

LETTER

# A radiation-hardened Buck converter

Pengbo Yang<sup>1</sup>, Ping Luo<sup>1a)</sup>, Bo Li<sup>1</sup>, Haoyang Xiao<sup>1</sup>, Rongxun Lin<sup>1</sup>, Xiao Zhou<sup>1</sup>, and Shaowei Zhen<sup>1</sup>

**Abstract** Buck converter is widely used in the aerospace field. However, radiation in the aerospace environment will result in degradation or failure of devices and circuits. This paper presents a radiation-hard Buck, which is an adaptive on-time Buck. A radiation-hard adaptive on-time generator is proposed by utilizing of leakage current compensation. The proposed radiation-hard adaptive on-time generator is composed of an adaptive on-time timing block and a charging current generator. Finally, the proposed Buck is fabricated in a standard 0.18  $\mu\text{m}$  BCD process. And the radiation tests show that the Buck still maintains stability after total ionizing dose irradiation at a total dose of 350 Krad (Si).

**Keywords:** Buck converter, radiation hardening, adaptive on-time, leakage current compensation

**Classification:** Power devices and circuits

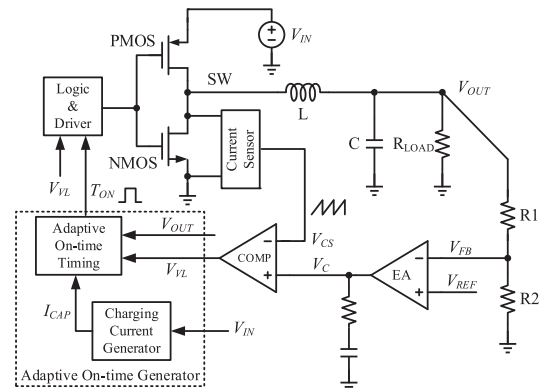


Fig. 1. Block diagram of a typical AOT Buck.

## 1. Introduction

Buck converter is a very widely used power management module. The application of Buck in space has to consider all kinds of radiation effect. For CMOS devices, total ionizing dose (TID) effect is prone to occur in the radiation environment, and it will lead to threshold voltage shift [1, 2], transconductance degradation [3, 4], carrier mobility reduction and leakage current [5, 6, 7, 8], resulting in the degradation or failure of devices and circuits [9, 10, 11, 12, 13, 14, 15]. In this aspect, it is of great significance to research on the radiation-resistant reinforcement of Buck. However, the existing research on radiation-hardened Buck is still limited to the analysis of Buck irradiation test and design of radiation devices [16, 17, 18, 19, 20, 21, 22, 23, 24], and the research on radiation-hard from circuit design is lacking. In this paper, a radiation-hard adaptive on-time generator is proposed by utilizing of leakage current compensation.

## 2. Structure of AOT Buck

The block diagram of a typical AOT Buck [25, 26, 27] is shown in Fig. 1. The adaptive on-time generator is the key block of an AOT Buck since it controls the stability of the loop and frequency of Buck most directly. And it should be paid more attention for radiation-hard design.

## 3. Radiation-hard circuit design for adaptive on-time generator

The leakage current caused by TID effect will influence the stability of Buck. And the leakage current of NMOS is more than that of PMOS [28]. The radiation-hard adaptive on-time generator designed in this paper corrects the errors caused by the leakage current in radiation environment. The proposed radiation-hard adaptive on-time generator is composed of an adaptive on-time timing block shown in Fig. 2 and a charging current generator shown in Fig. 3.

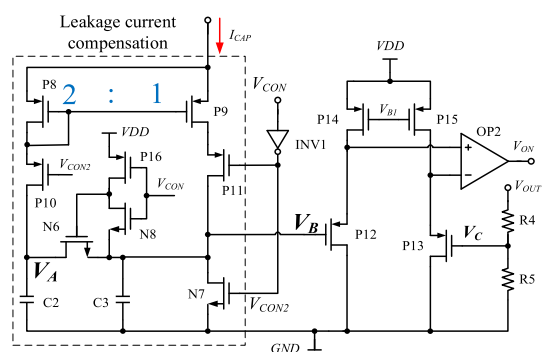


Fig. 2. The adaptive on-time timing block.

