ISSN 1674-1056
http://cpb.iphy.ac.cn
http://iopscience.iop.org/cpb
中国物理 B
Chinese Physics
中国物理 Chinese Physics B

Bulk and surface damages in complementary bipolar junction transistors produced by high dose irradiation

J Assaf
Citation: Chin. Phys. B . 2018, 27(1): 016103. **doi:** 10.1088/1674-1056/27/1/016103

Journal homepage: http://cpb.iphy.ac.cn; http://iopscience.iop.org/cpb

What follows is a list of articles you may be interested in

Ionizing radiation effect on single event upset sensitivity of ferroelectric random access memory

Jia-Nan Wei(魏佳男), Hong-Xia Guo(郭红霞), Feng-Qi Zhang(张凤祁), Yin-Hong Luo(罗尹虹), Li-Li Ding(丁李利), Xiao-Yu Pan(潘霄宇), Yang Zhang(张阳), Yu-Hui Liu(刘玉辉)
Chin. Phys. B . 2017, 26(9): 096102. **doi:** 10.1088/1674-1056/26/9/096102

Direct measurement and analysis of total ionizing dose effect on 130 nm PD SOI SRAM cell static noise margin

Qiwen Zheng(郑齐文), Jiangwei Cui(崔江维), Mengxin Liu(刘梦新), Dandan Su(苏丹丹), Hang Zhou(周航), Teng Ma(马腾), Xuefeng Yu(余学峰), Wu Lu(陆妩), Qi Guo(郭旗), Fazhan Zhao(赵发展)
Chin. Phys. B . 2017, 26(9): 096103. **doi:** 10.1088/1674-1056/26/9/096103

Correlation of polishing-induced shallow subsurface damages with laser-induced gray haze damages in fused silica optics

Xiang He(何祥), Heng Zhao(赵恒), Gang Wang(王刚), Peifan Zhou(周佩璠), Ping Ma(马平)
Chin. Phys. B . 2016, 25(8): 088105. **doi:** 10.1088/1674-1056/25/8/088105

Radiation-induced 1/*f* noise degradation of PNP bipolar junction transistors at different dose rates

Qi-Feng Zhao(赵启凤), Yi-Qi Zhuang(庄奕琪), Jun-Lin Bao(包军林), Wei Hu(胡为)
Chin. Phys. B . 2016, 25(4): 046104. **doi:** 10.1088/1674-1056/25/4/046104

Optical study of D–D neutron irradiation-induced defects in Co- and Cu-doped ZnO wafers

Wang Yun-Bo, Li Gong-Ping, Xu Nan-Nan, Pan Xiao-Dong
Chin. Phys. B . 2013, 22(3): 036102. **doi:** 10.1088/1674-1056/22/3/036102

Bulk and surface damages in complementary bipolar junction transistors produced by high dose irradiation

J Assaf[†]

Atomic Energy Commission, Damascus, Syria

(Received 9 August 2017; revised manuscript received 26 September 2017; published online 25 November 2017)

Two complementary types NPN and PNP of bipolar junction transistors (BJTs) were exposed to high dose of neutrons and gamma rays. The change in the base and collector currents, minority carriers lifetime, and current gain factor β with respect to the dose were analyzed. The contributions of the base current according to the defect types were also reported. It was declared that the radiation effect of neutrons was almost similar between the two transistor types, this effect at high dose may decrease the value of β to less than one. The Messenger–Spratt equation was used to describe the experimental results in this case. However, the experimental data demonstrated that the effect of gamma rays was generally higher on NPN than PNP transistors. This is mainly attributed to the difference in the behavior of the trapped positive charges in the SiO_2 layers. Meanwhile, this difference tends to be small for high gamma dose.

Keywords: bipolar junction transistors, radiation effects, surface damage, bulk damage

PACS: 61.80.Hg, 61.80.Ed, 61.82.Fk, 81.40.Wx **DOI:** 10.1088/1674-1056/27/1/016103

1. Introduction

Basic mechanisms of total radiation effects have been investigated continually. Considerable efforts have been devoted to acquire more knowledge about the hardness of semiconductor devices. Due to high performance characteristics in switching and amplification, bipolar junction transistors (BJTs) are used in various electronic systems. However, the exposure of BJTs to nuclear radiation can affect their characteristics. Meanwhile, there are still some advantages even when used in the circuits under radiation.[1]

The main degradation of irradiated semiconductor devices is produced by the effect of ionization and atomic displacement. According to their origin, ionization and atomic displacement are conventionally referred to as the total ionization dose (TID) and the non ionization energy losses (NIEL), respectively. The radiation effect is related to the energy and type of radiation, and depends on the structure of the transistor. The two main types of BJT (NPN and PNP) exhibit qualitatively the same radiation effects. However, for vertical BJTs design, it was noticed that NPN is more degraded by irradiation than PNP. Several mechanisms describing the damage effects in both types have been reported. Whatever the source of damage in BJTs, its main final effect is the decrease of the β factor, this effect was widely approached in several works for various types and structures of BJTs.[2–4]

The aim of this study is to obtain more knowledge about the effect of neutrons and gamma rays on complementary small signal BJTs. This was accomplished by analyzing the changes in the collector current I_C, base current I_B and β, on vertical NPN and PNP transistors, and comparing their behaviors. Moreover, the comparison between the effect of surface and bulk damages according to the transistor and radiation types would be reported. The important role of the recombination of the minority carrier charges occurring in the transistor bases after irradiation will also be addressed. Another aim of this work is using the Messenger–Spratt equation to illustrate the change in the transistor parameters for a large range of radiation dose. This issue was also useful for analyzing other types of radiation.[4]

