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Failure analysis of damages on advanced technologies induced by picosecond pulsed laser during space radiation SEE testing

C.T. Chua^{1,2}, Q. Liu¹, S. Chef¹, K. Sanchez³, P. Perdu^{1,3} and C.L. Gan^{1,2,*}

¹Temasek Laboratories@NTU, Nanyang Technological University, Singapore 637553, Singapore.

²School of Material Sciences Engineering, Nanyang Technological University, Singapore 639798, Singapore.

³Centre National d'Etudes Spatiales (CNES), 18 Avenue Edouard Belin, Toulouse 31401, France

*Phone: +65 6790 6821 Fax: +65 6790 0215 Email: CLGAN@ntu.edu.sg

Abstract- Picosecond pulsed laser, customarily perceived to offer advantages of flexibility and ease of testing over heavy ion particle accelerator test, was conducted on a chain of inverters during Single Event Effect (SEE) evaluation. In this paper, we report on the unexpected permanent damage induced by 1064 nm pulsed laser on test structures fabricated with 65 nm bulk CMOS process technology. Light emission microscopy (EMMI) localized hotspots within the area previously scanned by the pulsed laser. Electro Optical Frequency Mapping (EOFM) verified the undesired termination of signal propagation along the chain of inverters while Electro Optical Probing (EOP) confirmed the unexpected phase change and eventual loss of the output signal waveform. Focused Ion Beam (FIB), Transmission Microscopy (TEM) and Energy Dispersive X-ray spectroscopy (EDX) confirmed the physical failure and identified nickel as the diffusing species. This paper aims to advise caution to the research communities (both space radiation and optical failure analysis) in employing similar laser test technique and highlights the need to define the safe operating region of such technique, especially for emerging technology nodes.

Keywords – Pulsed laser, 1064 nm, laser damage, SEE, 65 nm, optical failure analysis, FIB, TEM.

I. INTRODUCTION

Short pulse-width pulsed laser was first employed in radiation SEE testing in 1965 [1] and over the years, there have been increased adoption of this technique [2, 3]. The pulsed laser SEE test method is widely accepted as non-cumulative as it does not induce permanent damages (displacement damage and total ionizing dose) which were commonly induced [4-6] during particle radiation tests. In addition, in the field of failure analysis, picosecond 1064 nm pulsed laser techniques have recently been demonstrated as a useful tool to conduct time resolved laser assisted device alteration analysis [7]. With the aggressive scaling down in technology nodes, advanced microelectronic devices utilize new materials and processing methods, of which, the full comprehension on material reactions and reliability can be difficult to accomplish. Most recently, Penzes and co-workers [8] reported new observations of induced damages on 28 nm test structures via a 1340 nm continuous wave laser (commonly used in optical failure analysis). This raises concerns to the suitability of employing 1064 nm pulsed laser tests in the field of test, qualification and

failure analysis as the technique itself may generate undesired artifacts.

In this paper, investigations into the suitability of using picosecond 1064 nm pulsed laser for SEE tests on advanced microelectronics were conducted. Laser damage was observed and EMMI was utilized to locate the site of damage. Subsequent EOFM analysis verified the failure of the chain and EOP confirmed the unexpected change in phase and loss of propagation of the signal after the damaged site. Focused ion beam (FIB) cross-sectioning was employed to reveal the failure site and scanning electron microscopy (SEM) images were acquired. Transmission electron microscopy (TEM) samples were prepared for the final verification of elemental analysis via energy-dispersive x-ray spectroscopy (EDX).

II. EXPERIMENTAL DETAILS

A. Test structure description

The test structure utilized in this study consisted of a chain of 100 inverters fabricated with 65 nm bulk CMOS process technology. Fig. 1 illustrates the circuit schematic of the chain with OUTx, latch and OUTy designed for the observance of SEE during pulsed laser SEE testing. As the chain consisted of an even-numbered of inverters, the OUTx terminal would naturally follow the logic state of the input while the OUTy terminal would give the opposite state of the input.

Fig. 1 Circuit schematic of chain of 100 inverters utilized in this study. The OUTx, latch and OUTy components were designed for observance of SEE during pulsed laser SEE testing.

Prior to pulsed laser test, the sample was prepared to allow for backside optical access. An x-ray image of the packaged device was first taken to locate the position of the die. Next, laser pre-decapsulation was conducted to remove the plastic molding compound and further milling was conducted to reveal

the silicon substrate. The silicon substrate was finally polished to a mirror surface to allow uniform backside optical access during pulsed laser SEE test. For reference of laser energy loss, the substrate thickness of the sample was approximately 230 μm .