The ratio of current mirrors P8 and P9 in Fig. 2 is 2:1. When  $V_{CON}$  turns to high level at  $t_1$ , P10 and P11 turn on and N7 turns off, then, the top PMOS turns on and on-time starts timing. Furthermore, N8 controlled by  $V_{CON}$  turns on, and the voltage between gate and source of N6 is 0 V, which is same to that of N7. Meanwhile, because the capacitance of C2 and C3 are equal and charging current of C2 is two times of that of C3,  $V_A$  is two times of  $V_B$ ,

<sup>1</sup>State Key Laboratory of Electronic Thin Films and Integrated Devices, University of Electronic Science and Technology of China, Chengdu 610054, China

a) pingl@uestc.edu.cn

DOI: 10.1587/ele.16.20190244

Received April 12, 2019

Accepted May 27, 2019

Published June 17, 2019

Copied July 10, 2019

which also means that voltage between drain and source of N6 is equal to that of N7. For N6 and N7, same voltage between drain and source, and same voltage between gate and source mean that the leakage current of N6 is equal to the leakage current of N7. Therefore, the error caused by the leakage current of N7 during on-time timing in the radiation environment will be corrected with the compensation. The leakage current of NMOS during discharging won't influence on-time of Buck.

Besides, it is noteworthy that the leakage current of N8 won't affect the on-time of Buck. During the top PMOS on-time, the voltage of  $V_{CON}$  is  $V_{DD}$ , which means P16 is off and there is no leakage current for N8. And the leakage current of N8 during discharging time won't influence the Buck either.

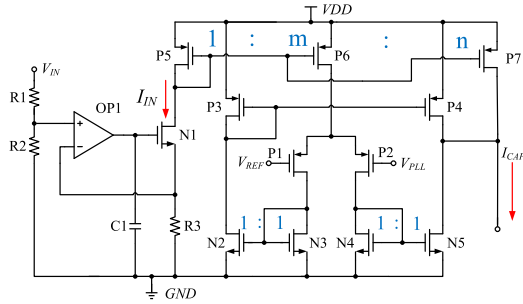


Fig. 3. The charging current generator of adaptive on-time generator.

Charging current  $I_{CAP}$  charges capacitance C2 and C3 with the charging control signal  $V_{CON}$ . The charging time  $T_{ON}$  is:

$$T_{ON} = \frac{2V_{OUT}R_5C_3}{I_{CAP}(R_4 + R_5)} \quad (1)$$

By means of operational amplifier clamping,  $I_{CAP}$  is:

$$I_{CAP} = \frac{V_{IN}R_2}{R_3(R_1 + R_2)} \quad (2)$$

where,  $V_{IN}$  is the input voltage of Buck.

Substituting Eq. (2) in Eq. (1),  $T_{ON}$  can be rewritten as:

$$T_{ON} = \frac{2R_3R_5C_3(R_1 + R_2)}{R_2(R_4 + R_5)} \times Duty = k \times Duty \quad (3)$$

The frequency of Buck is determined by  $k$  in Eq. (3), which is the period of Buck, and this makes the switching frequency of Buck always be near a fixed value.

The path of leakage current of NMOS in the radiation environment can be equivalent to a resistance in parallel with MOS, of which the value varies with dose rate [28, 29, 30]. Fig. 4 illustrates the simulation results of improvement of this paper compared with the normal AOT Buck in control of on-time with different parallel resistance, which means different leakage current and different radiation dose rates. And the normal AOT Buck is the traditional AOT Buck without leakage current compensation.

