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THE SENSITIVITY OF MICROWAVE BIPOLAR TRANSISTORS AND AMPLIFIERS TO IONIZING RADIATION

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ABSTRACT

It has been previously shown that small-signal microwave transistors are sensitive to ionizing radiation [2] and that this can lead to application limitations [3]. This paper extends the work to a wider range of currently used transistor types and amplifiers with applications ranging from low noise front-end to class C power output amplifiers. Two types of h_{FE} degradation have been identified viz. "permanent" and room-temperature current dependent "recoverable". Both types of degradation have been found throughout the range of transistor types and it is shown that they can also be simulated by avalanching the emitter-base junctions.

Class A amplifier performance of all power levels can be directly affected by either type of degradation and a detailed example is given in the more complex case of "recoverable" characteristics. Class C amplifiers are not directly affected by cumulative ionizing radiation doses of up to 1 Mrad (Si) or emitter-base avalanche although significant transistor h_{FE} degradation can occur in both cases. One example of microwave performance degradation in a Class B/C amplifier is described to illustrate the only known exception to this rule.

1. INTRODUCTION

Microwave bipolar transistors are frequently found in applications where the radiation environment must be considered. One practical example of such an application is that of the space environment where limitations due to the cumulative damaging effects of ionizing radiation on electronic components has led to a large effort on characterization and "hardening" of lower frequency devices [1]. The same effort has not been expended on microwave bipolar transistors despite the fact that they are now commonly used in communications spacecraft with 7 to 10 years design lives in geosynchronous orbits. There are also applications in scientific spacecraft which are intended to pass through high radiation fields such as those in the vicinity of Jupiter.

A recent study of small-signal microwave transistors has shown that commonly used devices can be sensitive to the cumulative effects of ionizing radiation [2]. The h_{FE} was shown to be the most radiation sensitive parameter and significant permanent degradation occurred under normal operating conditions at dose levels expected in many space applications. This d.c. degradation was shown to have an indirect but significant effect on the microwave performance of these devices due to the resulting change in bias conditions in practical bias circuits [3]. Irradiation of complete amplifier assemblies containing such transistors has confirmed that significant microwave performance degradation can occur at relatively moderate cumulative dose levels [3]. Estimates of equipment performance in geosynchronous orbits indicated that, with the present knowledge of the expected radiation environment and the aforementioned ground-based testing results, specifications would not be met for the full design life of the satellite without due care to radiation "hardening" design [3].

Detailed component and amplifier characterisation and analysis work referred to in References 2 and 3 related to three types of small-signal transistors from a specific manufacturer and in linear amplifier applications. Although similar effects had been observed on a wide range of transistor types from various manufacturers, not all these devices had been studied in the same detail [2].

Microwave bipolar transistors are used in a wide variety of applications from low noise linear receivers to high power class C transmitters and in view of the results of references 2 and 3 on small-signal linear applications, it is important to determine whether or not similar problems can occur in other device types and other applications. This paper presents the results of a study of the sensitivity of a wide range of microwave bipolar transistor to cumulative ionizing radiation effects. The problems of high dose rate irradiations such as those simulated in flash X-ray systems are not addressed in this paper. Supplementary work on emitter-base avalanche stress is also discussed. Results are presented for two general groups of transistors : 1) small-signal, 2) medium and high power. The former group is always used in class A applications, whereas the latter operates at higher current densities in class A through class C applications. Data already presented on small-signal devices is supplemented here with results on other manufacturer's devices and detailed new results are presented on other device types which exhibit current-dependent annealing. Individual transistor and amplifier degradation are discussed in terms of their effect on applications performance for both groups of devices.

2. SENSITIVITY OF SMALL-SIGNAL TRANSISTORS AND AMPLIFIERS

The effects of cumulative ionizing radiation on small-signal transistors have been described in some detail elsewhere [2] and an expression has been derived for the degradation of h_{FE} as a function of radiation dose, measured collector current, and starting value of h_{FE}. Since the h_{FE}'s of these commonly used devices were found to be very sensitive to radiation, small-signal transistors from other manufacturers were studied to determine the generality of the problem. In addition, amplifiers using these devices were also irradiated in instances where it was considered that this would add to the knowledge already gained from previous amplifier irradiation work [3]. Two types of parameter degradation were found viz. "permanent" and "recoverable"; and the experimental results are now presented separately in terms of these descriptions since they require different treatments.

2.1 Permanent Parameter Degradation

Permanent parameter degradation has been discussed in detail for three different transistor types from the Nippon Electric Co. (NEC) which are denoted A, B and C in Reference 2. The h_{FE} degradation of transistors A, B and C, whose commercial designations are 2SC1268, 2SC1336 (2N5650) and V222, respectively, obeyed the

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following relationship for the normalized h_{FE}, H, ($\equiv h_{FE}/h_{FEO}$) :

$$H = \left[1 + h_{FEO}\, C\, (I_C)^{(1/m)-1} (1-e^{-\beta D}) \right]^{-1} \qquad (1)$$

h_{FEO} is the pre-irradiation value of h_{FE}, I_C is the collector current in Amps and D is the radiation dose at chip level. For the transistor types discussed in Reference 2, the constants C, m and β were found to be 10^{-3}, 1.9 and 12 Mrads $(Si)^{-1}$, respectively. In order to compare the previously studied devices with new results, H is shown in Figure 1 as a function of h_{FEO} for a dose of 500 Krads (Si) which ensures saturated degradation. These results apply for a collector current value of 4 mA. This value of collector current has been chosen since results may be more easily compared with devices described in the next section.

