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Abstract
By inducing two-photon absorption within the active layer of a 28nm test chip, we demonstrate nonlinear laser-assisted device alteration and single-event upsets by temporarily perturbing the timing characteristics of sensitive transistors. Individual qualitative and quantitative evaluations are presented for both techniques, with lateral resolutions demonstrated with sub-100nm performance. A simplistic signal response rate comparison analysis of these two technologies is also presented.

Introduction
Dynamic laser stimulation [1] covers an extensive range of microelectronic device probing configurations and technologies for advanced complementary metal oxide semiconductor (CMOS) integrated-circuit (IC) failure analysis (FA). Recent developments in this regime of semiconductor device FA have exploited the use of laser scanning near infrared microscopy for the purposes of through-silicon fault localization and defect characterization. Based on the acquisition of either laser-induced photo-electric or photo-thermal functional test mapping, these precision through-substrate technologies traditionally utilize a continuous-wave (CW) 1064nm or 1340nm laser source, respectively, for set-up simplicity and minimal cost. Examples of such analytical optoelectronic probing platforms include soft defect localization (SDL) [2] and laser-assisted device alteration (LADA) [3]. These advanced modalities function by coaxing operationally sensitive transistors to advance or delay their switching characteristics in order to alter the pass/fail outcome of a pre-determined marginal test stimulus. This outcome provides vital information for globally localizing, with diffraction-limited lateral isolation performance, critical speed path design marginalities. However, the absence of temporally-profiled functional device information overlooks an important facet of the potential root cause silicon data set. Consequently, several within the semiconductor FA community have begun to develop custom pulsed laser-based, applications-driven, laser probing variations for the advanced interrogation of nanoscale flip-chip architectures. Interestingly, the optoelectronic probing conditions required for this variety of dynamic laser stimulation can also enable another avenue of silicon device FA to be exploited and explored. Femtosecond near-infrared radiation can deliver significant levels of peak optical power to a functional device which, in turn, can temporarily disturb the prescribed digitization level in local memory cells, holding their individual transistors in artificially high electronic states until the operational sequence is reiterated. This particular situation describes single-event upsets (SEU). SEU, which belong to a wider group of radiation-induced anomalies known as single-event effects [4-8], is characterized by the non-permanent perturbation (or, more specifically, change of state) in a microprocessor’s functionality caused by an individual node’s sensitivity to incident high-energy particles or electromagnetic radiation. These soft errors have been widely studied in many programmable logic devices [9-10] and have even, as is demonstrated here, been generated through the use of two-photon absorption (TPA) [11-12]. However, although linear and nonlinear SEU implementation and characterization are commonplace in the
aerospace and defense research communities, the originality of this particular result originates in the unique signal extraction methodology. CMOS SEU tolerance is typically assessed by observing the output operational states of critical logic elements as systematic increments of the incident ionization energy stimulate the device. In this particular configuration however, the magnitudes of SEU are monitored by way of a pass / fail test stimulus where a single laser-induced disturbance during any test cycle causes the test to fail by producing logic upsets of the flip-flops during the scan-in and scan-out portions of the test.

As a result, we demonstrate here the first observation of solid immersion lens (SIL)-enhanced TPA-induced SEU’s (2pSEU) monitored and assessed by way of an electrical LADA-based tester stimulus. Qualitative discussions are made to compare and contrast the optoelectronic properties of continuous wave (CW) 1064nm LADA, 2pLADA and 2pSEU generation. In addition, an individual quantitative analysis of both lateral fault localization resolution (2pLADA) and lateral response rate (2pSEU) is offered which will serve as a varied discussion on our nonlinear optical and tester-based optoelectronic interactions. Lateral performance approaching 100nm and 40nm, respectively, is reported.

**Experimental Procedure**

The device under test (DUT) was a proprietary 28nm bulk silicon test device containing production logic blocks. To exercise the device, a production scan test was modified to engineer a race condition. The race was created by reducing the time between the rising edges of a capture clock pair. The race was then between the clock pair timing and the propagation time through the connecting data path logic. Using the capture clock pair, it was possible to bias the test close to a 50% pass and 50% fail probability boundary after each successive test loop, which lasted for 21μs. This condition is ideal for performing LADA. The device was housed in a custom load board which was connected to a full capacity test platform (LTX Credence D10 Diamond Series) through a 768 pin interface board (RTI Technologies). Control and implementation of the race condition was performed using the D10 tester. Observation and acquisition of the resulting fail rate was performed by a custom field-programmable gate array (FPGA) applications board and associated software. Optical interrogation of the device for simultaneous confocal reflection and optoelectronic imaging was performed by a femtosecond 1280nm laser scanning microscope (LSM) using both a 0.8NA (100X) air-objective lens and a 2.45NA (220X) GaAs SIL-enhanced probing platform. The laser employed was a linearly polarized Raman-soliton fiber laser (pulse duration = 200fs, repetition rate = 100MHz, average power = 20mW, peak power = 5kW) whose repetition rate was locked to 100MHz by using the error signal acquired from a feedback locking circuit. This repetition-rate locking feedback circuit was controlled in the MATLAB programming environment. The pulse arrival time from the laser to the DUT was calibrated and controlled by a phase-locked loop (PLL) circuit, whereby phase adjustments to the locked PLL output signal would dictate the pulse phase (temporal position) of the laser [14]. Control and visualization of the PLL board parameters, the device fail rate and the LSM were achieved through a personal computer.

