Silicon Detector Simulations

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Silicon detectors are commonly used in particle physics due to the fast response and small size. The combination of these factors gives modern physics detectors high energy and spatial resolution at the price of potential long-term radiation damage. These detectors may be simulated in order to better understand the properties of Silicon and Germanium detectors.

1 Theory

Semiconductor-based detectors rely upon the interfaces of different materials. If the materials have differing properties related to the electron affinity, then contact will allow charge carriers to flow across the junction, producing a net electric field and potential. Elements may be added to the materials in order to increase the affinity for either electrons (N-type doping) or for "holes" (P-type doping). In the case that the acceptor concentration N_A and donor concentration follow $N_A \gg N_D$, the potential ψ will have a magnitude

$$\psi_0 = \frac{k_B T}{q} ln \left(\frac{N_a N_D}{n_i^2} \right) \tag{1}$$

where kB is the Boltzmann constant, T the temperature and q is the elementary charge [1].

These moving charge carriers will move from one material to the other and be captured, resulting in a **depletion region** in which no free charge carriers exist. For the asymmetric doping case, the size of the depletion region is

$$d \approx \sqrt{\frac{2\epsilon_0 \epsilon_S (\psi_0 + V_R)}{qN_A}} \tag{2}$$

where ϵ_0 and ϵ_S are the permittivity constants of the vacuum and of the semiconductor respectively and V_R is an applied bias voltage. The devie will be fully depleted at the **depletion voltage** (V_d), which is calculated as

$$V_d = \frac{qd^2 N_d}{2\epsilon_0 * \epsilon_S} \left(1 + \frac{N_d}{N_a} \right) \tag{3}$$

2 Simulations

The freely available program GSS version 0.4x is used for all simulations.

The basic geometry for the PN diode is constructed with the values of Table 1. The doping for the P-type interface is varied from 10^{14} to 10^{16}. The temperature of the diode is also varied between 100 and 600 Kelvin. Both Silicon and Germanium are simulated with identical geometries.

	Type	X (μm)	Y (-1 μm)	N	Distribution
A	$P+$	$0-50$	$0-3$	Varied	Gaussian
B	$P-$	$0-50$	$97-3$	10^{12}	Uniform
C	$N+$	$0-50$	$97-100$	10^{14}	Gaussian

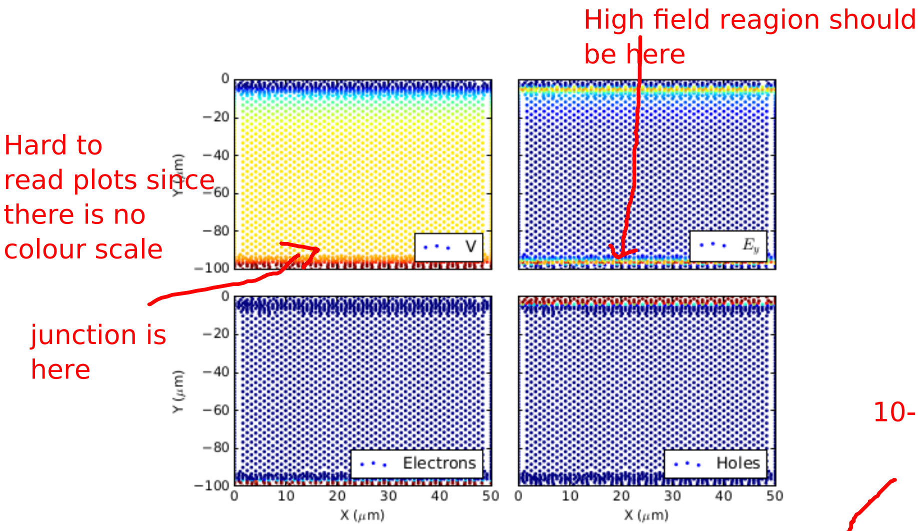
In this geometry you will create a pn-junction between B and C.

