Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

SILVACO simulation of a monolithic active pixel low energy X-rays sensor

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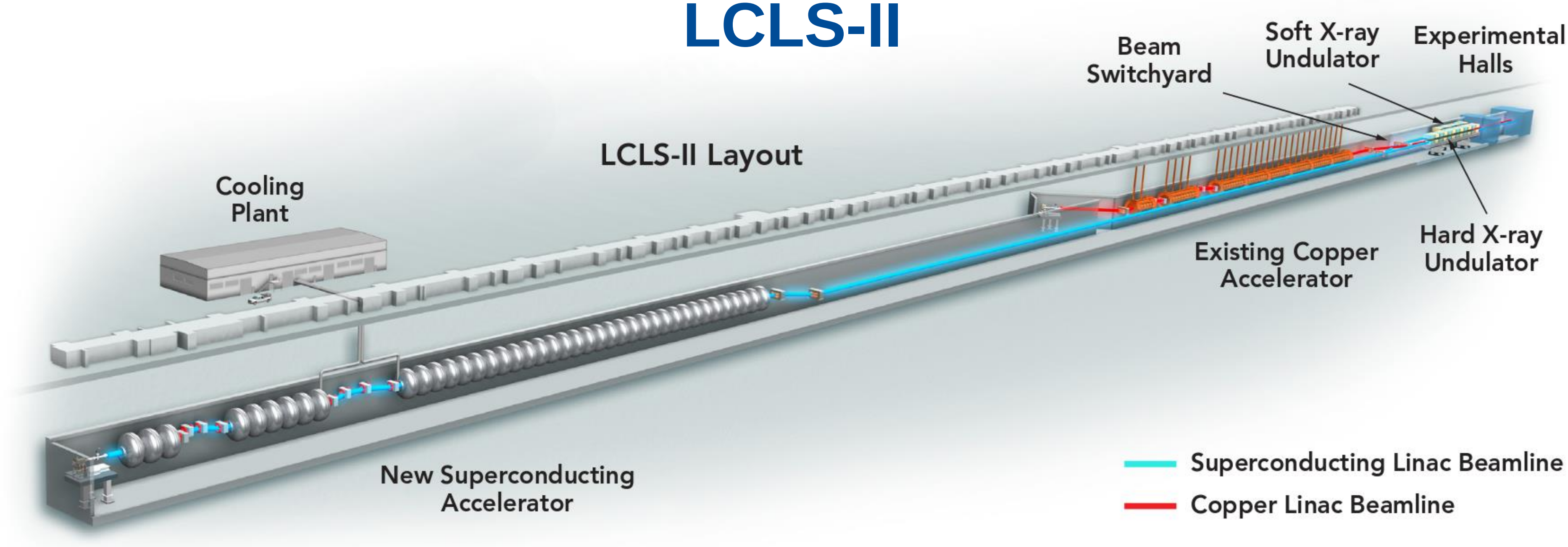
Final presentation - 09/28/2017

LCLS-II



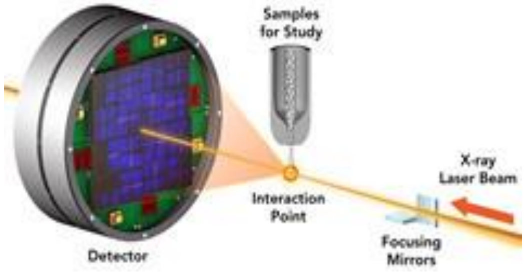
The Linac Coherent Light Source at SLAC National Accelerator Laboratory is an Office of Science User Facility operated for the Department of Energy by Stanford University.

It will be the world's only X-ray free-electron laser capable of supplying a uniformly-spaced train of pulses with programmable repetition rate with the highest speed and brightness ever realized (up to 1 million pulses per second).

Electrons will be accelerated through superconducting RF cavities, and they will emit X-rays thanks to undulator magnets.

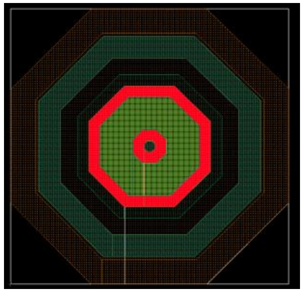
It produces waves with coherent phase, good for sampling matter and taking picture at the atomic levels: it allows advanced research in chemistry, biology and science of materials.

FLORA pixel: new x-rays detector for imaging experiments at LCLS-II



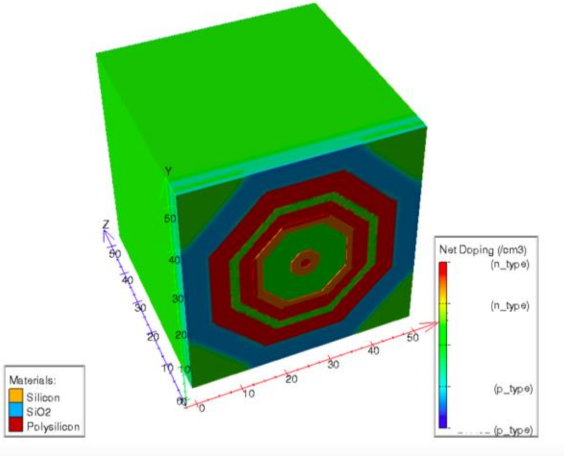
New detector proposal:
FLORA (**F**ermilab-**L**CLS CM**O**S 3D-integ**R**ated detector with **A**utogain)

- Sensor with two signal paths
  - Low noise, small signals with traditional MAPS
  - Automatic overflow for large signals thru ROIC
- High dynamic range (1x10e4 photons)
- High signal to noise ratio, single photon detection (200 eV–2 keV)



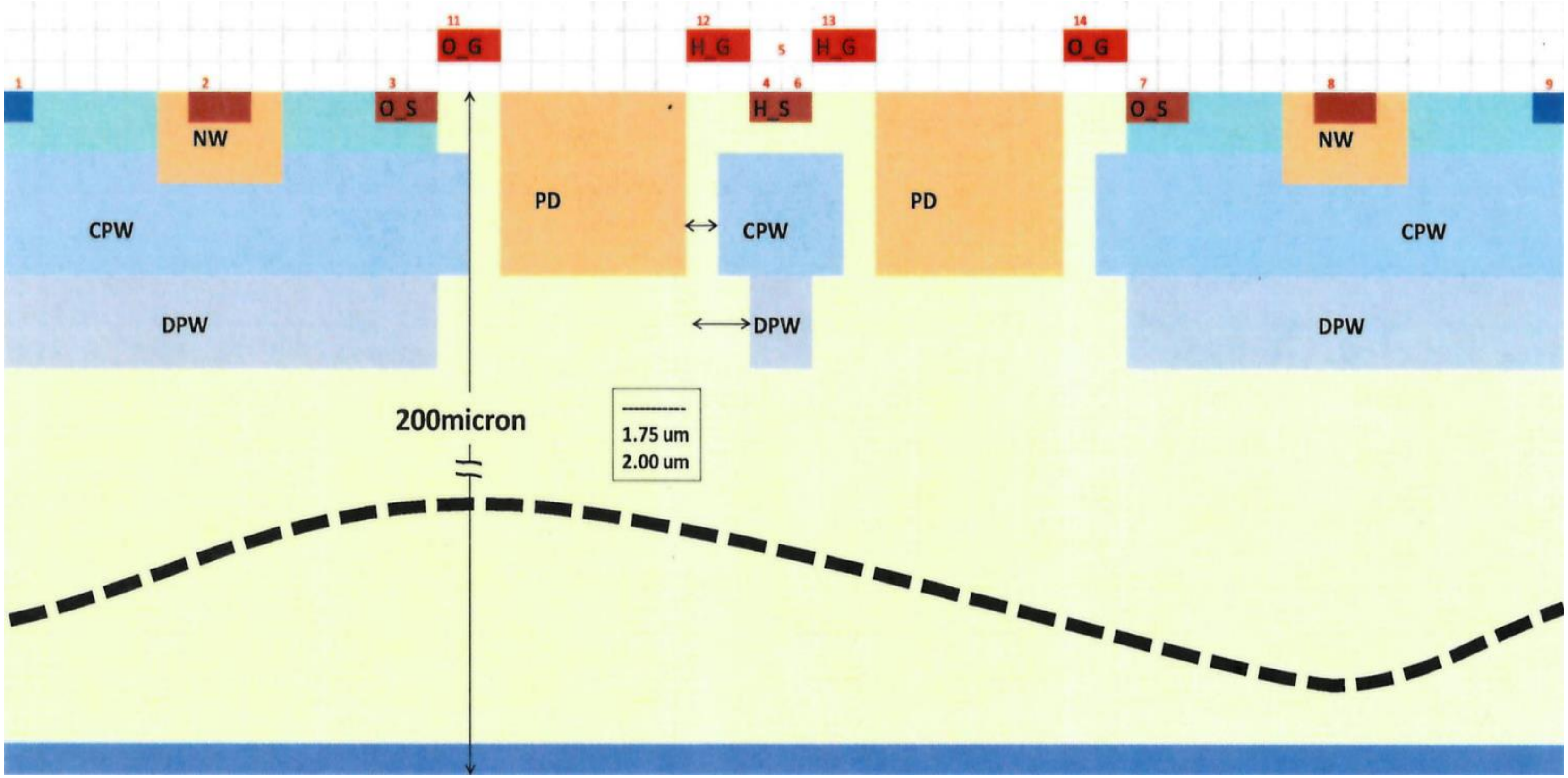
TCAD SIMULATIONS REQUIRED

Target of the project:
Simulating the operation of the flora pixel and giving guidelines for its realization.