2. Parameters affected by radiation

The flow of the minority carrier provides the basic mechanism of the BJT operation. TID and NIEL are the matter of defects in the BJT structure. They increase the recombination rate in the base region of the transistor and then decrease the minority carrier lifetime τ. This decrease is the fundamental mechanism which describes the β degradation, and then the transistor operation. In fact, β is physically determined by the fraction of the majority carriers injected from the emitter that passes through the base as minority carriers and collected finally by the collector; this fraction equals then to I_C/I_B. The lifetime τ represents the surviving average time of these minority carriers before the recombination with the majority carriers of the base. Therefore, the practical consequences of this effect on the transistor function lead in general to varying the values of I_C and I_B currents.[5–8] As the role of I_B is essential in the degradation process, it is useful to present some details about its contributions. For a conventional BJT type, the total base current I_B is composed of three components I_{B1}, I_{B2}, and I_{B3}. The component I_{B1} represents the main component resulted by the injection of the minority carriers from the base

[†]Corresponding author. E-mail: pscientific12@aec.org.sy

© 2018 Chinese Physical Society and IOP Publishing Ltd

to the emitter, and it is independent of τ. The I_{B2} is due to the recombination in the depletion zone (DZ) of the emitter–base junction. The last component I_{B3} also represents a recombination current but inside the neutral base region; it is inversely proportional to τ. Thus, I_{B2} and I_{B3} are produced by recombination occurring between diffused majority carriers traversing the base and the base minority carries.[7] Figure 1 shows the emitter–base section in a conventional vertical BJT before and after irradiation as well as the location of the two kinds of defects in the emitter–base junction which is the most sensitive part to the radiation. The component I_{B1} and the sum of $I_{B2}+I_{B3}$ are the main contribution of the base current before and after irradiation, respectively.

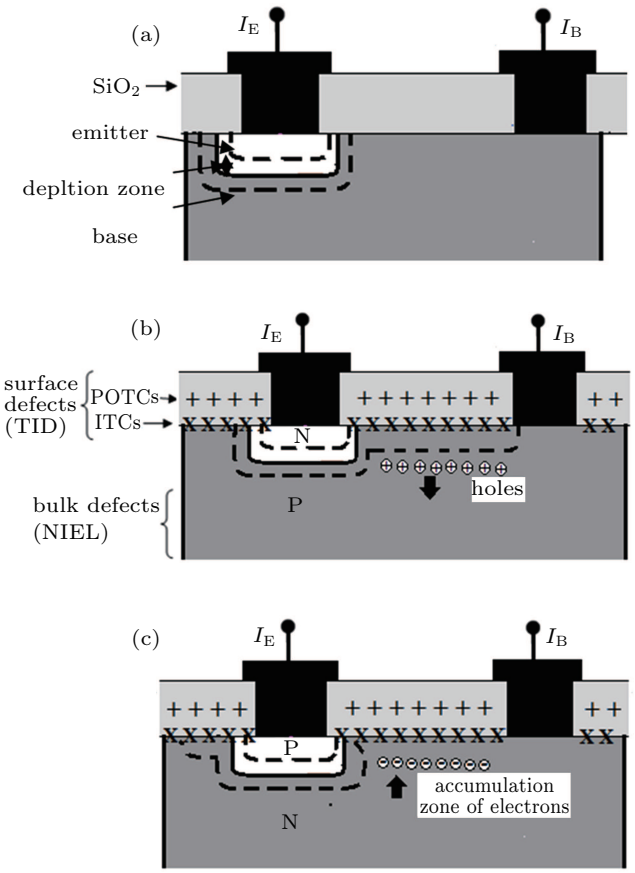


Fig. 1. Emitter–base section in a conventional vertical BJT: pre-radiation (a), after irradiation for NPN structure (b), and after irradiation for PNP structure (c).

3. TID damages

In electronic devices, the ionization produces electron–hole pairs within the semiconductors such as silicon (Si) and the dielectric layers such as silicon dioxide (SiO_2). The free electrons are much more mobile than holes and those do not immediately recombine but they diffuse away by means of the electric field after a short time. While, the holes will make their way towards the SiO_2 and Si/SiO_2 interface over a longer time. Some of them will eventually recombine in the route and the rest will be captured by intrinsic defects in the SiO_2 and Si/SiO_2 interface regions. This capture creates two types of trapped charge. The first is the positive oxide trapped charges (POTCs) in the SiO_2 layer, and the second is the interface trapped charges (ITCs) at the Si/SiO_2 interface as shown in Fig. 1. A single POTC is formed by the capture of a hole at the strained Si–Si bond (oxygen vacancy) defect. After that, the Si–Si bond is broken and the lattice relaxes giving the positively charged Si. While an ITC defect is the result of the reaction of a hole with the defect site containing hydrogen, which finally produces a trapped state in the form of Si dangling bonds.[9–12] In the BJT structure, both POTCs and ITCs activate the hole–electron recombination process, which increases mainly the current components I_{B2} and I_{B3} and then the total base current.

3.1. Effects of ITC and POTC charges

Since POTCs are positive charges, their influence varies according to the doping of the adjacent Si layer, and then to the transistor type.

For the $Si(P)/SiO_2$ interface, POTCs push the positive holes of the Si(P) layer toward the bulk away from the interface. As a result, a DZ below the POTCs layer will be expanded inside this P region. On the contrary, in the $Si(N)/SiO_2$ interface, POTCs attract the negative electrons to the interface forming an accumulation zone (AZ) below it.

The created DZ in the case of the $Si(P)/SiO_2$ interface incites to the creation of a new contribution of the base current labeled $I_{B2surface}$, in addition to the main contribution denoted I_{B2Bulk} in the main part of DZ. The contribution $I_{B2surface}$ is independent of τ, while I_{B2Bulk} is inversely proportional to τ.