Table 1: The geomtry used while simulating the PN diode.

there is a small depletion region at equilibrium

The PN diode is started at an initial state with no depletion region. A equally space grid of 30x30 points is chosen for simulation. The first step of simulation corrects for the doping and refines the grid, adaptively adding points near the boundaries of the three regions. The simulation continues until a steady-state is achieved.

Many final combinations of settings are calculated by disabling the visual plotting of data. The output .tkl and .vtk files provide full information on the final equilibrium state for every point in the mesh. An example



10-14 in the table

Figure 1: An example of the output from GSS showing the voltage, electric field, and hole and ion concentrations for a Silicon detector at 300 K, a P-doped region of 10^{16}, and an N-doped region of 10^{16}. The geometry used is described in Table 1. Red regions indicate higher values and blue regions indicate lower values.

of the output is shown in Figure 1. As expected, the electric field E_y is largest at the AB and BC interfaces. In addition, the electron concentration is highest near the N-doped electrode while the hole concentration is largest near the P-doped electrode.

A Schottky device was simulated using GSS and the parameters in Table 2. Note that a Schottky device requires the bulk material be highly doped.

	Type	X (μm)	Y (-1 μm)	N	Distribution
Contact	–	$0-3$	$97-3$	–	–
Bulk	N	$10-3$	$0-3$	Varied	Uniform

Table 2: The geometry used while simulating the Schottky Device.

An example of the information produced by the Schottky device simulation is shown in Figure 2.

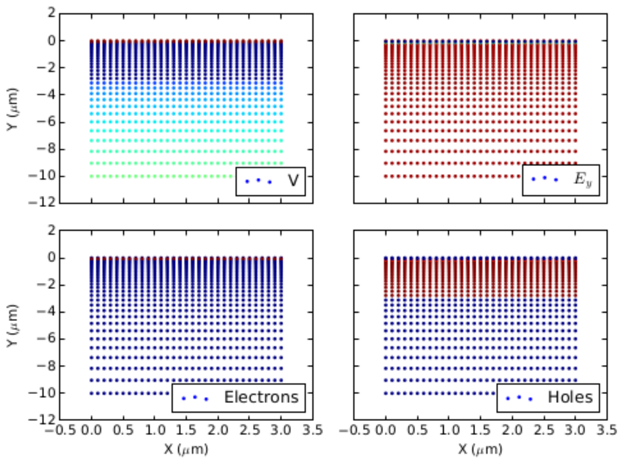


Figure 2: An example of the output from GSS showing the voltage, electric field, and hole and ion concentrations for a Schottky device at 300 K, a P-doped region of 10^{18}, and a work function of 4.2 eV. Red regions indicate higher values and blue regions indicate lower values.

¿ Expect it to be V. I am not sure what you have calculated....

	Type	Potential (mV)	Width (μm)	Depletion Voltage (V)
Theory	Si	0.455	24.24	7.29
	Ge	0.218	12.19	5.26
GSS	Si	0.471	20.65	$\approx 5-10$
	Ge	0.158	4.62	$\approx 0-5$

Table 3: A comparison of the theory and simulation values. Note that the definition of the width in simulation is empirically defined to be the region of 90% in the electric field from maximum. The depletion voltages from the simulated IV curves are given as a range due to limitations in the scans.

3 Results

3.1 The P-N Diode

A PN diode with various parameters was simulated following the geometry of Table 1. The width of the depletion region was estimated from the central 90% of the electric E_y as a function of y. The voltage is the maximum potential difference between points found after reaching equilibrium.