#### 4. Radiation tests and analysis

The Buck chip is designed and implemented in a standard 0.18  $\mu\text{m}$  BCD process. Experiments of irradiation and tests

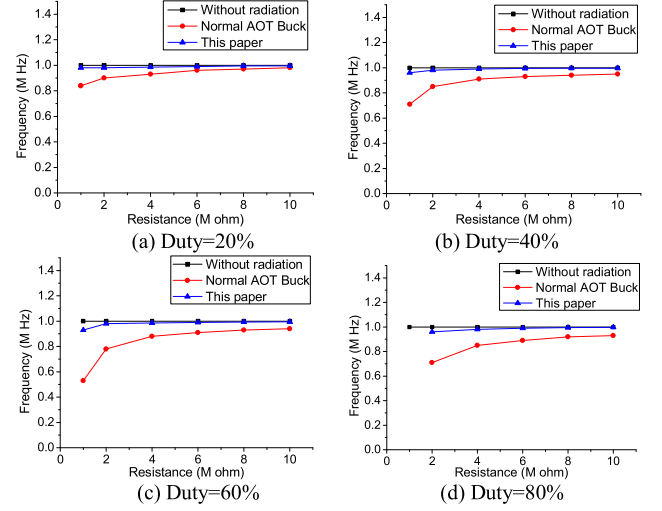


Fig. 4. The simulation results of equivalent frequency of adaptive on-time with different duty of Buck with diverse leakage currents.

are carried out. In this experiment, a Co-60 gamma-ray is used to irradiate the packaged chips on PCB at a dose rate of 50 rad/s, and the total dose increases up to 350 Krad(Si) in several steps. The designed radiation-hard AOT Buck chip and PCB are shown in Fig. 5.

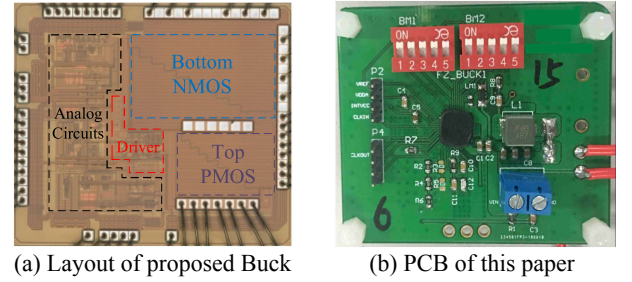


Fig. 5. The layout of proposed Buck and test PCB.

Fig. 6 shows the radiation testing results, which are tested at  $V_{IN} = 6\text{ V}$  and  $V_{OUT} = 1.2\text{ V}$  and the total dose increases up to 350 Krad (Si) in several steps. From the testing results, the normal AOT Buck is unstable after TID irradiation at a total dose of 350 Krad(Si). However, the proposed Buck will still maintain stability and the ripple of output voltage is much smaller than that of normal AOT Buck.

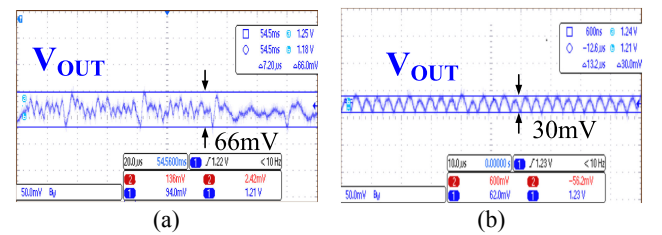


Fig. 6. Output voltage of: (a) normal AOT Buck with 350 Krad(Si); (b) proposed Buck with 350 Krad(Si) radiation.

From results in Fig. 7, the frequency of the proposed Buck will maintain at 1 MHz with different input and output voltage at a total dose of 350 Krad(Si).

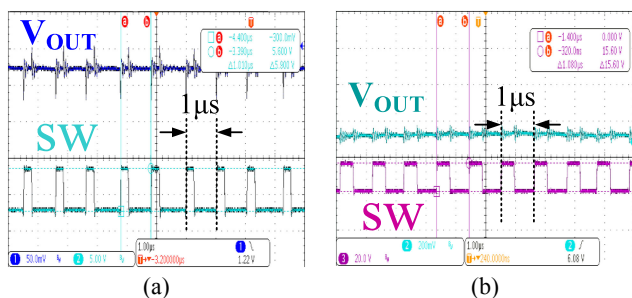


Fig. 7. Frequency of the proposed Buck with 350 Krad(Si) radiation of: (a)  $V_{IN} = 6\text{ V}$ ,  $V_{OUT} = 1.2\text{ V}$ ; (b)  $V_{IN} = 15\text{ V}$ ,  $V_{OUT} = 6\text{ V}$ .

