Simulation of charge collection in chronopixel device

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Topics:

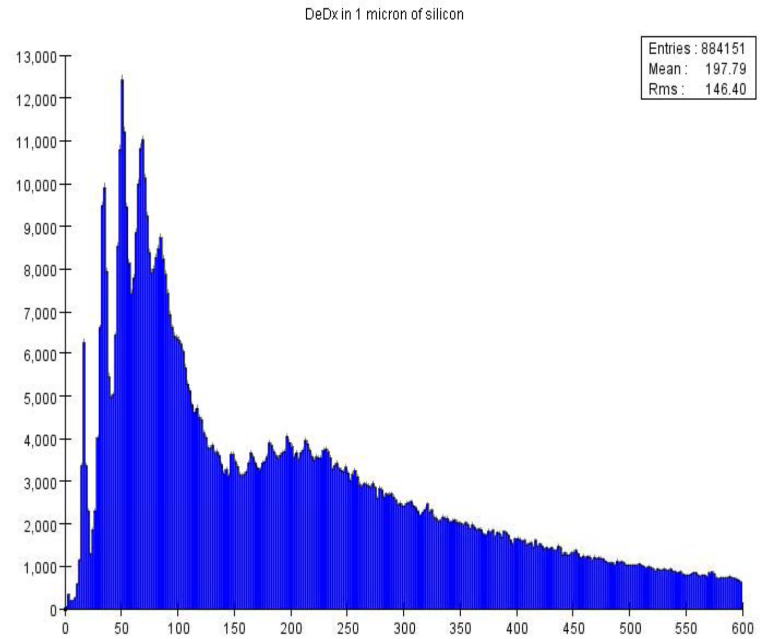
- 1. How it was done
- 2. Effect of electric field in non-depleted regions
- 3. Effect of pixel size
- 4. Effect of incidence angle
- 5. Hit registration efficiency
- 6. Cluster size
- 7. Conclusions

How it was done

- I was using device simulation from Synopsys TCAD package. Device simulation program, widely known as “DESSIS” – Device Simulation for Smart Integrated Systems.
- One of the result of this simulation – electric field inside sensor I have used as input for another simulation package, written by myself in the JAS framework, which generated ionization charge along charged particle path in the sensor, and simulated movement of every electron from this charge in the sensor electric field. This movement included drift in electrical field, according to carrier mobility in the given field, and stochastic diffusion movement calculated for each step according to diffusion coefficient and time needed for drifting given distance. I used 0.1 micron steps in such simulation

How it was done - continue

- For the energy loss of the charged particle in the sensor I have used single collision energy loss tables, calculated by Hans Bichsel ionization loss package. I have simulated every ionizing collision, as there are only 4 such collisions per 1 micron path in silicon in average. Our sensors are few microns thick, so usage of Landau distributions would not be correct.

