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Effect of irradiation of silicon photodiode arrays for ITER radial x-ray camera investigated by measuring response and current–voltage characteristics

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ABSTRACT

The response and current–voltage (I–V) characteristics of irradiated and non-irradiated silicon photodiode arrays (SPDAs) for use in the International Thermonuclear Experimental Reactor camera are measured and compared. Irradiation experiments are carried out using a uranium–zirconium hydride pulsed reactor. The total equivalent 1 MeV neutron fluence with energy above 0.01 MeV is ~9.89×10^{13} n cm^{-2}. The output signal of the irradiated SPDA (XD2) shows a nonlinear trend during the irradiation experiment. The final signal is about 5.6% of the original one in the visible light region. Tests on the Experimental Advanced Superconducting Tokamak (EAST) show that the XD2 signal is 70%–80% of that of a non-irradiated SPDA (XD3). This indicates that irradiated SPDAs can still observe plasma radiation after exposure to 9.89×10^{13} n cm^{-2} neutron fluence. However, because the neutron fluence of external camera detectors will reach 1.4×10^{16} n cm^{-2} in D-T phase, the SPDAs might become unusable at some point. The responsivity ratio of irradiated and non-irradiated SPDAs is about 4%–20% from 7 to 13 keV. The degradation of responsivity is related to the energy level. After irradiation, the reversed dark current rises from 0.1 to 10 nA to a level of around 1 μA. In terms of tests of XD2 on EAST, zero bias is a good working condition for irradiated SPDAs.

I. INTRODUCTION

Soft x-ray systems are important tools for investigating plasma phenomena through their soft x-ray emissions.[1] The object of the International Thermonuclear Experimental Reactor (ITER) Radial X-ray Camera (RXC) is to measure the poloidal profile of plasma x-ray emissions, and then study low (m, n) magnetohydrodynamic modes, sawtooth patterns, disruption, and edge-localized modes.[2]

In the pre-fusion operation phases of ITER, a silicon photodiode array (SPDA) detector is used to detect x-rays by the RXC due to its fast response and small volume. In the fusion operation phase, however, there are strong neutron and gamma rays in the working environment of the SPDAs. Such irradiation causes the detector performance to degrade, with a deterioration in the response and an increase in the reversed dark current because of changes to the crystal structure of the semiconductor and lattice defects.[3] This raises the question of whether SPDAs can be used during the whole fusion operation phase. Therefore, further research on the effects of irradiation on SPDAs is indispensable.

The deterioration of the detector's response leads to a loss of information from plasma radiation. This is an important aspect of research on the irradiation effect. Cho *et al.*[4–8] investigated the deterioration and recovery of the detector's response after neutron irradiation using synchrotron radiation from a 2.5-GeV positron storage ring at the Photon Factory. In addition, they developed a theoretical model to interpret the x-ray response and its deterioration of semiconductor detectors.[9,10]

The reversed dark current can produce a nonzero baseline in the output signal of detectors. This is positively correlated with the applied reversed bias, although adding a reversed bias can improve the response of semiconductor detectors. To find an appropriate reversed bias for irradiated detectors, the relationship between the dark current and the working voltage, i.e., current–voltage (I–V) characteristics, must be determined. Additionally, investigating the I–V characteristics can also identify the irradiation damage of the semiconductor detectors.[11–13]

A neutron irradiation experiment was carried out in a fission reactor to investigate the irradiation effects of neutrons on the main components of the RXC. The purpose of this paper is to clarify the irradiation effects on SPDAs by measuring the deterioration of the response and the I–V characteristics. Section II describes the experiment in terms of the detectors, parameters of the neutron experiment, and parameter measurement methods. In Sec. III, the irradiation effects on the response and I–V characteristic of SPDAs are analyzed. The deterioration of the response is investigated by the following methods: (1) monitoring the signal of SPDAs during the irradiation experiment, (2) comparing the signals of irradiated and non-irradiated SPDAs in an Experimental Advanced Superconducting Tokamak (EAST) experiment, and (3) calibrating irradiated and non-irradiated SPDAs using synchrotron radiation. Section IV presents our conclusions from this study regarding the irradiation effects on SPDAs and discusses their application in ITER.

