Origins of Total-Dose Response Variability in Linear Bipolar Microcircuits*

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Abstract-- **LM111 voltage comparators exhibit a wide range of total-dose-induced degradation. Simulations show this variability may be a natural consequence of the low base doping of the substrate PNP (SPNP) input transistors. Low base doping increases the SPNP's collector to base breakdown voltage, current gain, and sensitivity to small fluctuations in the radiation-induced oxide defect densities. The build-up of oxide trapped charge (N_{OT}) and interface traps (N_{IT}) is shown to be a function of pre-irradiation bakes. Experimental data indicate that, despite its structural similarities to the LM111, irradiated input transistors of the LM124 operational amplifier do not exhibit the same sensitivity to variations in pre-irradiation thermal cycles. Further disparities in LM111 and LM124 responses may result from a difference in the oxide defect build-up in the two part types. Variations in processing, packaging, and circuit effects are suggested as potential explanations.**

I. Introduction

The radiation-induced degradation in the LM111 voltage comparator's input bias current (I_{IB}) has been the subject of numerous studies [1-8]. Among the distinctive features of this circuit's response to radiation exposure are: 1) the dependence of I_{IB} on the type of radiation (Cobalt-60 gamma rays versus 2 MeV electrons) [6] and 2) the appearance of a "true" dose rate effect [1-5, 7, 8]. Furthermore, recent papers that consider the enhanced low dose rate sensitivity (ELDRS) of bipolar linear circuits have revealed an extremely broad distribution in the total dose response of the LM111 [1, 3].

The input bias current of the LM124 operational amplifier has also demonstrated a "true" dose rate effect [4, 5, 9-11]. Moreover, the enhanced dose rate sensitivity of the LM124 has been shown to be comparable to the LM111 [5]. However, comparisons of the two circuits reveal the LM124 to be a harder part [5] that exhibits very little part-to-part variability in its I_{IB} response. The LM111 and LM124 parts considered in this work were manufactured by National Semiconductor in the same basic process.

An analysis of the input transistors of the circuits is presented in this paper in order to identify mechanisms responsible for the radiation responses. The input devices in the LM111 and LM124 are substrate PNP (SPNP) transistors that are nearly identical in the LM111 and LM124. Radiation-induced increases in the base current of these input structures, have been shown to be directly related to the degradation in I_{IB} [1, 3].

The purpose of this paper is to identify mechanisms responsible for variations observed in the total dose responses of LM111 comparators. These variations, among other characteristics, are not observed in LM124 operational amplifiers. Thus, this paper will also endeavor to identify potential causes for these radiation-response disparities. Since the LM111 and LM124 are relatively similar linear microcircuits, a detailed understanding of the causes of these disparities may help to improve the hardness assurance procedures developed for bipolar devices and circuits [4].

II. Experiments

A. Motivation

The experimental data in this section are presented in order to demonstrate two characteristics regarding the radiation response of linear bipolar circuits. The first characteristic is the part-to-part response variation for a given circuit type exposed under identical radiation conditions (e.g., total dose, dose rate, etc.). As mentioned above, the LM111 exhibits a broad radiation response distribution. Experimental results included in this section indicate that one cause for the large variability in the LM111 data may be variations in the part's pre-irradiation thermal cycles [12]. In later sections, it is suggested that the relationship between pre-irradiation thermal cycles and radiation response is a function of the structure of the LM111 input transistors and the dependence of oxide defect build-up on thermal stress. Our analysis suggests that although the cumulative radiation-induced build-up of oxide defects in the LM111 follows the same general

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trajectory, variations in the experimental data may be caused by local fluctuations in the defect densities that are brought about by variations in the part's thermal history.

LM124 circuits, although similar in many respects to the LM111, are shown to be less sensitive to variations in pre-irradiation thermal cycles. Moreover, the LM124 shows less radiation-induced degradation and different post-irradiation anneal characteristics. The differences in the LM111 and LM124 data reveal the second characteristic of linear bipolar parts exposed to ionizing radiation. That is, although bipolar circuits may have similar designs and processes, their radiation responses can be very different. It is argued in later sections that the differences in the LM111 and LM124 responses are due to a difference in the cumulative build-up of oxide defects.

B. Distribution in LM111 Radiation Response

Recently, total ionizing dose experiments on LM111 parts performed at NAVSEA revealed a bimodal distribution in the input bias current response [3]. In these studies, approximately one in three of the irradiated comparator circuits demonstrated a significantly larger increase in I_{IB} with total dose exposure, which will be referred to here as a "high mode response." The remaining parts demonstrated a "low mode response." The circuits were tested at various dose rates. Although there was some variation in the distribution at lower dose rates, in general the separation in the high and low response sets was distinct and the scatter in each set is small [3]. The radiation source for these experiments was a Cobalt-60 gamma cell. A comparison of the average high and low mode response for the irradiations at 50 rad(Si)/s is illustrated in Fig. 1. Of the 15 comparators exposed at this dose rate, three showed a high mode response and the remaining 12 were low mode. The low mode characteristics are consistent with most of the experimental data reported in previous lot acceptance reports [3]. However, high mode data, as well as broad response distributions, have also been reported in several studies [3, 13].

