# Report on semiconductor detectors

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## 1 Introduction

As charged particles travel through a semiconductor they ionize the material leaving holes and electrons free to diffuse throughout the medium. By introducing heavy p- and n-type doping on opposite sides of a slightly doped bulk of Si or Ge and applying a bias, the bulk becomes depleted of free charge carriers and the holes and electrons created by the ionization can dissipate towards the cathode and anode where the charge (signal) can be read out.

Two important factors for semiconductor detectors are the depletion voltage and the leakage current. The amount of doping, the operating temperature, and the semiconductor material all affect the properties of the detector.

In part one of this experiment we simulate semiconductor diodes of different composition and in different operating conditions. Two types of diodes are simulated: pn and Schottky.

Part two describes noise measurement, calibration, and measurements of the radiation from two sources using an experimental setup consisting of a semiconductor detector, a pre-amplifier, a signal shaper, and a multi-channel analyser along with an oscilloscope and a computer.

In part three a pn-type semiconductor diode is simulated, and the depletion voltage and leakage current from the simulation is compared to measurements using a real diode.

## 2 Simulation

### 2.1 Theory

The potential of a junction in equilibrium is determined by

$$\Psi_0 = V_{\mathrm{T}} \ln \frac{N_{\mathrm{A}} N_{\mathrm{D}}}{n_i} \tag{1}$$

where $N_{\mathrm{A}}$ and $N_{\mathrm{D}}$ are the concentrations of acceptor and donor ions in the p- and n-type doped regions respectively, $n_i$ is the concentration of charge carriers characteristic to the semiconductor material. Further

$$V_{\mathrm{T}} = \frac{k_{\mathrm{B}} T}{q} \tag{2}$$

where $k_{\mathrm{B}} \approx 1.38 \cdot 10^{-23}\mathrm{JK}^{-1}$ is Boltzmann's constant, $T$ is the operating temperature, and $q = e \approx 1.60 \cdot 10^{-19}\,\mathrm{A\,s}$ is the elementary charge. $V_{\mathrm{T}}$ for the different operating temperatures used in this exercise can be found in Table 1.

| $T$(K) | $V_{\mathrm{T}}$(mV) |
|---:|---:|
| 50 | 4.3 |
| 250 | 21.6 |
| 300 | 25.9 |

Table 1: $V_{\mathrm{T}}$ for different operating temperatures

The junction width is directly proportional to the concentration of acceptor and donor ions. For a two sided junction (e.g. a pn-junction) in equilibrium the widths of the two sides are related in the following way

$$W_{\mathrm{A}} N_{\mathrm{A}} = W_{\mathrm{D}} N_{\mathrm{D}} \tag{3}$$

and the total junction width is

$$W = W_{\mathrm{A}} + W_{\mathrm{D}} \tag{4}$$

For an asymmetric junction where $N_{\mathrm{A}} >> N_{\mathrm{D}}$ this simplifies to

$$W \approx W_{\mathrm{D}} \tag{5}$$

In equilibrium, the junction width $W_{\mathrm{D}}$ can be found from the potential $\Psi_0$ through the relation

$$W_{\mathrm{A}} = \sqrt{\frac{2\varepsilon_0\varepsilon_R}{qN_{\mathrm{A}}}(\Psi_0 + V_R)\left(1 + \frac{N_{\mathrm{A}}}{N_{\mathrm{D}}}\right)} \tag{6}$$

where $V_R$ is the applied bias. $W_{\mathrm{A}}$ can be found in an equivalent manner, and in the case of a symmetric junction $W_{\mathrm{D}} = W_{\mathrm{D}}$.

Finally the electric field of the junction in the region $x = [-W_{\mathrm{A}}, 0]$ is

$$E = \frac{-qN_{\mathrm{D}}}{\varepsilon_0\varepsilon_R}(x + W_{\mathrm{A}}) \tag{7}$$

An equivalent equation can be found for $x = [0, W_{\mathrm{D}}]$.

