Fast simulation of the Silicon Pad Detector

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Introduction

Silicon Detector

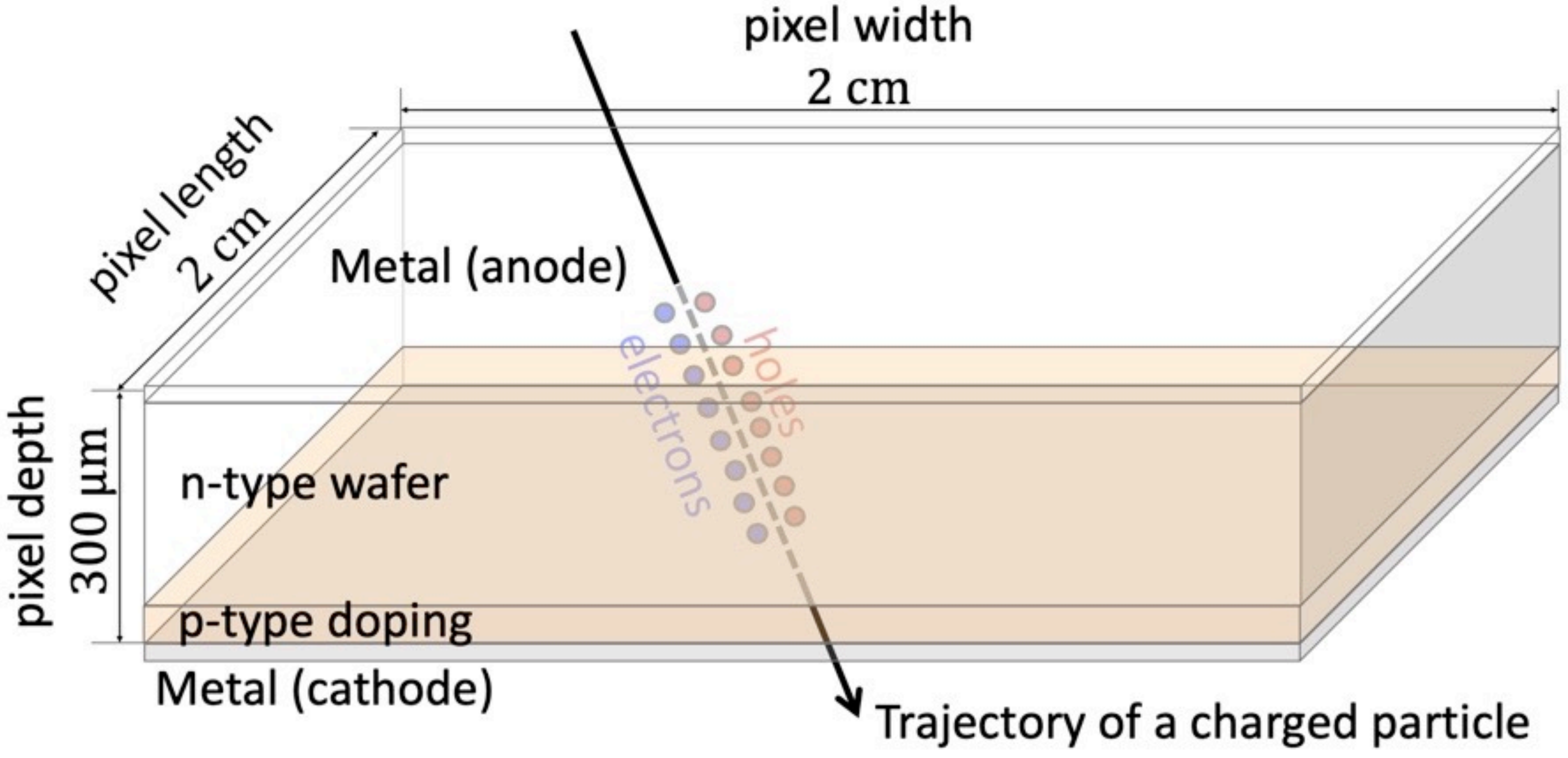
- Because of their superior spatial and kinematic resolution and good response time, silicon detectors are widely used in particle and nuclear physics to detect charged particles.
- The region where any free charge carrier (electrons and holes) rarely exists is called the depletion region.
- When the charged particles pass through the depletion region, they loss their energy by creating electron-hole pairs along the trajectory.
- Created electrons and holes are drifted to the electrodes because of the external electric field.
- To increase the depletion region, a reverse-bias voltage is applied to the device.

Detector Simulation

- We introduce an open-source-silicon-detector simulator named "*Fast Silicon Simulation*".
- Calculated results by "*Fast Silicon Simulation*" is compared with the results by a commercial simulation.

Simulation Set Up

- We construct a 2cmx2cmx300μm volume of device composed of lightly doped n-type bulk and heavily doped p-type pad.
- To simplify electron-hole-pair generation process, we consider the MIP(Minimum Ionizing Particles).



Input parameter		
Size(width×length×depth)	2cm×2cm×300μm	
Reverse bias voltage	140V(fully depleted)	
Operation temperature	300K	
Doping density	n-type	$1.9\times10^{18}\ m^{-3}$
	p-type	$10^{21}\ m^{-3}$
Mobility	Electron	$0.135\ m^2V^{-1}s^{-1}$
	Hole	$0.048\ m^2V^{-1}s^{-1}$

Incident beam and its energy loss	
Density	$75\mu m^{-1}$(MIP)
Angle of incidence	0 degree(vertically incidence)
Position	(0,0,0)→(0,0,300)

