TCAD Simulation of Electrical Crosstalk in 4T-Active Pixel Sensors

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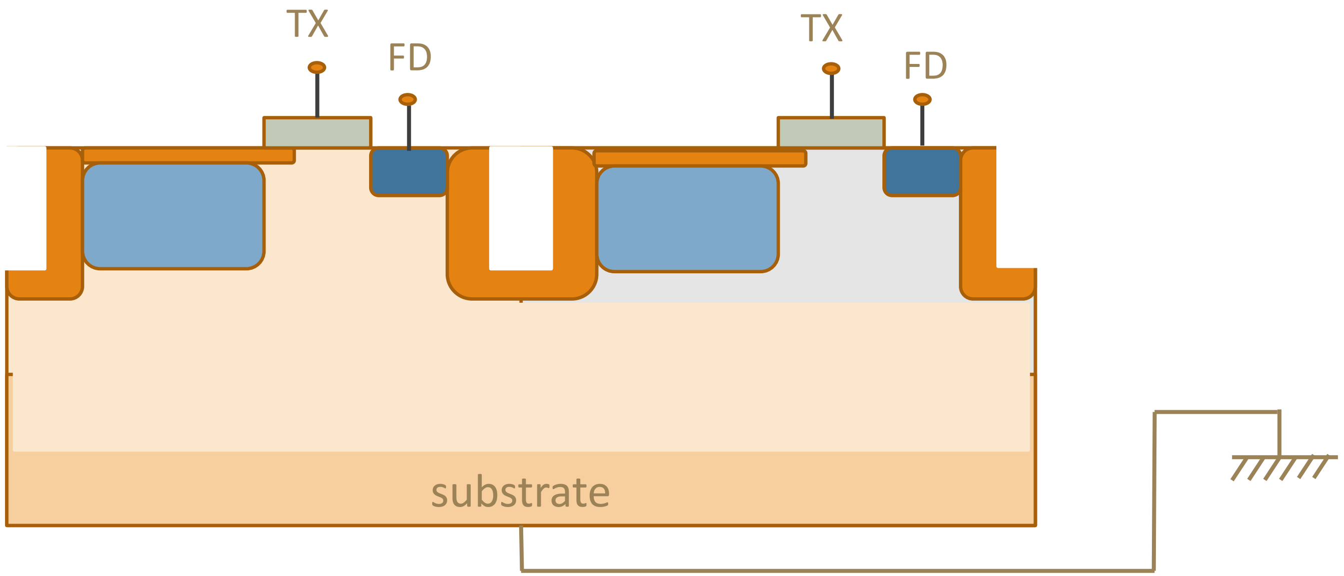
7. Conclusion.

What is crosstalk?

The signal crosstalk arising from carrier diffusion is the process when photocarriers generated in a particular pixel undergo diffusion and are trapped by a different pixel.



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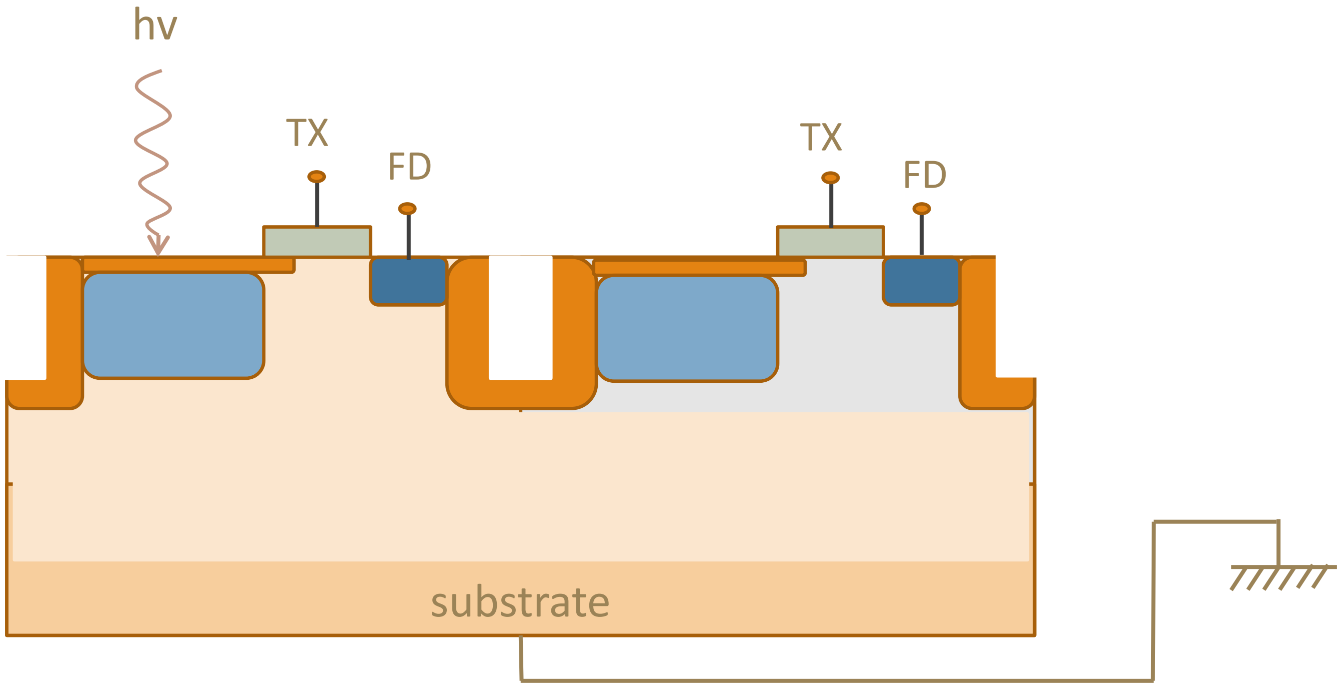

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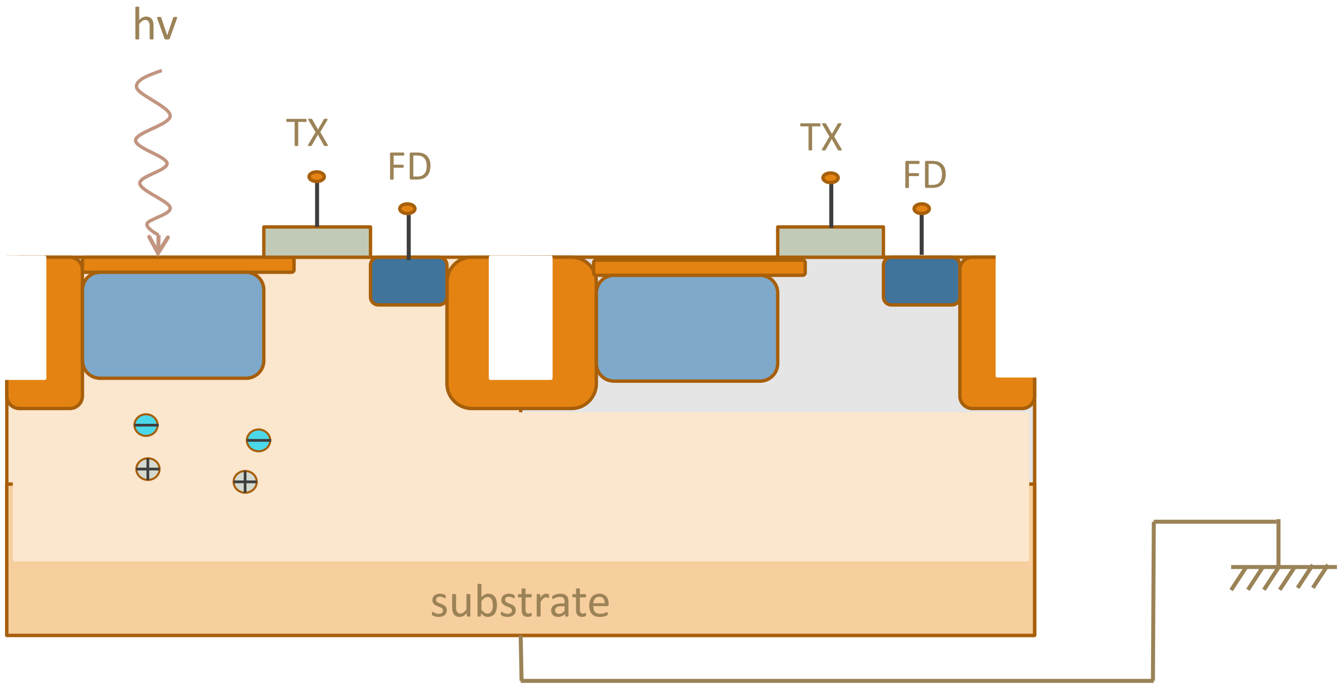