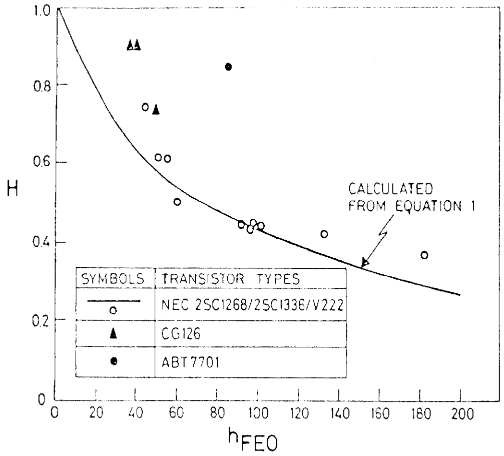

Figure 1. A comparison of permanent h_{FE} degradation of small-signal transistors from different manufacturers for the same collector current (4 mA) and irradiation dose (500 Krads (Si)).

Results of irradiating similar devices from other manufacturers are also shown on the same figure. Fewer devices were available from other manufacturers (2 to 5 each) and a large spread of h_{FEO} values was not possible for comparison. Ionization damage dominates displacement damage from high energy electrons up to cumulative doses 2 x 10^6 rads (Si) [2] and, consequently, the devices were irradiated with X-rays since this was more convenient. A 150 KV tungsten target bremsstrahlung X-ray tube which was calibrated with TLD's was used at dose rates between 1 and 10 Krads (Si) min^{-1}. The transistors were clamped in a 50 ohm microstrip jig with bias tees and 50 ohm terminations to ensure stable operation at the operating bias during irradiation. In general, these transistors were less sensitive than those of NEC and did not saturate at 500 Krads (Si). Figure 1 does not, therefore, show the maximum degradation attainable for the Compagnie Generale d'Electricite CG 126 and the Avantek ABT 7701 but, since this occurs at dose levels in the Mrads (Si) region, this is of no practical interest for most applications. Figure 1 may therefore be used as direct comparison of the relative radiation sensitivity of the various devices and the basic sensitivity since the emitter peripheries were comparable. The differences in radiation-induced base current components, cannot, therefore, be explained by geometry alone. Apart from the difference in h_{FE} sensitivity, the transistors shown in Figure 1 behaved in the same general manner and the degradation was permanent. No significant annealing effects were measured at room temperature.

Since the microwave S-parameter/collector-current functions were found to be similar for all the above devices, it was not necessary to irradiate amplifiers built with these devices to determine their applications limitations. The results already obtained from amplifiers built with transistor types 2SC1268, 2SC1336 and V222 [3] can be extended to given an estimate of the results for devices with lower sensitivities.

It is concluded that transistors can be chosen which have a relatively low radiation sensitivity and the judicious choice of such devices is the first step in radiation hardening of the equipment in which they are used. Equipment designers have not taken radiation sensitivity into account in the past and have normally designed around devices which have the best microwave performance, but clearly these devices may be the most radiation sensitive. It should be noted that a determination of h_{FE} sensitivity alone may not be sufficient to predict overall equipment performance and the procedure for radiation hardening at equipment level described in Reference 3 is recommended for applications involving the aforementioned types of devices with permanent degradation.

2.2 Recoverable Parameter Degradation

2.2.1 General description

All the transistors described in the previous Section had similar gain and noise figure performance characteristics in the frequency range up to 4 GHz. These performances have been exceeded recently by two types of transistors with high f_T's (8.5 and 12 GHz) and lower noise figures (~1.7 dB[1] at 2 GHz). Both device types are produced by NEC and are designated NE 645 and 644 referring to the 8.5 and 12 GHz f_T's respectively. Equipment level performance advantages in using these transistors in broad-band low noise front end receivers is such that they are being designed into U.S. and European satellites. Both types of transistor exhibited a different radiation sensitivity behaviour from that reported for the devices described in the previous Section and a more detailed description of this behaviour is now presented.

Irradiations were carried out with X-rays as described in Section 2.1 and the V_{CE}/I_C bias conditions for minimum noise conditions applied during irradiation were : 8V/7mA for the NE 645 and 6V/5mA for the NE 644. These currents correspond to approximately the same collector current density as the 4mA current used for measuring the transistors of Figure 1. Both types of device exhibited a greater h_{FE} sensitivity than found for any of the devices described in Section 2.1. Since the basic technology and radiation behaviour were the same for both, detailed results are presented for the NE 645 only. The h_{FE} degradation was accompanied by a room temperature recovery with bias which was considerable but not complete. Figure 2 illustrates the degradation of an NE 645 transistor measured at three different collector currents covering all possible application levels. After each irradiation, the devices were allowed to recover at 8V/7 mA bias for about 30 mins. Results for a 2SC1268 transistor with a permanent degradation are shown for comparison. The h_{FEO} value for the 2SC1268 transistor is higher than that for the NE 645 device and yet it is considerably less sensitive at low doses. There is almost an order of magnitude difference in the dose which results in the same h_{FE} degradation before saturation effects take place.

