Effect of radiation and temperature on the performance of bipolar transistor circuits with statistical variation in components and device parameters

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Various radiation environments are likely to have a degrading effect on electronic devices and systems especially as smaller devices are developed. The aim of the present paper is to demonstrate a calculation line for the analysis of different circuit behavior due to radiation and temperature environments and to initiate a compilation of radiation effects data. We basically substitute the appropriate parts with the radiation-damaged models to see the difference in circuit performance. Statistical variation in device parameters was also taken into consideration. A voltage regulator circuit using BJTs was simulated. Bias point, as well as DC analysis was preformed. BJT Proved to be highly sensitive to total dose irradiation especially at high neutron doses and tolerable to other radiation environment like gamma, electrons, and protons. Irradiation at high temperatures counteracts the gain degradation due to irradiation. However, the effect of temperature is small compared with the effect of irradiation. Statistical variation in the resistance values has a significant effect on the circuit performance compared with the variation in transistor gain. The impact is reduced for the irradiated circuit especially at high temperatures.

يعتبر الإشعاع ذو تأثير مدمر على الدوائر الإلكترونية خاصة مع تطوير دوائر فائقة الصغر. يهدف هذا البحث لوضع خط بحثي لتحليل تأثير الإشعاع ودرجات الحرارة على أداء الدوائر الإلكترونية وبدء تجميع قاعدة معلومات لتأثير الإشعاع على مختلف الدوائر الإلكترونية. يمكن أخذ تأثير الإشعاع على الدوائر الإلكترونية في الاعتبار عن طريق استخدام نماذج للأجهزة الإلكترونية معدلة كدالة في كمية الإشعاع. تم في هذا البحث أيضا أخذ تأثير التغير العشوائي في ثوابت الأجهزة عند تحليل تأثير الإشعاع والحرارة. تمت دراسة منظم للجهد مكون من ترانزستورات ثنائية القطبية. تم حساب نقطة التشغيل وكذلك تحليل عمل الدائرة استجابة لتغير جهد التغذية. أثبتت النتائج أن الترانزستورات الثنائية القطبية شديدة الحساسية للتشعيع بواسطة النيوترونات وقليلة الحساسية للأنواع الأخرى من الإشعاع مثل أشعة جاما والإلكترونات والبروتونات. أظهرت النتائج أيضا أن درجات الحرارة العالية تضاد تأثير الإشعاع ولكن بمقدار ضئيل مقارنة بالإشعاع. ثم تبيان أن التغير العشوائي في قيم المقاومات بالدائرة لتأثير الإشعاع واضح على أداء الدائرة مقارنه بالتغير العشوائي في قيم مكسب الترانزستور. هذا التأثير يقل نتيجة للإشعاع وعند درجات الحرارة العالية.

Keywords: Radiation, Temperature, Monte Carlo, SPICE, BJT

1. Introduction

As electronic components have grown smaller in size and power and have increased in complexity, their enhanced sensitivity to the radiation environment has become a major source of concern [1].

Various radiation environments, namely; nuclear reactors (and radiation processing), space, and nuclear weapons; are likely to have a degrading effect on electronic devices and systems [2]. Table 1 presents a brief description of the characteristics associated with each of these environments. Also shown in table 1, the characteristic temperature of each environment since it is known that temperature also plays an important role in changing the values of the circuit components as well as device parameters [3]. Due to the appreciation of the effect of temperature on electronic circuit, standard operating conditions for most military circuits according to MIL-STD require operating over the temperature range –55 to 125 °C [4] and a power supply of voltage of 5.0 volts ± 10 percent [5].

Radiation effects on electronic components can be divided into [2]: (1) transient and (2) Long-lived. In both cases, the main mechanism is displacement and

Table 1
Characteristics associated with the different environments, which affect electronic circuit behavior

Environment	Main feature [6]	Typical temperature, °C [3]
Nuclear reactors	• Steady-state neutron flux • Low to moderate ionizing dose rate (gamma rays) • In the event of a LOCA (Loss of Coolant Accident), the gamma and beta dose can reach 2.0×10^7 and 2.0×10^8 rad (Si)* within 30 days, respectively [7].	• 24 to 66 During normal operation • 260 during accident
Space	• Low ionization dose rate (<< 1 rad/s) • Total dose ($\geq 10^5$ rad) • High-energy electrons and protons trapped in earth's magnetosphere • Cosmic rays (electrons, protons, alphas, heavy ions)	-40 to 30
Nuclear weapons	• High-dose-rate gamma flux ($\gamma \geq 10^8$ rad/s) • Total dose ($\geq 10^4$ rad) • Delayed high-energy neutron flux ($\geq 10^{13}$ n/cm^2)	-55 to 55

* Rad (Radiation Absorbed Dose) calculated in Si

ionization. Typically, it is assumed that the displacement damage and ionization effects are independent, so that damage characterization can be calculated separately [8].