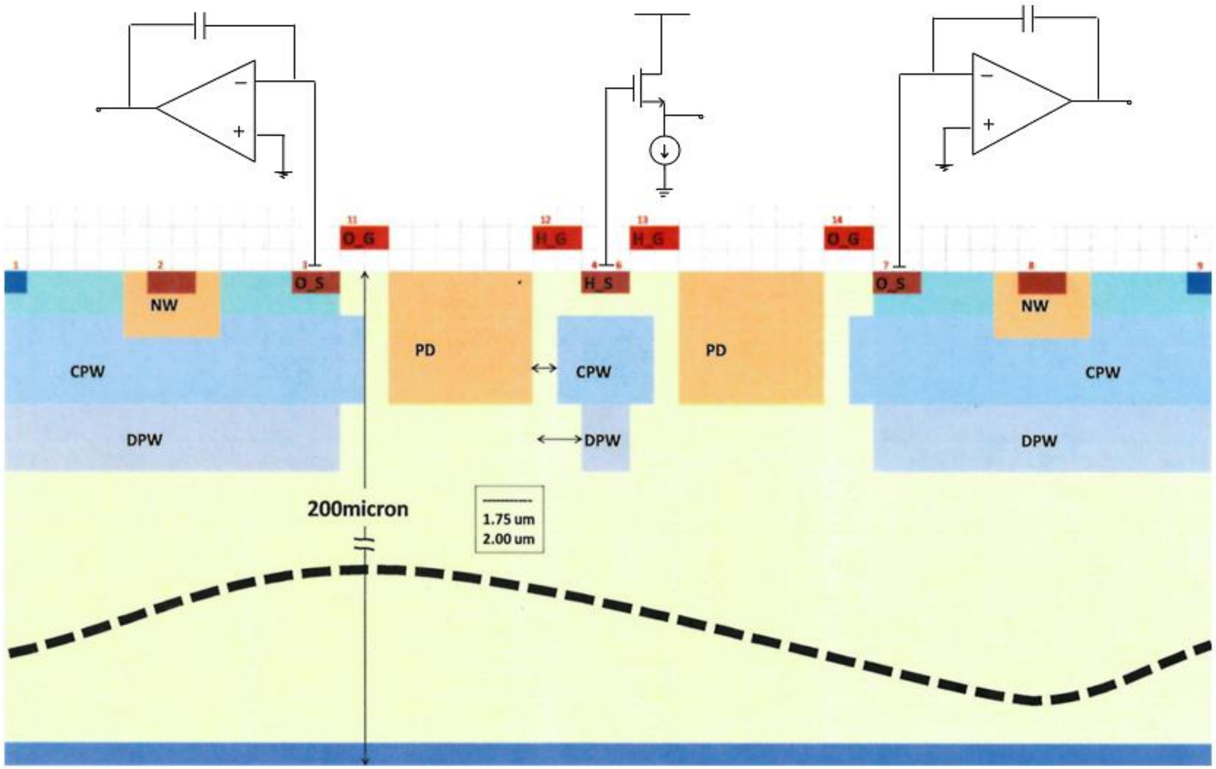
Collaboration with SLAC National Accelerator Laboratory, a U.S. laboratory operated by Stanford University.

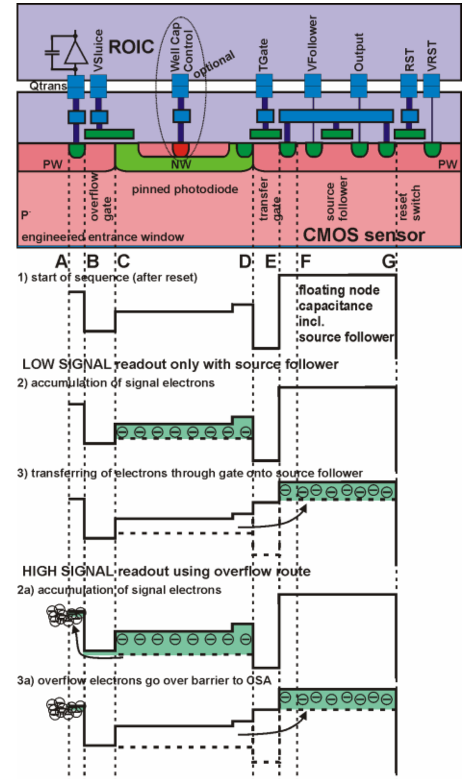
FLORA pixel: proposed structure



- **Back side illuminated photodiodes** (PD), fully depleted
- **High sensitivity node** (H_S): floating diffusion contact, for small signals
- **Overflow sense nodes** (O_S), for large signals
- **Transfer gates** (H_G, O_G)

FLORA pixel: charge measurement





- **Source follower** connected to the floating diffusion region (small capacitance) for measuring small amounts of charges, integrated in the silicon (MAPS).
- **Operational amplifier with feedback capacitor**: connected to the overflow electrodes (constant potential) for measuring large amounts of charges (continuous charge flowing), in an external ROIC layer above the silicon structure.

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SILVACO

SILVACO is a software which performs TCAD simulations of semiconductor devices.

TCAD allows fabrication process and device physics level simulations.

- 2D/3D Finite Element Method (FEM).
- Resolution of the semiconductor drift-diffusion (DD) equation and the Poisson's equation for the electric field over the mesh grid.
- Modeling of generation-recombination mechanisms, such as Shockley-Reed-Hall (SRH) for deep trap dynamics.

- ATHENA for process simulation.
- ATLAS for device simulation.

SILVACO

- Dealing with convergence problems.

Studies and attempts

Before working out the final version of the FLORA pixel sensor, many attempts and studies of several devices have been analyzed.

Simulation of charge transfer devices (from BSI to FD)

- Single gate charge transfer
  - With and without resetting the FD region
  - Study of the potential profile of the structure during charge transfer
- Charge transfer with an additional BSI gate
  - With and without resetting the FD region
- Pinned photodiode
- J-FET based transfer channel

Simulation of the FLORA pixel (addition of the overflow electrode)

- Complete sensor with BSI gate
- Complete sensor with pinned photodiode
  - Overflow electrode voltage optimization
  - Study of the behavior of the sensor under wide charge varations

FINAL PROPOSAL

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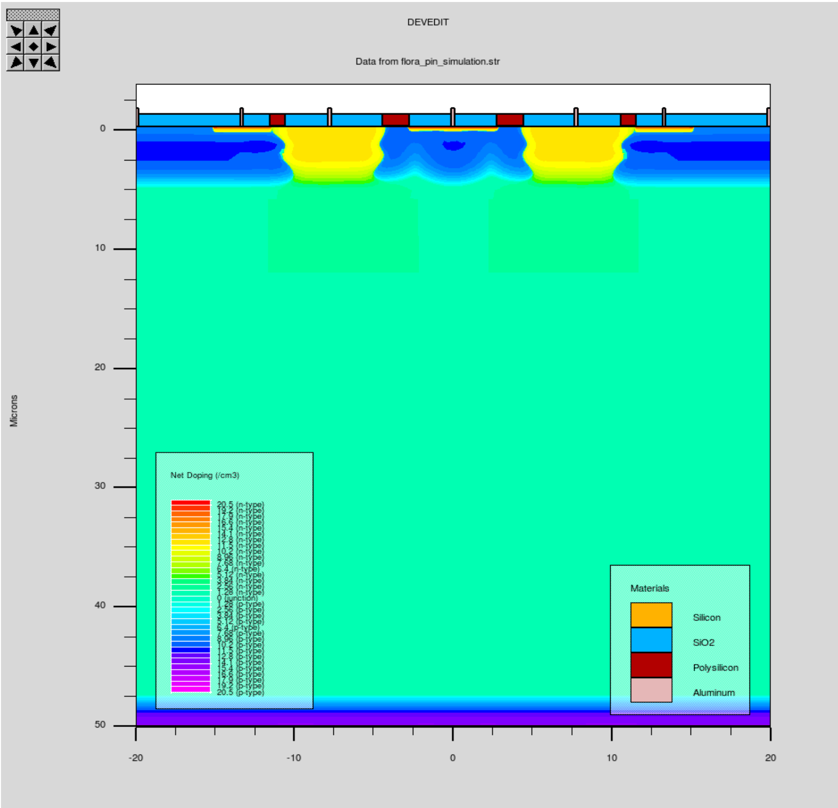
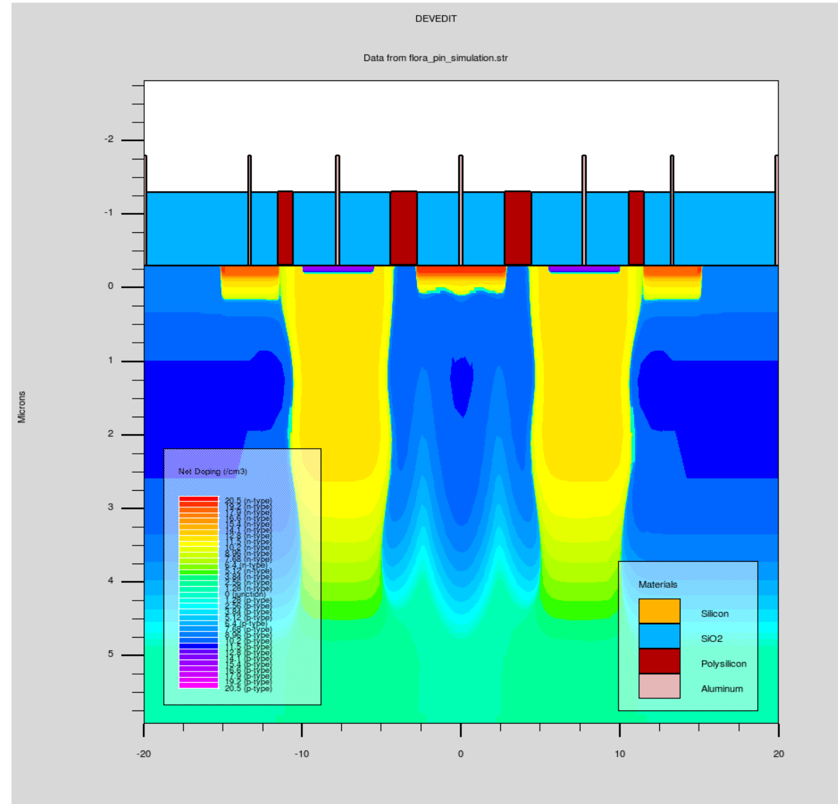
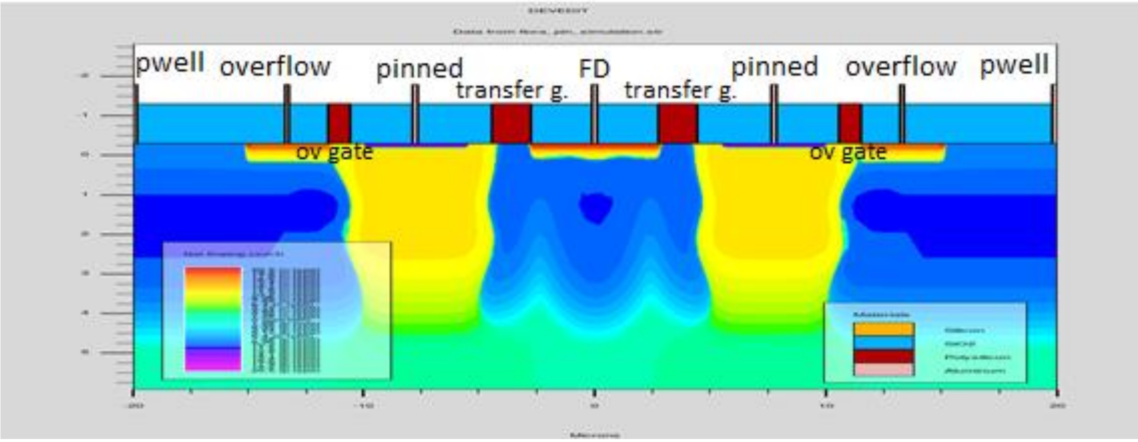
FLORA PIXEL: final proposal

