Two-photon absorption in CMOS image sensors

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Abstract

This paper characterises the response of a CMOS image sensor with 2.7 µm pixels to light at 1550 nm. Two-photon absorption (TPA) occurs when two photons with an energy lower than the silicon bandgap energy interact with the same electron within a short time window. This can be achieved by a focused pulsed laser beam above a critical light intensity. Our results show that for a burst of 450 fs light pulses at 1550 nm focused on a single pixel, a pulse light power of 66 mW is the minimal detectable level for this device. Due to the nature of TPA, the detection efficiency scales linearly with light power above this detection limit.

Index Terms: CMOS image sensor, two-photon absorption, laser, NIR, SWIR

I. Introduction and motivation

In traditional applications, the usable spectrum of CMOS image sensors is limited to wavelengths below 1100 nm where linear or single-photon absorption (SPA) occurs. In this case, one photon has sufficient energy to excite an electron from a valence band to the conduction band, which results in a detectable signal in an image sensor. For wavelengths above 1150 nm, photons are not absorbed and silicon is transparent. However, if two photons with an energy above half of the bandgap energy interact with the same electron within a short enough time window, their combined energy can be sufficient to excite an electron into the conduction band. This is called two-photon absorption (TPA) and can be achieved by focusing a high energy pulsed laser beam through a lens. For TPA to occur, two photons need to interact with each other within a few fs (in [1]) to a few hundred fs (in [2], [3]). Figure 1 visualises the two effects.

There have been some reports of TPA on image sensors in the past, but they always needed a big and powerful laser [1], [2], [4], [5]. Major improvements have been achieved however over the last decades in CMOS image sensor technology. The sensors have become more sensitive with much lower noise, almost capable of single photon detection [6]. At the same time lasers have also improved considerably the last few decades. They have become more compact and less expensive with a higher laser power [7]. One of our goals is to research if both CMOS image sensors and lasers have improved sufficiently to combine them for practical, miniaturised TPA sensing applications. Another goal is to see what the impact is of pixel design and CIS technology on TPA and if TPA can help to characterize CIS pixels.

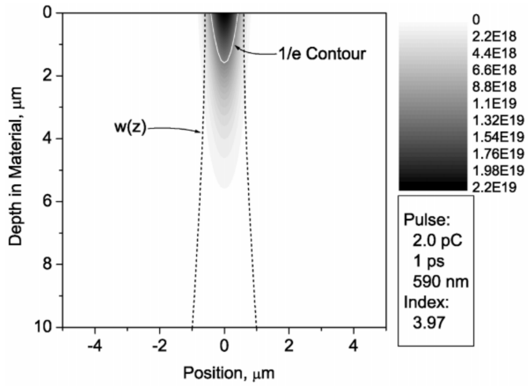
The combination of TPA with CMOS image sensors could lead to multiple short-wave infrared (SWIR) light applications for optimized CIS. The alignment of an optical inter-satellite communication link through TPA [2] has been reported. SWIR light sensing applications using standard CMOS could be considered in applications like SWIR spectroscopy, for example measuring H_2O content of plants in agriculture, food inspection and health monitoring. For TPA to occur, two photons need to interact with each other within a very short time window. This acts as an ultra-fast optical gating function, interesting for time-correlated applications. Considering that light travels only 30 μm in 100 fs, short range 3D time-of-flight imaging with high depth resolution and good background light immunity might be possible. Furthermore, the control of the depth where carriers are generated (fig. 1b), is interesting for characterisation of CIS and TOF pixels.