The material properties for the two semiconductor materials involved in the experiment are described in Table 2.

| Material | Charge carriers (cm$^{-3}$) | Rel. permeability |
|---|---:|---:|
| Si | $1.5 \cdot 10^{10}$ | 11.7 |
| Ge | $2.4 \cdot 10^{12}$ | 16.2 |

Table 2: Material properties

## 2.2 Software

The simulations of junctions and diodes are done with the GSS program.

## 2.3 Simulation of a pn-junction

A pn-junction is simulated with different combinations of acceptor/donor concentration, operating temperature, and semiconductor material. The properties of each simulation are shown in Table 3 and the results and comparison with the theoretical model are shown in Table 4. Plots of the $E$-field for the simulations can be found in Figure 1.

| | Material | Conc. (cm$^{-3}$) | Temp. (K) |
|---|---|---|---|
| Nominal | Si | $10^{16}$ | 300 |
| Doping | Si | $10^{17}$ | 300 |
| Temperature | Si | $10^{16}$ | 50 |
| Material | Ge | $10^{16}$ | 300 |

Table 3: Simulation properties for the pn-junction

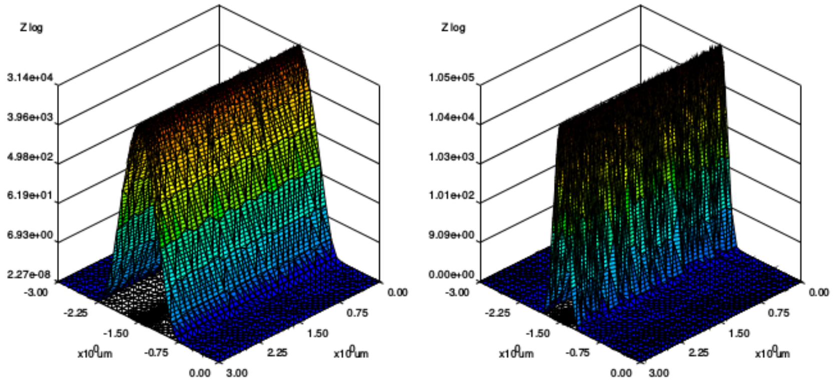
| | Potential (V) | | $E$-field (kV/cm) | | Width (µm) | |
|---|---|---|---|---|---|---|
| | Th. | Sim. | Th. | Sim. | Th. | Sim. |
| Nominal | 0.69 | 0.71 | -32.8 | -31.4 | 0.21 | 0.8 |
| Doping | 0.81 | 0.82 | -112.1 | -105.0 | 0.07 | 0.4 |
| Temperature | 0.12 | 1.15 | -13.4 | -41.5 | 0.09 | 0.6 |
| Material | 0.43 | 0.31 | -9.4 | -20.1 | 0.20 | 0.8 |

Table 4: Simulation results for the pn-junction

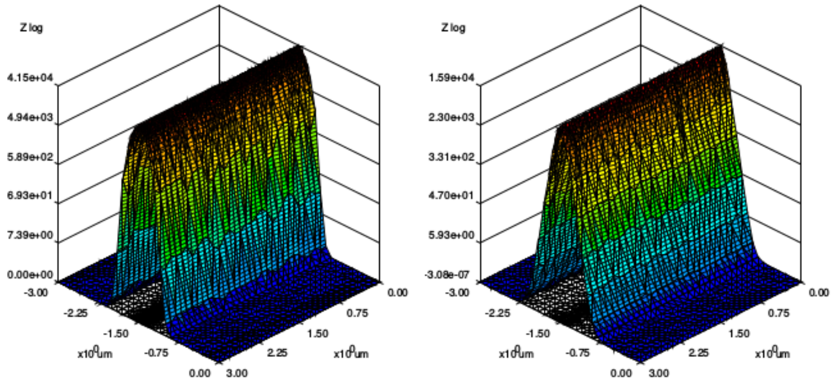
The values of the potential from the simulation agree reasonably well with the basic theoretical model, as do the values of the electric field, with the exception of the the values for the temperature variation. The simple model used here can probably not be used to describe operating temperatures as low as 50K. When it comes to the junction width there is a fairly large discrepancy between the values from simulation and from the model. The values from simulation are between $\sim 3.8$ to $\sim 5.7$ times larger than the values from the model.