As to the charges ITCs, they have an amphoteric nature, and behave like acceptors, donors or neutral charges, which depends on their position in the Si energy band gap. This is related to the position of Fermi level at the Si/SiO_2 interface, and depends mainly on the Si type. In all cases, ITCs act as traps of minority carriers at the surface of any formed DZ below this interface. Therefore, the effect of ITCs is qualitatively similar for the Si/SiO_2 interface whatever the type of Si.

The effects of POTCs and ITCs altogether at the transistor surface can be resumed as follows: the depletion and the accumulation (resulted from POTCs) enhances and reduces the electron–hole recombination rate, respectively. Both effects are accomplished throughout the ITCs, and lead to increasing and reducing the contribution of $I_{B2surface}$, respectively.[7,13]

3.2. TID effect according to BJT type

We now present the different TID behaviors on the two vertical BJT type as follows.

(I) For the NPN device: in the base $(P)/SiO_2$ interface, the DZ of the emitter–base junction spreads into the P-base region, which increases the DZ on the long side of the SiO_2

surface and then increases $I_{\mathrm{B2surface}}$. The other effect is represented by the increase of the recombination rate inside the intrinsic base between the repelled holes from the base surface and the diffused electrons from the emitter, which increases the component I_{B3}.[13]

(II) For the PNP device, the POTCs create a large AZ near the base (N)/SiO_2 interface and they expand a small DZ into the emitter (P)/SiO_2 interface. Therefore, there are a few increases in the $I_{\mathrm{B2surface}}$. However, at the same time, there are more electrons coming from the surface and injected into the emitter, which leads to some excess in the I_{B1}.[13] These two mechanisms have a little effect on the base current compared with NPN structure.

As a result from the above analysis, the PNP structure is more radiation hardened than NPN for the TID effect.

4. NIEL damage

In displacement damage, interstitials (displaced Si atoms) and vacancies are created in the form of point and cluster defects in the bulk of the transistor. These defects introduce deep level centers to serve as recombination sites and carrier traps within the lattice, which reduce the time τ. Since I_{B2Bulk} and I_{B3} are inversely proportional to τ; therefore, the NIEL damage is similar to the TID which increases the current base components and then increases the total current I_{B} leading to the decrease of the β factor.

The minority carriers in the base are electrons in NPN and holes in PNP structures. The value of τ for electrons and holes are almost equal in BJT structure, then we expect a similar effect on both structures.

The first original study characterizes the NIEL damage, which was based on the variation of the $1/\tau$ before and after irradiation by electrons, this variation for a wide range of electrons fluence ϕ is given by[14]

$$\frac{1}{\tau}-\frac{1}{\tau_0}=K_\tau\phi, \tag{1}$$

where τ_0 and τ are the values before and after irradiation, K_τ is the minority carriers lifetime damage constant representing the damage per unit fluence, and $\Delta(1/\tau)=(1/\tau-1/\tau_0)$ is the change in reciprocal of the minority carriers lifetime. The conventional units of ϕ, τ, and K_τ are: cm^{-2}, s, and cm^{-2}/s, respectively.

Furthermore, the term $1/\tau$ depends on the defect concentration N_{d} in the bulk as[15]

$$\frac{1}{\tau}=\sigma v_{\mathrm{th}}N_{\mathrm{d}}, \tag{2}$$

where σ is the cross section of the carrier trapping and v_{th} is the carrier thermal velocity. Since N_{d} increases with the increase of the radiation dose/fluence, the value of τ will then be decreased.

Introducing Eq. (2) into Eq. (1) gives the relationship between $\Delta(1/\tau)$ and the excess of the defect density ΔN_{d} due to irradiation as follows:

$$\Delta\left(\frac{1}{\tau}\right)=K_\tau\phi=\sigma v_{\mathrm{th}}\Delta N_{\mathrm{d}}. \tag{3}$$

Equations (1) and (3) show that $\Delta(1/\tau)$ expresses the degradation of the minority carriers lifetime produced by NIEL and it is proportional to the particles fluence or to the defect concentration.

A similar formula for the change in reciprocal current gain $\Delta(1/\beta)$ was also established later. It is then better now to analyze the different contributions of $1/\beta$. In fact, for radiation damage purposes, the total inverse current gain is composed from three terms and given by[16,17]

$$\frac{1}{\beta}=\frac{1}{\beta_0}+\frac{1}{\beta_{\mathrm{S}}}+\frac{1}{\beta_{\mathrm{B}}}, \tag{4}$$

where β_0, β_{S}, and β_{B} are the values before irradiation (initial gain), due to surface recombination, and due to bulk recombination, respectively. Only the term $1/\beta_{\mathrm{B}}$ depends on lifetime as follows:[16]

$$\frac{1}{\beta_{\mathrm{B}}}=\frac{\tau_{\mathrm{tr}}}{\tau}, \tag{5}$$

where τ_{tr} is the average transit time of the minority carrier injected from the emitter to the collector throughout the base. The τ_{tr} determines the intrinsic current gain cut-off frequency f_{T} or the gain band-width product such as $f_{\mathrm{T}}=1/2\pi\tau_{\mathrm{tr}}$.[8,15,16]

Therefore, by considering this contribution of the current gain, the combination of Eqs. (1) and (5) produces the change in reciprocal of the gain caused by NIEL (bulk damage) and given by the Messenger–Spratt equation as follows:[18]

$$\Delta\left(\frac{1}{\beta}\right)_{\mathrm{B}}=\frac{1}{\beta_{\mathrm{B}}}-\frac{1}{\beta_0}=\frac{K_\tau}{2\pi f_{\mathrm{T}}}\phi=K_\beta\phi, \tag{6}$$

where K_β is the damage constant of the current gain, which equals to $K_\tau\tau_{\mathrm{tr}}$ with the unit of cm^2.