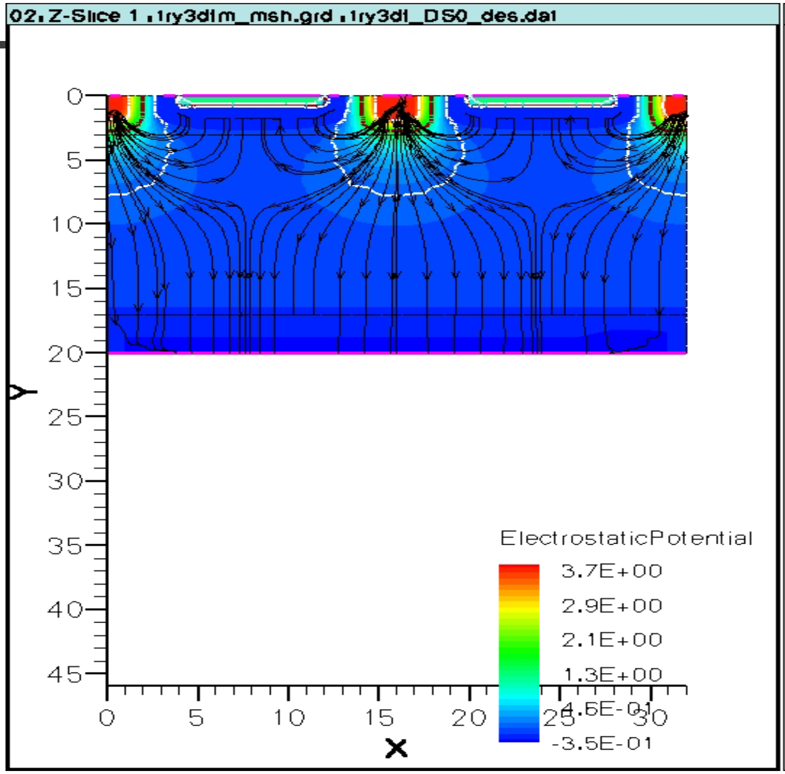


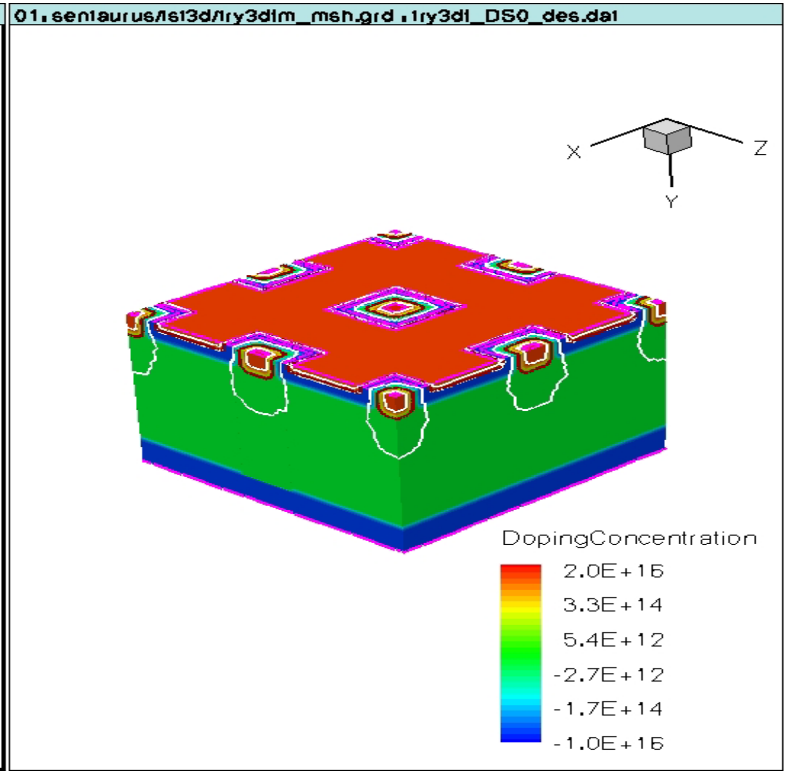
Example of energy loss distribution
For 1 micron thick silicon – output from my energy loss simulation

How it was done - continue

- For comparison, some of the simulations were done, assuming that electric field outside depleted regions is exactly 0. This assumption is the "naive" understanding of the depletion process in the silicon detector. But this is not correct, because diffusion of charge carriers makes it impossible to have sharply defined depleted region border. Usually electric fields inside depleted region have order of magnitude tens of thousands of V/cm, while in undepleted regions this value drops to hundreds V/cm, or even smaller. Diffusion became dominant over drift in electric field at the fields value below few hundreds V/cm, so, in the large portion of undepleted silicon, both drift and diffusion should be taken in the account. Pictures on next slide illustrate this

How it was done – DESSIS output





Here is the example of the output from DESSIS. The white line indicates the depleted region limit. You can notice, that electrostatic potential continue to change even in undepleted region. That means non-zero electric field here.