II. EXPERIMENTAL DETAILS

A. Detector

The SPDA tested in this study is PN photodiode produced with *n*-type silicon. Each array consists of 35 elements. The active area of each element measures $12 \times 2\,\mathrm{mm}^2$, which is half the size of the ITER version ($12 \times 4\,\mathrm{mm}^2$, with the same manufacturing process). The recommended operating voltage of these detectors is 0–12 V. According to test results supplied by the manufacturer, the reversed dark current of the SPDA is almost always less than 10 nA at 12 V. In the forward voltage region, the forward current is 10 mA when the forward voltage is about 0.77 V.

B. Irradiation experiment

The neutron irradiation experiment for testing the radiation hardness of electronic components of the RXC[14] was carried out at a uranium–zirconium hydride pulsed reactor.[15,16] This reactor has two types of operation modes: steady-state and pulse modes. The irradiation experiment was completed under the 100-kW steady-state mode. Considering the stability of the reactor power during the experiment, the intensity of irradiation could be regarded as steady. The whole experiment lasted ~282 min. According to the neutron spectrum of the reactor,[17] the total equivalent 1 MeV neutron fluence with energy above 0.01 MeV was approximately $9.89 \times 10^{13}\,\mathrm{n\,cm^{-2}}$, corresponding to a neutron flux of $5.84 \times 10^{9}\,\mathrm{n\,cm^{-2}\,s^{-1}}$. The ratio of neutron fluence to gamma dose was $7.7 \times 10^{11}\,\mathrm{n\,cm^{-2}\,Gy^{-1}}$. Thus, the total gamma dose was about 128 Gy. Compared with an experiment performed in the KAMINI nuclear reactor,[13] the gamma dose per unit time in our experiment was orders of magnitude less under the same total neutron fluence. Because the irradiation damage from gamma rays is negligible when compared with that of neutrons,[13] the contribution from gamma rays was neglected in the data analysis.

Two SPDAs, two pre-amplifiers (PAs), and two mid-amplifiers (MAs) were fixed on a customized PXIE chassis[14] and placed in the irradiation chamber of the reactor.[18] There were four experimental groups, as shown in Fig. 1. The two SPDAs in groups 1 and 4 were termed XD1 and XD2, respectively. Group 1 simulated the performance of an x-ray camera system in a nuclear irradiation environment. Group 4 was used to monitor the performance change of the SPDA during the experiment. Considering the radiation hardness of the light source, we used a tungsten lamp[19] as the light source of the detectors. The main output wavelength of this lamp is in the infrared and red regions.[20] The tungsten lamp was powered by an independent 220-V AC source. The voltage of the lamp was regulated by a voltage transformer (VT). Four experimental groups shared one DC power supply. Their output signals were acquired by the same data acquisition system (DAQ). As the DAQ only contained one data acquisition card, we could only save the data from one group at a time. During the experiment, data from the four groups were acquired in turn at intervals of 1 min.

C. EAST experiment

To investigate the performance of irradiated SPDAs in a plasma experiment, the irradiated XD2 and a non-irradiated SPDA (XD3) were installed in the same stainless-steel barrel of EAST's equatorial port A. According to the principle of pinhole imaging and the installation position of the two detectors, these two SPDAs had similar observation regions, as shown in Fig. 2. In addition, they both worked at zero bias. There were 25-μm Be windows at the pinhole of each SPDA.

D. Calibration experiment of SPDAs

A calibration experiment for the SPDAs was carried out in the BL16B1 beamline of the Shanghai Synchrotron Radiation Facility. According to the specifications of BL16B1, its radiation energy range is 5–20 keV. The energy resolution is less than 1×10^{-3}.[21] The instability of the beam intensity is within 10%.[22] The beam intensity monitor before sampling is a gas ionization chamber. Its output current and corresponding photon flux are both shown in real time in the control room.

During the calibration experiment, the radiation energy range was limited to 7–13 keV due to the operation situation of the monochromator of BL16B1. The photon flux measured by the

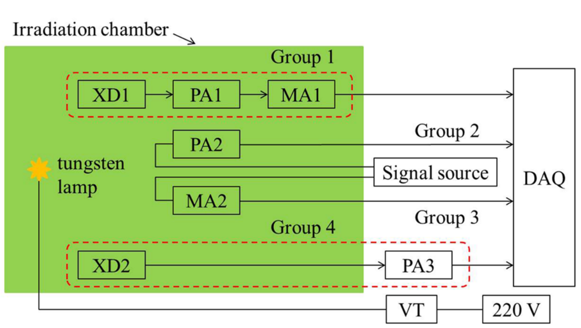

FIG. 1. Sketch of the experimental system.

