Nuclear Technology & Radiation Protection: Year 2014, Vol. 29, No. 1, pp. 46-52

ELECTRICAL CHARACTERIZATION OF COMMERCIAL NPN BIPOLAR JUNCTION TRANSISTORS UNDER NEUTRON AND GAMMA IRRADIATION

by

Myo Min OO [1]***, Nahrul Khair Bin Alang Md RASHID*** [2]***, Julia Bin Abdul KARIM*** [3]***, Muhammad Rawi Bin. MOHAMED ZIN*** [1]***, Rosminazuin Bt. Ab. RAHIM*** [1]***, Amelia Wong AZMAN*** [1]***, and Nurul Fadzlin HASBULLAH*** [1*]

[1]Department of Electrical and Computer Engineering, International Islamic University, Kuala Lumpur, Malaysia
[2]Department of Mechatronics Engineering, International Islamic University, Kuala Lumpur, Malaysia
[3]Nuclear Power Sector, Malaysian Nuclear Agency, Kuala Lumpur, Malaysia

Scientific paper
DOI: 10.2298/NTRP1401046O

Electronics components such as bipolar junction transistors, diodes, *etc*. which are used in deep space mission are required to be tolerant to extensive exposure to energetic neutrons and ionizing radiation. This paper examines neutron radiation with pneumatic transfer system of TRIGA Mark-II reactor at the Malaysian Nuclear Agency. The effects of the gamma radiation from Co-60 on silicon NPN bipolar junction transistors is also be examined. Analyses on irradiated transistors were performed in terms of the electrical characteristics such as current gain, collector current and base current. Experimental results showed that the current gain on the devices degraded significantly after neutron and gamma radiations. Neutron radiation can cause displacement damage in the bulk layer of the transistor structure and gamma radiation can induce ionizing damage in the oxide layer of emitter-base depletion layer. The current gain degradation is believed to be governed by the increasing recombination current in the base-emitter depletion region.

Key words: bipolar junction transistor, displacement damage, ionizing damage, recombination current

INTRODUCTION

Electronics circuits have many applications in rich-radiation environment such as in the space, aircraft system, nuclear reactor, satellite system, and military weapons. Thus, demand for radiation hard semiconductor devices also increases. Radiation can cause electrical characteristics degradation in electronics devices such as Memristors and MOSFET [1, 2]. It is also shown that the reliability of semiconductor devices was degraded with increasing radiation levels [3]. In particular, electronics components such as bipolar junction transistors (BJT) operation in radiation-rich environment encounter degradation due to the atomic displacement and ionizing along with the incident particle tracks. Radiation affects devices differently, depending on the radiation type; for instance gamma radiation which mostly induces ionizing damage in oxide layer while massive energetic particles *e. g.*, neutron create displacement damage [4, 5].

Current gain degradation induced by radiation is one of the important characteristics of occuring BJT. Many research works investigated the effects of radiation damage on the degradation of current gain for BJT induced by different particles such as protons, neutrons, electrons and Co-60 gamma rays. However, there is still a need to research the radiation response of BJT selection to be more robust in space-radiation application. Investigation on radiation response of BJT is helpful to understand the damage mechanisms before using them in the space radiation environment.

This research compares individual radiation effects of pneumatic transfer systems (PTS) neutron radiation and gamma radiation from Co-60 source at various radiation time and dose. The aim of this study is to characterize the radiations effects on the NPN BJT in terms of the degradation of electrical characteristics such as current gain.

EXPERIMENTAL DETAILS

The commercial silicon NPN BJT NTE123 (TO-39 metal casing), 2N2222 (TO-18 metal casing),

