Task 2: Silicon detector simulation with Weightfield2

Introduction

Silicon detectors are currently used in the tracker systems of the biggest experiments in the Large Hadron Collider (LHC) such as ATLAS and CMS. They are segmentated diodes, p-n junctions, inversely polarized that when a ionizing particle goes through the bulk creates electron holes pairs that are collected at the electrodes (here is more detailed information about silicon detectors https://link.springer.com/content/pdf/10.1007/978-3-319-64436-3.pdf).

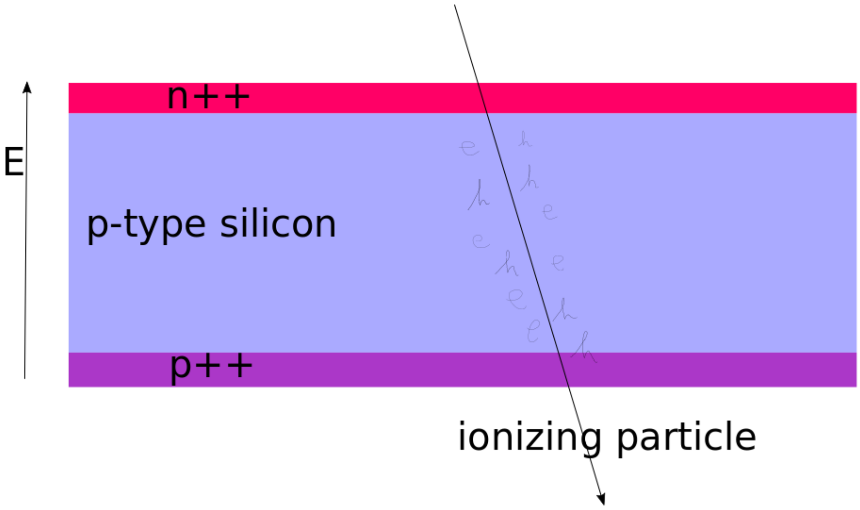


Figure 1: Scheme of an n-in-p silicon detector.

Weight field

The software weightfield 2 calculates the weight field of some semiconductor structures.

Weight field is a concept introduced by Ramo in 1939, to evaluate the induced current for a given electrode induced by a mobile charge:

$$i = \vec{E_v} \cdot q \cdot \vec{v}$$

where q is the charge, $\vec{v}$ is the current velocity and $\vec{E_v}$ is the weighting field in the direction of $\vec{v}$.

The induced charge on the electrode is:

$$Q = q \cdot \Delta\phi_0$$

where $_0$ is the difference in weighting potential. To find the weighting potential one should solve Laplace equation

$$\nabla^2\phi = 0$$

under the conditions:

1. a chosen electrode is at V=1V
2. the remaining electrodes are at V=0V
3. The trapping state of the charge is not taken into account.

More in https://www-physics.lbl.gov/~spieler/Heidelberg_Notes/pdf/II_Signal_Formation.pdf

Weightfield2

Weightield2 is a software developed by Nicolo Cartiglia among others (University of Torino) available here http://personalpages.to.infn.it/~cartigli/Weightfield2/Main.html (requires root preinstalled https://root.cern.ch/downloading-root): It looks like:

