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Displacement damage in optocouplers induced by high energy neutrons at back-n in China Spallation Neutron Source*

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Neutron radiation experiments of optocouplers at back-streaming white neutrons (back-n) in China Spallation Neutron Source (CSNS) are presented. The displacement damages induced by neutron radiation are analyzed. The performance degradations of two types of optocouplers are compared. The degradations of current transfer ratio (CTR) are analyzed, and the mechanisms induced by radiation are also demonstrated. With the increase of the accumulated fluence, the CTR is degrading linearly with neutron fluence. The radiation hardening of optocouplers can be improved when the forward current is increased. Other parameters related to CTR degradation of optocouplers are also analyzed.

Keywords: China Spallation Neutron Source, optocoupler, neutron radiation, displacement damage, current transfer ratio

PACS: 42.88.+h, 61.80.Hg, 52.59.–f, 61.80.–x **DOI:** 10.1088/1674-1056/ab5efb

1. Introduction

An optocoupler is a kind of electric–opto–electric conversion device which transmits electrical signals through the medium of optical signal between the two diodes. The light source and receiver are sealed in an airtight device. The most important parameter in an optocoupler is the current transfer ratio (CTR), which is defined as the radio of the output current of the photo detector to the current of the light source. Optocouplers are widely used in space environments where there is radiation by different particles. The main radiation damage effects include displacement damage (DD), total ionizing dose (TID), and single-event transient (SET).

Radiation damage effects may cause degradation or function failure in optocouplers. Some optocouplers in the TOPEX-Poseidon spacecraft failed after two years of operation. Later work showed that the proton displacement damage played an important role in the degradation for the type of optocouplers used in TOPEX.[1,2] Over the years, radiation effects in optocouplers induced by protons, gamma rays, and neutrons have been widely investigated to demonstrate the mechanisms.[1–6] However, fewer literatures have reported the researches of displacement damages at back-n in China Spallation Neutron Source (CSNS).

CSNS provides a large scientific platform, which can be used to study the properties of neutrons and to detect the microstructure and motion of matter. The back-streaming white neutrons (back-n) from a spallation target through the proton beam line in CSNS has a very wide neutron energy spectrum,[7] which is used to study the neutron radiation on optocouplers in this paper.

The primary purpose of this paper is to investigate the radiation experiments of the optocouplers at the back-n in CSNS. The degradations of LED and transistor induced by neutron radiation are presented to investigate the displacement damage in optocouplers. The CTR and other electrical parameters of optocouplers are analyzed to demonstrate the degradation mechanisms after irradiation. The output characteristic curve and the CTR of the two types of optocouplers are compared to illustrate some problems. The experimental results of the optocouplers will provide some suggestions and ideas for the radiation hardening design.

2. Experimental details

The neutron radiation experiments of the optocouplers were carried out at back-n in CSNS (Dongguan, China). The schematic layout that how the back-n are produced in CSNS is shown in Fig. 1 and the position where the experiments were carried out is located at endstation 2 (ES#2, 80 m). The neutron energy spectrum at back-n in CSNS ranges from 1 eV to 200 MeV and the detailed spectrums of back-n beam are shown in Fig. 2. The x and y axes are log scale, and the most common neutron energy is approximately 1.0 MeV.[8]

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The size of the beam is about Φ6 cm, with a flux of 3.5×10^6 n/(cm^2·s). The accumulated fluences in these radiation experiments are 1.0×10^{10}, 3.0×10^{10}, 5.0×10^{10}, 1.0×10^{11}, and 3.0×10^{11} n/cm^2. The TID induced by gamma rays and neutrons is no more than 300 rad(Si) when the neutron fluence is 3.0×10^{11} n/cm^2.[9] All the samples were in the unbiased and off-line condition when they were exposed. After irradiation, all the samplers were tested under the same condition as they were tested before irradiation. All the samples were tested at the room temperature about 25 °C.

