Single-event effects calibration using two-photon absorption and a CMOS image sensor

Daan Blommaert[1], Adhemar Caestecker[2], Paul Leroux[1] and Guy Meynants[1]
[1]KU Leuven, Dept. Electrical Engineering (ESAT), Belgium
[2]KU Leuven, Campus Geel, Belgium

Introduction

A two-photon absorption (TPA) laser setup can be used to emulate radiation effects of high-energy particles by tightly focusing an ultrafast laser on a sensitive node of an electronic circuit. At a certain energy per pulse, a single-event effect (SEE) can occur. We propose to measure the number of electron-hole pairs generated in the component and the characteristics of the laser beam through a CMOS image sensor. This method allows for better calibration of the TPA setup and makes the setup more representative for the radiation conditions. This information can then be used to predict or prevent SEEs in CMOS integrated circuits.

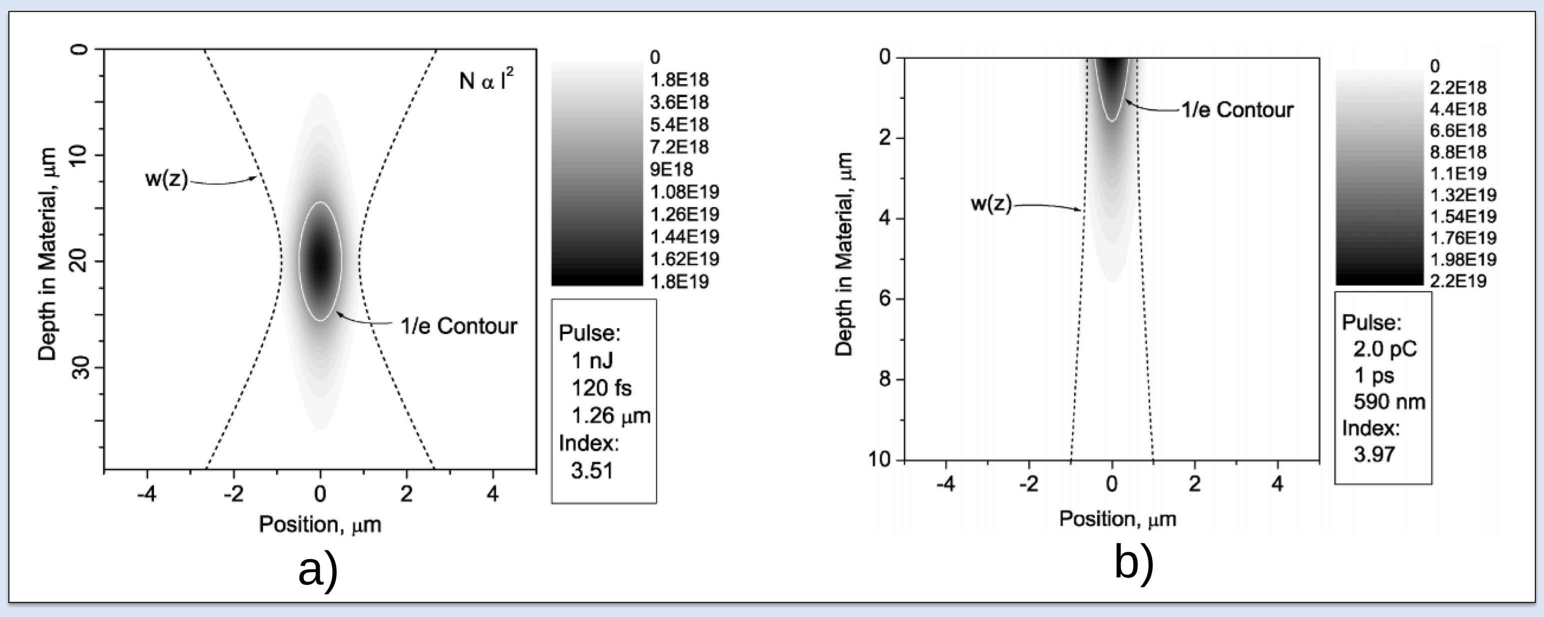
Two-photon absorption

TPA is the simultaneous absorption of two photons with an energy between half of the bandgap energy and the bandgap energy, which allows to excite an electron to the conduction band. Most electronics consist of silicon, which has a bandgap of 1.12 eV. For light wavelengths above 1100 nm, TPA is the main mechanism to generate electron-hole pairs in silicon. An ultrashort high-power laser beam pulse, focused by a lens, is commonly used to generate carriers by TPA because a high local light intensity is required.