* Corresponding author; e-mail: nfadzlinh@iium.edu.my

and 2N2219A (TO-39 metal casing), used as samples in this study, are audio amplifiers and switches. These devices are manufactured by NTE Electronics, Multicop and ST Electronics, respectively. The irradiation facility for neutron and gamma radiation used in this study is the TRIGA Mark-II with PTS and gamma with Co-60 gamma source located at the Malaysian Nuclear Agency (ANM). The BJT were prepared and labeled accordingly before the bombardment. All samples were inserted in the capped polyethylene vials before being exposed to radiation. Irradiation was performed on three devices of each transistor model to ensure repeatability of measurement. The neutron irradiation periods were 1, 3, and 5 minutes for all transistors. In gamma radiation, all transistors were irradiated with different doses: 10 Mrad, 30 Mrad, and 50 Mrad. After radiation, the samples were highly radioactive and nearly two weeks was needed to cool down the devices to ensure the radioactive level was safe. During all radiation exposures, all transistors were unbiased. All measurements of the samples were carried out in the dark using Keithley 4200 semiconductor characterization system (SCS). The BJT were placed on a metal test fixture to measure its current-voltage (I-V) characteristics. All measurements were conducted at a room temperature before and after irradiation. The chosen commercial BJT are specifically aimed at low cost devices for which may have the relative uncertainty of the parameter value ranges from 0.1% to 1%. For more uncertainty of measurement, please refer to references [6, 7] for further details.

EXPERIMENTAL RESULTS

Neutron radiation effects on BJT

Current gain

Degradation of static parameters in bipolar junction transistors is an effect of displacement damage induced by neutron radiation. The effects of neutron radiation with PTS on the current gain β *vs*. collector current I_C which is described by eq. (1)

$$\beta \quad \frac{I_C}{I_B} \tag{1}$$

of an NPN bipolar junction transistor (2N2222, NTE123 and 2N2219A) are shown in figs. 1, 2, and 3, respectively. Current gains β are plotted as a function of the collector current for different irradiation time for 1, 3, and 5 minutes.

In figs. 1, 2, and 3, the current gain for all transistors dramatically decreased after radiation. After 1 minute radiation, the current gain at $I_C = 1\ 10^{-2}$ A for 2N2222 and NTE123 transistors decreased by 94% approximately. After 3 minutes of radiation, the current gain for 2N2222 and NTE123 at the same IC value decreased by 98% and 97%, respectively. After 5 minutes of radiation, the current gain for 2N2222 and NTE123 at the same I_C value decreased by 99% and

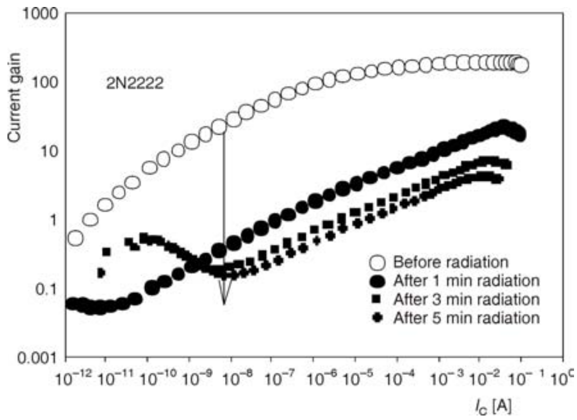

Figure 1. Plot of current gain β *vs*. collector current I_C with increasing radiation time for Si NPN BJT 2N2222 using PTS (neutron)

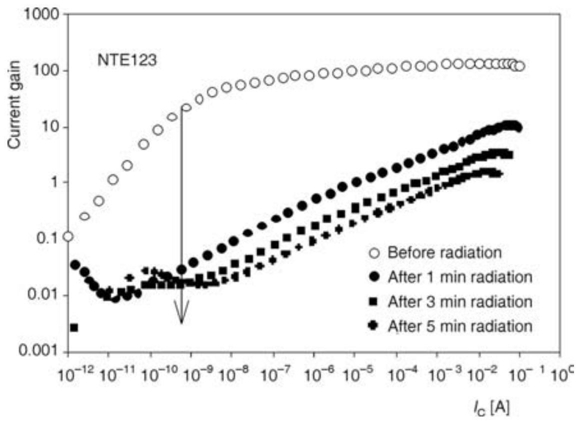

Figure 2. Plot of current gain β *vs*. collector current I_C with increasing radiation time for Si NPN BJT NTE123 using PTS (neutron)

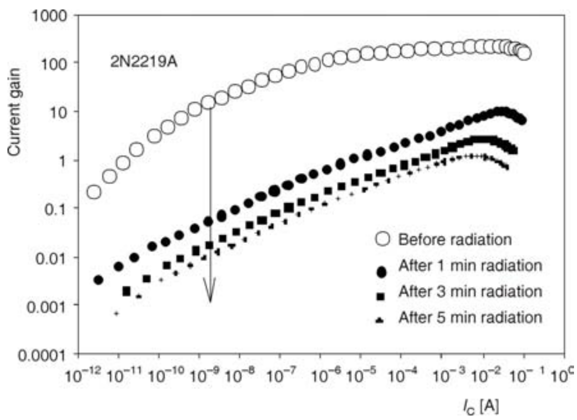

Figure 3. Plot of current gain β *vs*. collector current I_C with increasing radiation time for Si NPN BJT 2N2219A using PTS (neutron)