## 2.4 Simulation of IV curves for pn-diodes

A pn-diode is simulated with different combinations of operating temperature and semiconductor material. A voltage is applied over the diodes in both reverse and forward bias. The acceptor/donor concentrations are $10^{16}$ for the anode and the cathode and $10^{13}$ for the bulk. The voltage is scanned from $0 - 100$V and the resulting leakage current is simulated. The properties of each simulation are shown in Table 5 and plots of the $IV$ curves in reverse and forward bias can be found in Figure 2.



(a) Nominal (b) Doping

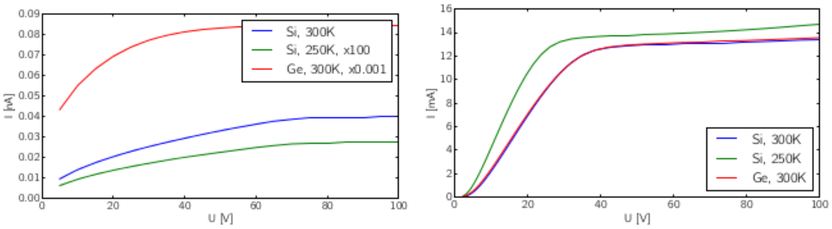


(c) Temperature (d) Material

Figure 1: Plots of the $E$-field for the pn-junction simulations

| | Material | Temp. (K) |
|---|---|---|
| Nominal | Si | 300 |
| Temperature | Si | 250 |
| Material | Ge | 300 |

Table 5: Simulation properties for the pn-diode



(a) Reverse bias (b) Forward bias

Figure 2: Plots of the $IV$ curves for the pn-diode simulations. For the reverse bias plot (a) the current Si diode at 250K has been multiplied by 100, and the Ge diode has been divided by 1000.

The depletion voltage for the Si diodes in reverse bias is about 70V, while for Ge it's about 40V. The leakage current at depletion voltage is about 30pA and 0.2pA for Si at 300K and 250K respectively, while for Ge it is 80nA.

The depletion voltage for the Si and Ge diodes at 300K in forward bias is about 25V, while for the Si diode at 250Kit's about 40V. The leakage current at depletion voltage is between $12 - 14$mA for all combinations.

There will be no depletion build up in forward. Other effects like compliance in teh simulation may do curves look like that.

## 2.5 Simulation of a Schottky junction

A Schottky junction is simulated with different combinations of acceptor concentration, operating temperature, and semiconductor material. The properties of each simulation are shown in Table 6 and the results and comparison with the theoretical model are shown in Table 7. Plots of the $E$-field for the simulations can be found in Figure 3.

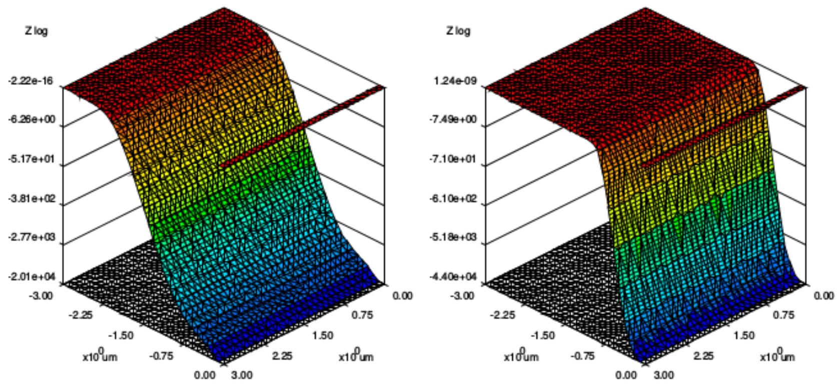
donor/acceptor?