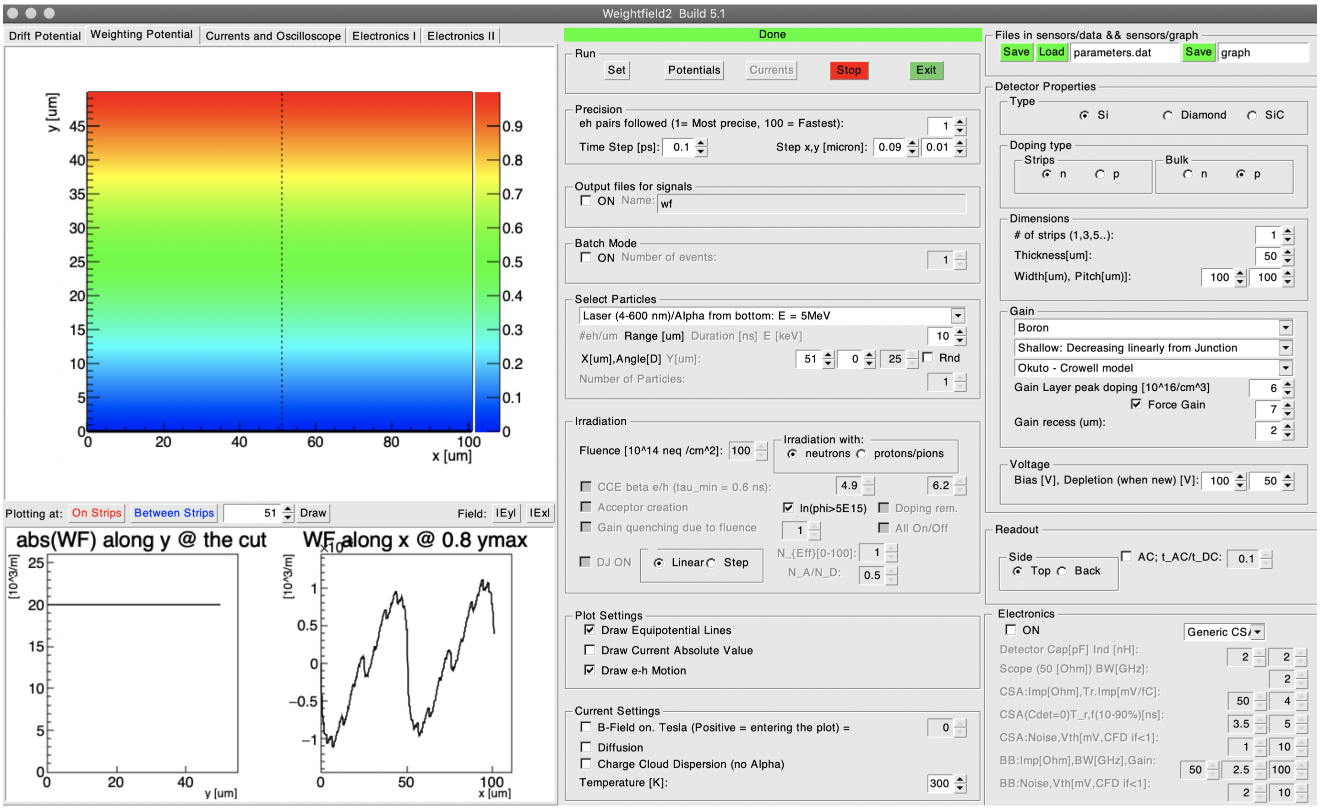


Figure 2: Screenshot of the weightfield software

The software can be used going to the weightfield folder and executing: ./weigthfield

The left panel has 5 tabs, and shows the drift potential, weigting potential, currents and oscilloscope, Electronics I and Electronics II. From the right panel, the different options of the menus can specify the detectors, particles and conditions of the simulation.

The software can be downloaded in naf with this comands (or without naf it needs root 6 preinstalled):

```
wget http://personalpages.to.infn.it/~cartigli/Weightfield2/Download_files/weightfield5.1.zip
unzip weightfield5.1.zip
cd weightfield5.1
make -f Makefile_MacOS10.13_root616
./weightfield
```

