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Temporal characteristic analysis of single event effects in pulse width modulator

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Abstract In this paper, the nature and origin of single event effects (SEE) are studied by injecting laser pulses into different circuit blocks, combining with analysis to map pulse width modulators circuitry in the microchip die. A time-domain error-identification method is used in the temporal characteristic analysis of SEE. SEE signatures of different injection times are compared. More serious SEE are observed when the laser shot occurs on a rising edge of the device output for blocks of the error amplifier, current sense comparator, and T and SR latches.

Keywords Single event effect (SEE) · Laser testing · Pulse width modulator

1 Introduction

Pulse width modulators (PWMs) are commonly used in switching mode power supply systems, on which the single event effect (SEE) is of growing concern for spaceflight. To fully understand the SEE mechanisms, PWMs were tested by broad ion beams [1–6] and SEE cross section as a function of heavy-ion linear energy transfer (LET) or proton energy was measured to provide information needed for predicting SEE error rates in space. However, due to the random nature of the individual ion strikes, the ion beam test does not provide the temporal and spatial information to understand the SEE mechanisms.

Subsequently, studies on SEE of PWMs were performed with laser beams [7–9] for detailed analysis of SEE mechanisms [10–14]. Chugg et al. [7] revealed some details of PWM SEE behavior by injecting laser pulses on few positions, such as delayed onset of latch-up near the single-event latch-up threshold. Ren et al. [8, 9] showed that single event transient (SET) pulses on the internal reference voltage circuit might interfere with the protection circuits and cause system reset and reported the effect of temperature-induced quiescent operating point shift on SET sensitivity. Other studies focused on the correlation of heavy ion and laser testing on PWMs [15−16] or the relationship between proton and laser testing data on PWMs [17].

However, reports on temporal characteristic analysis of SEE in PWMs are rarely seen. Pouget et al. [18] showed that the SEE sensitive areas of a portion of the AD7821 ADC changed with time after the conversion start, indicating the temporal characteristic analysis would be required to comprehensively characterize the SEE performance.

In this work, we obtained the SEE signatures for different injection times through the output cycle in different modes of oscilloscope trigger. A time-domain error-identification method was used in the temporal characteristic analysis of SEE.

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2 Experimental

A current-mode PWM implemented in bipolar technology was investigated in this work. Top package was removed for the laser beams to irradiate the active silicon regions. In addition, there is only one layer of metal interconnection in the chip and the routing is not dense, so some fraction of the laser may bypass the metal and generate SEEs.

The extracted circuitry has been mapped back onto the physical die layout and the block diagram. Figure 1a shows a photomicrograph of the device and the main blocks, which include the OSC (oscillator) block, the Error Amp (error amplifier) block, the UVLO (under voltage lock out) block, the VREF (reference voltage) Good Logic block, the Current Sense Comparator block, the SR Latch block and the T Latch block.

The device under test (DUT) was irradiated on a picosecond neodymium-YAG laser system PL2210 (Fig. 1b) at the Northwest Institute of Nuclear Technology. The system delivers laser pulses centered at 1064 nm (1.2 eV) with pulse width of 21.8 ps and 1 kHz repetition rate. The single photon energy is greater than the silicon band-gap (1.12 eV) so that an electron in the valence band can be excited to the conduction band and leaves a hole there. The strong laser beams were attenuated and passed through a wave plate-polarizer combination to precisely control the incident pulse energy. With a 100× microscope objective, the laser beam was focused on the device in a 1.4 μm Gaussian spot (FWHM).

The laser pulses were injected on the bipolar transistors of different circuit blocks. Relevant signals were captured for each SEE event using a digital oscilloscope. They include the reference voltage (V_{REF}), the device output (OUTPUT), the oscillator input signal named R_T/C_T, and the error amplifier output (COMP). The incident laser energy was 50 nJ. Making an accurate determination of the fraction of incident light reaching the active silicon regions is necessary for quantitative measurements, but this is out of the scope of this paper.