Table I. Ripple of output voltage of Buck with different total dose.

Total Dose (rad)	0	100 K	200 K	300 K	350 K
Normal AOT Buck	25 mV	52 mV	53 mV	56 mV	66 mV
This paper	24 mV	26 mV	30 mV	24 mV	30 mV

Table I illustrates the value of ripple of output voltage of Buck with different total dose in radiation.

## 5. Conclusion

A radiation-hard AOT Buck is proposed in this paper. From aspect of circuit, this paper makes design with radiation hardening. The Buck chip is fabricated in a standard  $0.18\mu\text{m}$  BCD process. The radiation tests are carried out at a total dose of 350 Krad(Si), and the results show that the proposed radiation-hard AOT Buck can work more stable than normal AOT Buck.

## References

- [1] P. C. Adell, *et al.*: "Total-dose and single-event effects in switching DC/DC power converters," IEEE Trans. Nucl. Sci. **49** (2002) 3217 (DOI: 10.1109/TNS.2002.805425).
- [2] R. C. Lacoe, *et al.*: "Total-dose tolerance of the commercial Taiwan semiconductor manufacturing company (TSMC) 0.35- $\mu\text{m}$  CMOS process," REDW (2001) 72 (DOI: 10.1109/REDW.2001.960453).
- [3] F. Faccio, *et al.*: "TID and displacement damage effects in vertical and lateral power MOSFETs for integrated DC-DC converters," IEEE Trans. Nucl. Sci. **57** (2010) 1790 (DOI: 10.1109/TNS.2010.2049584).
- [4] Z. Liu, *et al.*: "Design of a total-dose radiation hardened monolithic CMOS DC-DC boost converter," J. Semicond. **32** (2011) 075006 (DOI: 10.1088/1674-4926/32/7/075006).
- [5] P. C. Adell, *et al.*: "Total-dose and single-event effects in DC/DC converter control circuitry," IEEE Trans. Nucl. Sci. **50** (2003) 1867 (DOI: 10.1109/TNS.2003.820757).
- [6] S. Michelis, *et al.*: "An 8 W-2 MHz buck converter with adaptive dead time tolerant to radiation and high magnetic field," ESSCIRC (2010) 438 (DOI: 10.1109/ESSCIRC.2010.5619737).
- [7] C. Alessandra, *et al.*: "CMOS IC radiation hardening by design," FUEE **27** (2014) 251 (DOI: 10.2298/FUEE1402251C).
- [8] H. L. Hughes and J. M. Benedetto: "Radiation effects and hardening of MOS technology: Devices and circuits," IEEE Trans. Nucl. Sci. **50** (2003) 500 (DOI: 10.1109/TNS.2003.812928).
- [9] H. Pan, *et al.*: "Method to improve total dose radiation hardness in a CMOS dc-dc boost converter," APEC (2005) 1491 (DOI: 10.1109/APEC.2005.1453230).
- [10] I. S. Esqueda, *et al.*: "Compact modeling of total ionizing dose and aging effects in MOS technologies," IEEE Trans. Nucl. Sci. **62** (2015) 1501 (DOI: 10.1109/TNS.2015.2414426).
- [11] J. R. Schwank, *et al.*: "Radiation effects in MOS oxides," IEEE

