JOURNAL OF OPTOELECTRONICS AND ADVANCED MATERIALS Vol. 21, No. 9-10, September – October 2019, p. 641 - 648

Recovering of irradiation damaged BJTs by isothermal and isochronal annealing processes

J. ASSAF*
Department of Scientific Services, Atomic Energy Commission, P. O. Box 6091, Damascus, Syria

The recovery of damaged Bipolar Junction Transistors (BJTs) by irradiation is discussed. Two complementary types of BJTs (NPN and PNP) were exposed to high doses of neutrons and gamma rays. The irradiated transistors were recovered by isothermal annealing at ambient temperature and isochronal annealing with temperature increase up to 300 °C. Small and high recovery was obtained by using isothermal and isochronal annealing, respectively. Neutrons damaged transistors were less recovered than that of gamma rays. For BJTs irradiated by gamma rays, PNP type was less recovered than NPN type. While, similar recovery was obtained for both BJT types irradiated by neutrons.

(Received November 21, 2018; accepted October 9, 2019)

Keywords: Radiation defects on BJTs, Recovery, Isothermal annealing, Isochronal annealing

1. Introduction

The main degradation of irradiated electronic components such as BJTs is caused by the effects of ionization and atomic displacement. Ionization produces two types of charges, which are considered as defects. The Positive Oxide Trapped Charges (POTCs) in the SiO_2 layer; and the Interface Trapped Charges (ITCs) at the Si/SiO_2 interface. These charges increase the density of recombination centers at the surface, which leads to increase of the surface recombination velocity. Thus, more recombination can occur in the regions adjacent to the Si/SiO_2 interface, especially in the base region of the BJT, and as a consequence the transistor base current I_B increases. This increase depends on the base doping type of the BJT (P or N), the doping concentration and the surface of the emitter and base regions [1-4].

Atomic displacement produces Interstitials (displaced Si atoms) and Vacancies (their former place). As a result, a pair of V-I is created in the bulk of the transistor. These defects increase also the base current through different mechanisms [4,5]. In fact the main impact of radiation on BJTs is a considerable increase in the I_B current as it was investigated by many works [1-5]. Furthermore, a small decrease in the collector current I_C has been observed in our previous work [4], while, other research results show a negligible effect on I_C [7]. In all cases, the current gain factor known as $\beta= I_C/I_B$ will be then decreased.

Concerning the recovery the transistor parameters affected by irradiation, thermal annealing processes are the most used methods to reduce the irradiation defects. They can also reveal some qualitative information about the nature of the defects. They can be achieved either at a constant temperature (isothermal annealing), or with increasing temperature steps during a fixed period (isochronal annealing) [8-12]. The quality of recovery depends on the defects type which is related mainly to radiation type, the BJT structure, and the parameters of annealing method.

The aim of this paper is to present experimental results of isothermal and isochronal annealing effects applied on two complementary small signal BJTs(NPN and PNP). These, transistors were damaged by defects resulted from the exposure to gamma rays and to neutrons from nuclear research reactor. Moreover, the predicted forms of defects before and after annealing were also analyzed.

2. Recovery by annealing

Understanding the nature of defects and their recovering process is instrumental in explaining the experimental results. Thus, a short overview of these issues will be presented in this section.

Iionization defects (TICs and POTCs) are produced by the reaction of holes with intrinsic precursor defects. The holes are created by irradiation, while the precursor defects are either existed before irradiation, such as Oxygen Vacancy or created during irradiation such as Hydrogen [3,13,14].

The recovery of POTCs is based on the reaction of a negative electron with this defect. The dominated mechanism that provides electrons for compensation is the thermal emission of electrons from the valence band into a trap [13,15]. This type of recovering can be considered as a neutralization through the electron trapping. It is time dependant if it is achieved at constant ambient temperature. It is often accelerated by higher temperature through annealing, where temperature as high as 100°C is sufficient to enhance the annealing rate of POTCs [15].

The ITC is also recovered through an annealing passivation process. Unlike POTCs, ITCs do not readily anneal at room temperature and their concentrations drop slowly starting from 100ºC. However, higher temperatures are normally required to observe a significant annealing [3,16].

Atomic displacement point defects are produced by transferring particle kinetic energy to the crystal lattice (such as Silicon) with a value higher than the displacement threshold. For higher energy, large density of point defects are transformed to cluster defects. According to the origin of the displaced atoms, defects can be classified as intrinsic and extrinsic. Some defcts can be located also in interstitial site or in a regular position similarly to Si atom known as Substitution Site. Point defects can contain also more than one vacancy such as:V_2 (Divacancy) and V_3 (Trivacancy) [17, 18].