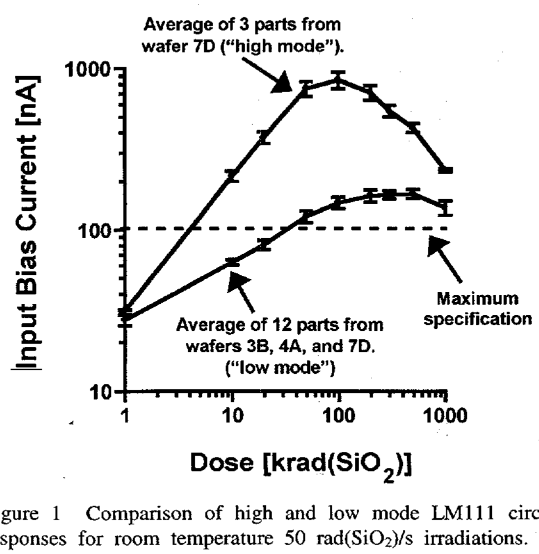

Figure 1 Comparison of high and low mode LM111 circuits responses for room temperature 50 rad(SiO_2)/s irradiations. The results indicate a broad distribution in circuit response.

The experimental data discussed above were obtained from measurements on packaged parts from a single wafer lot. The circuits were fabricated by National Semiconductor Corporation (NSC) in their Glasgow (UK) facility. Five parts from each of three different wafers were tested. All five parts off two wafers (3B and 4A) and two of the five parts off a third wafer (7D) were low responders. The remaining three parts off wafer 7D were high responders. The distinct variation in wafer 7D data suggests that the different characteristics are not a result of wafer-to-wafer process variation. Indeed, recent experiments have identified variability in the thermal temperatures used during part packaging as a potential cause for the broad response distribution [12].

C. Distribution in Input Transistor Radiation Response

For the LM111 parts discussed above it was previously demonstrated that, at total doses below 100 krad(Si), increased I_{IB} is due primarily to increased base current in the circuit's input transistors [1, 3, 8]. At high total doses, above 100 krad(SiO_2), the circuit response is also influenced by compensating circuit mechanisms [1]. Pre- and post-irradiation (50 rad(Si)/s) SPNP measurements were taken from the two types of pre-packaged parts: 1) de-coupled LM111 circuit input transistors and 2) similar test devices integrated onto test chips from the same wafer lot. Similar packaging techniques were used for both the test chips and the LM111 circuits. Thus, all the transistors tested would have experienced the same variability in post-processing thermal cycles.

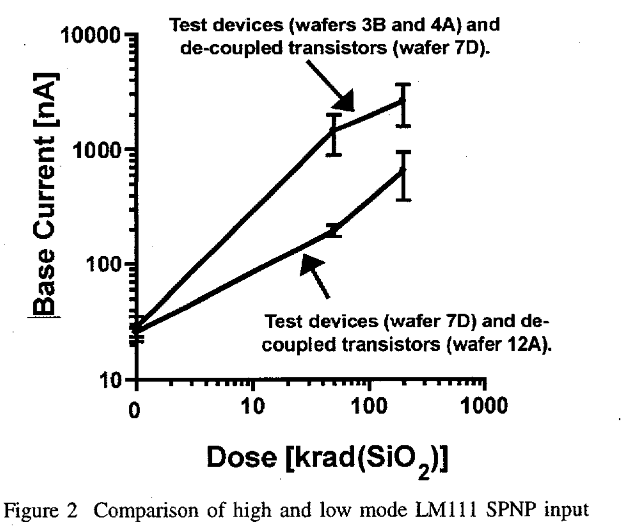

Figure 2 Comparison of high and low mode LM111 SPNP input transistor responses for room temperature 50 rad(SiO_2)/s irradiations. Transistor distribution is similar to circuit.

In order to associate the parametric degradation in the circuit with the total dose responses of the SPNP devices, the transistor's forward active mode base current (I_B) is measured at an emitter-base bias (V_{EB}) of 0.59V. SPICE simulations on the LM111 circuit indicate that this voltage is the pre-irradiation DC emitter-base operating point voltage of the input transistors [1]. The increase in base current for the various SPNPs is illustrated in Fig. 2.

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Test chip devices from wafer 7D and de-coupled transistors from wafer 12A are low responders. Test devices from wafers 3B and 4A and de-coupled transistors from wafer 7D are high responders. These data clearly illustrate that, as with I_{IB}, the input transistors show a broad distribution in radiation response. Thus, the mechanisms responsible for the distribution in the post-irradiation circuit parameters are evidently coupled to the distribution in the input device behavior.