Effect of the electric field

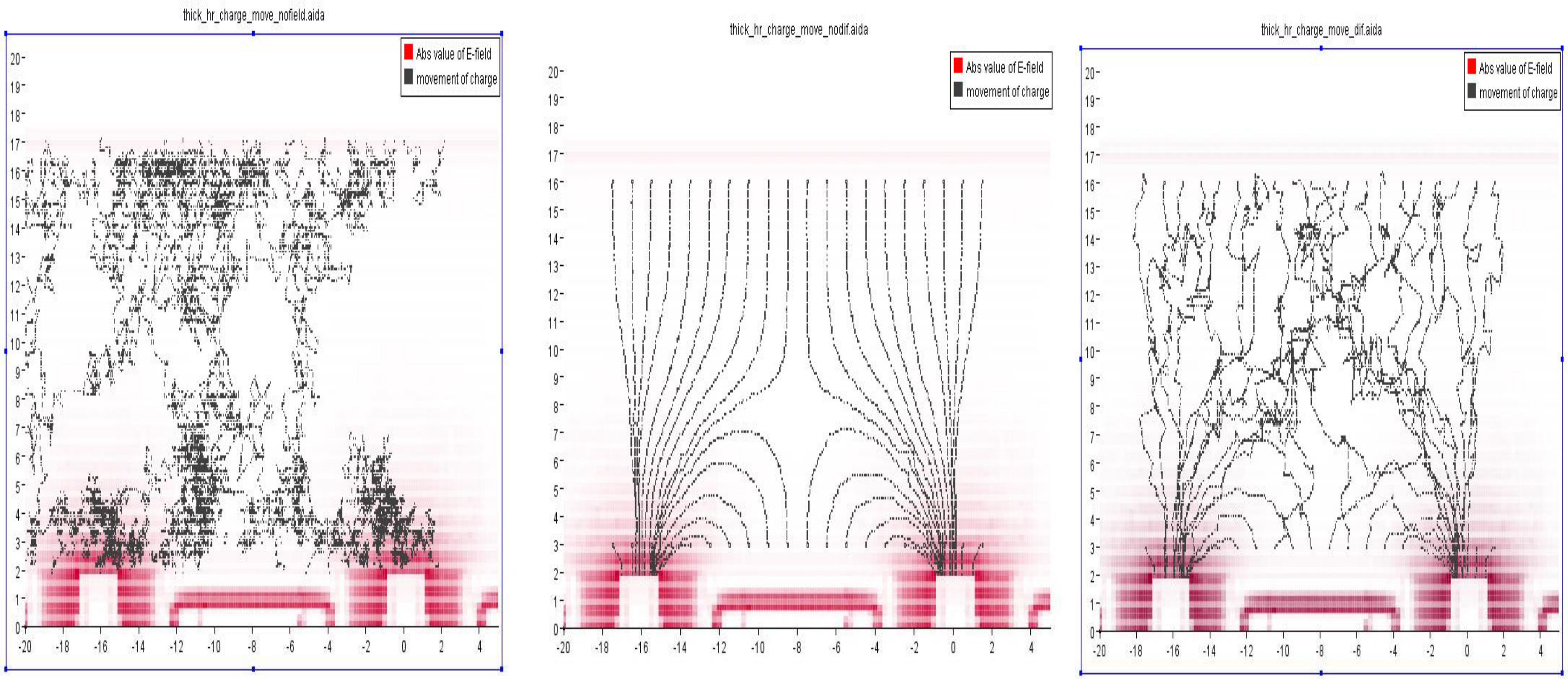
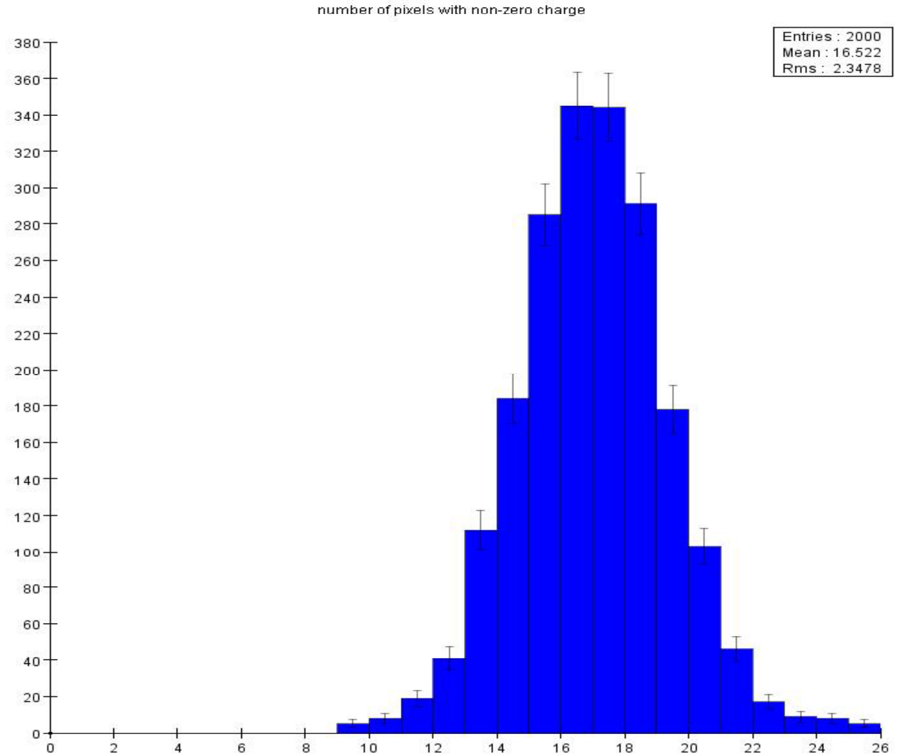
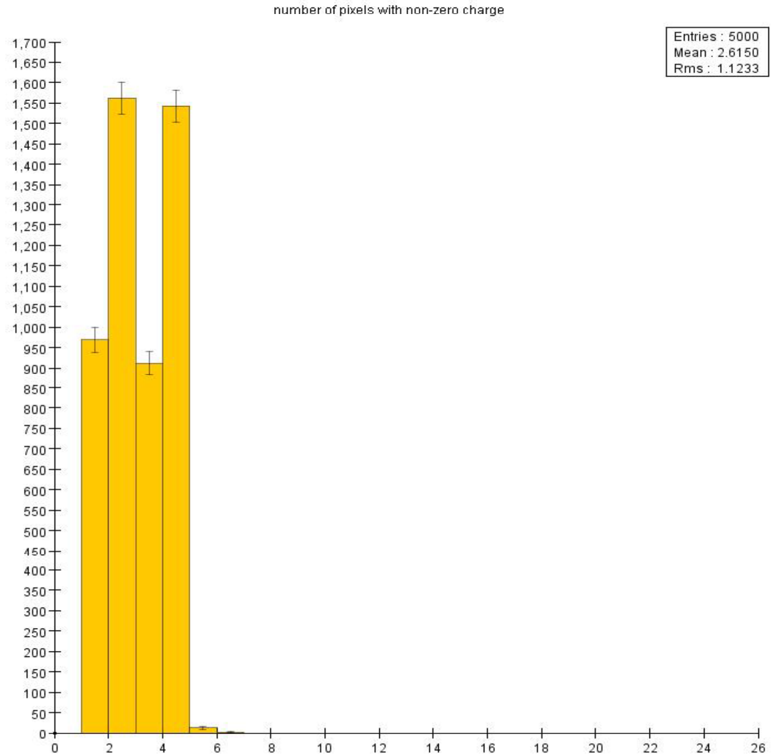


