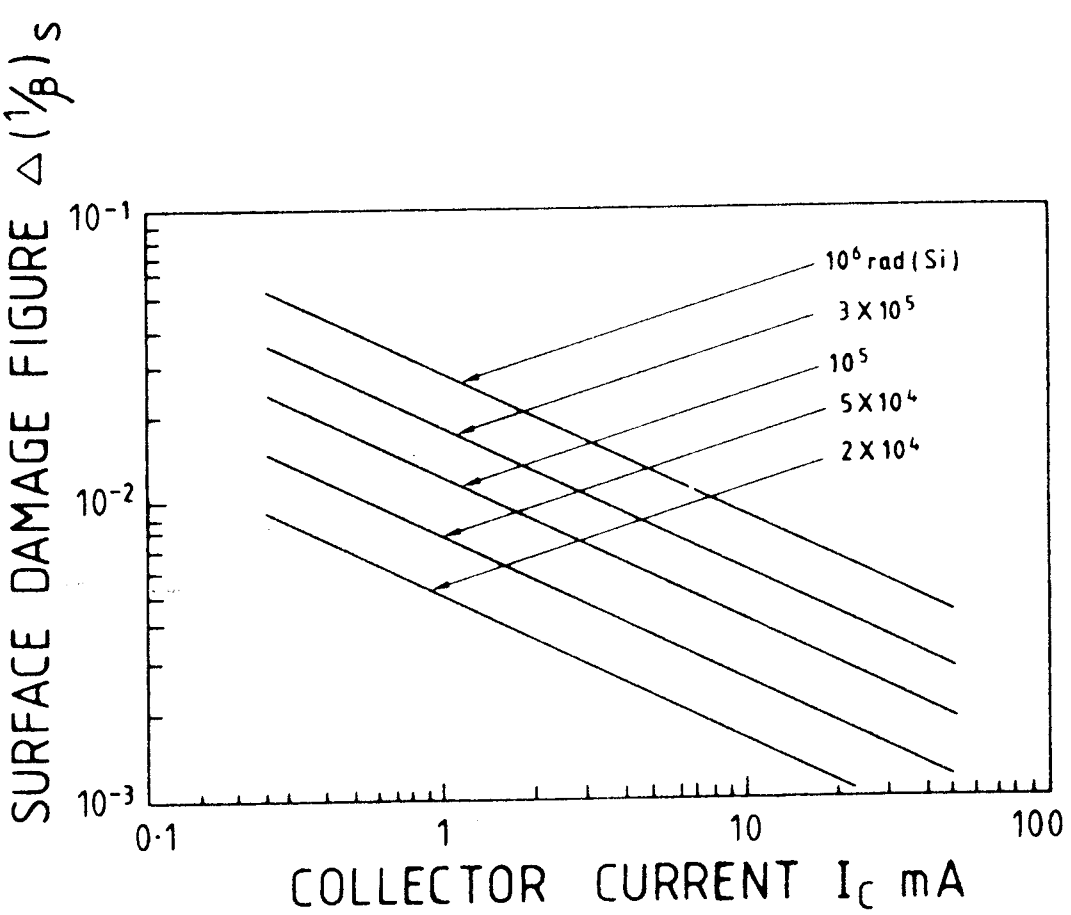
Figure 7.5 shows the gain degradation exhibited by a batch of transistors from one day's production, as a function of dose during gamma irradiation, which produces mainly surface effects at the doses shown. Units with identical functional specifications, but from different manufacturers, may vary even more widely after irradiation. For these effects, the "surface damage figure", $(1/\beta)_S$, was found to be a useful tool in that it provides a routine method of recording and characterising the surface effect. An example of the variation of surface damage figure with the collector current 'I_C' used for measurement (equivalent to emitter injection level) is shown in Figure 7.6. A reasonably close linear relationship between 'I_C ' and damage figure is demonstrated.