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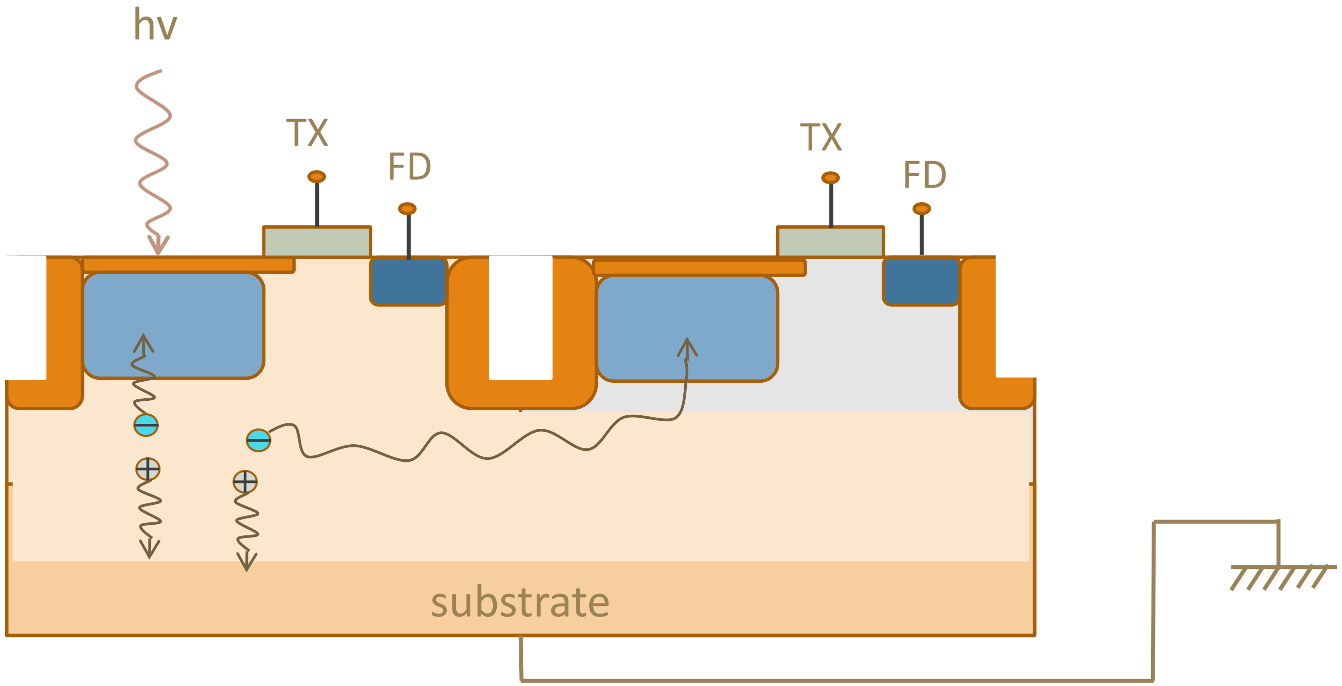

Why is crosstalk important?

Crosstalk effect on the final photo-signal is twofold.

On the one hand pixel signal is intensified which is good in poor photon flux conditions.

- Space applications
- Night vision

On the other hand, it seriously degrades performance of image sensor arrays. It cuts down spatial resolution by blurring sharp edges and reduces overall sensitivity.

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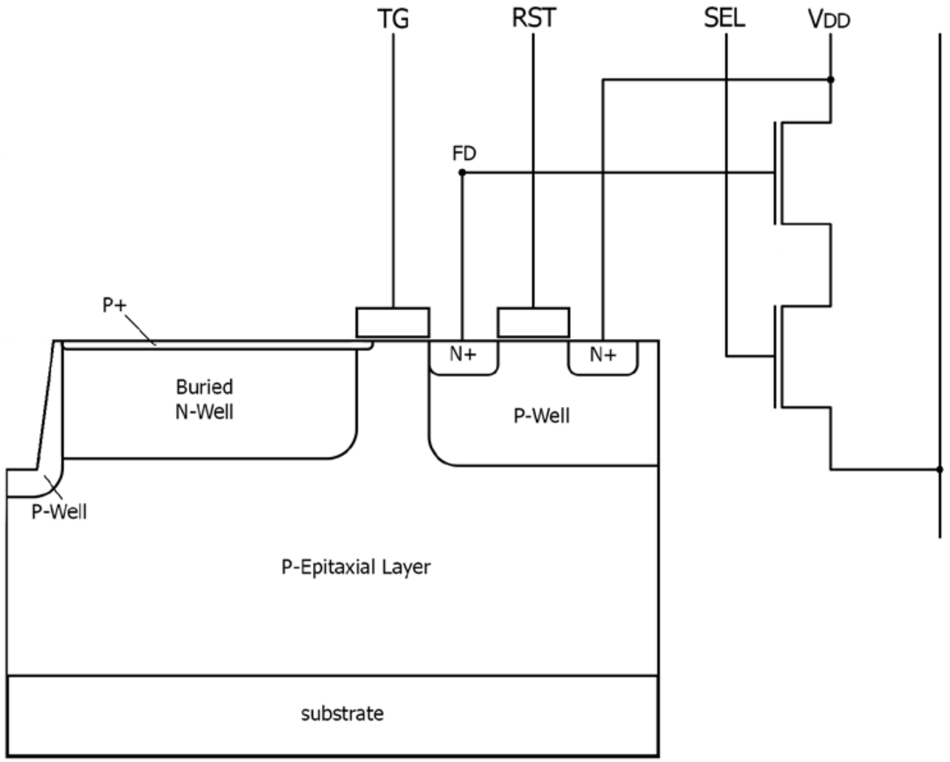
TCAD Simulation