Illustration of the electric field effect on the charge collection in silicon sensor:
On the left picture only diffusion is simulated, in the middle charge is moving only by electric forces, and the right picture shows how it moved in our simulations

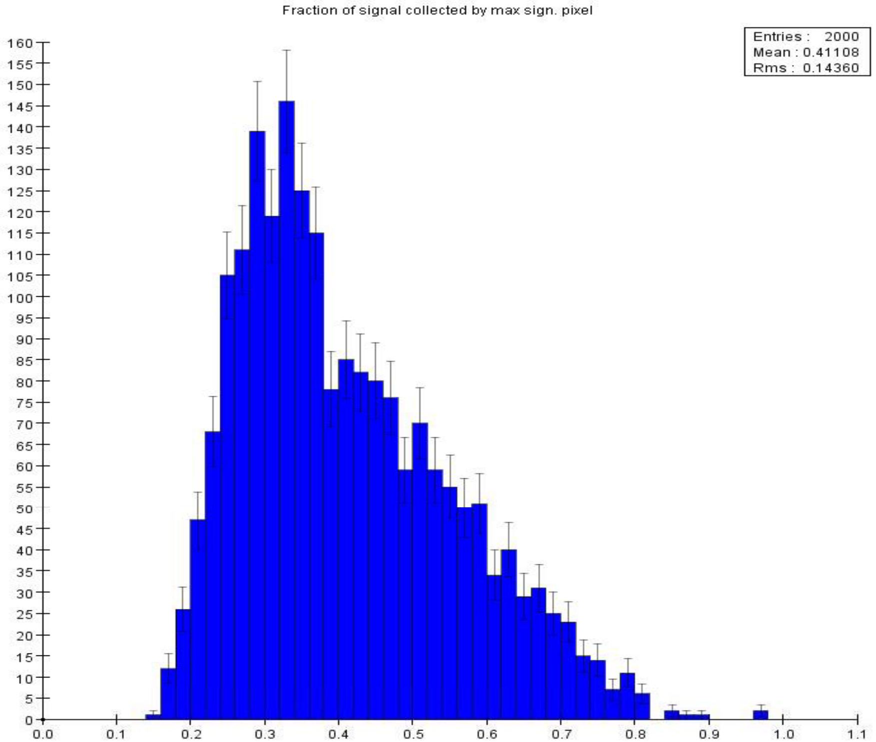
Effect of electric field - continue

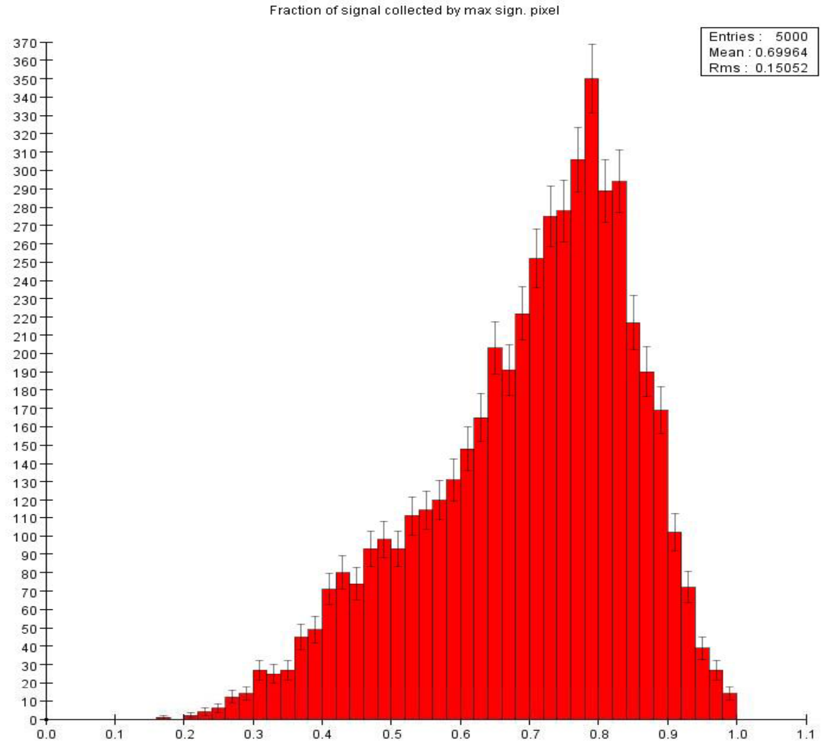




Here I plotted the number of pixels in 16x16 microns pixel size device with 20 micron total epi layer thickness which collected any charge (even if it is 1 electron) from charged particle ionization without taking into account e-field in undepleted area and with such field effect. You can see dramatic effect on charge confinement.