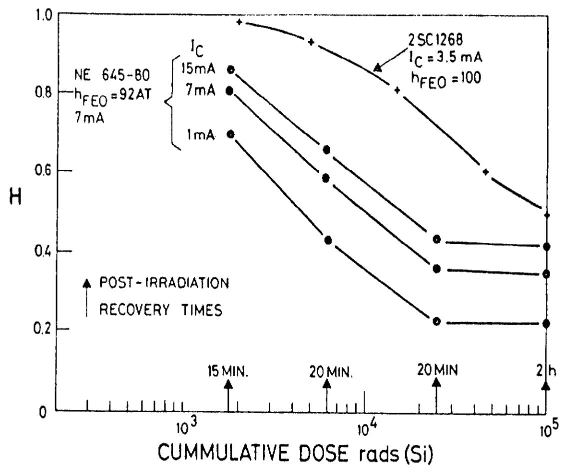

Figure 2. h_{FE} degradation of an NE 645 transistor after short-term stabilization periods. The permanent degradation curve for a 2SC1268 device is shown for comparison.

This type of behaviour was not limited to NE 644 and 645 types of transistors. Hewlett-Packard (HP) transistor type HXTR 6104 which has a similar microwave performance exhibited similar effects at the same collector current density. There was no significant difference in sensitivity, with, in this case, H = 0.6 at D = 5 x 10^4 rads (Si) and saturating at H = 0.35 at D = 5 x 10^5 rads (Si) for an h_{FEO} of 160. These figures indicate a lower sensitivity than that shown for an NE 645 in Figure 2 at low doses. Values of H at doses high enough for saturation are not significantly different between the two device types.

It is clear that the radiation-induced h_{FE} degradation could lead to severe performance limitations since the S-parameters of these devices are as sensitive to collector current as those of Section 2.1.. The degradation mechanism did not fit the pattern previously described for permanent degradation [2] so more detailed characterisation was necessary and most of this was carried out on the NE 644/645 transistors.

2.2.2 Detailed characterization of degradation and recovery effects

Detailed characterization of d.c. current-voltage relationships were performed to compare with the 2SC1336, 2SC1268 and V222 transistors. In addition, low frequency noise measurements were performed since this is a measurement of interface state density which is otherwise impossible on bipolar transistors that do not have specially constructed base gate regions [4]. This electrical characterization was carried out for degradation and recovery studies of irradiated devices and control devices intentionally degraded by emitter-base avalanche. The reason for this comparison was that the latter degradation mechanism has been studied, longer[5] has also been reported to have recovery effects [6], and a comparison could lead to more insight into the mechanisms of radiation induced degradation [7] and recovery. It should be noted that, although the term "avalanche" is used here, the doping densities in the emitter-base regions of microwave transistors result in breakdown voltages in the region of 3 to 5 volts. This certainly indicates that tunneling, rather than avalanche is the dominant current generating mechanism [8].

The basic reason for h_{FE} degradation by radiation or hot carriers is the generation of interface states and/or positive change trapped in the oxide. Both effects can give rise to an increase in surface recombination but it is difficult to separate one from the other with the present device structures [2]. Increased surface recombination gives rise to an increased base recombination current with the form $I_B \sim \exp\left(\frac{q V_{BE}}{2kT}\right)$. Figure 3 illustrates this effect by displaying I_C and I_B as functions of V_{BE} before and after an irradiation dose of 500 Krads (Si). The collector current is unaltered by radiation and retains its form $I_C \sim \exp\left(\frac{q V_{BE}}{2kT}\right)$ over most of the range of values. Exactly the same detailed characteristics were found for emitter-base avalanche degradation. There is no difference in this base current increase feature between any of the device types discussed thus far in this paper including those in Section 2.1..

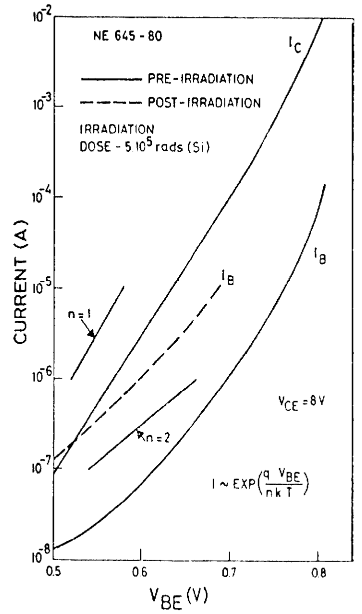

Figure 3. Collector (I_C) and base (I_B) currents as a function of emitter-base voltage (V_{BE}) before and after irradiation, demonstrating increase in base surface recombination current (n = 2). I_C is not radiation sensitive.

Although the reverse leakage current I_{CBO} and I_{CEO} increased due to irradiation, the absolute level was still low (<100 pA at 8V) and I_{BEO} did not change. On the other hand I_{EBO} was the only parameter which did change in the case of avalanche stress. Breakdown voltages BV_{CBO}, BV_{EBO} did not change due to either type of stress. Transistors with permanent degradation effects on the other hand demonstrated marked BV_{CBO} degradations (e.g. -13% for 500 Krads (Si))and this has been explained in terms of positive charge generated in the oxide [2].

An example of the change in the noise characteristic after irradiation is shown in Figure 4 for the same device and radiation conditions as shown in Figure 3.