D. Thermal Dependence of LM111 Response

The thermal histories of the parts prior to radiation exposure appear to affect the variability in the radiation response of the SPNP base current and LM111 I_{IB} [12]. Experimental data on cold-packaged LM111s indicate that the thermal cycles experienced during packaging may play a role in build-up of oxide defects. Bare LM111 die, obtained from the same wafer lot as the parts discussed above, were specially packaged at Sandia National Laboratories (SNL) in a controlled, low temperature environment. The parts were exposed to a variety of pre-irradiation bake regimes in order to assess the thermal dependence. In one experiment, parts were baked at 100°C for various time intervals between zero (no bake) and 1000 hours. After heat treatments, the parts were irradiated to a total dose of 30 krad(SiO_2) at SNL in a Co-60 source. The dose rate for these experiments was 50 rad(SiO_2)/s. The input bias current behavior is shown in Fig 3 [12]. As the figure indicates, the circuit response can vary widely as a result of the bake time. For the "no bake" parts, the average I_{IB} is 180 nA. Fifteen-minute heat treatments increase the average post-irradiation input current to 230 nA. Longer pre-irradiation bakes, beyond 100 hours, result in post-irradiation input currents below 100 nA [12].

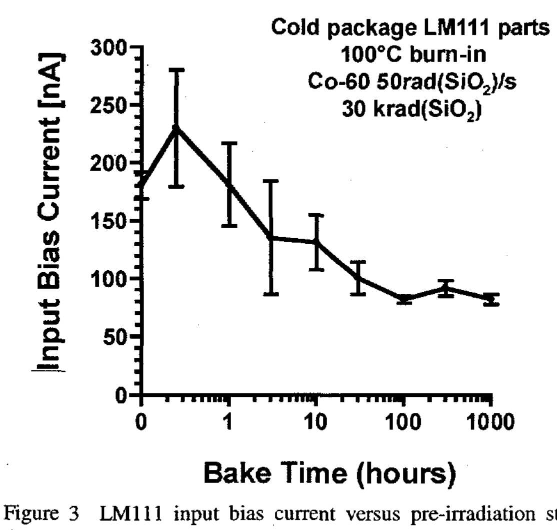


Figure 3 LM111 input bias current versus pre-irradiation stress time. Cold-packaged parts irradiated to 30 krad(SiO_2) show significant variability as a result of bakes (After Ref. [12]).

The dependence of oxide defect build-up on the pre-irradiation thermal stress is a potential mechanism for the circuit's sensitivity to the bake interval. Previous studies by Shaneyfelt, *et al.* demonstrated that in MOS field oxides (thickness similar to bipolar oxides) increasing thermal stress time increases oxide-trapped charge and slightly decreases interface-trap build-up [14]. Thus, the build-up of oxide-trapped charge (N_{OT}) and interface traps (N_{IT}) is a function of pre-irradiation bakes. The data in Fig. 3 are consistent with this response pattern. Indeed, as will be discussed in detail in section III, increasing N_{OT} and decreasing N_{IT} in the oxide will decrease base current in an SPNP transistor [15]. This correlates to the reduction of I_{IB} shown in Fig. 3.

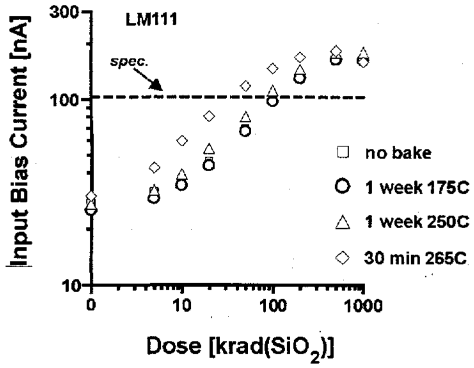
E. COTS LM111 and LM124 Bake Experiments

In order to compare the LM111's pre-irradiation thermal stress sensitivity to other similar linear bipolar microcircuits, experiments were performed at Vanderbilt University on pre-packaged commercial-off-the-shelf (COTS) LM111 and LM124 operational amplifier circuits. All of the parts were fabricated in the same process line at the NSC Glasgow facility. The LM124 operational amplifiers and LM111 voltage comparators are manufactured with SPNP input transistors. Various properties of these input devices are listed in Table 1. These properties are similar for both linear circuit types.