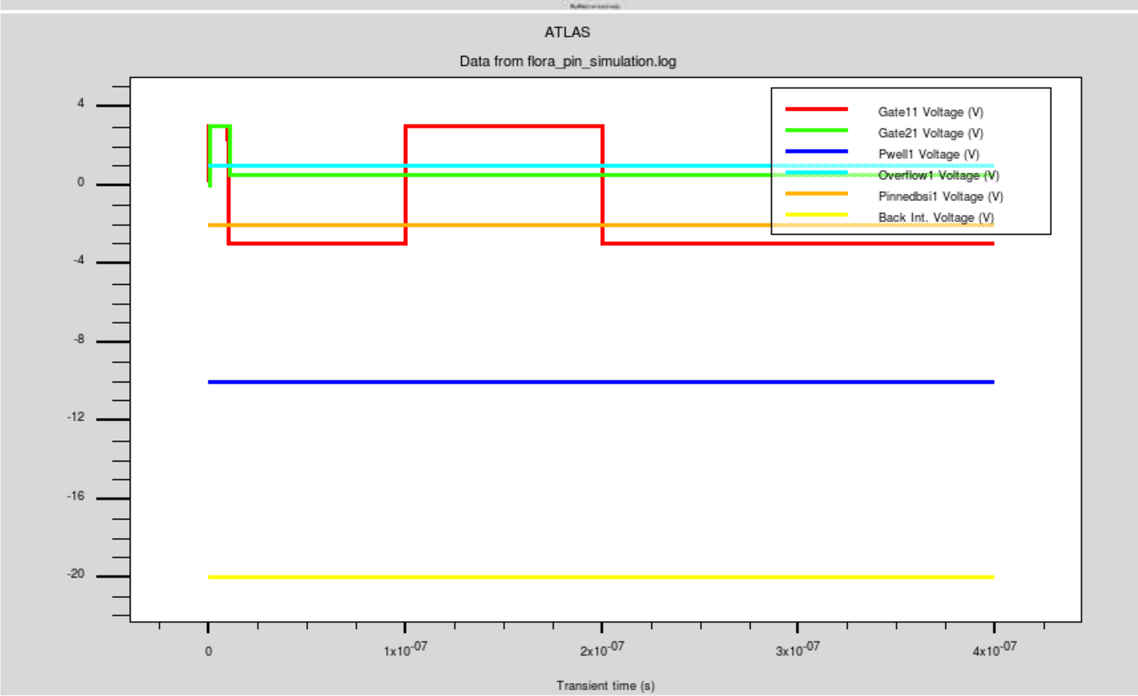




n-doped substrate; p layer in the back for creating the junction to be depleted; n-imp floating diffusion (FD) at the center; back side illuminated (BSI) diodes at its sides; p-pinned layers over the BSI regions; external n-imp overflow electrodes; deep and contact p-wells as barriers; polysilicon gates both for the transfer from the BSI to the FD; and from the continuous charge flowing from the BSI to the overflow electrodes.

Device operation





Constant voltages:
- Back @ -20 V
- Pwell electrodes @ -10 V
- Pinned photodiode @ -2 V
- Overflow electrodes @ 1 V

Depletion:
- FD @ 3 V (resetting)
- Overflow gates @ 3 V
- Transfer gates @ 3 V

Waiting for charges:
- FD floating
- Overflow gates @ 0.5 V
- Transfer gates @ -3 V

Charge transfer:
- Transfer gates @ 3 V

Blocking:
- Transfer gates @ -3 V

Charge collection
- Closing FD switch

Simulation results: overview

The results of the simulations performed will be presented according to the following guideline:

SMALL SIGNALS

Analysis of the basic operation of the charge transfer

- Charge transfer from the BSI to the FD
- Charge collection verification

LARGE SIGNALS

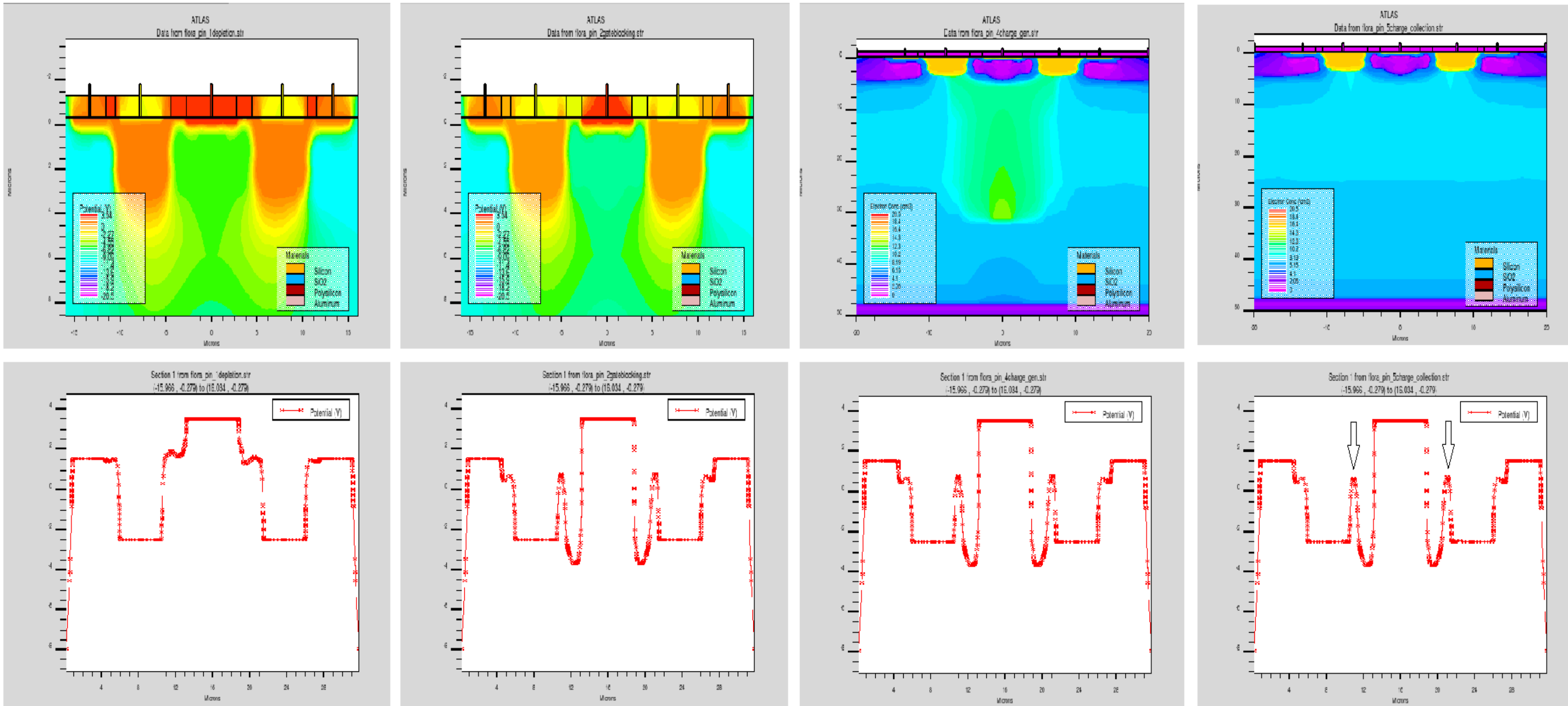
Analysis of the continue charge flowing

- Analysis of the overflow electrode effectiveness
- Activation threshold and overflow gates' voltage optimization

GENERAL ANALYSES

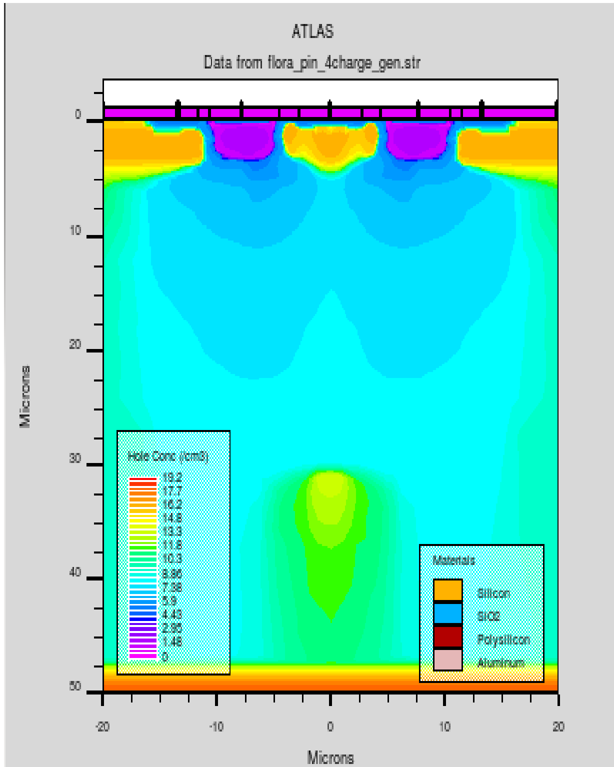
- Collection error with respect to the generated charge
- Possible improvements