For recovery by annealing, three main process is observed: Migration, Complex Defects by diffusion, and Dissociation. In general, both *V* and *I* are not stable, especially the later; they are less mobile at room temperature in Si lattice. At higher temperatures, however, the vibration of the atoms in the lattice increases leading to migrate the displaced atom and fall again into the regular site *V*, *i.e. I* and *V* are recombined [19]. Occasionally *I-V* pairs can associate with similar or different type of defects. This is accomplished through their diffusion to form a considerable complex defect. This new defect has a larger thermal stability at room temperature and it requires then higher temperatures to move. For example, C_i (*i* refers to interstitial) is very mobile at room temperature and it readily reacts with C_s (*s* refers to substitutional) and O_i defects forming the C_iC_s and C_iO_i pairs, respectively. The new complex defect can still be stable up to about 300 ºC [20,21]. If the annealing temperature is high enough to overcome the binding energy of the complex defects, they can be dissociated into their original components.

3. Experimental

Two types of complementary BJTs: NPN (2N2222 A) and PNP (2N2907 A) have been tested. They are discrete commercial transistors having a vertical design. The pre-rad value of β_l labeled β_0 of the used transistors varied from 130 to 180. For a specific test, five transistors having as much as possible equal β_0 were submitted to an accumulated irradiation dose. The transistors were irradiated by Co-60 gamma ray source having an average radiation energy of 1.25 MeV. The gamma rays dose is measured by a chemical dosimeter. The neutrons irradiation was achieved inside a Miniature Neutrons Source Reactor (MNSR). The MNSR produces a large spectrum of neutrons accompanied with the associated fission gamma rays. Referring to the radiation types, two issues are considered in this work. The first is that the most damage effect on BJT irradiated inside the MNSR comes from the neutrons compared with the fission gamma [4]. So, the terms of neutrons and gamma rays irradiations are assigned to the irradiation inside the reactor and by Co-60 source, respectively. The second issue is that the neutrons dose is presented by the irradiation time inside the reactor at a fixed neutrons flux.

Equipment used for transistors characterization consisted of a Curve Tracer device. It provides the I_C-V_{CE} characteristics and the gain factor β, where this factor is measured at I_B equals to 50 μA for all the tests.

Concerning annealing procedures, the isothermal annealing is achieved at ambient temperature (about 25°C) either for many period steps or for one long period (long ambient annealing). While isochronal annealing is accomplished in an oven in air for an increased temperature up to 300 °C through either only one step (annealing at 300 °C) or several steps. The period of each step equals to 100 minutes.

The maximum annealing is obtained after a long ambient period for the isothermal annealing, and after one step isochronal annealing at 300 °C.

4. Results and discussion

4.1. Maximum annealing effect

In order to study the main difference between the effect of isothermal and isochronal annealing on the NPN and PNP types, tests were performed in successive steps: pre-rad, after irradiated, and after two annealing cycles at the maximum annealing condition.

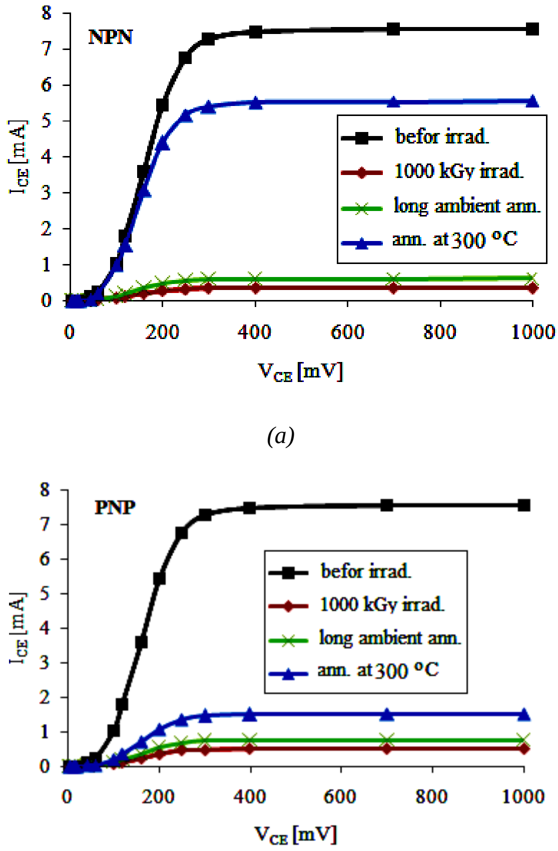
The first set of tests were performed on I_C- V_{CE} curve shown in Fig.1 for irradiation up-to a gamma rays dose of 1000 kGy. It can be seen that the recovery of NPN type is much higher than PNP type, and it is also greater for isochronal annealing compared with isothermal annealing. The same annealing tests were performed for BJTs irradiated by neutrons. Unlike the case of gamma rays, the radiation and annealing effects are almost similar for NPN and PNP types. Fig. 2 shows an example of an annealed sample of NPN 50 sec of neutrons irradiation.