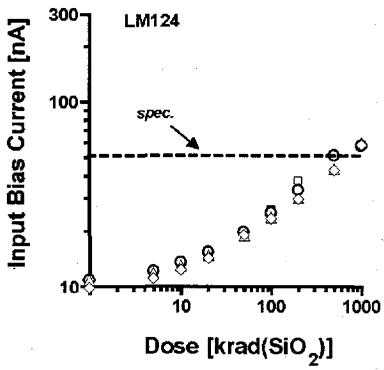
TABLE I
PROPERTIES OF INPUT TRANSISTORS

	LM111	**LM124**
Input Transistor Type	SPNP	SPNP
Lateral Base Width	12 μm	12 μm
Base Doping	~ 10^{15} cm^{-3}	~ 10^{15} cm^{-3}
Pre-Irradiation Current Gain	675 - 911	403 - 856
Base Oxide Thickness	1.20 μm	1.07 μm

Fig. 4 shows the I_{IB} radiation responses of both circuits for various bake regimes. Prior to exposure, the parts were baked for one week at 175° C, one week at 250° C, or 30 minutes at 265° C. Circuits receiving no heat treatments were also irradiated. The parts were irradiated in an ARACOR x-ray source at 250 rad(SiO_2)/s. As Fig. 4a indicates, the LM111 circuits stressed for short times at high temperature (30 minutes at 265° C) show considerably softer responses. These data are consistent with the cold-packaged data shown in Fig. 3. In contrast, the LM124 data shown in Fig. 4b show virtually no dependence on the thermal stress. Moreover, the LM124's are considerably harder than the LM111 circuits.



(a)



(b)

Figure 4 Input bias current versus dose for COTS a) LM111 and b) LM124 for different pre-irradiation thermal stress regimes. Results indicate LM111s are sensitive to stress and the LM124s are not sensitive.

F. COTS LM111 and LM124 Anneal Responses

In addition to the differences in pre-irradiation bake sensitivity and relative hardness, the post-irradiation room temperature anneal responses of the LM111 and LM124 parts are dissimilar. This difference is illustrated in Fig. 5. In this figure, the input bias currents of COTS circuits (receiving no pre-irradiation stress) are plotted versus time. In the first 1.67 hours, the parts were exposed to x-rays at a dose rate of 250 rad(SiO_2)/s. After an irradiation of 2 Mrad(SiO_2), the parts were annealed at room temperature for one week and re-measured. As Fig. 5 demonstrates, a sharp contrast is observed in the anneal responses. Indeed, the LM124 devices show only a slight increase in I_{IB}. This is consistent with data previously reported by McClure, *et al.* [9]. Conversely, the LM111 input parameter shows an increase of nearly four-times its 2 Mrad(SiO_2) value. These data suggest that, in the LM111 parts, interface traps continue to build up after the irradiations are terminated [9, 15].

The experiments on these two linear bipolar microcircuits have demonstrated that, despite key structural similarities, the radiation responses of LM111 and LM124 integrated circuits show different: 1) sensitivities to pre-irradiation thermal stress, 2) relative hardness, and 3) post-irradiation room temperature anneal characteristics. These three differences may share a common origin.

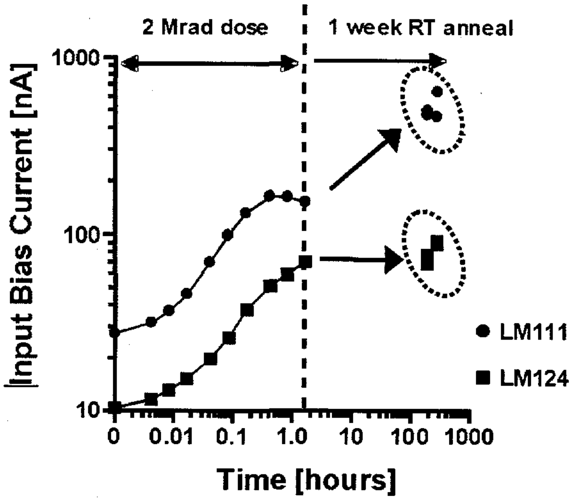


Figure 5 Input bias current versus time for "no bake" LM111 and LM124. Results indicate LM111s show enhanced degradation after one week room temperature anneal.

III. Device Simulations

Two-dimensional simulations on structures representative of the LM111 and LM124 SPNP input transistors indicate that the base current in these devices is sensitive to the concentrations of radiation-induced oxide defects, N_{OT} and N_{IT}. The simulations indicate that the low base doping of the SPNP transistors plays an important role in determining this sensitivity. The computer simulations were performed with ATLAS from the SILVACO suite of simulation tools. A representational cross-section of the SPNP input transistor is illustrated in Fig. 6.

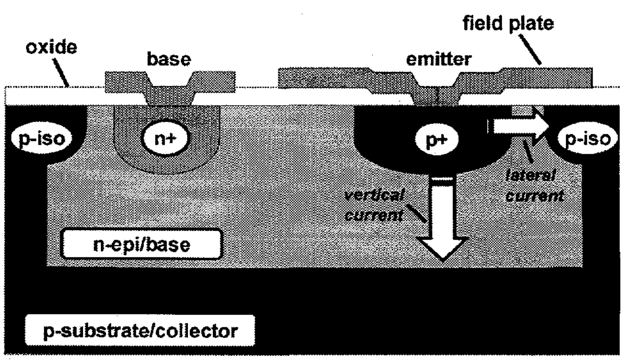


Figure 6 Representational cross-section of SPNP device. The figure indicates both the vertical and lateral current components and the presence of an emitter-tied field plate over the active base surface.