$$\frac{dI(r,z)}{dz} = \underbrace{-\alpha I(r,z)}_{\text{SPA}} - \underbrace{\beta_2 I^2(r,z)}_{\text{TPA}} - \sigma_{ex} N I(r,z)$$

z = depth in silicon
r = radius from beam center
I = light intensity [W/m²]
α = linear (single-photon) absorption coefficient [cm^{-1}]
β = two-photon absorption coefficient [cm/GW]
N = density of free carriers

Figure 1: Density of generated electron-hole pairs for a) Two-photon absorption b) Single-photon absorption [1]



CMOS image sensors

CMOS image sensors will store/integrate the generated electron-hole pairs for a certain time. Present day, they are almost capable of single-photon detection. This means they are able to accurately measure how many electron-hole pairs are generated at a certain TPA laser energy.

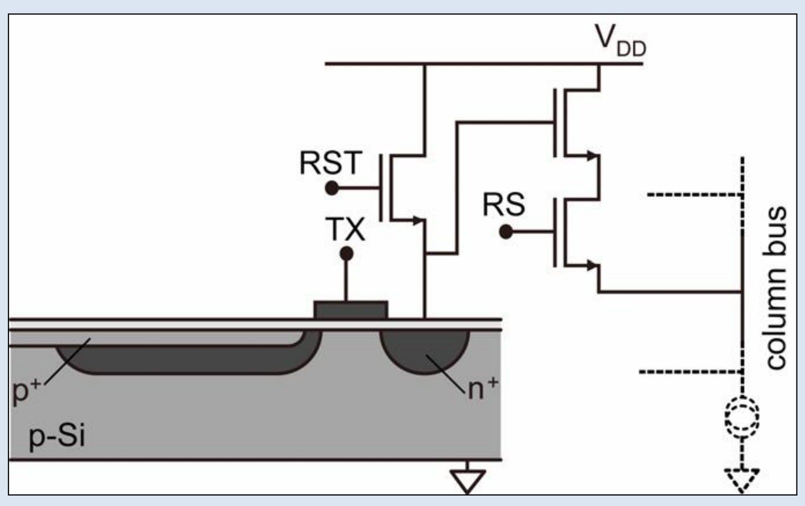


Figure 2: Pinned photodiode pixel structure [2]

References

[1] McMorrow D., et al. , "Subbandgap laser-induced single event effects: carrier generation via two-photon absorption," in IEEE Transactions on Nuclear. (2002)

[2] Theuwissen, Albert & Snoeij, Martijn & Wang, X. & Rao, Padmakumar & Bodegom, Erik. CMOS Image Sensors for Ambient Intelligence. (2006)

Test setup

As a test setup, a two-photon absorption laser setup from manufacturer PULSCAN was used.

Parameters:

- 1550 nm wavelength
- 450 fs pulse width
- Up to 1 MHz pulse frequency
- Spot size ±1.45 µm x 3.128 µm