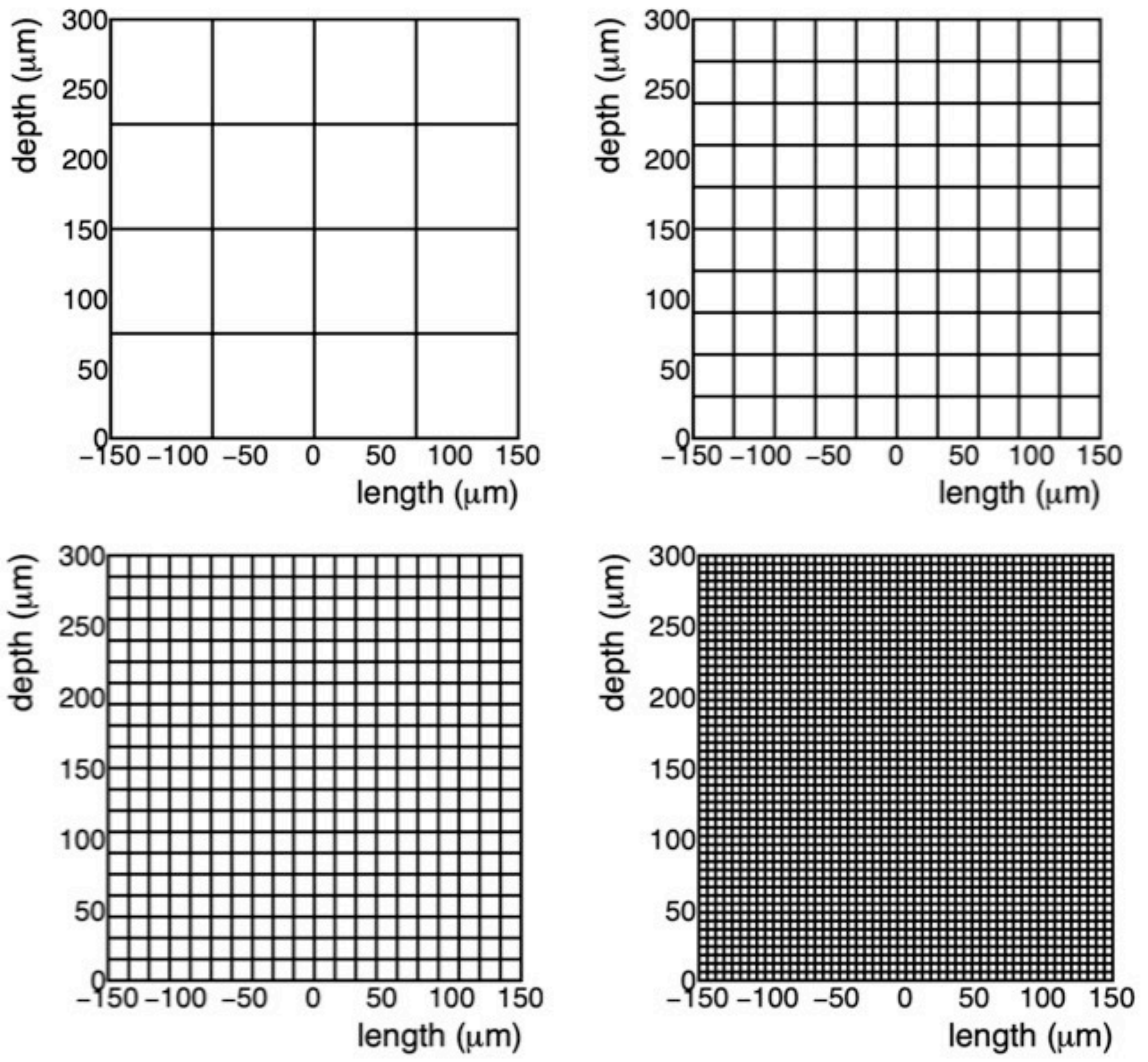
Calculation

Electric potential

$$\nabla^2\phi = -\frac{\rho}{\epsilon}$$

where ϕ : electric potential, ρ : volume density, ϵ : permittivity of the material

In this study, electric potential is calculated by the *Multi-grid method*.



Multi-grid method

- Apply the iteration method to wider lattices as an initial condition.
- By interpolating with the values of the surrounding lattice components, the denser lattices are created.
- For each step, the iteration method is repeated until the potential values at the lattices do not change by less than 0.01%.
- By filling the inside of the grid with the average value, calculation time can be reduced.

Calculation

When the potential is calculated, other quantities are calculated by following the equations below.

Electric field $\vec{E} = -\nabla\phi$

Induced current for electron $\vec{J_e} = e\rho_e\mu_e\vec{E} + eD_e\nabla n_e$

And hole $\vec{J_h} = e\rho_h\mu_h\vec{E} - eD_h\nabla n_h$

where $\vec{J_e}(\vec{J_h})$: current density of electron(hole), $\rho_e(\rho_h)$: volume charge density of electron(hole), e : elementary charge, $n_e(n_h)$: electron(hole) density, Einstein's relation $D_e = -k_BT\mu_e/e$ $(D_h = k_BT\mu_h/e)$

Mobility

$$\mu_e(E) = \mu_{0,e}\left(\frac{1}{1+\left(\frac{\mu_{0,e}E}{v_{sat,e}}\right)^2}\right)^{1/2} \qquad \mu_h(E) = \mu_{0,e}\frac{1}{1+\frac{\mu_{0,h}E}{v_{sat,h}}}$$