For a mixed radiation damage (surface and bulk), the total $\Delta(1/\beta)$ can also be composed from two contributions given by the following equation:[19]

$$\Delta\left(\frac{1}{\beta}\right)=\Delta\left(\frac{1}{\beta}\right)_{\mathrm{B}}+\Delta\left(\frac{1}{\beta}\right)_{\mathrm{S}}, \tag{7}$$

where $\Delta(1/\beta)_{\mathrm{S}}=(1/\beta_{\mathrm{S}}-1/\beta_0)$ is the change in reciprocal of gain caused by surface damage.

Before presenting the results, the following point should to clarified: the dominant mechanism that resulted from the neutrons reaction is the displacement damage, which produces a lot of damage in the form of cluster defects of atomic displacement. A small ionization can also occur which depends on the neutrons energy. While, gamma rays produce mainly the ionization, but it can also create very few damages resulted from point defects through energetic Compton electrons of high gamma energy.

5. Experimental

The devices under test (DUTs) are complementary BJTs: NPN (2N2222 A) and PNP (2N2907 A). They are discrete commercial transistors having a vertical design. The pre-rad value of β labeled β_0, is specified in each DUT and varies from one to another even for the same product. The β_0 of the used transistors varied from 130 to 180. For a specific test, five DUTs having as much as possible equal β_0 were submitted to the accumulated radiation dose.

DUTs were irradiated by Co-60 gamma source having an average radiation energy of 1.25 MeV. The gamma dose was measured by a chemical dosimeter. The neutron irradiation was achieved by a miniature neutron source reactor (MNSR). DUTs were exposed to a wide spectrum of neutrons inside MNSR in addition to associated fission gamma rays. As the irradiation dose inside the reactor is proportional to the fluence and to the period of irradiation, its effect was studied in this work as a function of the irradiation time at a fixed value of the fluence.

The tests were performed using two experimental set-ups. The first set-up was a curve tracer device, which plotted many curves of the current I_C versus the collector–emitter voltage V_{CE} known as the I_C–V_{CE} characteristics. Each curve corresponds to a fixed value of the current I_B and then to β. The second set-up was a typical common emitter circuit built around the DUT. This circuit was connected to a signal generator, a digital oscilloscope, a DC power supply, and a current meter.

6. Results and discussion

The obtained result in previous work revealed that the most damage effecting on the semiconductor after irradiation inside the MNSR comes from the neutrons compared with the fission gamma.[6] This issue is considered during presenting the results of this work through replacing the irradiation inside the reactor by neutron irradiation term. On the other hand, error bars are shown on the curves of the experimental results, and do not appear on the deduced and calculated curves. The bar represents the standard deviation error of five successive tests.

6.1. I_C–V_{CE} characteristics after irradiation

These tests were achieved at a constant value of I_B equal to 50 μA. Figure 2 shows the results for NPN and PNP transistors irradiated up-to a total gamma source dose of 200 kGy. It can be seen that the values of I_C in the saturated region of the obtained curves decrease with the increase of the dose, and this decreasing is higher in NPN than in PNP transistors. Similar behaviors of these characteristics have been obtained in the case of irradiation by neutrons, but unlike gamma rays, the I_C–V_{CE} curves of NPN and PNP transistors are almost identical.

6.2. Change of β after irradiation

The β is to be considered as the most important parameter of the BJT to illustrate the radiation influence on such a device. The value of β is also obtained by the curve tracer. The variation of β is the function of the dose can then be presented by the curve β(dose). Figure 3 presents an example of β(dose) curves related to neutrons and to the gamma source for NPN and PNP transistors. As a result, β decreases with the dose increasing, and then higher damage corresponds to a lower value of β. Based on the analysis of these results, the following points can be concluded.

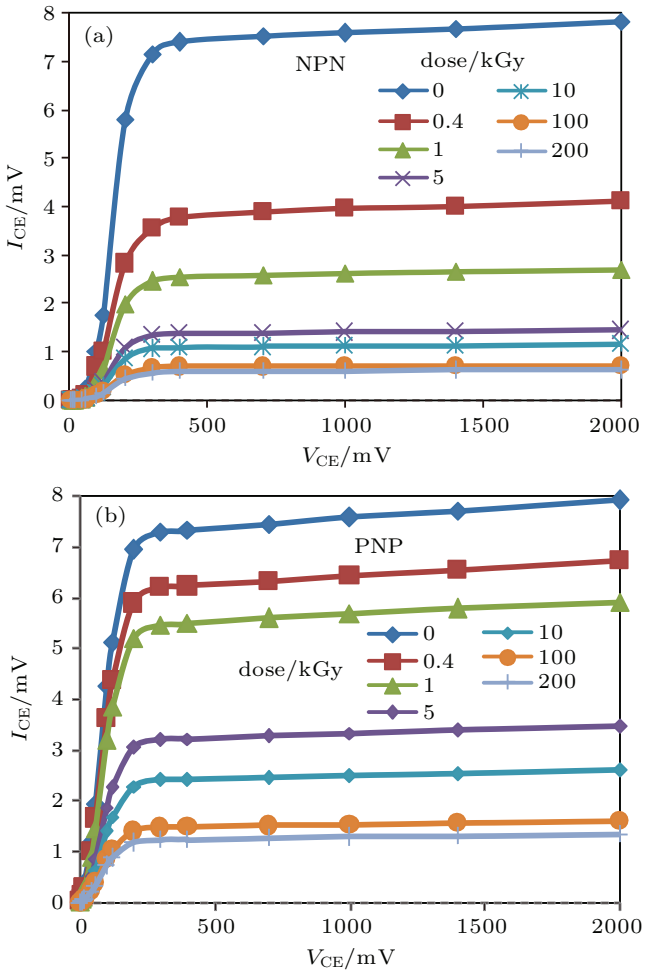


Fig. 2. (color online) I_{CE}–V_{CE} characteristics of NPN (a) and PNP (b) transistors after irradiation by several doses of gamma sources.