The second set of tests were related to the β factor (normalized toβ_0) as a function of the dose. As generally known, β decreases and increases (recovered) after irradiation and annealing, respectively. Figs. 3 and 4 show the curves of β/β_0 versus the dose for annealed samples by the same two annealing successive cycles after irradiation by gamma rays and neutrons. We can also her summarize the following results:

- Whatever the type of annealing, transistor, or radiation, the recovery is in general inversely proportional to the dose.
- Isothermal annealing can weakly recover the gamma damage, and it has a negligent effect for neutrons damage. According to the annealing behavior of defects presented in the section 2, isothermal anneals partially the POTC defects, while all ITC and displacement defects are still insensible to this type of annealing.
- For isochronal annealing, an almost complete recovering can be reached for gamma rays in doses of less than 600 and 100 kGy for NPN and PNP, respectively. For high gamma dose (more than 600 kGy), the defects of PNP type are less recovered than NPN type. In fact, the main difference between the defects of the two transistor

types is determined mainly by the difference of the base doping. In the N base doping (PNP type), it is possible to find displacement defects in high gamma rays dose resulted from more donor vacancy defects such as *VP* and V_2 [22, 23], where these both defect types are mostly contribute to gain degradation [1]. The *VP* contribution anneals out by about 140 °C, while V_2 requires more than 300 °C [10]. Therefore, maximum isochronal annealing at 300 °C can restore almost all types of ionization defects in addition to some displacement point defects. It can be predicted that increasing the temperature above 300 °C may expand the total recovery to the whole of the studied dose range.

- In case of neutrons defects, the same annealing behavior for both BJT types has been found. However, compared with the gamma rays defects, less recovery was obtained and more temperature increasing was needed. Concerning, the recovery by isochronal annealing, it can be partially occurred for small doses (less than 20 sec), while for higher dose it becomes negligent. That is due to the fact that the neutrons defects in high doses are mostly due to cluster and complex defects such as C_iO_i, C_iC_s and V_2 , thus, they require higher temperatures to be recovered [9, 23, 24].



(a)

(b)

Fig. 1. I_C-V_{CE} characteristics of NPN (a) and PNP (b) samples before irradiation and after the following successive stages: irradiation by1000 kGy of gamma rays, maximum isothermal annealing, and maximum isochronal annealing

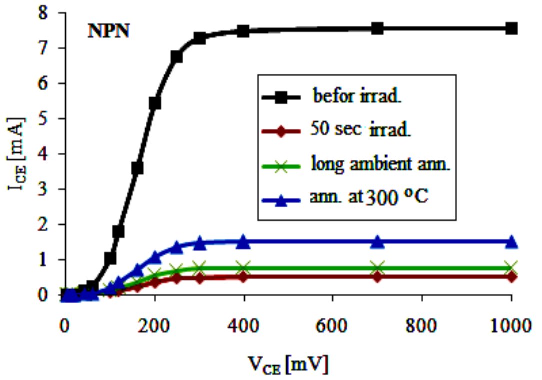
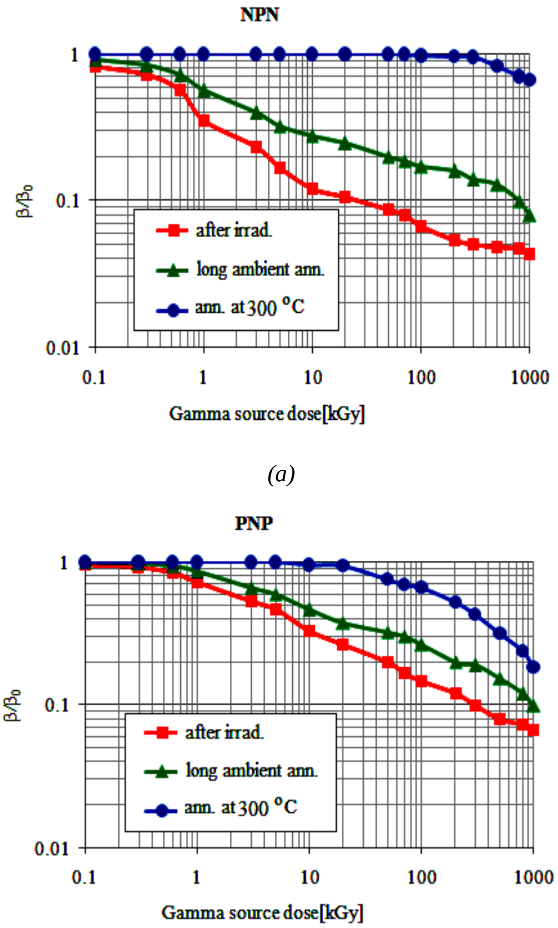


Fig. 2. I_C-V_{CE} characteristics of NPN sample before irradiation and after the following successive stages: irradiation by 50 sec of neutrons, maximum isothermal annealing, and maximum isochronal annealing



(a)

(b)

Fig. 3. Normalized current gain β/β_0 versus gamma source dose of: (a) NPN and (b) PNP samples after the following successive stages: irradiation, maximum isothermal annealing, and maximum isochronal annealing