All transistors exhibit lower gain values at low current than at high current. This is because, at low currents, the flow of minority carriers is greater near the surface. The recombination of carriers at the surface removes carriers more effectively at low currents. It appears that this surface gain factor is always present and is simply increased by irradiation, an unexpected result since interface states are surface recombination sites and these are increased by irradiation. The change in gain can thus be interpreted as a change in the surface recombination term in the well-known Webster equation for the bipolar transistor. Stanley and co-workers obtained a large amount of data on the surface effect in bipolar transistors as part of the hardening programme for the Voyager project. $\Delta(1/\beta)$ versus collector current after irradiation by electrons of energy near 2.5 MeV was measured and found to vary from type to type by as much as 100 times.



The variability of gain degradation due to the surface ionisation effect is shown by the results of tests on a batch from one day's production. Irradiation was by ^{60}Co gamma radiation and the collector current was 10 mA (after Poch and Holmes-Siedle, 1968).

FIGURE 7.5 - VARIABILITY OF SURFACE EFFECT GAIN AS A FUNCTION OF DEPOSITED DOSE IN NPN BIPOLAR TRANSISTOR, TYPE 2N2102



Form of an engineering specification for "worst case" of surface damage figure as a function of collector current in 2N916 transistors of a given manufacturer. The specification is for a 99% probability of staying below the indicated degradation level (after Poch and Holmes-Siedle, 1968).

FIGURE 7.6 - SPECIFICATION OF SURFACE DAMAGE FIGURE IN BIPOLAR TRANSISTOR

7.4.2. Statistical prediction of surface damage

The radiation-induced loss of gain for a batch of devices analysed statistically, with $\Delta(1/\beta)_S$ as a measure of damage, has been found to have a frequency distribution fitting the normal Gaussian curve. For example, a set of 32 2N2102-type planar NPN transistors was irradiated to a dose level of 10^6 rads gamma radiation. When 'β' and 'β'$_0$ were measured at a collector current of 0.7 mA, the mean value of the damage figure was 22 x 10^{-3} and the standard deviation 7.4 x 10^{-3}.

If the assumption of normal distribution is valid and this 2N2102 sample can be considered typical of the entire population, then the probability that the anticipated value of the ionisation damage figure will not exceed a specified maximum at a specified radiation dose can be calculated. Values of $\Delta(1/\beta)_S$ determined in this manner can be treated as a "worst case" upper limit of anticipated transistor gain degradation. It is therefore feasible to predict degradation in the form of a "worst expected surface damage figure" plotted against collector current. This form of prediction may be a useful method of specifying surface effects in design documents.

7.4.3. Collector-base leakage currents

Increase in collector-base leakage currents I_{CBO} is usually due to the formation of a surface channel. Although slight increases in the 'I_R' term for the collector-base junction are produced by a reduction in the minority carrier lifetime, the values are usually a minor component of the reverse leakage. By contrast, a charge build-up in the oxide layer over the junction can produce a surface channel which conducts strongly. As a result, I_{CBO} values which, for planar transistors, are usually 10^{-9} or thereabouts, may increase tenfold for a dose in the 10^4 rad range. Onset as a function of dose is often quite sudden and probably not amenable to statistical treatment. Figure 7.7 shows a case of sudden onset and scattered results in a batch of 5 specimens.

7.4.4. The "Maverick" device

Unfortunately, one of the characteristics of bipolar transistor performance is the occurrence of the "maverick" or anomalous device. Such a device may be discovered in an otherwise normal batch, all processed in an essentially similar manner. It is anomalous in that it exhibits a radiation-induced gain degradation much more severe than the "worst expected case". While most of the devices follow a well-defined band of surface-damage figure, the anomalously sensitive unit may show a degradation level which is higher by a factor of 50 or more. To design all circuits and associated shielding to tolerate this abnormal sensitivity and wide range of degradation characteristics would impose severe penalties with regard to size, weight, power drain and complexity. On the other hand, the occurrence of such a degree of degradation in a particularly vital component would be catastrophic to equipment performance. The existence of a "maverick" could easily be missed if small-sample tests were performed and, therefore, preselection test programmes should - if possible - specify large statistical samples of devices.