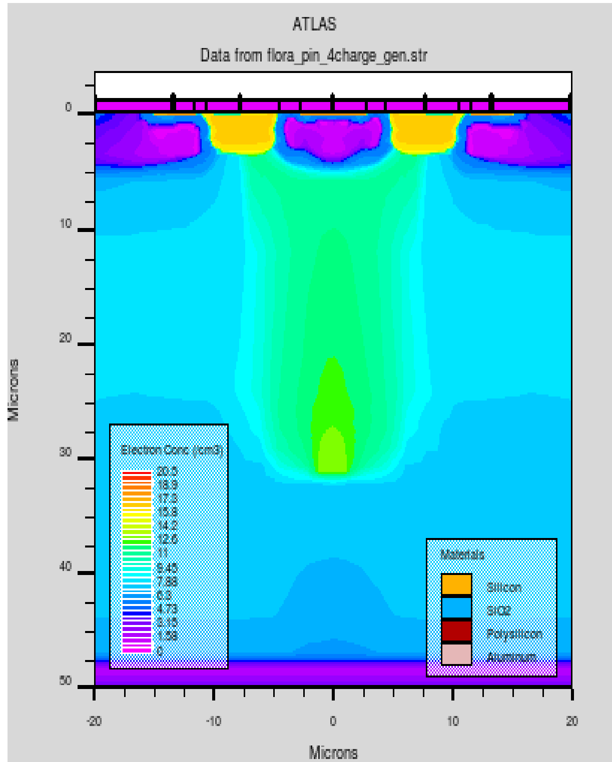
Depletion, charge generation and collection

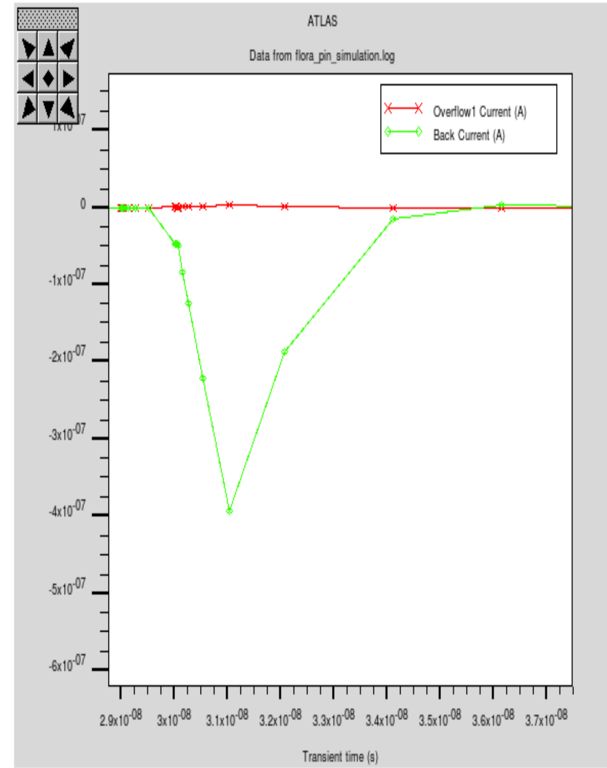


- The structure is completely depleted while all gates are turn on.
- Then the transfer channels are blocked and the FD electrodes are reset before floating.
- The generated charge collects in the BSI region and lower its potential.
- In this simulation it is not sufficient to activate the flowing through the overflow electrode.

Back current



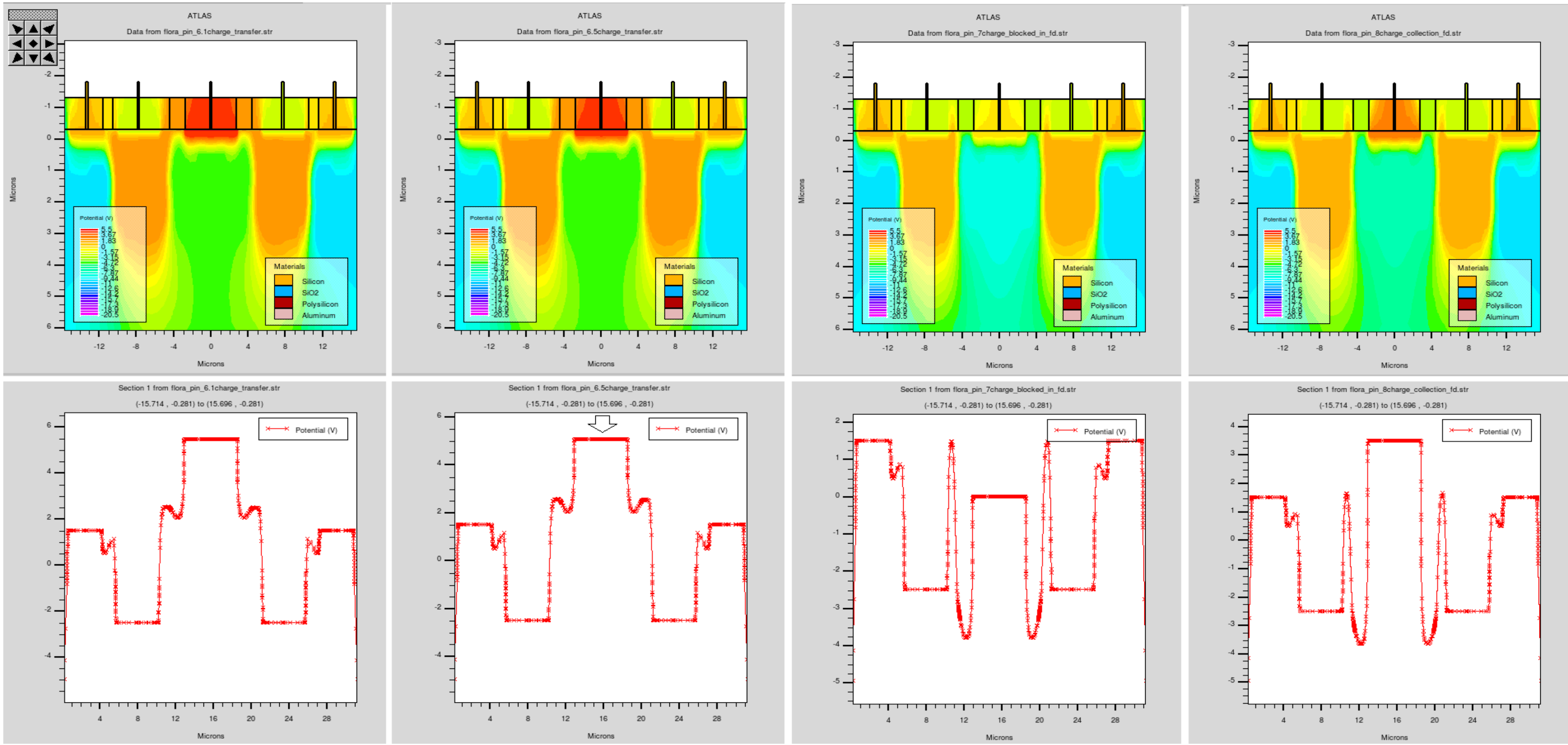




- An hitting X-ray generates electron-hole pairs in the silicon structure.
- Electrons either are collected in the BSI regions or flow through the overflow electrode.
- Holes drift immediately toward the back of the structure.

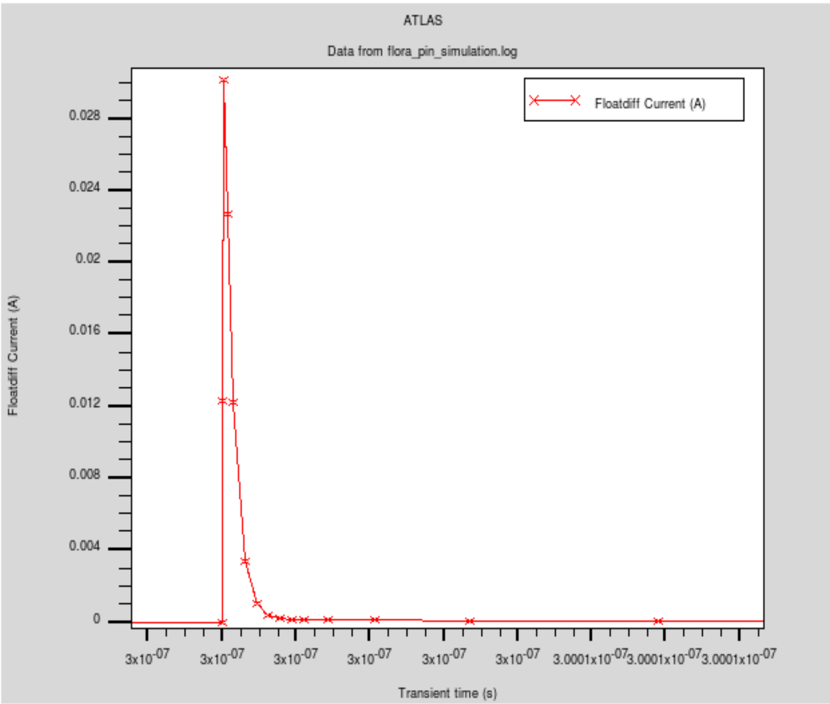
- The charge collected at the back during charge generation is used to compute the exact amount of generated charge in every simulation.

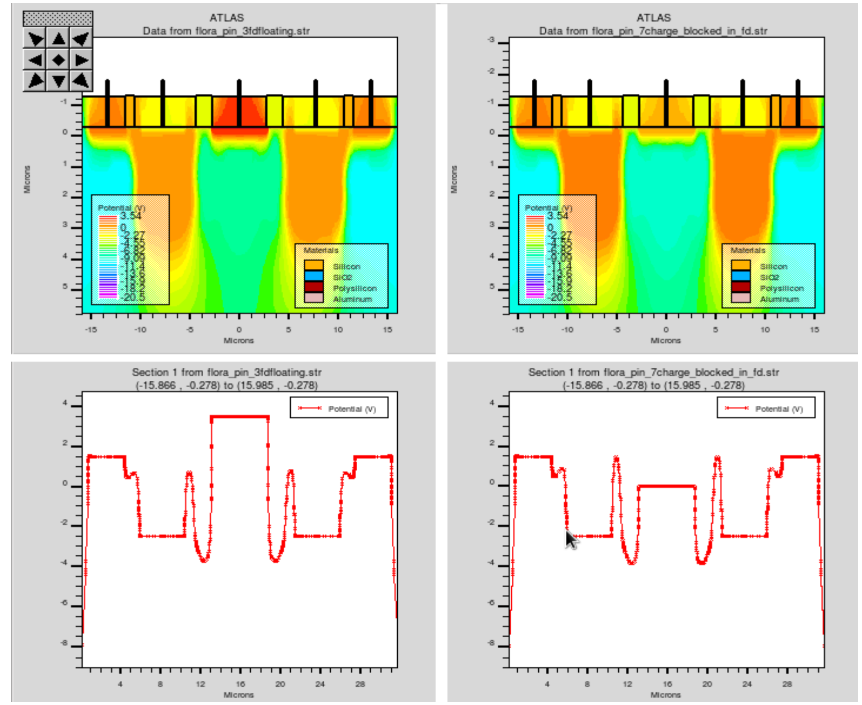
Small signals: charge transfer



- From the BSI charges are transferred to the floating diffusion region by means of the transfer gates. Thanks to the FD resetting, a potential difference between BSI and FD exists.
  - Once charges are collected in the FD region, its potential lowers.
- Then the transfer channels are blocked to isolate the FD region, before closing the switch.