(I) The non-linear decreasing of the curves β(dose) was observed for both radiation effects. The factor β decreases rapidly at the beginning and slowly for higher doses until the saturation.

(II) The neutrons effect is the same between NPN and PNP types. Therefore, the NIEL damage producing the bulk defects is the same.

In general, the effect of gamma rays is higher on NPN than on PNP, i.e., $\beta(\text{dose})_{\text{NPN}} > \beta(\text{dose})_{\text{PNP}}$. However, the experimental results show that the difference $\Delta\beta(\text{dose}) = \beta(\text{dose})_{\text{NPN}} - \beta(\text{dose})_{\text{PNP}}$ for gamma rays is not constant, but varies according to the dose. It is maximum in the range between 0.1 and 10 kGy, and decreases with the increased dose. For doses more than 500 kGy, this difference tends to be small, which is due to the high rate decreasing of the curve $\beta(\text{dose})_{\text{PNP}}$. This behavior may be explained by the fact that the high dose produces a lot of POTCs, which increase significantly the electrons of the N-base repelled from the surface in the PNP structure. Therefore, more electrons are injected into the emitter causing significant increase in the component I_{B1}. Another reason may be moving the recombination into the bulk for the high doses, where the radiation effect behaves similarly between the two types.

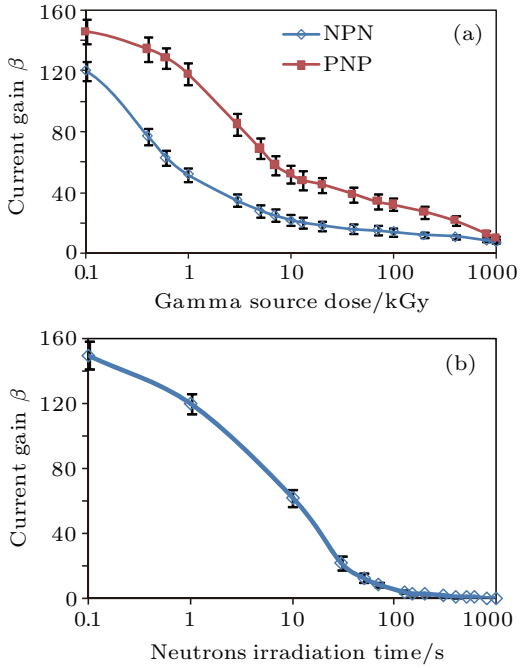


Fig. 3. (color online) The variation of the current gain β with the dose after irradiation by gamma source for both transistor types NPN and PNP (a), and neutrons for NPN and PNP types (b). For both types $\beta_0 = 150$.

6.3. Variations of I_{C} and I_{B} with the dose

The measurement of the variation of I_{C} and I_{B} in real circuit conditions was accomplished by means of a typical common emitter circuit with bias voltage $V_{\text{CC}} = 20$ V. Opposite change in the values of I_{B} and I_{C} currents after irradiation has been reported; this change is represented by increasing and decreasing of these currents, respectively. The behaviors of I_{B} and I_{C} are the origin of the β decreasing shown in Fig. 3, and it is attributed to the recombination between the diffused carriers from the emitter to the collector through the base. The evolution of I_{C} and I_{B} regarding the dose depends on the radiation type as follows:

(I) Irradiation by neutrons: Similar change in I_{B} and I_{C} was obtained for NPN and PNP. Figure 4 shows these changes versus irradiation time for NPN as an example. The variation of β and the relationship between I_{C} and I_{B} are given in Table 1, which summarizes the results of Figs. 3(a) and 4. It can be concluded that $I_{\text{C}} > I_{\text{B}}$ in normal conditions and for low irradiation time. The increasing in irradiation time up to the range of 500–1000 s gives rise to a situation in which $I_{\text{C}} < I_{\text{B}}$ and then to $\beta < 1$. This situation makes the transistor work out its normal function.

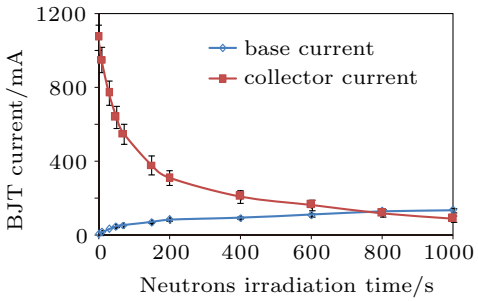


Fig. 4. (color online) The variations of the currents I_{B} and I_{C} versus neutrons irradiation time for an irradiated NPN transistor (similar result for PNP).

Table 1. The variations of β, I_{C}, and I_{B} according to the range of neutrons irradiation time of NPN sample (similar result for PNP).

