Reply for Reviewer

First of all, I want to present my sincere respect to this reviewer, for his/her detailed and profound comments, which gives me much inspiration and makes me think deeper about my testing.

Following part is my response to the comments from the reviewer (comments are written in red color, and my response is in black color).

1. Title: remove The…..

Ans:

Changed the title as comment suggested.

2. Abstract: Z axis?? Define that… instead e.g. write in the axial direction…

Ans:

The Z axis means the direction of the injection of our laser beam. If our testing board is in a X-Y plane, the Z axis is perpendicular to that plane, which is shown in Fig. 1

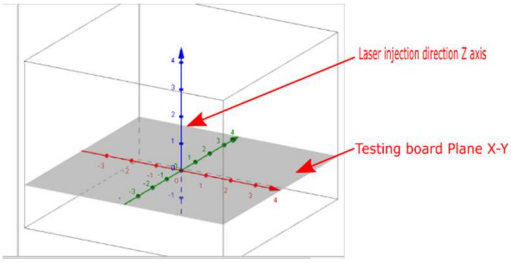


Figure 1. Relationship for X-Y and Z axis

3. Page 2 line 35: 1.108 um, remove one digit: 1,11 um

Ans:

The threshold value λ_0 (1108 nm) of wavelength is calculated from the Planck's equation ($E = hv$) and light speed equation ($c = \lambda v$), with the $E = 1.12$ eV.

If the wavelength of injected laser is less than λ_0 (1108 nm), the Single Photon Absorption (SPA) will occur, whereas if the input wavelength is more than λ_0 and less than $2\lambda_0$ (the input energy should be larger than half of the band gap), the Two Photon Absorption (TPA) will occur.

So here, I want to keep the accurate number of this threshold value.

4. Page 2 line 35: …the injected laser light…

Ans:

Changed the content as comment suggested.

5. Page 2 line 44-45: ….in a semiconductor material….

Ans:

Changed the content as comment suggested.

6. Page 2 line 47: ….the linear and non linear TPA…coefficients….

Ans:

At this part, α is the linear absorption coefficient for SPA; β_2 is the non-linear absorption coefficient for TPA.

7. Equation 2: write an approximation when the TP process dominates..

Ans:

Changed the content as comment suggested.

8. Equation 3: how has is the time dependence been removed?

Ans:

The right part of equation (2) is independent with time. So if we integrate both sides of equation (2), the following equation can be gotten.

$$N(r,z) = T_{pulse\ duration} \times \frac{\beta_2}{2\bar{h}\omega} I^2(r,z)$$

Thank you very much to point this fault to me.

9. Page 2 line 62: Assuming a Gaussian beam…

Ans:

Changed the content as comment suggested.

10. Equation 6: w, w0 and omega looks quite similar!!

Ans:

In latex, the letter of ‘w’ in an equation looks quite close to Greek letter ‘omega’. I replaced the symbol ‘omega’ by ‘nu’ (ν), so all the symbol ‘w’ in this paper stands for letter ‘w’.

11. Equation 8: write approx. and for r->0

Ans:

Changed the content as comment suggested. Meanwhile, the equation (8) has been re-derived.

12. Page 3 line 83: Z axis ??

Ans:

The meaning of Z axis has been explained upwards.

13. Page 3 line 97: Why exactly 1250 nm wavelength and not eg. 1300 nm?

Ans:

When our laser beam came out from RegA 9000, with the wavelength of 800 nm and power around 40 mW, it will go into the OPA9800. Once the beam enters the OPA9800, it will be split into two portions: one with 25% energy and the other with 75% energy. The 25% beam will be converted into white light by a sapphire crystal, and work as a seeding source; whereas the 75% beam will work as a pump source. Finally, these two beams will meet at an OPA non-linear crystal, which will pick up a signal beam with specific wavelength by being different angle.

The reason why I choose the wavelength as 1250 nm is on one hand, the wavelength should be as close to 1108 nm (threshold wavelength) as possible, because the shorter of the wavelength, the larger of the energy for each photon; on the other hand, our hardware (optics) can work at this wavelength with most stable status.

