NUCL SCI TECH (2017) 28:31
DOI 10.1007/s41365-017-0189-8

# Effects of electron radiation on commercial power MOSFET with buck converter application

**Sheik Fareed Ookar Abubakkar[1] · Nor Farahidah Zabah[1] · Yusof Abdullah[2] · Dhiyauddin Ahmad Fauzi[1] · Norasmahan Muridan[1] · Nurul Fadzlin Hasbullah[1]**

Received: 18 February 2016 / Revised: 30 July 2016 / Accepted: 12 August 2016 / Published online: 31 January 2017


**Abstract** Microelectronic power converters such as buck and boost converter are required to be tolerant to radiations including electron radiation. This paper examines electron radiation effects on the *I–V* characteristics of VDMOSFET and its corresponding effects in buck converter. Analysis of the electrical characteristics shows that after irradiation the threshold voltage and drain current for all VDMOSFETs degraded more than two orders of magnitude. The impact of this electrical degradation has been investigated in an application of typical buck converter circuit. The buck converter with n-channel switching transistor shows that after irradiation its output voltage increased with the drain current in the n-channel ZVN4424A VDMOSFET, while the buck converter with p-channel switching transistor shows its output voltage decreased with the drain current in the p-channel ZVP4424A VDMOSFET after irradiation.

**Keywords** VDMOSFET · *I–V* characteristics · Drain current · Buck converter · Electron radiation

The work is funded by International Islamic University Malaysia (No. EDW B14-159-1044).

✉ Sheik Fareed Ookar Abubakkar
fareedcahcet12@gmail.com

[1] Department of Electrical and Computer Engineering, International Islamic University, Kuala Lumpur 53100, Malaysia

[2] Industrial Technology Division, Agency Nuclear Malaysia, Kuala Lumpur 43000, Malaysia

## 1 Introduction

The commercial diodes and transistors such as BJT (bipolar junction transistor) and VDMOSFET (vertical double diffused power MOSFET) have attracted considerable interest in the satellite and power converter applications due to its low drive requirement, low 'on' resistance and high frequency of operations [1–3]. Most of the recent works in these fields focus on the study of radiation-induced single-event response, single-event burnout and single-event gate rupture as to provide a better understanding on the device radiation resistance with respect to the single-ion striking at a sensitive node [4]. Although significant improvements have been observed in the performance of the VDMOSFET in recent years, some other factors such as switching speed of the VDMOSFET have not been widely reported. Previously, there were several works associated with the investigation of total ionizing dose effects on the VDMOSFET [5] utilized as the switching transistor in the microelectronics power converters. In this paper, we present the electrical performance degradation of the individual VDMOSFET components that are used in power converter circuit. For n-channel VDMOSFET, the induced damage can be manifested as positive charges trapped in the oxide layer, while in the p-channel, the defects can be either in the physical damaged region or scattering centers [6, 7]. As a result of these defects, the switching performance of the VDMOSFET changes with the amount of charges inside the non-isolated gate oxide layer [8, 9]. To study the impact of electrical characteristics degradation, the VDMOSFET performance is assessed by utilizing it in a buck converter circuit at different switching frequencies [10]. The *I–V* characteristics of the VDMOSFET before and after radiation, and the buck converter response after the VDMOSFET being irradiated, are discussed in details.

## 2 Experimental details

Commercial VDMOSFET from Diode Inc consisting of n-channel (ZVN4424A) and p-channel (ZVP4424A), with voltage rating of 20–200 V, was chosen for investigation. Electrical characterization of all devices before and after irradiation was carried out using Keithley measurement system 4200 in the Electronics Laboratory at International Islamic University Malaysia. The electrical characteristics of the n-channel ZVN4424A and p-channel ZVP4424A were done on three devices to check for repeatability. The selected VDMOSFETs were irradiated to 50, 100 and 200 kGy with 3 MeV electron beams from the Alutron accelerator at Agency Nuclear Malaysia. In the irradiation, all the test components were placed in a metallic tray for proper exposure, and all devices were made electrically floating. For each n-type and p-type VDMOSFET, eight devices from the same model were measured for each dose. All the irradiated devices were then used as switching transistors in the 10 V input and 5.5 V output voltage DC/DC buck converter.