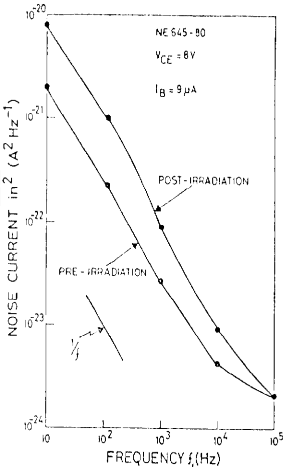

Figure 4. Noise current as a function of frequency, showing the increase in the 1/f region due to irradiation. Device and irradiation conditions are the same as those of Fig. 3.

The relationship between the equivalent input noise current, i_n, and surface recombination velocity in the 1/f region is given by[9] : -

$$\overline{i_n^2} \propto \frac{S_o I_B^n}{f} \qquad (2)$$

where n is a constant (1-1.5), f is the frequency, I_B the base current and S_o is the surface recombination velocity. Since S_o is proportional to the interface state density N_{ss}, the noise current is also directly related to N_{ss} through (2). I_B was kept constant for all noise measurements. Although the contributions to 1/f noise from bulk and surface recombination centers cannot be separated before irradiation, the post-irradiation base current is certainly dominated by surface currents as shown in Figure 3. The results shown in Figure 4 indicate, therefore, that the ratio N_{ss} (post-irradiation) : N_{ss} (pre-irradiation) is at least 3 : 1. Similar results were obtained with an emitter-base avalanched device which was degraded to give the same relative I_B/V_{BE} relationship shown in Figure 3.

NE 644 and 645 transistor types were found to recover their characteristics at room temperature if they were biased in the forward (active) mode. The recovery rate was a non-linear function of collector current as shown in Figure 5. Recovery of H for two similarly degraded transistors is shown for 7 mA, 15 mA and 35 mA.

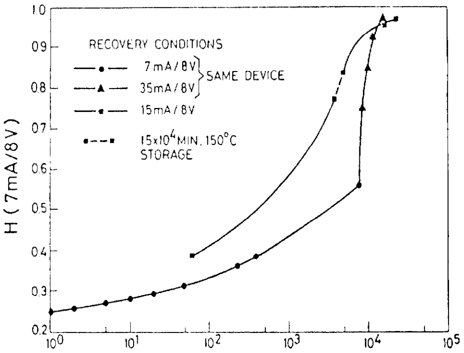

Figure 5. Room temperature recovery of the function H with different constant collector currents for two NE 645-80 transistors after irradiation.

This shows that both the form of recovery and its current dependence are complex and it is only possible to express H as segmented logarithmic functions. The effect was not a purely thermal one since junction temperatures of less than 100°C arose from heating and the isothermal annealing step of 1.5 x 10^4 min. at 150°C shown in Figure 5 resulted in a negligible annealing effect on the 15 mA recovery characteristic. This is supported by the fact that slow but significant annealing was measured at collector currents as low as 100 µA (8V) where the junction temperature rise above ambient is less than 1°C. In contrast to this, only slight long term annealing at high currents was observed on "permanently" degraded devices. As a further complication to quantifying the effect, it was found that the recovery characteristic is, to a certain extent, dependent on the depth of degradation as shown in Figure 6.

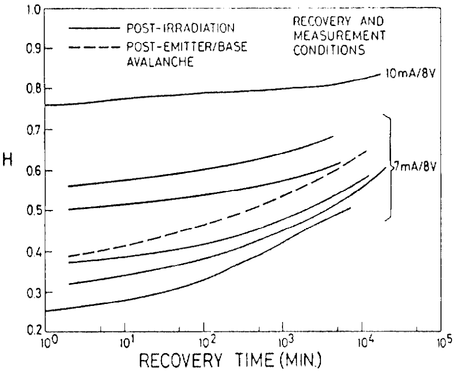

Figure 6. Room temperature recovery of H for NE 645-80 transistors showing dependence on depth of degradation and similarity between irradiation and emitter base avalanche stressed devices.

In this example, the recovery of three different devices at 7 mA and one at 10 mA is shown. Some of the curves were generated by sequentially irradiating and recovering the same device. The greater the degradation, the faster is the recovery. This is clearly illustrated by the device which was degraded to H≈0.75 and, although it was recovered at a higher current, it will clearly take an extremely long time to fully recover. Where almost complete recovery has been achieved by using high collector currents, the d.c. characteristics and 1/f noise returned to their pre-irradiation values at normal operating bias levels. Recovery of a device which was degraded by emitter-base avalanche is also shown in Figure 6 and, despite the faster recovery rate, the recovery mechanism is clearly very similar to that of irradiated devices.

Similar 1/f noise measurement results and recovery behaviour were found for HP HXTR 6104 type transistors. A comparable set of recovery curves as those shown in Figure 6 were generated by sequential irradiate and anneal experiments and the significant difference was that the recovery rate was much faster than in the case of the NE 645 transistors. For example H recovered from 0.37 to 0.5 in 140 minutes for an HXTR 6104 whereas, for the same recovery with the same collector current density, an NE 645 device took an order of magnitude of time longer.

It is quite clear from the results of these experiments that these device types are extremely radiation sensitive but, in any specific application, the current-dependent recovery effect must be accounted for. This problem is now discussed in detail for the NE 645 transistors since, of those devices studied thus far, these exemplify the highest sensitivity and lowest recovery rate. Devices operated in cold redundancy (i.e. no bias) for long periods may, when switched on, have h_{FE} values only 10% of the original value and, unless they are operated at high currents (e.g. 20-30 mA), recovery could be too long to be of any practical benefit. Devices continuously operated at high currents may not show any appreciable net degradation since their recovery rate may exceed their degradation rate.