The input device is a hybrid structure. In forward active mode, its operation is similar to two parallel transistors: a vertical PNP and a lateral PNP. In the vertical structure, holes are injected vertically from the lower portion of the emitter diffusion, diffuse across the n-type bulk, and are collected at the substrate. In the lateral device, holes are injected near the base surface and are collected by the p-type isolation (p-iso) region. As Fig. 6 indicates, the p-iso is electrically connected to the substrate. Another structural feature of this device is the existence of an emitter-tied field plate extending over the active base region. Previous studies indicate that field plates and other metallization runs can have an impact on the rate of build-up of oxide defects during radiation exposure [6, 16-18]. However, simulations show that neither the emitter-tied field plate nor the hybrid structure is a primary cause of the high level of sensitivity to variations in N_{OT} and N_{IT} observed in these devices.

With respect to oxide defect sensitivity, the critical device characteristic considered in this study is the low doping level of the n-type epitaxial layer (base). Spreading resistance measurements by Solecon Labs determined that the donor concentration of this layer is near 10^{15} cm^{-3} for both the LM111 and LM124 input transistors. This is considerably lighter than the epitaxial concentrations in the bipolar processes analyzed in previous studies [15, 19, 20]. The low base doping combined with a p-type emitter doping of over 10^{18} cm^{-3} is the primary cause of the high current gain measured in these parts (high emitter injection efficiency).

As mentioned previously, I_{IB} degradation in the linear circuits considered in this paper is coupled to radiation-induced excess base current in the SPNP input devices. Excess base current in SPNPs is caused primarily by the build-up of interface traps [15, 18, 19, 21]. Interface traps provide recombination centers for free carriers traveling along the surface near the Si/SiO_2 interface and increase the surface recombination velocity in the device. This increase is typically moderated by N_{OT}. The presence of positive oxide trapped charge suppresses recombination by reducing the emitter-base depletion width and increasing the difference in electron and hole concentration near the base surface [15, 19, 21]. For similar devices exposed to the same levels of total dose, variations in base current responses are most likely caused by small variations in the build-up of these oxide defects. For example, if one SPNP structure has a higher N_{OT} density and a lower N_{IT} density than a second nominally identical transistor, the first device will, in general, exhibit a lower base current. Therefore, it is suggested that a "low mode" response is caused by the presence of a higher positive oxide trapped charge concentration and/or a lower interface trap density.

In order to analyze the transistor's response to variations in both positive oxide trapped charge and interface traps, a response surface was generated. The surface represents base current (I_B) for different combinations of oxide defect densities. The surface shown in Fig. 7 is a two-dimensional plot of I_B (V_{EB} = 0.59V) for each point in the defect matrix. The N_{OT} and N_{IT} domains vary from 10^9 to 10^{12} cm^{-2}. The calculated current is normalized to I_B at the minimum simulated values of the defect densities. For oxide charge densities below 10^{11} cm^{-2}, the response surface shows a steep rise in I_B for N_{IT} values between 10^{10} and 10^{12} cm/s. For trap densities above 10^{11} cm^{-2}, the simulation results indicate a steep decline in I_B as N_{OT} increases between 10^{10} and 10^{11} cm^2. This is consistent with the aforementioned impact of both defects on PNP base current. As Fig. 7 indicates, the surface maps out a region of high sensitivity when the N_{IT} concentration ranges between 10^{10} and 10^{12} cm^{-2} and the N_{OT} concentration ranges between 10^{10} and 10^{11} cm^{-2}. This domains correlates well to the radiation-induced defect concentrations observed in previous studies of bipolar base oxides [22]. The figure also shows that variation in oxide trapped charge densities above 10^{11} cm^{-2} have little impact on the response. This is due to a saturation in the effects of N_{OT} on the surface potential at the n-type base interface. As positive oxide charge builds up, majority carrier electrons move to the interface. At high charge densities these negatively charged carriers accumulate at the surface thus reducing the effectiveness of N_{OT} in modulating the surface potential. It should be noted that the variability in N_{OT} build-up is most likely not a signature of space charge effects or other phenomena associated with ELDRS and elevated temperature irradiations [22]. Indeed, there is no evidence that the differences observed in the "high" and "low" mode data sets are caused by differences in either radiation-induced hole generation or transport in the bipolar oxide. A more probable mechanism for defect build-up variation is likely related to differences in charge trapping probability at the interface.

