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Experimental study of neutron irradiation effect on elementary semiconductor devices using Am-Be neutron source

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An experiment has been conducted to evaluate the lifetime, reliability and operational performance of elementary semiconductor devices in the neutron radiation environment which supports to reduce the fatal in measurements and plan the preventive actions in nuclear facilities. It will also support the enhancement of electronics for nuclear facilities. The elementary semiconductor devices used in the experiment are Diode (1n4007), Zener Diode (5.1v), Light Emitting Diode, Transistor (BC547, 2n3904), Voltage controlling IC (7805), Operational Amplifier (LM741) and Optocoupler (4n35). The selection of devices has been made by keeping in mind their application in transmitting devices (*i.e.* Temperature transmitter, pressure transmitter, flow transmitter, monitors and controllers) for Indian test blanket system in ITER. Such devices are also used in general nuclear electronics. The devices have been irradiated in the Am-Be neutron source environment. The maximum fluence has been given up to 10^{11} n/cm^2. The neutron source has energy range from low to high. All semiconductor devices have been characterized before and after irradiations. The deviation of 5 - 10% is observed in diodes I-V characteristics whereas transistors show a bit higher deflection in basic functionality. Optocoupler shows more than 50% deviation in its basic characteristics whereas voltage-controlling IC is not even functioning after the irradiation of 10^{11} n/cm^2. The paper describes the details of the experiment and the behavior of semiconductor devices after irradiation. The experiment supports the selection and further research of the Indian test blanket system instruments.

Keyword: Neutron, Radiation effect, Am-Be Source, Semiconductor device, Integrated Circuits

1 Introduction

The elementary semiconductor devices are kind of inherent part of all integrated circuits, sensors, instruments and control devices. Such sensors and devices are used in monitoring and controlling the various responses of machines and equipment i.e. temperature, pressure, flow rate, level of coolants, stress, vibration. Those devices are used in a variety of harsh environments like space, nuclear[1-3].

The measurement and controlling of the parameters in nuclear facilities are very important, since investment protection and occupational safety are associated with it[4]. Various types of sensors/ diagnostics and associated electronics are required for the physical parameter measurements of the power plants, nuclear reactor, and nuclear facilities. Integrated sensors and front-end electronics contain signal conditioners like amplifiers, signal converters, *etc.* for converting the physical signal to an electrical signal and sending them to control system. The sensor/diagnostics and signal conditioning devices are having semiconductors and such devices are going to expose in a radiation environment for the control of nuclear facilities and devices[4]. As per past studies that materials get damaged due to neutron irradiation and semiconductor devices are more sensitive to such environment[5-9].

It is very important that signal conditioning devices should be more accurate and highly reliable otherwise such devices process incorrect data. It may lead to an accident which results in loss of human and cost. It is essential to ensure the healthiness of semiconductors based signal conditioning devices before using them in the radiation environment. Therefore, the study of elementary semiconductor devices and few integrated circuits in the neutron radiation environment has been conducted using Am-Be neutron source. The purpose of the experiment is to study the neutron radiation effects on integrated circuits and associated elementary devices which may be utilized in nuclear fusion devices and more specific to the test module of

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tritium breeding blankets[10-12]. However, the scope is not limited up to the fusion devices only because the study may benefit the other facilities and projects where the same kind of neutron environment is foreseen.

The phenomena of neutron effects on semiconductor can understand using the neutron interaction with matter. The neutrons interaction with materials happens in three general ways. It is through elastic scattering, inelastic scattering and transmutation process. In the process of elastic scattering, neutrons transfer the part of their kinetic energy to the atoms of material and can dislocate the atom from its position in lattice. Elastic collisions continue as long as the energy of neutrons remains higher than the atom displacement energy (for most materials, it is 25 eV). The dislocated atoms as a primary knocked atom loses its energy through ionization process. It can also collide and displace other lattice atoms. Inelastic scattering happens through the capture of incident neutron which is following by the emission of low energy neutron. The energy transfer is left the nucleus in excided state and it comes back in ground state by emitting gamma rays. Inelastic scattering can also initiate displacement of atoms. The transmutation process also involves the incident neutron capture and emission of other particles such as a proton, alpha, etc. subsequently. The interacted atom is converted in other nuclei in the transmutation process. The interaction of neutron also happens in the same way in semiconductor and electronic devices. The high energy neutrons cause the displacement as well as ionizations in semiconductors. The displacement of atoms changes the band-gap energy of semiconductors and also causes the carriers motilities reduction. Ionization process can enhance the buildup of free charge in oxide layered semiconductor devices. The impact of irradiation on electronic devices reflected through variation in their electrical properties[13-15].