In most practical applications the current operating range is 7-10 mA and, since the net degradation of a device depends in a very complex manner on the dose rate and collector current, it has been impossible with the number of devices available for experiment to derive a general mathematical expression which accounts for the net degradation of devices at different collector currents and dose rates. There is sufficient data on degradation and recovery at the typical application current level of 7 mA to make a graphical representation of degradation and recovery when these effects occur simultaneously. The first step was to experimentally determine H at 7 mA/8V bias as a function of dose, D, under conditions where negligible recovery was allowed. H was then calculated as a function of time for four different chip level dose rates viz. : $\dot{D} = 1$, 10^{-1}, 10^{-2}, 10^{-3} rads min^{-1}. This results in a family of degradation curves H (7mA/8V) as a function of time and these are displayed as broken lines in Figure 7.

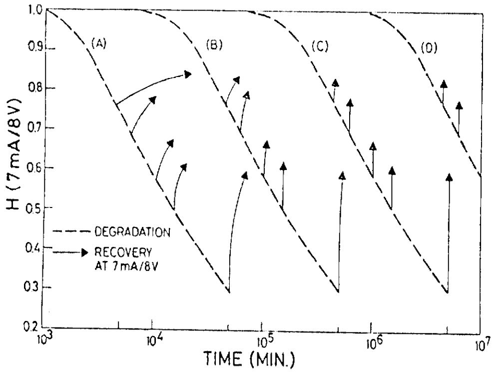

Figure 7. Degradation and recovery of H as a function of time for different irradiation dose rates (A) $\dot{D} = 1$ rad min^{-1}, (B) $\dot{D} = 10^{-1}$ rad min^{-1}, (C) $\dot{D} = 10^{-2}$ rad min^{-1}, (D) $\dot{D} = 10^{-3}$ rad min^{-1}.

Superimposed on the degradation curves are recovery curves which start at the specific values of H where they have been measured. In a practical situation where degradation and recovery co-exist, there would be no net degradation if $\dot{H} = 0$. In the case of $\dot{D} = 1$ rad min^{-1} the degradation rate is faster than the recovery rate until H = 0.6 to 0.7. At this level, degradation and recovery rates are equal and H (t) will the saturate. In order to confirm this, a device was irradiated at a dose rate of $\dot{D} = 1$ rad min^{-1} which was simulated by slow irradiation and recovery and it was found that H = 0.6 was indeed the saturated value. It is impractical to determine experimentally whether this would apply equally well in practice for the lower dose rates. If it is assumed that it would apply, the saturated values of H can be determine from Figure 7 by determining where the slopes of the degradation and recovery curves are equal. Since the recovery curves are a function of time, and are steeper for lower dose rate curves, the points at which $\dot{H} = 0$ occur at higher values of H for the lower dose rates. From Figure 7 the saturated H values are estimated at H = 0.7-0.8 for $\dot{D} = 10^{-1}$ rad min^{-1}, and H = 0.9 for $\dot{D} = 10^{-2}$ rad min^{-1}. Degradation would be almost entirely dominated by recovery for lower dose rates.

Additional recovery experiments were carried out whereby the base current, rather than the collector current was held constant. In practice the bias circuit usually biases the devices somewhere between these two conditions [3]. Recovery curves for H and I_c were comparable to those of Figure 6 and it may be concluded that Figure 7 may be used to estimate the effect of dose rate on net degradation of NE 645 transistors operating at normal collector currents. The time taken to reach this level of degradation is also found from this Figure.

2.3 Physical Mechanisms for Permanent and Recoverable Degradation Effects

The radiation-induced d.c. parameter changes observed in the cases of permanent and recoverable degradation effects indicate that the basic physical mechanisms involved are entirely different. This is further supported by the emitter-base avalanche experiments whereby h_{FE} degradation was found to require much less stress for an NE 645 than 2SC1336 device. (In the former case H = 0.4 after an avalanche current stress of 100 μA for 15 mins., whereas in the latter case, it took one hour to reach H = 0.77 with five times the current density). A physical model based on the well known generation of positive oxide charge has already been proposed to explain the permanent degradation effects observed on small-signal microwave transistors [2]. This model does not, however, fit the experimental observations on NE 645 and HP HXTR 6104 transistors described in Section 2.2.2 of this paper. These results indicate that there is very little effective oxide charge since there is no significant change in collector breakdown voltage. On the other hand there is clearly a large increase in the surface component of base and collector currents which is due to an increase in surface state density N_{ss}. The experimental evidence points to a more direct increase in N_{ss} rather than an indirect effect due to a change in surface potential as is postulated for the case of permanently degraded devices [2]. This hypothesis is further strengthened by the similarity between the effects of irradiation and emitter-base avalanche stress for recoverable devices. In the case of emitter-base stress it is known that interface states and oxide charge may be simultaneously generated and the technique has recently been proposed to study these effects in MOS structures to compare radiation hardness of different oxides [7]. Our results indicate that this is also a valid technique for bipolar transistors. The fact that both types of stress induce effects which may be annealed using forward bias currents indicates once more that direct production of N_{ss} is the basic physical mechanism for degradation. The majority carriers injected into the surface emitter-base region under forward bias recovery conditions do not have the energy required to overcome the Si-SiO$_2$ barrier to annihilate oxide charge, but could reach charge within tunneling distance.