98%, respectively. However, for the 2N22219A transistor, current gain at same I_C value only degraded by 95% after 1 min radiation. Although the subsequent 3 and 5 minutes showed further degradation in the current gain, it is less dramatic compared to the first two transistors as can be seen in fig. 3. At large collector current of over 1 10^{-2} A, there is a sudden noticeable drop in the current gain for all devices. This is due to the high level injection or series resistance of collector terminal [8].

To quantify the degradation in β and for comparison purposes, we calculated the damage factor d_h which is defined as

$$d_h = \frac{\beta_{post}}{\beta_{pre}} \qquad (2)$$

as a function of neutron fluence as shown in fig. 4. In this equation, d_h represents damage factor and β_{post} and β_{pre} are current gain after radiation and before radiation, respectively. In fig. 4, it can be seen that the damage factor decreases with increasing fluence for all models. Together in fig. 4, damage factor for Si transistors [9] and SiGe transistors were plotted for comparison. It can be seen that BJT are roughly 10 to 100 times less radiation hard compared to the reported custom-made BJT by Roldan *et al*. [10]. These results also show that NTE 123 transistor has the highest damage factor compared to 2N2222 and 2N2219A.

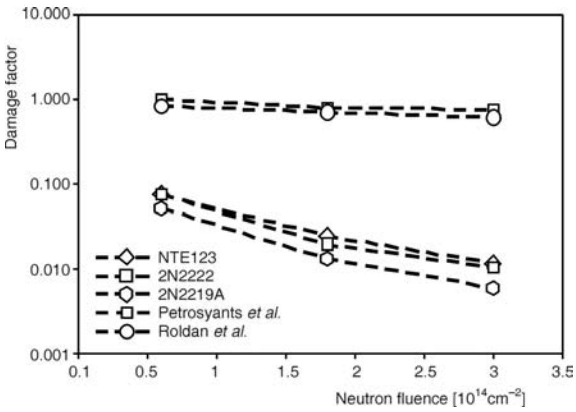

Figure 4. Plot of damage factor d_h *vs*. neutron fluence for all Si BJT measured at V_{BE} = 0.8 V

Base current

Figures 5, 6, and 7 show the plot of base current (IB) against base-emitter voltage (VBE) for the silicon NPN 2N2222, NTE123, and 2N2219A bipolar transistors irradiated with neutron radiation at different irradiation time. The base current for all transistors can be seen increasing after neutron radiation, especially at lower V_{BE}. This is because the radiation induced excess current in the base is expected to come from recombination phenomena in the space charge region

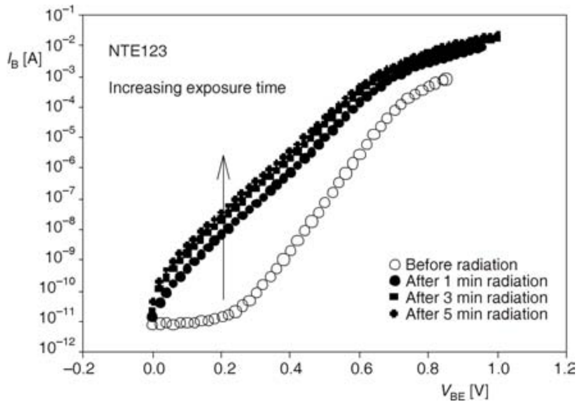

Figure 5. Plot of base current I_B *vs*. base-emitter voltage V_{BE} with increasing radiation time for Si NPN BJT 2N2222 using PTS (neutron)