B. Pulsed laser test setup and scan procedure

Two pulsed laser systems (at CNES and NTU) were utilized in this study for cross-verification of the reported laser-induced damage. The CNES setup consists of the integration of an external 1064 nm pulsed laser source of 7.5 ps pulse width to a commercial laser scanning microscope system (DCG Systems). For the NTU setup, an external 1064 nm pulsed laser source of 9.5 ps pulse width was integrated to a commercial laser scanning microscope (Semicaps) which consists of 5X, 20X, 50X and solid immersion lens objective lenses. The laser raster scheme of both setups enables the scanning of laser across the backside of the device surface in order to avoid complications from front-side metallization. In addition to the pulsed laser, the NTU setup consists of three other laser sources to conduct different optical failure analysis techniques. Table 1 shows the wavelength, type of lasing and technique capabilities of these other laser sources.

Table 1 Details of three other laser sources (in addition to the integrated pulsed laser) installed on the laser setup at NTU.

Laser Wavelength (nm)	Lasing Type	Possible Techniques
1064	Continuous Wave	OBIC ¹ , LIVA ²
1340	Continuous Wave	OBIRCH ³ , TIVA ⁴
1319	Continuous Wave	LTP ⁵

¹OBIC = Optical Beam Induced Current, ²LIVA = Light Induced Voltage Alteration, ³OBIRCH = Optical Beam Induced Resistance Change, ⁴TIVA = Thermal Induced Voltage Alteration, ⁵LTP = Laser Timing Probe

During the pulsed laser tests, the chains of inverters were biased with V_{DD} of 1.2 V, clock frequency of 1 MHz and inputs of logical state ‘0’. In this biasing condition, the OUTx terminal of the device was at a logical state of ‘0’. Pulsed laser SEE tests were conducted at a pulse repetition rate of 1 kHz and in a localized manner through restricting the laser scan area to a single inverter chain at a time. Outputs of the inverter chain were connected to an oscilloscope for observance and capture of any Single Event Transient (SET) or Single Event Upset (SEU). SET is characterized by a transient peak in device voltage due to the electron-hole pairs generated by the pulsed laser and would appear at the OUTx terminal of the test structure. If the SET possesses sufficient amplitude and duration, it will be captured by the following latch and be displayed as a change in voltage state at the OUTy terminal of the test structure (thus representing the occurrence of a SEU). Pulsed laser energy was then progressively increased until SET, SEU or permanent failure of the chain of inverters was observed.

III. Experimental RESULTS

A. Pulsed laser test results

No SET or SEU was observed at the start of the pulsed laser SEE tests and thus, laser energy was progressively increased. This increase ultimately resulted in the failure of the chain of 100 inverters. The only event observed during the pulsed laser SEE test was the rise in OUTx from a logic state of ‘0’ to ‘1’. Thereafter, power cycling and toggling of input states did not reset the device and thus, this event did not qualify as a SET or SEU. This change was permanent and OUTx of the device was stuck at a logical state of ‘1’. This denoted the permanent failure (or loss of functionality) of the chain to operate according to changes in input states.

B. Fault localization via EMMI

The Hamamatsu TriPHEMOS system was utilized to conduct EMMI through the backside of the sample using a 50X objective lens with 180 seconds of sensor integration. Fig. 2 (a) presents the results obtained via the InGaAs camera with superimposition of the device micrograph while Fig. 2 (b) presents the overlaid image of device layout and the area scanned during the previous pulsed laser SEE test. Strong photon emission spots were observed within the pulsed laser scan area and gave an indication of possible laser damage, thereby assisting in localizing the damaged region. It could also be observed that an abnormal hotspot (indicated by green arrow in Fig. 2 (a)) was located at the V_{DD} side of the inverter chain.

Fig. 2 Superimposed images of: (a) Light emission on the device micrograph and (b) Light emission overlaid with design layout and pulsed laser scan area (as indicated by yellow box). Results showed localization of light emission hot spots within pulsed laser scan area and abnormal hotspot (indicated by green arrow) at the V_{DD} side of the inverter chain.

C. Fault analysis via EOFM and EOP

EOFM and EOP were employed to conduct further fault analysis. Briefly, EOFM is based on the analysis of the reflected laser beam via a spectrum analyzer and enables the user to locate the propagating signal (at a frequency of interest) in the die. Consequently, an AC signal of 200 kHz was sent to the inputs of two inverter chains (the failed chain and an adjacent fully-functional chain). Fig. 3 (b) and (c) show that the signal propagates fully in the entire length of the adjacent fully-functional chain. However, for the failed chain, it can be observed that the signal terminates in the area previously

scanned during the pulsed laser SEE test. This further reinforced our hypothesis that the damage could have been induced during the pulsed laser SEE test and thus, causing the signal to be unable to propagate beyond this region.

Fig. 3 EOFM study showing: (a) Device micrograph, (b) Amplitude and (c) Phase. Results showed that the signal propagation terminated after the hotspot region localized in previous light emission study.