Regardless of the basic ideas of analyzing radiation effect on electronic devices, work in this area is highly dominated by defense agencies in USA and Europe due to the military applications of such issues in space programs as well as in areas related to nuclear defense systems [9]. While considerable experiment data exist on radiation effects, they exist in a large number of papers, documents, and reports [10] as well as classified documents.

Most radiation effects in semiconductor materials have been explained and are well-understood [12]. However, analyzing the effects of radiation on system performance has proved extremely difficult [12]. From the earliest history of numerical device modeling, the radiation effects community has recognized the value of computational modeling for providing insight into the effects of ionizing radiation on microelectronic devices [13]. Because of increased simulator availability and the prohibitive cost of running special tests for design studies, process and device simulation are regularly done for semiconductor manufacturers [13]. Semiconductor simulation capability enables comprehensive "what if" technology-development studies that are not experimentally feasible from the standpoints of time and money [13]. Taking into consideration the cost of experimental lot fabrication, as well as testing, a simulation capability providing qualitative insight, as well as quantitatively accurate predictions, has a very high payoff [13]. With the simulation, we can study how resistant a circuit is to changes due to irradiation and design circuit to be functionally radiation "hard" [1].

From the designer's point of view, the usual way of representing the circuit-level behavior of devices is to use SPICE models. Radiation-induced degradation can be modeled in a first-order approach by degrading the standard SPICE parameters with increasing dose (i.e., radiation flunece) [14]. For radiation simulations, there are few models in the SPICE library that are modeled with radiation damage [11].

The aim of the present work is to demonstrate a calculation line for the analysis of different circuit behavior due to radiation and temperature environments. In the course of this work, we initiated a compilation of radiation data to properly assess the impact of radiation on different electronic circuits. Impacts of radiation are accounted for by using the radiation-damaged models and analyze their impact on the circuit behavior [11]. Needless to say that the accuracy of the circuit simulator is directly related to the accuracy of the information used to define the circuit and the device parameters [5].

2. Effect of radiation on bipolar transistors

Bipolar junction transistors (BJTs) have important applications in digital, mixed-signal, bipolar complementary metal oxide semiconductor (BiCMOS), and integrated Circuits (ICs). This is because of the BJT current-driven capability, linearity, and excellent matching characteristics. Many of the bipolar-ICs used in space systems, including op amps, comparators, and voltage regulators, are used to accomplish analog functions [15]. Gain degradation and leakage are the most striking and common effects of radiation on bipolar transistor [2].

2.1. Gain degradation

One cause of gain degradation is atomic displacement in the bulk of a semiconductor. This bulk damage produces an increase in the number of a recombination centers and therefore reduces minority carrier lifetime. The other main cause of gain degradation is ionization in the oxide passivation layer, particularly that part of the oxide covering the emitter-base junction region. By a process similar to that in MOS devices, charge trapping and the generation of new interface states produces degradation of gain due to the increase in minority-carrier surface recombination velocity [2].

2.2. Other effects

Apart from causing gain degradation, irradiation also causes other effects in bipolar transistors. Increase in the junction leakage currents (e.g., collector-base reverse leakage, I_{CBO}) results from ionization in the surface oxide, particularly in the region over the collector-base junction [2]. Furthermore, heavy atomic displacement damage in the semiconductor causes an increase in the collector-emitter saturation voltage. The rate of this increase with fluence is roughly the same as that with which gain decreases [2].

2.3. Modeling of radiation damage in BJT

For submicron bipolar silicon devices, for neutron fluences between 10^8 and 10^{15} n/cm^2, radiation decreases carrier lifetime, concentration, and mobility by as much as an order of magnitude from their respective unirradiated values [16].

The mechanisms responsible for radiation-induced degradation in BJTs have been examined in several papers [17]. The initial emphasis was on NPN transistors, because the dose rate effect was first observed in NPN devices [17]. The gain degradation of bipolar junction transistors under neutron irradiation can be considered as a function of the interstitial-vacancy Frenkel pairs [18] and is independent of the type of radiation [18]. Thus, it is possible to evaluate the change in bipolar gain, once the expected Frenkel pair density is known (for example by simulation of the expected radiation damage) [18]. The change in forward current gain (β) depends on the Frenkel pair density according to the equation [18]:

$$\Delta \{1/\beta\} = K\ CF.$$

Where CF is the Frenkel pair density and K_b is the damage constant.
The damage constant K_b was fit to:

$$K_b = A\ I^b,$$

where I is the collector current and A and b are constants that are determined from the curve fitting procedure.