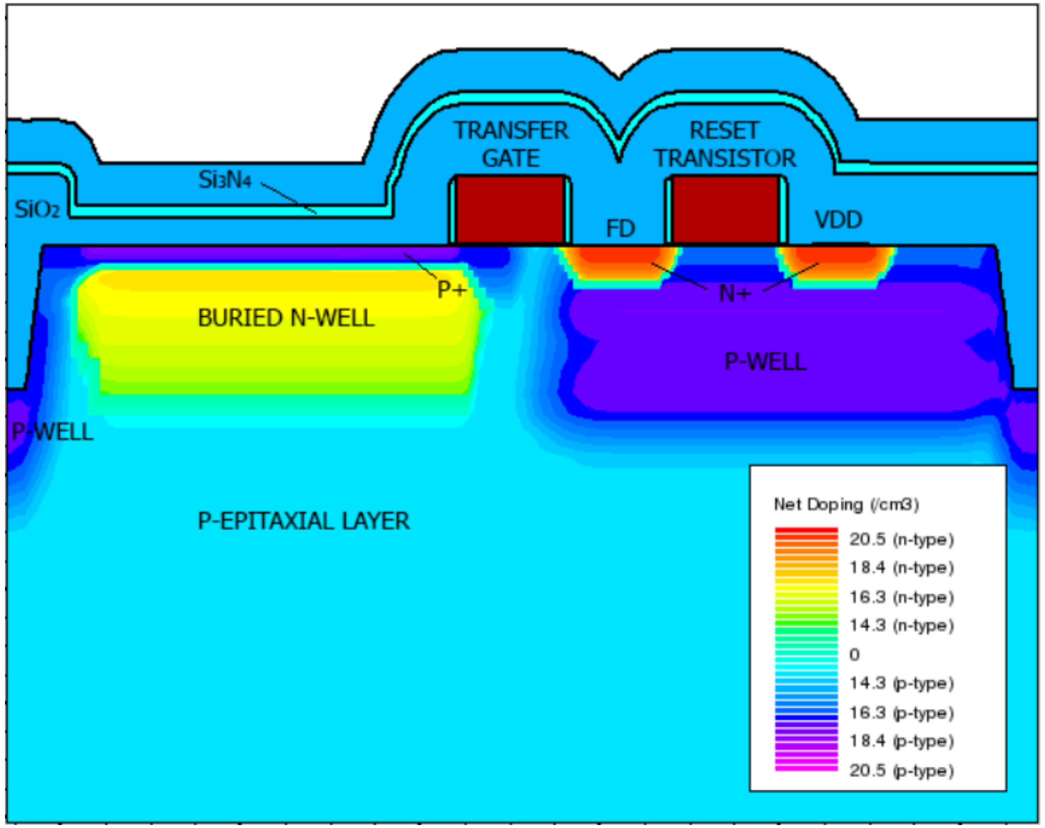
Although crosstalk is a known source of sensitivity degradation, and assessed for CCDs and some CMOS devices, studies on crosstalk on CMOS 4T-APS pixels have not been adequately addressed. This may be due, among other reasons, to the fact that CIS technology parameters are commonly unavailable.

This work aims to study the crosstalk of a two-dimensional array of five 4T-APS pixels through TCAD simulations.

The TCAD tools allow to simulate the fabrication and electrical behavior of semiconductor devices, enabling the visualization of parameters that can not be measured in any other way, and thus improving our knowledge about its operation.

Simulated devices

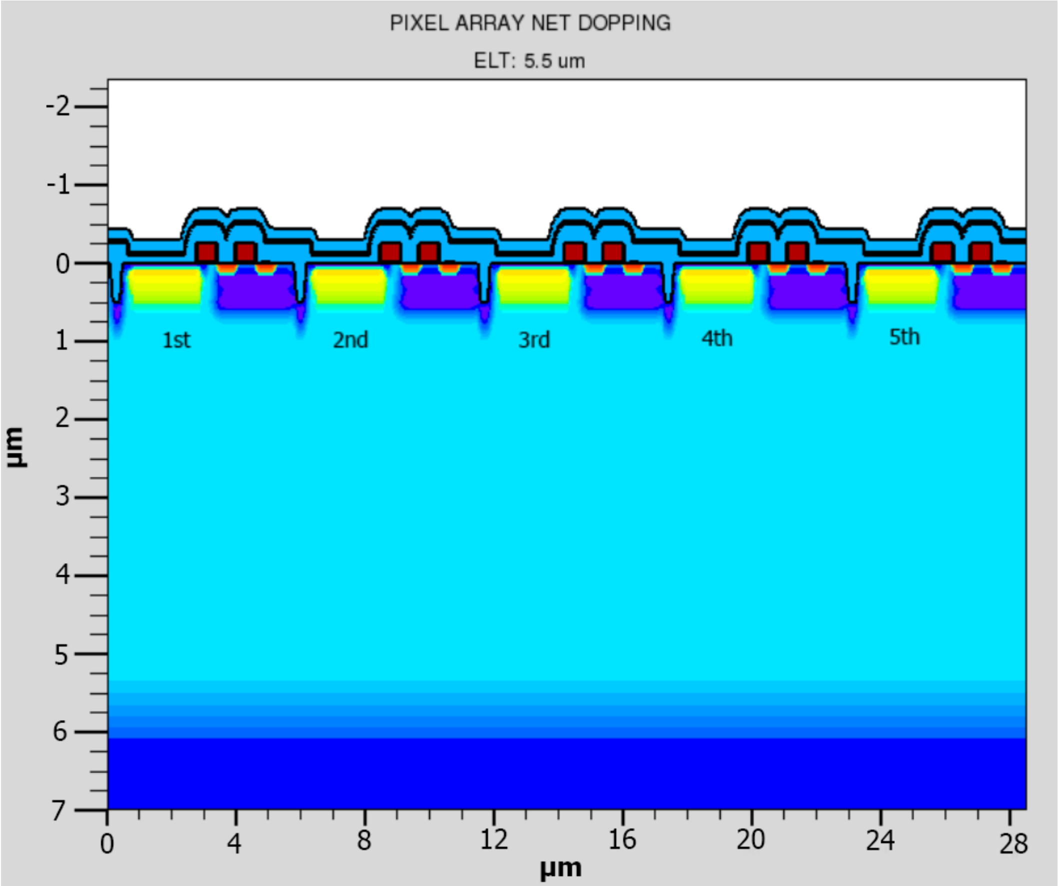




[Fossum 2014]

Simulated devices

- 11 device structures were designed.
- All of them consist in a two-dimensional array of five pixels, in which the variation of a key parameter, the epitaxial layer thickness (ELT), is evaluated.
- ELT affects both Quantum Efficiency and Crosstalk.



Simulated tests: considerations

- To characterize the crosstalk, a spot scanning technique has been employed. It consists in illuminating an individual pixel and then measuring its effects on adjacent pixels.
- Crosstalk is defined as:

$$CTK(\%) = \frac{I_0}{I_T} \cdot 100$$

$I_0 \equiv$ Induced current by stray carriers in adjacent pixels.

$I_T \equiv$ Total photo-generated current.

- The whole array is considered masked, except for the active area of the illuminated pixel.
- The pixel will be illuminated with a fixed intensity of $1.4 \cdot 10^{-2}$ W/cm^2, so that the pixel does not saturate and avoid the blooming effect.

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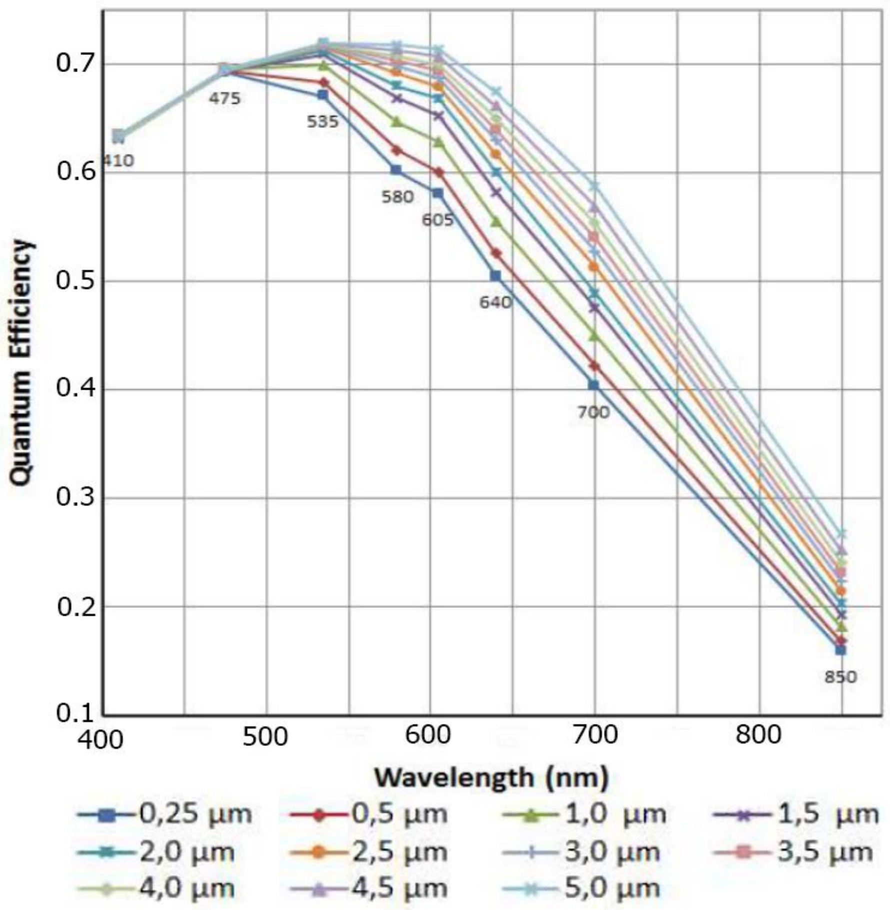
Quantum efficiency and ELT