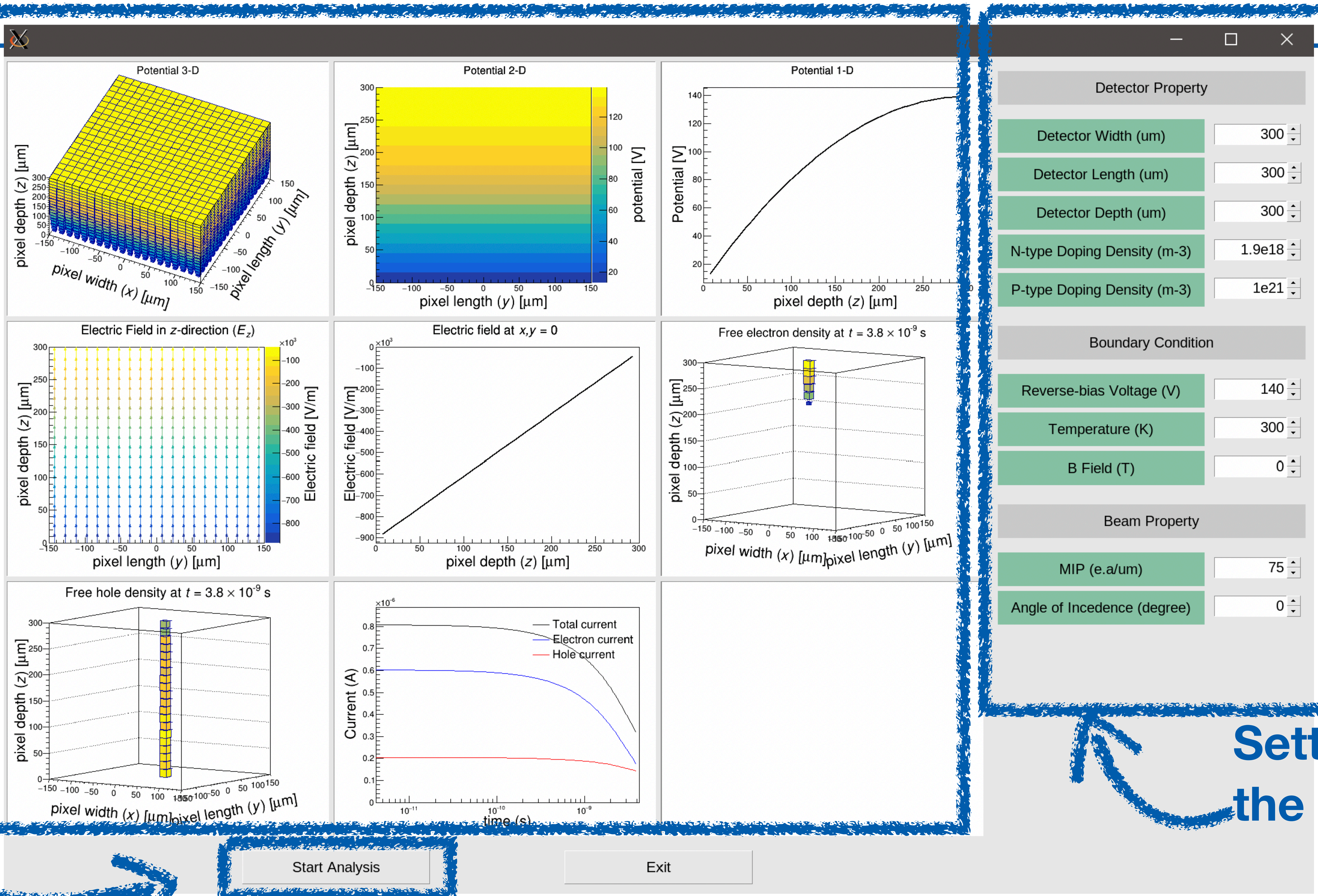
Where $\mu_{0,e}(\mu_{0,h})$: mobility for electron(hole), $v_{sat,e}(v_{sat,h})$: saturation velocity of electron(hole)

Results

Result panel

Analysis Start!

Setting the Input Parameter



Detector Property

Detector Width (um)	300
Detector Length (um)	300
Detector Depth (um)	300
N-type Doping Density (m-3)	1.9e18
P-type Doping Density (m-3)	1e21