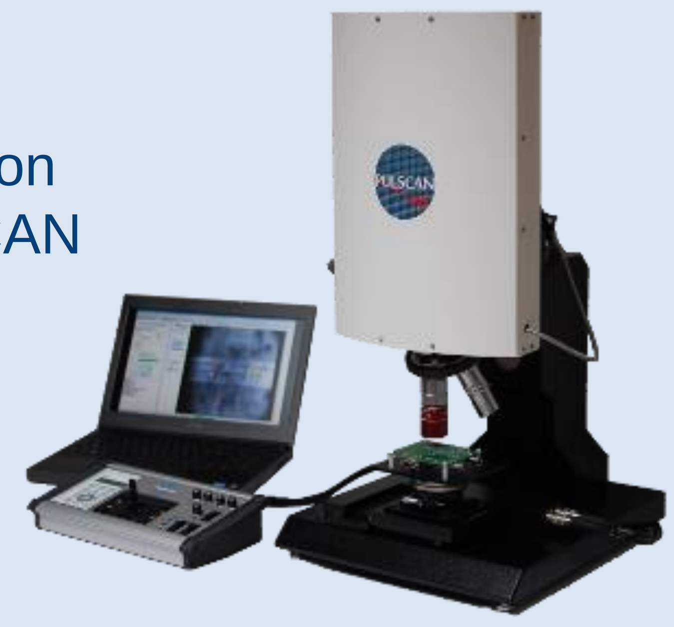


Figure 3: PULSCAN PULSBOX 2P

Results

Theoretically, silicon has a quadratic relationship with the light intensity for TPA and a linear dependency with the number of pulses. Both theoretical characteristics are confirmed in our case for large pixels (> 5 µm). For smaller pixels, sometimes a higher order relationship occurs. This unexpected behavior could also be in play in for example SRAMS, when evaluated in a TPA setup.

This setup can also be used for a 3D pixel profile scan, as shown in figure 4.