**Experimental Results**

Figure 1 (a) through (d) illustrate our initial observations of both 2pLADA and 2pSEU signatures using a 100X objective lens. Figures (a) and (b) represent the simultaneously acquired confocal reflectance and optoelectronic image of a pre-determined region of interest (ROI) containing dense logic blocks, respectively. As can be seen in Fig. 1 (b), there is a diffuse 2pLADA site which is manifested as a laterally extended black (passing) signal surrounding a simple inverter structure, but there is also additional information in the form of a cluster of intense failing (white) sites which are highly localized to individual transistors in a series of flip-flops. Although captured in a LADA image, these strong electrical signatures do not correspond to the customary pass / fail signals produced by LADA stimulation. Instead, they represent a collection of 2pSEU. Figures (c) and (d) represent the same ROI’s as described above; however, this time with a 16.5μm lateral shift. The lateral shift was implemented to confirm that the 2pSEU sites were not artificial and that they could be repeated and traced out with respect to the 2pLADA site. This result confirmed that not only were both the 2pLADA site and the 2pSEU sites valid but also that it was possible to map out, with high spatial accuracy and sensitivity, 2pSEU activity by way of a LADA-based acquisition methodology.
Extending the analysis further, it was decided to examine both the spatial extent to which these 2pSEU sites could be observed as well as their sensitivity to fail rate – which, for LADA measurements, is typically set to 50% before data acquisition. Therefore, a larger ROI was interrogated and two predefined fail rates were used. The results are shown in Fig. 2 with (a) and (b) representing the optical and electronic image of the extended ROI with a fail rate of 20%, respectively, and (c) and (d) representing the optical and electronic image of the extended ROI with a fail rate of 90% respectively. It is clear from these data sets that the 2pLADA sites exhibit an, as expected, fail rate dependence, highlighted by the faded black signals in Fig. 2(b) and the stronger black signals in Fig. 2 (d), whereas the 2pSEU sites on the other hand exhibit a weaker fail rate dependence since they are still observed with considerable magnitude no matter the fail rate setting. In addition, with regard to the magnitude of 2pSEU global interaction, these sites can be activated over a significant portion of the logical area.

In addition to fail rate, an analysis was also performed to investigate the 2pSEU dependency on pixel dwell time. This was an important evaluation since the LADA-based acquisition scheme was sensitive to the duration of the loop length of the test (which was configured to be 21μs). The results are illustrated in Fig. 3 and demonstrate a significant outcome. Figure 3 (a) shows a similar ROI to that captured in Fig. 2 and Fig. 3 (b) highlights the resulting 2pLADA image taken with a 4% fail rate and an 8μs pixel dwell time. Figure 3(c) also shows a laterally-shifted ROI; however, Fig. 3 (d) shows the resulting 2pLADA image taken with a 45% fail rate and a 32μs pixel dwell time. This is a key result since it demonstrates that even though the loop length has been reduced by 4X the 2pSEU sites are still intense. This leads to the conclusion that, unlike with the 2pLADA analysis where the laser pulse arrival time is critical, the 2pSEU sites do not exhibit a laser pulse arrival time dependency and are therefore an artifact of the stimulus scheme. The 2pSEU fail sites occur at flip flops that are not directly related to the engineered stimulus condition. These flip flops, however, during the scan-in and scan-out portions of the scan test, propagate the stimulus to the engineered race and to other circuits in the device, and output the response of the race and other circuits back to the
The test loop time is dominated by both the load and unload portions of the test. Due to the high cumulative probability of laser-induced disturbances due to the thousands of laser pulses interacting with the device during every test loop, the 2pSEU site causes a failing LADA test result that is significantly stronger, and more localized, than its 2pLADA counterparts.