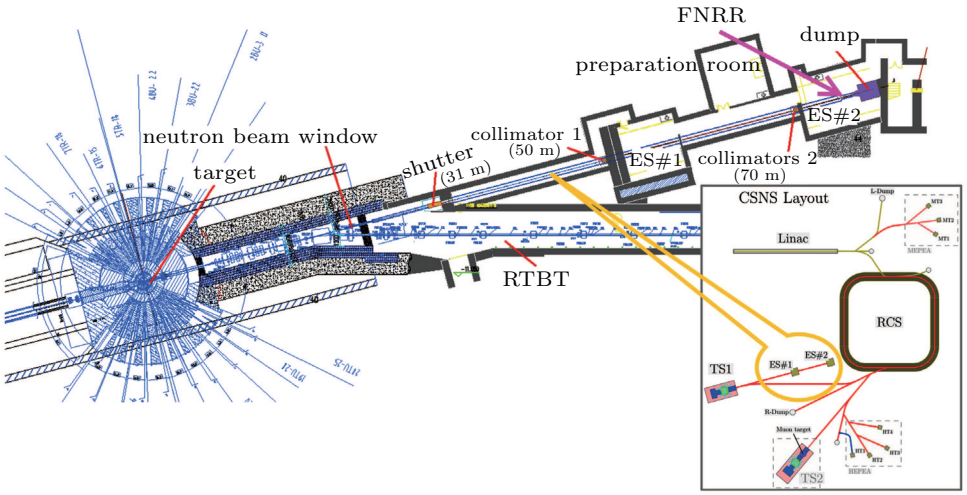


Fig. 1. Schematic layout of back-n in CSNS.[7]

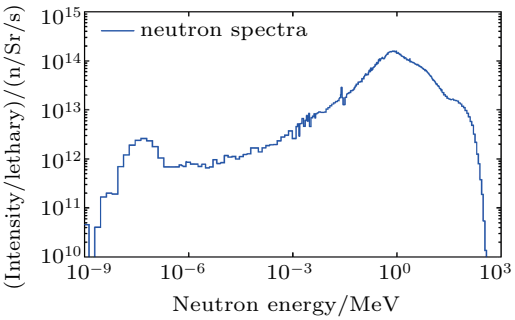


Fig. 2. Spectrum of the white neutron beamline.[8]

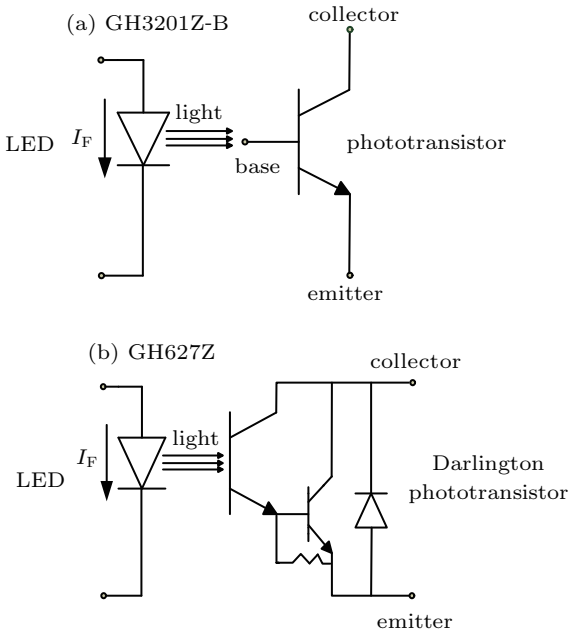


Fig. 3. Diagrams of two types of optocouplers.

The optocouplers used in these experiments are GH3201Z-B optocoupler and GH627Z optocoupler. The diagrams of the two optocouplers are shown in Fig. 3. These two types of optocouplers are both single-channel, consisting of a GaAlAs light emitting diode (LED) and a photo detector. The GH3201Z-B uses a common phototransistor while the GH627-Z uses a Darlington phototransistor. It is obvious that the GH627Z-B will have a high CTR even though the LEDs of the optocouplers are the same. The wavelength of the LED is 930 nm. The coupling medium of the two optocouplers are both nitrogen instead of silica gel which may produce pollutants in the vacuum environment.

3. Results and discussion

3.1. LED degradation

As an important part of optocoupler, the degradation of the LED output has an important influence on the optocoupler. Johnston, *et al.*[10] have reported the degradation of the LED output induced by the displacement damage. We can analyze the change of *I*–*V* characteristics to get the degradation of the LED output. Figure 4 shows the dependence of forward voltage on the forward current. From Fig. 4, one can see that the voltage decreases with increasing neutron fluence under the same current. In other words, higher current will be generated when the biased condition is not changed.

At low injection levels, the LED current mainly depends on the recombination current in the space charge region. When the LED is in the normal working state, the recombination of minority carriers will generate photons. The LED output de-

pends on the number of photons. However, the carrier recombination can be divided into two parts: radiative recombination and nonradiative recombination. The radiative recombination determines the light power while the nonradiative recombination determines the forward current. Neutron radiation mainly induces displacement damages in optocouplers and introduces defects in LED materials. The number of the defects increases with increasing neutron fluence. The defects determine the decrease of the minority carrier lifetime and the probability of nonradiative recombination. The increase of the forward current indicates that the ratio of nonradiative recombination increases, which corresponds to the defect increase. When the forward voltage is constant, the relative ratio of the radiative recombination decreases, so the LED output decreases.