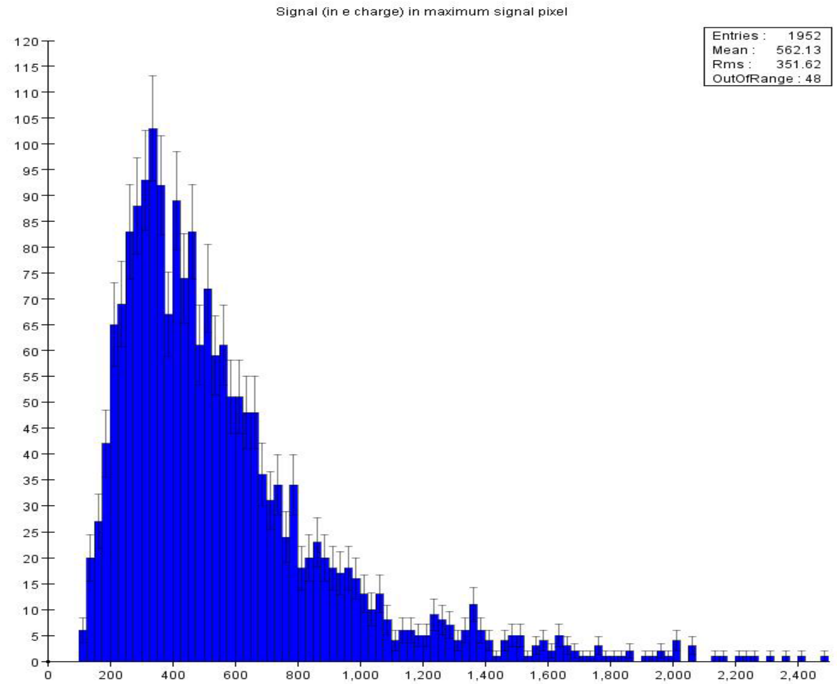
Effect of electric field – charge collected by maximum signal pixel

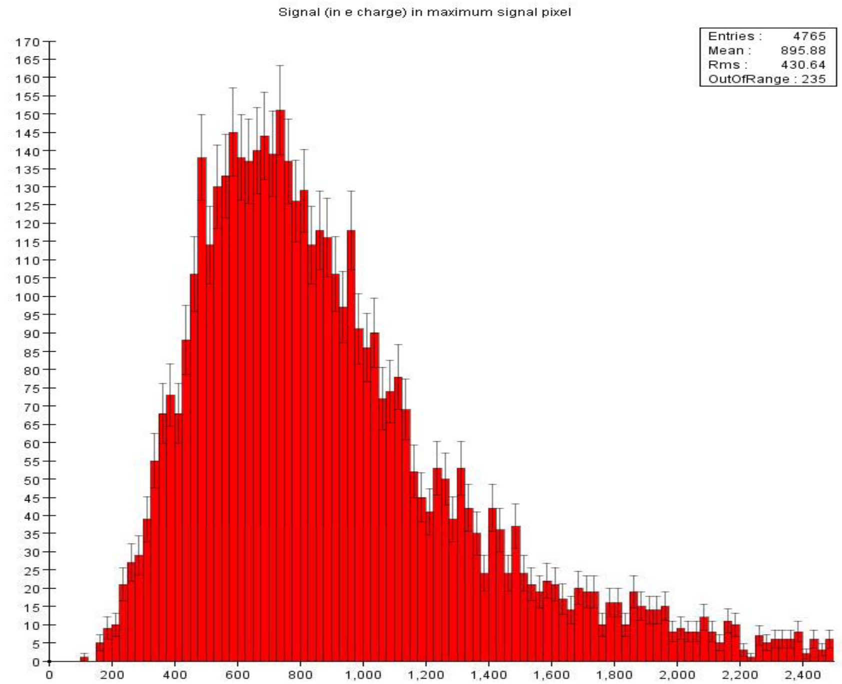




Fraction of total charge generated by ionizing particle, collected by pixel with maximum signal in the case electric field in udepleted area ignored (left), and taken into account (right).