14. Figure 1: add more figure test description (the is the same for almost all figures!)

Ans:

Real practical testing figures were added as comment suggested.

15. Should stage 1 not contain a pump?

Ans:

Yes, it definitely needs to contain a pump laser. I made a HUGE mistake here, **APOLOGIZE** for this carelessness. The figure 1 was re-drawn.

16. What is the SPA output used for??

Ans:

The SPA output (OPA9400) is used to generate laser pulses with the wavelength in range of 480—700 nm. This signal is used for SPA testing. However, presently we don't use the methodology of SPA, because it can not penetrate deep into the silicon chips. Since we don't use it, I removed the SPA part from the figure 1.

17. Figure 2: please show the correct direction of z with only one arrow

Ans:

The arrow for Z in figure 2 shows the direction that our objective lens can move. It can move upwards and downwards. Below the objective lens, there is a moving stage from ThorLab. It can provide us ability to move the Device Under Testing (DUT) in X-Y plane.

To our system, the Z direction means we can move the objective lens up and down, consequently the focus point would be moved up and down correspondingly. This ability provides us the technical tool to make an energy distribution profile in Part 2.2 of this paper.

18. Page 5 line 118: Remove "once a week" amd in line 144 remove "in the morning"

Ans:

Changed the content as comment suggested.

19. Page 5 line 126: This equation is NOT valid for e Gaussian beam!!!! This is the equation valid for diffraction through a circular aperture!! What is the beam diameter before entering the microscope objective compared to the entrance diameter??

Ans:

The equation I used is from Airy ring theory, which is based on diffraction theory. The reason why I chose this equation is that our microscope is set up by ThorLab company, and this equation is listed in their website.

In our system, I use a beam reducer to control the beam size. When the laser beam reaches the objective lens (back side), the beam size is just filling the entrance side of the objective, to make sure there will be maximum output from the lens.

For a Gaussian beam, the minimum waist w_0 has such relationship with the diverging angle θ:

$\Theta = 2\lambda/(\pi w_0)$; and if D is the diameter of the lens, f is the focal length, then $\theta \approx D/f$. Meanwhile, NA = D/2f.

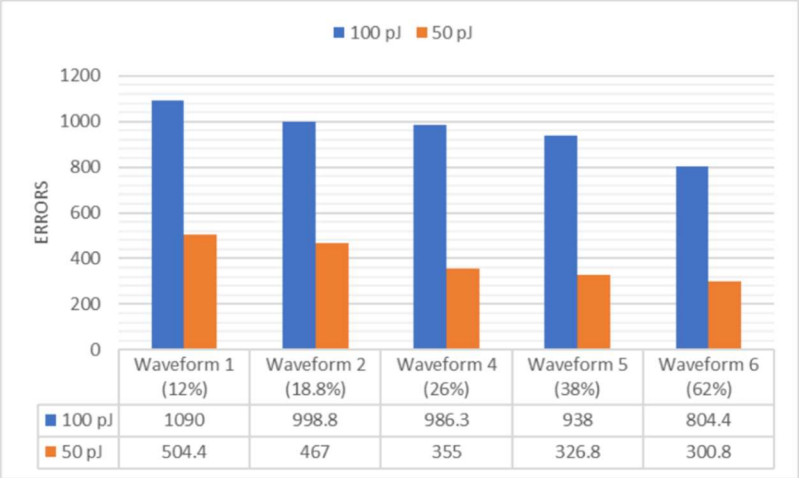
So finally, we can get the expression of w_0.

$W_0=2\lambda/(\pi NA)$

20. Figure 3: the interpretation of this figure is not clear, please update text accordingly.

Ans:

Here, 3 more groups of data have been added into the figure 3, which are with different noise level from 26% to 62%, shown in following figure.



	Waveform 1 (12%)	Waveform 2 (18.8%)	Waveform 4 (26%)	Waveform 5 (38%)	Waveform 6 (62%)
100 pJ	1090	998.8	986.3	938	804.4
50 pJ	504.4	467	355	326.8	300.8

The percentage in the brackets means the waveform noise level of laser pulses. By comparing the error number and noise level, it's also helpful to find out the trend of error change with different noise level, so as to find a stable working condition for laser system.

