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Qualification of Operational Amplifier used in Satellite Subsystem using Picosecond Pulsed Laser System

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***Abstract**: Picosecond Pulsed Laser System (PPLS) was used to simulate the single event effects (SEE) on satellite electronic components. Single event transients effect induced in an operational amplifier (LM324) to determine how transient amplitude and charge collection varied with pulsed laser energies. The wavelength and the focused spot size are the primary factors generating the resultant charge density profile. The degradation performance of LM324 induced by pulsed laser irradiation with two wavelength (1064nm, 532nm) is determined as a function of laser cross section. The transient voltage changed due to pulsed laser hitting specific transistors. This research shows the sensitivity mapping of LM324 under the effect of fundamental and second harmonic wavelengths. Determine the threshold energy of the SET in both wavelength, and compare the laser cross section of 1064 nm beam and 532 nm beam.*

***Keywords** : Pulsed Laser Single Event Effect System, Single Event Transient, operational amplifier.*

I. INTRODUCTION

The Electronic components (ECs), which are equipped in spacecrafts, have huge importance, and require qualifications and testing in order to ensure their functionality. This is largely due to the high degree of radiations in the space environment. Space contains a high energetic particles that can dramatically affect the functionality of space electronics components.[1] [2]

There are three types of the space radiation effects on EC: Total Ionizing Dose (TID), Displacement Damage Dose (DDD) and Single Event Effect (SEE). TID is accumulated radiation dose over a lifetime of the ECs. While, DDD when incident energetic particles knock-on an atom from its lattice site inducing efficiency degradation in optical devices. SEE is electrical disturbance in a microelectronic circuit caused by the passage of proton or heavy ions through a semiconductor. A circuit functional error or a circuit failure either temporarily or permanently.[3]

SEE can be distinguished by more different types of effects, in this research we will concern on two types Single Event Transients (SET), and Single Event Burnout (SEB):

Single Event Transient (SET): The ionization induces a current pulse in a p-n junction. The charge is injected by the current at a sensitive "off" node of a data storage element may exceed the critical charge, required to change the logic state of the element.

Single Event Burnout (SEB) is an event where a heavy-ion is passed into a transistor and deposed appropriate charge to turn the transistor on. If the transistor keeps in this state, the great currents over the transistor can be enough to damage the full circuit.

As the scores of integrated circuits get smaller, the probability of SET gets higher since less and less charge is required to reduce the voltage levels in a memory node. [3] [4] There are two types of Electronic Components: analogue devices and digital devices. In analogue devices, (SET) also called Analog Single Event Transient (ASET) are mainly transient pulses in operational amplifiers, comparators or reference voltage circuits [5]. In combinatorial logic, SET is transient pulses generated in a gate that may propagate in a combinatorial circuit path and eventually be latched in the storage cell. In this paper, the analogue components, specifically Operation Amplifier (LM324) is concerned.

Space-COTs are selected high quality commercial components, which must be qualified to withstand space radiation especially; SEE [6]. These tests are usually use energetic particles induced by accelerators and reactors, which is very expensive and time consuming.

Pulsed laser system is an effective solution to achieve these tests in the laboratory, to provide the radiation sensitivity in accordance with the spatial and temporal distributions. [7] [8]. The PPLS is a powerful tool for inducing SET and SEB process in complex integrated circuits. A primary advantage of laser-based techniques is the ability to locate and characterize sensitive nodes with sub-micron precision. [11]

The objectives of this research are explaining the usage of PPLS which is low cost, high power facility; to simulate the effects of high energetic particles in space on ECs. Determine the SET sensitivity mapping for LM324. Provide qualitative and quantitative information of SET rate for Op-Amp (LM324) with the determination of laser cross-section at different Energies. Finally, compare the laser test results of two-wavelength on LM324.

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II. EXPERIMENTAL SETUP

A. Picosecond Pulsed Laser System (PPLS)

Fig. 1 PPLS for SEE testing at NARSS

As shown in Fig. 1 Picosecond Pulsed Laser System Facility, at National Authority for Remote Sensing and Space Science (NARSS), Cairo, Egypt is used to irradiate the DUT. PPLS consists of picoseconds pulsed laser source, which has maximum energy is about 0.4 mJ and maximum power is about 16 MW. The laser source is Nd: YAG which followed by a regenerative amplifier. The wavelengths are fundamental (1064 nm) and second harmonic (532 nm) and delivering pulses of duration is 25 picoseconds. The repetition rate is varying from 990 Hz to 1010 Hz. The laser's beam diameter is about 3 mm and after leaving from the microscope becomes spot size is about 2 µm. The penetration depth of fundamental radiation (1064 nm) in silicon material is 676 µm and the penetration depth of second harmonic (532 nm) in silicon is 1.27 µm [12]. On a horizontal axis, an externally triggered laser module is mounted horizontally followed by an optics system composed attenuator, a Polarizing Plate Beam splitter (BS), power meter (PM), Broadband Dielectric Mirror (750 - 1100 nm), and a microscope (VMU 50x long working distance) connected with CCD Camera, shown in Fig. 1 Device Under Test (DUT) is located on an XYZ motorized mechanical alignment stage in front of the microscope objective.