The selected electronic devices are diodes, transistors, Integrated Circuits (ICs), Optocoupler which are part of many sensors for control and monitoring temperature, pressure, flow rate, *etc.*. The selected devices are the part of electronic equipment and circuits used in monitoring and controlling of nuclear facilities and systems. They are useful in voltage protection and stabilizing circuits, electronic switches, and amplifications, current limiting circuits, analog to digital converter, voltage follower, hold circuits, summing amplifiers, and signal isolations, *etc.*[16-20].

The experiment has been conducted using the Am-Be neutron source[21-23]. In Am-Be source, the neutron has been produced by the interaction of the alpha particle with beryllium. The neutron source has a wide range of emission energy whereas the average energy of the neutron is around 4 MeV[23]. It makes the experiments different from other experiments where a mono-energetic neutron source were used to irradiate the semiconductor devices. The spectrum is relevant for ITER kind of facilities where many equipment will be placed in port cell near to biological shielding[11, 12]. The estimated neutron strength near to the target is around 2×10^7 n/s and the flux is 1.8×10^4 n/cm^2.s. The experiment has been performed in a sequence of 3 steps by achieving the total fluence of exposure to the devices around 1×10^9, 1×10^{10} and 1×10^{11} neutrons/cm^2. To achieve the neutron fluence of 1×10^{11} neutrons/cm^2, the samples were irradiated for effective 67 days. The devices function has been checked at all stage of the experiment. For the shack of assurance on the results, the irradiation has been repeated twice for the same amount of dose.

The study of neutron irradiation effects on specific electronic devices is conducted to understand the life of such devices under neutron environment and it is the initiation towards the explorations of utilization of commonly used electronics and integrated circuits in neutron environment.

The paper covers the entire sequence of the experiment. Section -2 gives the description of semiconductor devices and it is followed by experimental set-up in section -3. The post-irradiation function details and deviation from its base characteristics have been detailed out in section-4. The conclusion of the experiment is given in section-5.

2 Description of Elementary devices and ICs

The description of the devices chosen for the experimental study is given in below sections with the applicability of such device[16-20]. The electronic devices are diodes, transistors, Integrated Circuits (ICs), Optocouplers. These devices are part of many sensors for control and monitoring temperature, pressure, and flow rate. Such devices are also the part of various electronic equipment and circuits used in monitoring and controlling of nuclear systems. Devices are also important in voltage protection and stabilizing circuits. They are used in electronic switches, and amplifications systems. They are utilized in various other applications such as current limiting circuits, analog to digital converter, voltage follower, hold circuits, summing amplifiers, and signal isolations, *etc*. These devices are considered as per their expected utilization in Indian ITER Test Blanket Module instruments.

a. Diode (LED, 1n4007, 5.1v zener)

The diode is a basic elementary electronics device which is made of semiconductor such as silicon. It has two terminals *i.e.* cathode and anode. It is basically used for the application where one direction current flow is required. For the irradiation experiment, three diodes have been chosen which are Light Emitting diodes (LED), PN diode (1n4007) and 5.1 V Zener diode. LED diode is relevant for the experiment because it is used in sensing any substance speed. Such kind of application is required in the fusion reactor to track the substance speed and location for online measurement of neutron flux in a nuclear fusion device[24]. The second selected diode is PN 1n4007. It is silicon-based rectifier diode and it is widely used in general purpose rectification in power supplies, microcontrollers, and embedded systems. Such kinds of diodes have multi-uses in sensors and control devices for physical parameter measurements. The third diode used in the experiment is Zener diode 5.1V. It has the function of reverse breakdown. It is broadly used in voltage protection circuits, low voltage current circuits, input voltage protection for microcontrollers and integrated circuits. It is also used in voltage stabilizing circuits.

b. Transistor (BC547, 2n3904)

The basic function of the transistor is to transfer the residence. The main application is to enhance the current. Transistors are categorized using their power ratings. The first transistor chosen for the irradiation is BC547. The BC547 transistor has made of silicon semiconductor with doping and also has three terminals NPN. It is a bipolar junction transistor. The BC547 is used for the switches and amplification. It is utilized in all type of circuits and electronic gadgets. The second transistor used in the experiment is 2n3904. It is also made of silicon material and it is an NPN bipolar junction transistor. It is commonly used in the purpose of amplification and it can amplify the frequency up to 100 MHz. It is used in small charge switches which are having low saturation voltage and high gain.