Carrier generation in semiconductor materials has previously been characterised in [1], [3], [4], [8]. The following equation describes the light absorption in semiconductor materials:

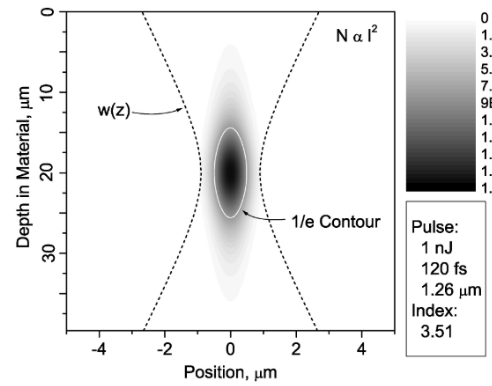
$$\frac{dI(r,z)}{dz} = -\alpha I(r,z) - \beta I^2(r,z) - \sigma_{ex} N I(r,z) \tag{1}$$

In this formula, α [cm^{-1}] is the linear absorption coefficient, β [cm/GW] is the two-photon absorption coefficient, σ_{ex} [cm^2] is the free carriers absorption cross section, N [cm^{-3}] the density of free carriers and I [W/m^2] the pulse irradiance. The first term represents SPA and behaves linearly with the irradiance. The second term represents TPA and has a quadratic dependence to the irradiance. The third term is relevant for highly doped regions and is expected to not contribute much to TPA for CMOS image sensors, given the low doping concentration of the vast majority of the pixel volume. For wavelengths above 1150 nm, the linear absorption coefficient is zero, which means a quadratic relationship to the light intensity would be expected. For silicon, a β of 0.6 cm/GW is reported at 1550 nm [9]. If only the TPA term remains, and the light beam is planar with intensity I_0 at the surface, the solution of above differential equation is:

$$I(z) = \frac{I_0}{1 + \beta I_0 z} \tag{2}$$



(a) Single-photon absorption (SPA) example behaviour



(b) Two-photon absorption (TPA) example behaviour

Fig. 1: Example plots of the density of photogenerated electron-hole pairs for SPA (a) and TPA (b). In (a), an exponential attenuation can be seen (Beer's law), starting at the top of the material where the laser beam is incident. In (b), no electron-hole pair generation is present at the top nor bottom of the material, but there is in the focal point of the laser beam (from [3]).

The carrier generation equation for a carrier density N is given by :

$$\frac{dN(r,z)}{dt} = \frac{\alpha I(r,z)}{\hbar\omega} + \frac{\beta I^2(r,z)}{2\hbar\omega} \tag{3}$$

A pixel will integrate the generated carriers during its exposure time and over its collection depth. Above 1150 nm, only the second term remains in eq. 3 and the response to intensity becomes quadratic.

This paper will describe the test setup, followed by multiple characterisation results. Finally, a conclusion is drawn from the measurements and future research plans will be outlined.