It should be mentioned that in recent years it has been demonstrated that many bipolar linear microcircuits are much more sensitive at low dose rates (<1 rad/s) than at typical laboratory dose rates (50-300 rad/s) [19]. Thus, after a given irradiation, the modified gain (β) can be expressed as [19]:

$$\beta = \beta_0 / (1 + \beta_0 K_b \phi),$$

where ϕ is the neutron fluence in n/cm^2 and (β_0) is the initial gain.

Damage constants (K_b) for a number of transistors after exposure to reactor neutrons (Energy > 10 keV) are of the order of 1.0×10^{-15} cm^2 [2].

3. Incorporating radiation analysis in SPICE

Every device parameter (e.g. current gain) that is affected by radiation is expressed as a function of radiation fluence. The parametric analysis has been done with the fluence as the varying parameter. Although computing power has increased, these advances have been overshadowed by the need to simulate more complex circuits [20].

The way to check the effects of component variations in circuit designs is by using SPICE-based Monte Carlo methods as explained below [21].

3.1. Statistical variation of circuit performance due to variations in device parameters

Practical circuit performances vary from the ideal because component parameters vary typically due to tolerance, temperature, or aging [22]. These variations of parameters can be classified according to whether they can be accurately predicted (deterministic) or whether statistical methods must be applied [22].

Monte Carlo analysis is the evaluation of circuit performance based on the statistical variations of parameter tolerances. Monte Carlo analysis is vital to predicting how a circuit whose component values vary in the real world will perform when it is actually fabricated [23]. There are two analyses that can be performed [23]:

1- The worst-case analysis is used to find the maximum or minimum value of a parameter given device tolerances. Device tolerances are varied to their maximum or minimum limits such that the maximum or minimum of the specified parameter is found.

2- The Monte Carlo analysis: If the worst case analysis shows that not all designs will pass, the Monte Carlo analysis can be used to estimate what percentage of the circuits will pass. The Monte Carlo analysis varies device parameters within the specified tolerance. The analysis randomly picks a value for each device parameter that has tolerance and simulates the circuit using the random values. A specified output can be observed.

The process of performing a Monte Carlo analysis begins by developing a working circuit description. After making sure that the circuit topology is correct, component or model parameter value(s) may be given a tolerance [23]. Tolerances can be created using two models [23]:

1- Libraries already have a number of parts with tolerance.

2- Creating parts with distributions:

a. Uniform distribution: The part is equally likely to have a value anywhere in the specified tolerance range.

b. Gaussian distribution: It specifies the nominal values and the standard deviation. All parts distribution are limited to ± 4σ. The Gaussian distribution is considered a better model of a part's distribution than the uniform distribution [24].

It is worth mentioning that the circuit simulation is described as nominal because the component values will be at their mean levels. The user will then utilize the results of this nominal case study to select the various performance criteria that will be investigated.

3.2. Impact of temperature on device parameters

Initially, all input data for SPICE is assumed to have been measured at a nominal temperature of 27°C. Temperature dependent support is provided for resistors, diodes, JFETs, BJTs, and MOSFETs [25].

Temperature appears explicitly in the exponential terms of the BJT and diode model equations. In addition, saturation currents have built-in temperature dependence. The temperature dependence of the saturation current in the BJT models is determined by [25]:

$$I_s(T_1) = I_s(T_0)\left[\frac{T_1}{T_0}\right]^{XTI} \exp\left[\frac{E_g q(T_1 T_0)}{k(T_1 - T_1)}\right],$$

where k is Boltzmann's constant, q is the electronic charge, E_g is the energy gap which is a model parameter, XTI is the saturation current temperature exponent (also a model parameter, and usually equal to 3), and T_1 is the circuit temperature, T_0 is the nominal temperature, both in degrees Kelvin.

The temperature dependence of forward and reverse beta (i.e., current gain) is according to the formula [25]:

$$\beta(T_1) = \beta(T_0)\left[\frac{T_1}{T_0}\right]^{XTB} ,$$

where XTB is a user-supplied model parameter. Temperature effects on beta are carried out by appropriate adjustment to the values of the SPICE model parameters; β_F, I_{SE}, β_R, and I_{SC} (BF, ISE, BR, and ISC, respectively in SPICE code). Where BF is the ideal maximum forward current gain, BR is the ideal maximum reverse current gain, ISE is the saturation current for common emitter and ISC is the saturation current for common collector).