Fig. 4 illustrates another magnified scan of the device micrograph and layout, superimposed with the EOFM amplitude. The red spots indicate the region with the highest EOFM amplitude and the red arrows point to the various inverters where EOP was subsequently carried out.

Fig. 4 Device micrograph and layout superimposed with EOFM amplitude. Red spots indicate regions with highest EOFM amplitude. Points P1 to P4 indicate the various inverters where subsequent EOP were to be carried out.

Fig. 5 presents the waveforms acquired when EOP was conducted on the various inverters identified in Fig. 4. The normal signal propagation was in the direction from top to bottom of Fig. 4 and therefore, at P1, it can be observed that the initial signal waveform had a clear and defined edge. At the next inverter (where we expect an inverted waveform), the EOP results revealed an unexpected change in the phase of the signal at P2 of Fig. 4. Following this at P3, the signal was consequently inverted but a drop off in edge sharpness can be clearly observed. Ultimately, the AC signal failed to propagate to P4 and this explained the unexpected output voltage level observed after pulsed laser SEE test.

Fig. 5 EOP waveforms obtained at various inverters. At P1, a clear edge of the initial signal was observed. At the next inverter (P2), an unexpected signal phase was observed. At P3, the edge sharpness of the signal drops off and final verification of chain failure was obtained at P4 where no AC signal was able to propagate to the output of the inverter chain.

D. Physical failure analysis via FIB and TEM

The entire set of experiments was repeated on several other chains of inverters and damage was confirmed in all cases after laser energy was progressively increased. This was also verified using the pulsed laser setup at NTU and in order to further understand the failure site and possible failure mechanisms, physical failure analysis was conducted. Fig. 6 shows the photon emission micrograph taken after 1.44 nJ and 2.60 nJ of pulsed laser irradiation. Pulsed laser energies were independently measured using an energy sensor and represents the energy incident on the device under test. At 2.60 nJ, OUTx of the device changed from logical state of '0' to '1'. Power cycling or toggling of input states did not reset the device (similar characteristics as the case induced by the CNES pulsed laser setup). In Fig. 6, the device layout was overlaid to indicate positions of inverters in the design and similar to the case induced by the CNES pulsed laser setup, it can be observed that the hotspots occurred on the V_{DD} side of the layout. It was identified that the hotspots were at the locations of the 17th, 19th and 20th inverter of the chain of 100 inverters.

Fig. 6 Photon emission micrograph overlaid with device layout after pulsed laser irradiation at (a) 1.44 nJ and (b) 2.60 nJ using the NTU pulsed laser setup. Results showed abnormal hot spot at the V_{DD} side of the inverter chain, consistent with the case induced by the CNES pulsed laser setup.

With the localization of hotspot sites, FIB was subsequently employed to study the physical site of failure. Fig. 7 shows the SEM images after FIB cross sectional cuts at two locations of the 17th inverter. The device layout was included to facilitate visualization of the SEM images and it can be observed that there was an abnormal extension (yellow arrows) of the suspected silicide layer at A-A', as compared to B-B'.

Fig. 7 (a) Device layout showing the PMOS transistor and V_{DD} side of the inverter chain and (b) SEM imaging after FIB cross sectional cuts at two locations (A-A' and B-B') of the 17th inverter. Yellow arrows point to abnormal extension of the suspected silicide layer at A-A', as compared to B-B'.

Fig. 8 (a) shows the high resolution SEM image of the A-A' cut (PMOS of 17th inverter). The extension of the suspected silicide layer towards the gate terminals can be clearly observed. Another FIB cut was made at the 19th inverter and Fig. 8 (b) shows that the extension of the suspected silicide layer to the gate terminals were consistent.

Fig. 8 High resolution SEM images of: (a) PMOS of the 17th inverter and (b) PMOS of the 19th inverter. Results showed that abnormal diffusion of the suspected silicide layer was consistent in both inverters. Yellow arrows point to abnormal extension of the suspected silicide layer towards the gate terminals.

With the verification and localization of the failure site in the 19th inverter, TEM samples were prepared and EDX mapping was conducted to verify the suspicion of silicide diffusion. Fig. 9 shows the TEM images and EDX mapping centered around the two gates of the 19th inverter. From the TEM images, it was clear that the dark layer had extended under both gates and

subsequent EDX mapping confirmed that these dark layers were actually nickel diffusion.

Fig. 9 TEM images and EDX mappings centered on (a) left gate terminal of Fig. 8b and (b) right gate terminal of Fig. 8b. Green, red and blue traces were EDX mappings of Nickel, Copper and Tungsten respectively. Results verified nickel diffusion as the root cause of the laser-induced damage in the chain of inverters.

