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ELONGATION OF LED LIGHTING LIFETIME UNDER X-RAY DOMINANT RADIATION ENVIRONMENT

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Abstract

Recently incandescent and fluorescent light have been replaced by light-emitting diodes (LEDs), which offer superior electricity-to-light conversion efficiency. In accelerator facilities, too, the time has come to replace conventional lighting with LEDs and other high-efficiency, green lighting. In order to promote the replacement of lighting in an accelerator tunnel, we investigated the process of the radiation damage for commercially available LED lightings in an X-ray radiation environment such as in the electron storage ring SPring-8. It was found that metal-oxide-semiconductor field-effect transistors (MOSFETs) to be supply power for the LED lighting were damaged by X-ray irradiation with the total dose effect greater than several hundred Gy (air kerma). In situ measurements of the MOSFET under an irradiation by an X-ray tube clearly showed a sudden increase of the current accompanying with a sharp increase of MOSFET temperature as a function of radiation dose, which eventually caused the device failure. This presentation shows two effective countermeasures for the longer lifetime of LED and application examples.

INTRODUCTION

Recently the lighting environments is increasingly replacing incandescent and fluorescent bulbs with light-emitting diodes (LEDs), which offer superior electricity-to-light conversion efficiency and also mercury-free. In accelerator facilities, the time has come to replace conventional lighting with LEDs and other high-efficiency, green lighting.

The large synchrotron radiation facility SPring-8 in Japan has been used to generate highly brilliant X-rays for a variety of research since 1997 [1]. An electron beam with an energy of 8 GeV and a beam current of 100 mA is stored in a storage ring with a circumference of 1436 m. Fluorescent lamps have been used in the ring tunnel for more than 20 years. Although some of them were replaced with LED lightings on a trial basis in 2019, they stopped working after a few months. In order to promote the replacement of lighting in an accelerator tunnel we started an investigation of the radiation damage process for commercially available LED lightings in an X-ray radiation environment such as in the SPring-8. It was found that metal-oxide-semiconductor field-effect transistors (MOSFETs) to be supply power for the LED lighting were damaged by X-ray irradiation with the total dose effect greater than several hundred Gy (air kerma). In the storage ring tunnel, not only scattered X-rays but also neutrons and high-energy gamma-rays are produced due to the beam loss of high-energy electrons. Table 1 shows dose levels of X-rays and neutrons at several place of the SPring-8 tunnel. It is clearly showed the neutron generated by beam loss of electrons is well controlled to a sufficiently low-level during user operations, and hence scattered low-energy X-rays from filter or absorber dominate the radiation dose.

Because the power supplies that drive the LEDs were burned out under these conditions, the LED lightings were thought to have been damaged by the effect of the total ionizing dose [2] of scattered X-rays originating from synchrotron radiation. At SPring-8 and other SR facilities, low energy X-ray radiation below 100 keV is the dominant radiation source in the accelerator tunnels. In such a circumstance, the total dose effect dominates the degradation mechanism.

In this paper, we first evaluated the damage dose of LED lightings by observing the radiation damage in the SPring-8 tunnel. MOSFET in the power supply was clearly damaged by irradiation at total doses greater than several hundred Gy (air kerma), while the LED itself had relatively higher radiation resistance except for radiation-induced discoloration. The next step, we visualized the damage process by performing in-situ observation of MOSFET properties under X-ray irradiation by an X-ray tube. The leakage current of the MOSFET was found to increase exponentially with total dose, and once the current exceeded the safe operating area of the MOSFET, the device was destroyed.

Table 1: The dose levels (mSv) of X-rays and neutrons at several place of the SPring-8 tunnel with 840 hours operation. A character of each beam line (BL) is 04B2 as a bending, 05XU and 09XU as a undulator with hard X-ray, 07LSU as a soft X-ray and 08W as a wiggler.

Place	X-ray	Thermal Neutron	Fast Neutron
Injection septum	10000 <	0.2	3.9
RF-Station	10000 <	0.1 >	0.2 >
BL04B2	10000 <	0.1 >	0.2 >
BL05XU	10000 <	0.1 >	0.2 >
BL07LSU	10000 <	0.1 >	0.7
BL08W	10000 <	0.1 >	0.2 >

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RADIATION DAMAGE MEASUREMENTS OF LED LIGHTINGS AT SPRING-8

To examine which part of the LED lightings was damaged. We prepared several sets of LED lightings with power supplies separated from the LEDs. We placed them in a high dose area of the SPring-8 storage ring tunnel, and measure the radiation dose at same time. We examined the failure depending on the setup conditions. The measurements were performed around the BL08W wiggler radiation beamline because the dose rate near its components was measured to be higher than elsewhere.