c. Voltage controlling IC (7805),

Integrated Circuit (IC) 7805 is a voltage regulator IC which has the constant 5V output for the input of 7 to 35 V. It is a positive voltage regulator. It prevents the voltage fluctuation in the electronic device. It is useful for a verity of electronic applications. The applicability of the IC is most appropriate where constant voltage output is required. It is widely used in current limiting circuits. It is also used for the application of high temperature and pressure.

d. Operational Amplifier (LM741)

IC 741 is a general-purpose operational amplifier and it gives high gain and short circuit protection. It also favors a larger range of input voltage. The application of LM-741 is very extensive. It can be used in various electronic circuits like analog to digital convertor and voltage follower. It is also used in hold circuits, summing amplifiers. It is also utilized in a voltage to current and current to voltage converter. Such circuits are part of most of the control and monitoring systems.

e. Optocoupler (4n35)

Optocoupler is also a semiconductor-based electronic device which is used in interconnecting of two different electrical circuits via an optical interface. Optocoupler can also provide the electrical isolation in between input and output load using light. It is made of the light emitter, LED and a semiconductor light-sensitive receiver (diode, transistor, *etc.*). The optocoupler is applied in many common applications such as microprocessor switching, signal insolation, and power supply regulation. It is also used in AC and DC power control, and PC communications.

3 Set-up of irradiation experiment

The neutron irradiation experiment for semiconductor based electronic devices is done using the Am-Be neutron source[21]. The neutron source is based on (α, n) reaction where alpha particle interacts with a beryllium and produces the neutrons. The role of alpha emitter is played by Americium-241 radionuclide. The schematic of the Am-Be neutron facility is given in Fig. 1. The emitted neutrons from source have a wide energy range due to various energies of bombarding alphas. The average energy of the neutron is around 4 MeV[22]. As shown in Fig. 1, it is a cylindrical container which is filled with paraffin for the radiation shielding. The source is located in the lower part of the container. The loading of samples is done from the top. The measurement of the neutron flux has been done at the top of the facility. The neutron detection has been conducted using the Helium-3 detector. The sample has been placed near to the source as shown in the Fig. 1.

The estimated neutron fluence near to the target is around 2.0×10^7 n/s. The neutron flux at the irradiation location of the samples is around 1.8×10^4 n/cm^2.s. The uncertainty in the flux measurement is around 15% approximately. The energy spectrum at the irradiation location of the sample is given in Fig. 2. It shows the neutrons from thermal to high energy range. The wide energy range of neutron provides a unique feature to the experiment