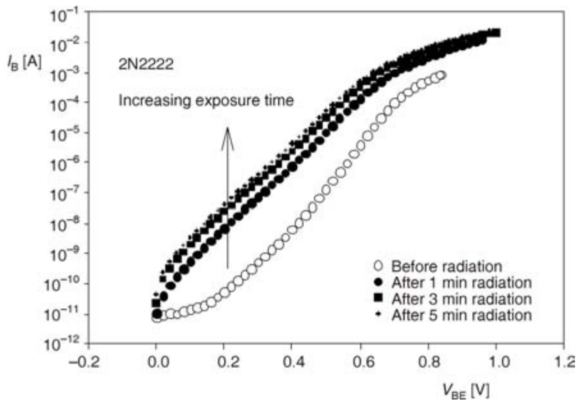

Figure 6. Plot of base current I_B *vs*. base-emitter voltage V_{BE} with increasing radiation time for Si NPN BJT NTE123 using PTS (neutron)

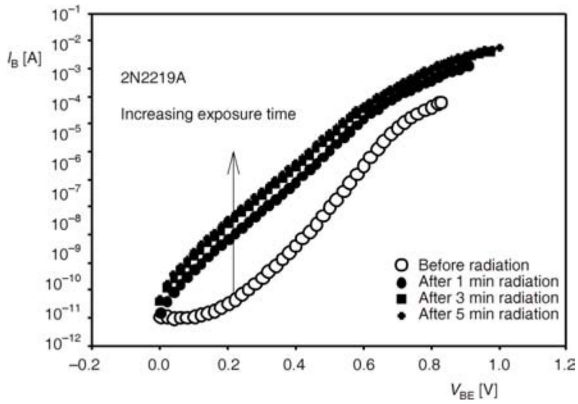

Figure 7. Plot of base current I_B *vs*. base-emitter voltage V_{BE} with increasing radiation time for Si NPN BJT 2N2219A using PTS (neutron)

which predominates at small V_{BE}. We believe the current gain degradation is due to the increase in the base current. Our results showed no significant changes in the collector current after radiation for all three transistors which is not shown in this paper, but similar to other references [10, 11].

Gamma radiation effect on NPN transistors

The NPN silicon BJT were investigated for the effect of ionizing radiation (gamma radiation) induced current gain degradation. Figures 8, 9, and 10 show the current gain β *vs*. base to emitter voltage V_{BE} for all transistors (2N2222, NTE123 and 2N2219A) irradiated with variation of doses: 10 Mrad, 30 Mrad, and 50 Mrad.

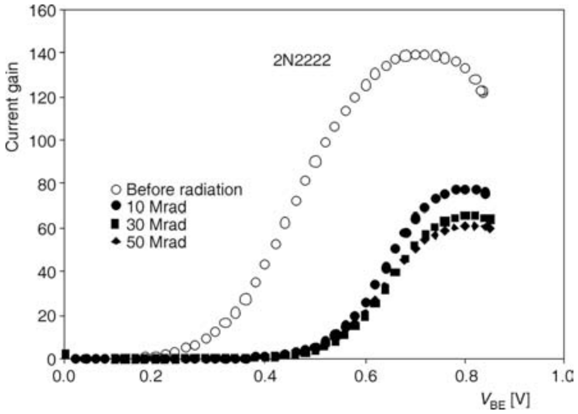

Figure 8. Plot of current gain β *vs*. base-emitter voltage V_{BE} with increasing dose for Si NPN BJT 2N2222 using Co-60

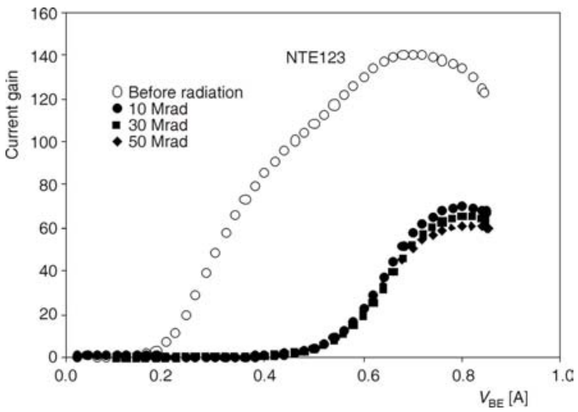

Figure 9. Plot of current gain β *vs*. base-emitter voltage V_{BE} with increasing dose for Si NPN BJT NTE123 using Co-60

The current gain for all transistors after gamma radiation degraded significantly. Current gain degradation for all transistors dramatically deteriorated with increasing dose for a range of base-emitter voltage, especially at lower V_{BE}. For this type of radiation, damage factor equation is also used to quantify the degradation in current gain and compare damage factor of different transistor types. Figure 9 shows damage factor d_h *vs*. dose value for all models measured. It can be seen that the damage factor decreases with increasing