## 3 Results and discussion

### 3.1 *I–V* characteristics

Room temperature subthreshold *I–V* characteristics of the n-channel ZVN4424A and the p-channel ZVP4424A irradiated to 0, 50, 100 and 200 kGy are shown in Fig. 1. It is observed that the threshold voltage of the devices, $V_{th}$, shifted as a function of radiation dose for all devices. Before irradiation, the threshold voltage was $V_{th} = -1.5$ V for the p-channel ZVP4424A and $V_{th} = 1.7$ V for the n-channel ZVN4424A, while after 50, 100 and 200 kGy irradiation, the threshold voltages decreased by $8 \pm 3$ V, $10 \pm 5$ V, $13 \pm 6$ V in ZVP4424A and by $2 \pm 1$ V, $4 \pm 1$ V, $7 \pm 1$ V in ZVN4424A, respectively.

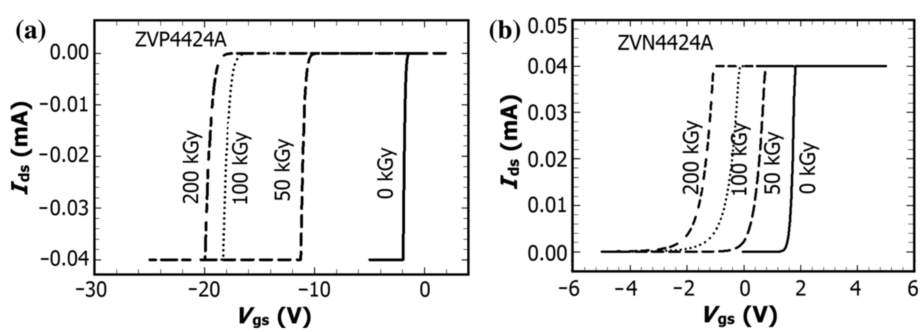


**Fig. 1** Subthreshold *I–V* characteristics of **a** ZVP4424A and **b** ZVN4424A before and after electron irradiation

The threshold voltage shifts in the p-channel is due to radiation induce positive charges in the interface traps [8]. As more negative voltage is applied to the gate of a pmos device, the interface traps move below the Fermi level and act as donors [11]. When this negative gate-source voltage increases, the donor interface traps contribute more positive charges for channel conduction. Therefore, the threshold voltage becomes more negative in the p-channel VDMOSFET.

As for the n-channel VDMOSFETs, the threshold voltage becomes negative as a result of radiation-induced positive charges dominated in the oxide traps [12]. Charges in the traps forced the device to turn on at negative bias when the electric field direction changes from the silicon substrate to the insulator.

Figure 2 shows the threshold voltage shift ($\Delta V_{th}$) for the n-channel and p-channel devices irradiated to 50, 100 and 200 kGy. The square and circular bars indicate the n-channel and p-channel VDMOSFET threshold voltage shifts, respectively. Each data point represents the average $\Delta V_{th}$, while the error bars indicate the standard deviations. It can be seen that the threshold voltage shifts in the p-channel VDMOSFET are larger than that of the n-channel VDMOSFET [13]. As Ristic et al. discussed in Ref. [14], this is due to the hot-carrier injection by negative electric field in the p-channel VDMOSFET. The hot-carrier injection affects the threshold voltage through the

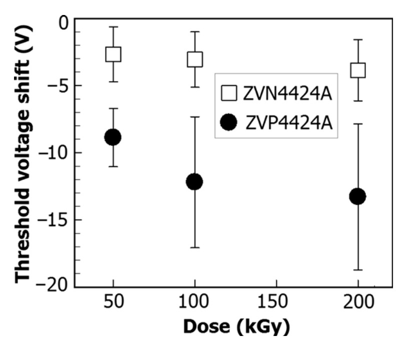


**Fig. 2** $\Delta V_{th}$ of ZVN4424A and ZVP4424A irradiated to 50, 100 and 200 kGy. *Error bars* indicate standard deviations of the threshold voltages

tunneling process of hot electrons from the gate/substrate into the oxide. Hot electrons accelerate by the negative electric field and produce more electron–hole pairs in the oxide. These cause a large decrease in threshold voltage of pMOS devices.