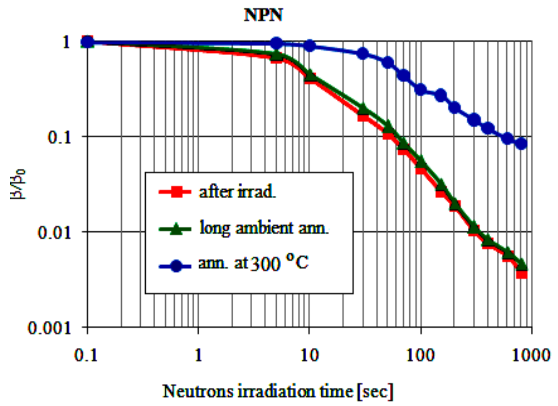


Fig. 4. Normalized current gain β/β_0 versus neutrons irradiation time of NPN sample after the following successive stages: irradiation, maximum isothermal annealing, and maximum isochronal annealing

4.2. Evolution of the isothermal annealing with time

As we have already seen from the experimental results, some gamma rays defects such as POTCs, were recovered after a maximum isothermal annealing, wwhile the rest of the gamma rays defects and the neutrons defects were not significantly recovered. This is also was remarked in other works [20]. Fig. 5 shows the variation of β/β_0 versus isothermal annealing period for NPN and PNP. The transistors were irradiated, as an example, by 100 kGy gamma, where the most recovered defects in this case are ITCs.

4.3. Evolution of the isochronal annealing with the temperature

In order to study the effect of temperature on the performance of isochronal annealing, some tests were performed for the restoration of β with increasing temperature from room temperature up to 300 °C, as is illustrated in Figs. 6 and 7. It can be concluded that whatever the type of radiation and the transistor, the recovery is directly proportional to the temperature and inversely to the dose. It is also noticeable that the isochronal annealing effect differs between NPN and PNP irradiated by gamma rays, while this difference becomes small in the case of neutrons.

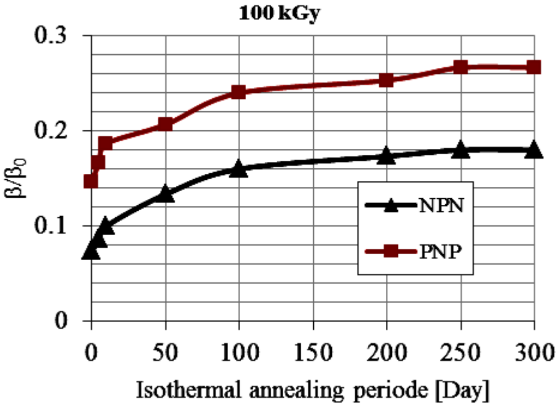
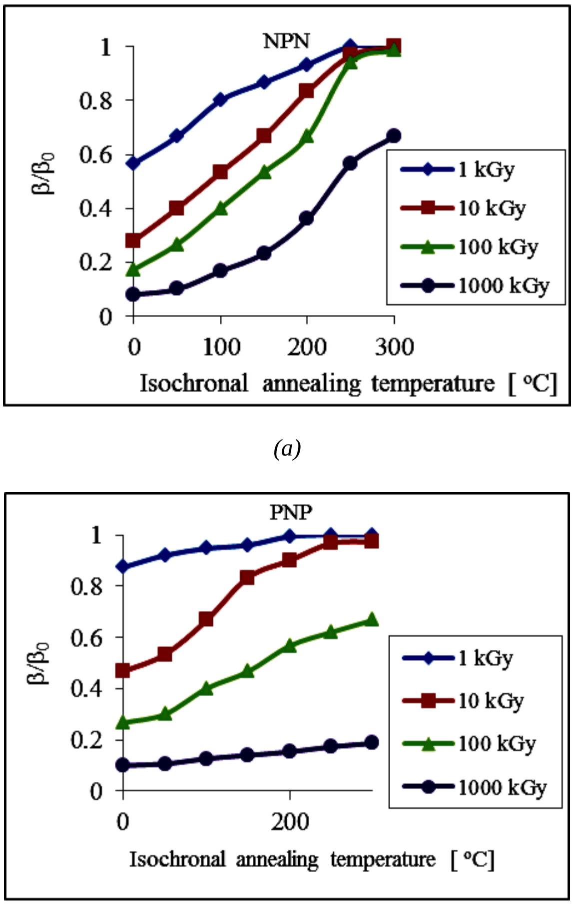