Another important parameter to investigate was the focal sensitivity of the 2pSEU generation. As is well known, two-photon absorption is a nonlinear optical process in which the resulting signal generation is proportional to the square of the incident optical intensity [13-15]. Naturally, femtosecond laser sources are ideal candidates for this type of interaction due to the magnitude of peak power per laser pulse on offer (up to 5kW in this work). However, aside from the temporal domain, the spatial domain also facilitates such requirements through the adoption of high-NA optics. This leads to both a lateral and axial intensity dependence which, for this evaluation, the latter serves as the parameter of interest. Due to our tight focusing arrangement, there will be a pseudo optical sectioning capability which can be utilized as an additional evaluation opportunity (i.e. an intensity-dependent focal dependence which can be exploited). For this, the focal plane of the imaging system was translated by 1μm and the resulting 2pSEU generation observed. The results are shown in Fig. 4 (b) and (d). It is clear that there is a strong 2pSEU focal dependence which confirms that the optoelectronic stimulation is of a nonlinear nature. It should be noted here that the objective lens used in this evaluation was a 100X air-objective. Therefore, care must be taken when considering the same effects in a solid immersion lens- (SIL) enhanced system. When using a hemispherical SIL, there is an axial scaling factor of n which must be considered, with n representing the refractive index of the SIL material. Therefore, for a hemispherical SIL, a 1μm axial translation of the device is reduced to an optical translation of only 287nm if n is taken to be 3.48 (silicon).

Figure 3: (a) A 1280nm confocal reflectance image of a larger ROI; (b) the resulting 2pLADA image taken with a 4% fail rate and an 8μs pixel dwell time; (c) Another 1280nm confocal reflectance image of the larger ROI and; (b) the resulting 2pLADA image taken with a 45% fail rate and a 32μs pixel dwell time. It is clear that in addition to fail rate, the 2pSEU sites demonstrate a reduced pixel dwell time sensitivity in comparison to conventional LADA acquisitions.

Figure 4: (a) A 1280nm confocal reflectance image of a reduced ROI; (b) the resulting 2pLADA image taken for optimized 2pSEU generation; (c) Another 1280nm confocal reflectance image of the same ROI as in (a) but which has been axially shifted by 1μm and; (b) the resulting 2pLADA image. It is clear that the 2pSEU sites show a strong focal dependence, characterized by their nonlinear interaction.
When considering only the 2pLADA results, and to serve as a direct qualitative comparison, Fig. 5(a) and (b) illustrate the imaging capabilities of an optimized conventional CW 1064nm LADA system and 2pLADA system, respectively. The optical power incident before the 2.45NA GaAs SIL (for both configurations) was only 0.35mW (peak power = 16.4W for the pulsed laser), the number of averaged images was 200, the optical zoom was set to 8X, the pixel dwell time was 32μs, the LSM resolution was 512 × 512, the fail rate was set to 50%, and the laser pulses (separated by 10ns) were synchronized to start arriving 3.06ns after the test loop trigger. It is immediately clear from Fig. 5(a) that the traditional CW 1064nm LADA methodology is unable to localize its weak signal to individual transistor sites, offering instead a global single polarity (i.e. predominantly passing) signal distribution which cannot be overlaid with accompanying CAD details. 2pLADA on the other hand overcomes these limitations and can produce a plurality of highly localized LADA signatures which, when the incident laser pulse is accurately synchronized to the inverter’s switching event, emanate from vertically displaced PMOS and NMOS transistors comprising a simple inverter structure that is not limited by PMOS dominance. Moreover, with only 0.35mW incident at the device, and with only 200 averages performed per imaging technique, it is clear that 2pLADA outperforms its CW 1064nm LADA counterpart in terms of signal acquisition rate. The high peak power of the pulsed laser interrogation makes it possible to perturb and visualize weaker LADA spots to a larger degree without damaging the device – laser damage is of great concern as transistor size shrinks with scaling.

For the purpose of evaluating the lateral fault localization performance of our 2pLADA scheme, we offer the following argument: Conventional spatial resolution metrics, such as Rayleigh’s criterion for example, were derived by defining the minimum resolvable separation distance between neighboring point sources, which assume an isotropic signal distribution when observed. Therefore, for LADA-based evaluations, were physical circuit features (assuming an extended geometrical distribution) are involved, an identical comparison simply cannot be made. As a result, since measured LADA signals occupy a digitized (i.e. either pass or fail) 2D physical area, we argue that the more appropriate methodology to adopt is a direct measurement of the electronic response representing the physical distance between the critical structures under test. Therefore, in terms of quantitatively evaluating the 2pLADA isolation resolution performance from this data, it was decided that the vertical gap separating the two neighboring 2pLADA signatures in Fig. 5 (b) should be used as the defining spatial metric. This gap between the active PMOS and NMOS nodes of this simple inverter was measured to be 117nm from the computer-aided design (CAD). For this analysis, a total of 630 2pLADA images were accumulated as a running average and a collection of 4 neighboring vertical line-cuts were extracted which suitably traversed the 2pLADA signatures in Fig. 5 (a). These 4 line-cuts were then averaged and plotted. However, due to the opposing polarities of the neighboring 2pLADA sites, it was difficult to accurately determine their separation. Therefore, the absolute value of the averaged line-cut was plotted. This enhanced the measurement since an all-positive data set revealed a more distinct separation between adjacent signatures. However, before measuring the physical separation between the neighboring pass/fail 2pLADA signatures, we first need to determine the magnitude of the 50% fail rate biasing fluctuations, since this variance represents our reference point. Anything above or below this 50% threshold will represent clear laser-induced delays to the switching transistors. This result is shown in Fig. 6(a) and a magnified section containing only the 2pLADA sites is given in Fig. 6 (b). From this data, it was possible to measure a 2pLADA isolation resolution performance approaching 100nm.
Figure 5: (a) A CW 1064nm LADA image and (b) a 2pLADA image acquired using 200 averages. The CAD overlay in (b) highlights the active area silicon (orange) and poly-silicon gates (green).

