Method to Improve Total Dose Radiation Hardness in a CMOS dc-dc Boost Converter

Huadian Pan[1], Herbert L. Hess[1], Kevin M. Buck[1], Bogdan M. Wilamowski[2], Mohammad M. Mojarradi[3]
[1]Microelectronics Research and Communication Institute, University of Idaho, Moscow, Idaho 83844
[2]Auburn University, Department of Electrical and Computer Engineering, 200 Broun Hall, Auburn, Alabama 36849
[3]Jet Propulsion Laboratory, California Institute of Tech., 4800 Oak Grove Drive, Pasadena, CA 91109

Abstract---MOSFETs used in space are subject to exposure to natural radiation in space. Among the effects of ionizing radiation are shifts in threshold voltage and reduction of carrier mobility. In this paper, total-dose effects in switching dc/dc Boost converter are examined using SPICE simulations. Then a new circuit design for an open loop dc/dc Boost converter that is much less sensitive to radiation is proposed. By adding four more MOSFETs to the conventional design, good radiation hard behavior is observed under SPICE simulation. The improved design converter can work properly in a wide range of radiation environment, with increasing total dose radiation. The efficiency also greatly improves, and so does the leakage performance.

I. Introduction

. The trend toward minimization demands that more and more circuitry be integrated onto one chip. Fully integrated dc-dc converters are one step toward full system integration. CMOS is a particularly attractive technology because of low power dissipation and because of the continual improvements in feature size. As a result, the trend is to focus on CMOS implementation of low-power power converters such that a system can be fabricated on the same chip for low-power applications [1],[2].

It is known that radiation has many effects on MOSFETs, such as decreased threshold voltage, increased leakage current, reduced mobility, etc [3]. In this work, we just consider threshold voltage (V_{th}) as a controllable variable. Thus the design can be simplified as the design of a threshold-voltage-variation inert circuit [4].

Dc-dc switching power converters are commonly used to generate a regulated dc output voltage from a different dc input source. Any change in the output voltage caused by radiation may affect the operation of other circuits related with the converter. Failure may occur if the output voltage change is sufficiently large [5], [6].

Proper operation of a switching converter relies on the ability of the switching MOSFETs to continually switch between the triode and cut-off region. However, if radiation causes the threshold voltage degrade to a certain level, the switching transistors can not be shut off and cause subsequent circuit failure [6]. This effect is explained in this work with the aid of SPICE simulation. Then a new circuit design to improve radiation hardness for a CMOS dc-dc boost converter is proposed.

II. Basic Circuit Operation

A switching converter utilizes one or more energy storage elements such as inductors, capacitors, or transformers to effectively transfer energy from the input to the output at periodic intervals. The dc-dc boost converter is capable of providing an output voltage that is greater than the input voltage.

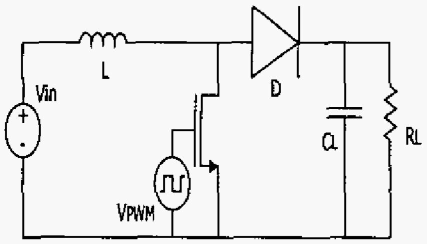

Fig.1 Open-loop boost converter circuit diagram

Fig.1 illustrates a basic voltage-mode PWM boost converter. The operation of the boost converter can be divided into two modes, depending on the switching actions. When the MOSFET is in the on state, the current in the inductor increases linearly and the diode is off at that time. When the MOSFET is turned off, the energy stored in the inductor is released through the diode to the output RC circuit. The boost converter operates in the continuous conduction mode (CCM) for $L > L_b$ where

$$L_b = \frac{(1-D)^2 \cdot D \cdot R}{2 \cdot f} \quad (1)$$

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D: duty cycle of switching signal R: Load f: frequency of switching signal. And the output voltage for converter working in the CCM mode is described by

$$V_{out} = \frac{1}{1-D} \cdot V_{in} \quad (2)$$

III. Total Dose Effect on Converter

It is known that radiation will introduce the generation of holes in MOSFET gate oxide. Some of them will be captured by the Si/SiO_2 interface trap centers and form oxide charges that will cause changes of important parameters [3],[4]. Normally, in a CMOS dc-dc converter, the switching MOSFET has a relatively large gate size, so the performance of the converter will be seriously affected by the ionizing radiation in space.