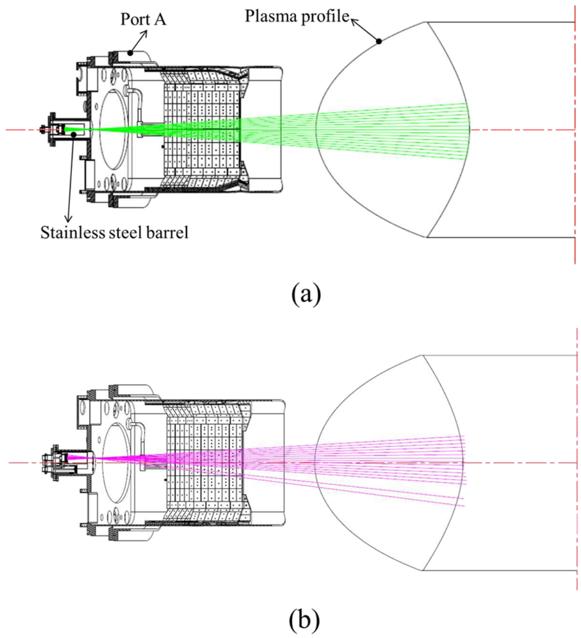

FIG. 2. Light paths of (a) XD3 and (b) XD2 in EAST.

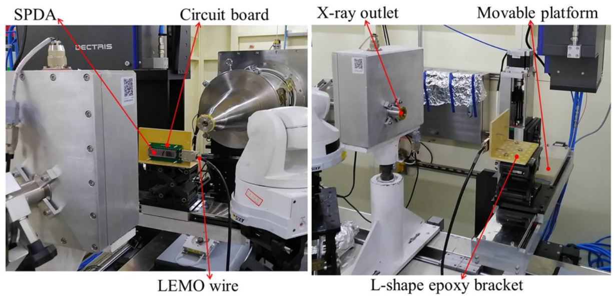

FIG. 3. Setup of the calibration experiment.

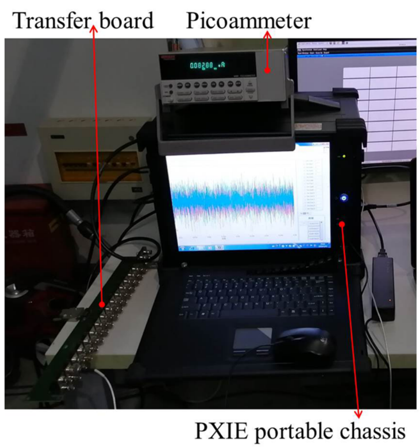

FIG. 4. DAQs of SPDAs.

ionization chamber is presented in Table I. The size of the beam spot was 0.5 × 0.5 mm^2. The tested detectors contained irradiated XD1 and a non-irradiated SPDA (XD4). Because of the limited duration of the experiment, for each 35-channel SPDA, 9–12 channels were randomly chosen and calibrated.

The SPDAs and their circuit boards were mounted on an L-shaped epoxy bracket and fixed to the movable platform of BL16B1, as shown in Fig. 3. The distance between the SPDAs and the x-ray outlet was about 0.3 m. The output signals of the SPDAs were transmitted to the DAQ using a 30-m LEMO wire. There were two DAQs, as shown in Fig. 4: (1) the transfer board and the Keithley 6485 picoammeter, and (2) a PXIE portable chassis containing the pre-amplifier and the data acquisition card. The gain of the pre-amplifier was set to 4 × 10^6 V/A. Due to its maximum output voltage of 10 V, the maximum input current was 2.5 μA. When the current of the SPDAs exceeded 2.5 μA, it was measured by the picoammeter. In the calibration experiment, only experimental results at 7 keV were obtained using the PXIE portable chassis.

TABLE I. Photon flux of x-ray with energy in the calibration experiment.

Energy (keV)	Photons flux (10^{11} photons/s)
7	1.82
8	1.96
10	1.90–2.04 (1.97)[a]
13	1.33

[a]1.97 is the mid-value of the photon flux at 10 keV. In the data analysis, this value was used as the photon flux at 10 keV.