Fig. 2: Cabinet with microscope and xyz table

Fig. 3: Device under test (DUT) mounted on xyz table

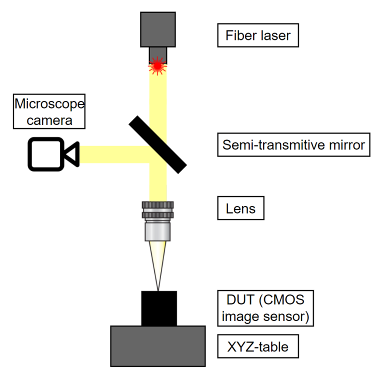


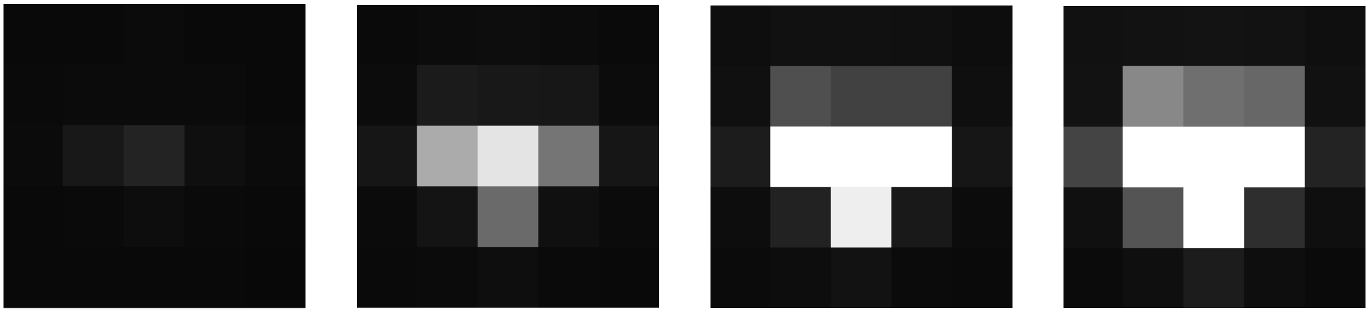
Fig. 4: Block diagram of test setup

II. Test Setup

For the TPA generation, the PULSBOX 2P from manufacturer PULSCAN was used. It contains a pulsed fiber laser with a wavelength of 1550 nm, pulse duration of 450 fs and a laser frequency of 1 MHz. The laser pulse power ranges from 10 fJ to a few nJ. The laser beam is injected through a fiber into the lens of a microscope objective. The device under test (DUT), the CMOS image sensor in this case, is placed on an XYZ translation stage. Figures 2 and 3 show the test setup. This machine is mostly used at KU Leuven to simulate radiation effects in electronics. Since TPA can generate a lot of localized electron-hole pairs, it can help to identify regions in a circuit sensitive to single event upsets or latchup.

The setup has been characterized with an InGaAs photodiode (Thorlabs DET10C2) and a silicon photodiode (Thorlabs DET10B6) by varying laser pulse energy. The laser beam wavelength is 1550 nm, which results in single-photon absorption and a linear response to the light intensity with the InGaAs photodiode, and in two-photon absorption and a quadratic response with the silicon photodiode. These characteristics have been validated in our test setup. The beam spot was characterized with the InGaAs detector to about 1.5 µm diameter (defined as 1 σ of the Gaussian beam), so most energy gets focused inside one pixel.

A 2.7 µm pixel backside-illuminated global shutter CMOS image sensor from ams-OSRAM was used for these experiments, processed with NIR (near-infrared radiation) enhancement structures to achieve a QE (quantum efficiency) of 36% at 940 nm wavelength.



(a) 4 pJ, 1k pulses (b) 4 pJ, 6k pulses (c) 4 pJ, 12k pulses (d) 4 pJ, 17k pulses

Fig. 5: Example of pixel response to 1550 nm pulsed laser light while varying the number of pulses. Exposure time is 18 ms.

III. Test results

The occurrence of TPA in this CMOS image sensor will be demonstrated. First, an optimal vertical focus height for TPA will be determined as well as the vertical range over which TPA occurs. Then, the laser pulse energy and corresponding number of generated electrons in the image sensor will be presented. The observed quadratic relation between light intensity and pixel signal indicates TPA. Every measurement, value or image, is actually the mean of 50 consecutive images in order to attenuate the thermal and shot noise from the sensor and readout.

A. *Determining the optimal Z height*

First of all, an optimal Z height needs to be determined. Figure 6 shows the pixel response as function of the Z dimension. TPA is maximal in a range of 10 µm, where the focal point of the beam is inside the pixel volume. Outside of this focal point, the signal attenuates. Figure 5 shows four images taken during testing with the response of a 5x5 pixel matrix of this sensor to the 1550 nm light, as an example of the pixel response. There are only a few pixels that do illuminate because the laser beam is focused on the center pixel.