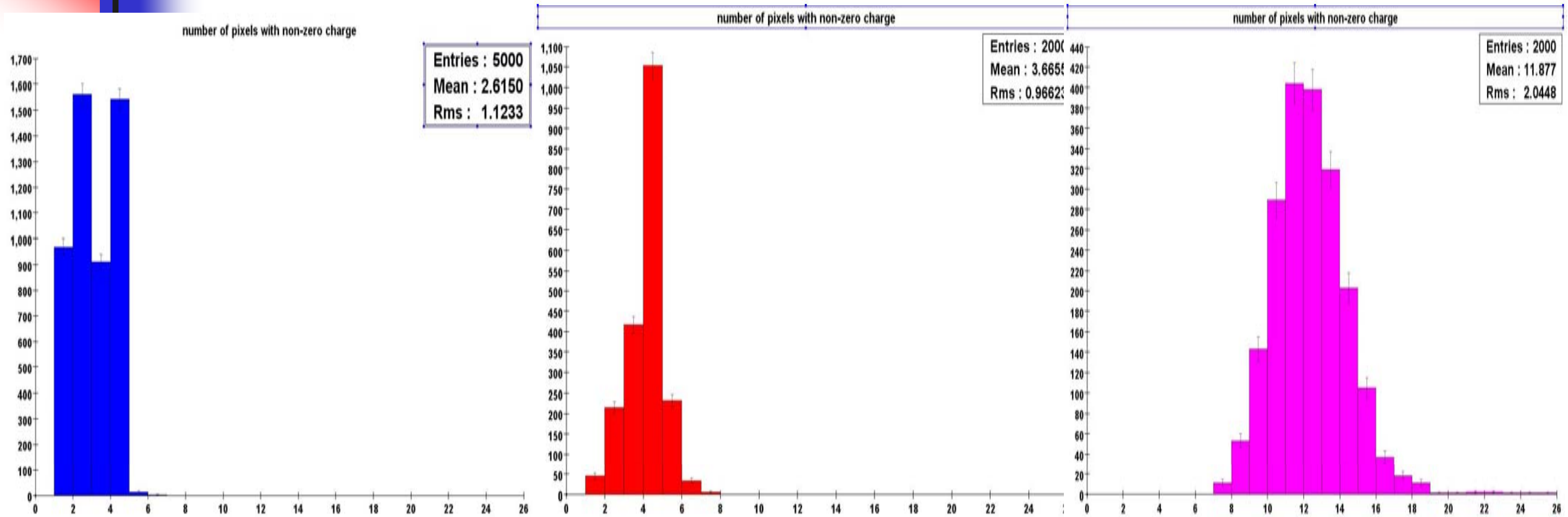
Effect of electric field – charge collected by maximum signal pixel





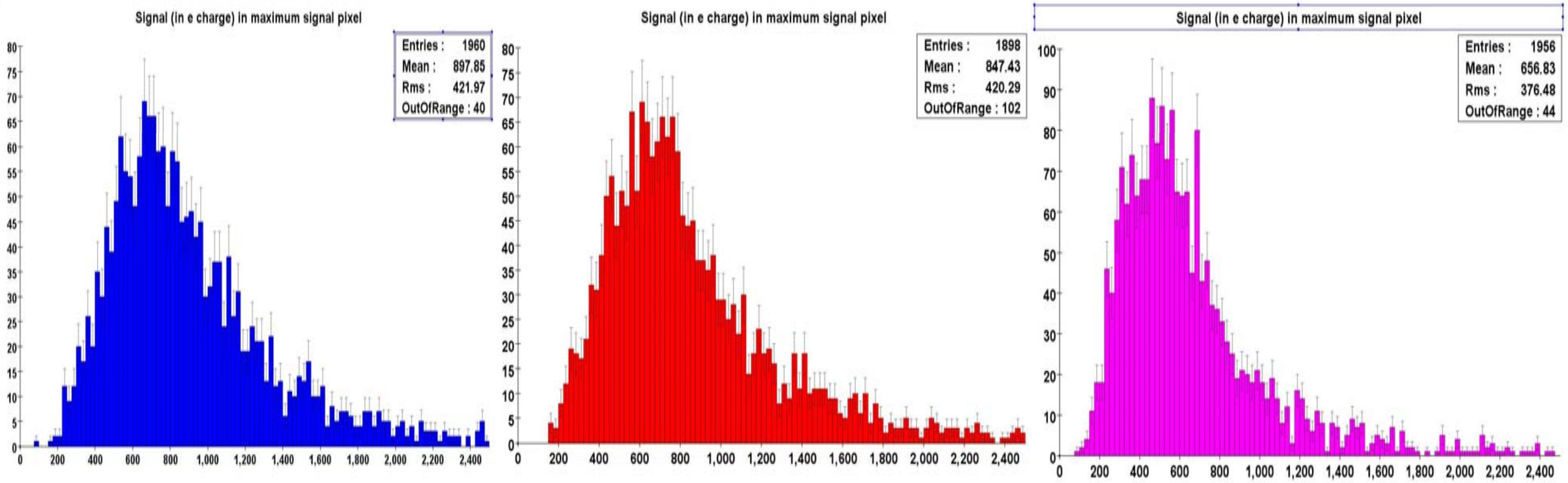
Amount of charge, collected by pixel with maximum signal in the case electric field in udepleted area ignored (left), and taken into account (right). Horizontal axis is in the units of electron charge. EPI layer thickness 20 μ. Depending on noise level, our registration threshold may be between 100 and 200 e charge.