- Quantum efficiency (QE) degrades when the epitaxial layer thickness decreases at longer wavelengths.
- When the diode is reverse biased photo-generated carriers are collected in the buried N-Well. When the ELT is small, the substrate is closer to the surface. There recombination is more likely due to a higher impurity concentration. Carriers generated at greater depths by longer wavelengths are more likely to recombine, hence the QE degradation.



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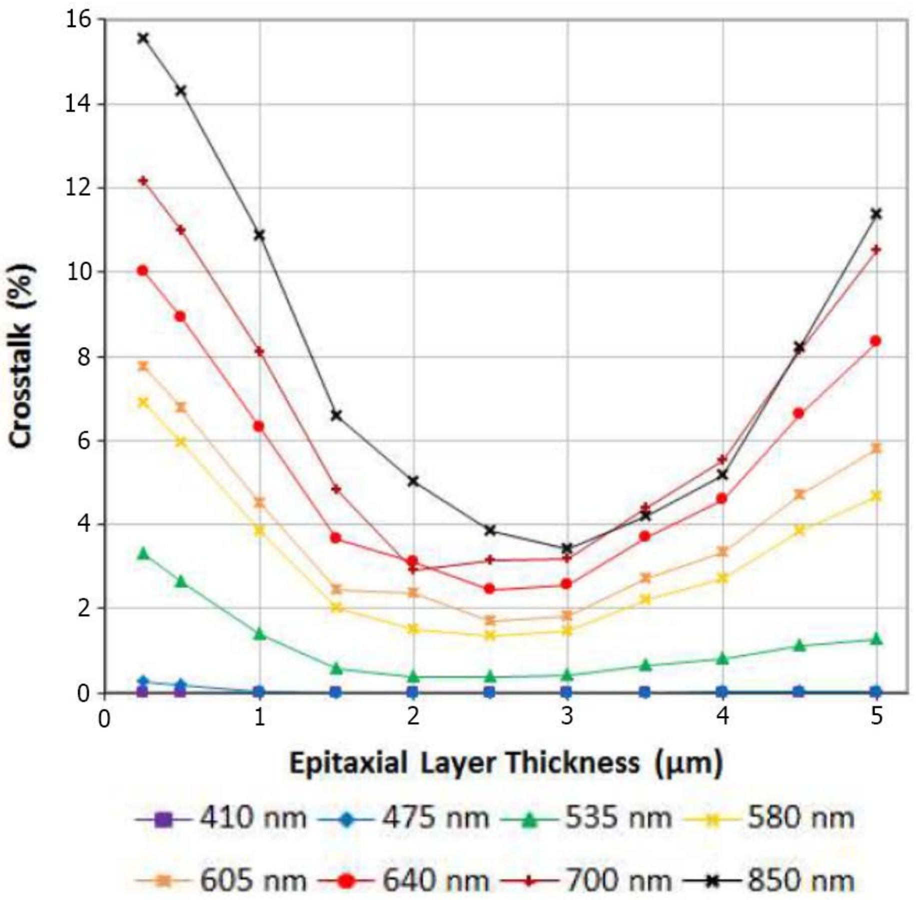
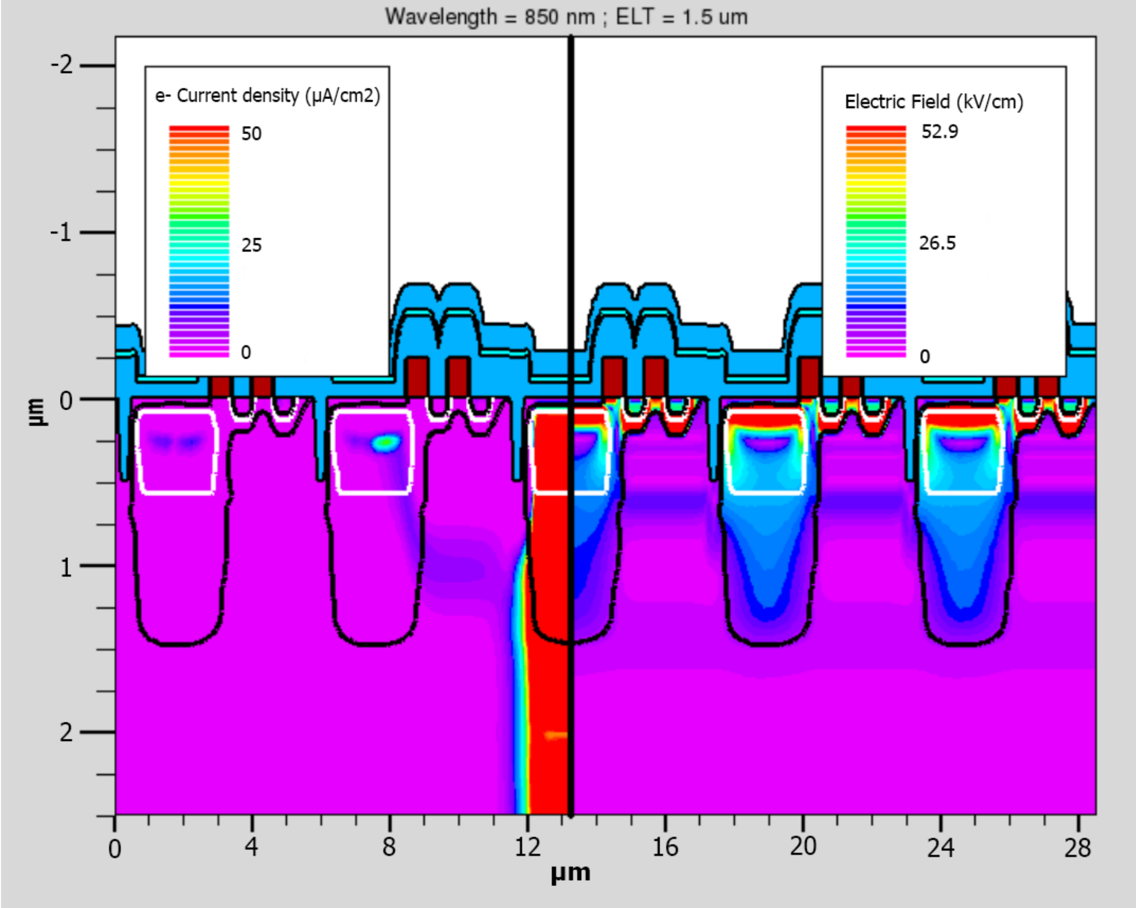
Crosstalk and ELT

- The epitaxial layer thickness affects crosstalk in a different way.
- Crosstalk is higher when ELT is either, too small or too large, and rises with wavelength.
- As can be seen there is an optimal ELT interval, between 2 and 3 µm deep, where the crosstalk is lower. This zone matches roughly the depletion region edge of the NW/p-epi union. Although the lowest point is wavelength dependent, because is related to the depth where photon absorption rate is higher.