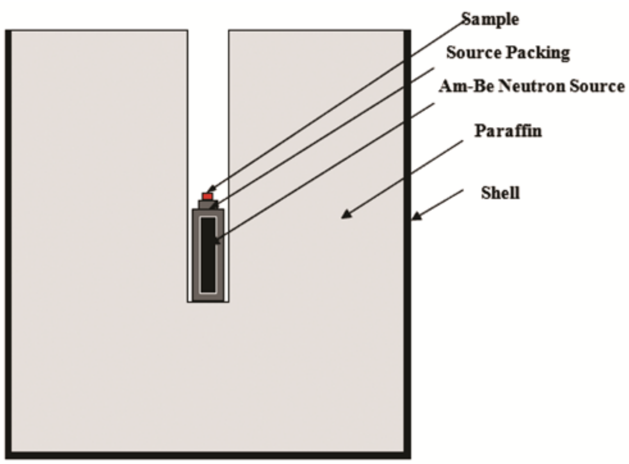

Fig. 1 — Schematic diagram of Am-Be facility

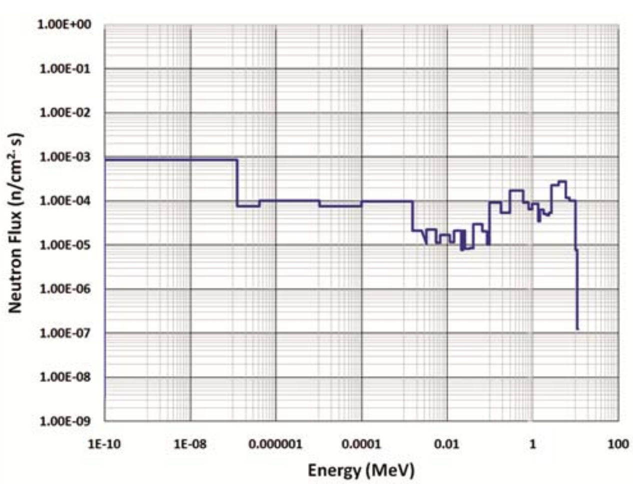

Fig. 2 — Neutron energy spectrum at location of samples

and makes it more relevant for realistic condition where variety of neutron are foreseen. For the case of Indian Test Blanket Module (TBM) port cell of ITER, the energy spectrum have all kind of neutron from thermal to high energy[12, 25]. The experiment are planned to accommodate the energy range near to TBM port cell region[12, 25] which makes it more relevant to Indian TBM instruments. The experiment is an offline experiment where the devices are irradiated using the neutron source and functionality of devices are checked post irradiation. The conducted experiment can represent only permanent damage to the devices due to neutron irradiation. It demonstrate the changes in devices which cannot be revert back after irradiation. The instant changes happened during the irradiation can not be measured in the experiment.

The irradiation of electronic devices is conducted in three steps and the maximum neutron fluence achieved in the current experiment is 10^{11} neutrons/cm^2. The samples were irradiated for effective 67 days to achieve the neutron fluence of 1×10^{11} neutrons/cm^2. Initially, the devices were irradiated for 10^9 neutrons/cm^2 and it is followed by 10^{10} and 10^{11} neutrons/cm^2. The cumulative effects of neutron on electronic devices have been observed. The functionality of all irradiated devices was checked on each step of irradiation. The device have characterized many times before the irradiation to insure the appropriate functionality and the same process has been also applied during the functionality characterization in each post irradiation steps.

4 Functioning of devices post irradiation

The functionality of the electronic devices has been assessed before irradiation and post-irradiation on each step. In order to check the functionality, electronic circuits have been prepared as per the particular device function at the laboratory. The I-V characteristics of diodes and transistors have been generated and for ICs their input-output dependency has been produced. The functionality of devices has been plotted to check the impact of neutron irradiation on devices. The assessment of the health of the devices has been checked by observing the deviation in the basic functionality after irradiation. The functionality has been checked after each step of irradiation to see their health. The degradation of the devices has been observed at each step. The experiment is done only to detect the permanent degradation. The instant impact of the neutron on the device which can be reflected only through online measurement of electric properties, has not been assessed.

The impact of the neutron on devices occurs through displacement of atoms from lattice and the ionization process. The process lead to the band-gap change, charge accumulation and carriers mobility reduction in electronic devices. It impact on the functionality of electronic devices.

The functionality of light-emitting diode before and after irradiations are presented in Fig. 3. The forward bias I-V characteristic of the diode has been generated and very minor change around 4-5 % has been observed after the exposure of 10^{11} n/cm^2. It is clear that there is not any significant functionality deviation. It happens because silicon semiconductor may require high neutron fluence to get the sustainable displacement damage. The sustainable damage can only start the degradation in terms of leakage in insulator part. It gives the assurance that LED can survive without deviating from its function up-to the 10^{11} n/cm^2. It validates that LED can perform satisfactorily in a high energy neutron environment which seen the neutron fluence of 10^{11}.

The functionality plot of 1N4007 diode also shows the same trend as LED. It is presented in Fig. 4. The deviation is slightly higher than LED but it is not significant. The variation in I-V response of 1N4007 diode is less than 2%. The diode responses are quite stable upto the fluence of 10^{11} neutrons/cm^2. The small observed deviation in diode could be due to the fluctuation. It also validates the applicability of 1N4007 in high energy neutron environment.

The pre and post irradiation I-V characteristics of Zener diode have been obtained for forwarding bias which is shown in Fig. 5. The deviation in Zener is also not significant. The Zener 5.1 V diode can work in neutron radiation without any major deflection in response up to the 10^{11} n/cm^2.