A time-domain error-identification method should be used in the temporal characteristic analysis of SEE. Here we use reference signals to decide the phase relationship between the injection times and the output cycle. The choice of reference signals for different circuit blocks will be discussed below.

3 Results

3.1 The OSC block

For the OSC block, the typical SEE signatures after each laser shot were both a disturbance in the oscillator input signal and a phase shift in OUTPUT. As can be seen in the block diagram of the PWM (Fig. 2), the pulse width modulation is achieved by both SR latch and T latch. The OSC block provides the oscillator signal to control the S input of SR latch and the clock signal of T latch. The S input of SR latch can hardly change the latch output when the R input is disabled. Therefore, SEE for the OSC block may be primarily due to the changes in the clock signal of T latch, which is related to the oscillator input signal. In view of the above analysis, the reference signal of the OSC block can be the oscillator input signal named R_T/C_T.

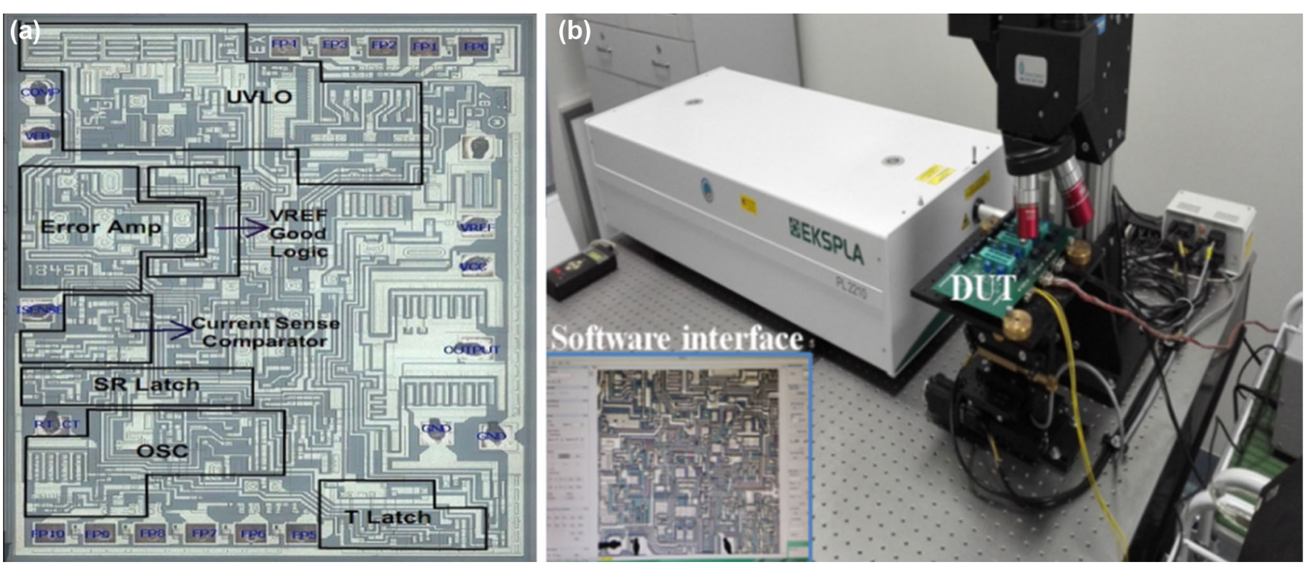

Fig. 1 (Color online) The device under test (**a**) with the main block locations, and the experimental setup (**b**)