| | Material | Conc. (cm$^{-3}$) | Temp. (K) |
|---|---|---|---|
| Nominal | Si | $10^{15}$ | 300 |
| Doping | Si | $10^{16}$ | 300 |
| Temperature | Si | $10^{15}$ | 50 |
| Material | Ge | $10^{15}$ | 300 |

Table 6: Simulation properties for the Schottky junction

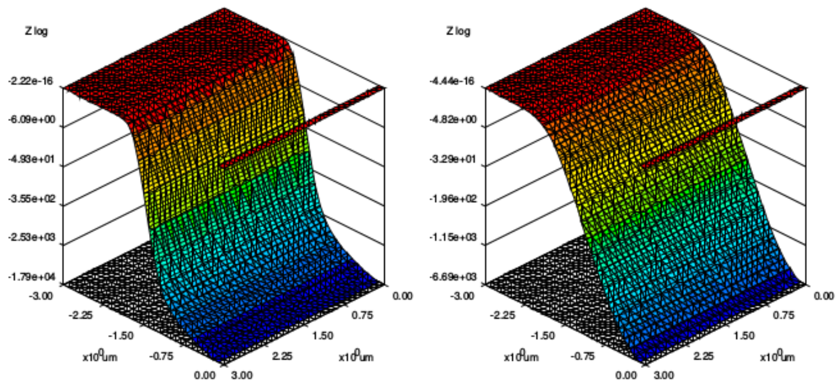
| | Potential (V) | | $E$-field (kV/cm) | | Width (µm) | |
|---|---|---|---|---|---|---|
| | Th. | Sim. | Th. | Sim. | Th. | Sim. |
| Nominal | 0.57 | 0.83 | -9.4 | -20.1 | 0.61 | 2.2 |
| Doping | 0.69 | 0.89 | -32.8 | -44.0 | 0.21 | 0.9 |
| Temperature | 0.10 | 1.13 | -3.9 | -51.7 | 0.25 | 1.7 |
| Material | 0.31 | 0.24 | -5.9 | -6.7 | 0.53 | 2.0 |

Table 7: Simulation results for the Schottky junction



(a) Nominal

(b) Doping



(c) Temperature

(d) Material

Figure 3: Plots of the $E$-field for the Schottky junction simulations

The Schottky junction is one sided and the junction width is defined to the region between $x = 0$ and up to the value of $x$ where the $E$-field reaches 95% of its maximum value.

The agreement between simulation and the basic model is worse for the Schottky junction than for the pn-junction. Since the basic model describes a pn-junction this is not surprising. No comparison with a theoretical model describing a Schottky junction has been made.

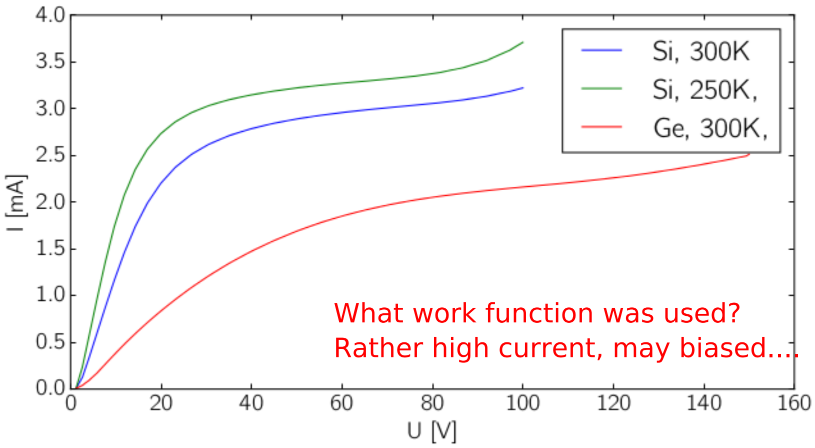
The doping of the Schottky junction is one order of magnitude smaller than for the pn-junction. The values of the potential from the simulations are comparable in the two cases, but the $E$-field is larger for the pn-junction resulting in a smaller junction width than for the Schottky junction.