It was observed that h_{FE} degradation was highly dependent on whether or not the transistor was actively biased. This effect was of the same magnitude as that found previously for permanently degraded transistors [2].

Further experiments comparing devices irradiated with normal active bias, 3V reverse bias on emitter-base only and no bias whatsoever, show that forward or reverse biased junctions result in the same higher h_{FE} sensitivity. This means that in the interdigitated transistor structure, the field in the parallel MOS capacitor plays a negligible role compared to the junction fringing field as was proposed in reference 2. It is known that bias conditions can also affect the production of N_{ss} in MOS devices[10] and this can be due to a complex interaction with positive charge produced in the oxide and forced to the interface by an electric field[11]. It cannot therefore be categorically stated that there is no influence of oxide charge on the production of N_{ss}. Even in studies on gated bipolar transistors a separation of these effects has proven difficult[4].

It is possible that the interface states introduced (directly or indirectly) by radiation or hot carriers may be annealed by interaction with the diffusion current or possibly the recombination current itself. The experiments indicate that, since the recovery process is independent of whether or not the diffusion current is constant (constant I_C) or varies (constant I_B) during recovery, there is no direct relationship. Recombination current annealing has been observed in irradiated GaAs light emitting diodes[12] and this may be explained by a mechanism whereby electron-hole recombination at the defect enhances its annealing[13]. This mechanism may equally well apply to the recovery process described here for bipolar transistors.

2.4 Amplifier Performance Degradation

In view of the relatively high sensitivity of the NE 644/645 transistors, a typical low noise front-end amplifier using these devices was irradiated. Figure 8 shows the amplifier schematic and the associated bias circuits for each stage.

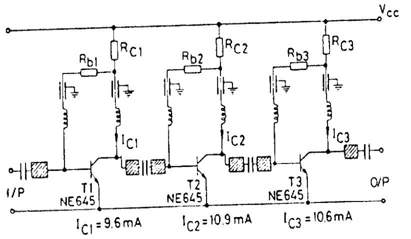

Figure 8. Schematic diagram of MIC (0.8-1.3 GHz) low noise amplifier. Distributed microstrip elements are indicated by shaded areas.

Since complex recovery and degradation effects were expected, the results are presented in terms of performance changes for specific h_{FE} changes. The radiation doses required to arrive at these changes are relative since the transistors were allowed sufficient time to recover after irradiation so that stable microwave measurements were possible. Results of radiation-induced degradation on overall gain and noise figure are shown in Figure 9.

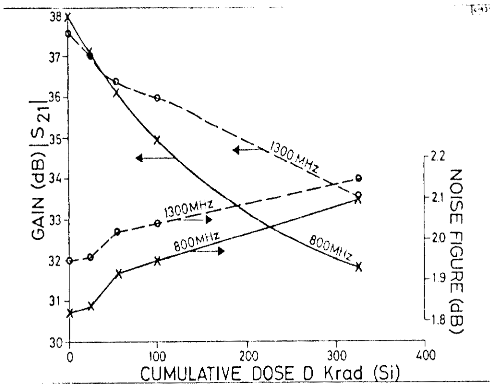

Figure 9. Gain and noise figure as a function of cumulative irradiation dose, D, for amplifier shown in Figure 8.

These parameter changes correspond to h_{FE} changes in the three transistors as shown in Figure 10 where the same relative dose as Figure 9 is displayed.

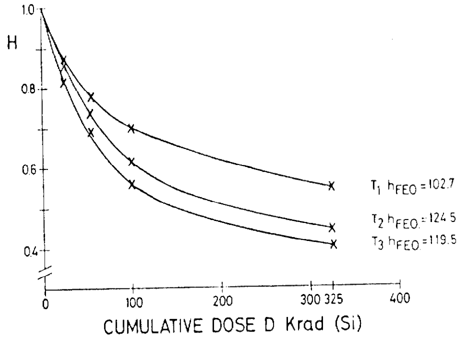

Figure 10. Normalized h_{FE} (H) as a function of cumulative irradiation dose, D, for the three transistors T_1, T_2 and T_3 of Figure 8.

There are slightly different h_{FEO} sensitivities for different devices due to different h_{FEO} and I_C values, but in general the amplifier goes out of gain specification (ΔG = 2 dB) at $H \doteqdot 0.8$. Further optimization of the bias networks will not eliminate h_{FE} degradation unless active bias networks are used[3]. Survival time predictions of the type detailed in Reference 3 for amplifiers showing permanent degradation effects are not useful to the designer in this instance since they are a function of dose rate. It is more useful to calculate the dose rate at which H saturates at an acceptable level. In the case of the present amplifier we require $H \geqslant 0.8$ and, in order to find on which curve H saturates at 0.8, we refer to Figure 7. The recovery rate is greater than the degradation rate at $D \leqslant 10^{-2}$ rad min^{-1} for $H \geqslant 0.8$.

If we apply the same geosynchronous dose-depth curve as used for previous space amplifier shielding calculations[3], and assume that the incident dose is linear with time, the 4 π shielding thickness required to give $\dot{D} < 10^{-2}$ rad min^{-1} is $\geqslant$ 4.5 mm Al. Two other linear amplifiers using the same transistors operating at higher current level (17mA) were also irradiated. Due to the lower sensitivity of h_{FE} at higher collector currents there was no significant performance degradation ($\Delta G < 0.5$ dB for radiation doses up to 1 Mrad).