Crosstalk and ELT

- When the epitaxial layer thickness is less than 2.5-3.0 µm, the depletion region is constrained by the substrate. A weak electric field is then formed in the border of the substrate.
- This electric field and that formed in the border of the P-Well, creates an potential valley where electrons can diffuse between adjacent depletion regions.
- If ELT decreases even further, the valley region becomes thicker and the cross-section of the current decreases. This enhances electron drift velocity and therefore current density to keep the intensity constant. As more carriers are able to reach the adjacent depletion region before recombination, crosstalk signal rises.



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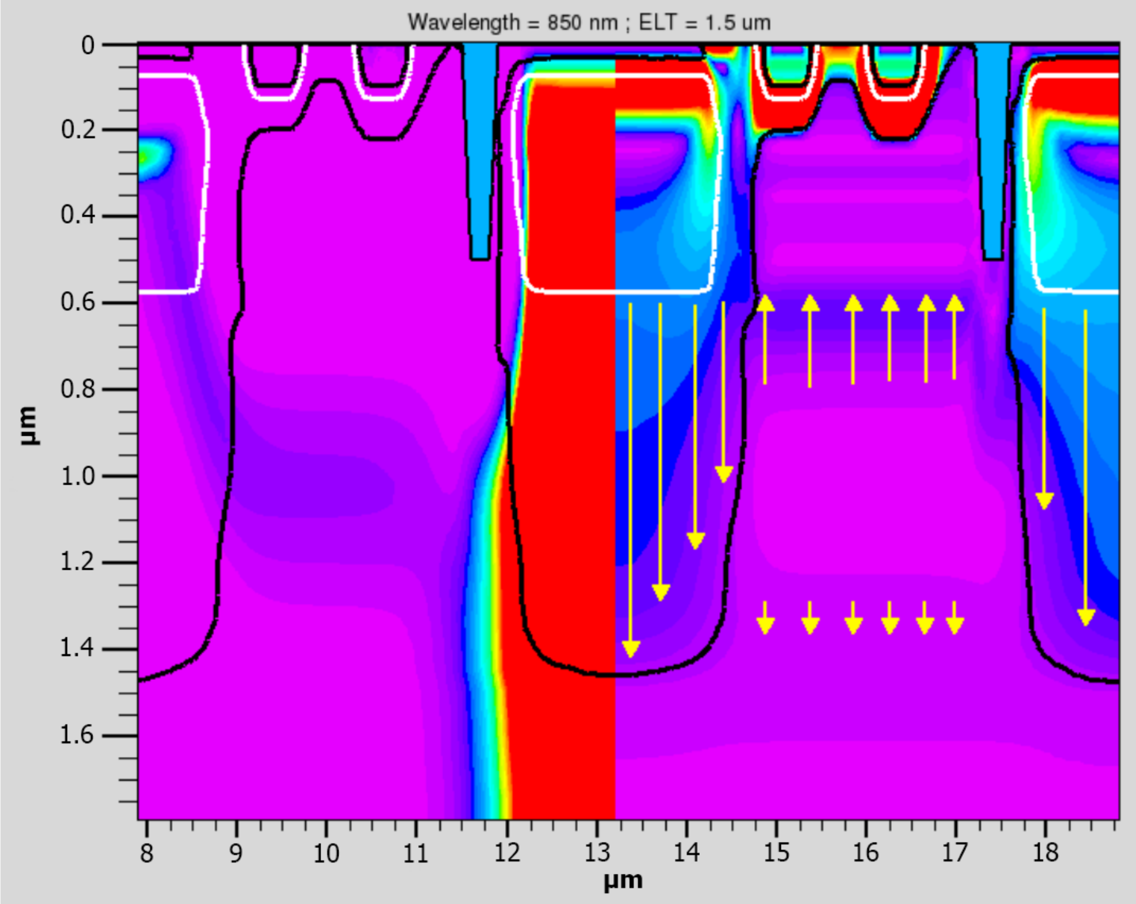

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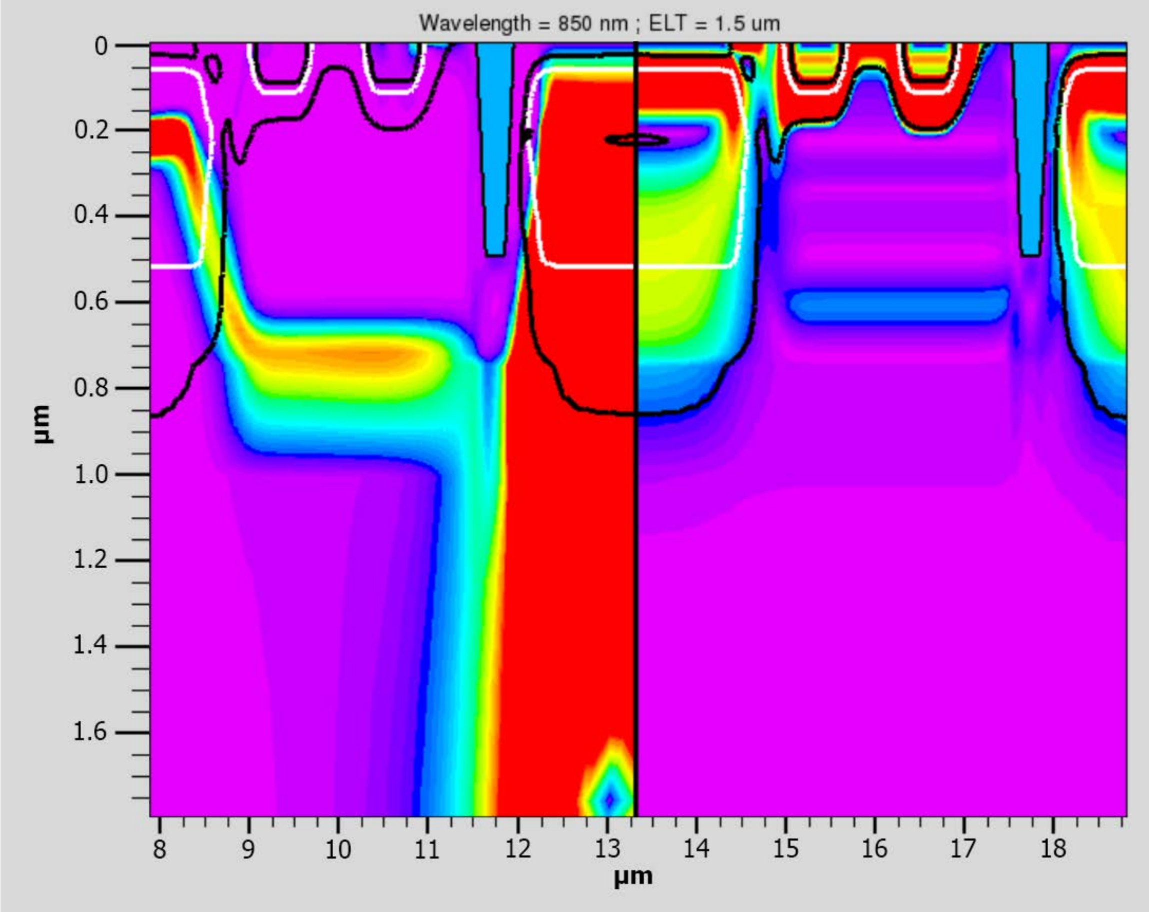
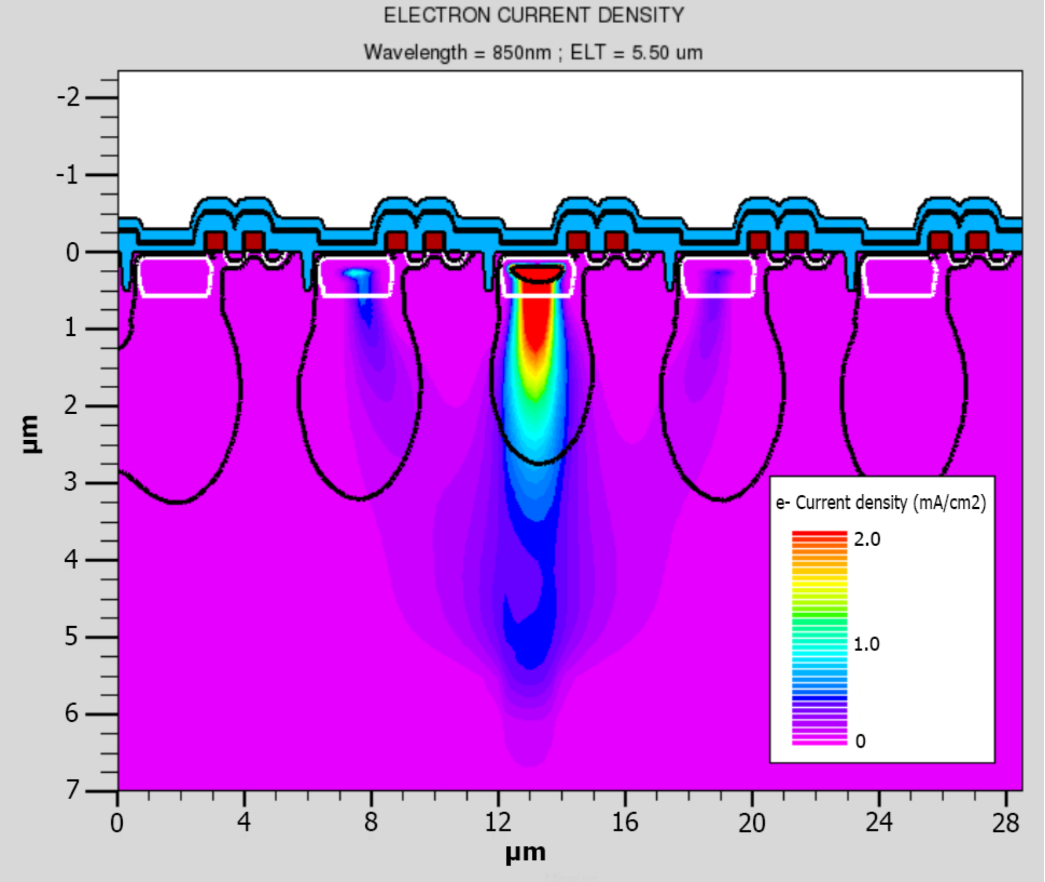