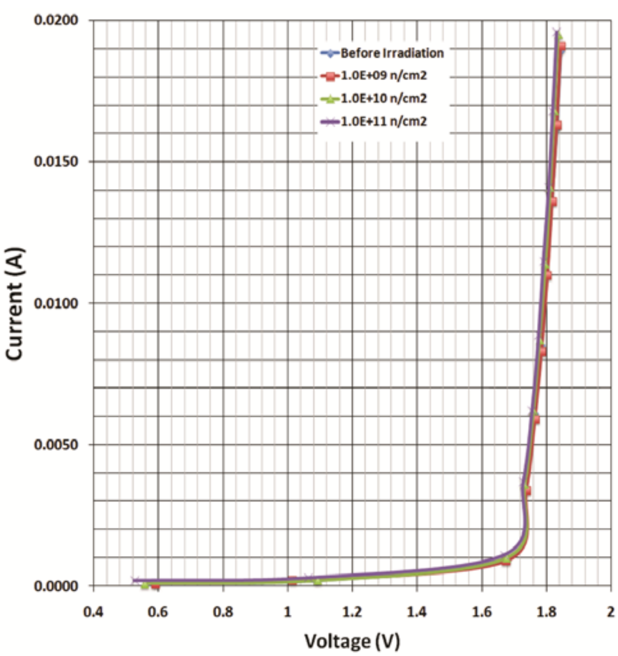

Fig. 3 — I-V characteristics of LED

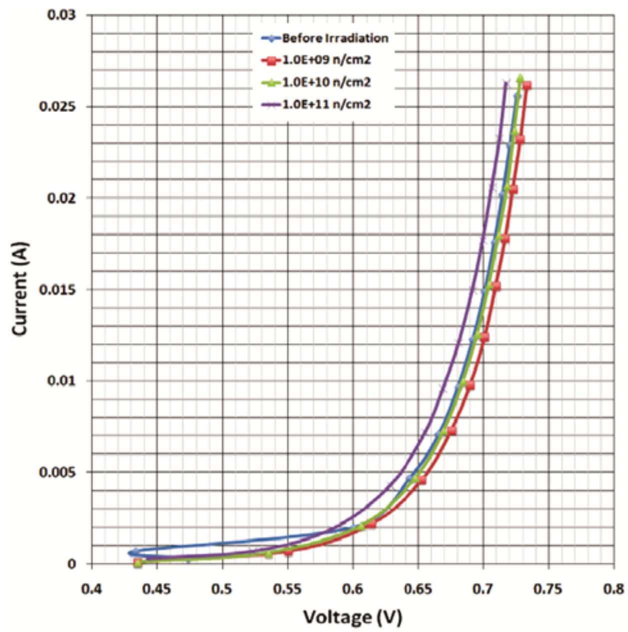

Fig. 4 — I-V characteristics of 1N4007 diode

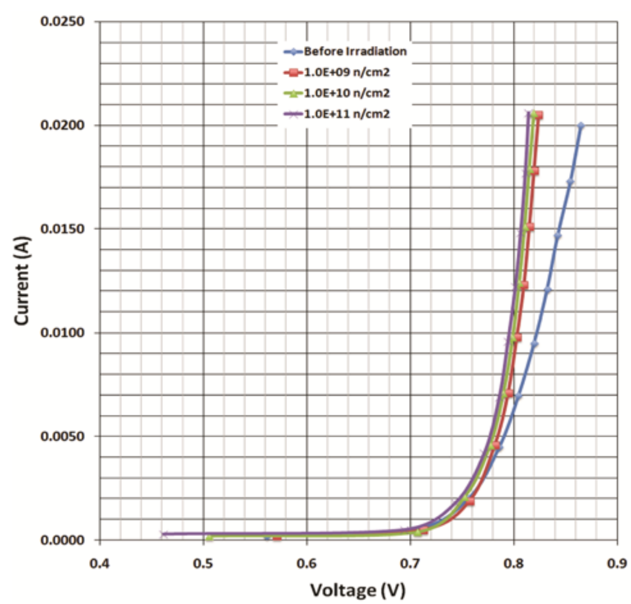

Fig. 5 — I-V characteristics of Zener diode 5.1v

It seems that diodes sustainability limits in high energy neutrons are higher than 10^{11} n/cm^2. The given irradiation is not able to make any significant displacement damage and ionization in terms of free charge accumulation or mobility variation.

Pre and post irradiation functionality of the bipolar junction transistor BC547 and transistor 2N4007 have been given in Fig. 6 and Fig. 7 respectively. It is observed that after irradiation the mobility of free carriers is reduced. However, transistor 2N4007 is not deviating significantly from its basic functionality even after 10^{11} neutrons/cm^2 exposure which makes it applicability in the same kind of irradiation environment. The bipolar junction transistor BC547 deviates from its basic function by 10-15% which is quite significant for some occupational safety. It reduces the chance of such transistors to use in a neutron environment.