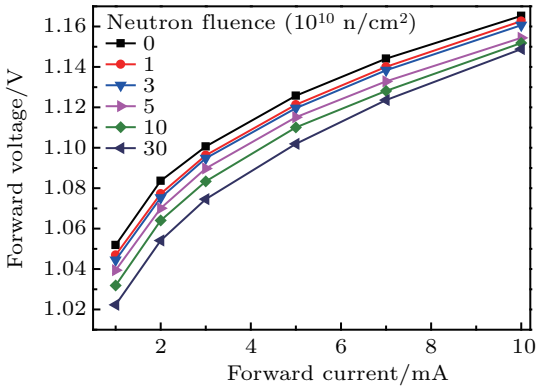


Fig. 4. Voltage *versus* forward current at each of neutron fluence.

3.2. Detector degradation

Another important part of the optocoupler is the photo detector. From Fig. 3, one can see that the value of the base current determines the output current of the photo detector at a certain extent. Figure 5 shows the base current of the phototransistor *versus* the LED current. The base current consists of the drift current and diffusion current. The former is influenced by the incident light intensity and the ability to produce photo-generated carriers while the latter is influenced by the minority carrier lifetime and the diffusion length. After irradiation, the minority carrier lifetime and the diffusion length decrease because of the displacement damage. The photo-generated carriers far away from the depletion layer cannot reach the edge, so the diffusion current decreases. Because of the decrease of the LED output (as described in Subsection 3.1), the incident light intensity decreases. Then the drift current decreases. For the decrease of the drift current and diffusion current, the base current inevitably decreases.

Another parameter to measure the degradation of the phototransistor is the output characteristic curve. Figure 6 shows the dependence of output current on the voltage between the collector and the emitter. From Fig. 6(a), one can see that the saturation voltage decreases markedly after neutron irradiation, and it even decreases by more than half at the neutron fluence of 3.0×10^{11} n/cm^2. The change is caused by the degradation of the base current. After neutron irradiation, the irradiated devices cannot collect as many carriers at the same bias voltage, which induces the decrease of the output current. Although the structure of the Darlington phototransistor is different, the degradation of it can also provide reference for the degradation analysis of the whole photo detector.

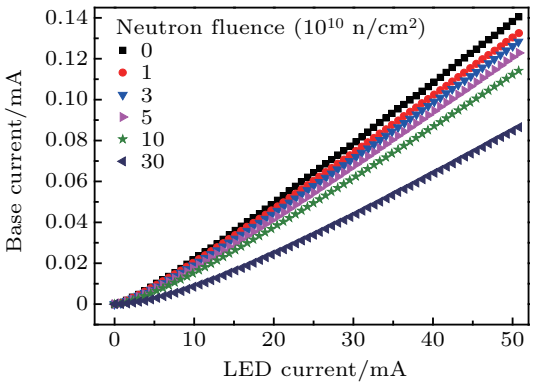


Fig. 5. Base current *versus* the LED current for the GH3201Z-B at each of neutron fluence.

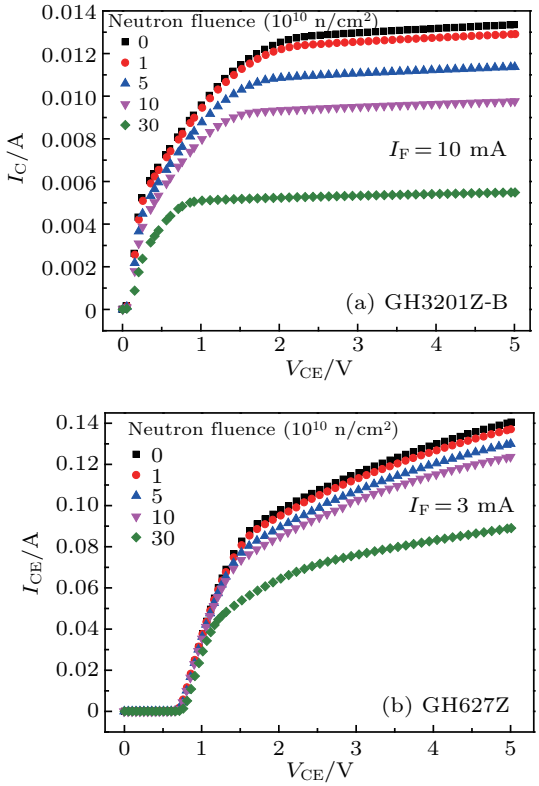


Fig. 6. Output current *versus* voltage between collector and emitter of photo detector.