B. *Pulse energy compared to number of electrons*

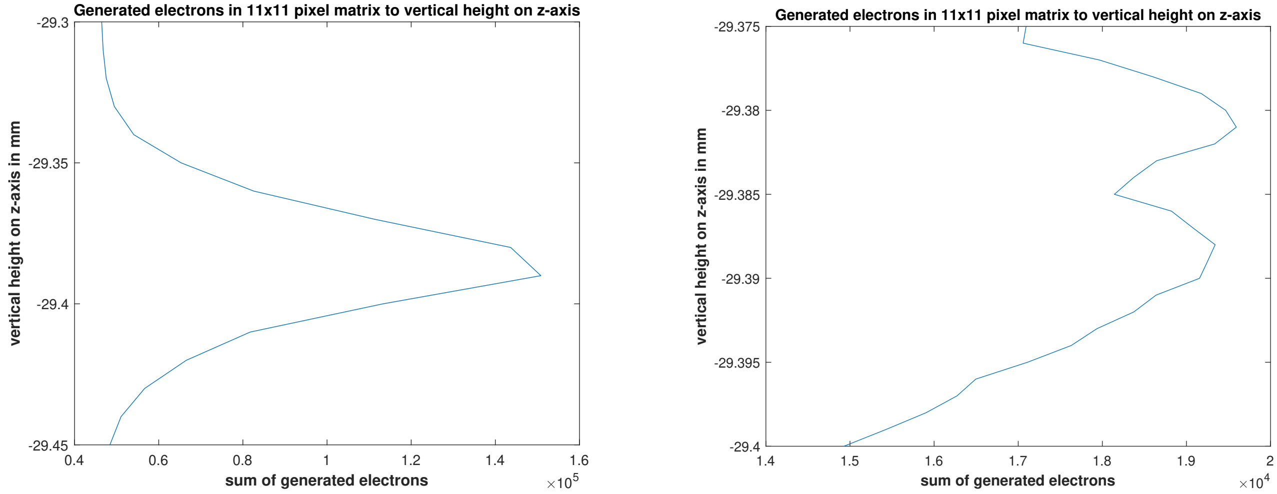
The energy of the laser pulses is varied and compared to the amount of generated electrons in the image sensor. This is illustrated in figure 7a for a high amount of laser pulses (1k to 17k pulses). A quadratic relationship can be observed between the number of detected electrons and the pulse energy, proving that TPA is the dominant generation mechanism. 0.03 pJ is needed for reliable detection of charge. Similar results are found when testing a lower amount of laser pulses (5 to 700 pulses). Figure 7b shows the same quadratic relationship, and with less pulses about 0.1 pJ is needed for reliable detection of charge. Unlike single-photon absorption, the TPA process is typically not characterized by a fixed Quantum Efficiecy (QE) value due to the quadratic dependency of the detected signal on the light intensity. If we stick to the definition of QE as the number of detected electrons over the number of incident photons, then for TPA QE grows linearly with the amount of incident photons. For example, for 17.9k incident photons during 17k pulses (about 1 photon/pulse) we measure a quantum efficiency of 0.0289% and for 9.36k incident photons we measure a quantum efficiency of 0.0144%. The photon-electron conversion process seems rather inefficient but it does increase linearly with increased light intensity.

A linear relationship is also observed between the number of detected electrons and the number of laser pulses, for a fixed pulse energy. This shows that a fixed average number of electrons are generated by each laser pulse. For 2 pJ, approximately four laser pulses are needed to generate one electron.

IV. Conclusions and future work

This paper demonstrates the occurrence of TPA in CMOS image sensors. A burst of light pulses of 450 fs at 1550 nm with an energy of 0.03 pJ can be detected. This corresponds to a light power of 66 mW, focussed inside a single pixel. The detection efficiency (a generalized ”QE”) increases linearly with light intensity. By using TPA, the usable range of CMOS image sensors can be extended into the SWIR range, which could prove beneficial for specific applications.