The quantity of V_{th} shift has a close relationship with the total dose of radiation. The V_{th} shift increases when total dose increases. Also the V_{th} shift becomes larger when gate bias is positive because the Si/SiO_2 interface trap centers will capture more positive charges [3],[4]. So we can study a total dose effect on the boost converter by circuit simulation using V_{th} as a variable. The converter was simulated using SPICE, with degraded MOSFET parameters to account for the effects of ionizing radiation. The MOSFET model used for these simulations is AMI 0.5 μ process BSIM3v3 model.

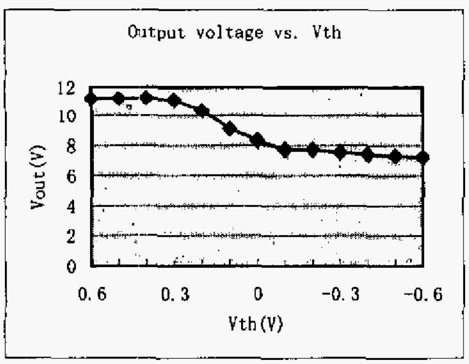

Fig.2 Output voltage vs. threshold voltage for the basic boost converter

Fig.2 shows the simulated output voltages of a traditional designed CMOS dc-dc boost converter versus V_{th} of the switching NMOS. From this simulation, it is observed that the output voltage shift is negligible until the threshold voltage of the switching NMOS decreases to the point where gate voltage is not low enough to fully turn off the MOSFET. For the simulation, the dc input is 5 volts, and a 0 to V_{in} (5 V) 1 MHz pulse square wave was applied to the switching MOSFET gate. With radiation increases, the V_{th} of the switching MOSFET decreases and the leakage current increases, so the output voltage will come down. When V_{th} of the MOSFET decreases to a negative value, as switching signal goes zero, the MOSFET remains in a conducting state, and operates in the saturation region at this period. At this point, the converter has functionally failed. The plot of the leakage current through switching transistor when the switching signal is low vs. V_{th} is shown as Fig.3.

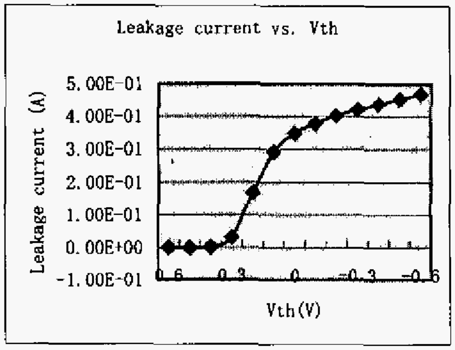

Fig.3 Leakage current vs. threshold voltage for the basic boost converter

Fig.4 shows the efficiency degradation of the boost converter. As it can be seen from the figure, efficiency decreases dramatically as MOSFET threshold voltage decreases past a certain point. At that point, the MOSFET cannot totally shut off as the switching signal goes low, and the leakage current through the MOSFET is much larger than that at the normal condition.

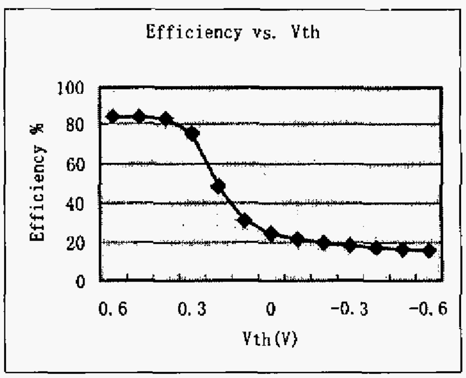

Fig.4 Efficiency vs. threshold voltage for the basic boost converter

IV. Design of Radiation Hardened Boost Converter

As to the negative threshold voltage shift of the switching transistor, from the circuit design perspective, one way is to increase the source voltage of the transistor to compensate for threshold voltage decrease. With this idea in mind, the open loop dc-dc boost converter was designed as Fig. 5. the additional n-type transistor M2 was connected in series with the switch transistor M1, and two gates are connected together.

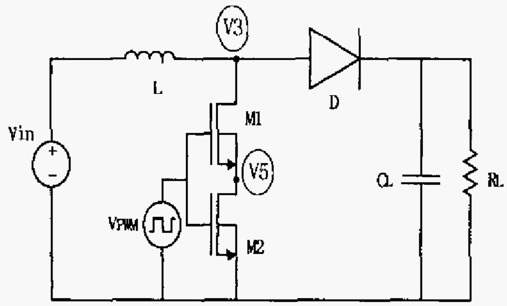

Fig. 5 Schematic of Re-designed boost converter

The operation of this circuit is as follows: assume V_{pwn} is low, the switching transistors M1 and M2 are off initially.