Charge collection at the floating diffusion electrodes

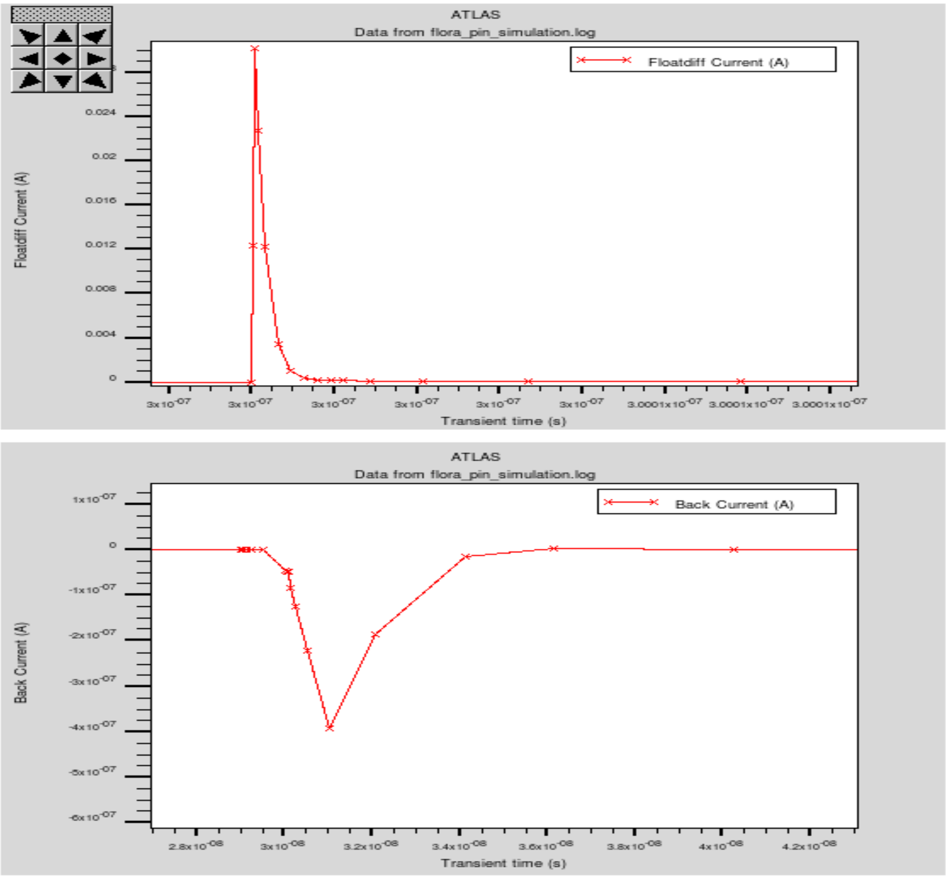




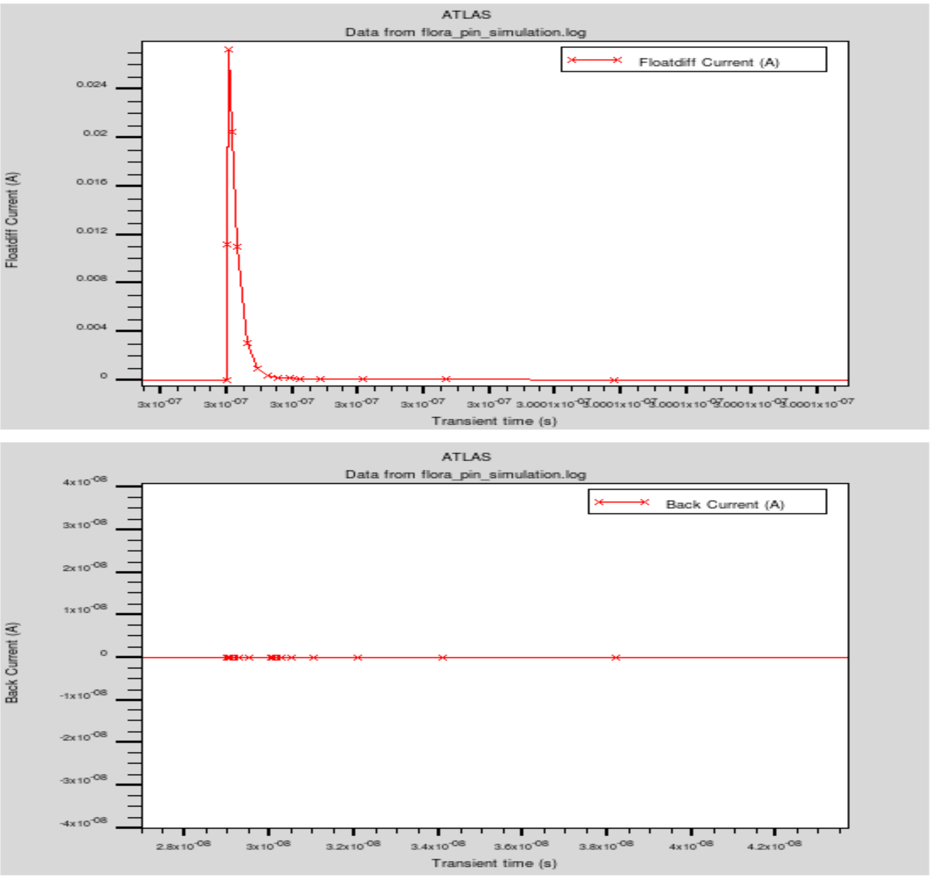
- After the floating diffusion switch is closed, charge is collected at the electrode.
- This is done only for simulation purposes: in the real operation of the sensor the floating diffusion region is always floating.
- Charge is measured by looking at the voltage difference of the FD region before and after charge collects there, known the (small) capacitance of the region.
- The overflow electrode's voltage must be set in order to allow in the BSI an amount of charges which does not saturate the FD region.

Charge collection verification

Charge generation



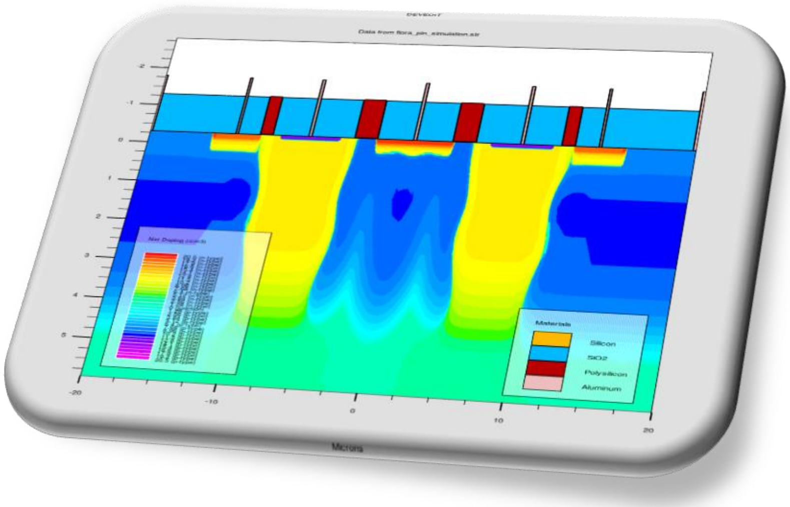
No charge generation

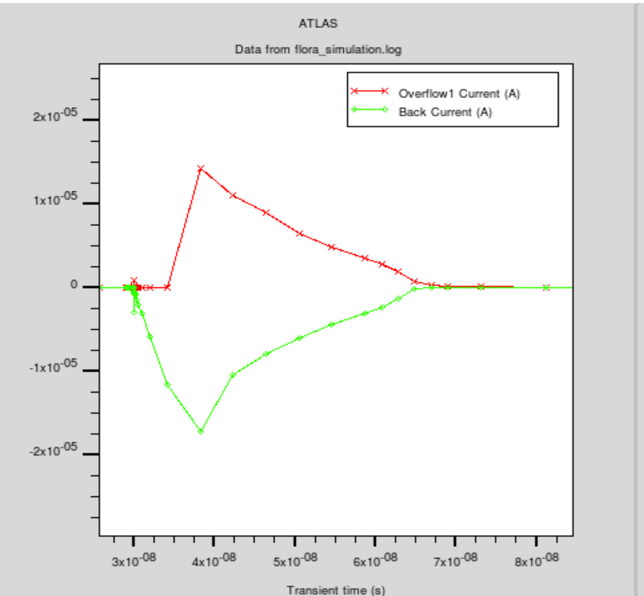


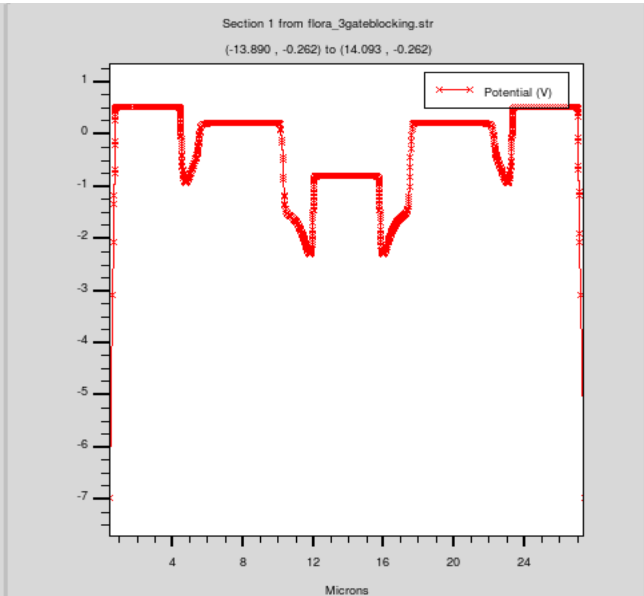
- Two simulations performed: with and without charge generation.
- Comparison of the difference between the charge collected at the back in the two situations with the difference between the charge collected at the front in the same situations.