Crosstalk and ELT

- When the epitaxial layer thickness is greater than that of the depletion region edge, they are no longer constrained by the substrate, a no electric field is formed in the border of the substrate.
- This allow minority carriers to diffuse freely through the epitaxial layer.
- The wider the ELT, the farthest the electrons can drift in the epitaxial layer, and the probability of being trapped by the electric field of a depletion region rises. And so do the crosstalk.



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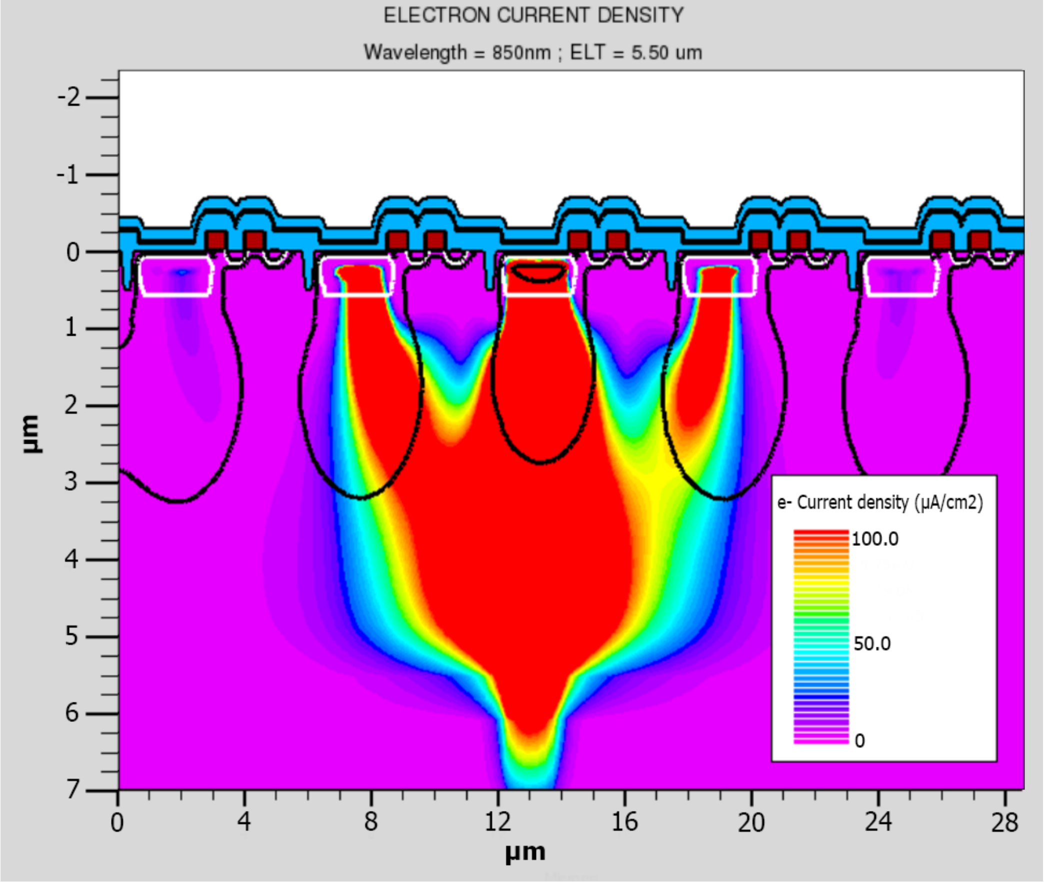