Temperature appears explicitly in the value of junction potential, (ϕ), for all the device models. The temperature dependence is determined by [25]:

$$\phi(T) = \frac{kT}{q} L_{11}\left[\frac{N_a N_d}{N_i(T_1)^2}\right] ,$$

where N_a is the acceptor impurity density, N_d is the donor impurity density and N_i is the intrinsic carrier concentration.

The effects of temperature on resistors is modeled by the formula [25]:

$$R(T_1) = R(T_o)\ [1+TC_1(T_1 - T_0) + TC_2(T_1 - T_0)^2],$$

where TC_1 and TC_2 are the first- and second-order temperature coefficients.

4. Prediction of the behavior of a voltage regulator

To demonstrate the ability of SPICE to predict the combined effects of radiation and temperature, the voltage regulator circuit shown in fig. 1. was simulated. First, bias point analysis for V_{in} = 20 V was performed and it is found to be 10.6 V for T = 27 °C. Next, DC analysis was performed between 10 and 30 V. V_{out} is shown in fig. 2.

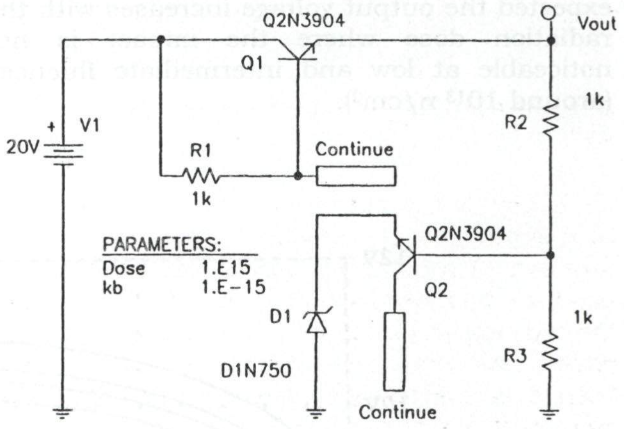

Fig. 1. Voltage regulator circuit.

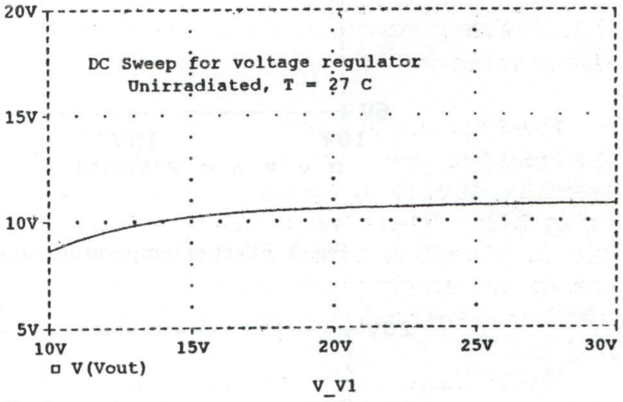

Fig. 2. DC sweep for the voltage regulator.

4.1. Effect of temperature

Effect of temperature in the different relevant environments was analyzed as shown in fig. 3. It is clear that the output voltage decreases as the temperature increases.

4.2. Effect of irradiation

The change in β_f due to radiation was modeled taking the damage constant K_b in the order of 10^{-15} as explained in section 2.3. Regardless of the fact that K_b depends on the specific BJT, it suffices here to estimate the order of magnitude of the impact of radiation on the specified circuit.

As shown in fig. 4, radiation increases the output voltage relative to the bias point. As expected the output voltage increases with the radiation dose where the impact is not noticeable at low and intermediate fluences (around 10^{13} n/cm^2).

4.3. Effect of radiation at different temperatures

To investigate the combined effect of radiation and temperature, the simulation was carried out for neutron fluence of 10^{15} n/cm^2 at different temperatures. Due to the contradicting effect of radiation and temperature, the increase in output voltage decreases as shown in fig. 5.