A timing routine controls all system is programmed in LabVIEW program running on a PC and interfaced to the laser system by a National Instruments card allows acquiring the current waveform, set, and monitor all relevant beam parameters such as beam spot position and energy. This synchronization routine confirms that there is time enough to check the signal and store it in an excel file before the next pulse arrives at the DUT.

B. LM324 and its test board

Devaice under test (DUT) used is Operational Amplifier (Op-Amp; LM324) which a high-gain operational amplifier (DC voltage gain of 100 dB), which is manufactured by National Semiconductor.

In this work, the LM324 was configured as a voltage supporter with (Vcc= +15V) ($V_{in} = +1V$) and ($V_{out} = 2\ V$). **Fig. 2** shows the LM324 simplified circuit schematics.

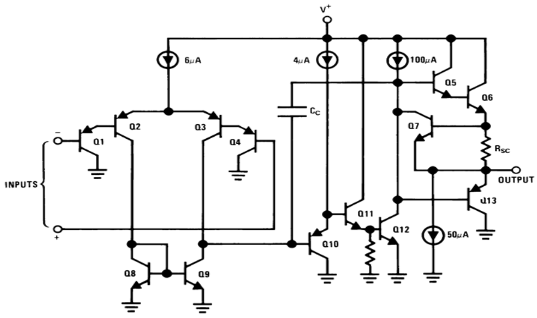

Fig. 2 LM324 simplified circuit schematics.

(a). **(b)**

Fig.3 LM324 (a) layout and size of the die (2.5 x 2.5 mm). (b) Photomicrograph of one of the four amplifiers on the LM124 chip.

Chip must be decaping before test in order to overcome the low penetration depth of pulsed laser in material as shown in Fig.3(a). Decaping was done manually after x-ray invistigation using the Scanning Electron Microscope (SEM) on FEG LAB (Field Emission Gun) at The Egyptian Mineral Resources Authority Central Laboratories Sector, which is used also to study the design layout to measure the sizes of the die, before exposure to PLS, as shown in Fig.3(b).

The chimical etching treatment using mix of H_2SO_4 and HNO_3 was done to complet the decaping process.[14]

Fig 4 shows the schematic diagram of printed circuit board (PCB) for biasing LM324 to generate the voltage signal of Op-Amp, read it and record the data during the laser pulse scanning.

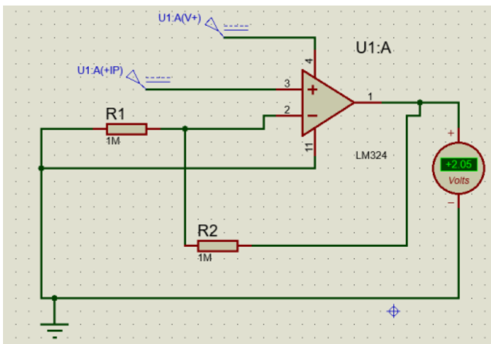

Fig 4 schimatic diagram of PCB for biasing LM324

C. Test Phases

DUT is adjusted on XYZ motorized mechanical alignment stage, with permitting 10 µm moving steps. The focus of the laser beam is adjusted on a reference point using the layout of LM324 and focused down to a spot diameter size of 2 µm on the surface of the DUT. The PPLS is programmed to scan with the laser spot over a defined area, allowing synchronization between the DUT's motion, the laser pulses, and the control of the input/output signal of LM324.

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Thus to facilitate the SET sensitivity mapping for LM324 with excellent reproducibility and acquires an illustration of the sensitive areas.

Initialization DUT with connecting the LM324 with test board to get the output signals.

Start exposure with the minimum laser energy value then varies the energies using attenuator to determine the thershold energy and saturated energy.

LM324 signal must be recorded after laser pulse exposure , as well as the movement of DUT holder to the next exposure position must be before the next pulse emission. The increment between every two points is 0.01 mm (10µm) in order to generate SET and avoid interference may caused by the laser beam spot size and internal transistors size. Through the process, the signal data of LM324 are frequently read and stored using LabVIEW. The synchronizing of the location pulse shots would also be recorded. The scan is finished after the defined area is scanned completely, which may take about 8 hours.