## 2.6 Simulation of IV curves for Schottky diodes

A Schottky diode is simulated with different combinations of operating temperature and semiconductor material. A voltage is applied over the diodes in reverse bias. The voltage is scanned from $0-100$V and the resulting leakage current is simulated. The properties of each simulation are shown in Table 8 and plots of the $IV$ curves in reverse bias can be found in Figure 4.

| | Material | Temp. (K) |
|---|---|---|
| Nominal | Si | 300 |
| Temperature | Si | 250 |
| Material | Ge | 300 |

Table 8: Simulation properties for the Schottky diode



What work function was used?
Rather high current, may biased....

Figure 4: Plots of the $IV$ curves for the Schottky diode simulations

The depletion voltage for the Si diodes is about 30V, while for Ge it's very difficult to tell but it could be about 80V. The leakage current at depletion voltage is between $2.5-3$mA for the Si diode, and about 2mA for Ge.

The Schottky diode do nt behave like a pn-junction an will not deplete. The curve looks like it depletes for the same reason as the forward biased pn-junction. You would't expect the Ge to leak less than Si!

## 3 Lab exercise

A lab setup with a sensor consisting of a pn-diode, a pre-amplifier, a shaper, a multi-channel analyser (MCA), an oscilloscope, a pulse generator, and a computer is used to investigate the different types of noise involved when using semiconductor detectors. Then two radioactive samples are placed on the sensor to take energy resolved histograms of the radiation.

### 3.1 Pre-amplifier noise measurement

The pre-amplifier consists of an RC-circuit that amplifies the incoming signal. The capacitance of the test capacitor is $C_{\text{cal}} = 0.4$pF and a test charge of 1

For LAB check feed-back given to A. Burgman....

minimum ionizing pulse (MIP) ($\approx 25000$e) corresponds to a signal amplitude of $\approx 10$mV.

To measure the noise of the pre-amplifier under different capacitive loads, a capacitor with capacitance $C_{\mathrm{load}}$ is connected to the pre-amplifier and the pulse generator is set to deliver pulses of 10mA. Then the amplitude, noise (RMS), and the rise time of the output from the pre-amplifier is measured using an oscilloscope. The results for different values of $C_{\mathrm{load}}$ can be found in Table 9 and plots of the same results can be found in Figure 5. The noise of the pre-amplifier without capactive load can also be found in Figure 5c.

| $C_{\mathrm{load}}$ (pF) | Amplitude (mV) | Rise time (ns) | Noise (µV) |
|---:|---:|---:|---:|
| 100 | 20.3 | 56.9 | 291 |
| 54 | 27.3 | 50.5 | 247 |
| 27 | 33.3 | 39.3 | 212 |
| 10 | 38.9 | 32.5 | 193 |
| 4.7 | 40.2 | 30.5 | 184 |
| 1.0 | 40.0 | 28.1 | 179 |

Table 9: Amplitude, nosie (RMS), and rise time of different $C_{\mathrm{load}}$ measured from the pre-amplifier

The equivalent noise charge (ENC) can be calulated by

$$\mathrm{ENC} = Q = C_{\mathrm{load}} \cdot V_{\mathrm{noise}} \tag{8}$$

A plot of ENC versus $C_{\mathrm{load}}$ can be found in Figure 5d. After a fit to a straight line the pedestal noise is found to be $438 \pm 13$e and the slope is $3.05 \pm 0.11$e/pF. The ENC of the pre-amplifier without capacitive load can also be found here.