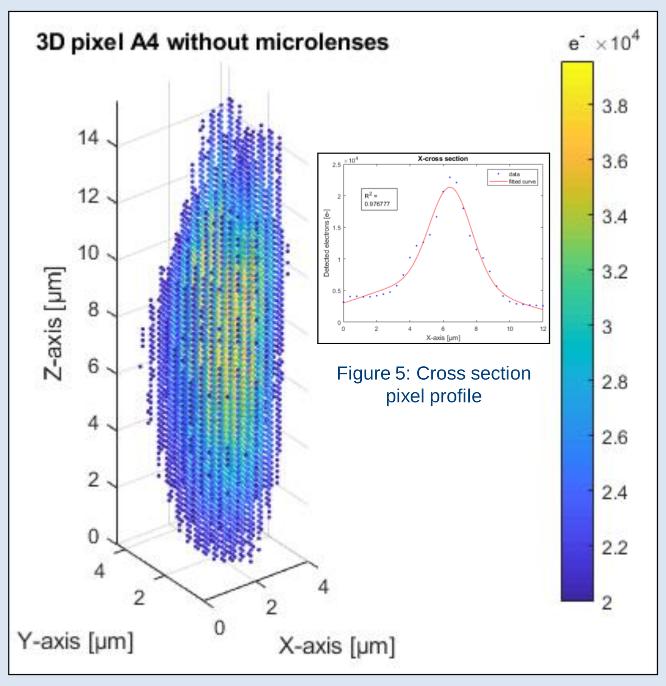


Figure 4: 3D pixel profile scan

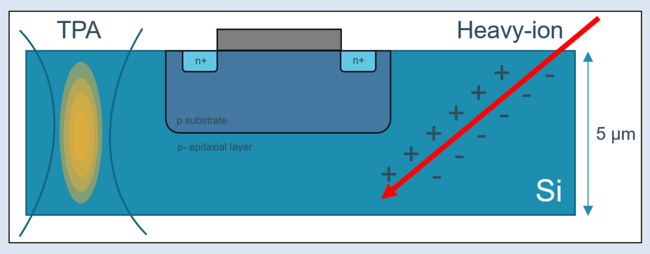


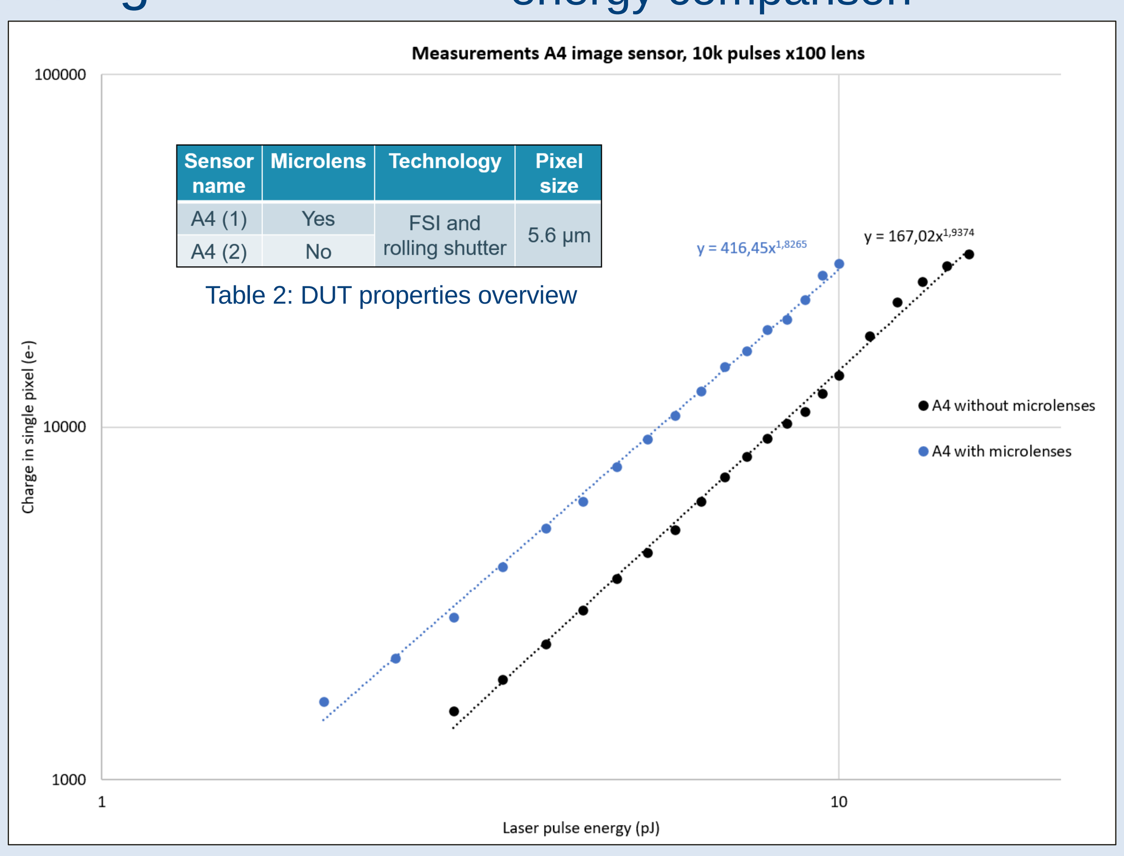
Figure 6: TPA vs heavy-ion charge generation principles

Compared to heavy ion irradiation, TPA is capable of generating the same number of electron-hole pairs or way more.

Heavy ion	LET [MeV.cm²/mg]	Epi thickness [µm]	Generated charge [Me-]	Corresponding TPA laser power [pJ]
$^{15}N^{4+}$	6.0	4	1.55	200
$^{40}Ar^{12+}$	18.6	4	4.81	300
$^{56}Fe^{15+}$	29.3	4	7.58	360
$^{83}Kr^{22+}$	40.9	4	10.6	410
$^{131}Xe^{35+}$	69.3	4	17.9	500

Table 1: TPA vs heavy-ion energy comparison

For example, a Xe^{35+} ion with an LET of 69.3 MeV.cm²/mg generates 17.9 million electron-hole pairs in 4 µm epi layer. In our TPA setup, one pulse of 500 pJ generates a similar number of electrons.



Sensor name	Microlens	Technology	Pixel size
A4 (1)	Yes	FSI and rolling shutter	5.6 µm
A4 (2)	No		

Table 2: DUT properties overview

Figure 7: Laser pulse energy vs detected number of electrons

Conclusion

The number of electron-hole pairs necessary to trigger a SEE in electronics can be measured by measuring the number of generated electron-hole pairs in a CMOS image sensor for the same laser energy. More research is however required to study the observed non-quadratic behavior for smaller pixels and the effect of diffraction and internal reflections in a pixel. This behavior may also occur in other SEE tests with comparatively small structures. TPA is capable of generating the same or more electron-hole pairs as heavy ion irradiation does in a few µm.