E. I–V characteristic measurement

The I–V characteristics of the SPDAs were measured using Keithley 4200A-SCS parameter analyzer. To isolate impacts from their surroundings, the SPDAs were placed in a dark metal box during the measurements. The forward I–V characteristics of the non-irradiated SPDAs were measured from 0 to 1 V with a step size of 20 mV. For the irradiated SPDAs, because of the upper limit of current and the present research needs, the forward current was measured from 0 to 35 V with a step size of 0.5 V. For all SPDAs, the reversed dark current was measured from 0 to 12 V with step size of 0.2 V.

III. RESULTS AND DISCUSSION

A. Signal response during irradiation experiment

Considering the above experimental setup (Fig. 1), the signal from XD2 more precisely exhibits the trend of the SPDA response with neutron fluence. The experimental results show that the signals of different elements display the same trend. Without loss of generality, we now discuss the output signal of the ninth element of XD2, as shown in Fig. 5.

The output signal of the ninth element of the non-irradiated XD2 was 6.91 V when the tungsten lamp was operating at 33.62 V. Because there was an obvious signal fall in group 1 when the reactor's

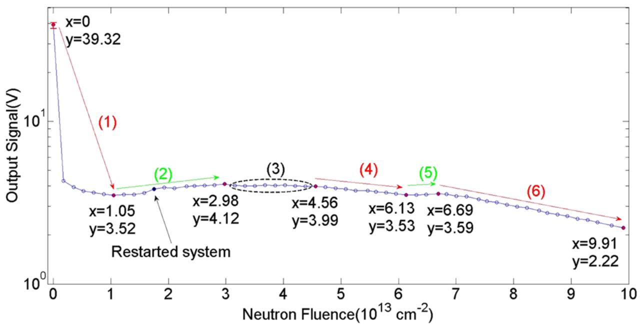

FIG. 5. Signal response of the ninth element of XD2 during the experiment.

TABLE II. Signal variation of each signal stage.

Stages	Original fluence (10^{13} n cm^{-2})	Final fluence (10^{13} n cm^{-2})	Signal variation (%)[a]
1	0	1.05	$\downarrow$91.0
2	1.05	2.98	$\uparrow$1.5
3	2.98	4.56	$\downarrow$0.3
4	4.56	6.13	$\downarrow$1.2
5	6.13	6.69	$\uparrow$0.2
6	6.69	9.91	$\downarrow$3.5

[a]Signal variation = [signal (large) − signal (small)]/39.32.

power was rising, we adjusted the voltage of the lamp from 33.62 to 49.7 V for signal observation. In other words, except for the first point, all points in Fig. 5 were directly measured under a 49.7-V lamp. The change in the luminance of the lamp due to the working voltage was measured with XD4 in the lab. Because the output current of the non-irradiated SPDA was beyond the maximum input current of the pre-amplifier when the tungsten lamp was operating at 49.7 V, we covered the upper and lower halves of the sensitive area of XD4 during the measurement. The measurement results show that the increase in the output signal due to the change in the lamp's voltage was basically independent of the covered area. The output signal of XD4 under the 49.7-V lamp is about 5.37–5.85 times that of the 33.62-V lamp, with an average multiple of 5.69. Thus, the output signal of the non-irradiated XD2 was estimated for 37.11–40.42 V, and its average value was found to be 39.32 V when the lamp was operating at 49.7 V, as shown in Fig. 5. There is a relatively slow decrease after the initial sharp drop until the neutron fluence reaches 1.05×10^{13} n cm^{-2}. In this stage, the signal decreases from 39.32 to 3.52 V.

In stage 2, from 1.05×10^{13} to 2.98×10^{13} n cm^{-2}, the signal rises from 3.52 to 4.12 V. Note that, when the neutron fluence was 2.76×10^{13} n cm^{-2} (we were recording the signal of group 3 at this time), the DC power supply was restarted because of the signal saturation of MA2.

In stage 3, from 2.98×10^{13} to 4.56×10^{13} n cm^{-2}, the signal is basically steady. In stage 4, from 4.56×10^{13} to 6.31×10^{13} n cm^{-2}, the signal decreases from 3.99 to 3.53 V. In stage 5, however, there is a tiny increase in the signal (from 3.53 to 3.59 V) when the neutron fluence increases from 6.31×10^{13} to 6.69×10^{13} n cm^{-2}. In stage 6, when the neutron fluence is above 6.69×10^{13} n cm^{-2}, there is an obvious and continuous drop. At the end of the experiment, the output voltage was about 2.22 V. The signal variation in each stage with respect to the original signal of 39.32 V is listed in Table II. The final signal is about 5.6% of the original signal.