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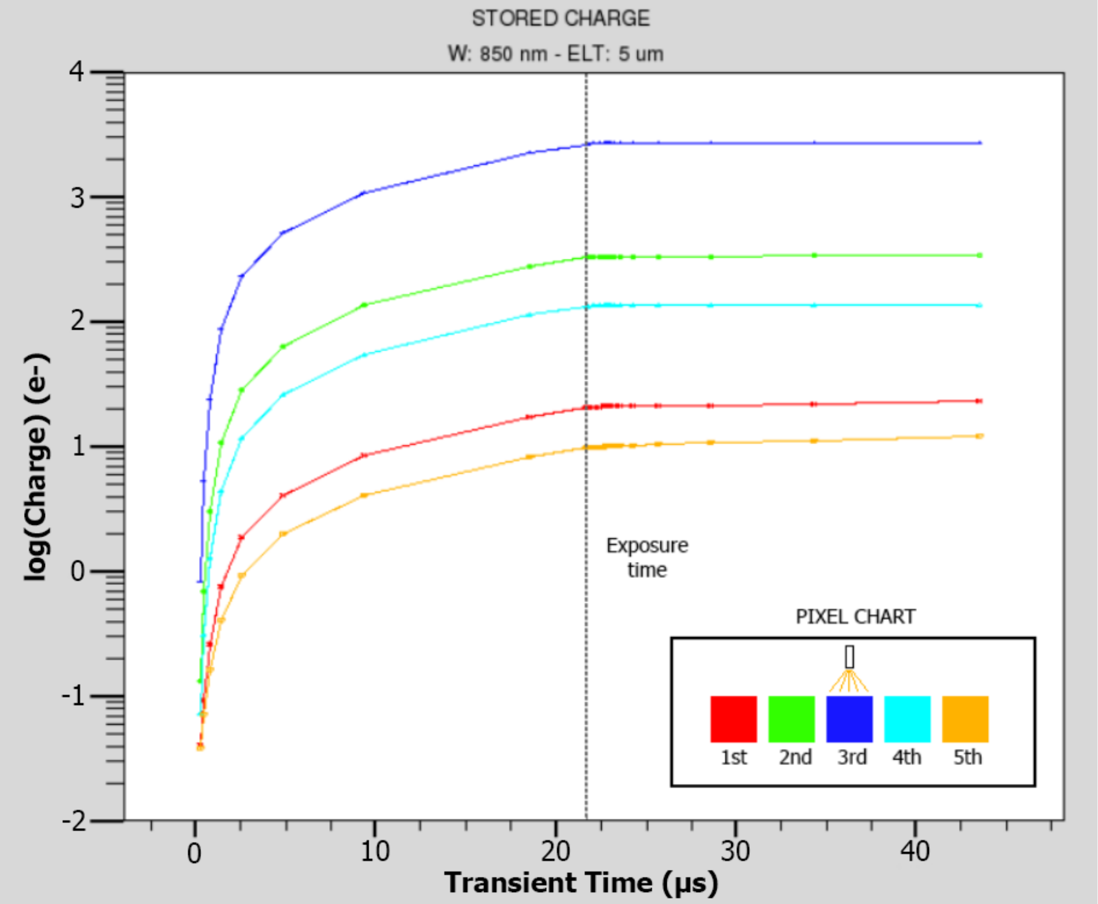
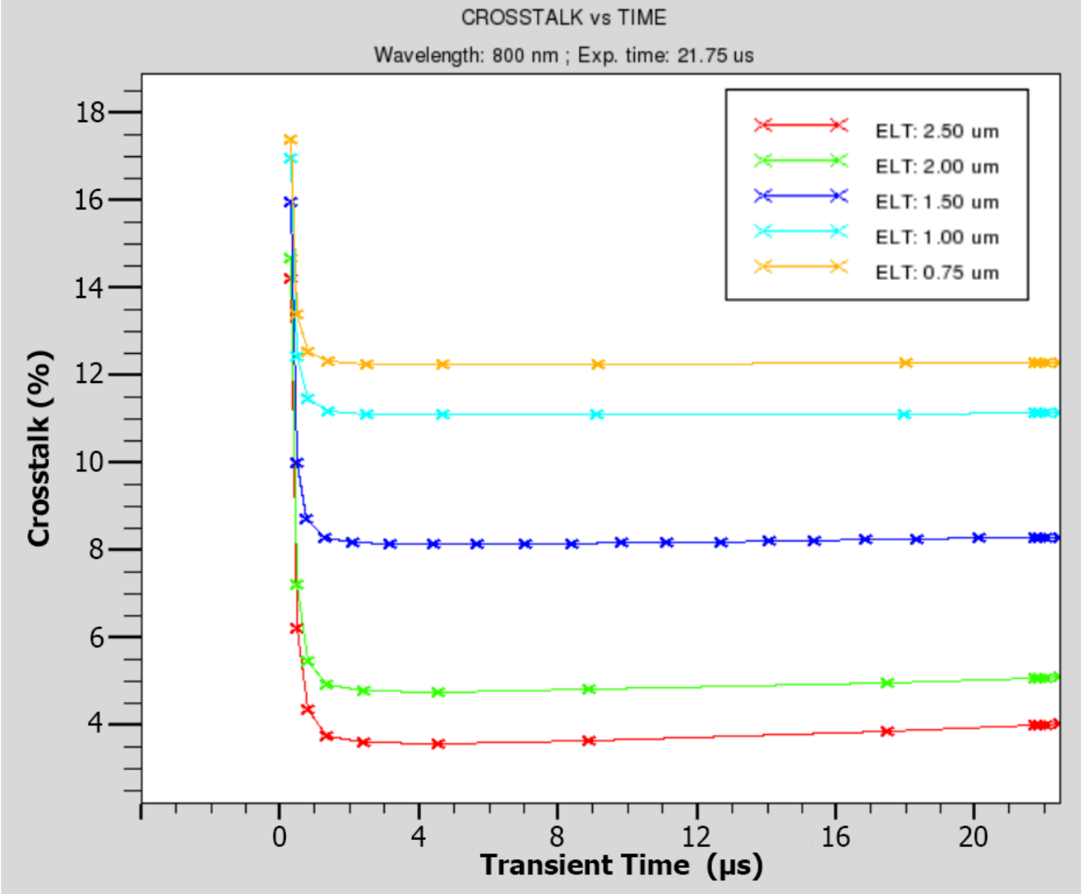
Crosstalk over time

- The charge accumulates in a linear fashion during the exposure time in the pixels.



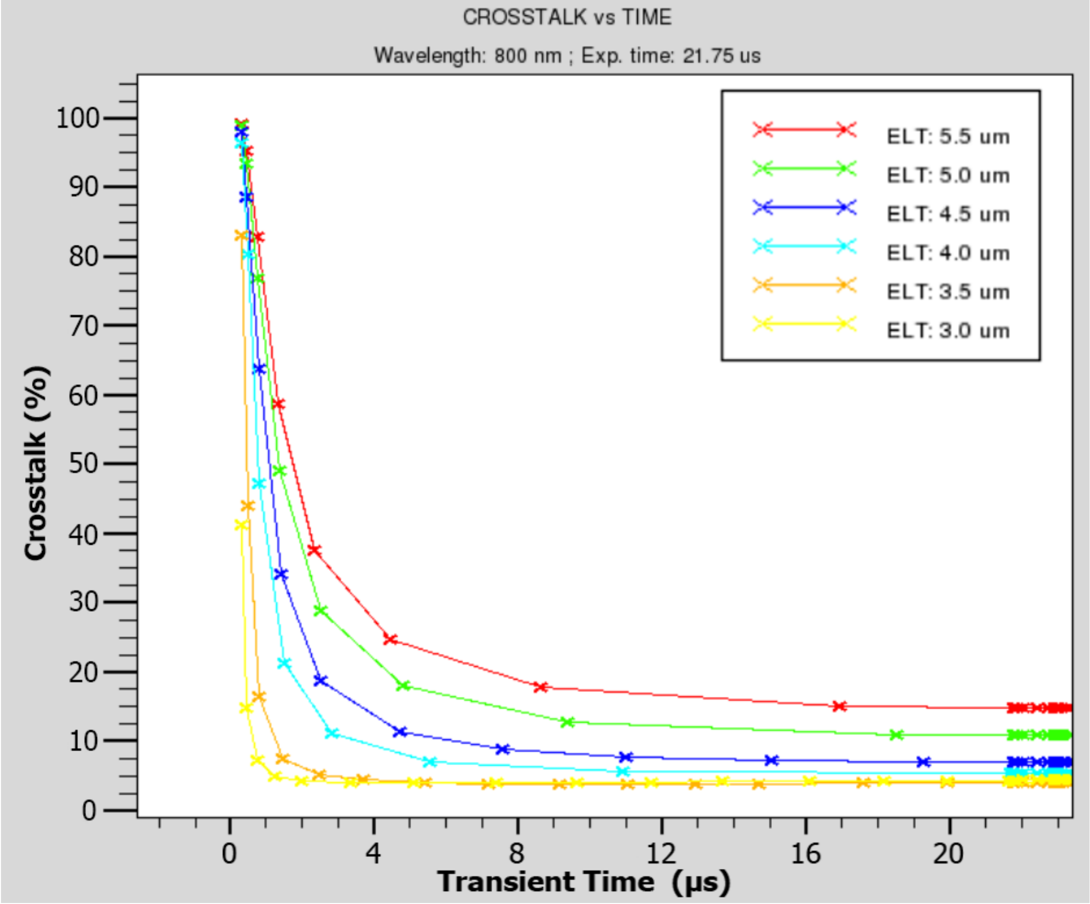
Crosstalk over time

- The charge accumulates in a linear fashion during the exposure time in the pixels.
- This should mean that crosstalk should be constant over time, however that is only true when the epitaxial layer thickness is less than the reach of the depletion region edge. As crosstalk is evaluated as the ratio between the current in adjacent pixels and total photo-generated current, the high crosstalk peak the beginning of the integration time is due to thermal noise.