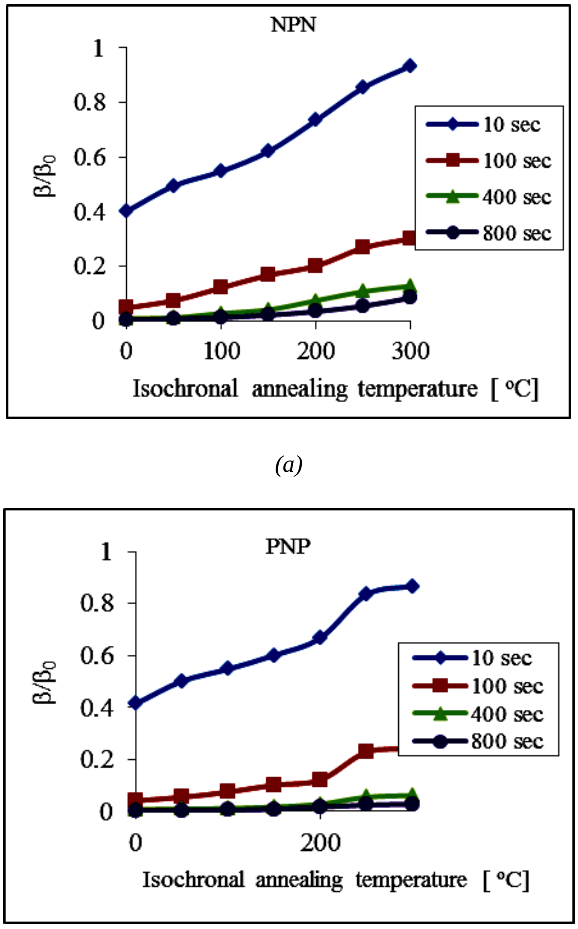
Fig. 5. Normalized current gain β/β_0 versus the isothermal annealing period (at ambient temperature) for transistor NPN and PNP irradiated by100 kGy of gamma rays



(a)

(b)

Fig. 6. Normalized current gain β/β_0 versus the isothermal annealing temperature for transistor (a) NPN, and (b) PNP irradiated by several gamma rays dose



(a)

(b)

Fig. 7. Normalized current gain β/β_0 versus the isochronal annealing temperature for transistor (a) NPN ,and (b) PNP irradiated by several neutrons irradiation time

For resuming overall behavior of irradiation and annealing, Fig. 8 shows an example of the β decreasing resulted from 100 kGy gamma rays irradiation, followed by recovering due to successive isothermal and isochronal annealing cycles as a function of their specific parameters. In this manner, a separation between the POTC and ITC defects can be achieved; where in the first annealing step the POTCs are recovered and the rest of defects are mostly ITCs.

4.4. Maximum recovery factor

The evaluation of the annealing processes yield, is achieved by studying the maximum recovery efficiency of β. This efficiency is denoted η and defined to be equals to the ratio between $\Delta\beta_{\text{Irrad}}$ and $\Delta\beta_{\text{Recov}}$, which are the maximum amount of loss by irradiation, and recovery by annealing, respectively. The factor η is then given by:

$$\eta\% = \frac{\Delta\beta_{\text{Recov}}}{\Delta\beta_{\text{Irrad}}}\,\% = \frac{\beta_{\text{Ann}} - \beta_{\text{Irrad}}}{\beta_0 - \beta_{\text{Irrad}}}\,\% \qquad (1)$$

where β_{Irrad} and β_{Ann} are the values of β after irradiation and maximum annealing, respectively. Since the effect of isothermal annealing is practically significantly smaller than that of isochronal, the latter will be only considered, *i.e* one annealing step at 300 °C. Before presenting the result of this efficiency factor, it is advised to study the behavior of their related contributions $\Delta\beta_{\text{Recovery}}$ and $\Delta\beta_{\text{Irrad}}$ (normalized also to β_0), versus the dose as described below.