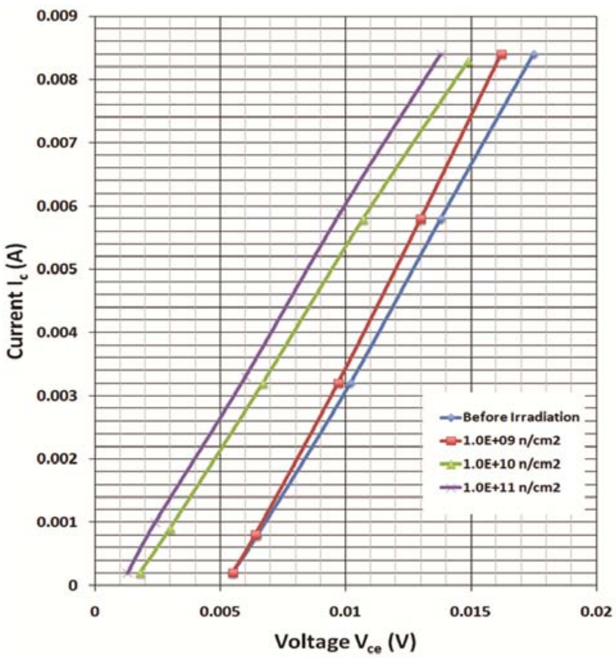

Fig. 6 — I-V characteristics of transistor BC547

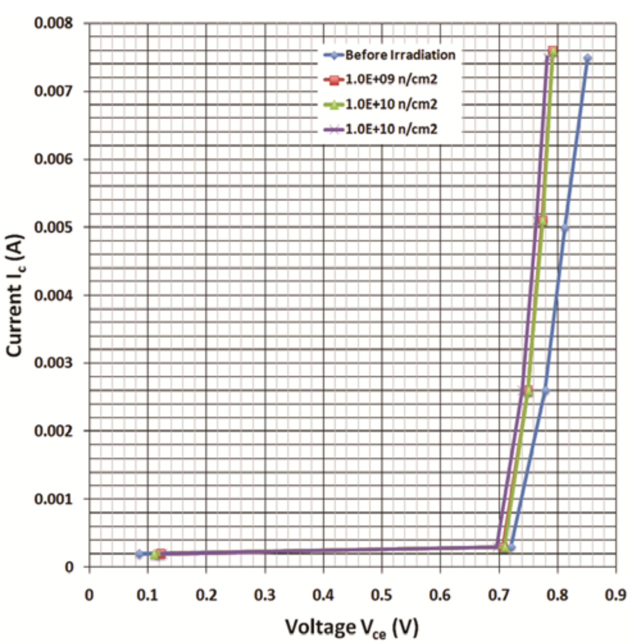

Fig. 7 — I-V characteristics of transistor 2N3904

The integrated circuits were also irradiated along with diode and transistors. The integrated circuits have the oxide layered silicon along with many other microelectronic parts. The displacement damage and ionization may occur more prominently in integrated circuits than diodes and transistors.

The voltage controlling IC LM 7805 is irradiated and the functional behavior of the same has been presented in Fig. 8. The IC supposed to give the output of 5 V for the input range of 7-35 volts. It is seen that it is working properly up to the neutron exposure of 10^{10} n/cm^2, however once it is irradiated for 10^{11} n/cm^2 then it completely deviates from the basic output. It happens because the threshold of effective enhancement in ionization and displacement of atoms process may have occurred in the device. The ionization may result in the large free charge accumulation and it may resultant in the heating and damage of the IC. Therefore the LM7805 can work in the area where the neutron fluence may reach only up to 10^{10} n/cm^2.