LED damage measurements were performed using various combinations of shielding of the power supply and LED, as shown in Table 2. The LED lightings used

- Type A: ERG5393SA and RX394N (ENDO Lighting Corporation)
- Type B: NNY24814 and NNY28125 LE9 (Panasonic Corporation)
- Type C: PA00007PS (Panasonic Corporation)
- Type D: NTN81341 and NTN81993 LI9 (Panasonic Corporation)

Power supplies were installed in two locations: one near the LED inside the tunnel, and the other outside the tunnel. These LED lightings were irradiated during SPring-8 user operation times and were monitored by camera to record when the LEDs failed. The radiation dose of failure was evaluated from the dose measurement results using the GAFCHROMIC Film HD-V2. This result shows the power supplies of the LED lightings are damaged with a threshold of several hundred Gy (air kerma). The LED itself and plastic lens attached to the LED are not obviously damaged up to a total dose of 6000 Gy. The total dose corresponds to that for 10 years of user operations at positions where lightings are typically placed at SPring-8. The failure of an LED lighting can thus be prevented by placing a separate power supply outside the storage ring tunnel.

INVESTIGATION OF THE PROCESS OF RADIATION DAMAGE TO MOSFETS BY USING AN X-RAY TUBE

To study the process of radiation damage of MOSFET in an LED power supply, we performed in-situ measurement of a MOSFET mounted on an LED power supply circuit board under X-ray irradiation by an X-ray tube. Figure 1 shows the experimental setup. The X-ray source was an X-ray tube (Ultra18X, Rigaku) [3]. We measured the X-ray radiation dose rate on the target by using a GAFCHROMIC Film HD-V2. The critical requirements were homogeneous irradiation on a MOSFET and an appropriate dose rate of ~0.2 Gy/s (air kerma) to make the measurement time reasonable. Figure 2 shows the schematic circuit diagram of the LED driver evaluation board (MTO-EV001, Marutsuelec). This board is a simple flyback power supply composed of only one N-channel MOSFET (NMOS) (TK5A65D, Toshiba Corp.) [4] and a flyback LED controler (TC62D902FG, Toshiba Corp.) [5] We provided 100 V to the circuit board via a DC power supply instead of an AC voltage in order to stabilize the MOSFET drain source voltage and drain current for our measurements. We measured the drain, source, and gate voltages of the MOSFET as well as the MOSFET temperature.

Table 2: Results of radiation damage test of LED lightings with various combinations of type of LED lighting, power supply (P.S.) location, and shielding with total dose of more than 6000 Gy.

Type of LED lighting	P.S. shielding	LED shielding	Radiation dose of failure
Type A	None	None	199Gy
Type B	None	None	843Gy
Type B	None	1mm Pb	867Gy
Type C	1mm Pb	None	1680Gy
Type A	Outside	None	No failure
Type A	Outside	1mm Pb	No failure
Type B	Outside	None	No failure
Type B	Outside	1mm Pb	No failure
Type D	Outside	1mm Pb	No failure

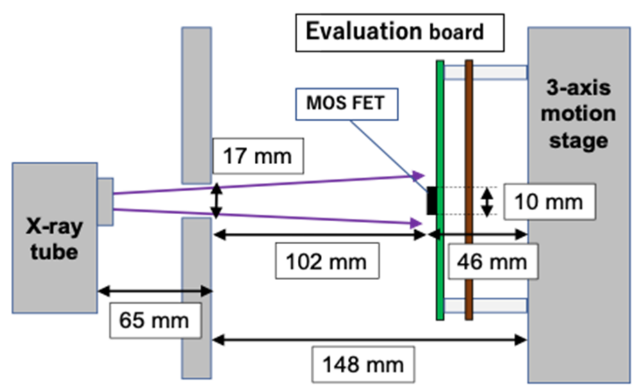

Figure 1: Experimental setup of in-situ measurement of the radiation damage of LED power supply board.

Figure 3(a) shows the turn-off leakage current (VG = 0 V) as a function of the total dose to the MOSFET. The LED driver circuit was kept on during irradiation by the X-ray tube. The drain current was recorded continuously during the in-situ measurements as red circles. The current started to exponentially increase above 500 Gy and increased sharply above roughly 700 Gy. As seen in Fig. 3(c), a clear increase of the turn-off leakage occurs during stage (iii). The leakage current measured by the high-resolution setup are shown in Fig. 3(a) as solid green diamonds, and agreed well with that measured by the in-situ measurement more than 500 Gy dose.