7.4.5. Annealing of surface effects

The thermal annealing of the surface effects in bipolar transistors follows the same trends as that in MOS devices. Interface states should anneal out at temperatures in the 100 to 200°C range and trapped charge should be removed between 150 and 300°C. Some relaxation may occur even at room temperature. Many, but not all, bipolar devices can be annealed by baking although quite a large amount of damage persists in some types. Thermal annealing as a basic preselection technique is not widely used.

The Irradiate-Anneal (IRAN) preselection procedure involves testing the entire quantity of any device proposed for use. On the basis of test results and design criteria, in the form of specified allowable degradation, the acceptable devices are retained (those that degraded within acceptable limits) and the unacceptable ones set aside for other, less critical, uses. Normally, the original (pre-irradiation) electrical characteristics can be restored, through an annealing process, to the samples selected for use without unacceptable loss of reliability. It must then be assumed that any subsequent in-flight irradiation to the same dose levels will cause the devices to degrade to approximately the same extent as during the test in the simulated environment. Following this procedure, the engineer has the added advantage of knowing in advance exactly what the degradation will be. Experiments by RCA and JPL to further evaluate the feasibility of this technique showed that IRAN preselection has limitations. JPL experience uncovered a number of cases where the degradation of devices subjected to re-irradiation was not the same as that of the original IRAN irradiation. From the JPL and RCA results, it would appear that the technique works only for certain bipolar devices.