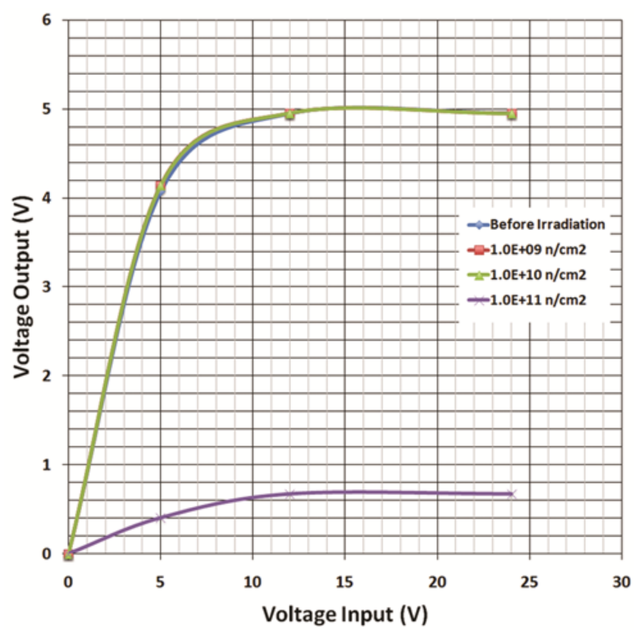

Fig. 8 — Characteristics of IC 7805

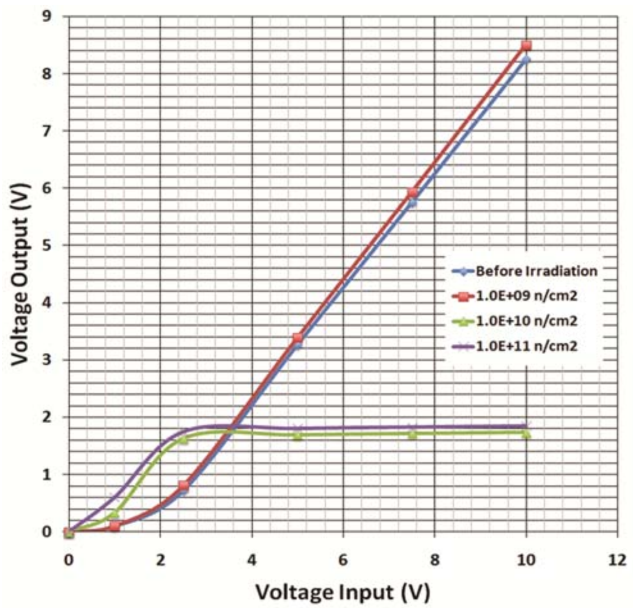

Fig. 9 — Characteristics of IC 741

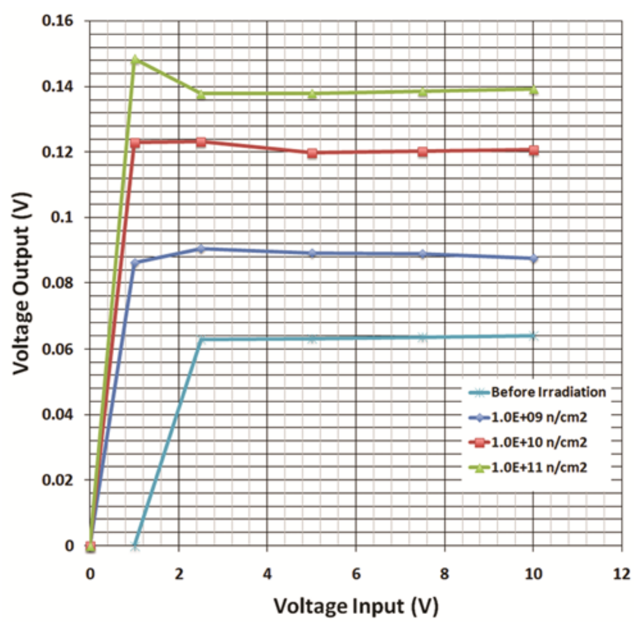

Fig. 10 — Characteristics of Optocoupler IC 4N37

The operational amplifier IC 741 has been also tested in the neutron irradiation and the function of the same has been given in Fig. 9. The IC shows the same kind of behavior after the irradiation of 10^9 n/cm^2. It shows that there is no damage and charge accumulations happening in the IC after 10^9 n/cm^2. The basic functional behavior of the IC completely deviates even after the 10^{10} n/cm^2 which gives the ICs working limit in high energy neutron environment 10^9 n/cm^2. The significant amount of damage has been seen in the IC 741 after the irradiation of 10^{10} n/cm^2. The device is further irradiated for 10^{11} n/cm^2 and it shows the same trend as after 10^{10} n/cm^2. The experiment validates the usage of IC is only good under 10^9 n/cm^2.

The pre and post irradiation functionality characterization of optocoupler have been shown in Fig. 10. The outcome of the optocoupler IC 4N37 is changed significantly even after the 1st step of irradiation which is clearly represented in the Fig. 10. It happens due to neutrons interaction with optocoupler and it leads to the leakage of current in optocoupler. The significant damage is happened even after the irradiation of 10^9 n/cm^2. It further gets degraded after 10^{10} n/cm^2 and the current is increased drastically after the irradiation of 10^{11} n/cm^2. It deviates more than 50 % from its basic functionality. The experiment demonstrates the issue in optocoupler functionality in radiation environment.

It clearly reducing the probability of such optocoupler device in high neutron radiation fields.