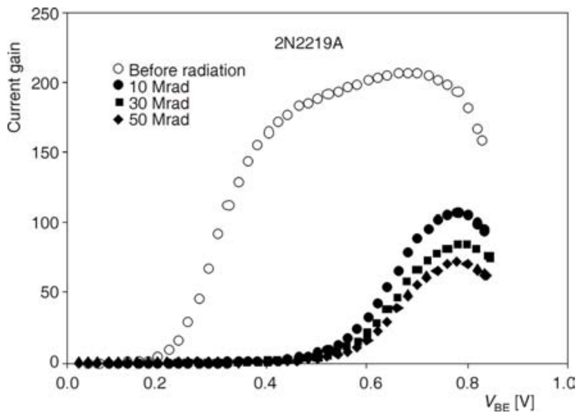

Figure 10. Plot of current gain β *vs*. base-emitter V_{BE} with increasing dose for Si NPN BJT 2N2219A using Co-60

dose for all models. These results show that NTE123 has the highest damage factor which suggests that NTE123 transistor has the lowest current gain degradation. Together in fig. 11, damage factor for NPN BC549C by Philips manufacturer [12] was also plotted for comparison. It can be seen that the present models investigated in this paper are significantly more robust with respect to gamma radiation than the transistor reported by Pater *et al*.

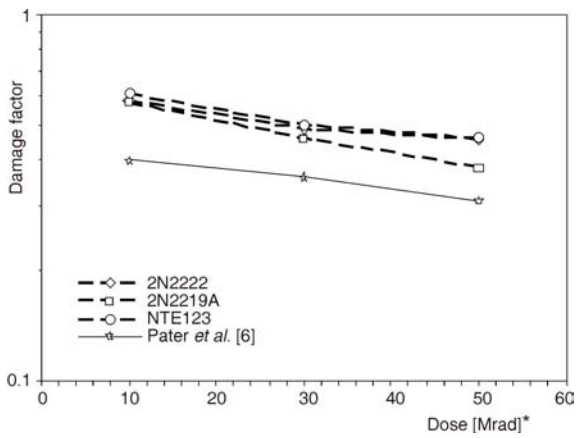

Figure 11. Plot of damage factor d_h *vs*. dose for all Si BJT at V_{BE} = 0.8 V

*1 rad = 10^{-2} Gy

Base current

Figures 12-14 show effect of gamma radiation on current gain which is reflected by the base current. The base and collector current is shown here as a function of base-emitter voltage for the devices. The base current increased markedly with increasing dose value regardless of V_{BE} value. However, it can be seen in all of the figures that changes in collector currents due to radiation exposure were negligible for all transistors.

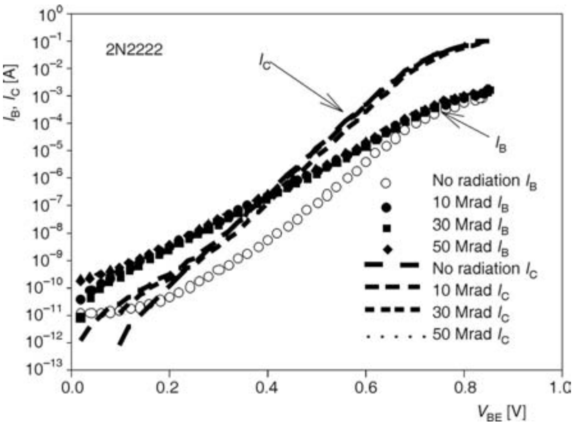

Figure 12. Plot of base current I_B and collector current I_C *vs.* base-emitter voltage V_{BE} irradiated with gamma radiation for Si NPN BJT 2N2222

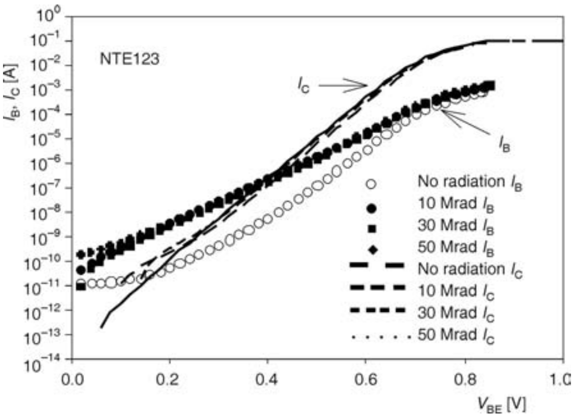

Figure 13. Plot of base current I_B and collector current I_C *vs.* base-emitter voltage V_{BE} irradiated with gamma radiation for Si NPN BJT NTE123