Boundary Condition

Reverse-bias Voltage (V)	140
Temperature (K)	300
B Field (T)	0

Beam Property

MIP (e.a/um)	75
Angle of Incedence (degree)	0

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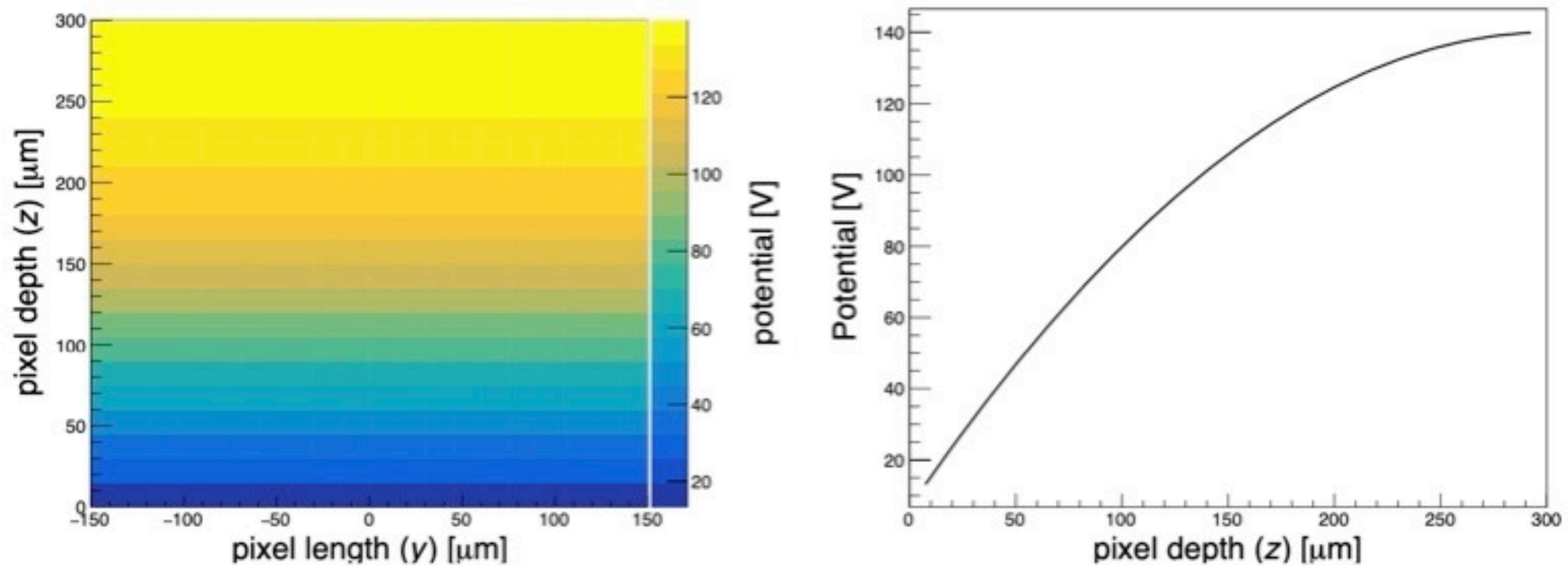
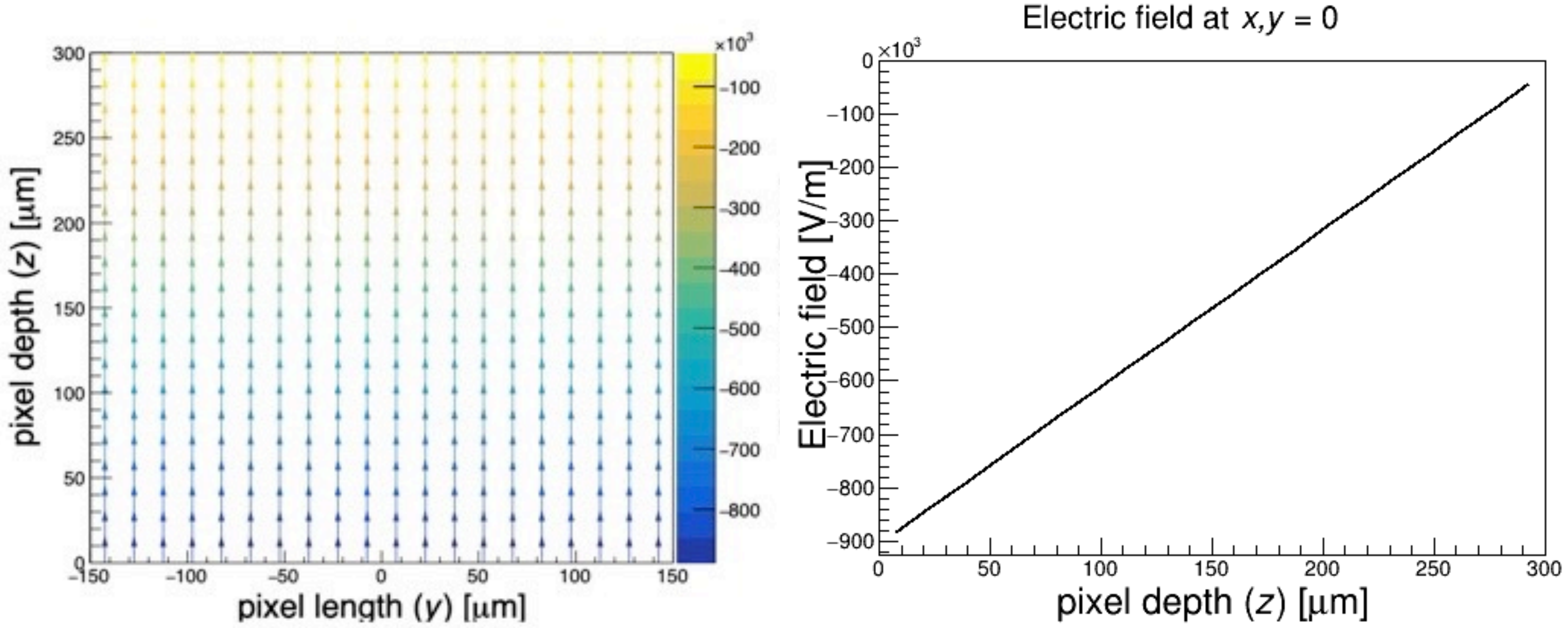
Results



Potential

- The potential projected in yz-plane at $x = 0$
- The potential distribution along the depth direction of the device in the depleted p-n junction follows the second-order polynomial.



Electric field

- The direction and magnitude of the electric field along the depth axis.
- The electric field varies linearly from top to bottom of the device due to its uniform doping density.