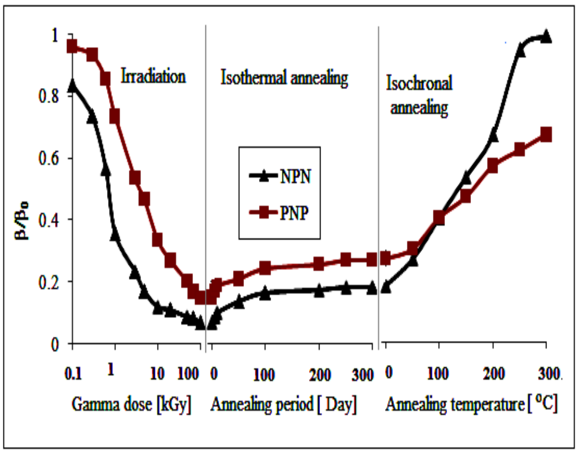
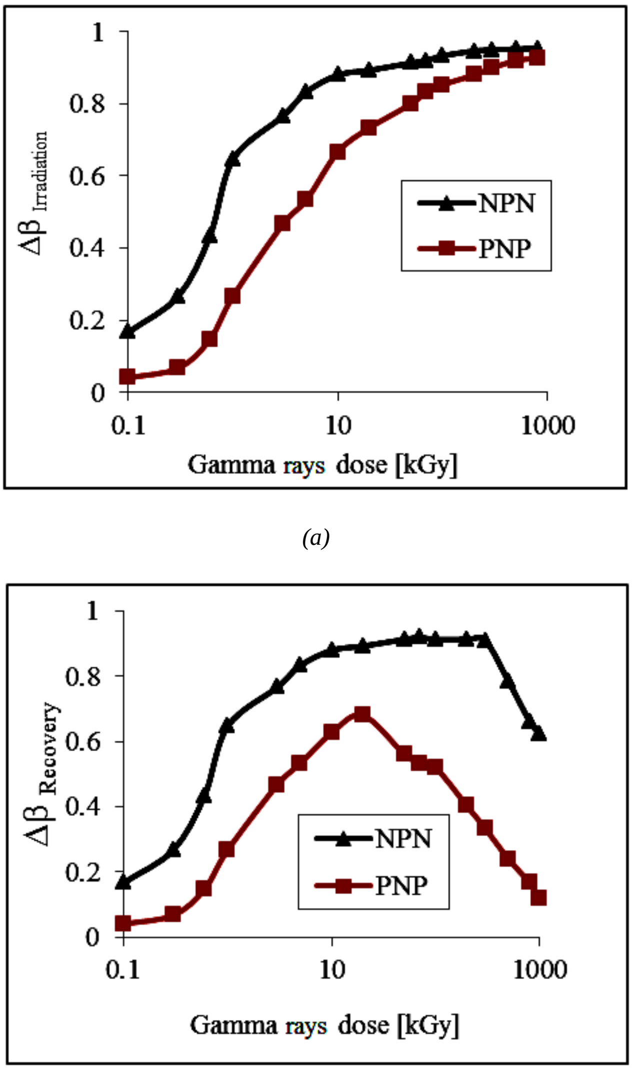


Fig. 8. An example of the decreasing of β/β_0 resulted from gamma irradiation (up to 100 kGy) followed by the re-increasing due to successive isothermal and isochronal annealing as a function of the specific parameter of each step

4.4.1. Irradiation by gamma rays

Fig. 9 shows the curves of $\Delta\beta_{\text{Irrad}}$ and $\Delta\beta_{\text{Recov}}$ versus the dose. They are obtained according to the equation (1) and the experimental data of Figs. 3 and 4. Noticeably both terms are higher in NPN than in PNP ,that is because NPN is more recovered than PNP. To clarify their behaviors in a simplified way, Table 1 summarizes the variation of $\beta_{\text{Irrad.}}$ and β_{Ann}, and presents their effects on the resulted $\Delta\beta_{\text{Irrad}}$ and $\Delta\beta_{\text{Recov}}$ according to the three main ranges of the dose.

It is now possible to deduce the $\eta\%$ value versus dose according to the equation (1) and present the result in Fig. 10. The curves of this figure summarize previous findings of an almost complete recovery of the surface defects in the NPN up to 300 kGy, and then decreases until 60% at the highest dose. In PNP, $\eta\%$ begins to fall rapidly at 10 kGy, and reaches less than 20% at the highest dose.



(a)

b

Fig. 9. Evolution the of normalized amounts: (a) $\Delta\beta_{\text{Irrad}}$ *and (b)* $\Delta\beta_{\text{Recov}}$ *versus gamma rays dose in NPN and PNP types.*

4.4.2. Irradiation by neutrons

The behaviors of $\Delta\beta_{\text{Irrad}}$ and $\Delta\beta_{\text{Recov}}$ are more similar for NPN and PNP in this case. They were also obtained in the same manner and presented in Fig. 11. The efficiency factor $\eta\%$ was then deduced and presented in Fig.12. As it is seen, this factor drops fast from 80% at low dose (for both NPN and PNP) up to less than 8% (for NPN) and 3% (for PNP) at high doses.