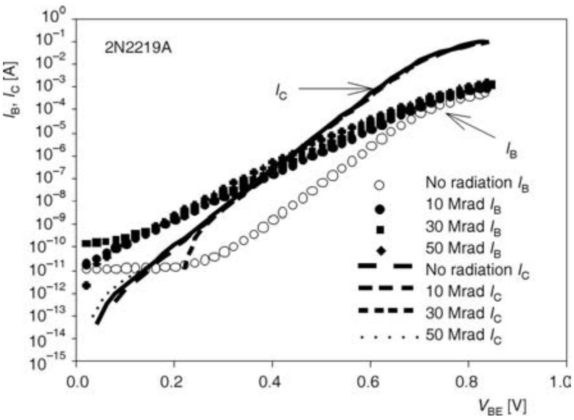

Figure 14. Plot of base current I_B and collector current I_C *vs.* base-emitter voltage V_{BE} irradiated with gamma radiation for Si NPN BJT 2N2219A

DISCUSSION

The susceptibility of NPN BJT to radiation damage can be examined by current gain degradation. Neutron radiation can induce displacement damage in Si bulk and ionization damage in the oxide layer. However, the ionization damage can be negligible in neutron radiation as reported by Barnaby *et al.*, [13]. For neutron radiation, the displacement damage is initiated by collision of neutron particles with atoms in the semiconductor lattice causing the atoms to displace from their primary positions [14, 15]. Results in figs. 1, 2, and 3 showed that current gain after neutron radiation significantly degraded with exposure time. We believe this is because of displacement damage in bulk Si induced by neutron particles. The damage could produce stable vacancy defect that are effective centers of recombination and trapping, leading to a decrease of minority carrier lifetime [16]. This degradation of minority carrier lifetime can increase the base current and thus, decrease the current gain [17, 18].

It is worth noted that gamma radiation from Co-60 can give rise to ionizing damage. Our results in figs. 7 to 9 show that current gain for all transistors decreased after gamma radiation. The latter may be due to the ionizing damage induced by gamma radiation in the oxide layer. The ionization damage could create the interface traps and net positive charge in the oxide overlying the emitter-base junction. Then it leads to an increase in the recombination base current [19] as can be seen in figs. 10 to 12. The recombination base current increases because of increased surface recombination velocity v_{sr} as reported by Kosier *et al*., [20] which is proportional to the formation of the generation-recombination centers at silicon-silicon dioxide (Si/SiO_2) interface covering emitter-base junction [21, 22] and increased emitter-base depletion region. The surface recombination velocity increases because of the increase in the interface traps at the Si/SiO_2 interface. The increase in the emitter-base depletion region is due to the build-up of the positive charge in the oxide layer [23]. Consequently, there is a relation between the positive oxide charge and the interface traps. As the positive charge increases, the depletion region increases in which more recombination centers are exposed due to interface traps. Therefore, as long as the oxide charge and interface traps increase, recombination base current also increases [24]. Hence, the current gain degrades when the base current increases.

In both type of radiations, the damage factors for all models were calculated to compare the current gain degradation. From figs. 4 and 11, damage factors decreased with increasing neutron fluence and gamma dose value for all models. The results indicate that NTE 123 transistor by NTE Electronics has the highest damage factor while 2N2219A transistor by ST Electronics has the lowest damage factor after both neutron and gamma radiations. These results suggest that from all models measured, NTE123 is the most radiation hard when compared to 2N2222 and 2N2219A.

In 2010 Vukić and Osmokrović [25] experimented on PNP power transistor with Co-60 gamma source. They found serial transistor's emitter current gain to degrade significantly with dose levels. They suggested that the degradation is due to quiescent current; however, overall performance was not affected. Our experiment gave similar results in which the current gain degraded with increasing dose due to increasing base current.