The trend of the output signal of the SPDAs with respect to the neutron fluence is similar to the nonlinear response behavior found by Kohagura *et al.*[8] Such a nonlinear response can be interpreted in terms of the change of the thickness of the depletion layer (d_{dep}) and the diffusion length of the charges (L). The basic structure of SPDA contains a p+ and an n-region. The depletion layer is mainly in the n-region. According to the theory developed by Cho *et al.*,[9,10] the SPDA signals might come from two parts: (1) charges created in the depletion layer and (2) diffusing charges from other regions that reach the depletion layer. These two parts are positive correlation with d_{dep} and L, respectively. It is possible that d_{dep} will increase due to the change of effective doping concentration caused by neutron irradiation. This would lead to a rising output signal. In contrast, neutron irradiation causes L to decrease by producing damage. This will lead to a decline in the response. These two effects combine to cause the nonlinear trend of the output signal. Because the main output wavelength of tungsten lamp is at infrared and red region, parts of its output radiation might be absorbed by the p+ region. Thus, the contribution from diffusion charges might be a main part of the signal. The obvious drop in L will cause a substantial degradation of the output signal.

According to the neutron analysis of the RXC, the neutron flux of an external camera might reach 8.4×10^8 n cm^{-2} s^{-1} in the ITER D-T phase. The total operating time of the D-T phase of ITER is 4700 h.[23] Thus, the neutron fluence of the external camera detectors is about 1.4×10^{16} n cm^{-2}. Considering the output energy spectrum of the tungsten lamp and the results of the irradiation experiment, the SPDAs will observe little visible light over the whole fusion operation phase.

B. Tests on EAST

Figure 6(a) shows shot 94 837, a typical sawtooth phenomenon in EAST. It can be seen from Fig. 6(b) that the sawtooth signal of XD2 is similar to that of XD3 in terms of the sawtooth cycle and shape. This implies that irradiated SPDAs can still be used to observe plasma radiation. The value of the signal from XD2 is 70%–80% of that from XD3. This ratio of signals of irradiated and non-irradiated SPDAs is obviously higher than that observed in the irradiation experiment. There are various possible reasons for this, such as the energy spectrum of the radiation source and the recovery effect of the detector. The 25-μm Be windows at the pinhole can shield the vast majority of radiation that has an energy of less than 0.8 keV. This means that the main energy of the input radiation in EAST is higher than that of the irradiation experiment. If the energy of most of radiation is not sufficiently high to pass through the depletion layer, most of the input radiation is absorbed in the depletion region of the SPDAs. Thus, the signal contribution from the depletion region might be the main part of the signal. If the post-irradiation d_{dep} is comparable with the pre-irradiation value, the response of the SPDAs will not be obviously degraded after neutron irradiation. Besides the decrease of L, charge loss in the depletion layer might

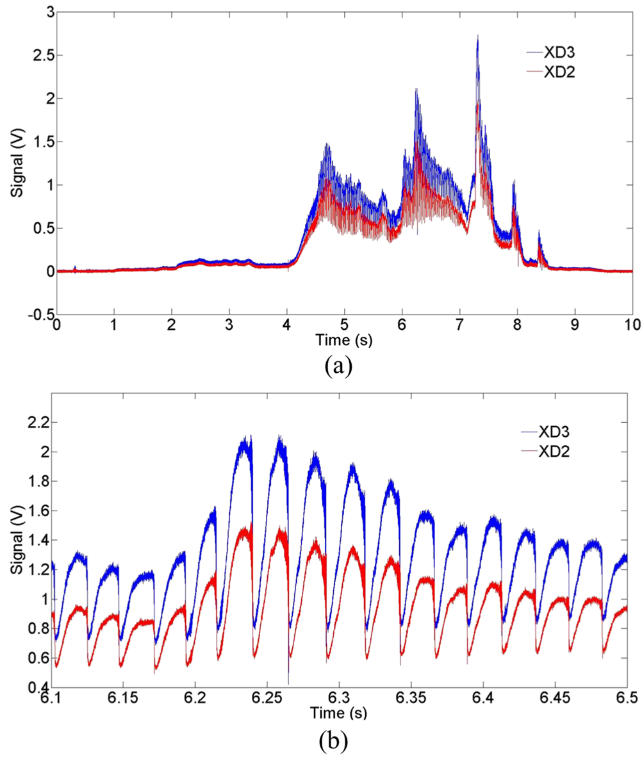

FIG. 6. (a) Signal from XD3 (blue) and XD2 (red) for shot 94 837; (b) shot 94 837 from 6.1 to 6.4 s.