In above figure, there are five groups of data, with increasing noise level from 12% to 62%. In real testing, if the level of noise could be controlled under 20%, the error number with 50 pJ would be close to half the error number with 100 pJ, which means the laser system works in a stable status; however, as the noise level increased, the total errors generated from both energy declined correspondingly, and the error number with 50 pJ deviates from half the error number with 100 pJ.

21. Page 6 line 158: kHz not KHz (also a mistake other places in the manus)

Ans:

All the ‘KHz’ in the paper has been changed to ‘kHz’.

22. Figure 4 is not giving any information, can be written using only text. And, if the figure should be used, convert data to a nice graph in a suitable graph program and not a screen-shot from an oscilloscope.

Ans:

I tried to use the figure 4 to show the ability of system to control the laser pulses. Since it can hardly provide such information, the figure 4 is abandoned, and only text is used to describe the content.

23. Figure 5; what does the red color indicate??

Ans:

Inside the real SRAM die, there are metal wires around SRAM cells. These metals will reflect light extensively, which will form that 'red area'. It means high reflection area, and will not affect our testing results.

24. Figure 6: change to "proposed"

Ans:

Changed the content as comment suggested.

25. Page 9 line 203: Is alpha radiation the same as Heavy Ion (HI) testing?. If yes, use the same nomenclature.

Ans:

Alpha radiation is not that similar to Heavy Ion (HI) testing. HI testing needs to use accelerator to gain energy; whereas, alpha testing just needs to put a radiative source on top of our DUT. The physical function of them are also not quite the same. For HI testing, it is more directional and has more energy.

26. Merge table 3 and 4 for direct comparison.

Ans:

Changed the content as comment suggested. Corresponding modification in paper has also been finished.

27. Figure 7: is this a calculated plot??

What info is gained from this simple plot – it is not clear for what purpose it has been used in the obtained measurement results. I think this figure can be removed.

Ans:

Because our testing is based on the TPA theory, so it's quite important to make it clear for the energy distribution along Z axis. The TPA process can only happen in the focused region (it highly depends on the irradiation of the laser pulse).

In this part of paper, I firstly find the best focused region and record the threshold energy. After that, I move the beam upwards and downwards to monitor the change between moving distance and threshold energy, which is shown in table 5.

The figure 7 would show us a direct profile of the energy distribution along Z axis. In the central / yellow region, it's in the best focused region and has the full energy. If we move upwards or downwards along Z axis, figure 7 can give us information for the changing of the energy, which will be helpful during the real testing when you plan to check your focused region.

28. Figure 10: explain color scale. One could also using a fine mesh indicate the step size of 0.18 um , in total 60 scan-points.

What is the speed of this scanning TPA method?

Ans:

With the all zero data pattern, only one energy (90 pJ) was used for testing. The red region represents the location that generates the error, which is sensitive area. So there is no color scale for this sensitive map.

The grid has been changed as comment suggested.

Our system uses a Beam Scanner Module (BSM) to inject laser pulse into DUT, rather than moving the stage that holds the DUT. Inside the BSM, there are two voltage-controlled mirrors used to reflect laser beam into the ROI precisely. In real testing, the laser beam would dwell at each step inside the ROI by 100 us, which is the opening window time of the pockel cell, to ensure one pulse can be injected into this location.

29. Figure 11: explain color scale, grid,….

Ans:

Answered in question 28.

30. Figure 12: text is to small. Indicate node A and node B. Explain color scale.

Ans:

Changed the content as comment suggested.

The color scale is the LET energy ranging from 0.01 to 0.5 pC/um.

31. Page 14 line 285: eq. 8 has not been used to correlate N with puls energy. This is an important information!!

Ans:

Calculation for theoretical number of free charge generated by a single laser pulse with certain threshold energy has been added in the Section 2.1.

In Table 3, the first column is the threshold energy for each SRAM structure; the second column is the Error rate by Alpha radiation; the third column is the number of free charge calculated by equation (8).

At last, Thank you very much again for the meaningful comments!