The response surface may be used to explain the first characteristic of radiation response in linear bipolar circuits discussed in II-A. Part-to-part variation in the total dose response of the LM111 is due to relatively small variations in the oxide defect densities that are brought about by variations in the parts' thermal histories. These small variations are able to produce significant effects on the base current if the devices have defect densities corresponding to the steep portion of the response surface. As previously mentioned, N_{OT} increases and N_{IT} decreases in MOS field oxides when the duration of the pre-irradiation bake is increased [14]. If the bipolar oxides act in a similar way, then increased bake time will drive the transistor response down the surface gradient (as indicated in Fig. 7) and reduce the post-irradiation base current. Since the circuit response is coupled to the base current behavior, the surface indicates that I_{IB} should decrease with increased bake time. This interpretation correlates to the experimental data shown in Figs. 3 and 4a.

One of the primary factors responsible for the input SPNP transistor's strong dependence on oxide defect variation is the low doping of the n-type epitaxial/base region. A low doping level reduces the majority carrier concentration at the base surface, thereby increasing the probability of recombination at radiation-induced interface traps [15, 21]. Moreover, the light doping makes the surface potential in the base more sensitive to oxide charge [19].

The effect of base doping is illustrated by comparing Fig.7 to a second response surface shown in Fig. 8. The base doping of the simulation structure used to generate Fig. 8 was 10^{17} cm^{-3} (two orders of magnitude higher than the actual device). Aside from the variation in the base doping, both the structures and simulations were identical. The simulations demonstrate that an increase in base doping reduces the device's sensitivity to defect variation. High doping increases the free electron concentration in the base thereby reducing the probability of carrier recombination with N_{IT} and reducing the effectiveness of N_{OT} in modulating the base surface potential. These results identify low base doping as one explanation for the sensitivity of I_B and I_{IB} to relatively small fluctuations in radiation-induced defect densities.

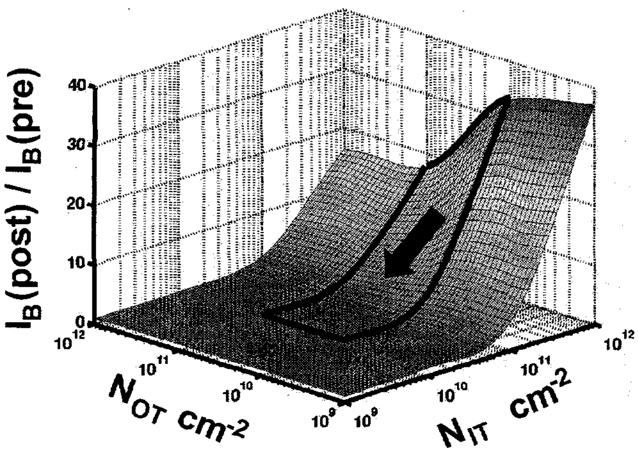


Figure 7 Normalized base current versus N_{OX} and N_{IT}. Simulations indicate the region of sensitivity range (black box) is 10^{10} and 10^{12} cm^{-2} for N_{IT} and 10^{10} and 10^{11} cm^{-2} for N_{OX}. The black arrow indicates direction of current in response to increase bake time interval.

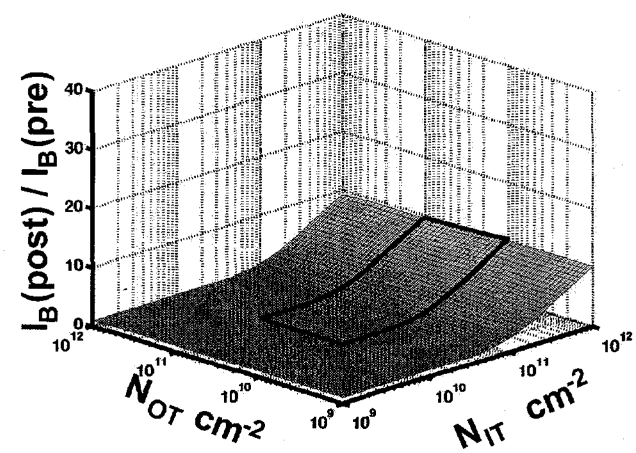


Figure 8 Normalized base current versus N_{OX} and N_{IT} for highly doped base ($10^{17}cm^{-3}$) structure. Simulations indicate device sensitivity reduced by increased doping density.

In light of the response surface results illustrated in the previous two figures, it is tempting to conclude that by increasing the n-type epitaxial layer doping, reductions in thermal sensitivity and increased radiation hardness may be achieved. However, there are inherent tradeoffs to this approach. In particular, the high current gain and collector-base breakdown voltage of the transistors will be decreased by increasing base doping.