Range of the irradiation time in s	Range of β variation	Resulted inequality between I_{C} and I_{B}
0–50	150–13	$I_{\text{C}} \gg I_{\text{B}}$
60–400	10–1.3	$I_{\text{C}} > I_{\text{B}}$
500–1000	1–0.5	$I_{\text{C}} < I_{\text{B}}$

(II) Irradiation by gamma source: The currents I_{C} and I_{B} are also decreased and increased with the dose, respectively. However, the variations in I_{C} and I_{B} for NPN and PNP are different as it is shown in Fig. 5. Comparison between I_{C} and I_{B} versus dose for NPN and PNP is also presented in Fig. 6. It can be seen that $I_{\text{C}} > I_{\text{B}}$ and $\beta > 1$ for both transistor types and for the whole dose range. A saturation in the values of I_{C} and I_{B} at a dose of about 4 kGy has occurred. The saturation of β, shown in the previous section, originated from the same effect. The literature has reported various reasons for this behavior. It could be attributed to the fact that the oxide layer cannot trap more charge, particularly for thin oxide layers;[21] or to the high density of POTCs produced at high dose, which moves the recombination into the bulk and becomes less sensitive to surface effects.[21,22] Finally, the electric field in the oxide may be decreased at high dose due to screening of its initial value by charged defect near the interface.[23] Whatever the reason, this saturation point represents the transition from the surface to bulk effects, where further increase in ionization dose will give a little base current excess.

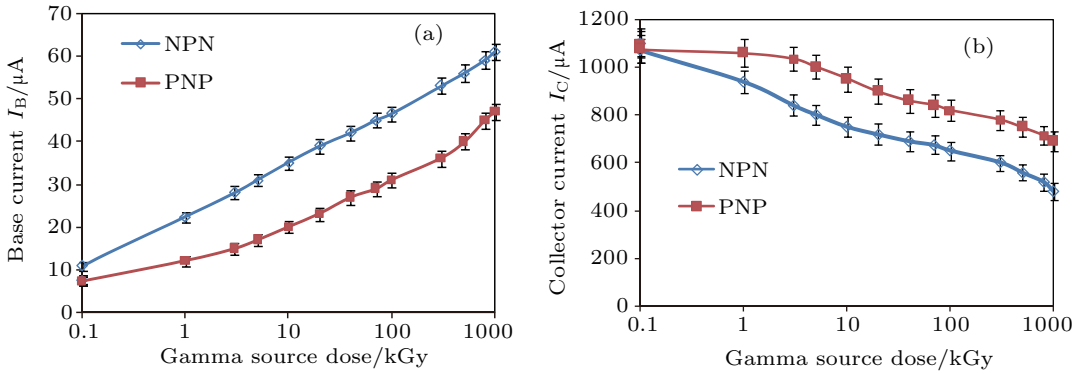


Fig. 5. (color online) The variations of the base current I_B (a) and the collector current I_C (b), for irradiated NPN and PNP transistors as a function of the gamma source dose.

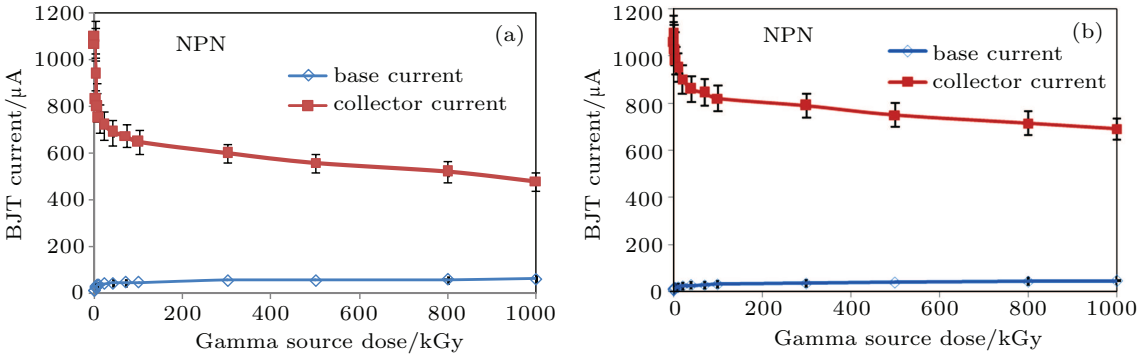


Fig. 6. (color online) The variations of I_B and I_C versus gamma source dose for irradiated NPN (a) and PNP (b) transistors.

Table 2. The percentage variations of I_C and I_B after irradiation by the maximum dose of gamma rays and neutrons for NPN and PNP transistors.

Radiation and dose	ΔI_B% increasing		ΔI_C% decreasing		$\beta_0 \rightarrow \beta_{(\text{max dose})}$	
	NPN	PNP	NPN	PNP	NPN	PNP
Gamma source/1000 kGy	702%	543%	56.2%	37.7%	150→7.5	150→10
Neutrons/1000 s	1750%		90%		150→0.75	

A quantitative analysis of the variations of I_C and I_B was conducted to identify the reason of β decreasing in both transistor structures. The relative change of current $\Delta I\% = \Delta I/I_0$, as well as the corresponding values of β, is presented in Table 2, whereas ΔI is the difference between the current value after the maximum dose and the current value before irradiation I_0. The $\Delta I_B\%$ and the $\Delta I_C\%$ in addition to the corresponded β variation are shown. The average values related to neutrons are presented in this table because of the similarity in the result for NPN and PNP transistors. The table reveals large relative variations of I_B compared with small variations of I_C.

6.4. Characterization of the radiation damage type

The Messenger–Spratt equation describes only the β_B degradation; thereby, it is widely used to predict the type of damage. In the beginning, this equation was related to the particle fluence. Then became used later for any parameter proportional to the fluence such as the dose.[22] In this context, equation (6) can be expressed as follows:

$$\Delta\left(\frac{1}{\beta}\right)_B = K_\beta \psi, \tag{8}$$

where K_β is the damage constant, and ψ is a factor proportional to the absorbed dose, which is in this work the irradiation time in units of s or the dose in units of kGy. The unit of K_β in Eq. (8) is then the inverse of the unit of ψ. The experimental curve of $\Delta(1/\beta)$ as a function of ψ indicates clearly the damage type. If this curve is linear, the bulk damage is then dominated and the surface damage is negligent. While, a non-linear curve means either the domination of the TID effect, or the presence of the NIEL contribution for low particle flounce.[4,24] The strength of the damage can also be concluded from Eq. (8); since the damage corresponds to low β value, therefore, high values of $\Delta(1/\beta)$ and K_β correspond to high damage.