Scanning is done with fundamental and second harmonic laser.The profile map for sensitive nodes are detected as voltage shift noticed.

Finally, compare the results and declear the difference between the effect of two wavelengths on OpAmp.

Laser Cross Section calculation at each sensitive node [14]:

$$Threshold\ Energy = \frac{Power}{Repetition\ Rate}\ (\mu W/Hz) = \mu J * 10^6 = PJ \qquad (1)$$

$$\text{Laser Fluence}= \frac{\text{Number of shots}}{\text{Irradiated area}}\ (\text{shots}/\text{cm}^2)\ . \qquad (2)$$

$$\text{Laser Cross Section}= \frac{\text{Number of events at irradiated area}}{\text{Laser Fluence}}\ (\text{cm}^2/\text{device orbit}\ ). \qquad (3)$$

After these calculations, the laser cross-section as a function of pulsed laser energies at the sensitive node can be determined.

III. RESULTS AND DISCUSSION

A. Mapping of fundamental beam for DUT

Firstly, with scanning the DUT at different energies, the threshold energy experimentally determined to be 0.05 PJ (the minimum energy which induced SET) and the saturated energy experimentally determined to be 5.84 PJ (the maximum energy which induced SET, after this energy DUT may burnout).

Secondly, the laser scan for mapping of DUT (LM324) performed by wavelength 1064 nm, with penetration depth in silicon material is (676 µm), at pulse energy (saturated energy) 5.84 PJ is shown in Fig.5. Whereas X-Y axes express the positions and Z-axis expresses the voltage.

The area which covered by a different color than green showed the affected area by the pulsed laser, which is called the sensitive region. The color legend on the right of figure showed the the change of voltage due to irradition compered to the configured output voltage. If the transiant voltage above 2 volt it is postive transiant, else it is negative.

With comparing the LM324 simplified circuit schematics Fig. 2 with profile mapping, the investigated sensitive region are, transistors (Q18, Q19, and Q9), and the resistance (R1). These transistors and resistance found in each one of the four Op-Amp in the LM324 die.

As shown in Fig.5 using the color legend map, Q9 and Q19 is showed negative transiane, while Q18 and R1 showed positive transiant. This can be illustrated as R1 resistor has been identified as a floating base transistor [15]. When an pulsed energy struck this resistor, it was turning on pulling the base of Q9 low and turning Q9 off. The output voltage signals for R1 and each Q9 exist on the four Op-Amp parts of the LM324 die.

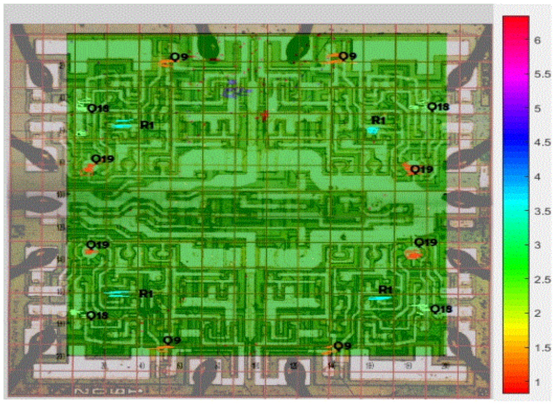

Fig.5 The mapping of fundamental beam for DUT after completing the laser scan.

B. Mapping of second harmonic beam for DUT

Firstly, with scanning the DUT at different energies, the threshold energy experimentally determined to be 0.05 PJ) and the saturated energy experimentally determined to be 3.4 PJ.

Secondly, the laser scan mapping for DUT (LM324) performed by wavelength 532 nm, with penetration depth in silicon material is (1.27 µm), at pulse energy 3.4 PJ is shown in Fig.6. Whereas X-Y axes express the positions and Z-axis expresses the voltage.

With comparing the LM324 simplified circuit schematics Fig. 2 with profile mapping, the investigated sensitive region are the transistors (Q16, Q19, Q18, Q5, and Q2). SETs generated at transistors Q16, Q19, Q18, Q5, and Q2 all have approximately the same tarnsiant shape.