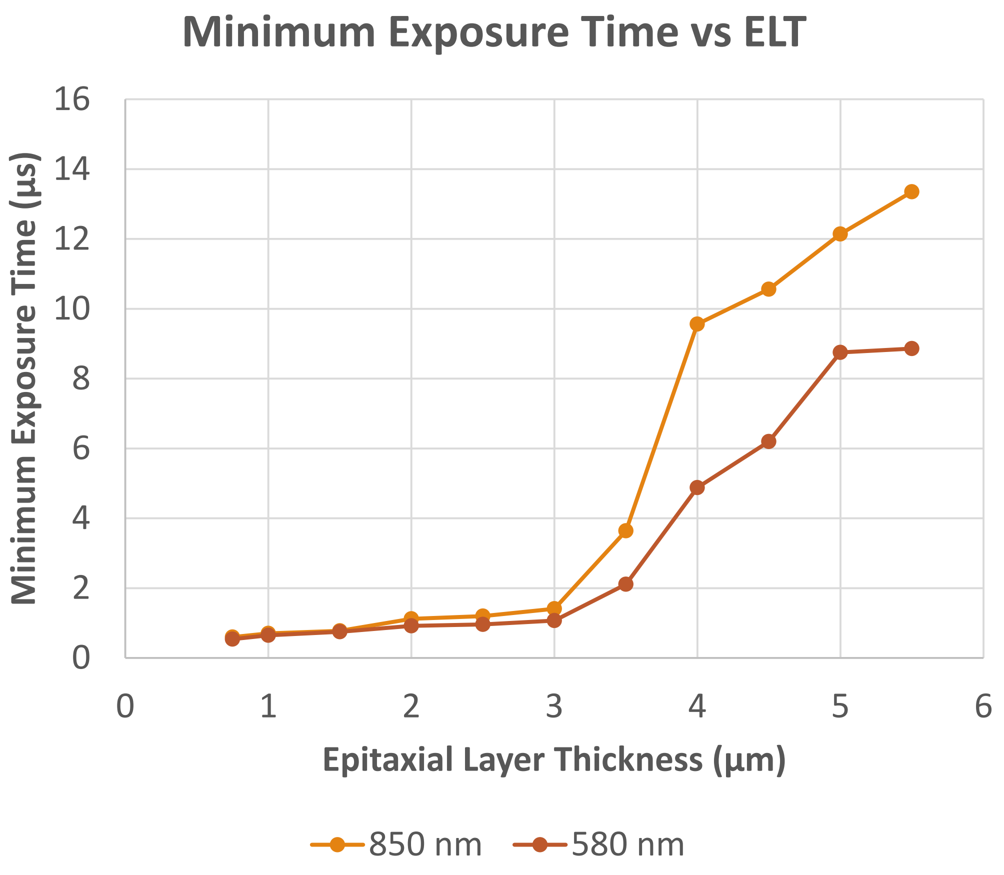
Crosstalk over time

- When the epitaxial layer thickness is greater than the depletion region edge, the crosstalk takes some time to decay to its final value.
- This force to define a minimum exposure time, so that the crosstalk measured is acceptable when it compared to the final value.



Crosstalk over time

- If we set that acceptable value in the 110% of the final value, the minimum exposure time can be as great as 10 µs for longer wavelengths and ELT.
- This is less significant for shorter wavelengths a they suffer less from crosstalk.



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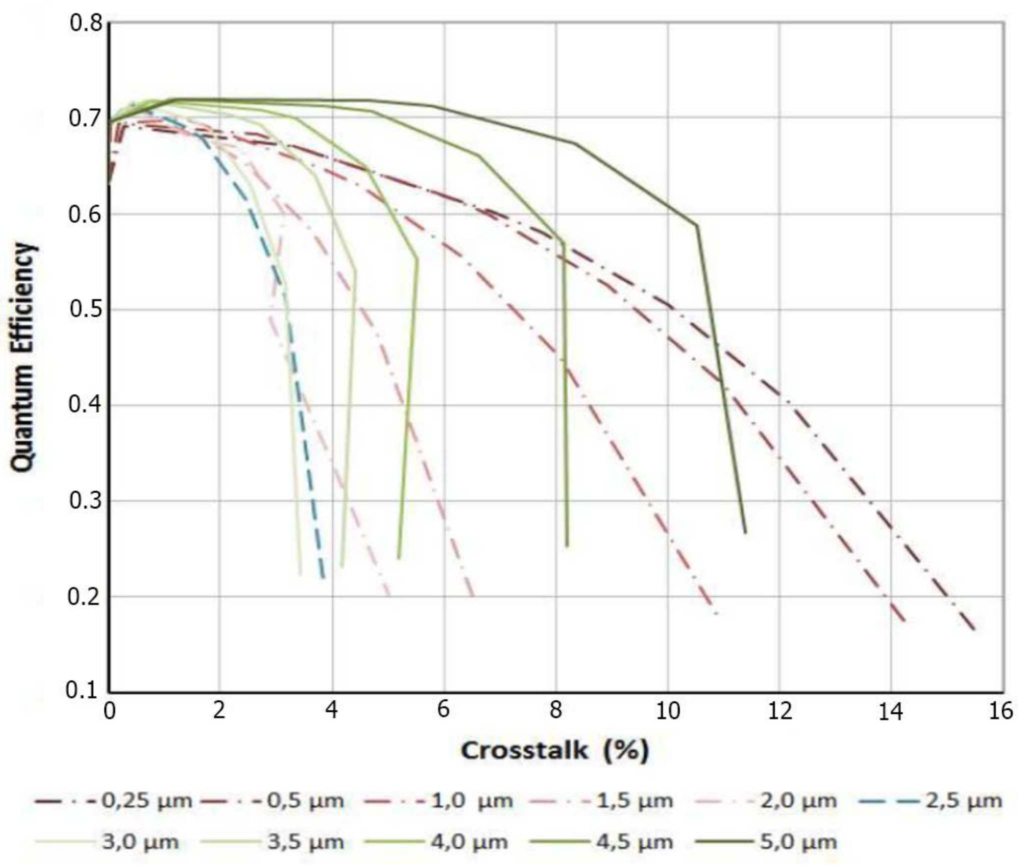
Crosstalk and QE

- Quantum efficiency and crosstalk both are dependent of the epitaxial layer thickness, there had to be a correlation between them.
- This correlation varies according to whether the ELT is greater or lower than the depletion region edge. Although it can be affirmed that a poor quantum efficiency means a high crosstalk signal, and good quantum efficiency gives a low crosstalk signal.



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Conclusions

This work shows an application of TCAD simulations, where a physical parameter of the device structure can affect the performance of a image sensor. If we have to design a device, we should have to face important decisions in view of this results:

1. Quantum efficiency is greater if the ELT increases.
2. However, Crosstalk rises if the ELT is too small or too large.
3. Also, if the ELT is large we will need a minimum time so that crosstalk can decay to an acceptable value.

Conclusions

These results show that choosing an adequate epitaxial layer thickness for a proper wavelength is crucial to adjust the balance between QE and crosstalk.

Results obtained show that the TCAD simulations are a good tool to characterize electrical crosstalk. The main downside is the computational cost, that make simulation of larger arrays inviable.

Acknowledgments

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References

[1] E.R. Fossum and B. D. Hondogwa, "A review of the pinned photodiode for CCD and CMOS image sensors" *IEEE J. Electron Devices Soc*., vol. 2, no. 3, pp. 33-43, May 2014.

Thank you very much