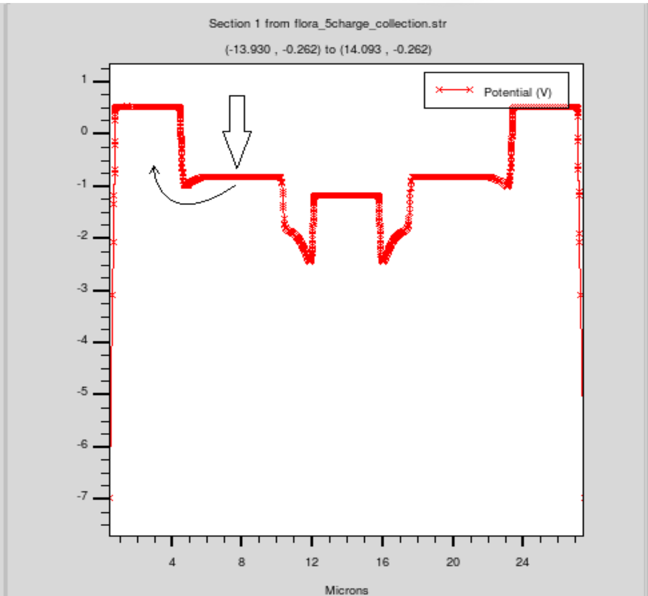
Overflow electrode

- Charges gather in the BSI region and lower its potential.
- When the BSI region's potential reaches the potential of the overflow gate, charges continue flowing through the overflow electrode.
  - Modulation of the charge capacity of the BSI acting on the overflow gate voltage .



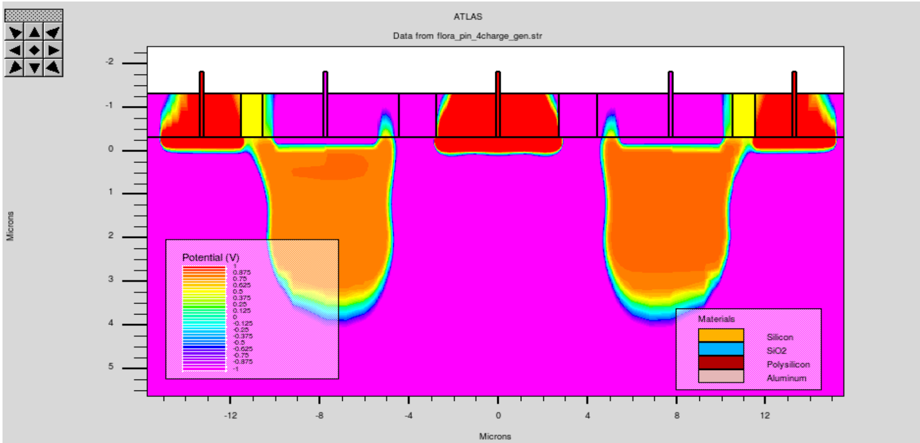


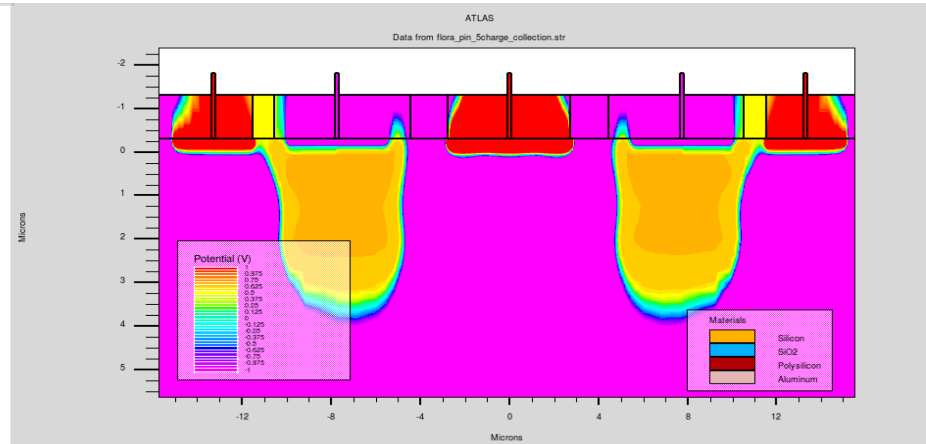




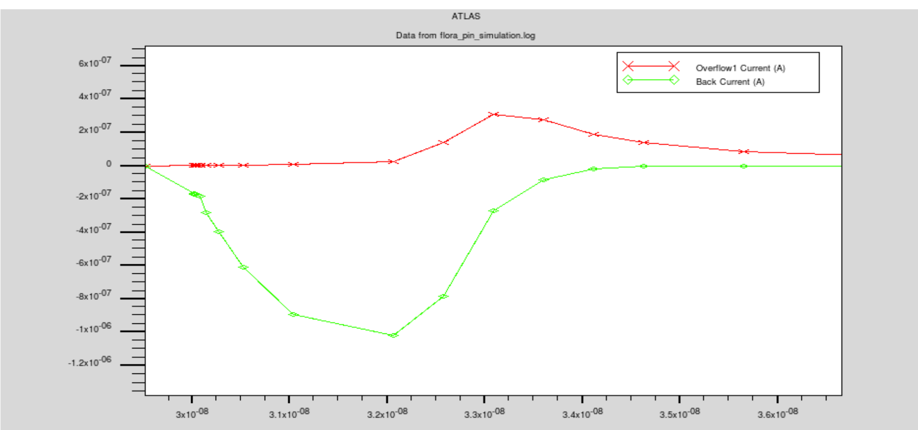
Images taken only for explanation purposes.

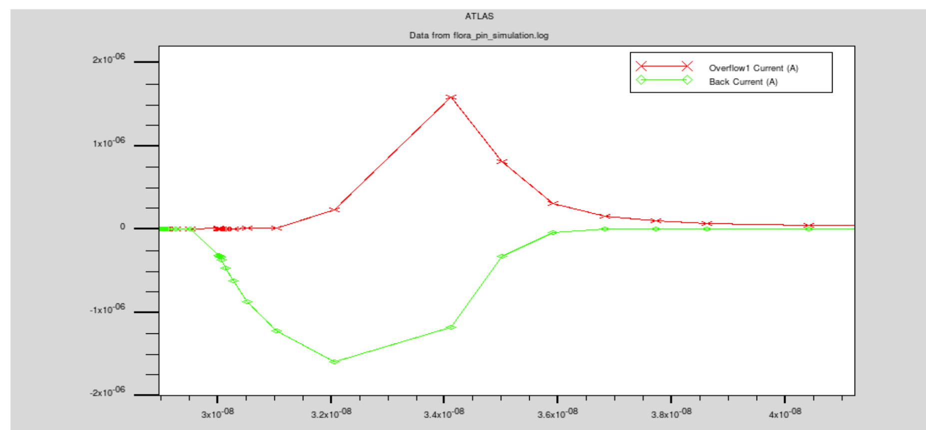
Continuous charge flowing





- If many charges are generated, the BSI potential lowers till it reaches the value fixed by the overflow gates. In this case charges will overcome the bump and flow continuously through the overflow electrodes, just after they are generated.





- Here two different amounts of generated charges with the same threshold are represented.

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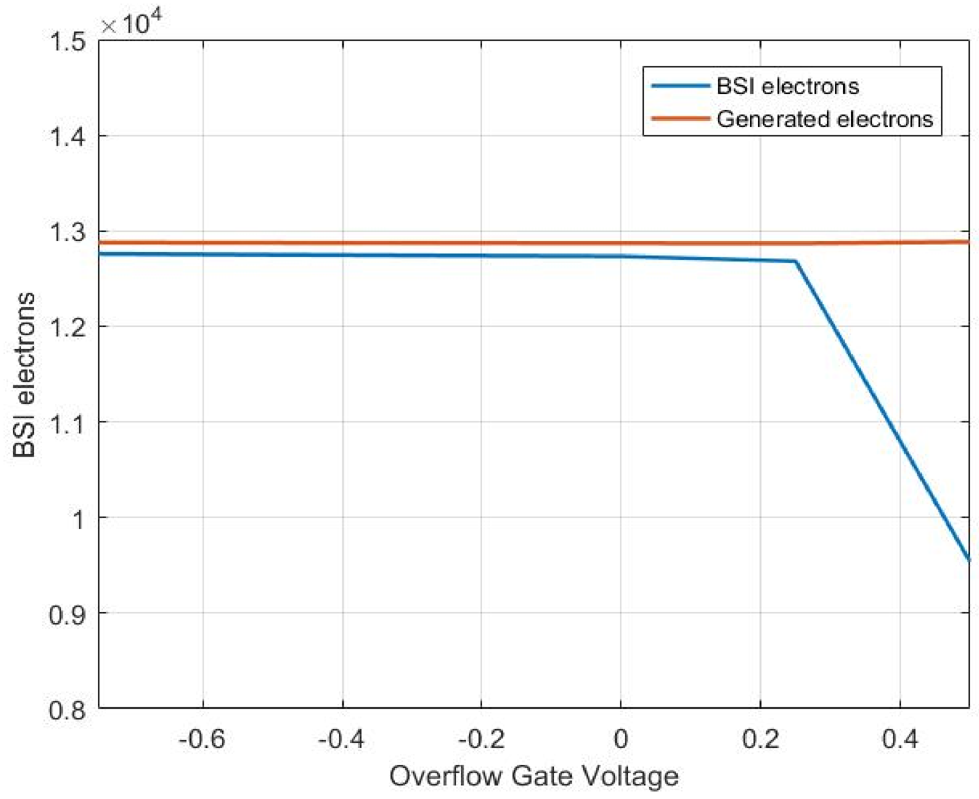
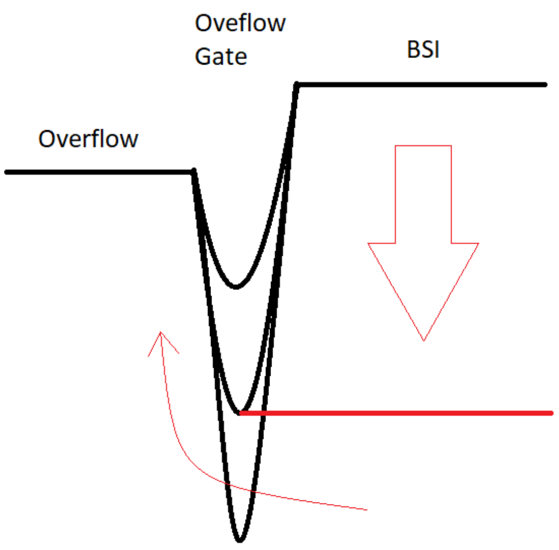
Activation threshold

According to the desired number of electrons in the BSI region, the overflow gate voltage must be regulated. The pinned diode has the role of not allowing the BSI potential to go down during blocking.