On state: when the switching signal goes high, transistor M2 will turn on, then the drain voltage of M2 comes down and transistor M1 turn on. With the switch on, the diode is reverse biased, thus isolating the output stage. The input supplies energy to the inductor and the inductor current increases linearly.

Off state: when the switching signal goes to zero, the node voltage V5 goes up, allowing M1 shut off completely. Here we also take advantage of transistor leakage current increase under irradiation, the structure proposed is self-limiting its leakage current by applying positive feedback voltage to the source of the M1 transistor. In this case, transistor M2 is equivalent to a resistor, which is the least model for M2 here. The emergence of M1 leakage current raises V5 and therefore compensates for its threshold voltage decrease.

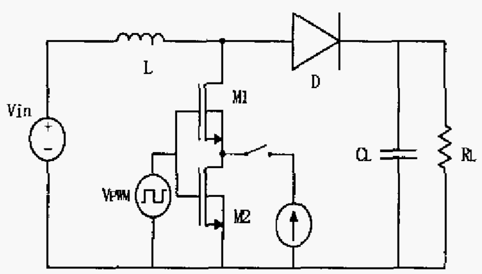

Fig 6. The design radiation hardened boost converter

However, in a dc-dc boost converter, one wants the leakage current as small as possible when the switch is off. The smaller the leakage current, the higher efficiency of the converter. So one can't just rely on the leakage current to provide positive feedback to raise V5. Therefore the circuit is re-designed as Fig. 6.

As illustrated in Fig. 6, we add a current source, which is connected between drain of M2 and ground, to provide current to raise V5 when V_{pwn} is low. And during V_{pwn} is high the current source will be disconnected.

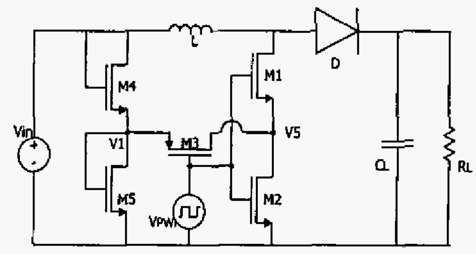

Fig.7 The complete design radiation hardened boost converter

The complete design is shown as Fig.7. Here the P-type transistor M3 is designed as the switch: when V_{pwn} is low, it turns on; when V_{pwn} is high, it turns off. Instead of using a current source in Fig. 6, we use a voltage source in Fig 7, which is implemented by transistors M4 and M5.

Both M4 and M5 are diode-connected; they act as a voltage divider to divide the input voltage (V_{in}) to V1, which is connected to the source of transistor M3. M4 and M5 do not carry the main current, so the power consumption of the addition circuit is negligible when compared with that of the whole converter circuits. One can vary the size of transistors M4 and M5 to achieve the desired V1. The voltage V1 should be less than the high pulse of V_{pwn} so that transistor M3 can be fully turned off when the gate signal is high. Also, V1 should be designed high enough to compensate the threshold voltage decrease of transistor M1.

With this design, when the switching signal goes down to zero, M3 turns on, and voltage divider supplies a current to raise the V5 up. It can be seen from Fig.8, which is a plot of gate switch signal and node voltage V5 with the time.

One benefit of this additional circuit is that it reduces the leakage current of transistor M1 when it's off. At same time it raises the voltage of V5 when the transistor M3 is on, the higher voltage of V5 helps the transistor M1 turn off more quickly and completely. This is the other benefit of this additional circuit.

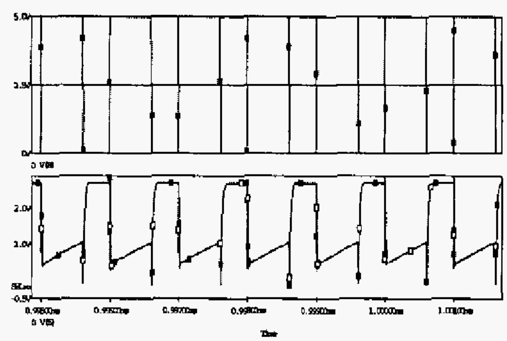

Fig.8 the switching signal (upper) and the source voltage of M1 (lower)

In this improved design, the principle used in the improvement is to add corrective elements to the structure to raise source voltage of NMOS transistor to compensate the Vth decreases. Here, the source voltage of M1 is raised to higher value than the amount of its threshold voltage shift. With this configuration, even if the threshold voltage of NMOS transistor goes down to a negative value, switching transistor M1 still can be guaranteed shutting off when the switching signal is low.