Another important factor is the drain current degradation, as this affects the switching characteristics [15]. Figure 3 shows the drain current characteristics of p-channel and n-channel VDMOSFET before and after EB irradiation. At drain-source voltage of −3 V, the drain current decreased by 0.047, 0.048 and 0.050 µA for 50, 100 and 200 kGy irradiations, respectively. The 0.050 µA decrease at 200 kGy corresponds to two orders of magnitude decrease in the drain leakage current. This decrease is likely due to radiation-induced oxide damage [16] also known as the formation of physically damaged region (PDR). When these defects localized in the interface of the p-channel VDMOSFET, it decreases the drain leakage current by formation of scattering centers that reduces the carrier mobility [6]. Unlike the p-channel VDMOSFET, the drain leakage current of the n-channel is found to increase by five orders of magnitude for all dose levels. As Cester et al. pointed out, [17, 18] this may be due to accumulation of positive charges in the oxide layer of the n-channel VDMOSFET. The positive charges induce current through recombination process.

The drain current degradation in the n-channel and p-channel VDMOSFET is a consequence of negative threshold voltage shifts which forces the device to turn on earlier in the n-channel and delay the turn on in the p-channel VDMOSFET. The next part illustrates these effects of degradation in the buck converter.

### 3.2 Irradiated VDMOSFETs impact on buck converter

The degradation of threshold voltage affects the *I–V* characteristics and hence the switching behaviors of the VDMOSFET in power converter applications [15, 19]. A buck converter circuit with 10 V DC input and 5.5 V output shows degradation in its switching characteristics through radiation-induced threshold voltage shifts in VDMOSFET. The circuit of the buck converter is shown in Fig. 4. The switching speed is increased by varying signal generator output frequencies from 1 to 100 kHz, while a clamped inductive load is connected at the VDMOSFET drain to reduce power dissipation [20].

A buck converter circuit shown in Fig. 4 was simulated in pspice for the n-channel and p-channel switching transistors. The output voltage of the circuit was investigated for each model of the VDMOSFET before and after irradiation. The simulation of the resistors, capacitors and inductors was chosen to be implemented in the experimental setup. In the experimental analysis, the amount of output voltage degradation was measured by calculating the ratio of the output voltage. Figure 5a shows a plot of the experimental output voltage ratio of buck converter consisting of p-channel ZVP4424A before and after being irradiated to 50, 100 and 200 kGy. One sees that the ratio of output voltages decreases with increasing doses. This is due to the consequence of the drain current decrease in the VDMOSFET after irradiation as shown in Fig. 3a.

The output voltage of the p-channel buck converter decreases with the drain leakage current of the VDMOSFET. This implies that there is degradation of the power conversion in the buck converter. In addition to this, the output voltage ratio $V_{out\_after}/V_{out\_before}$ was investigated at frequencies of 1, 10 and 100 kHz, which were chosen based on its application in radiation harsh environments as