IV. DISCUSSION

From the presented results, it can be observed that there was diffusion of nickel in the silicide layer to the gate terminals of the test structure. The extent of diffusion observed in the experiments indicates that these diffusions could cause potential shorts between the source-gate, drain-gate or even source-drain-gate terminals. For an even-numbered chain of inverters, the OUTx terminal of the test structure is expected to follow the logical state of the input. Considering the electrical characteristic of the induced damage where the OUTx terminals were stuck at a logical state of '1', several paths of failure could be proposed. Suppose the induced damage occurred at an odd-numbered inverter's PMOS, a short between the gate (input to this stage of inverter) and the source (V_{DD}) would

cause the NMOS to be permanently 'ON' and thus, the OUTx terminal would be stuck at a logical state of '1'. Suppose the induced damage occurred at an even-numbered inverter's PMOS, a short between the drain (input to the next stage of inverter) and source (V_{DD}) would cause OUTx terminal to be stuck at a logical state of '1'. Lastly, in the case where the gate is shorted to the drain terminal, the phase of the OUTx terminal would be inverted. It should be noted that these failure paths were possible and such electrical characteristics were indeed observed during the series of conducted experiments. Further investigations conducted via single-point pulsed laser irradiation could limit the damage to a single inverter (be it odd or even) and potentially pin down the relevant failure paths. Nevertheless, the conclusion and observance of laser-induced damages in this study would still be valid.

In addition, another topic for discussion would be the relevance of laser energies used in this study. It was already well known that high laser power would cause material degradation or vaporization. In fact, this property had been commonly utilized to conduct laser ablation of materials [9] and these systems usually require much higher powered lasers with longer pulse widths. However, in the case presented in this paper, the laser energy used was not expected to be excessively damaging to the device. Several other pulsed laser facilities [10, 11] had been reported to conduct SEE tests using even higher energies of up to 50 nJ. It remained unclear if the laser energy values quoted in these facilities were measured at the source or at the device under test level. It would be rewarding if this study ultimately encourages the importance of establishing cross-calibration methods or standards between various pulsed laser SEE test facilities. With a common standard for specifying the pulsed laser energies at each pulsed laser SEE test facility, the community could benefit from the establishment of the safe operating region of laser energies to conduct SEE tests on advanced devices. Also, it should be noted that pulsed laser SEE tests conducted by the author on other commercial silicon based devices fabricated with older technology nodes did not suffer from such permanent laser-induced damages. These damages could be specific to the fabrication processes or new materials used in this (or more advanced) technology nodes.

Lastly, the role of electric field in the observed laser-induced damages should be discussed. The 1064 nm wavelength was commonly used in optical failure analysis as the wavelength is above the bandgap of the silicon semiconductor and thus, electron-hole pair generation is the dominant mechanism (as compared to thermal effects). On the contrary, the 1340 nm laser was commonly used to induce thermal effects as the photon energy was less than the silicon bandgap. In the attempt to separate these effects, the authors had conducted pulsed laser SEE tests without biasing of the device and still observed laser induced damages at relatively similar laser energies. In the absence of electric field, several other research groups [12-14] had already demonstrated that pulsed laser was capable of inducing annealing effects on nickel silicide layers. However, these were demonstrated via pulsed laser of much shorter

wavelengths (or higher photon energy) which were less than 355 nm and longer pulse duration (10 to 150 ns) than the pulsed laser utilized in this paper. Also, these research groups found that the pulsed laser caused annealing effects and impacted the nickel silicide layer after laser fluence of 0.3 to 0.6 J/cm². In contrast, for this paper, a maximum laser fluence of 0.06 J/cm² was utilized during the experiments and impacts on nickel silicide layer were already observed. Further investigations are needed to fully ascertain the mechanism driving the impact of 1064 nm picosecond pulsed laser on nickel silicide layers. Nevertheless, this paper provided clues on the laser fluence required to induce impacts on nickel silicide and thus, could form the basis for establishing the safe operating area for future tests on advanced microelectronic devices.

V. CONCLUSION

With the increasing popularity of using short-pulsewidth laser in various communities (e.g., radiation test and optical failure analysis), we can expect an increased rate of adoption for such techniques. With the laser-induced damage findings presented in this paper, the authors aim to raise awareness of the need to determine a safe laser energy operating area for future tests on advanced microelectronic devices. This is especially crucial in view of the new materials and processing methods in emerging technologies. Further investigations are planned to study the impact of electric field, laser repetition rate and laser spot size (optical density) on the induced damages. These investigations could contribute to the establishment of a safe operating region for the conduct of pulsed laser SEE tests on advanced microelectronic devices. Lastly, as discussed in section IV of this paper, it is possible that such low damage threshold could be specific to the fabrication process or materials used in this paper. More investigations are needed before generalizing these laser-induced damages on this (or more advanced) technology node(s).

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