Figure 7 shows the resulting curve for the two radiation types. A similar effect of neutrons for NPN and PNP can be

observed in Fig. 7(a). The linear behavior, especially at high dose, indicates that mainly the displacement damage takes place. The slope of the curve equals to the average value of K_β of about 2×10^{-3} s^{-1}.

On the contrary, the curve of $\Delta(1/\beta)$ versus gamma source dose in Fig. 7(b) has a non-linear characteristic in the range of 100–400 kGy with an almost saturation form, which means that the ionization effect dominates in this range. For higher dose than the 500 kGy dose, the linear behavior indicates the presence of the displacement damage due to the secondary Compton electrons effect. The slope of the linear curves portion represents K_β values, which are 6.8×10^{-5} and 4.7×10^{-5} kGy^{-1} for NPN and PNP, respectively. In Fig. 7(b), we can also see that $\Delta(1/\beta)_{\rm NPN} > \Delta(1/\beta)_{\rm PNP}$, which proves again the high suffering of NPN due to gamma ray radiation compared with PNP.

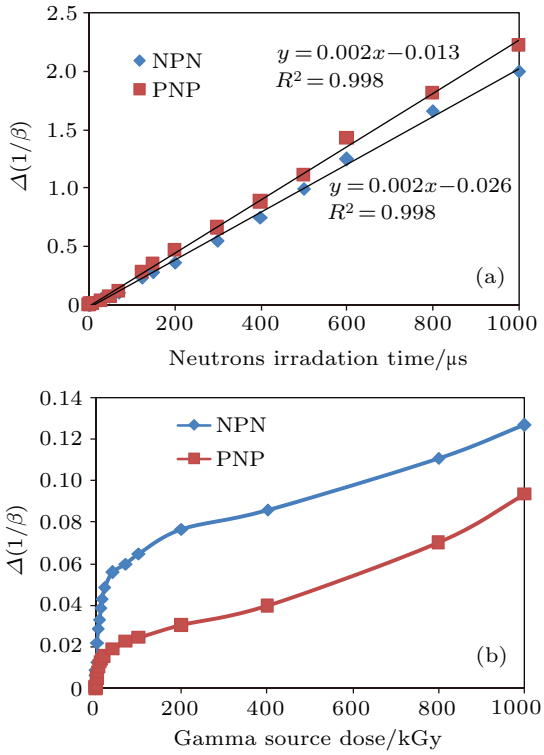


Fig. 7. (color online) The change in reciprocal current gain $\Delta(1/\beta)$ for irradiated NPN and PNP transistors as a function of the neutrons irradiation time (a), and gamma source dose (b).

The change of the minority carrier lifetime τ can also be obtained from the experimental data of β using Eq. (5). We start from the result of neutrons effect shown in Fig. 3(a), which shows the effect leading mainly to the bulk damage. Taking into account the values of $f_{\rm T}$ from the data sheet, it is possible to calculate $\tau_{\rm tr}$ for the used NPN and PNP transistors, so the data provides the minimum of $f_{\rm T}$, one calculates the maximum values of $\tau_{\rm tr}$ and τ. The maximum value of $\tau_{\rm tr}$ is fixed and equals to 0.530 ns and 0.796 ns for NPN and PNP transistors, respectively. The variation of the maximum minority carrier lifetime $\tau_{\rm max}$ is illustrated in Fig. 8. The minority carrier lifetime, like the current gain β, decreases with the neutron irradiation time, which corresponds to the increase of the recombination in the transistor's bulk, particularly in the base region.

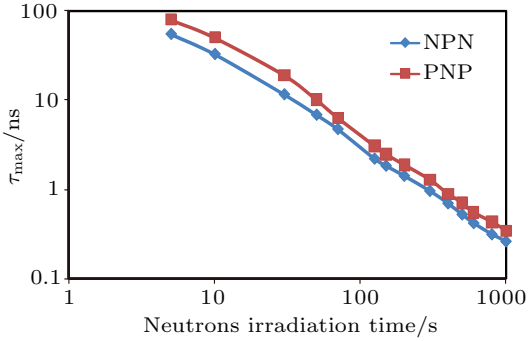


Fig. 8. (color online) The calculated maximum minority carrier lifetime $\tau_{\rm max}$ as a function of the neutron irradiation time for irradiated NPN and PNP transistors.

6.5. Variation of the current circuit consumption

The variation of the consumption current $I_{\rm CC}$ in the common emitter circuit using NPN and PNP was investigated. Figure 9 shows the results for the irradiation by gamma rays and neutrons. In all cases, the $I_{\rm CC}$ decreases with the dose but through different behaviors according to the types of transistor and radiation. A high rate of this decreasing takes place at doses more than 10 kGy and 10 s. Since the current $I_{\rm C}$ forms the main contribution of the current $I_{\rm CC}$, the decrease of $I_{\rm CC}$ with the increase of the dose is compatible with the similar behavior of $I_{\rm C}$ shown in Figs. 5(b) and 6.