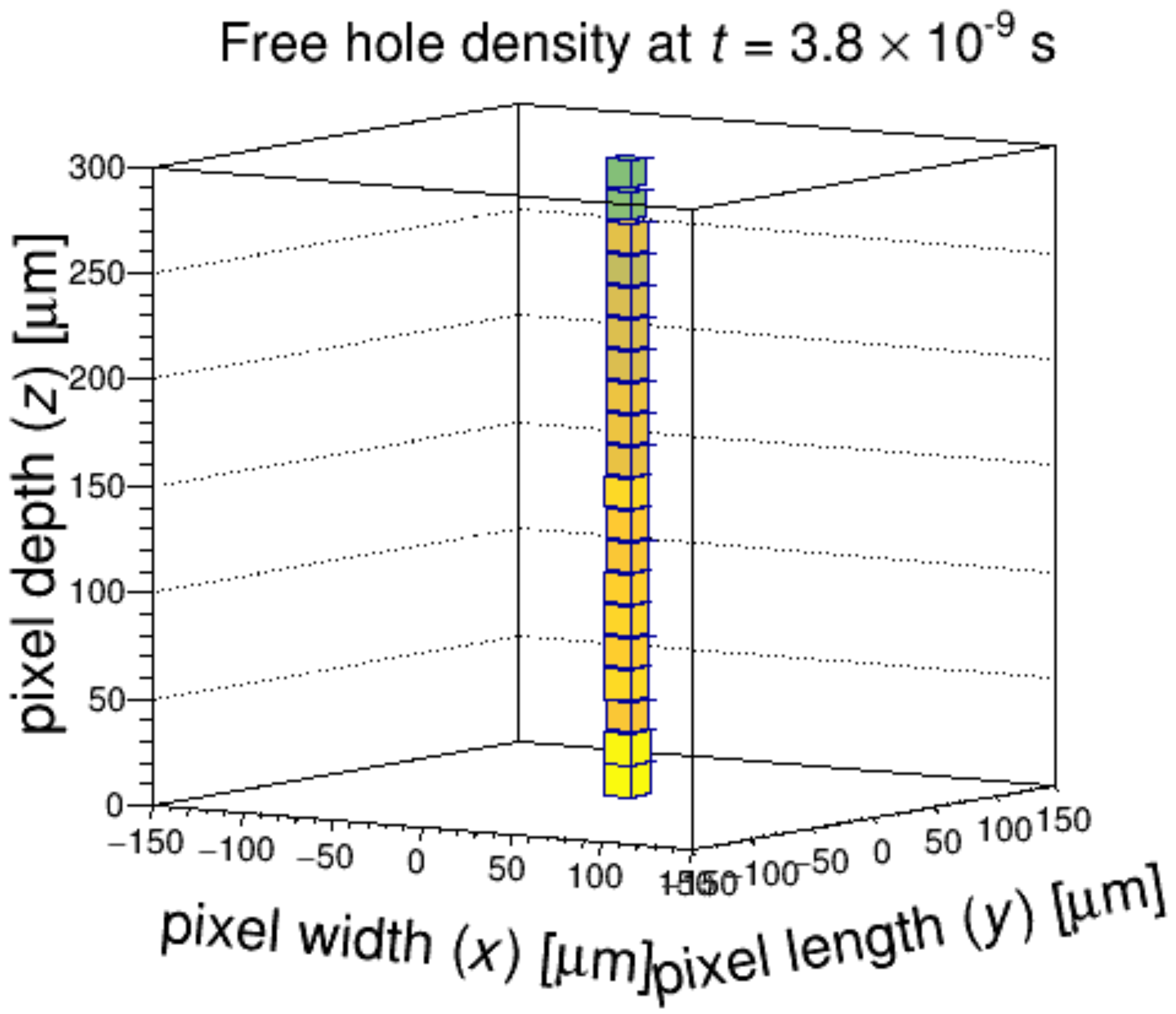
Results

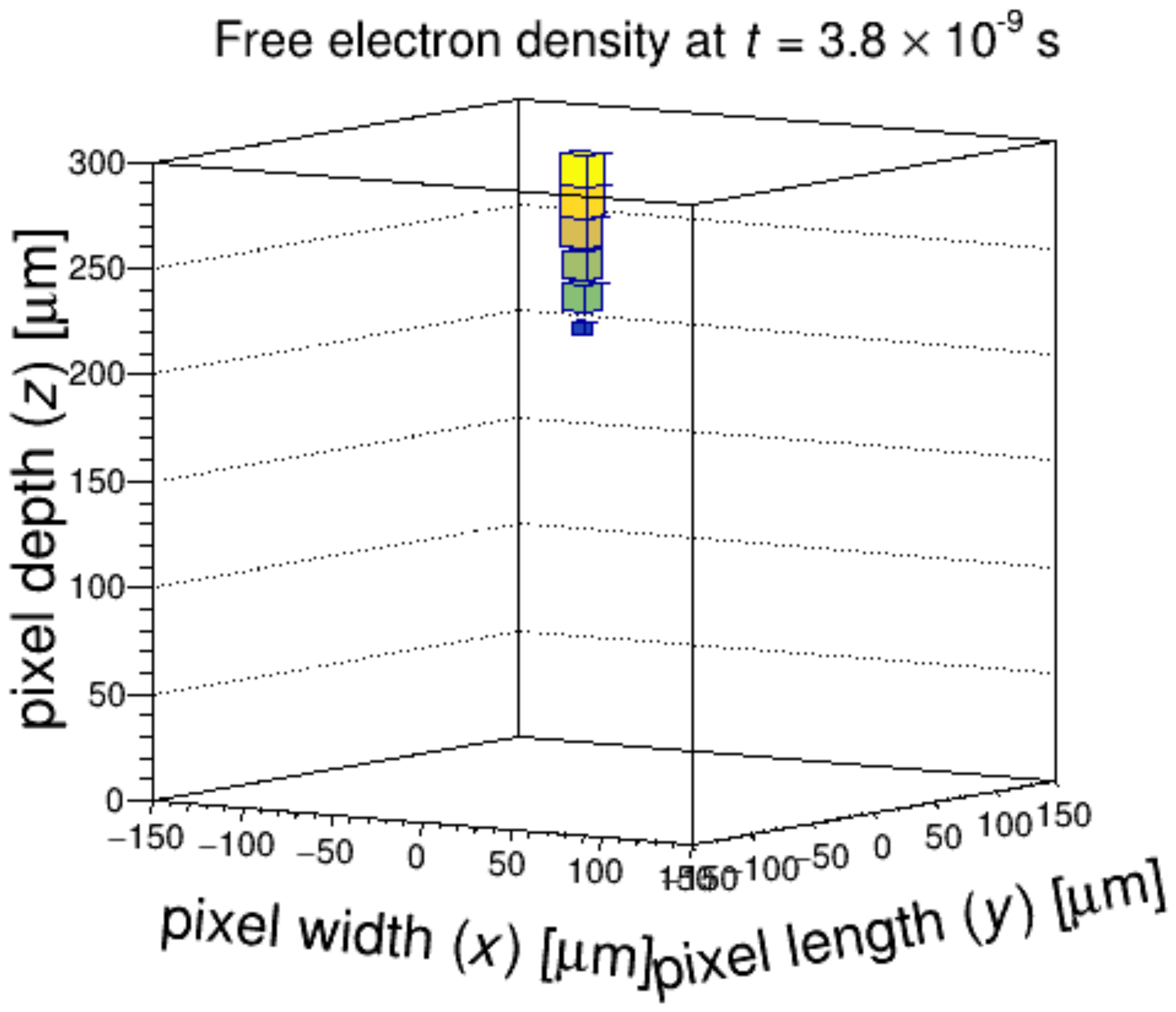
Induced current

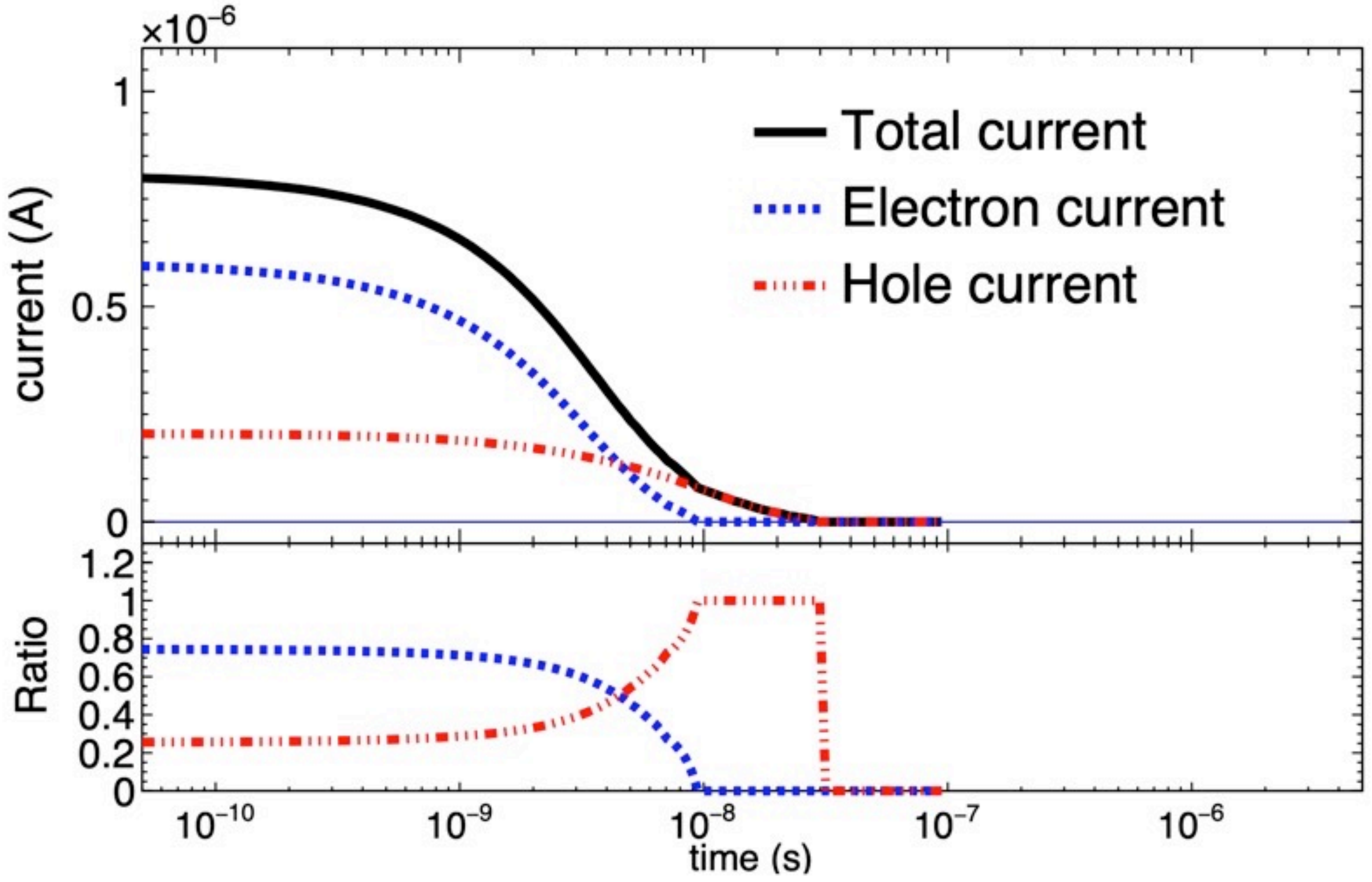
- The number of generated electron-hole pairs is set by 75 per µm in the silicon volume.

- Holes move slower than electrons in the device, resulting makes the magnitude of the hole current is lower than electron current.

- Because of the same reason, electrons are collected quickly to the anode than holes.