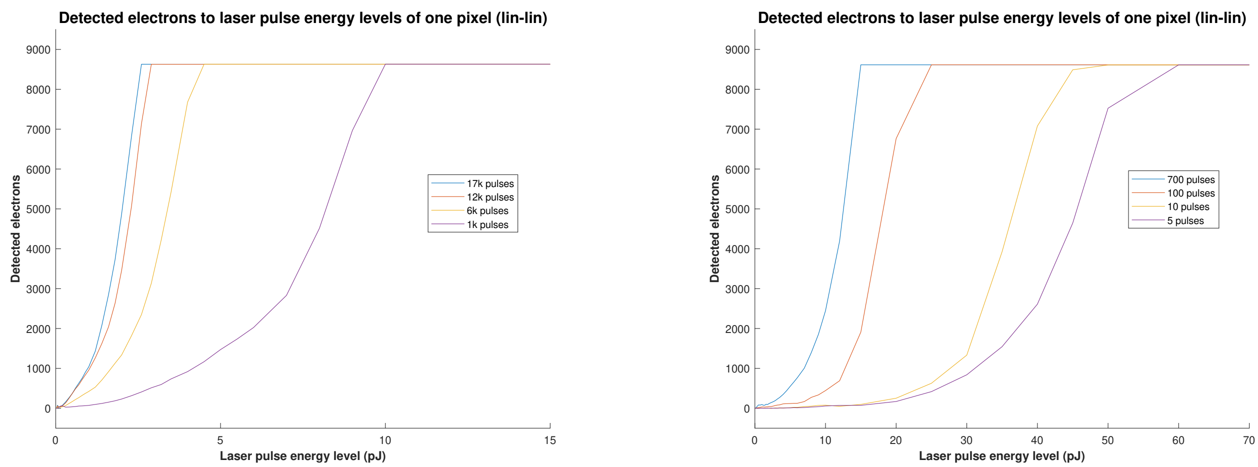
More research on this topic is needed, before this technique can be used in practical applications. Pixel variants of the CIS and other CIS devices with lower noise and larger pixels will be tested. This will allow to verify the current results and to understand the influence of differences in pixel design and CIS processing. We will also investigate the light power needed for TPA by using a single-photon avalanche diode (SPAD) provided by ams-OSRAM. We also plan to test miniaturised SWIR lasers from ams-OSRAM. From this work, we expect to reconfirm the β value for TPA in silicon and better understand the impact of pixel design and process measures on TPA.



(a) 10 µm steps

(b) 1 µm steps

Fig. 6: An maximum in the vertical height of the focal point can be observed, over a range of 10 µm.



(a) 1k to 17k pulses

(b) 5 to 700 pulses

Fig. 7: Detected charge in a single pixel vs the number of laser pulses for a high (a) and a low (b) amount of pulses. A quadratic relation is observed. In (a), only 0.03 pJ is enough for reliable charge generation while in (b), 0.1 pJ is enough for reliable charge generation. The full-well capacity of this pixel is 9 ke- and the dark offset is subtracted.

V. Acknowledgement

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References

[1] Marcos Fernández and Iván Vila, "High resolution 3D characterization of silicon detectors using a Two Photon Absorption Transient Current Technique", Vienna conference on instrumentation, 2019.
[2] Gerardo G. Ortiz and William H. Farr, "Two-Photon Absorption Long-Wavelength Optical Beam Tracking", NASA, 2008.
[3] McMorrow D., et al. , "Subbandgap laser-induced single event effects: carrier generation via two-photon absorption," in IEEE Transactions on Nuclear Science, vol. 49, no. 6, pp. 3002-3008, 2002, doi: 10.1109/TNS.2002.805337.
[4] Wiehe M., et al., "Development of a Tabletop Setup for the Transient Current Technique Using Two-Photon Absorption in Silicon Particle Detectors", IEEE Transactions on Nuclear Science, 68(2), 220–228, 2021.
[5] Boggess T., et al., "Simultaneous Measurement of the Two-Photon Coefficient and Free-Carrier Cross Section Above the Bandgap of Crystalline Silicon", IEEE Journal of Quantum Electronics, 22(2), 360–368, 1986.
[6] Ma J., et al., "A 0.19e- rms Read Noise 16.7Mpixel Stacked Quanta Image Sensor With 1.1 m-Pitch Backside Illuminated Pixels", IEEE Electron Device Letters, vol. 42, no. 6, pp. 891-894, 2021, doi: 10.1109/LED.2021.3072842.
[7] J.F. Seurin, et al., "High-efficiency VCSEL arrays for illumination and sensing in consumer applications", SPIE proc. Vol. 97660D, 2016.
[8] Sang, X., et al., "Applications of two-photon absorption in silicon", journal of optoelectronics and advanced material, 11(1), 15–25,2008
[9] Bristow A. D., et al., "Two-photon absorption and Kerr coefficients of silicon for 850-2200 nm", Applied Physics Letters, 90(19), 2007.