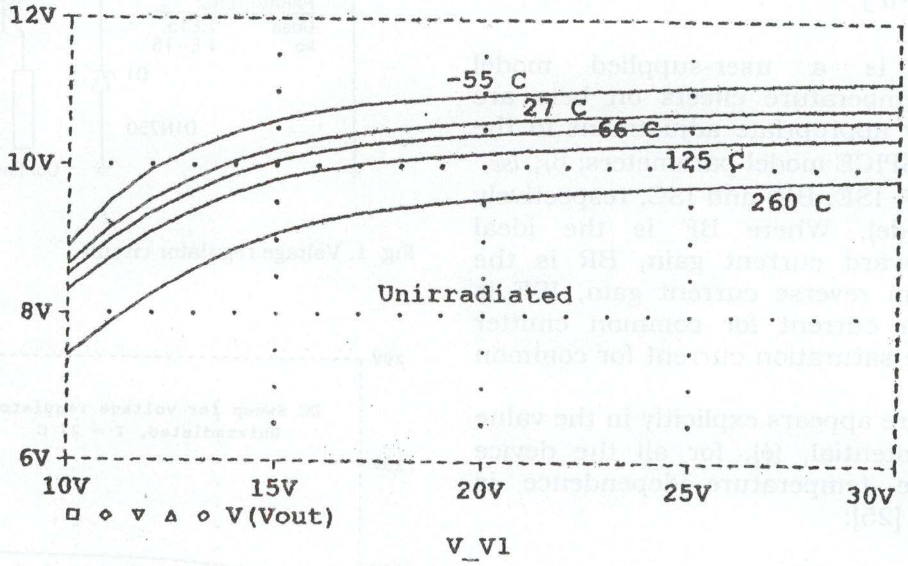

Fig. 3. Effect of temperature on the DC behavior of the voltage regulator.

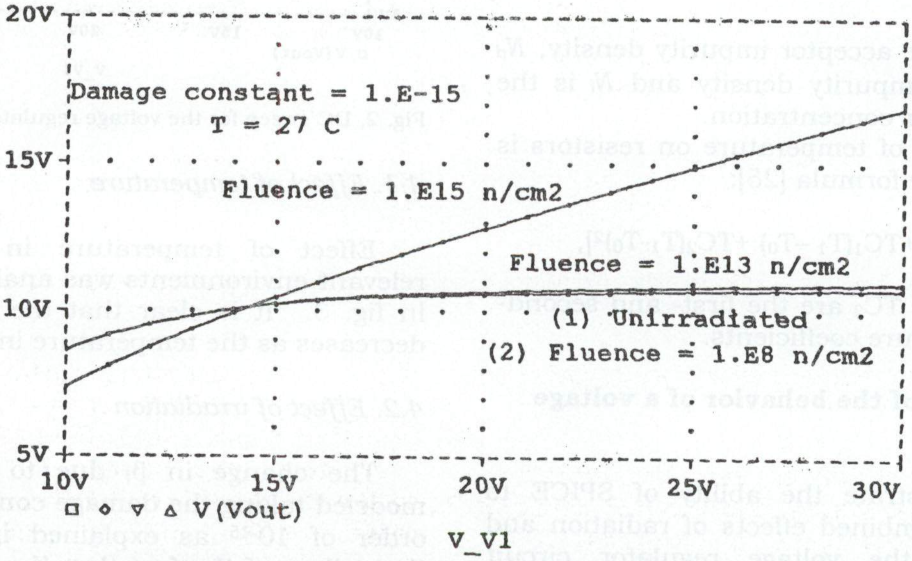

Fig. 4. Effect of neutron fluence on the DC sweep of the voltage regulator.