- Trans. Nucl. Sci. **55** (2008) 1833 (DOI: 10.1109/TNS.2008.2001040).
- [12] H. M. Joseph: "Radiation-induced effects on special super large n-channel power MOSFETs for space applications," RADECS (1991) 128 (DOI: 10.1109/RADECS.1991.213595).
- [13] E. Garcia-Moreno, *et al.*: "Temperature compensated floating gate MOS radiation sensor with current output," IEEE Trans. Nucl. Sci. **60** (2013) 4026 (DOI: 10.1109/TNS.2013.2277605).
- [14] F. Faccio, *et al.*: "Total ionizing dose effects in shallow trench isolation oxides," Microelectron. Reliab. **48** (2008) 1000 (DOI: 10.1016/j.microrel.2008.04.004).
- [15] M. Hao, *et al.*: "Total ionizing dose radiation effect on the threshold voltage for the uniaxial strained Si nano NMOSFET," IEICE Electron. Express **14** (2017) 20170411 (DOI: 10.1587/elex.14.20170411).
- [16] F. Faccio, *et al.*: "FEAST2: A radiation and magnetic field tolerant point-of-load Buck DC/DC converter," REDW (2014) 1 (DOI: 10.1109/REDW.2014.7004569).
- [17] Y. He, *et al.*: "The irradiation effect and failure analysis of DC-DC power converter," IPFA (2009) 385 (DOI: 10.1109/IPFA.2009.5232625).
- [18] L. N. Kessarinskiy, *et al.*: "DC-DC's total ionizing dose hardness decrease in passive reserve mode," Microelectron. Reliab. **55** (2015) 1527 (DOI: 10.1016/J.MICROREL.2015.06.113).
- [19] F. Faccio, *et al.*: "Development of custom radiation-tolerant DCDC converter ASICs," JINST **5** (2010) C11016 (DOI: 10.1088/1748-0221/5/11/C11016).
- [20] J. W. Swonger, *et al.*: "Radiation-hardened point-of-load Buck regulators for space applications," REDW (2012) 1 (DOI: 10.1109/REDW.2012.6353711).
- [21] Y. H. Lho, *et al.*: "A study on radiation effects on PWM-IC controller of DC/DC power buck converter," ICCAS (2013) 1754 (DOI: 10.1109/ICCAS.2013.6704221).
- [22] P. C. Adell, *et al.*: "Radiation effects in power systems: A review," IEEE Trans. Nucl. Sci. **60** (2013) 1929 (DOI: 10.1109/TNS.2013.2262235).
- [23] X. Xie, *et al.*: "A radiation-hardened programmable read only memory for space applications," IEICE Electron. Express **15** (2018) 20180675 (DOI: 10.1587/elex.15.20180675).
- [24] M. Hao, *et al.*: "Effects of gamma-ray radiation on channel current of the uniaxial strained Si nano-scale NMOSFET," IEICE Electron. Express **14** (2017) 20170866 (DOI: 10.1587/elex.14.20170866).
- [25] X. Jing, *et al.*: "Current-slope-controlled adaptive-on-time DC-DC converter with fixed frequency and fast transient response," ISCAS (2011) 1908 (DOI: 10.1109/ISCAS.2011.5937961).
- [26] Y. Mo, *et al.*: "A flexible pulse skip modulation buck DC-DC converter enabling minimum energy point tracking," ICSICT (2012) 1 (DOI: 10.1109/ICSICT.2012.6467720).
- [27] D. Wang, *et al.*: "A pulse skipping modulation with adaptive duty ratio in buck converter application," IEICE Electron. Express **12** (2015) 20150548 (DOI: 10.1587/elex.12.20150548).
- [28] H. J. Barnaby: "Total-ionizing-dose effects in modern CMOS technologies," IEEE Trans. Nucl. Sci. **53** (2006) 3103 (DOI: 10.1109/TNS.2006.885952).
- [29] T. Vergine, *et al.*: "A 65 nm CMOS technology radiation-hard bandgap reference circuit," PRIME (2014) 1 (DOI: 10.1109/PRIME.2014.6872688).
- [30] X. Zhou, *et al.*: "A radiation waffle layout for BCD power MOSFET," ASICON (2017) 773 (DOI: 10.1109/ASICON.2017.8252590).