CONCLUSIONS

Exposures of neutron and gamma radiations were performed to study the radiation response of commercial NPN bipolar junction transistors. The results in this paper suggested that all silicon transistors measured show a significant degradation in the current gain after neutron and gamma radiations. The base current of all transistors after neutron and gamma exposure were found to increase with increasing neutron fluence and gamma dose values. This is due to the increase in the recombination current as the result of the displacement damage in the bulk layer for neutron radiation and ionization damage in oxide layer for gamma radiation. Our results show that among the transistors investigated, NTE 123 is the most robust transistor to neutron and gamma radiations while the 2N2219A is the least robust.

ACKNOWLEDGEMENTS

The work is partially funded by Ministry of Education under the grant of FRGS12-081-0230 and Nuclear Agency Malaysia.

AUTHOR CONTRIBUTIONS

The manuscript was written by M. M. Oo, and N. F. Hasbullah. Theoretical analysis was carried out by M. M. Oo, and N. F. Hasbullah, and experiments were carried out by M. M. Oo. All authors analyzed, discussed the results and checked the manuscript.

REFERENCES

[1] Marjanović, N. S., *et al*., Simulated Exposure of Titanium Dioxide Memristors to Ion Beams, *Nucl Technol Radiat, 25* (2010), 2, pp. 120-125

[2] Pejović, M. M., *et al*., Successive Gamma-Ray Irradiation and Corresponding Post-Irradiation Annealing of PMOS Dosimeters, *Nucl Technol Radiat, 27* (2012), 4, pp 341-345

[3] Stanković, K. Dj., Vujisić, M., Dolićanin, E., Reliability of Semiconductor and Gas-Filled Diodes for over-Voltage Protection Exposed to Ionizing Radiation, *Nucl Technol Radiat, 24* (2009) 2, pp. 132-137

[4] Usman, M., Buono, B., Hallen, A., Impact of Ionizing Radiation on the SiO_2/SiC Interface in 4H-SiC BJT, *IEEE Transactions on Electron Devices, 59* (2012), 6, pp. 3371-3376

[5] Vujisić, M, *et al*., Radiation Hardness of COTS EPROM and E2PROM Radiation Effects and Defects in Solids, *165* (2010), pp. 362-369

[6] Stanković, K. Dj., Vujisić, M. Lj., Osmokrović, P. V., Statistical Analysis of the Characteristics of Some Basis Mass-Produced Passive Electrical Circuits Used in Measurements, *Measurement, 44* (2011), 9, pp. 1173-1722

[7] Kovačević, A. M., Osmokrović, P. V., Evaluation of Measurement Uncertainty in Electromagnetic Compatibility Testing, *Proceedings*, 20th Telecomunications Forum (TELFOR), Belgrade, Serbia, 2012, pp. 1108-1114

[8] Johnston, A. H., Rax, B. G., Testing and Qualifying Linear Integrated Circuits for Radiation Degradation in Space, *IEEE Transactions on Nuclear Science, 53* (2006), 4, pp. 1779-1786

[9] Shatalov, A., Subramanian, S., Dentai, A., Neutron Irradiation Effects in InP/InGaAs Single Heterojunction bipolar Transistors, *IEEE Transactions on Nuclear Science, 47* (2000) 6, pp. 2551-255

[10] Roldan, J. M., *et al*., Neutron Radiation Tolerance of Advanced UHV/CVD SiGe HBT BiCMOS Technology, *IEEE Transactions on Nuclear Science, 44* (1997), 6, pp. 1965-1973

[11] Pater, S. L., Sharp, R. E., Gamma Radiation Effects on Bipolar Transistors a Comparison of Surface Mount Standard Packages Radiation and its Effects on Components and Systems, *Proceedings,* RADECS 95, Third European Conference on, 1995, pp. 165-169

[12] Shatalov, A., *et al*., Neutron Irradiation Induced Degradation of the Collector-Emitter Offset Voltage in InP/InGaAs Single Heterojunction Bipolar Transistors, *Journal of Applied Physics, 88* (2000), 6, pp. 3765-3767

[13] Barnaby, H. J., *et al*., Proton Radiation Response Mechanisms in Bipolar Analog Circuits, *IEEE Transactions on Nuclear Science, 48* (2001), 6, pp. 2074-2080