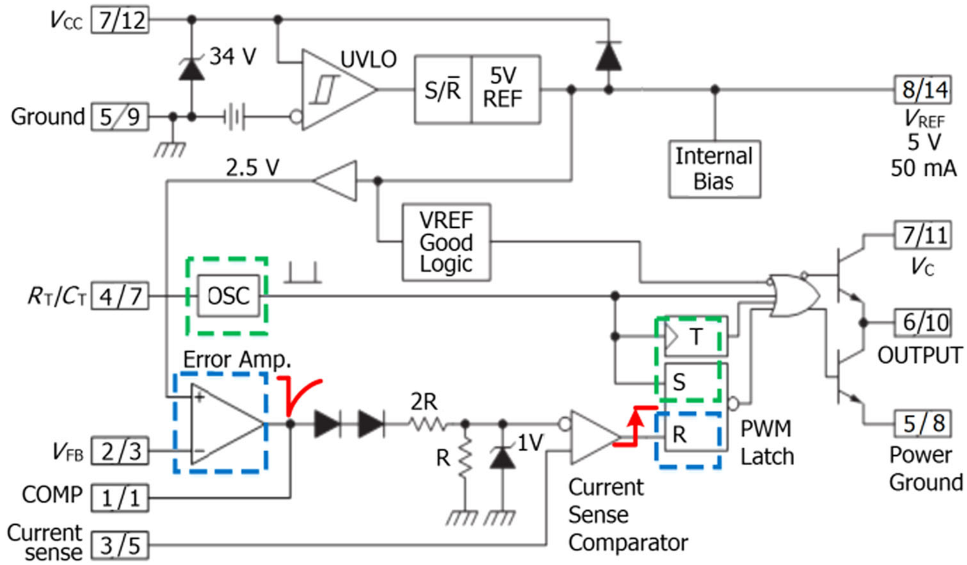

Fig. 2 (Color online) Block diagram of PWM

According to the change of the oscillator input signal after each laser shot, the phase relationship between the injection time and the output cycle could be determined. The results for a laser shot occurring on a high level and a low level of OUTPUT are illustrated in Fig. 3. Figure 4 provides the timing waveforms. With the laser shot on a high level of OUTPUT, the clock signal of T latch that controls the falling edge of OUTPUT was delayed; with the laser shot on a low level of OUTPUT, the clock signal of T latch controlling the rising edge of OUTPUT was delayed.

3.2 The Error Amp block

For the Error Amp block, the typical SEE signatures after each laser shot were both a voltage transient in the error amplifier output and a change in OUTPUT. This block can reset the SR latch by pulling the error amplifier output below a voltage, which forces highlevel output of the current sense comparator (Fig. 2). Therefore, SEE for this block may be explained that the negative transient in the error amplifier output affected OUTPUT by resetting the SR latch temporarily. So, the reference signal of the block can be the error amplifier output, COMP.

According to the change of the COMP after each laser shot, the phase relationship between the injection time and the output cycle was observed (Fig. 5a). With the laser shot on a rising edge of OUTPUT, there was a missing pulse. For other injection times, there might be a change in duty cycle (Fig. 5b) or even no errors (for example, the laser shot on a low level of OUTPUT).

Figure 6 provides the timing waveforms for different resetting times through the output cycle. It can be seen that the error was more serious when the resetting occurs on a rising edge of OUTPUT (blue waveforms), which means that the SEE behavior may be more serious when the laser shot occurs on a rising edge of OUTPUT.

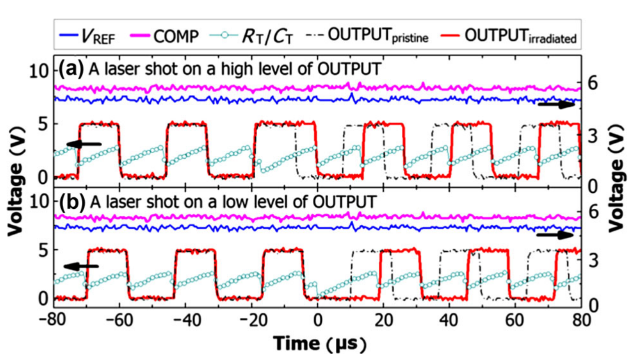

Fig. 3 (Color online) Typical SEE signatures after each laser shot for the OSC block, with a laser shot on a high (*a*) or low (*b*) level of OUTPUT

3.3 The UVLO block and the VREF Good Logic block

For the UVLO block and the VREF Good Logic block, all the measured signals might be affected by a laser shot, because the blocks have the function of providing signals to other blocks. Two typical SEE signatures are shown in Fig. 7.