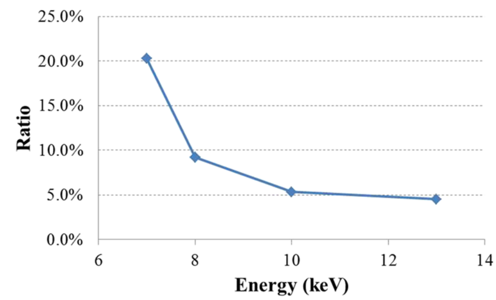

FIG. 7. Ratio of responsivity of XD1 and XD4.

also be a reason of the degradation of response. Defects created by irradiation might trap signal charges, and cause the decrease of signal.[3] Regarding the recovery effect, Kohagura *et al.*[8] showed that it is very weak if the detectors are kept at room temperature after irradiation. Thus, it can be inferred that XD2 did not experience any obvious recovery effect after the irradiation experiment. Test results from EAST indicate that SPDAs working at zero bias can still observe plasma radiation after being subjected to 9.89×10^{13} n cm^{-2} neutron fluence. However, the total neutron fluence of external camera detectors during the D-T phase (1.4×10^{16} n cm^{-2}) is about a 100 times that realized in the reactor irradiation experiment. It can be inferred that the SPDAs will become unusable at some point in the D-T phase. However, the data will still have considerable value to the ITER research program up to that point.

C. Responsivity of SPDAs

Because the absolute calibration of input power of SPDAs has not been finished, the calculation results of responsivity are not shown here. However, the stability of the intensity of synchrotron radiation means that the input power of radiation of different SPDAs are basically equal. Under this condition, according to the definition of responsivity, the ratio of output currents from radiated/non-radiated SPDAs is equal to the ratio of responsivity. With the average value of output current, the ratio of responsivity between XD1 and XD4 for various energy levels is shown in Fig. 7. As the energy increases, the responsivity ratio decreases from 20.3% to 4.5%. This indicates the obvious degradation of the responsivity of SPDAs due to neutron irradiation. Moreover, the degradation of the responsivity is related to energy. In the range 7–13 keV, an increase in energy allows more radiation to pass through the depletion layer and reach the substrate. Thus, the contribution from diffusion charges will increase. This will cause responsivity ratio of the SPDAs to decrease as the energy level increases.

D. I–V characteristics analysis

According to the theory of semiconductors,[24] the forward current of the ideal model of a diode and the forward voltage satisfies

$$I_F \propto \exp\left(\frac{qV}{nkT}\right),$$

where I_F is the total forward current, q is the electronic charge, k is the Boltzmann constant, T is the temperature, and n is the ideality factor, which is equal to 1 for the ideal diode. By fitting the experimental results to this expression (Fig. 8), we find that the forward I–V characteristics of XD3 under low forward voltages (≤0.4 V) satisfy the ideal model of a diode. This indicates that non-irradiated SPDAs can be seen as ideal semiconductor diodes. In addition, the consistency of the I–V characteristics of different elements of XD3 implies that they have similar performance. Taking account of SPDAs working at zero or reversed bias on ITER, the I–V characteristics at high forward voltages (>0.4 V) are not discussed in this paper.

By comparison, it is found that neutron irradiation causes an obvious change in the forward I–V characteristics of SPDAs, as shown in Fig. 9. When the forward voltage is greater than 0.5 V, the forward current of the non-irradiated SPDA is obviously greater than that of the irradiated SPDA. The forward conduction voltage (V_{fc}) is defined as the voltage when the forward current is equal to 10 mA. The V_{fc} of XD3 is about 0.77 V, equal to the measurement result given by the manufacturer. However, the V_{fc} of irradiated SPDAs is around 30 V. Considering the increasing rate of forward current per volt, the forward conductivity of SPDAs substantially decreases following irradiation. One possible reason is that defects caused by irradiation appear near the center of the band gap.[12] These defects act as traps, which will decrease the lifetime of the charge carriers.[13]