IV. Discussion

A. Device Level Mechanisms for Circuit Responses

The base current characteristics of the LM111 and LM124 input transistors are similar prior to radiation exposure. However, irradiated LM111 devices show more degradation. In Fig. 9, the base currents (no bake) are plotted versus emitter-base voltage for both circuit types. The LM111 and LM124 pre-irradiation base currents are nearly identical, but, after a 2 Mrad(SiO_2) irradiation and a one week anneal, the LM111 I_B is approximately twice the LM124 current. These results suggest that the differences in the circuit anneal responses (Fig. 5) are partially due to different levels of degradation in the input SPNPs. As will be discussed in the next section, circuit-level effects also play a role in the divergent I_{IB} data.

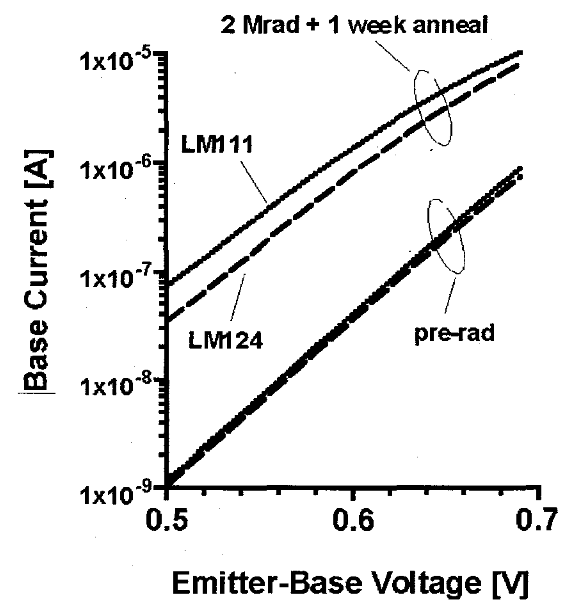


Figure 9 Base current versus emitter-base voltage for de-coupled LM11 and LM124 SPNP input transistors. Characteristics are co-linear for both parts prior to radiation exposure. After 2 Mrad(SiO_2) irradiation and one week anneal, the LM111 device shows two-time the degradation of the LM124.

The simulations suggest that the post-irradiation base current disparity could be caused by a difference in the rate of oxide defect build-up in the two devices. Due to the structural similarities, the input SPNP defect sensitivities of both circuits are described by the same surface plot (Fig. 7). However, what may differentiate the two input transistor responses is the path along the surface that the device follows in response to ionizing radiation. The possible effects of this can be seen qualitatively by tracing two hypothetical paths along the response surface, as shown in shown in Fig. 10.

It should be noted that, at the present time, the relative trajectories of the LM111 and LM124 devices along the response surface are not known. Indeed, more detailed sets of experiments are required to determine precisely the relative rates of defect build-up in the two circuits. However, the suggested paths do provide a qualitative explanation for the second characteristic of linear bipolar radiation response discussed in section II-A. If, as Fig. 10 illustrates, the cumulative defect build-up in the LM111 oxide puts the base current in a high region of sensitivity, the input device and the circuit parameters would exhibit large variations brought on by relatively small local fluctuations in defect densities. By contrast, the cumulative defect build-up in the LM124 oxide may put the device in a less sensitive region. Thus, even though the oxide defect densities in the LM124 parts may exhibit a similar range of local fluctuation, the device and circuit parameters would exhibit little variation.

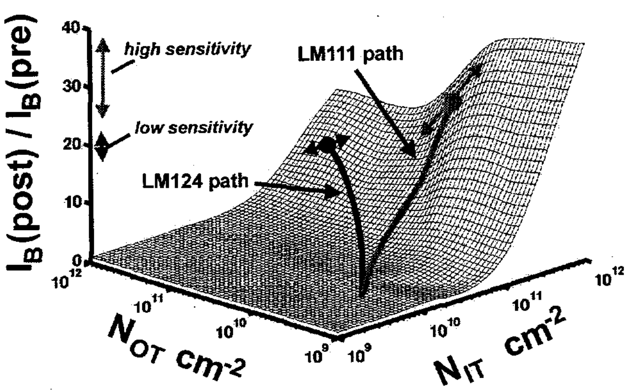


Figure 10 Hypothesized radiation-induced degradation paths along the SPNP response surface. The LM111 path moves the device into a region of high sensitivity.

Although it is beyond the scope of this paper to identify the exact mechanisms responsible for these differences in oxide defect build-up, likely explanations may be variables related to the hydrogen densities in the oxides [23].

B. Interaction of Device and Circuit Level Mechanisms

Despite having similar input devices, the topologies of the LM111 and LM124 are considerably different. For example, the input transistors of the LM124 are elements of the differential amplifier subcircuit. The LM111 input transistors form emitter followers that act as input voltage buffers [1, 3].