For Type 1 SEE signatures (Fig. 7a), OUTPUT was decided by the oscillator signal and the error amplifier output. There was also a disturbance in the reference voltage, contributing to the voltage transient in the error amplifier output. The disturbance in the oscillator signal affected the clock signal of T latch, and the negative transient in the error amplifier output reset the SR latch temporarily.

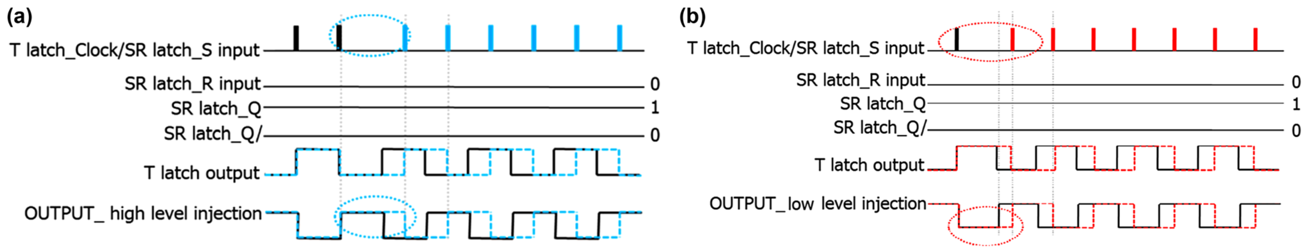

Fig. 4 (Color online) Timing waveforms of SEE for the OSC block: a laser shot on a high (**a**) or low (**b**) level of OUTPUT

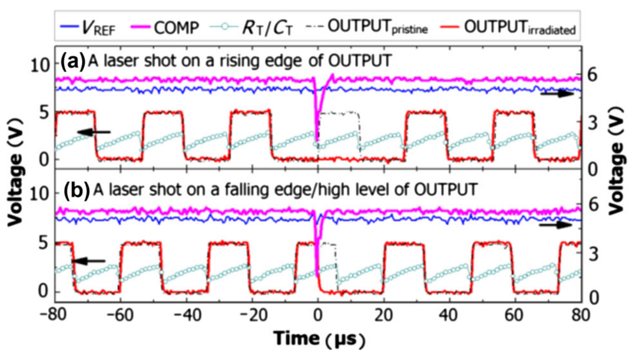

Fig. 5 (Color online) Typical SEE signatures after each laser shot for the Error Amp block: a laser shot on a rising (*a*) or falling edge/high level (*b*) of OUTPUT

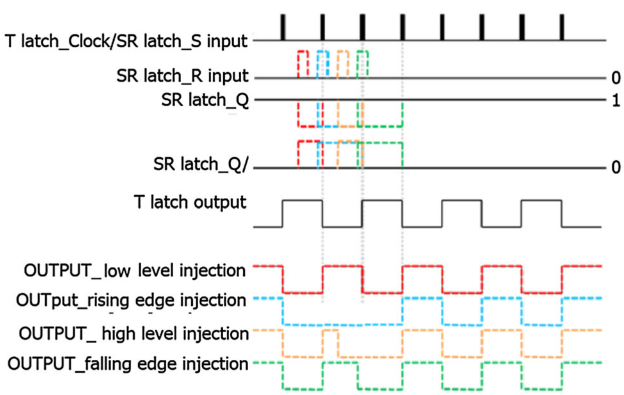

Fig. 6 (Color online) Timing waveforms for different resetting times through the output cycle

For Type 2 SEE signatures (Fig. 7b), OUTPUT was decided by the oscillator signal and the reference voltage. The disturbance in the oscillator signal affected the clock signal of T latch, and the disturbance in the reference voltage raised CURRENT SENSE pin (Fig. 2) above 1 V, resetting the SR latch temporarily.

The temporal characteristics of SEE in the two blocks depend on the SEE response of some related blocks.