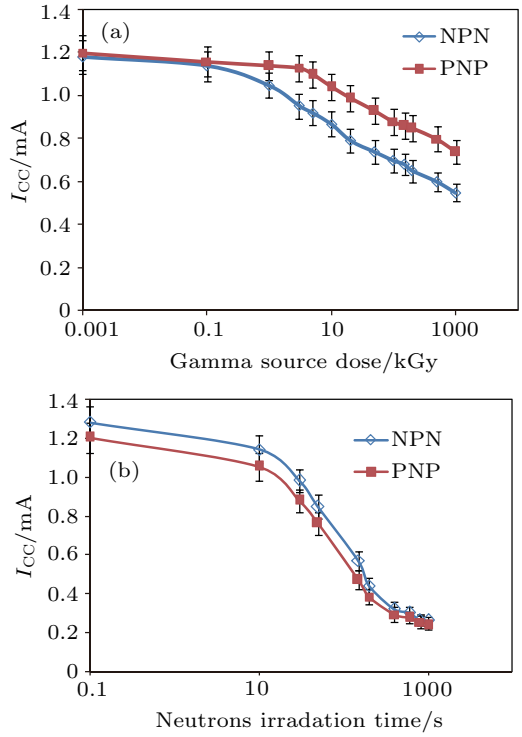


Fig. 9. (color online) The total consumption current $I_{\rm CC}$ of NPN and PNP transistors irradiated by gamma rays (a), and neutrons (b).

7. Conclusion

Large decreasing of the current gain β for irradiated complementary BJTs by high dose of gamma rays and neutrons has been observed. This decreasing is caused by a significant increase in I_B and a small decrease in I_C. The effects of charges resulting from the irradiation in the oxide, at the interface, and in the bulk of the transistor structure are presented with their impact on the current base contributions.

The effect of neutrons is almost similar for both transistor types NPN and PNP, while the effect of gamma rays is in general higher on NPN than PNP. The difference between the base and the emitter of the transistors regarding the sensitivity to the gamma rays is attributed to the expansion of the positive oxide trapped charges toward the emitter in PNP and into the base for NPN. However, this difference for the gamma rays effect on NPN and PNP types varies precisely according to the dose, it is maximum for doses less than 10 kGy. Whereas for doses more than 500 kGy, the effect on both transistor types tends to be similar and saturation can be seen. The reasons for this saturation are related to the phenomena occurring at high gamma source doses.

The application of the Messenger–Spratt equation confirms the similarly of neutrons effect on both transistor types and shows the domination of the displacement damage. For high irradiation time at about 800 s, β becomes equal to 1 and then $I_C = I_B$. Further increase in the irradiation time leads to the decrease of β to a value lower than 1 and then $I_C < I_B$. The transistor in this situation would work out of its normal function.

In the case of gamma rays, the plotted curves of the Messenger–Spratt equation show a non-linear form for doses less than 400 kGy resulting from the saturation behavior, which leads then to the domination of the ionization. While for the higher dose, a linear behavior is attributed to the displacement damage due to the secondary Compton electrons effect.

Acknowledgements

The author would like to express his gratitude to Prof. I. Othman, Director General of AECS for his continuous encouragement and support.

References

[1] Lee T H and Kim H D 2007 *Nucl. Instr. Metal A* **579** 260
[2] Schmidt D M, Fleetwood D M, Schrimpf R D, Pease R L, Graves R J, Johnston G H, Galloway K F and Combs W E 1995 *IEEE Trans. Nucl. Sci.* **42** 1541
[3] Schrimpf R D 2004 *Int. J. High Speed Electron. Syst.* **14** 503
[4] Liu C M, Li X J, Geng H B, Rui E, Guo X and Yang J Q 2011 *Chin. Phys. B* **21** 080703
[5] Kulkami S R and Damle R 2011 *Indian J. Phys.* **85** 391
[6] Assaf J, Shwiekani R and Ghazi N 2014 *Radiat. Phys. Chem.* **103** 142
[7] Johnston A H, Swift G M and Rax G 1994 *IEEE Trans. Nucl. Sci.* **41** 2427
[8] Li X J, Geng H B, Lan M J, Yang D Z, He S Y and Liu C M 2010 *Chin. Phys. B* **19** 066103
[9] Lenahan P M and Dressendorfer P V 1984 *J. Appl. Phys.* **55** 3495
[10] Feigl F J, Fowler W B and Yip K L 1974 *Solid State Commun.* **14** 225
[11] Chen X J, Barnaby H J, Schrimpf R D, Fleetwood D M, Pease R L, Platteter D G and Dunham G W 2006 *IEEE Trans. Nucl. Sci.* **53** 3649
[12] Chris G R, van de Wall and Street R A 1994 *Phys. Rev. B* **49** 14766
[13] Campbell P M and Wix S D 2013 Sadia Report SAND2013-3769
[14] Wertheim G K 1957 *Phys. Rev.* **105** 1730
[15] Sze S M 1981 *Physics of Semiconductors Device* (2nd Edn.) (NY: Wiley)
[16] Messnger G C 1992 *IEEE Trans. Nucl. Sci.* **39** 468
[17] Vukic V and Osmokrovic P 2006 *J. Optoelectron. Dev. Mater.* **8** 1538
[18] Messenger G C and Spratt J P 1958 *Proc. IRE* **46** 1038
[19] Li X, Geng H, Liu C, Zhao Z, Lan M, Yang D and He S 2009 *Nucl. Instr. Meth. A* **612** 171
[20] Ma T P and Dressendorfer P V 1989 *Ionizing Radiation Effects in MOS Devices & Circuits*, I (Wiley & Sons)
[21] Schrimpf R D 1996 *IEEE Trans. Nucl. Sci.* **43** 787
[22] Kosier S L, Wei A, Schrimpf R D, Fleetwood D M, DeLaus M, Pease R L and Combs W E 1995 *IEEE Trans. Nucl. Sci.* **42** 436
[23] Pushpa N, Praveen K C, Gnana P A, Gupta S K and Revannasiddaiaha D 2013 *Curr. Appl. Phys.* **13** 66
[24] Liu C M, Li X J, Geng H B, Yang D Z and He S Y 2012 *Chin. Phys. B* **21** 080703