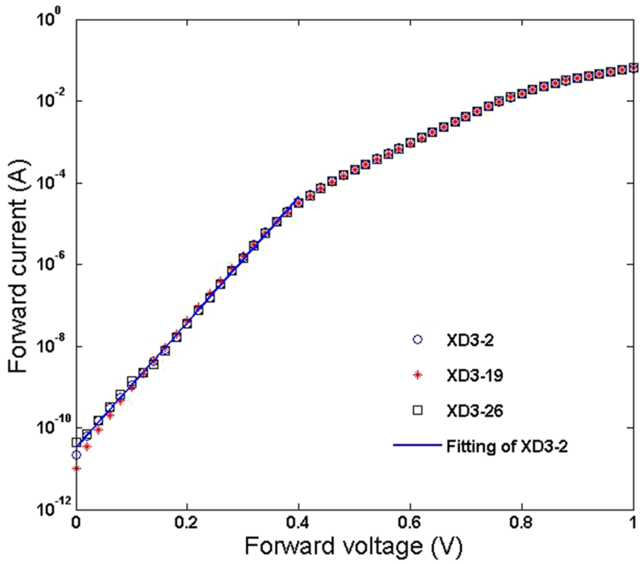

FIG. 8. Fitting of forward current of XD3.

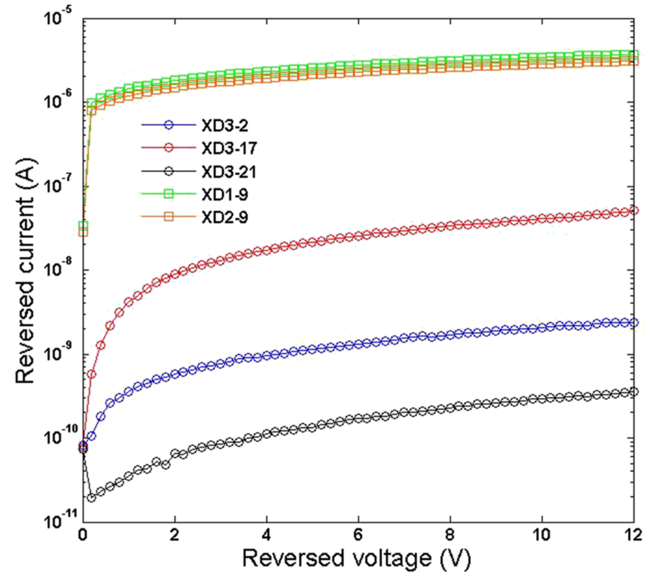

FIG. 10. Reversed current of XD1, XD2, and XD3.

Although the reversed dark current has a different magnitude in each element of XD3, as shown in Fig. 10, the level is generally from 0.1 to 10 nA. However, the reversed dark current of the irradiated SPDAs are obviously larger than in XD3, reaching a level of around 1 μA. This represents an increase of around three orders of magnitude. According to the theory of semiconductors,[24] the generation current (I_{gen}) of an abrupt junction is proportional to the square root of the voltage:

$$I_{gen} \propto (V_{bi} + V)^{1/2},$$

where V denotes the reversed voltage and V_{bi} is the built-in voltage. The fitting curve matches the measurement results, as shown in Fig. 11. This indicates that the generation current is the main part of the reversed dark current of irradiated SPDAs. Defects created by

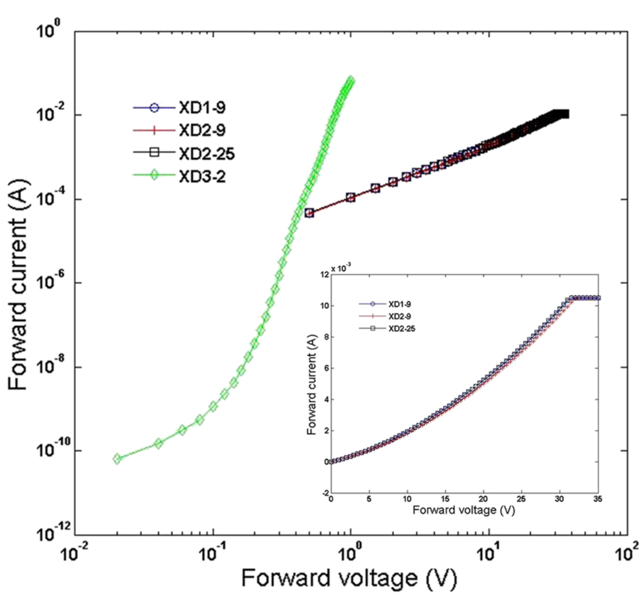

FIG. 9. Forward current of XD1, XD2, and XD3.