Simulations performed with a fixed number of generated charges, looking for the activation threshold.



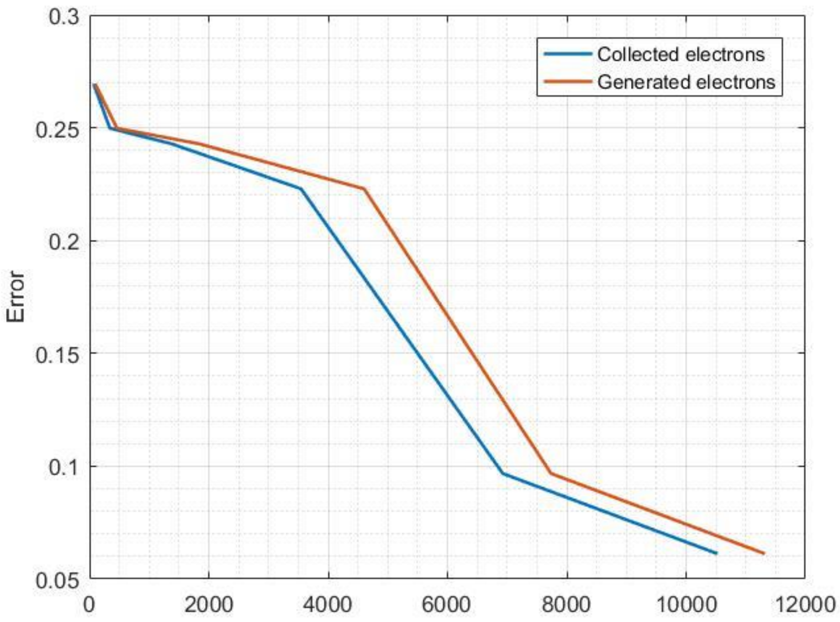
⟶ Overflow gate voltage optimization

Collection error

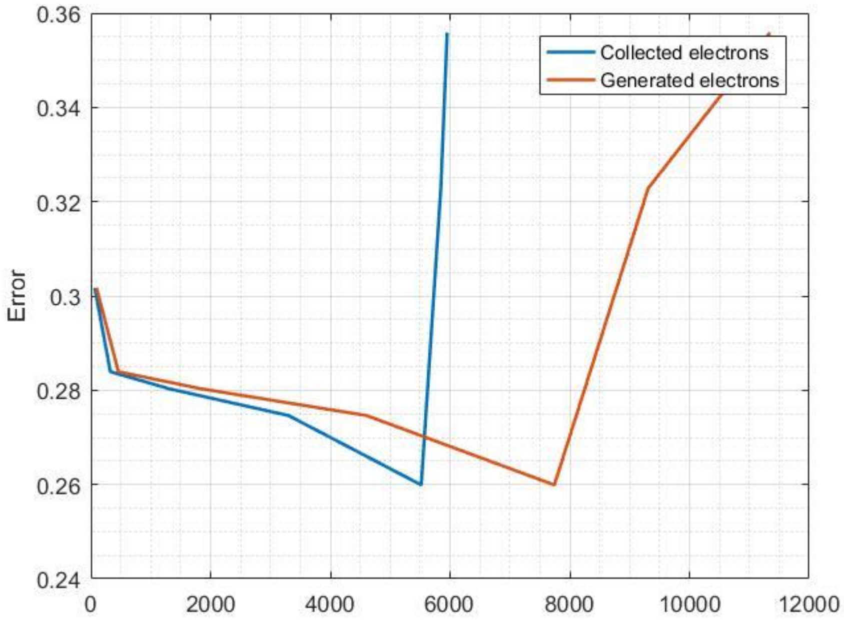
The floating diffusion region has a given charge capacity depending on its dimensions and on the reset voltage, which limits the charge than can be collected there. The overflow gate has to be regulated to allow in the BSI an amount of charges which can be processed also by the FD region.

But with higher values of the overflow electrode's gate voltage, the collection results less effective.

Overflow gates @ -1 V



Overflow gates @ 0.5 V



⟶ Need to find the best compromise

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Possible improvements

The operation of the sensor is as desired.
Nevertheless the performances can still be improved much.

⟶ *Finding the best compromise for the overflow gate electrode*

⟶ *Changing the dimensions of the floating diffusion region in order to allow it to host the optimal amount of charges (remember that a very small capacitance is needed for a sensitive measurement)*

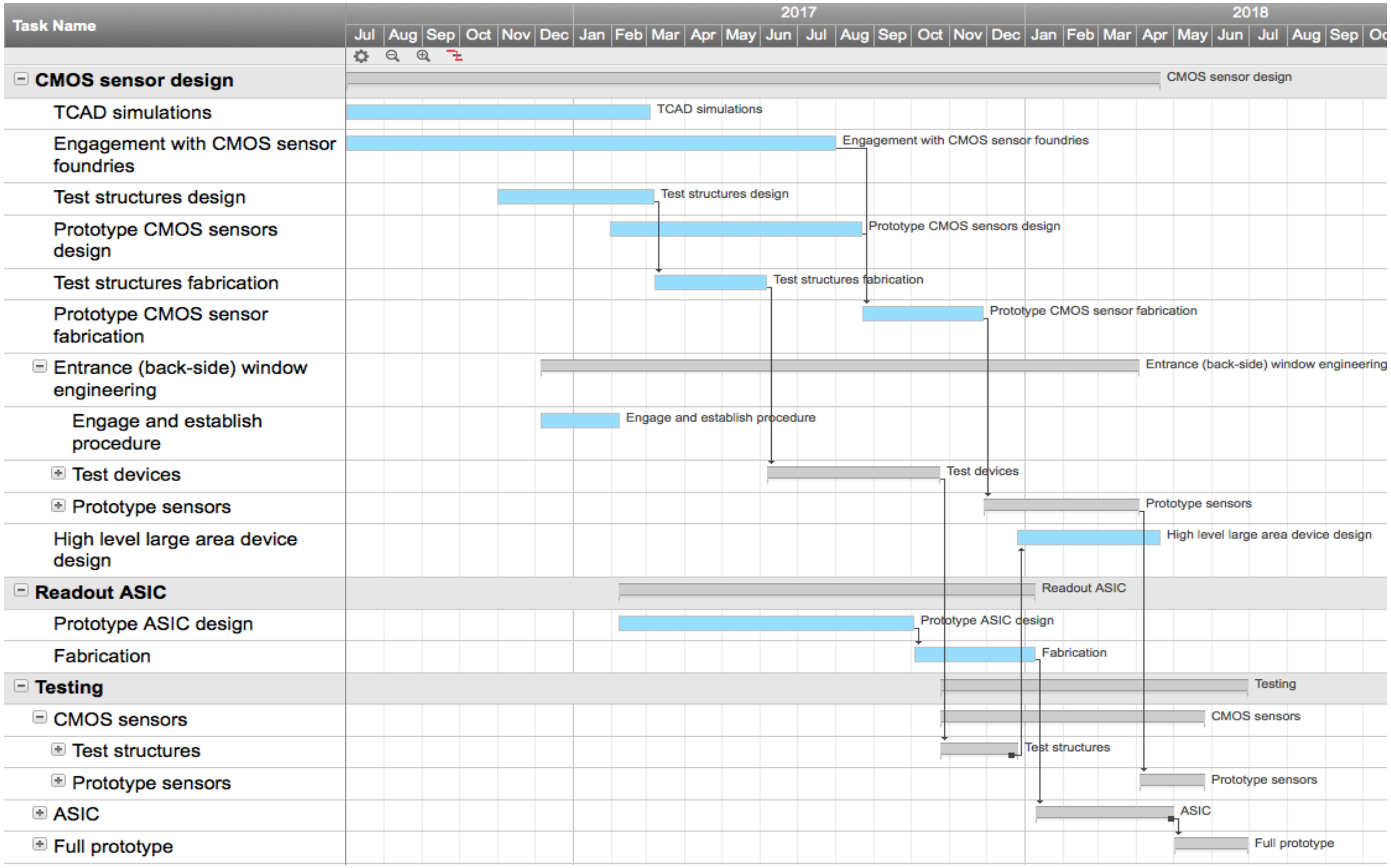
⟶ *Studying the behavior of the sensor when changing the pinned layer voltage*

⟶ *J-FET stage for charge transfer possible, in order to make the transfer happen more deeply in the structure and avoid electrons trapped on the oxide surface.*

Conclusions

Hope to have provided effective guidelines for the fabrication of the FLORA pixel and important hints for its further development.

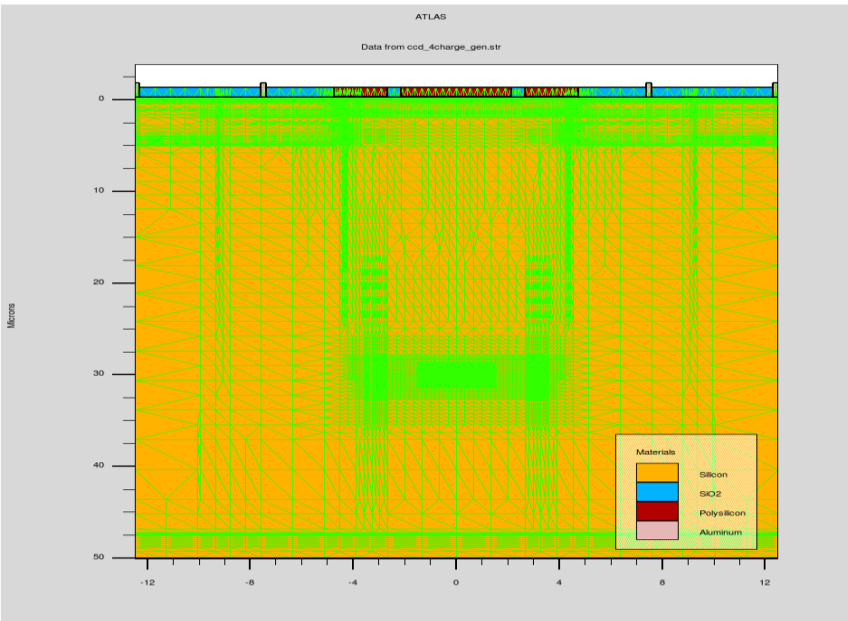
Looking forward for the realization and testing of the sensor.