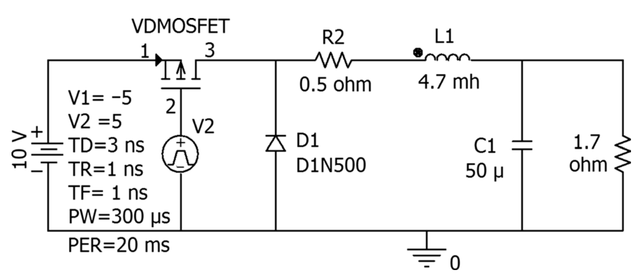


**Fig. 4** DC/DC buck converter circuit

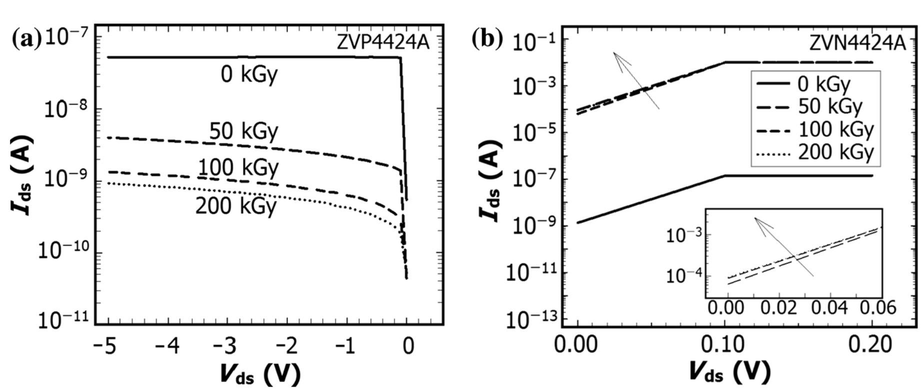


**Fig. 3** Drain current characteristics of **a** ZVP4424A and **b** ZVN4424A before and after EB irradiation. The *insect* shows the increase in drain current before saturation of ZVN4424A

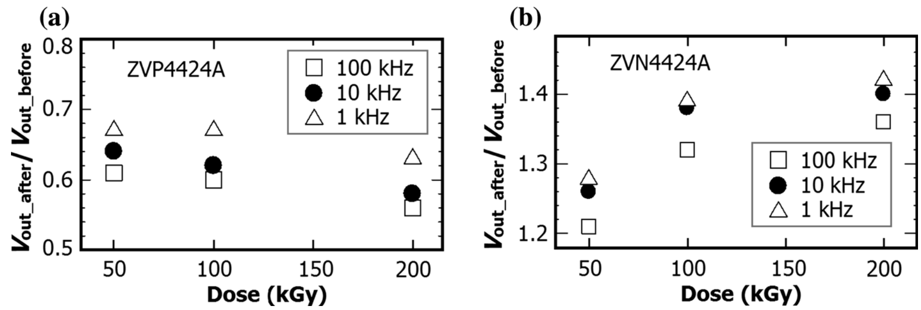


**Fig. 5** Ratio of output voltage of **a** ZVP4424A p-channel and **b** ZVN4424A n-channel buck converter

**Table 1** Summary of **a** ZVP44244A and **b** ZVN44244A buck converter output voltage response after irradiation

| Doses (kGy) | Frequency (kHz) | Output voltage (V) | | $V_{out\_after}/V_{out\_before}$ | |
|---|---|---|---|---|---|
| | | ZVP | ZVN | ZVP | ZVN |
| 50 | 1 | 1.3 | 6.3 | 0.26 | 1.26 |
| | 10 | 1.4 | 6.3 | 0.28 | 1.26 |
| | 100 | 1.7 | 6.4 | 0.34 | 1.28 |
| 100 | 1 | 1.2 | 6.9 | 0.24 | 1.38 |
| | 1 | 1.4 | 6.9 | 0.28 | 1.38 |
| | 100 | 1.6 | 6.6 | 0.32 | 1.32 |
| 200 | 1 | 1.2 | 7.1 | 0.24 | 1.42 |
| | 10 | 1.2 | 7.0 | 0.24 | 1.40 |
| | 100 | 1.5 | 6.8 | 0.30 | 1.36 |

shown in previous work [21]. The $V_{out\_after}/V_{out\_before}$ ratio decreased with the initial output voltage before irradiation. Table 1 summarizes the p-channel buck converter output voltage at 50, 100 and 200 kGy with respect to switching frequencies.

From Table 1, the $V_{out\_after}/V_{out\_before}$ ratio increases with the frequency for all dose levels. The output voltage ratio calculation shows that when the frequencies increase the output voltage comes closer to the desired value. It is believed that this is due to the increase in drain current through charge pumping for larger frequencies [22]. When the current passes the inductive circuit, the output voltage increases by mutual inductance.

Figure 5b shows the $V_{out\_after}/V_{out\_before}$ ratio of buck converter consisting of ZVN4424A n-channel before and after being irradiated to 50, 100 and 200 kGy. Unlike the results of the p-channel circuit, the $V_{out\_after}/V_{out\_before}$ ratio of the n-channel irradiated buck converters increases with the irradiation dose. This is due to the VDMOSFET drain current increase after irradiation as shown in Fig. 3b. The buck converter output voltage increases with the drain leakage current which reduces the efficiency of the buck converter applications.