3.4 Other circuit blocks

For the current sense comparator block, and the T and SR latch blocks, the typical SEE signature observed after each laser shot is shown in Fig. 8. Except for OUTPUT, there was no obvious change in the measured signals. This behavior can be explained by the fact that an error in these blocks can hardly propagate into the front blocks for the open-loop test.

Although there is no reference signal for these circuit blocks, the phase relationship between the injection times and the output cycle can be indicated to some extent. For example, with a laser shot on a rising edge of OUTPUT (Fig. 8a), there was a phase shift; with a laser shot on a high level of OUTPUT (Fig. 8b), there was a transient in the high level of OUTPUT. It seems that the SEE behavior is more serious when the laser shot occurs on a rising edge of OUTPUT.

4 Discussion

In the experiments, we found that some SEE sensitive locations on the PWM die typically only produced an SEE response for one-in-tens of laser pulses delivered. This was reported by Chugg et al. [2], who attributed the phenomenon to enhanced sensitivity during output switching. According to our experiment results, there might be no errors when the laser shot occurs on the low level of OUTPUT for the Error Amp block. This means that the SEE sensitivity might be only exhibited during transitory periods of the output cycle for some locations. In addition, it should be noted that the error signatures for different injection times through the output cycle were sometimes obtained by setting different trigger modes. For example, Fig. 3a, b is obtained by using positive and negative pulse width triggering, respectively. This is a possible indication that some SEE behaviors might be neglected by using a single trigger mode.

To see the layout, the microchip die should be illuminated with a white light source directed through the microscope objectives. In our experiment, when the transistor TI9 in the schematic of the UVLO block (Fig. 9) was illuminated with a white light source directed through the 100 × microscope objective, the response waveforms for low and high illuminator brightness were observed

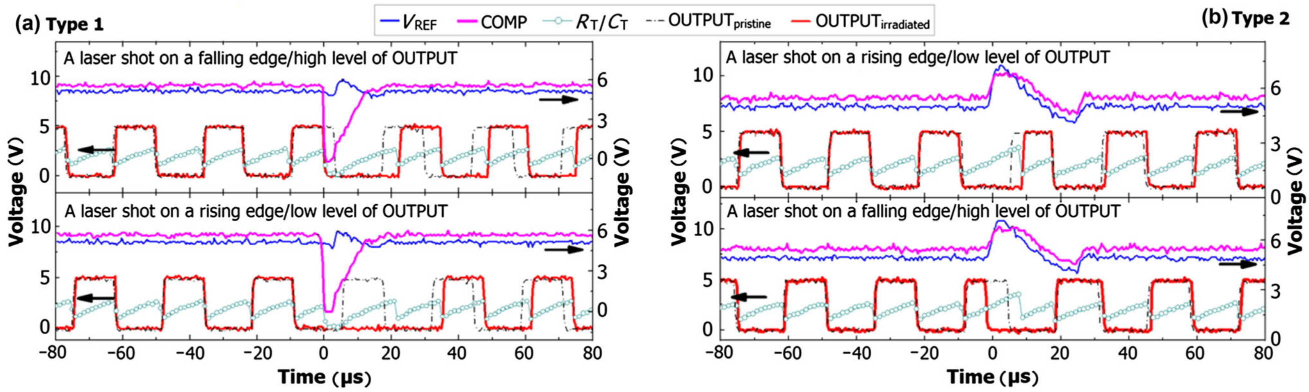

Fig. 7 (Color online) Typical SEE signatures after each laser shot for the UVLO block/the VREF Good Logic block of Types 1 (*a*) and 2 (*b*)

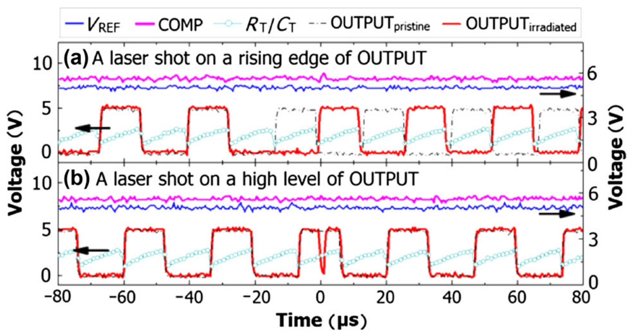

Fig. 8 (Color online) Typical SEE signatures after each laser shot for the current sense comparator block, the T latch block and the SR latch block: (*a*) a laser shot on a rising edge of OUTPUT, (*b*) a laser shot on a high level of OUTPUT