Experimental data from the two circuits and their respective input transistors reveal that topological differences contribute to the response disparities between the LM111 and LM124. The I_{IB} of the LM111 prior to radiation exposure is 30 nA. This corresponds to an emitter-base voltage (V_{EB}) of 0.594 V as indicated in Fig. 11. The emitter current at this bias point is approximately 20 µA. The data in this figure correspond to the base currents measured on de-coupled input transistors (see Fig. 9). After 2 Mrad(SiO_2) irradiations and a one-week anneal the average I_{IB} is 500 nA (Fig. 5) and the V_{EB} 0.565 V. These results demonstrate that the circuit design has an effect on the relative radiation responses. Degradation in the *non-input* transistors in the LM111 circuit's input stage lowers the emitter-base operating voltage of the input device by 29 mV [1]. This shift in bias compensates for degradation in the SPNP [1]. The same technique can be used to measure the operating point shift in the LM124. Before irradiation, the LM124 I_{IB} is 10 nA and V_{EB} is 0.571 V The emitter current at this bias point is approximately 8 µA. Thus, the pre-irradiation bias points for both the LM111 and LM124 input transistors are similar in magnitude. However, after irradiation, I_{IB} is 70 nA and V_{EB} is 0.524 V. For the LM124, the *non-input* transistors reduce the operating point by 47 mV, nearly twice the bias shift of the LM111. These circuit effects are summarized in Table 2.

TABLE II
LM111 AND LM124 OPERATING POINTS

	I_B (I_{IB}) (nA)	V_{EB} (mV)
LM111 (pre-irradiation)	30	594
LM111 (post-irradiation)	500	565
LM124 (pre-irradiation)	10	571
LM124 (post-irradiation)	70	524

These results demonstrate that the degradation in the *non-input* transistors of the LM124 circuit moderates the increase in I_{IB} more than the corresponding moderation in the LM111. Note, however, that this effect is not sufficient to explain the differences between the LM111 and LM124 ICs considered here. As demonstrated above, the individual transistors in the LM111 parts degrade more rapidly than those of the LM124.

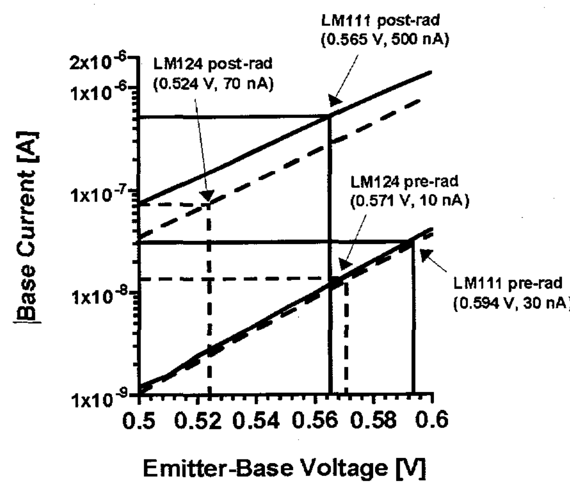


Figure 11 Demonstration of radiation-induced emitter-base voltage operating point shifts in LM111 and LM124 input transistors. The results indicate degradation in the *non-input* transistors of the LM124 cause greater shifts and provide more compensation for input bias current degradation.

V. CONCLUSIONS

Variations in the LM111 voltage comparator's thermal history may contribute to the part's broad radiation response distribution. Different thermal cycles may occur during the packaging of linear bipolar microcircuits. Previous studies have demonstrated the relationship between burn-in treatments and oxide defect densities in semiconductor devices. The connection between pre-irradiation thermal stress and N_{OT} and N_{IT} build-up is one of the essential mechanisms of the LM111's response variability. Through the use of device simulation, the low doping of the LM111's

SPNP input transistors has been identified as a second mechanism that can explain the sensitivity of base and input bias currents to relatively small variations in defect concentrations.

Experiments on COTS parts have demonstrated that, despite key structural similarities to the LM111, the LM124 operational amplifier exhibits essentially no variation in response as a function of the pre-irradiation thermal stress. The lack of variability in the LM124 data does not necessarily imply the circuit's oxide defects do not fluctuate with varying thermal stresses. Indeed, it is possible that both the LM111 and LM124 show the same amount of thermal-stress-induced fluctuation in their defect densities. However, the data indicate that the cumulative (global) build-up of N_{OT} and N_{IT} for both circuit types may be very different. The trajectory of defect accumulation in the LM111 makes the circuit highly sensitive to small local fluctuations. By contrast, the cumulative build-up of N_{OT} and N_{IT} in the LM124 makes it insensitive to similar local fluctuations. In addition to these potential differences in cumulative defect accumulation, circuit level effects also contribute to these part-type disparities.

Further work is needed to determine the different process and circuit design variables that are the fundamental causes of these different radiation responses. A detailed understanding of these mechanisms will support the development of more accurate hardness assurance procedures and may lead to the implementation of low cost mitigation techniques for bipolar devices and circuits exposure to ionizing radiation.

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VII. References

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