[14] Messenger, G. C., A Summary Review of Displacement Damage from High Energy Radiation in Silicon Semiconductors and Semiconductor Devices, *IEEE Transactions on Nuclear Science, 39* (1992), 3, pp. 468-473

[15] Srour, J. R., Marshall, C. J., Marshall, P. W., Review of Displacement Damage Effects in Silicon Devices, *IEEE Transactions on Nuclear Science, 50* (2003), 3, pp. 653-670

[16] Keiter, E. R., *et al*., A Physics-Based Device Model of Transient Neutron Damage in Bipolar Junction Transistors, *IEEE Transactions on Nuclear Science, 57* (2010), 6, pp. 3305-3313

[17] Xingji, L., *et al*., Simultaneous and Sequential Radiation Effects on NPN Transistors Induced by Protons and Electrons, *IEEE Transactions on Nuclear Science, 59* (2012), 3, pp. 625-633

[18] Kulkami, S. R., Damle, R., Co-60 γ-Ray Induced Gain Degradation in Bipolar Junction Transistors, *Indian Journal of Physics, 85* (2011), 3, pp. 391-400

[19] Xingji, L., *et al*., Combined Radiation Effects of Protons and Electrons on NPN Transistors, *IEEE Transactions on Nuclear Science, 57* (2010), 2, pp. 831-836

[20] Kosier, S. L., *et al*., Charge Separation for Bipolar Transistors, *IEEE Transactions on Nuclear Science, 40* (1993), 6, pp. 1276-1285

[21] Schrimpf, R. D., Recent Advances in Understanding Total-Dose Effects in Bipolar Transistors, *IEEE Transactions on Nuclear Science, 43* (1996), 3, pp. 787-796

[22] Meng, X.-T., *et al*., Effects of Neutron Irradiation on SiGe HBT and Si BJT Devices, *Journal of Materials Science*: *Materials in Electronics, 14* (2003), 4, pp. 199-203
[23] Johnston, A. H., Swift, G. M., Rax, B. G., Total Dose Effects in Conventional Bipolar Transistors and Linear Integrated Circuits, *IEEE Transactions on Nuclear Science, 41* (1994), 6, pp. 2427-2436
[24] Nowlin, R. N., *et al*., Trends in the Total-Dose Response of Modern Bipolar Transistors, *IEEE Transactions on Nuclear Science, 39* (1992), 6, pp. 2026-2035
[25] Vukić, V., Osmokrović, P. V., Impact of Forward Emitter Current Gain and Geometry of PNP Power Transistors on Radiation Tolerance of Voltage Regulator, *Nucl Technol Radiat, 25* (2010), 3, pp. 179-185

Received on October 10, 2013
Accepted on March 17, 2014

Мио Мин ОО, Нахрул Каир Бин Аланг РАШИД, Јулија Бин Абдул КАРИМ, Мухамад Рави Бин. МОХАМЕД ЗИН, Росминазуин Бт. Аб. РАХИМ, Амелија Вонг АЗМАН, Нурул Фадзлин ХАЗБУЛАХ

ОПИС ЕЛЕКТРИЧНИХ СВОЈСТАВА КОМЕРЦИЈАЛНИХ НПН БИПОЛАРНИХ ТРАНЗИСТОРА ИЗЛОЖЕНИХ НЕУТРОНСКОМ И ГАМА ЗРАЧЕЊУ

Електронске компоненте, као што су биполарни транзистори, диоде и друге, које се користе у мисијама у делаком свемиру, морају добро подносити широку изложеност неутронима високих енергија и другом јонизујућем зрачењу. У овом раду приказују се неутронско озрачивање помоћу пнеуматског трансфер система TRIGA Mark-II реактора Малезијске нуклеарне агенције. Поред овог, испитиван је и утицај гама зрачења из ^{60}Co извора на силиконске НПН биполарне транзисторе. Анализе озрачених транзистора обухватиле су електричне карактеристике као што су струјно појачање, струја колектора и струја базе. Експериментлани резултати показују значајно смањење струјног појачања после излагања неутронима и гама зрачењу. Неутронско зрачење може оштетити основни слој транзисторске структуре, док гама зрачење оштећује оксидни слој у области осиромашења база-емитор. Сматра се да смањење струјног појачања настаје услед пораста струје рекомбинације у области осиромашења база-емитор.

Кључне речи: биполарни транзистор, радијационо оштећење, струја рекомбинације