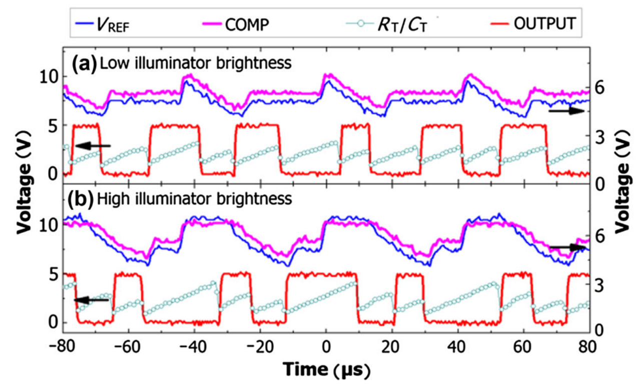

Fig. 10 (Color online) Response waveforms for the illumination located on TI9 of low (*a*) and high (*b*) illuminator brightness

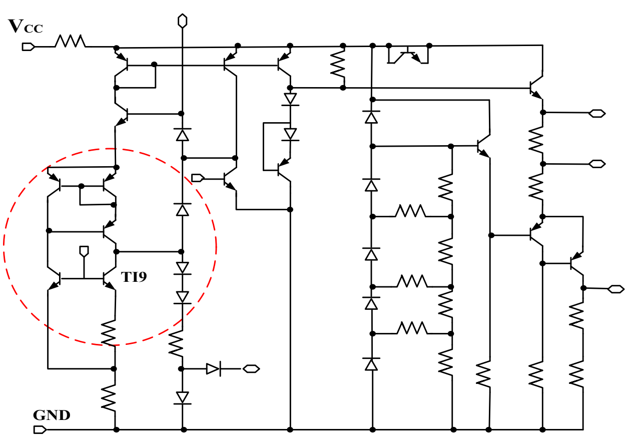

Fig. 9 (Color online) Schematic of the UVLO block. The transistors/diodes circled are sensitive to the illumination of the laser system

(Fig. 10). Some other transistors/diodes circled in Fig. 9 were also sensitive to the illumination. It can be seen that the normal function of the device was influenced and the influence was more serious for higher illuminator brightness. This phenomenon may be due to some light-dependent materials introduced in the semiconductor manufacturing process of these components. Fortunately, the device comes to normal when the illumination was turned off. Therefore, it is necessary to turn off the illumination during SEE measurements in some cases.

5 Conclusion

By injecting laser pulses in different circuit blocks, insights into the nature and origin of SEE are provided. SEEs for the OSC block are primarily due to the changes in the clock signal of T latch. SEEs for the Error Amp block can be explained that the negative transient in the error amplifier output affects OUTPUT by resetting the SR latch temporarily. SEEs for the UVLO block and the VREF Good Logic block result from the changes in the clock signal of T latch as well as the resetting of the SR latch. According to the above analysis, mitigation approaches are required for T latch and SR latch. Circuit hardening solutions can be added to mitigate the single event transients in the clock pin of T latch and the reset pin of SR latch. In addition, the reference signals used to decide the phase relationship between the injection times and the output cycle are selected for different circuit blocks through the mechanism analysis.

The SEE signatures for different injection times through the output cycle are compared and it is shown that the SEE behavior is more serious when the laser shot occurs on a rising edge of OUTPUT for the Error Amp block, the current sense comparator block, the T latch block and the SR latch block. In view of the result, SEE error rate may decline when the PWM works at lower frequency. Frequency dependence of SEE sensitivity of this device can be considered in heavy-ion beam testing.

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