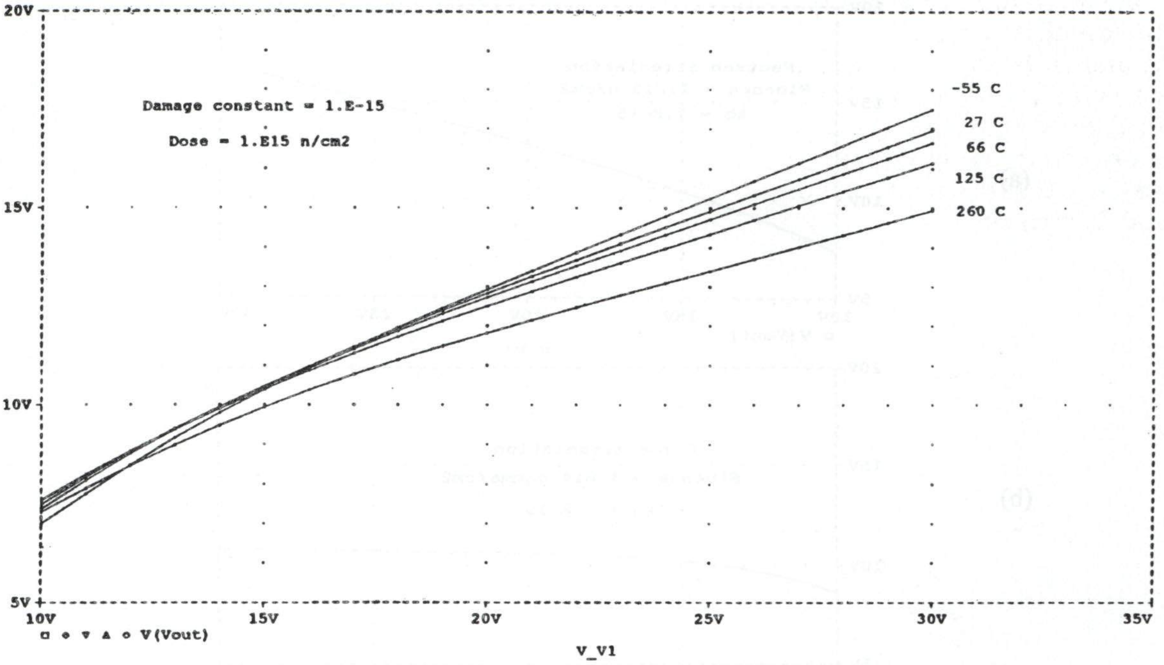

Fig. 5. Effect of irradiating temperature on the DC sweep of the voltage regulator.

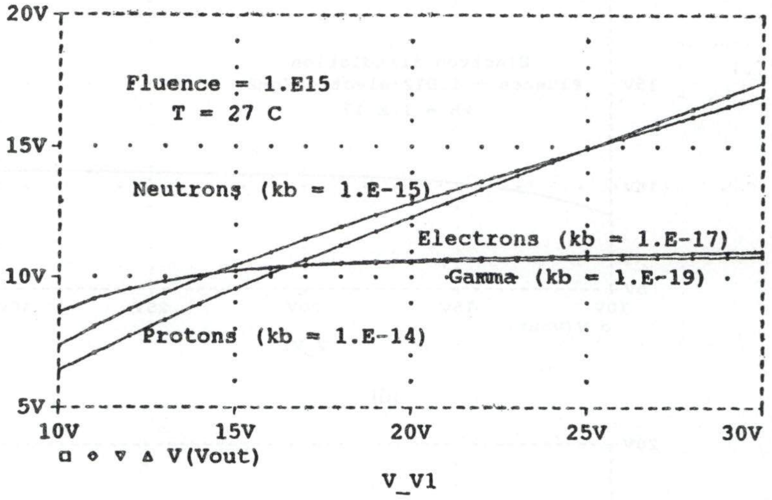

Fig. 6. Effect of different irradiation environment on the DC sweep of the voltage regulator.

4.4. Effect of irradiation with different radiation types

The impact of different radiation types was investigated by using the proper damage constant for gamma (10^{-19}), electrons (10^{-17}), reactor neutrons (10^{-15}), as well as protons (10^{-14}) at a fluence of 10^{15} particles/cm^2. As shown in figs 6 and 7, reactor neutrons show the highest effect compared with other radiation types. Regardless of the fact of the observable impact of proton irradiation, comparing the different environment needed to produce 100 Krad(Si) properly indicates the dominant effect of neutron irradiation.