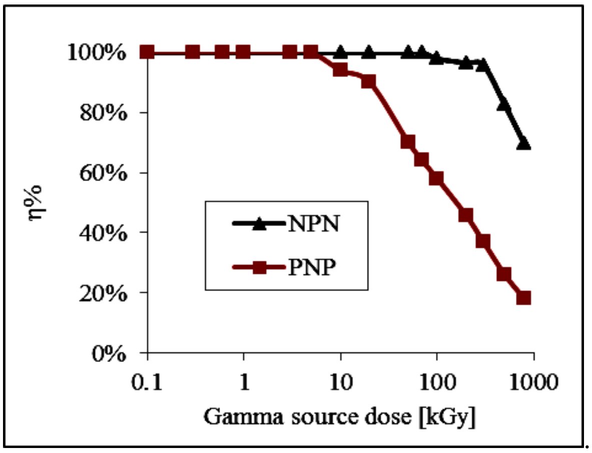
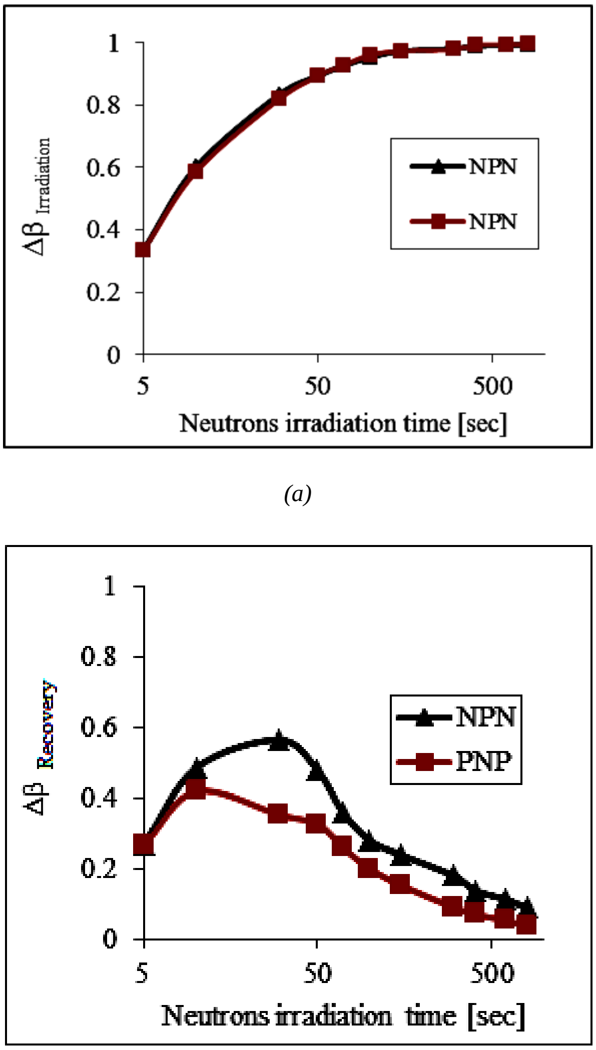


Fig. 10. Maximum recovery efficiency of β *versus gamma rays dose for NPN and PNP types.*



(a)

(b)

Fig. 11. Evolution of (a) $\Delta\beta_{\text{Irrad}}$ *and (b)* $\Delta\beta_{\text{Recov}}$ *versus neutrons irradiation time for NPN and PNP types*

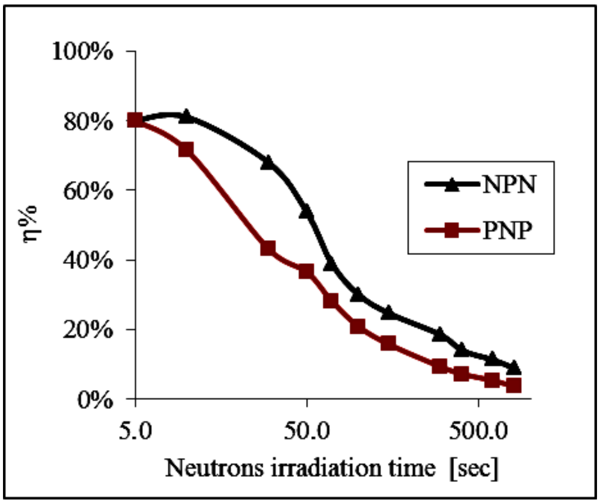


Fig. 12. Maximum recovery efficiency of β versus neutrons irradiation time for NPN and PNP types

Table 1. Behavior of $\beta_{\text{Irrad.}}$, β_{Ann} , $\Delta\beta_{\text{Irrad}}$ and $\Delta\beta_{Recov}$ as a function of the dose and according to the transistor types for the three used ranges of gamma ray source

Dose range in kGy	Transistor type	Behavior versus dose			
		$\beta_{\text{Irrad.}}$	β_{Ann}	$\Delta\beta_{\text{Irrad}}$	$\Delta\beta_{\text{Recov}}$
0.1-10	NPN	High decrease	Total recovery	High increase	High increase
	PNP	Medium decrease	Total recovery	High increase	High increase
20-300	NPN	Medium decrease	Total recovery	High saturated value	High saturated value
	PNP	Medium decrease	High recovery	Medium increase	Medium decrease
400-1000	NPN	Slow decrease	High recovery	High saturated value	High decrease
	PNP	Slow decrease	Medium recovery	Medium increase	High decrease

5. Conclusion

Types of defects induced by gamma rays and neutrons on BJTs transistors were studied. Ionization defects such as interface trap charges (ITCs) and positive trapped charges (POTCs) are created in case of irradiation by gamma rays. While atomic displacement defects such as point and cluster defects are produced after irradiation by neutrons. Isothermal and isochronal annealing processes were carried out on irradiated samples. The results show that the isothermal annealing recovers only some POTCs defects, and the PNP type are in general less recovered than NPN type. For isochronal annealing, an almost complete recovery can be reached for the rest of POTCs and most of ITCs defects in the dose ranges less than 600 and 100 kGy for NPN and PNP, respectively. Similar atomic displacement recovery is obtained for both types of the transistor. Maximum recovery was achieved by isochronal annealing at maximum used temperature equaled to 300 °C. The efficiency of the recovery related to the current gain factor was measured. The efficiency percentage varies from 100% to about 60% for NPN in the range of 0-1000 kGy for gamma rays defects, and from 100% to less than 20% for PNP. In the case of neutrons defects, this efficiency drops strongly from 80% at low dose up to less than 8% for NPN and 3% for PNP at high dose corresponding to 800 sec irradiation time. It was predicted in this case that the non-resorted damage is due to complex defects such as cluster, *V2* and *VP* types.