3. SENSITIVITY OF MEDIUM AND HIGH POWER TRANSISTORS AND AMPLIFIERS

3.1 Introduction

Although medium and high power microwave transistors operate at higher d.c. current levels and collector voltages, they have similar junction geometries to small-signal devices. Whereas small-signal low-noise transistors have interdigitated emitter-base junctions, higher power transistors can have structures with even higher emitter-periphery to base area ratios and often incorporate matching circuits comprising MOS capacitors [14, 15]. In addition, the use of larger numbers of emitter fingers and multi-cell designs for heat partitioning means that radiation-sensitivity at the working bias current is as likely as with small-signal devices. Since h_{FE} is clearly the most important radiation-sensitive parameter, the following results on irradiating and avalanche stressing medium and high power transistors and amplifiers concentrate on the sensitivity of this parameter and its effects on performance degradation.

3.2 Medium Power Cases

Medium power transistors are generally used either in linear class A applications similar to those described for small-signal transistors or in class C amplifiers. Both permanent and recoverable types of h_{FE} degradation have been observed in this category of transistor. Figure 11 shows the degradation at low current and recovery at different current levels for one of the latter types of device (TRW 54201).

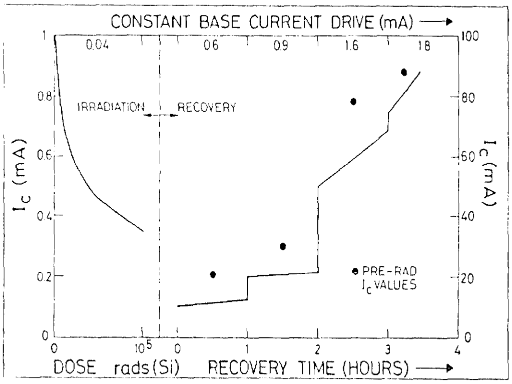

Figure 11. Radiation-induced degradation at low current and current-induced recovery at successively higher constant base currents for the TRW 54201 medium power transistor. Pre-irradiation collector currents are shown for the same base currents.

This device is normally operated in a class A, common emitter, medium power amplifier at 100 mA/20V with 500 mW output at 2 GHz and 10 dB gain. Unless the device is used in a cold redundancy condition, it is clear that the normal operating current should be sufficient to maintain a recovery rate higher than the degradation rate in most radiation environments. An example of permanent degradation is the RTC LKE 32001 which is also normally operated in a common-emitter configuration. In this case the normalized h_{FE} at the application bias of 50 mA/10V and a dose of 500 Krads (Si) was H = 0.5 for h_{FEO} values between 50 and 70. If this result is compared with those for small-signal devices in Figure 1 it is evident that this medium power device is inherently more sensitive. It should be noted that the current density at 50 mA in the medium power device is about twice that of the small-signal devices which were measured at 4 mA. It may be concluded from this that all class A linear amplifiers designed for applications in a radiation environment should follow the same design rules as laid out in Reference 3 for the special case of small-signal transistors. It cannot be assumed a-priori that high current applications necessarily mean low radiation sensitivity. This criterion may however apply to lower frequency transistors where the junction layout is differently designed. Comments on class C operation are the same for medium and high power transistors and, although the next section details results on high power transistors only, i.e. the results apply equally well to the few medium power applications in this class.

3.3 High Power Cases

Transistors operating in high power conditions either in class C or some similar hybrid class are expected to be less sensitive to changes in h_{FE}. The reason for this is that this mode of operation is similar to switching from cut off to saturation [16] and the h_{FE} does not directly affect this action, unless it is significantly degraded at high current levels. The transistor is not directly biased and only operates when the input power is above a certain level required to drive it into conduction and the d.c. current is the mean of resulting high current "pulses" in the collector. The h_{FE} does not affect this d.c. bias current directly as in class A amplifier since it is a function of input power, transistor a.c. gain and circuit topology. Different types of high power transistors have been found to show "permanent" h_{FE} degradation due to irradiation but, in the cases where they were operated in class C amplifiers, it was found that the microwave performance was not affected by h_{FE}.

Transistor Type	h_{FEO}	h_{FE} at 500 Krads	AMPLIFIER PERFORMANCE AT 1.5GHz, V_{CC}= 28V		
	I_C = 100 mA	V_{CE} = 5V	I_C mA	P in mW	P out W
MSC 3005	62	32	510	334	6
TRW 2003	23	18	468	220	3
TRW 1417-11	28	9	390	1160	5

Table 1. Results of single stage class C amplifier radiation-induced degradation.

Table 1 summarizes these results for three transistor types and three amplifiers. Operation at saturated power outputs for a few hours recovered the original h_{FE} values. In this case, the recovery is a combination of temperature ($T_j \sim 150^\circ C$) and current annealing. Since it occurs relatively rapidly and microwave performance is not affected by h_{FE} degradation or recovery the phenomenon has not been studied in any more detail.