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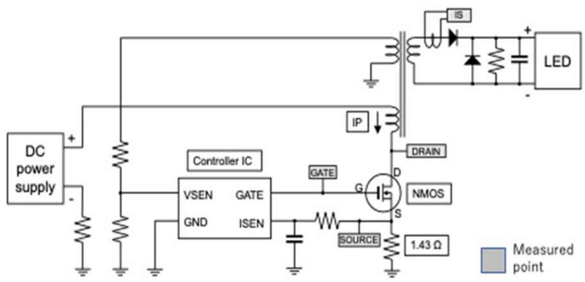

Figure 2: Schematic circuit diagram of the flyback LED driver evaluation board.

The solid blue squares in Fig. 3(a) show the temperature of the MOSFET. The temperature gradually in-creased as a function of dose during stage (ii). When the total dose reached around 700 Gy (air kerma), the current and temperature increase sharply (stage (iii)), and finally the MOSFET was destroyed in a short period. This indicates that the sharp increase of current was caused by breakdown the MOSFET in which temperature increase causes a decrease the gate threshold voltage of the MOSFET, resulting in a further increase of the current. We expected that the increase the current was caused by the accumulation of holes near the Si/SiO2 interface by applying voltage to the MOSFET. The detail of discussion is described a reference [6].

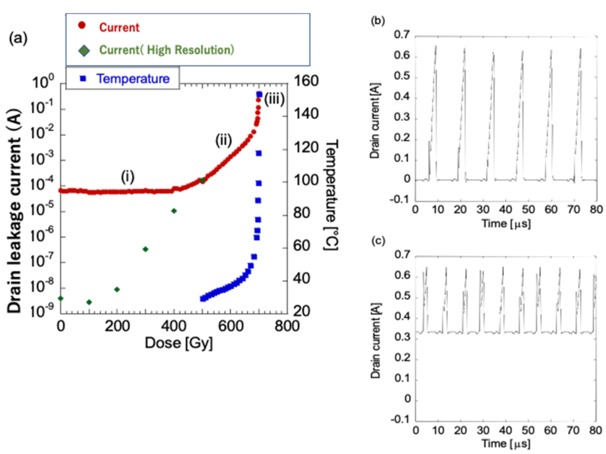

Figure 3: (a) leakage current (red circles and green diamonds) and temperature of the MOSFET (blue squares) as a function of dose (air kerma). (b) Typical waveform of IDSS during stage (ii). (c) Typical waveform of IDSS during stage (iii).

We measured the current with power off at each 200 Gy increment in dose until the total dose reached 800 Gy, as shown by the solid blue squares in Fig. 4. We found that the increase current was slow compared with power on, as represented by the red circles and green diamonds in Fig. 3(a). The measurements were repeated for each 400 Gy increment in dose until the total dose until 2000 Gy, and at 3000, 4000, and 6000 Gy. Although the leakage current increased as a function of dose. The increase rate was clearly suppressed compared with the case of power on.

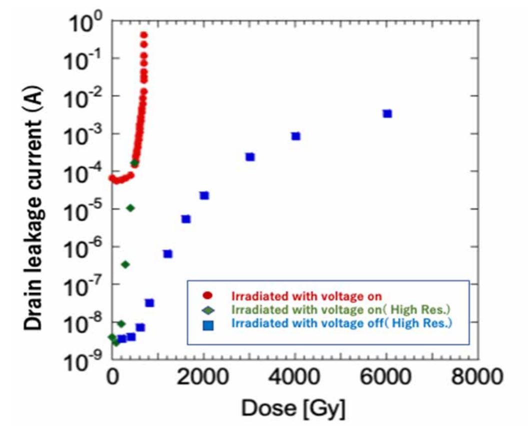

Figure 4: The leakage current as a function of cumulative dose (air kerma) when MOSFET is voltage on (red circles and green diamonds) and voltage off (blue squares).

This is interpreted as follows; accumulation of holes near the gate due to radiation is caused by the voltage between source and drain, which is unlikely to occur when the power supply is turned off. This result suggests that it may be effective for elongating the lifetime of LED lightings to minimize the net time that LED lightings are turned on during irradiation. The leakage current increased as a function of dose.

CONCLUSION

We evaluate the LED lightings radiation damage process at SPring-8 tunnel and X-ray irradiation by an X-ray tube. It shows enabled to use an inexpensive commercial LED lighting at the large synchrotron radiation facility. The radiation damage to the MOSFET is dramatically suppressed by switching off the LED power supply in the X-ray radiation environment, and the LED lightings can be used even after the total dose of 6000 Gy (air kerma). A separate power supply outside the storage ring tunnel is also useful for preventing the failure of LED lightings.

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