3.3. CTR degradation

Due to the different structures of the two types of photo detector of the optocouplers, their CTR performances are also different. Figure 7 shows how the LED current dependence of CTR is influenced by the irradiation level. As shown in Fig. 7, the CTR decreases obviously after neutron irradiation. The peaks both shift to the higher current with increasing neutron

fluence, but the GH627Z optocoupler shifts less. It is obvious that the neutron irradiation changes the dependence of CTR on the LED current. Before irradiation, the CTR changes rapidly even the LED current changes small. The rate of change decreases after irradiation. One can see from the definition of the CTR that the rate change is related to the detector degradation.

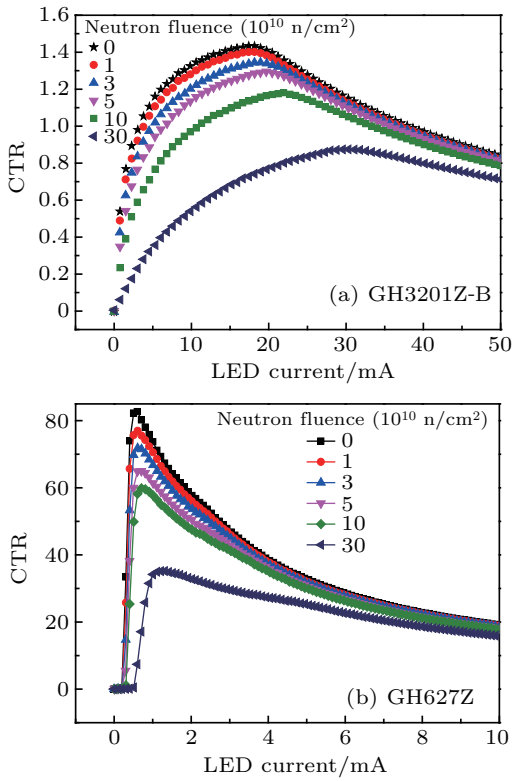


Fig. 7. CTR *versus* the LED current for the two optocouplers at each of neutron fluence.

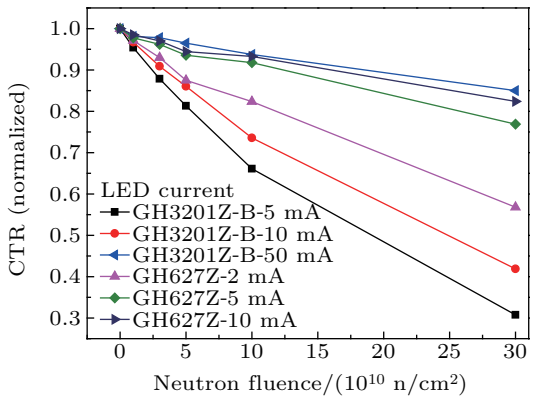


Fig. 8. CTR *versus* the neutron fluence for the two optocouplers at each of LED current.

We can present the response and the resistance of the two kinds of optocouplers CTR to the neutron fluence from another way. Figure 8 shows the normalized CTR of the two optocouplers *versus* neutron fluence. One can see that the degradations of the CTR are nearly linear. This is a good illustration of the displacement damage induced by neutron radiation. When comparing the two optocouplers at the same current, the degradation degree of the GH627Z optocoupler is relatively smaller. This may be related to the process and structure of the two optocouplers. The maximum current of GH627Z is 20 mA while the GH3201Z-B is 50 mA. From Fig. 8, one can also see that the CTR degradation varies with different currents at the same neutron fluence. The higher the LED current of the optocoupler is, the lower the CTR degradation is.

4. Conclusion

In this paper, the displacement damages in two types of optocouplers induced by neutron radiation at back-n CSNS have been reported. The degradation mechanisms induced by neutron radiation are demonstrated. The maximum neutron fluence reaches 3.0×10^{11} n/cm^2.

The results show that the CTR of the optocouplers is degraded by the neutron radiation. The degradation is affected by the degradation of the LED and photo detector. The decrease of the minority carrier lifetime and the diffusion length induced by displacement damage plays a significant role in it. The degradation of the LED output will decrease the base current of photo detector with the degradation of the detector itself. The degradation of photo detector can change the dependence of the CTR on the forward current. The experimental results indicate that the degradations of the two types of optocouplers are very different, which may be related to the process and structure of the two optocouplers. However, the CTR degradation can be improved by increasing the forward current. Using an optocoupler with a lower forward current may improve the radiation hardening.

In the future research, more experiments will be carried out to investigate the irradiation effects of optocouplers induced by different particles and rays. More tests of the microprobes and parameters will be carried out.

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