Tasks

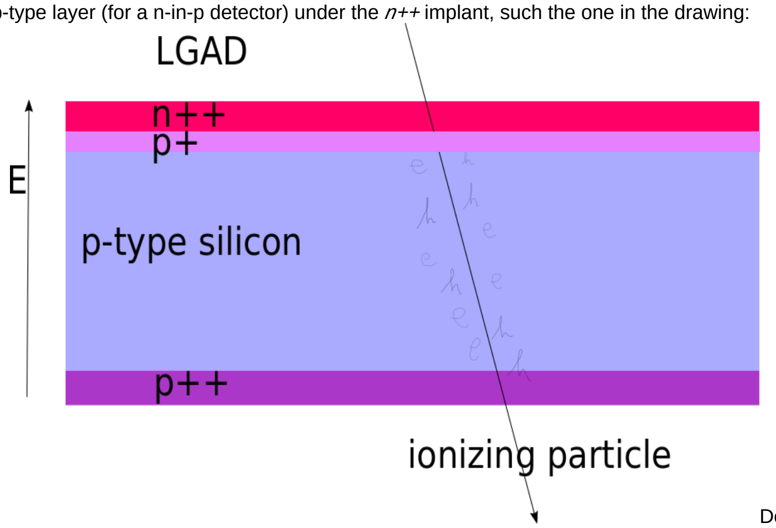
1. **Detectors type.** The silicon detector can have different configurations: p-in-n, n-in-p, p-in-p or n-in-n. The first letter (*p* or *n*) refers to the readout electrode, either it is *p* or *n* type. The second letter defines the silicon bulk. The detector in figure 1 is n-in-p as the detectors that will furnish the CMS and ATLAS trackers of the HL-LHC. Currently CMS and ATLAS trackers are populated with n-in-n detectors.
    a. Design a silicon detector with 1 strip, 50 µm width and pitch of 50 µm and 50 µm thickness. In the gain menu, chose without gain
    b. Apply a voltage of 160 V with a depletion voltage of 20 V, and select a particle *MIP: uniform Q, Qtot = q*[#eh/um]*Heigh*
    c. in the run part, execute *SetPotentials Currents.* After it finished, you can take a look at the drift potential, weighting potential and currents and oscilloscope part.
    d. change the configuration from p-in-n, n-in-p, p-in-p or n-in-n and study the signal created in the currents and oscilloscope tab. Which ones collect electrons and which ones collect holes?
    e. Why do you collect from one electrode electrons and holes?
2. **Depletion voltage.** The depletion voltage is the voltage needed to deplete the bulk of the detector of free charge. What is the effective doping if a detector depletes at 100V (with a n-in-p detector with the specification of the task 1).

$$V_{dep} = \frac{e}{2\epsilon_{Si}\epsilon} N_{eff} \cdot d^2$$

The ϵ_{Si} is the silicon permittivity, ϵ is the vacuum permittivity, d is the thickness of the detector, N_{eff} is the effective dopping and V_{dep} is the depletion voltage. Is it intrinsic compared to the silicon atom concentration (silicon density 5.02 $\cdot 10^{22}$atoms/cm^3)? (better write in units of atoms/cm^3).
3. **Under depletion.** If the detector is not fully depleted not all the volume collects charge.
    a. Design a silicon detector with 1 strip, 50 µm width and pitch of 50 µm for a p-in-n sensor
    b. Apply a voltage of 100 V with a depletion voltage of 160 V, and select a particle *MIP: uniform Q, Qtot = q*[#eh/um]*Heigh*
    c. Observe the weigthing potential, the empty (white) part of the volume is the not depleted. Then observe the charge, did it diminished from the one in task 1?

   d. Try the same with a n-in-p, p-in-p and n-in-n. Which ones do they show charge and which ones no? Why is that happening?