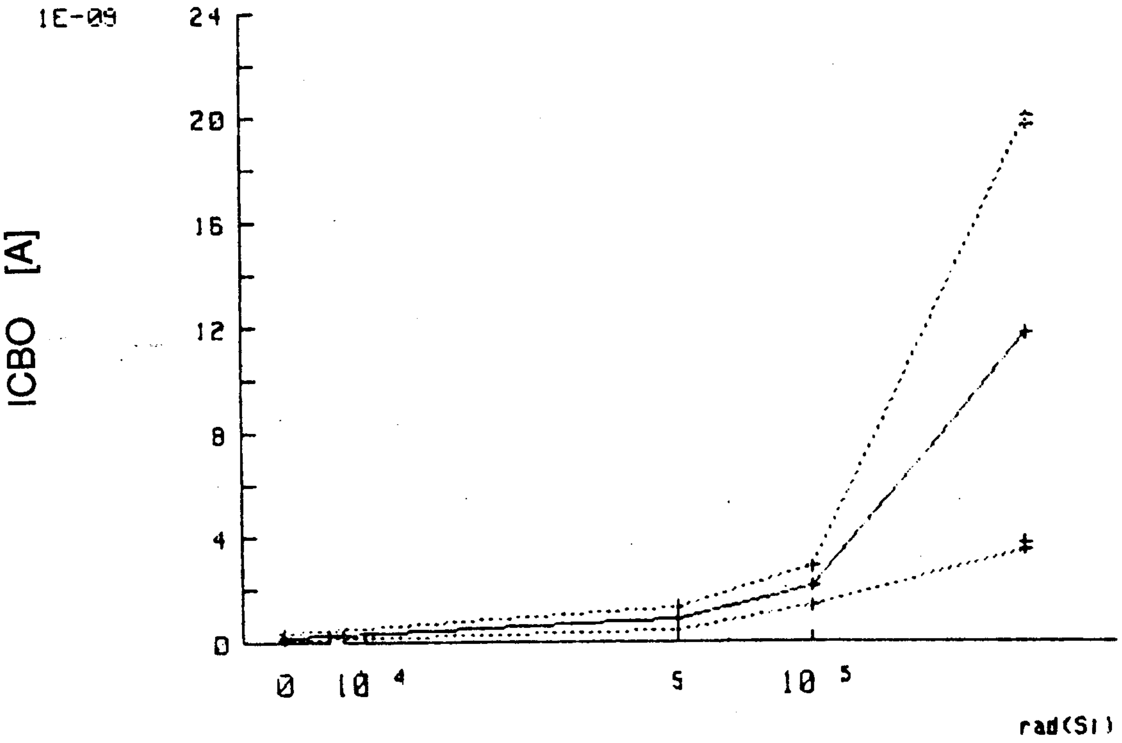


FIGURE 7.7 - EXAMPLE OF RADIATION-INDUCED LEAKAGE CURRENT IN A BIPOLAR TRANSISTOR

7.4.6. Thermal annealing of bulk damage

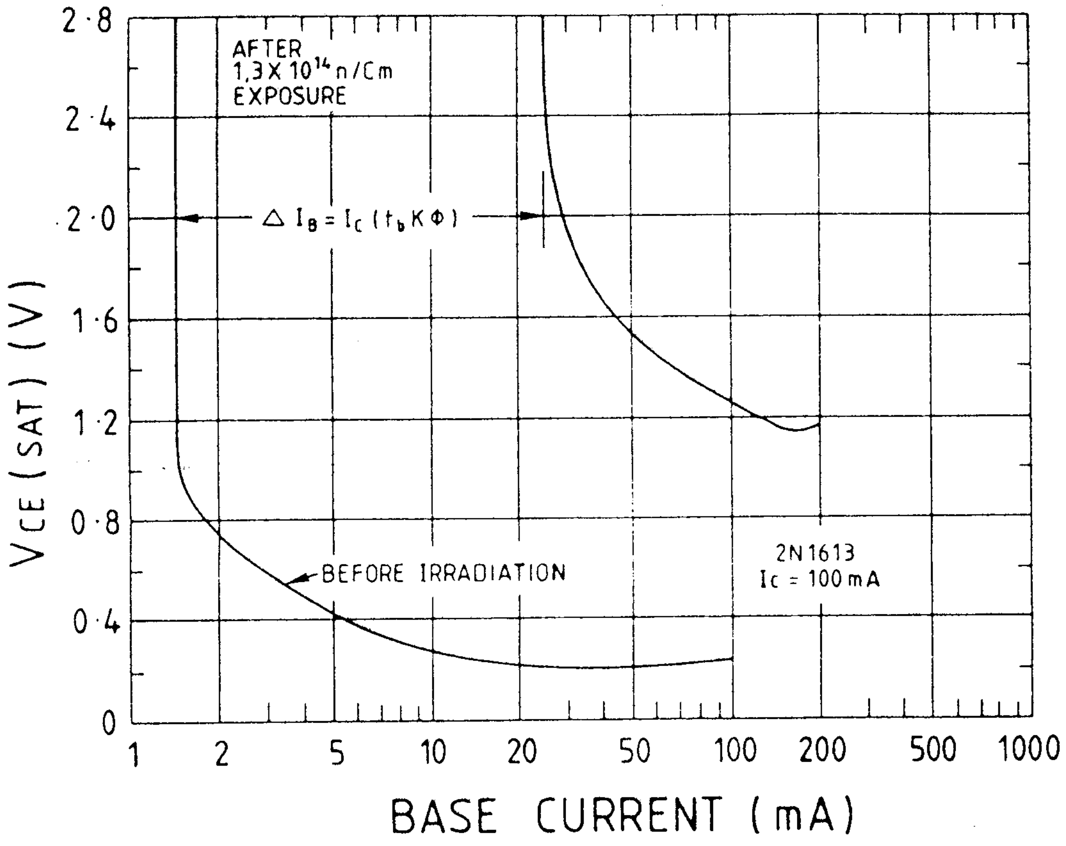
Radiation-induced displacement defects (bulk damage) in silicon do not anneal easily because the vacancies and interstitials created by the radiation are usually complexed with an impurity atom (oxygen or dopant). The defects which concern us most are those that are stable at room temperature, e.g. the 'A' centre (complex of a vacancy with oxygen) and the centres designated 'E' (phosphorus vacancy complex), 'J' (di-vacancy) and 'K' (divacancy-oxygen complex). These centres are completely stable at temperatures below 200°C, but the damage often anneals between 200 and 450°C completely. It is not easy to diagnose the damage effect in a commercial device. However, some information on the defects involved in transistor damage has been obtained by isochromal annealing in which devices are heated for the same time at several evenly spaced temperature steps.