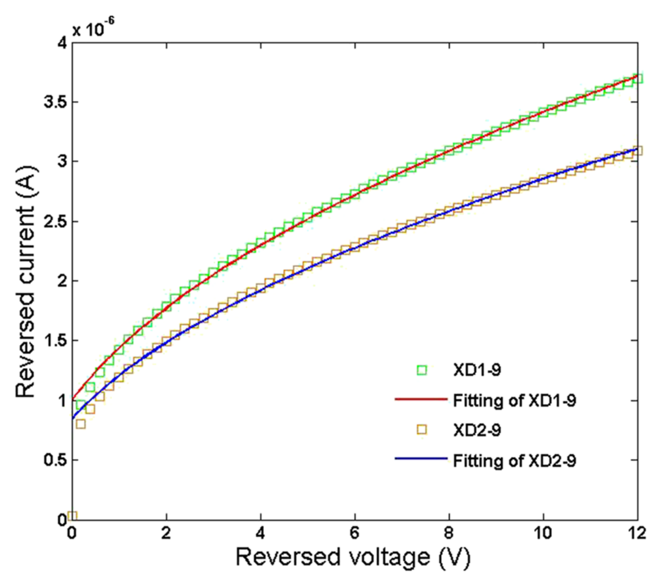

FIG. 11. Fitting of reversed current of irradiated array.

neutrons act as generation–recombination centers,[3,13] leading to an increase in the reversed dark current through emitting carriers. This explains the increased reversed dark current and why the generation current is dominant after irradiation.

The dark current of an SPDA is also a constituent of the input current of the pre-amplifier. It will create a nonzero baseline in the output signal of the RXC system. Changes in the dark current will cause variations to the baseline, which will affect the analysis of the signal. Thus, the dark current should be as small as possible in actual applications. The gain of the ITER pre-amplifier is 1×10^6 V/A, and its maximum output voltage is 10 V. This means that the pre-amplifier will become saturated when the detector's output current exceeds 10 μA. Thus, keeping a small dark current is conducive to observing strong plasma radiation. It requires the SPDAs to work at zero or low bias. However, adding a reversed bias can improve the SPDA's response, partly making up for the deterioration in the response due to irradiation. Considering the voltage of one lithium battery (1.5 V) and the magnitude of the reversed dark current of irradiated SPDAs (Fig. 11), adding a 1.5-V reversed bias will cause a 1-μA-level dark current, which might create a nonnegligible nonzero baseline. Test results on EAST have proved that irradiated SPDAs running at zero bias can be used to observe plasma radiation. Therefore, zero bias may be a better working condition for irradiated SPDAs.

IV. CONCLUSION

To investigate irradiation effects on silicon photodiode arrays (SPDAs), we have examined the response and I–V characteristics of irradiated and non-irradiated samples. The output signal of the irradiated SPDA (XD2) shows a nonlinear trend during the irradiation experiment. After being subjected to $9.89 \times 10^{13}\,\mathrm{n\,cm^{-2}}$ neutrons, the signal is about 5.6% of the original one in the visible light region. Considering the total neutron fluence of external camera detectors in the D-T phase ($1.4 \times 10^{16}\,\mathrm{n\,cm^{-2}}$), SPDAs can observe little visible light over the whole operating stage. However, tests on EAST show that the XD2 signal is 70%–80% of that from a non-irradiated SPDA (XD3). This indicates that SPDAs working at zero bias can still observe plasma radiation after being subjected to $9.89 \times 10^{13}\,\mathrm{n\,cm^{-2}}$ neutron fluence. However, the total neutron fluence of external camera detectors during the D-T phase is about a 100 times that realized in the reactor irradiation experiment. Thus, it can be inferred that SPDAs will become unusable at some point in the D-T phase. A calibration experiment has shown that the responsivity ratio of irradiated and non-irradiated SPDAs is about 4%–20% over the energy range 7–13 keV. The degradation of responsivity is related to the energy level. According to the above results, to satisfy the detector requirements for the RXC over the whole fusion operation phase, the irradiation hardness of SPDAs must be improved or advanced detectors should be developed.

After irradiation, the forward conductivity of SPDAs decreases significantly. In addition, the reversed dark current increases by around three orders of magnitude, from 0.1 to 10 nA to a level of 1 μA. Therefore, adding a reversed bias will create a non-negligible nonzero baseline. In terms of tests of XD2 on EAST, irradiated SPDAs should operate at zero bias.

ACKNOWLEDGMENTS

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DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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