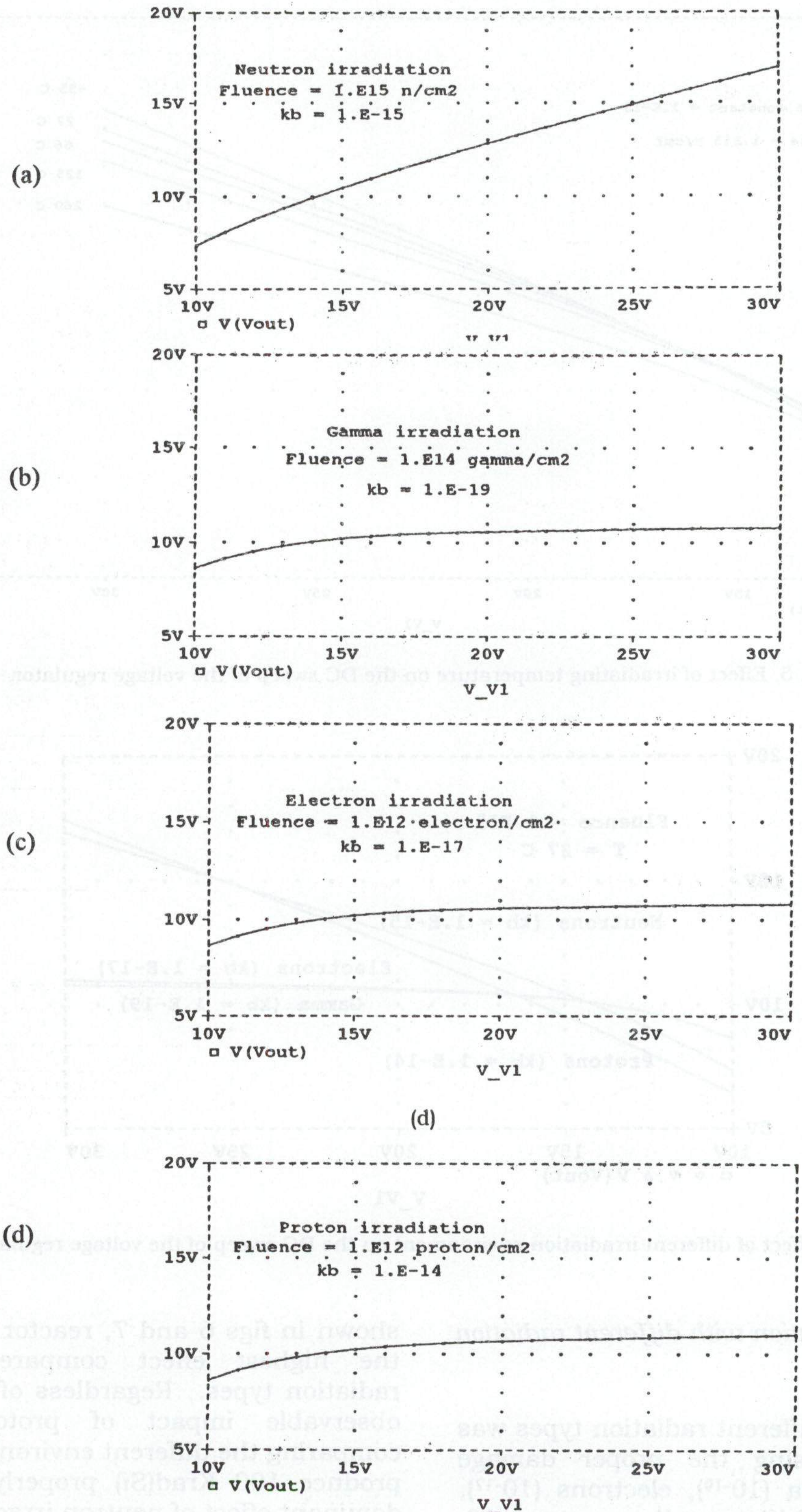

Fig. 7. Irradiation to produce 100 k rad(Si) using (a) neutrons, (b) Gamma, (c) Electrons, and (d) Protons.

4.5. Statistical analysis without irradiation

Monte Carlo analysis for unirradiated circuit was performed with the following distribution in parameter values:
20% Gaussian distribution in resistors, 20% Guassian distribution in B_f of the BJT.

As shown in table 2., three cases were compared: Variation in R's, variation in B_f, and variation in both of them. Results are shown as maximum deviation of V_{out} from the bias point of the circuit (= 10.6 V in case of unirradiated circuit at 27 °C). The maximum deviation was calculated at the two ends of the DC sweep, i.e., at V_{in} = 30 (upper end), and V_{in} = 10 (lower end).

Variation in the values of R determines the output voltage value and the spread in its value especially at the lower end of the DC sweep (V_{in} = 10 V).

4.6. Effect of resistor variation and β_f variation for irradiated circuit

First, the impact was analyzed for the irradiated and unirradiated conditions at T = 27 °C. Results are shown in table 3.

Statistical variation in R dominates the behavior of the circuit especially at the higher end of the DC sweep (i.e., V_{in} = 30 V). For irradiated circuit, the difference between the two cases (i.e., statistical variation in R and in Bf) is reduced. The impact is nearly the same at both the upper and lower ends of the DC sweep.

4.7. Effect of resistor variation and B_f variation for irradiated circuit at different temperatures

Analysis was made at T = 125 °C. Results at T = 27 °C and T = 125 °C were compared. Fig. 8 shows results at V_{in} = 30 V. Tables 4 and 5 compare results for T = 27 °C and T = 125 °C.

As shown, variation in R is responsible for the variation in the output voltage. Impact of variation in B_f is small compared with that of R. However, The impact of B_f increases with temperature.

Table 2
Effect of statistical variations in circuit parameters on the output voltage of the voltage regulator

	V(in) = 30 V			V(in) = 10 V		
	R	Bf	Both	R	Bf	Both
Mean of deviations	0.23	0.23	0.12	-1.98	-3.93	-2.02
Standard deviation	0.81	0.01	0.84	0.27	0.001	0.29

Table 3
Comparison between the effect of statistical variation in R and B_f on the output voltage at V_{in} = 30 V (Higher end) and V_{in} = 10 V (Lower end) for unirradiated and irradiated conditions at T = 27 C

	Upper end (Vin = 30 V)				Lower end (Vin = 10 V)			
	Unirradiated		Irradiated		Unirradiated		Irradiated	
	Bf	Both*	Bf	Both	Bf	Both	Bf	Both
Mean of deviations	0.23	0.12	4.03	3.99	-3.93	-2.02	-5.48	-5.53
Standard deviation	0.01	0.84	0.5	1.12	0.001	0.29	0.13	0.27