4. **Strip detector.** Since now, the simulation is considering a pad, a big wide detector. Strip detectors are segmented detectors of several μm width.
   a. Design a silicon detector with 3 strip, 20 µm width and pitch of 80 µm and n-in-p type
   b. Apply a voltage of 160 V with a depletion voltage of 20 V, and select a particle *MIP: uniform Q, Qtot = q*[#eh/um]*Heigh*
   c. in the run part, execute *SetPotentials Currents*
   d. What happens to the Weighting potential in the middle of the strip, and why is it happening?
5. **TCT**. Transient Current Technique is the measurement of the detector response in time. Selecting in the plot settings menu, the "*Draw e-h Motion*" allows to see the movement of the electrons and holes. Use the strip detector configuration from the last part, and
   a. Select particles *Laser (1064 nm): Top-TCT, Q =q*[#eh/um]*Height*. Here you are simulating the illumination of an IR laser from the top of the detector and you can see the movement of the electrons and holes. Which carrier is faster and where are they collected?
   b. Select particles *Laser (4-600 nm)/Alpha from top: E=5MeV*. Here you are simulating the illumination of a red laser or a alpha particle from the top of the detector and you can see the movement of the electrons and holes. Which carrier is faster and where are they collected?
   c. Select particles *Laser (4-600 nm)/Alpha from bottom: E=5MeV*. Here you are simulating the illumination of a red laser or a alpha particle from the bottom of the detector and you can see the movement of the electrons and holes. Which carrier is faster and where are they collected?
   d. What is the difference between the different light injection such as red and IR (https://www.pveducation.org/pvcdrom/materials/optical-properties-of-silicon)? What happens when you change a detector from p-in-n to p-in-p?
6. **Electronics**. Deactivate the e-h motion to fasten the software and select electronics on with the default values with the previous defined diode. Execute SetPotentials Currents, and now in currents and oscilloscope tap shows a new black line, that is supposed to be the selected oscilloscope.
   a. What change do you see with the oscilloscope and without oscilloscope results? Why is it in that way?
7. **Irradiation**. In the irradiation menu, chose irradiaiton with neutrons *CCE beta e/h* and a fluence of $100 \cdot 10^{14} n_{eq}/cm^2$. Use a particle MIP: uniform Q, Qtot = q*[#eh/um]*Heigh, a strip sensor as defined before (3 strips n-in-p type 20 µm width and pitch of 80 µm and apply a voltage of 160 V with a depletion voltage of 20 V).
   a. What happens in the weighting potential? and in the currents and oscilloscope?
   b. How do you describe the impact of the irradiation to the sensor?
   c. now change for a p-in-p type, and p-in-n and n-in-n. What happens for the other detector configurations?
   d. The current ATLAS and CMS detectors are n-in-n detectors, can you explain why is it like that, if after irradiation it does not collect any charge?
   e. Weightfield2 does not take into account double junction and type inversion effects. Can you test that it is that way?
8. **LGAD**. Faster detectors are needed for the HL-LHC, aiming to time precision of 30 ps to distinguish the primary vertex within centimeters. Thin detectors have faster signals although its charge is drastically diminished. Silicon detectors with a high implanted layer underneath the electrode creates a high electric field that leads to a charge multiplication mechanism. Thus, thinner detectors can be build with smaller drifting distances and faster signals. Those detectors are called LGADs (Low Gain Avalanche Detector). Weightfield2 allows to simulate LGADs in the Gain menu, using Boron as a doping atom, boron + carbon, germanium and germanium + carbon. The gain layer is a high doped p-type layer (for a n-in-p detector) under the *n++* implant, such the one in the drawing:



   a. Deactivate the irradiation of the detector and include the gain, using *Boron* with *Uniform 0.5 - 1. micron*, and with the *van Overstraeten de Man Model*. Include a *Gain Layer peak doping [$10^{16}/cm^3$]* of 4.3. Set a n-in-p detector of 1 strip (pad) with 50 µm thickness and 50 µm pitch and 50 µm thickness and apply a *Laser (4-600 nm)/ Alpha from bottom: E = 5 MeV*. Select draw e-h motion.
   b. What happens to the electrons and holes in the motion?
   c. When checking the *Currents and Oscilloscope* what happens to the charge? Can you explain each contribution for the gain detector?

Extra tasks:

Temperature. See what happens changing the temperature from 250 to 300 K, is the charge collected faster or slower? Why is that happening?

Irradiation. Check the irradiation with the same parameters before and check the DJ ON (double junction). Do you see any change with the weightfield potential of the detector?