5 Conclusion

The neutron irradiation experiment has been conducted in order to get the radiation environment applicability of some of the semiconductor devices. The electronic devices are chosen as per their general applicability and use of such device in physical parameter monitoring sensors. The Am-Be neutron source has been used which has the average energy around 4 MeV. The irradiation has been done up to the fluence of 10^{11} n/cm^2. The impact of the neutron in a semiconductor occurs through terms of displacement of atoms from lattice and the ionization process. The process may lead to the band-gap change, charge accumulation and carriers mobility reduction in electronic devices. It may affect the functionality of electronic devices in nuclear radiation environment which become the reason of occupational and investment safety compromises. The outcomes of the experiment suggest that the selected diodes and transistors are not affected much up to the exposure of 10^{11} n/cm^2 which validates the establishment of such diodes and transistors reliability in the same conditions. The voltage controlling IC-7805 gets damaged and deviates from its basic function after facing 10^{11} n/cm^2 whereas operational amplifier IC-741 is degraded even after 10^{10} n/cm^2. The optocoupler starts deviating from its functionality even after 10^9 n/cm^2. The study echoes that the selected integrated circuits are more sensitive than diodes and transistors in a high energy neutron environment. It is because of the silicon oxide-based ICs gets the displacement damages and effective ionization bit early than silicon-based diode and transistors. If the diode and transistor comparison are seen it observed that transistor get more impact from neutrons than a diode. The work has been carried out in support of the sensor and diagnostic selection for Indian test blanket module of ITER. The work may be extended in terms of more ICs and extended neutron fluence for irradiation. The study may help in other nuclear facilities and applications where such kind of electronic devices are expected to be used.

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References

1 Robert B N, Introduction to instrumentation and measurements (CRC Press, Boca Raton) 2nd Edn, 1997.
2 Sophie D, *Aerospace Sci Technol*, 9 (2005) 93.
3 Srivastava G P & Sadhana, *Indian Acad Sci*, 38 (2013) 897.
4 Yadav B K, Gandhi A & Verma A K, *Int J Phys Math Sci*, 8 (2014).
5 Srour J R, Marshall C J & Marshall P W, *IEEE Trans Nucl Sci*, 50 (2003) 653.
6 Srour J R & Palko J W, *IEEE Trans Nucl Sci*, 60 (2013).
7 Haider F, Amir A & Prayoto S, *Nat Nucl Agency-Yogyakarta*, 3 (2001) 10.
8 Iida T, Maekawa T & Sumita K, *J Nucl Sci Technol*, 1 (1984) 66.
9 Messenger G C, *IEEE Trans Nucl Sci*, 13 (1966) 141.
10 Chaudhuri P, Kumar E R & Sircar A, *Fusion Eng Des*, 87 (2012) 1009.
11 Yadav B K, Gandhi A & Verma A K, *Fusion Eng Des*, 124 (2017) 710.
12 Swami H L, Shaw A K, Danani C & Chaudhuri P, *J Phys Conf Ser*, 823 (2017) 012066.
13 Holmes-Siedel A & Adams L, *Handbook of Radiation Effects*, (Oxford University Press, Oxford) 2nd Edn, 2002.
14 Greenwood L R, *J Nucl Mater*, 216 (1994) 29.
15 Almenas K & Lee R, Neutron Interaction with Matter, Nuclear Engineering, Springer-Verlag, Berlin Heidelberg, (1992) 53.
16 Bogart T F, Beasley J S & Rico G, *Electron Dev Circuits*, (Pearson Education, India) 6th Edn, 2004.
17 Milnes A G, *Semiconductor Devices and Integrated electronics*, (Van Nostrand Reinhold company Inc., New York) 1980.
18 Boylestad R L & Nashelsky L, *Electron Dev Circuit Theory*, (Pearson Education, India) 2009.
19 Sze S M, *Physics of Semiconductor Devices*, (John Wiley & Sons, USA) 1981.
20 Horowitz P & Hill W, *The art of electronics*, (Cambridge University Press, USA) 2nd Edn, 1989.
21 Makwana R, Abhangi M & Tiwari S, Study of fast neutron moderation and shielding properties of water and boron assembly, (Proceedings of the seventeenth national symposium on solid state nuclear track detectors and their applications, India) 2011.
22 Shah S, Kumar S & Vala S, Neutron Irradiation Impact On ITER Grade Insulating Material, (Fusion Energy Conference, FIP/P3-27, 27th IAEA Fusion Energy Conference - IAEA, India) 2018.
23 Fantidis J G, *J Taibah Univ Sci*, 11 (2017) 1214.
24 Cheon M S, Lee Y S & England A C, *J Instrument*, **7** (2012).
25 Swami H L, Sharma S & Shaw A K, *Fusion Eng Des*, 137 (2018) 49.