*Both = Statistical variation in Bf and R

Table 4
Comparison between the effect of statistical variation in R and B_f on the output voltage at V_{in} = 30 V (Higher end) and V_{in} = 10 V (Lower end) for irradiated conditions at T = 27 C

	Vin = 30 V		Vin = 10 V	
	Bf	Both	Bf	Both
Mean of deviations	4.03	3.99	-5.48	-5.53
Standard deviation	0.5	1.12	0.13	0.27

Table 5
Comparison between the effect of statistical variation in R and B_f on the output voltage at V_{in} = 30 V (Higher end) and V_{in} = 10 V (Lower end) for irradiated conditions at T = 125 C

	Vin = 30 V		Vin = 10 V	
	Bf	Both	Bf	Both
Mean of deviations	3.55	3.54	-4.94	-4.99
Standard deviation	0.56	1.16	0.12	0.25

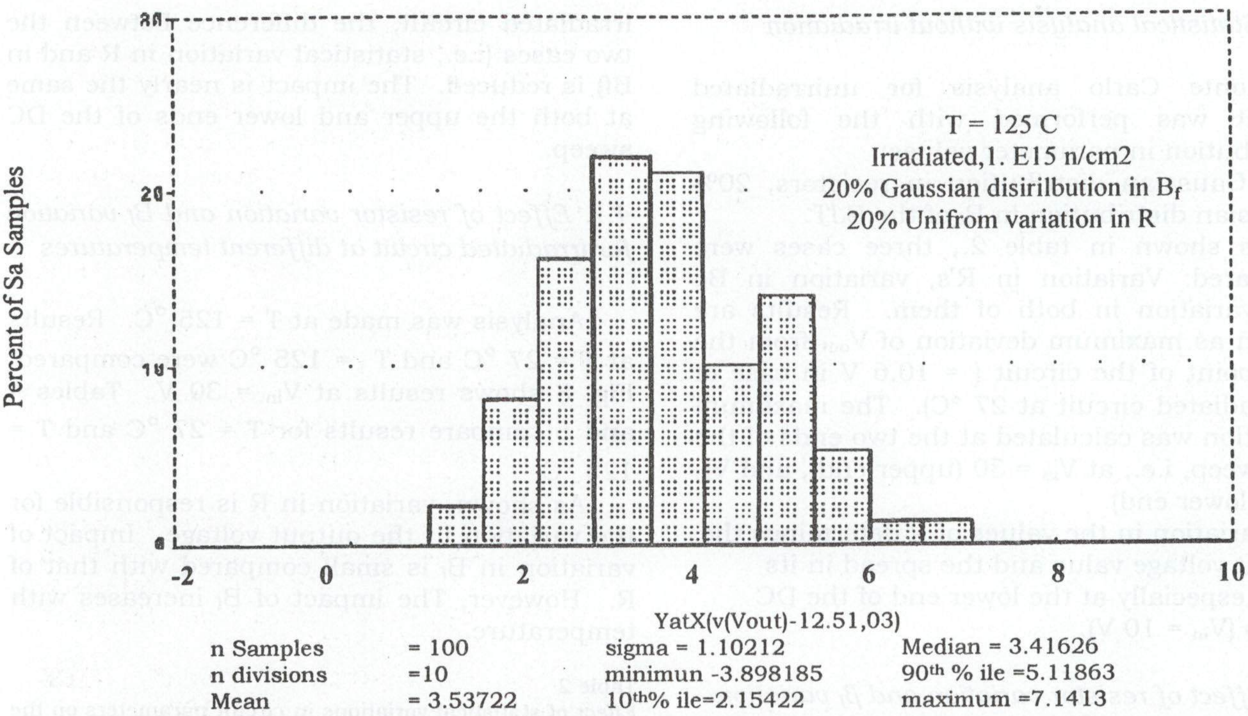

Fig. 8. Statistical variation in the output voltage for irradiated circuit at T = 125 °C.

5. Conclusions

BJTs are highly sensitive to total dose irradiation especially at high neutron doses of the order of 1.E15 neutrons/cm^2. For a comparable rad(si), BJT are tolerable to other radiation environment like gamma, electrons, and protons. Irradiation of the voltage regulator circuit under consideration at high temperatures counteracts the gain degradation due to irradiation. However, the effect of temperature is small compared with the effect of irradiation.

It is important to take all the statistical variation in the circuit to properly account for the circuit behavior in a radiation environment. This work proves that it is feasible to simulate the behavior of electronic circuits taking into consideration all the relevant variables, i.e, radiation, temperature, and statistical variation in device parameters.

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