Also, the output voltage and $V_{out\_after}/V_{out\_before}$ of the n-channel VDMOSFET buck converter circuit were investigated at 1, 10 and 100 kHz. Table 1 also shows the summary of the n-channel buck converter output voltage response at 50, 100 and 200 kGy with respect to the switching frequencies. The output $V_{out\_after}/V_{out\_before}$ ratio increases with the frequency for all dose levels. It is found that when the frequency increases the output voltage is closer to the desired value. The power loss of the buck converter is calculated using the equation below:

**Table 2** Power loss (in μW) for the investigated buck converter

| Doses (kGy) | ZVN4424A | ZVP4424A |
|---|---|---|
| 0 | 3.2 | 4.5 |
| 50 | 3.9 | 1.5 |
| 100 | 4.2 | 1.9 |
| 200 | 4.4 | 2.4 |

$$P_{loss} = I_{out}^2 RDs_{(on)} V_{out} / V_{in}$$

As shown in Table 2, the power loss increases for the irradiated n-channel VDMOSFET, but reduces for the irradiated p-channel VDMOSFET. After weighing all the results, it is clear that the degradation of the output voltage in p-channel is worse than the magnitude of the power loss than the n-channel. However, for critical applications where power losses are important perhaps p-channel based buck converter circuit may be preferred.

## 4 Conclusion

The radiation response of the VDMOSFET and its corresponding effects on the buck converter output voltage were investigated with electron radiation dose level of 50, 100 and 200 kGy. The results shows that both the p-channel ZVP4424A and the n-channel ZVN4424A VDMOSFET's threshold voltage shifts to negative with increasing dose level. The buck converter consisting of ZVP4424A p-channel shows a decrease in the output voltage with increasing radiation dose. Consequently, the output voltage increased with increasing frequencies in the p-channel buck converter. This is believed to be due to the decreased of drain current leakage of the ZVP4424A. On the other hand, buck converter consisting of ZVN4424A n-channel shows an increase in the output voltage with increasing radiation dose. Thus, the output voltage decreased with increasing frequencies in the n-channel buck converter. This is believed to be due to the increase in drain current leakage of the ZVN4424A. These results conclude that the n-channel buck converter circuit shows less degradation in the output voltage ratio compared to the n-channel buck converter. Increase in frequency improves the output voltage ratio of both the n-channel and the p-channel buck converter.