Free hole density at $t = 3.8 \times 10^{-9}$ s

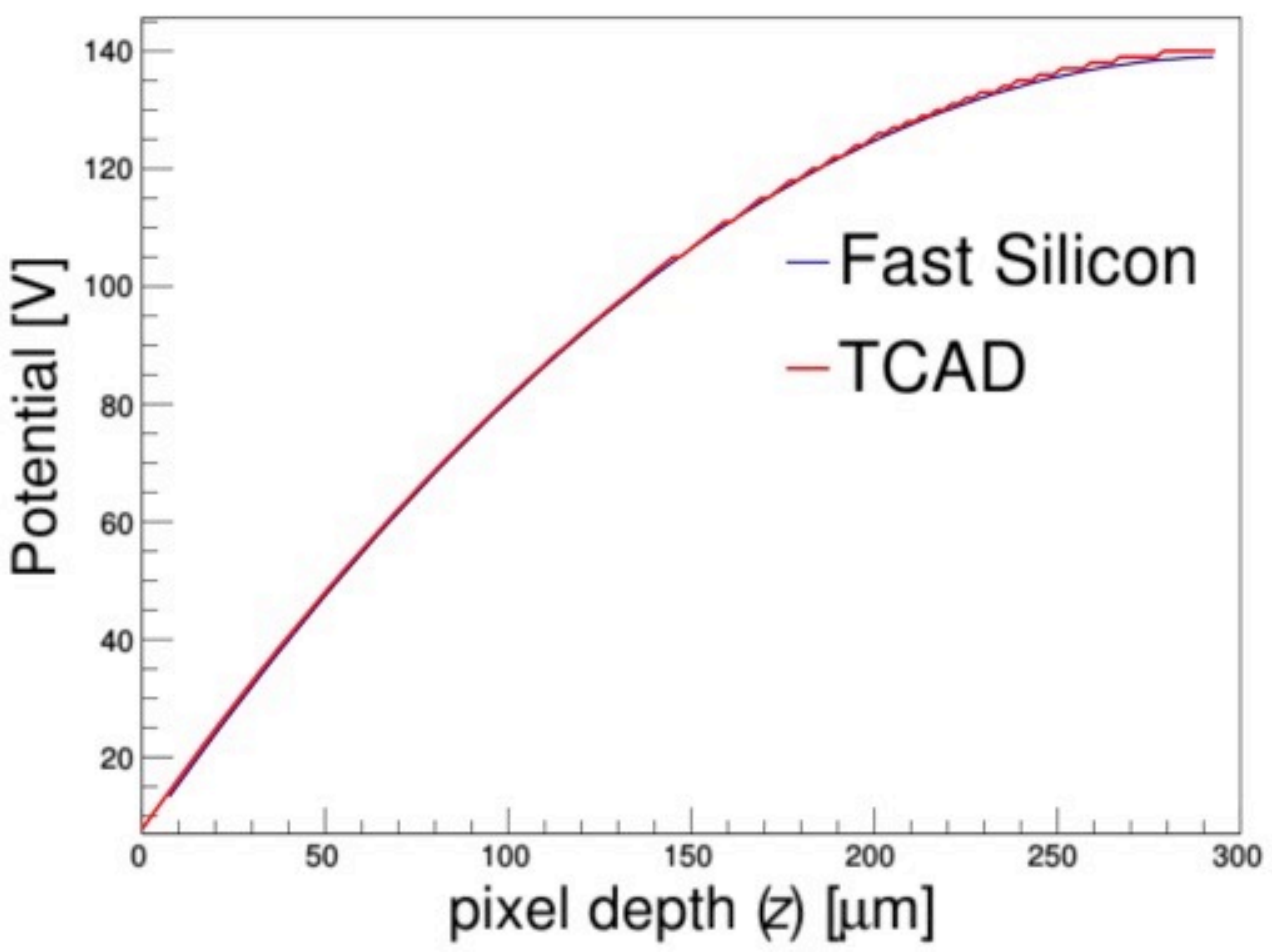

Free electron density at $t = 3.8 \times 10^{-9}$ s

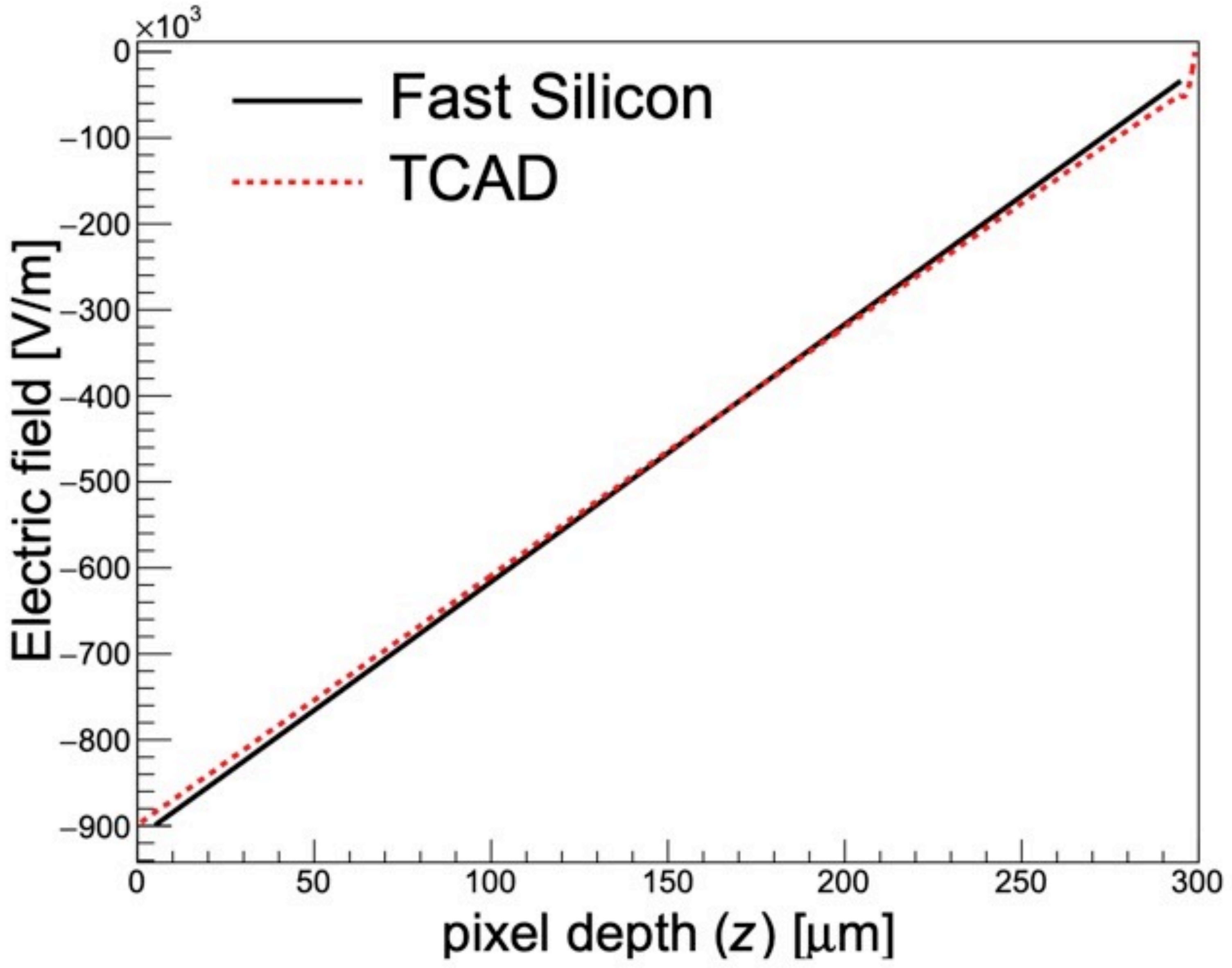


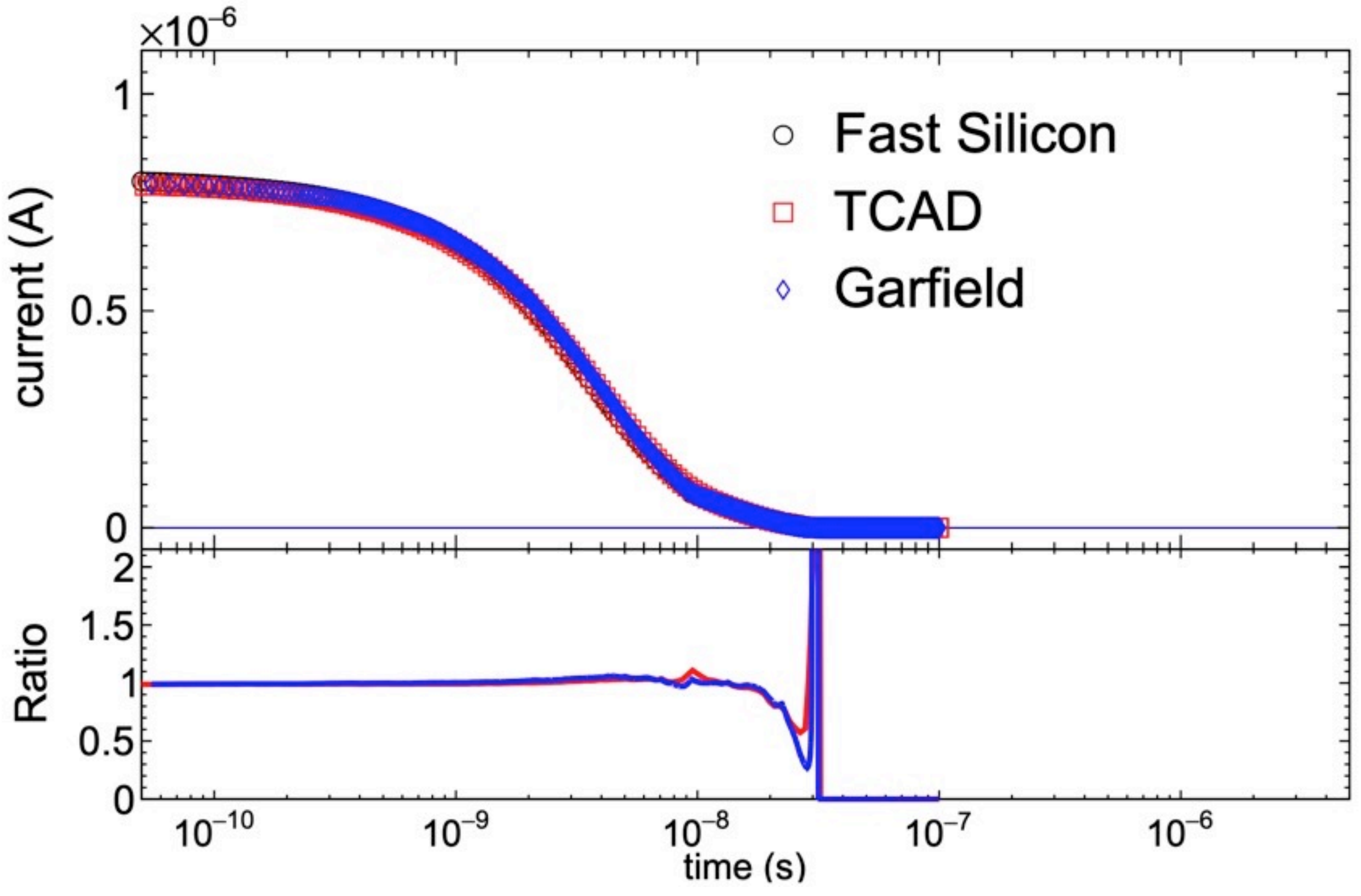
Results

Comparison with other simulation

- Silvaco TCAD (**T**echnology **C**omputer-**A**ided **D**esign) is the commercial semiconductor device simulator.
- Garfield++ is a simulation toolkit for particle detectors based on ionization measurement in gases or semiconductors.
- Electric field, potential and induced currents are almost the same with the results by TCAD and Garfield++.







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Conclusion & Summary

- In this study, We introduce a new open-source-silicon-detector simulator named "*Fast Silicon Simulation*".
- To calculate the potential and electric field, the multi-grid method and iterative method are used.
- Results by *Fast Silicon Simulation* are consistent to the results by TCAD simulation qualitatively and quantitatively.
- *Fast Silicon Simulation* is 100 times faster than TCAD simulation.
- This simulation method can be used to study the optimized design and physical properties of the silicon detector.
- We consider to compare the *Fast Silicon Simulation* results to TCAD simulation results, when the incident angles and the depths of device are changed.

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