Acknowledgements

The author would like to thank Prof. I. Othman, Director General of AECS for his continuous support, and to H. Alkassiri and A. Sarhil from the staff of irradiation laboratories.

References

[1] H. J. Barnaby, R. D. Schrimpf, A. L. Sternberg, V. Berthe, C. R. Cirba, R. L Pease, IEEE Trans. Nucl. Sci. **48** (2001).

[2] D. M. Fleetwood, IEEE Trans. Nucl. Sci. **60**, 1706 (2013).

[3] Xingji Li, Chaoming Liu, Jianqun Yang, Yuling Zhao, Guangqiao Liu, IEEE Trans. Nucl. Sci. **60**, 3931 (2013).

[4] J. Assaf, Chin. Phys. **B27**, 016103 (2018).

[5] R. D. Schrimpf, International Journal of High Speed Electronics and Systems **14**, 503 (2004).

[6] Yu Song, Ying zhang, Yang Liu, Jie Zhao, Dechao Meng,Hang Zhou, Xiaofeng Wang, Mu Lan, Su-Huai Wei, CS Appl. Electron. Mater., (March 2019).

[7] O. O. Myo Min, Nahrul Khair Bin Alang Md Rashid, Julia Bin Abdul Karim, Muhammad Rawi Bin Mohamed Zin, Rosminazuin Bt. Ab. Rahim, Amelia Wong Azman, Nurul Fadzlin Hasbullah, Nuclear Technology & Radiation Protection **29**, 46 (2014).

[8] S. Kaschieva, S. Alexandrova., Materials Sci. and Eng. **B95**, 295 (2002).

[9] G. P. Gaidar, A. P. Dolgolenko, P. G. Litovechenko, Ukr. J. Phys.**53**, 688 (2008).

[10] R. M. Fleming, C. H. Seager, D. V. Lang, J. M. Campbel, Journal of Applied Physics **108**, 063716 (2010).

[11] R. M Fleming, C. H. Seager, E. Bielejec, G. Vizkelethy, D. V. Lang, J. M. Campbel, Journal of Applied Physics **107**, 1 (2010).

[12] C. Chabrerie, J. Autran, P. Paillet, O. Flament, J. Leray, J. Boudenot, IEEE Trans. Nucl. Sci. **44**, 2007 (1997).

[13] T. R. Oldha, F. B. McLean, IEEE Trans. Nucl. Sci. **50**, 495 (2003).

[14] S. N. Rashkeev, D. M. Fleetwood, R. D. Schrimpf, S. T. Pantelides, IEEE Trans. Nucl. Sci. **51**, 3158 (2004).

[15] M. Gaillardin, IEEE Trans. Nucl. Sci. **60**, 2623 (2013).

[16] X. Jie Chen, Hugh J. Barnaby, Bert Vermeire, Keith E. Holbert, David Wright, Ronald L. Ronald, D. Schrimpf, Daniel M. Fleetwood, Sokrates T. Pantelides, Marty R. Shaneyfelt, Philippe Adell, IEEE Trans. Nucl. Sci. **55**, 3032 (2008).

[17] N. Pushpa, K. C. Praveen, A. P. Gnana Prakash, S. K. Gupta, D. Revannasiddaiah, Current Applied Physics **13**, 66 (2013).

[18] S. Lazanu, I. Lazanu, J. Optoelectron. Adv. M. **5**(3), 647 (2003).

[19] K. E. Holbert, Radiation Effect and Damage, http://www.eas.asu.edu/~holbert/eee460/Radiation Effects Damage.pdf

[20] R. M. Fleming, C. H. Seager, D. V. Lang, P. J. Cooper, E. Bielejec, J. M. Campbell, Journal of Applied Physics **102**, 043711 (2007).

[21] C. A. Londos, M. S. Potsidi, G. D. Antonaras, A. Andrianakis, Physica B **165**, 376 (2006).

[22] R. M. Fleming, C. H. Seager, D. V. Lang, E. Bielejec, J. M. Campb, Physica B **401-402**, 21 (2007).

[23] G. Lindstroem, E. Fretwurst, G. Kramberger, I. Pintilie, J. Optoelectron. Adv. M. **6**(1), 23 (2004).

[24] C. H. Seager, R. M. Fleming, D. V. Lang, P. J. Cooper, E. Bielejec, J. M. Campbell, Physica **B 401-402**, 491 (2007).

---

[*] Corresponding author: PScientific8@aec.org.sy