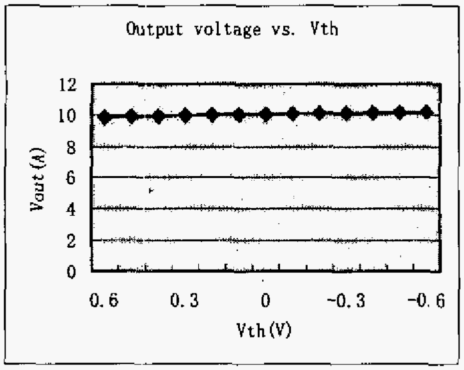

Fig.9 Output voltage vs. threshold voltage for the radiation-hardened boost converter

The converter output voltage versus threshold voltage for this improved design is shown as Fig.9. For this simulation, the input dc voltage is 5 volts, gate switching signal is 1MHz from 0 to 5 volts pulse wave. They are all set same with the previous simulations. From Fig. 9, it can be observed that the output of the converter keeps fairly constant under a wide range of radiation degradation. It is also interesting to note that the output voltage even goes up a little bit with transistor threshold decreases. The reason is that the on state resistance of the switching transistors reduce a little as the MOSFETs threshold voltage decreases.

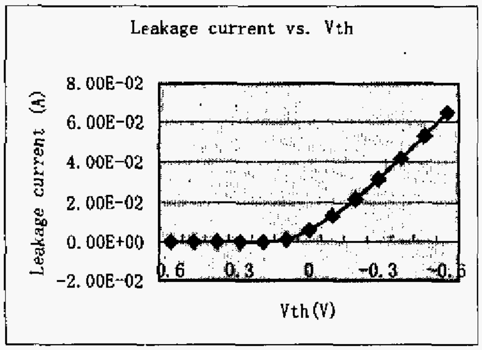

Fig 10. Leakage current vs. threshold voltage for the radiation-hardened boost converter

Compared with the basic design, the improved design also shows a better leakage performance when the switching transistor is off. The plot of leakage current vs. V_{th} for the radiation hardened design is shown as Fig. 10. For the basic design, when V_{th} decreases to less than 0.3V, the switching transistor will be remaining on all the time. The basic design circuit will fail to work at this point, while the improved design can work with a negative threshold voltage.

Fig.11 shows the efficiency of the improved converter versus threshold voltage. As we can see from this figure, the improved converter is less affected by total dose than the traditional design. The efficiency goes down slowly with increasing total dose. Why does the efficiency still go down with a fairly constant output voltage? Because the leakage current increases, so is the input current, then input power of converter increases. The efficiency of the converter is defined as the output power divides by the input power. With constant output power and increasing input power, the efficiency of this improved converter decreases slowly with the increasing total dose.

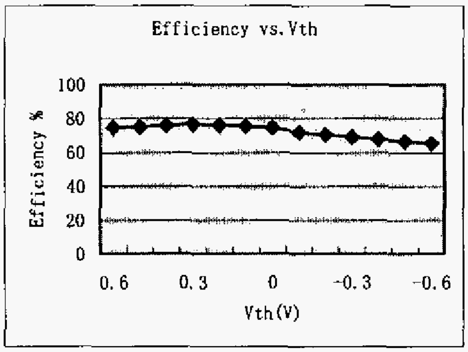

Fig.11 Efficiency vs. threshold voltage for the radiation-hardened boost converter

V. Conclusion

A new circuit design for an open-loop boost converter is proposed to minimize the impact of total dose radiation induced threshold voltage shift on the switching MOSFET in the converter. The idea proposed here is using auxiliary circuit to pull up the source voltage of the target MOSFET as a compensation for the threshold voltage decrease. From the circuit simulation, we can see that the improved converter has a much better performance than the traditional converter under a total dose radiation environment. It shows a fairly constant output in a wide range of radiation environment, the efficiency and leakage current performance also get a greatly improvement. The circuit has been laid out and sent for fabrication.

Acknowledgment

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