7.4.7. Saturation voltage

The well-known "knee" in a plot of 'I_C' versus 'V_{CE}' with 'I_B' constant) for a bipolar transistor occurs at a low value of 'V_{CE} ' (typically 0.1 to 1V). "Saturation" occurs when 'V_{CE}' falls to the same order of voltage as the forward voltage on the base-emitter junction 'V_{BE}'. As 'V_{CE} ' falls, the collector-base junction, which must be biased in the reverse direction in order to produce high gain, becomes forward-biased. The transistor is then said to be in "saturation". As a result the gain falls dramatically, producing the "knee" in the 'I_C' and 'V_{CE}' curves. For certain types of application (saturated switches, power transistors), it is necessary for transistors to operate in saturation. An increase in the saturation voltage 'V_{CE}(SAT)' is usually harmful. By decreasing gain and increasing the resistivity of the silicon, particle irradiation can increase the 'V_{CE}(SAT)' value. For measurement purposes, 'V_{CE}(SAT)' is usually defined as the 'V_{CE}' value required to produce a given value of 'I_B/I_C' ("forced gain") near the "knee" described above. Figure 7.8 shows the changes induced in the saturation region by neutron irradiation. Owing to the effects described earlier, gain has fallen, but increases in silicon resistivity have also affected the 'V_{CE}' values required for a given ratio of 'I_B' to 'I_C' in saturation. For example, at 'I_B' = 50 mA (forced gain = 2), the required 'V_{CE}' value has been changed from 0.2 to 1.3V by an exposure of 1.3×10^{14} n.cm^{-2} (reactor neutrons).

An increase in the values of 'V_{CE}(SAT)' under particle irradiation is important for "saturation bipolar logic" devices such as the TTL series. In logic devices, when the pull-down transistor is turned hard "on", the value of the voltage drop across the device is low and equal to 'V_{CE}(SAT)'. If the silicon forming those junctions increases in bulk resistivity, then that voltage drop will increase. This effect, in turn, causes a change in logic output and moreover produces higher power dissipation in the silicon.

In power transistors, changes of the above sort are also serious because, in "high-voltage types", silicon of low resistivity is employed in the collector so that low values of breakdown are avoided. When the initial doping levels are low, a given particle fluence will alter the resistivity of the silicon more radically than that of a heavily doped material. Thus, in high-voltage power transistors, the increase in 'V_{CE}(SAT)' proceeds more rapidly under neutron exposure than in "low-voltage" amplifying or "fast" logic devices possessing heavily doped collectors. For example, a fluence of 10^{12} n.cm^{-2} may cause a "high-voltage" device to undergo 100% change in 'V_{CE}(SAT)' while a "low-voltage" device may undergo only a few per cent change.



(1.3×10^{14} n cm^{-2} ; E > 10 keV) (after Larin)

FIGURE 7.8 - CHANGE IN SATURATION VOLTAGE OF A SILICON NPN MEDIUM POWER BIPOLAR TRANSISTOR (2N1613) UNDER REACTOR NEUTRON/GAMMA IRRADIATION

7.5. BIPOLAR TRANSISTORS - SUMMARY

The effects of radiation on bipolar transistors can be divided into surface bulk effects as follows:

Type of effect	Phenomenon	Deleterious effects	Important radiation types	Damage units
Surface effects	Ionisation in oxides Photocurrent	Changes in surface properties	- Space - Gamma radiation - Electron beams	rad (Si)
Bulk effects	Atomic displacement	Changes in current-carrier properties (bulk damage)	- Nuclear reactors - Nuclear weapons - Particle beams	Equivalent 1 MeV electrons or neutrons
Transcient effects	Photocurrent generation	No long-lived effects unless latch up or burn out levels are reached	- Pulsed radiation	Not applicable

Physical analysis of these responses is possible and methods of systematic prediction and control of the responses are available. It should be mentioned that these methods require detailed knowledge of process techniques and solid-state physics.

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