Effect of pixel size



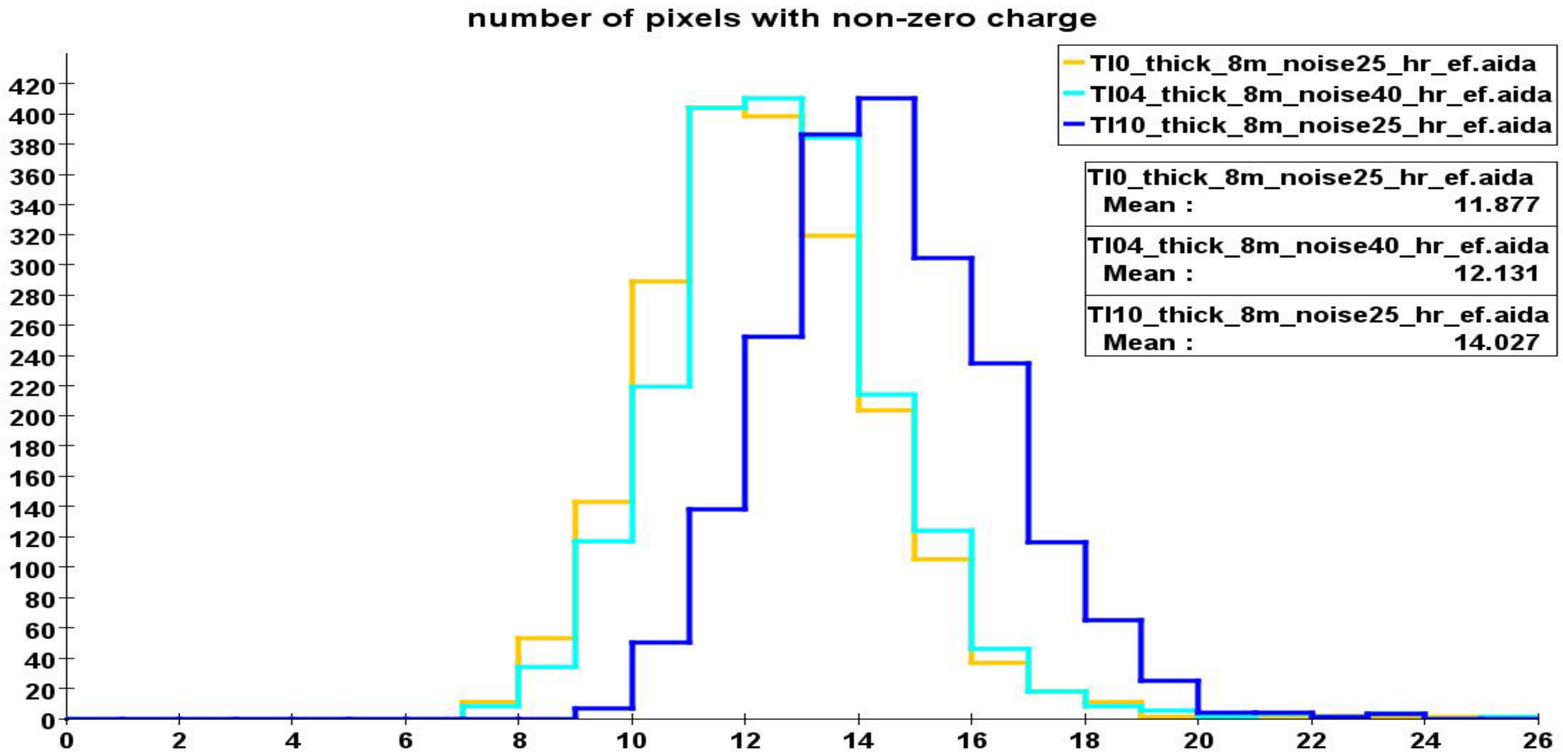
Number of pixels, collecting charge from track, for different pixel size: 16μ, 12μ and 8μ. Effect for smaller pixels not only from their smaller area, but also from the weaker field in non-depleted regions. If that field would be strong enough to keep charge from penetrating pixel borders, all 3 distributions would be similar to leftmost one.