## References


1. B.J. Baliga, *Modern Power Devices* (Wiley, New Jersy, 1987), pp. 404–452
2. M.M. Oo, N.K.B.A.M. Rashid, J.B.A. Karim et al., Electrical characterization of commercial NPN bipolar junction transistors under neutron and gamma irradiation. Nucl. Technol. Radiat. **29**, 46–52 (2014). doi:10.2298/NTRP1401046O
3. D.A. Fauzi, N.K.A. Md Rashid, M.R. Mohamed Zin et al., Neutron radiation effects on the electrical characteristics of InAs/GaAs quantum dot-in-a- well structures. IEEE Trans. Nucl. Sci. **62**, 3324–3329 (2015). doi:10.1109/TNS.2015.2478450
4. J.L. Titus, C.F. Wheatley, M. Allenspach et al., Influence of ion beam energy on SEGR failure thresholds of vertical power MOSFETs. IEEE Trans. Nucl. Sci. **43**, 2938–2943 (1996). doi:10.1109/23.556889
5. S.G. Cappello, C. Parlato, A. Rizzo et al., Gamma-ray irradiation tests of CMOS sensors used in imaging techniques. Nucl. Technol. Radiat. Prot. **29**, S14–S19 (2014). doi:10.2298/NTRP140SS14C
6. A. Cester, S. Gerardin, A. Paccagnella et al., Drain current decrease in MOSFETs after heavy ion irradiation. IEEE Trans. Nucl. Sci. **51**, 3150–3157 (2004). doi:10.1109/TNS.2004.839203
7. M.M. Pejović, S.M. Pejović, D. Stojanov et al., Sensitivity of RADFET for gamma and X-ray doses used in medicine. Nucl. Technol. Radiat. **29**, 179–185 (2014). doi:10.2298/NTRP1403179P
8. J.A. Felix, M.R. Shaneyfelt, P.E. Dodd et al., Radiation-induced off-state leakage current in commercial power MOSFETs. IEEE Trans. Nucl. Sci. **52**, 2378–2386 (2005). doi:10.1109/TNS.2005.860724
9. T.S. Kevkić, M.T. Odalović, D.M. Petković, A Stochstic model of gamma-ray induced oxide charge distribution and threshold voltage shift of MOS transistors. Nucl. Technol. Radiat. **27**, 33–39 (2012). doi:10.2298/NTRP1201033K
10. D.V. Boychenko, L.N. Kessarinkiy, A.Y. Nikiforov, Investigation of low dose rate effects in DC/DC converters. In 14th European Conference on Radiation and Its Effects on Components and System (RADECS), 2013, 1–3. Doi:10.1109/RADECS.2013.6937395
11. P.J. McWhorter, P.S. Winokur, R.A. Pastorek, Donor/acceptor nature of radiation-induced interface traps. IEEE Trans. Nucl. Sci. **35**, 1154–1159 (1998). doi:10.1109/23.25433
12. G. Prakash, P. Ganesh, Y.N. Nagesha et al., Effect of 30 Mev Li 3+ ion and 8 MeV electron irradiation on n-channel MOSFETs. Radiat. Eff. Defects Solids **157**, 323–331 (2002). doi:10.1080/10420150213002
13. M.M. Pejovic, M.M. Pejović, A.B. Jakšić et al., Successive gamma-ray irradiation and corresponding post-irradiation annealing of PMOS dosimeters. Nucl. Technol. Radiat. **27**, 341–345 (2012). doi:10.2298/NTRP1204341P
14. G.S. Ristic, Defect behaviors during high electric field stress of p-channel power MOSFETs. IEEE Trans. Device Mater. Reliab. **12**, 94–100 (2012). doi:10.1109/TDMR.2011.2168399
15. Y. He, Y. En, H. Luo, et al., The irradiation effect and failure analysis of DC-DC power converter, In 16th IEEE International Symposium on the Physical and Failure Analysis of Integrated Circuits, Suzhou, Jiangsu 2009, pp. 385–387, Doi:10.1109/IPFA.2009.5232625
16. A. Cester, S. Gerardin, A. Paccagnella et al., Drain current decrease in MOSFETs after heavy ion irradiation. IEEE Transaction on Nuclear Science **51**, 3150–3157 (2004). doi:10.1109/TNS.2004.839203
17. A.H. Johnston, T.F. Miyahira, Radiation damage in power MOSFET optocouplers. IEEE Trans. Nucl. Sci. **54**, 1104–1109 (2007). doi:10.1109/TNS.2007.903172
18. J.P. Colinge, V.S. Lysenko, A. Nazarov, *Physical and Technical Problems of SOI Structures and Devices* (Springer, Dordrecht, 1995), pp. 133–180
19. P.C. Adell, R.D. Schrimpf, B.K. Choi et al., Total-dose and single-event effects in switching DC/DC power converters. IEEE Trans. Nucl. Sci. **49**, 3217–3221 (2002). doi:10.1109/TNS.2002.805425
20. D. France, G. Charitat, P. Dupuy, et al. Clamped inductive switching of LDMOST for smart power IC's, In Proceedings of the 10th International Symposium, in Power Semiconductor Devices and ICs, Kyoto, 1998, 359–362, Doi:10.1109/ISPSD.1998.702715
21. V.L. Paul, M. Jules, *High performance Ka-band frequency down converter for deep space application* (European Space Agency's Operation Center, Darmstadt, 2004)
22. P. Habas, Z. Prijic, D. Pantic et al., Charge-pumping characterization of $SiO_2$/Si interface in virgin and irradiated power VDMOSFETs. IEEE Trans. Elect. Devices **43**, 2197–2209 (1996). doi:10.1109/16.544392