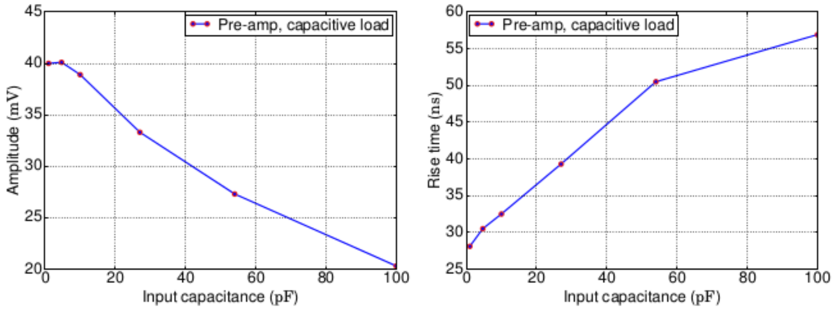
## 3.2 Noise measurement with spectroscopy amplifier

The pre-amplifier is accompanied with a spectroscopy amplifier (SA) and a pulse height amplifier (PHA). A capacitive load $C_{\mathrm{load}} = 27$pF is selected and measurements are made with 1, 2, and 3 MIP test pulses. From these measurements 3-point gain calibrations are made for these combinations of gain and shaping times: 100, 2µs; 100, 16µs; and 500, 16µs. The calibration curves and the fits are shown in Figure 6.

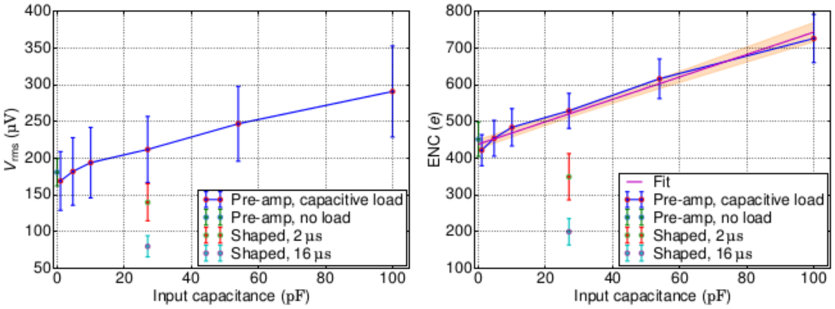
The noise for two shaping times – 2µs and 16µs – is also measured. The result is added to the ENC plot in Figure 5d. The ENC is reduced considerably by the introduction of the spectroscopy amplifier.

## 3.3 Measurements with radioactive sources

Measurements with the full detector chain (sensor, pre-amplifier, spectroscopy amplifier, and pulse height analyser) are made with $^{137}$Cs and $^{241}$Am. The gain is set to 500 and a shaping time of 16µs is selected. The parameters of the 3-point gain calibration are $y = 3.6 \cdot 10^{-4} + x \times 1.9 \cdot 10^{-6}$pC. The resulting spectra are shown in Figure 7.

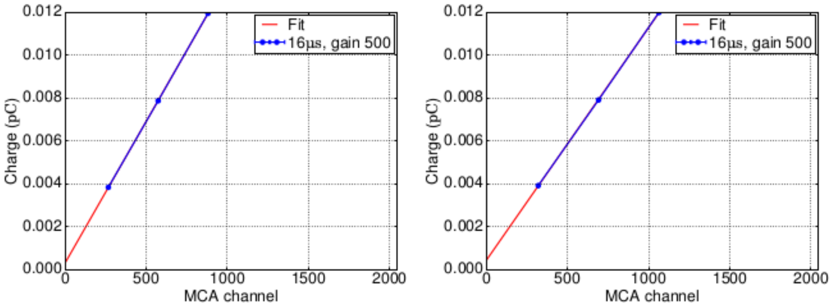


(a) Amplitude (b) Rise time



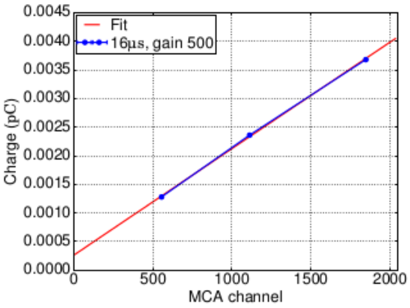
(c) Noise (d) ENC

Figure 5: Plots of the amplitude, rise time, noise, and ENC of the pre-amplifier output for different values of $C_{\mathrm{load}}$