Degradation of the same three amplifiers with an emitter-base d.c. avalanche current stress has also been studied and similar results for h_{FE} degradation and recovery without affecting the microwave performance were found. It cannot be assumed that all high power transistor cases are totally insensitive to h_{FE} degradation since it has been shown that significant power gain drops due to emitter-base microwave frequency avalanche stress can occur [17]. Figure 12 shows an example of the degradation of H as a function of time due to the aforementioned type of emitter-base stress.

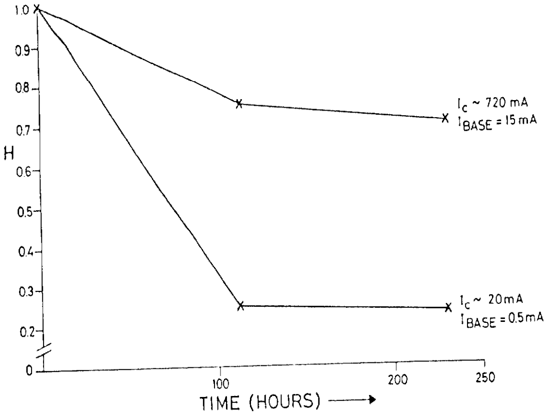

Figure 12. Degradation of normalized h_{FE} (H) of class B/C amplifier as a function of time for a peak multicarrier input drive of 4 W.

The class B/C amplifier operates at 10 W out at 1.5 GHz and uses an internally matched TRW transistor with four SB2000 cells which are exactly the same type as those used in the TRW 1417-11 four cell transistor shown in Table 1. The emitter-base stress was induced by driving the amplifier with an input pulse of 4 W peak, 1 W mean power which simulates the multicarrier input signal (>12 carriers) for which it was designed [17]. Figure 13 shows the microwave transfer characteristics corresponding to the pre- and post stress conditions.

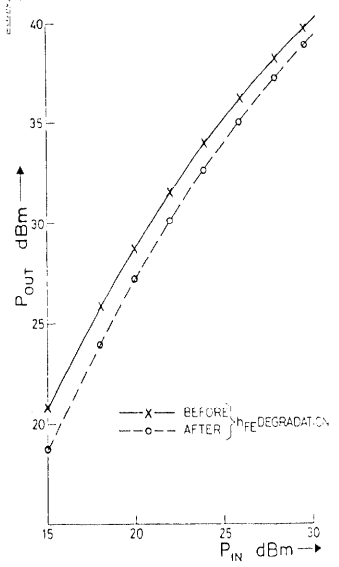

Figure 13. Power transfer characteristics of class B/C amplifier at 1.5 GHz before and after the h_{FE} degradation shown in Figure 12.

It can be seen that a gain degradation of 1 to 2 dB occurs and this can affect the overall amplifier performance [17]. Annealing under c.w. drive conditions was found to be similar to that mentioned for pure class C transistors. The class B/C amplifier results appear to contradict those of Table 1 but it should be noted that the degradation at the operational current level was lower for the class C amplifiers. It was impossible to determine whether or not the type of stress affected microwave performance degradation since the physical and circuit construction did not lend itself to radiation studies. The fact remains that microwave and d.c. degradation can be related even in large signal transistors and it is conceivable that radiation-induced degradation could lead to similar effects. It is therefore advisable to investigate each high power amplifier configuration on a case by case basis.

Since many types of high power transistors contain amplifier matching networks, it is important to determine whether or not the MOS matching capacitors used as part of these networks could drift in value due to radiation. Capacitance-voltage measurements have been made on the MOS capacitors in TRW 1417-11 transistors after isolating them from the transistor chips. It was found that there was no voltage dependence of the 1 MHz capacitance. This means that a high substrate doping level is used and that there should, consequently, be no change in the capacitance value with radiation. The latter fact was confirmed up to a cumulative dose of 2 Mrads (Si) and can also be inferred from the results of Table 1.

CONCLUSIONS

It has been shown that most microwave bipolar transistors are, to a certain extent, sensitive to accumulated ionizing radiation dose. Since h_{FE} is the most important parameter for linear amplifier applications, these investigations have concentrated on its sensitivity for the various power levels of transistors. Both permanent and recoverable types of h_{FE} degradation have been observed and it is concluded that, in both cases, significant amplifier performance degradation may occur in small-signal and medium power applications. In general, class C amplifiers are less sensitive to radiation-induced degradation but it has been shown that microwave performance can be impaired by emitter-base avalanche stress. It is, therefore difficult to pre-determine whether or not a specific transistor technology or amplifier configuration is radiation-sensitive. If sensitivity is established and the degradation is permanent, then there are well established guidelines for solving the ensuing radiation hardening problem [3]. On the other hand, the phenomenon of recoverable h_{FE} leads to a much more complex situation where the recovery characteristic at the bias level used in the application must first be determined. Once this is known, it may be decided that recovery is fast enough to overcome degradation in a slow dose rate environment (e.g. TRW 54201 Section 3.2). Recovery may also be so slow that a net degradation will result (e.g. NE 645 Section 2.2.3). It should be noted that this situation would be totally different in the case of high dose rate irradiations such as those simulated in flash X-ray systems but this type of problem is not addressed here.

Insufficient evidence has been gathered to determine the exact physical mechanism for this type of radiation sensitivity and the reasons for its variation from device type to device type. It is necessary to build special device structures to study these effects at a more fundamental level [4]. One tentative conclusion, based on a comparison between irradiated and emitter-base stressed devices, is that direct generation of interface states is the most likely mechanism for transistors which show current annealing effects.

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