Effect of pixel size



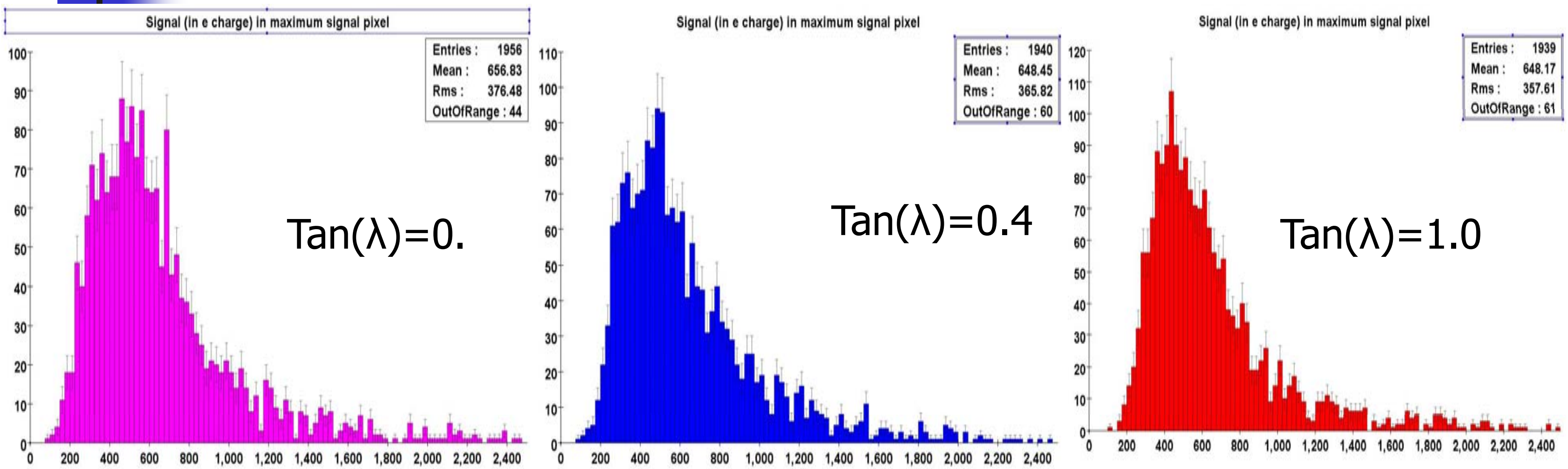
Signal in the max.signal pixel for different pixel size: 16μ, 12μ and 8μ. Mean values for these distributions are not changed as much as for distributions on previous page. This is because the value of the signal in max. signal pixel depends not only on how many pixels share charge, but also on value of largest e-loss in single collision occurred along track, and this does not depend on pixel size.

Effect of incident angle



Number of pixels seeing charge from track for different incident angles λ (tan(λ)=0., 0.4, 1.0). EPI layer 20 μ , pixel size 8x8 μ

Effect of incident angle



For pixel size smaller than EPI thickness one can expect reduction of track length, contributing into 1 pixel at large incident angles. However, total increase of path length increases probability of larger single collision loss, which should increase signal in max. signal pixel. As we see, for 8μ pixels and 20μ EPI thickness, these effects perfectly cancel each other. For 12μ and 16μ pixel sizes larger incident angles are beneficial for maximum signal amplitude.

Efficiency vs threshold

Pixel size (μ)	Tan(λ)	EPI layer 20μ thick				EPI layer 12μ thick			
		100e	125e	160e	200e	100e	125e	160e	200e
16x16	0.	100.	100.	100.	99.95	99.0	98.1	94.4	88.0
	0.2	100.	100.	100.	99.6	98.8	97.7	94.5	89.0
	0.4	100.	100.	100.	99.9	99.1	98.4	95.3	90.9
	0.7	100.	100.	100.	99.95	99.7	99.0	97.6	94.5
	1.0	100.	99.95	99.87	99.64	99.7	99.45	98.7	97.2
12x12	0.	100.	100.	99.95	99.65	99.2	97.5	95.0	87.6
	0.2	100.	100.	99.95	99.75	99.0	98.2	96.5	93.
	0.4	100.	99.95	99.85	99.6	99.1	97.8	95.6	90.6
	0.7	100.	100.	99.9	99.9	99.75	99.1	97.9	94.7
	1.0	100.	100.	100.	100.	99.9	99.7	98.7	96.5
8x8	0.	99.95	99.85	99.55	98.8				
	0.2	100.	99.9	99.5	98.0				
	0.4	99.95	99.85	99.65	98.7				
	0.7	100.	99.95	99.6	98.7				
	1.0	100.	100.	99.9	99.5				

Cluster size (number of pixels fired). Colors are copied from previous table to show good efficiency

Pixel size (μ)	Tan(λ)	EPI layer 20μ thick				EPI layer 12μ thick			
		100e	125e	160e	200e	100e	125e	160e	200e
16x16	0.	1.46	1.38	1.30	1.23	1.22	1.15		
	0.2	1.51	1.44			1.24	1.16		
	0.4	1.64	1.56			1.25	1.18	1.09	1.0
	0.7	1.85	1.75			1.35	1.28	1.18	1.08
	1.0	2.12	2.0			1.48	1.4		
12x12	0.	1.66	1.55			1.21	1.14		
	0.2	1.71	1.60			1.23	1.18		
	0.4	1.89	1.76			1.25	1.19	1.1	1.01
	0.7	2.14	1.99			1.38	1.30		
	1.0	2.53	2.36			1.56	1.45		
8x8	0.	2.43	2.12	1.7	1.47				
	0.2			1.77	1.53				
	0.4			2.06	1.76				
	0.7	3.17	2.79	2.43	2.08				
	1.0	3.72	3.28	2.84	2.41				

Conclusions

- Weak electric field in non-depleted region helps significantly limit charge spread
- Chronopixel devise can have good efficiency for 20μ epi layer thickness with any reasonable noise estimate
- 12μ epi layer can work if noise level 25e or less can be achieved.
- Effect of epi layer thickness on spatial resolution need to be evaluated, and it can be done, using software package shown here.