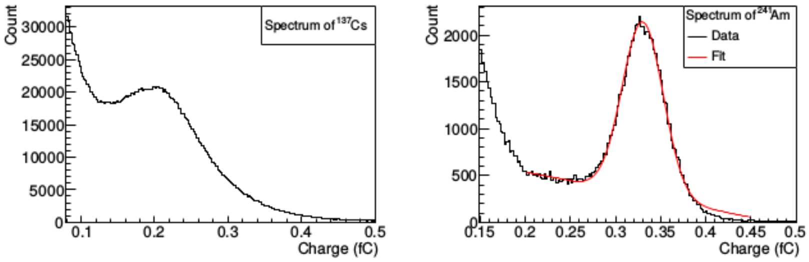
(a) Gain 100, 2µs

(b) Gain 100, 16µs



(c) Gain 500, 16µs

Figure 6: Plots of 3 point gain calibration curves and fits



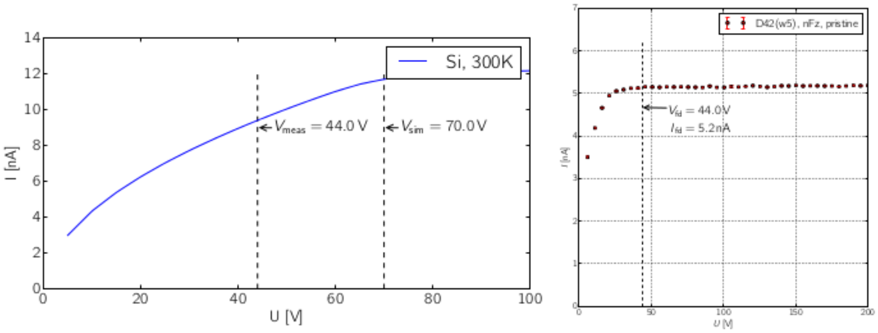
(a) $^{137}$Cs

(b) $^{241}$Am

Figure 7: Histograms from measurements of decays from $^{137}$Cs and $^{241}$Am

### 3.4 Simulation of clean room diode

A version of the diode used in the clean room experiment is simulated. The input file to GSS is listed in Listing 4.1. The simulation uses a sensor width of 50µm and the resulting leakage current is multiplied by 100 to emulate a sensor width of 5mm. The implanted doping is taken to cover the whole area of the sensor. The simulated and measured $IV$ curves can be found in Figure 8. The depletion voltage from the simulation is found to be $V_{\text{fd}} \approx 70\text{V}$ while the clean room measurement yields $V_{\text{fd}} = 44\text{V}$. The simulated leakage current is $I_{\text{fd}} \approx 12\text{nA}$ while the measured is $I_{\text{fd}} = 5.2\text{nA}$. The simulated values compare reasonably well with measurements, considering how the physical properties of simulation doesn't compare exactly to the real sample.