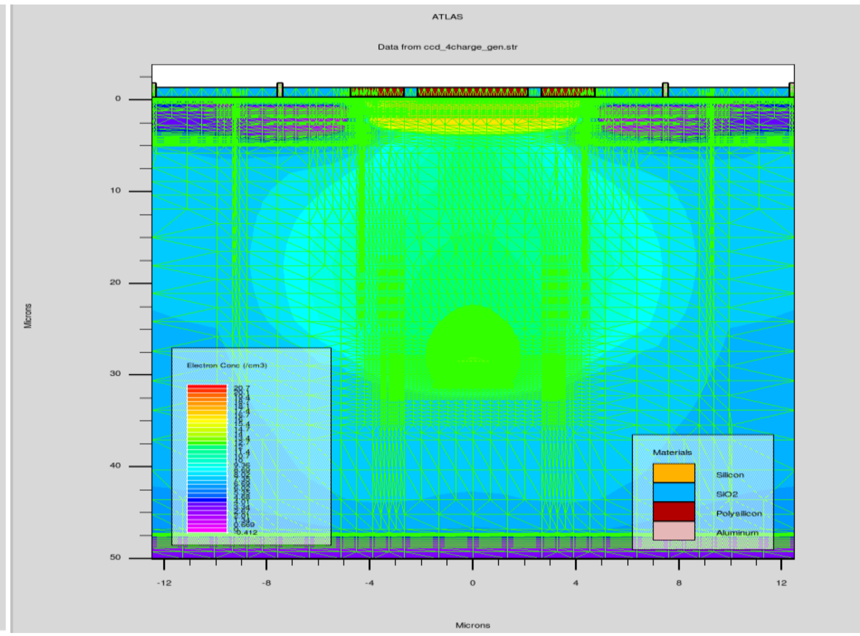


Thank you!

Convergence issues

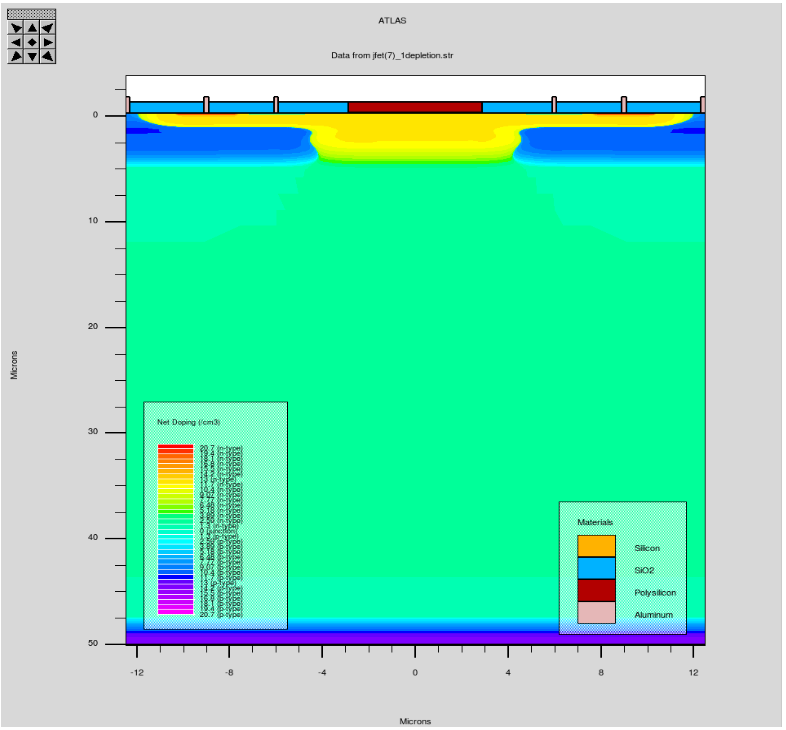
- **Mesh optimization**: compromise between speed and accuracy of the simulation; coarser in the substrate, finer in the junctions, under the gate and where charge is generated (DEVEDIT software used).

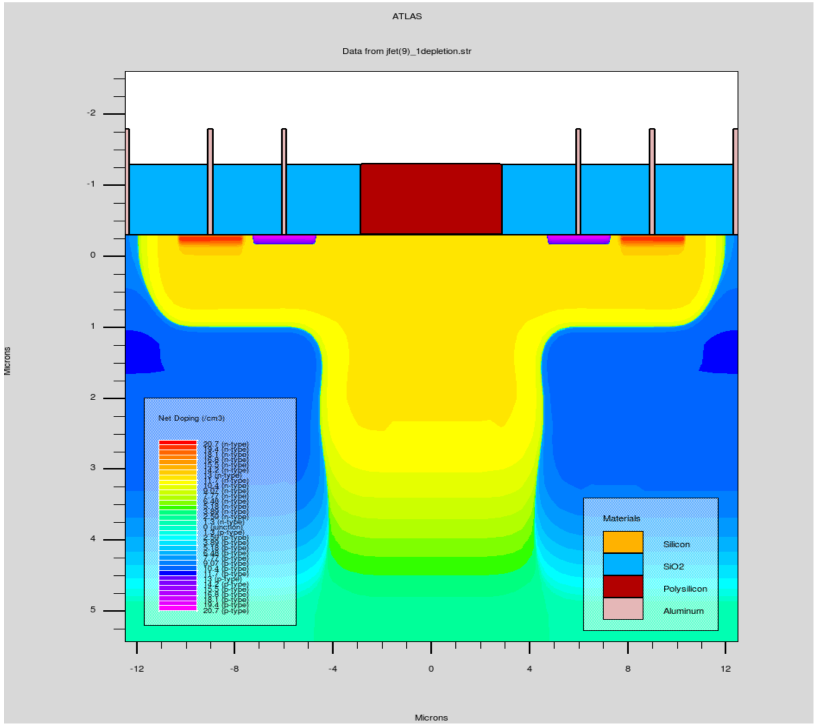




- Ramping voltages to help convergence during the transient simulations.
- Initial steady state condition solved by applying voltage to one electrode at the time.

J-FET charge transfer





- Modulation of the transfer channel with the voltage applied on the pimp electrode.
- The transfer happens more deeply in the structure and avoids electrons trapped on the oxide surface.
- Experiment tried with a BSI gate.

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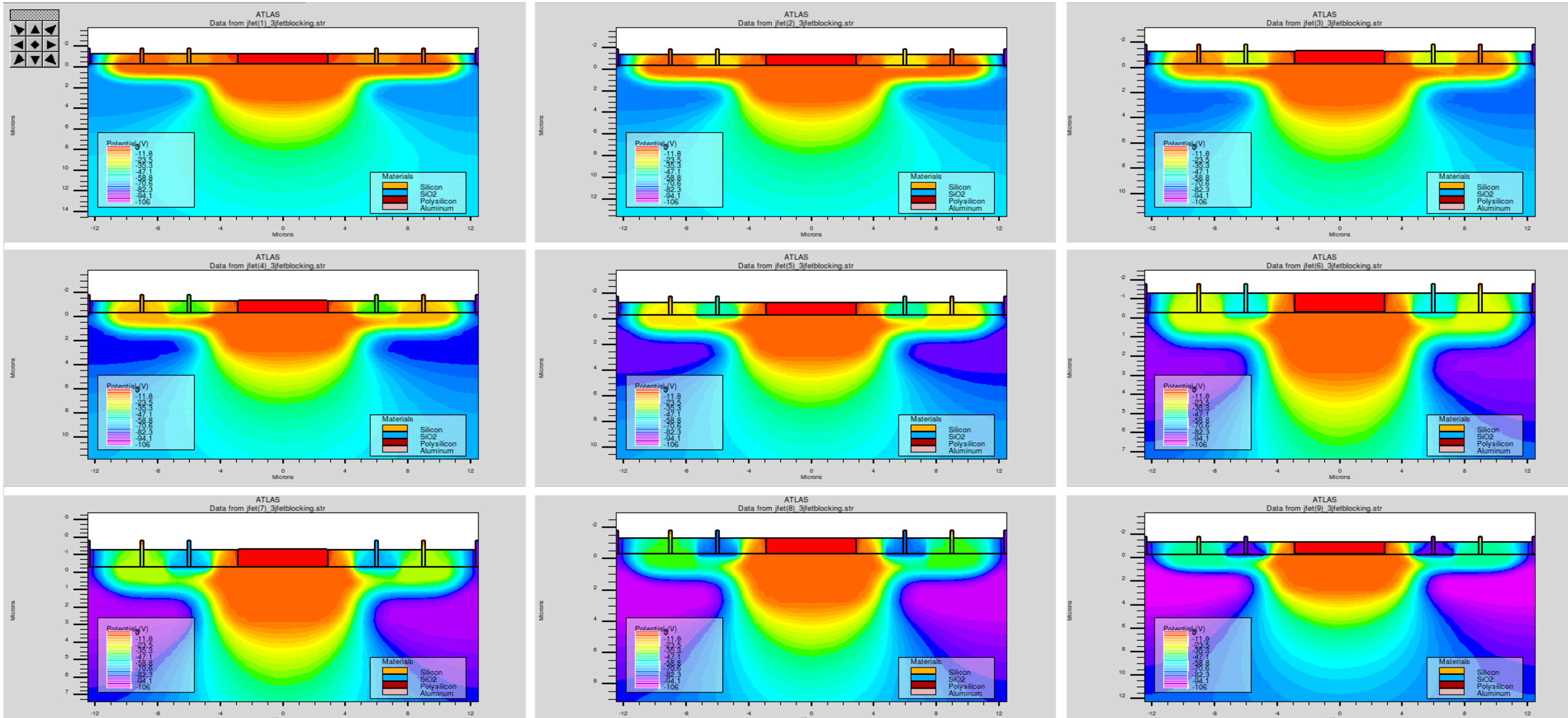
J-FET charge transfer

Study of the pimp voltage necessary to close the channel.



The transfer channel is too wide (30 V necessary to close it).

Possible improvements: deeper p-implant layer, shallower n-well region.

New doping definitions required.

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References

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