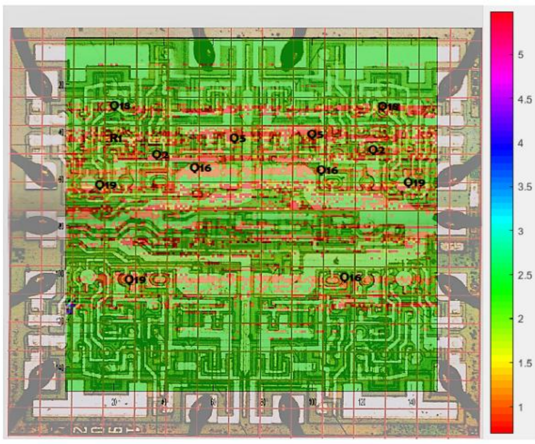

Fig.6 The profile mapping of second harmonic beam for DUT after completing the laser scan.

For the most part, Q18 shows little change in transiant shape with an increase in laser intensity, except for a region where the pulse broadens while the amplitude stays constant. At higher intensities the shape is once again unchanged with increasing intensity. The linear plots for SETs from Q18, Q19, Q16, Q2 and Q5 demonstrate that the shape for those SETs also does not change significantly with laser intensity.

C. SET characterization for DUT (LM324)

SET charactrization for LM324 after 1064 nm and 532nm exposures depends on calculating laser cross section as a function of laser flunce and laser energy as mention in Eq.1,2,3.

The laser fluence for both 1064 nm and 532 nm is 1E6 shots/cm2.

As shown in Fig.7 comparing the results of laser cross section as function of laser energy for 1064 nm and 532 nm shows that, the single transient caused by 1064nm beam is highr than 532 nm beam, this can be illustrated due to the penetration depth in silicon of green beam is 1.27 µm, while for 1064 nm is 676 µm. which refelcets on the laser beam ability to induce effect on the transistor inside the operetional amplifier.This can imply that 1064 wavelength is more suitalble for SET predictions and fault diagnostics for space applications.

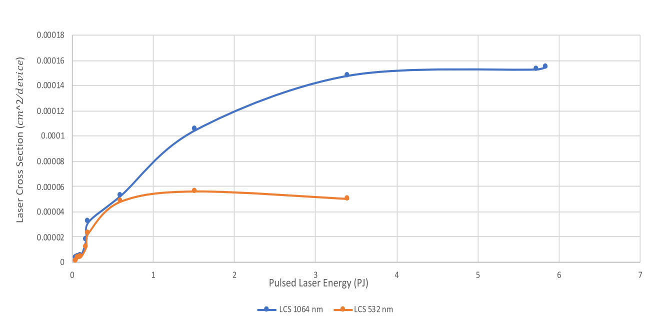

Fig.7 Comparison between laser cross section of fundamental and second harmonic beam.

D. Discussion

Table I summrize the pulsed laser exposure results of LM324. The presented results clarify that induced SET in LM324 depend on a variety of different variables, including the origin of SETs in LM324 circuit itself, which transistor is hitting by the laser beam, the amount of energy stored to active the SET, and the electric structure of the amplifier.

The shape (polarity) of the SETs depends on how each transistor respond to charge injected at just one node, and all transistors which "sense" the current or voltage changes as the SETs propagate from source to output.

Individual transistor degradation depends on its type (npn or pnp), physical layout, and bias configuration, which are different for each transistor. So, there's no way to determine which transistor may cause the degradation of the circuit.[16]

Table I The results of DUT (LM324) irradiation for PPLS.

Wavelength	Penetration depth	Threshold energy	Saturated Energy	Sensitive nodes	σ_{th} $(cm^2/device)$	σ_{St} $(cm^2/device)$
Fundamental (1064 nm)	676 µm	0.05 PJ	5.84 PJ	R1, Q18: +ve SET Q19, Q9: -ve SET	3E-6	1.55E-4
Second harmonic (532 nm)	1.27 µm	0.05 PJ	3.4 PJ	Q18, Q5: +ve SET Q19, Q2, Q16: -ve SET	1E-6	5E-5

IV. CONCLUSIONS

This research presents the procedure for using PPLS in order to avoid the high cost and time-consuming requiered in heavy-ion accelerators. The procedure depended on the excellent detection for single event transients induced by pulsed laser beam. The pulsed laser beam full scanning on DUT, shows the sensitive nodes of LM324 at energy 5.84 PJ of wavelength 1064 nm and at energy 3.4 PJ of wavelength 532 nm. Identified SET occurred in transistors (Q18, Q19, and Q9), and the resistance (R1) and the transistors (Q16, Q19, Q18, Q5, and Q2) respectively. The laser cross-section as a function of pulsed laser energies is calculated for both wavelength, showed that the single event transient induced by the fundamental laser beam is higher than second harmonic laser beam. Accordingly, 1064nm pulsed laser beam is suitable for SET predictions and fault diagnostics for space applications.

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