(a) Simulated $IV$ curve

(b) Measured $IV$ curve

Figure 8: $IV$ curve simulated by GSS and measured in the clean room

# 4 Appendix

## 4.1 Clean room sample

```
#==============================================================================
# GSS example: PN strip diode simulation
# On the first step, we will generate simulation structure for the diode.
# Then the generated CGNS file will be used on later steps.
#==============================================================================

# Create an initial simulation mesh
MESH      Type=GSS   ModelFile=pndiode_model.cgns Triangle="pzA"
XMESH     WIDTH=50.0  N.SPACES=25
YMESH     Y.MIN=0.0 Y.MAX=301.0 N.SPACES=60 H1=0.5 H2=0.5

# Region and electrode statements
REGION     Label=Cathode    Material=Al \
                 X.MIN=0.0 X.MAX=50.0 Y.MIN=0.0 Y.MAX=0.5
REGION     Label=Bulk      Material=Si \
                 X.MIN=0.0 X.MAX=50.0 Y.MIN=0.5 Y.MAX=300.5
REGION     Label=Anode      Material=Al \
                 X.MIN=0.0 X.MAX=50.0 Y.MIN=300.5 Y.MAX=301.0
#SEGMENT    Label=Anode    Location=TOP     X.MIN=0.0 X.MAX=50.0
#SEGMENT    Label=Cathode Location=BOTTOM X.MIN=0.0 X.MAX=50.0

# Specify impurity profiles
PROFILE    Type=Gauss Y.CHAR=0.5 Ion=Donor     N.PEAK=5E18 \
                X.MIN=0.0 X.MAX=50.0 Y.MIN=0.5    Y.MAX=2.5
PROFILE    Type=Uniform             Ion=Donor     N.PEAK=1E12 \
                X.MIN=0.0 X.MAX=50.0 Y.MIN=2.5    Y.MAX=298.5
PROFILE    Type=Gauss Y.CHAR=0.5 Ion=Acceptor N.PEAK=5E18  \
                X.MIN=0.0 X.MAX=50.0 Y.MIN=298.5 Y.MAX=300.5

#------------------------------------------------------------------------------
set Carrier     = pn         # specify carrier type
set LatticeTemp = 300        # room temperature
set Z.Width     = 5          # 5 mm
set DopingScale = 5e18

#------------------------------------------------------------------------------
# specify boundary condition.
#BOUNDARY Type=OhmicContact ID=Cathode Res=0 Cap=0 Ind=0
#BOUNDARY Type=OhmicContact ID=Anode Res=0 Cap=0 Ind=0
CONTACT Type=OhmicContact ID=Cathode Res=0 Cap=0 Ind=0
CONTACT Type=OhmicContact ID=Anode Res=0 Cap=0 Ind=0

#------------------------------------------------------------------------------
# Plot the initial mesh
PLOT      Variable=Mesh

## Refine by doping and plot the refined mesh
REFINE    Variable=Doping Measure=SignedLog Dispersion=3
PLOT      Variable=Mesh

# Define solver and solve for equilibrium state
METHOD    Type=DDML1   Scheme=Newton    NS=LineSearch LS=GMRES #Fermi=On
SOLVE     Type=EQUILIBRIUM

# Refine by potential and plot the refined mesh
REFINE    Variable=Potential Measure=Linear Dispersion=0.1
PLOT      Variable=Mesh

# Solve again for for the final mesh
SOLVE    Type=EQUILIBRIUM  #compute equilibrium state again on the refined mesh

# plot simulation variables
PLOT     Variable=Nd Resolution=RES.High AzAngle=30 ElAngle=30 \
```

```
                 Style=Color
PLOT     Variable=Na Resolution=RES.High AzAngle=30 ElAngle=30 \
                 Style=Color
PLOT     Variable=ElecDensity Resolution=RES.High Measure=SignedLog \
                 AzAngle=30 ElAngle=30
PLOT     Variable=HoleDensity Resolution=RES.High Measure=SignedLog \
                 AzAngle=30 ElAngle=30
PLOT     Variable=Potential Resolution=RES.High \
                 AzAngle=45 ElAngle=30 PS.OUT=potential.ps
PLOT     Variable=EFieldY Resolution=RES.High Measure=SignedLog \
                 AzAngle=45 ElAngle=30 PS.OUT=e_field.ps

# export mesh and solution
EXPORT   CoreFile=pndiode.cgns AscFile=pndiode.tif VTKFile=pndiode.vtk

END
```