Figure 6: (a) An averaged line-cut illustrating the absolute values taken from a collection of 4 neighboring vertical line-cuts extracted from the 2pLADA signatures shown in Fig. 5 (a) and; (b) a magnified version of (a) which concentrates only on the 2pLADA signals. The red dotted lines represent the biased 50% fail rate variance.
For the 2pSEU sites, we observed a sub-diffraction-limited fault localization performance which can be explained by considering how the apparent signal localization performance is enhanced by a number of experimental factors. First, the laser is pulsed once per test vector (100MHz, or every 10ns); second, the laser is pulsed during the scan-in and scan-out portions of the test; and third, incident laser pulses strike the device thousands of times during the 21μs test loop. As a result, in a scan test, it becomes highly probable for the contents of the flip-flops, which are exercised almost every test cycle, to be corrupted at some time during the test loop since a single disturb during the test cycle will cause the test to fail. As illustrated in Fig. 7(a) and Fig. 7(b), the full-width at half-maximum diameter of the smallest 2pSEU in our dataset was measured to be 150nm; however, since the 90nm wide active transistor area assumed abrupt edges, an apparent 2pSEU lateral signal response rate performance, when approximating the 10%-90% transition distance, returned ~40nm. However, please note here that this signal response and resulting resolution performance, however impressive, is amplified due to cumulative probability effects as a result of the tester’s response to the light-matter interactions. It is clear from this analysis that a more rigorous experimental investigation needs to be completed before we can adequately define our 2pSEU performance.

With that said, in an attempt to compare and contrast these two unique technologies, we have attempted a direct correlation analysis between the 2pLADA and 2pSEU sites by adopting this simplistic 10%-90% transition approach. The results from the 2pLADA data in Fig. 6(b) are given below:

- Left edge of passing site ~115.4nm
- Right edge of passing site ~123.1nm
- Left edge of failing site ~94.9nm
- Right edge of failing site ~92.3nm

Therefore, we have measured 2pLADA sites to have edge rise/fall response rates of approximately 92nm - 123nm. It is clear from this data that, when compared to the cumulative probability effect of the 2pSEU sites results, one can expect to recover rise/fall time improvements between 2.25X and 4X from this unique LADA-based 2pSEU stimulus.

Finally, it should also be noted that although the 2pSEU signals may appear to be visually distracting and limiting at first (especially if they interfere with a LADA signal of sufficient importance), it is straightforward to remove them completely by simply modifying the race condition applied to the device. Furthermore, their presence and generation sensitivity can be utilized to extract important device information. For example, they could be used for fault injection analysis, or as intense beacons for the purpose of addressing CAD alignment requirements and/or limitations.
**Conclusion**

In conclusion, we have demonstrated a custom ultrafast nonlinear optoelectronic probing platform for the purpose of advanced IC debug and characterization. Datasets qualitatively evaluating CW 1064nm LADA, 2pLADA and 2pSEU generation have been discussed with a quantitative evaluation of lateral signal localization (2pLADA) and signal response rate (2pSEU), deducing approximately 100nm and 40nm lateral resolution performance, respectively. By way of a simple comparative analysis, it was possible to deduce 2.25X to 4X improvements in rise/fail time response rates when utilizing 2pSEU over 2pLADA. This work demonstrates a new LADA-based evaluation opportunity for modern SEU analysis and offers a complementary toolset for other SIL-enhanced TPA-based IC characterization techniques [13-15]. We have now set the standard in optoelectronic microscopy of silicon ICs in terms of localized volumetric resolution performance, invasiveness, and opportunity. In addition to the impressive spatial performance of both 2pLADA and 2pSEU, the temporal performance of this technique also offers a significant advantage which has yet to be fully explored.

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