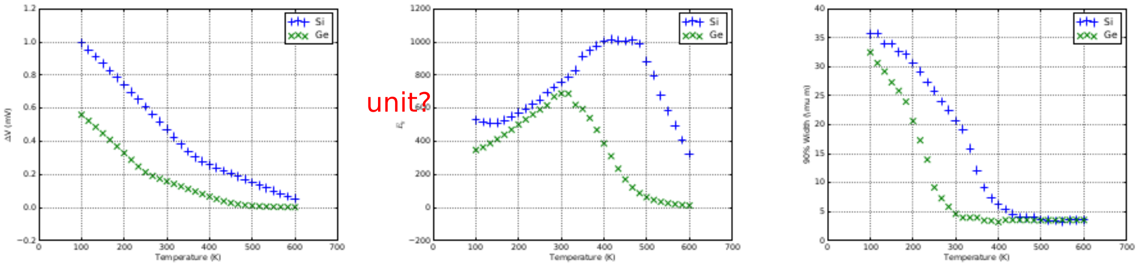
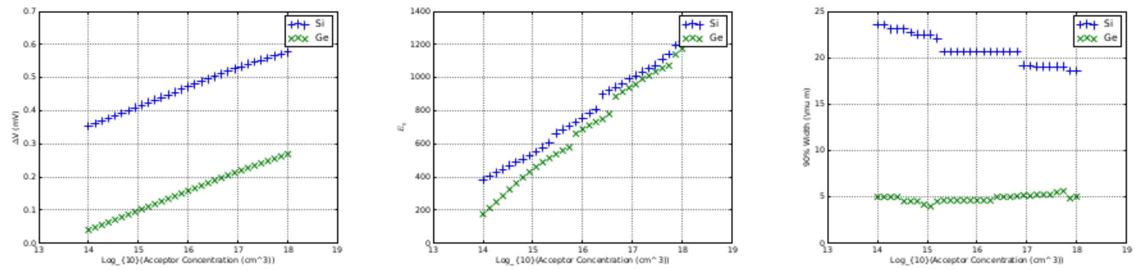


Figure 3: The effect of varying the temperature on the voltage, electric field, and width for both the Silicon and Germanium detectors.

The effect of varying the temperature is shown in Figure 3. As the temperature rises, the intrinsic potential across the diodes decrease and the depletion region shrinks. Interestingly, the electric field peaks for both Silicon (around 300 K) and Germanium (400-500 K). This could correspond to the energy at which electrons may tunnel through the depletion region.

It is probably an combination of the temp dependence of the field and the intrinsic carrier density.



surpisingly no effect?

Figure 4: The effect of varying the acceptor concentration on the voltage, electric field, and width for both the Silicon and Germanium detectors. The discrete structure of the depletion width is due to the finite grid of the simulation.

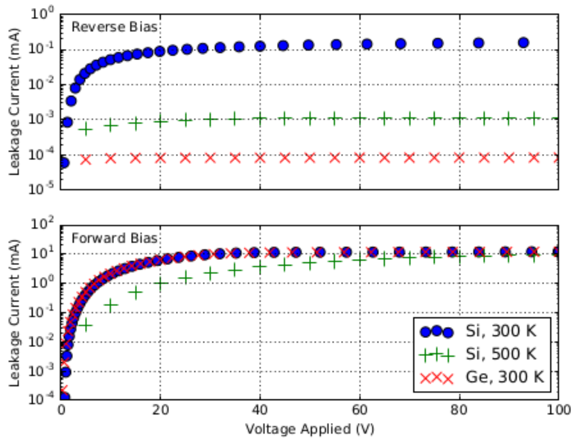
The effect of varying the level of doping for the P-doped region is shown in Figure 4.

The IV curve for both the forward and reverse bias was also calculated using the GSS simulation software and is shown in Figure 5. The forward bias, which forces charges through the depleted region and therefore reduces the size of the depleted region, has a significantly larger leakage current compared to the reverse bias.

A comparison of the simulated and theoretical values is given in Table 3. The theoretical values and simulated values from GSS broadly agree.

3.2 The Schottky Diode

Simulating the Schottky device with different temperatures gives the relationships shown in Figure 6.



Ge should have way higher reverse current than silicon

Figure 5: The IV curve for both forward and reverse bias. The detector geometry and doping levels are identical to that of Figure 1.

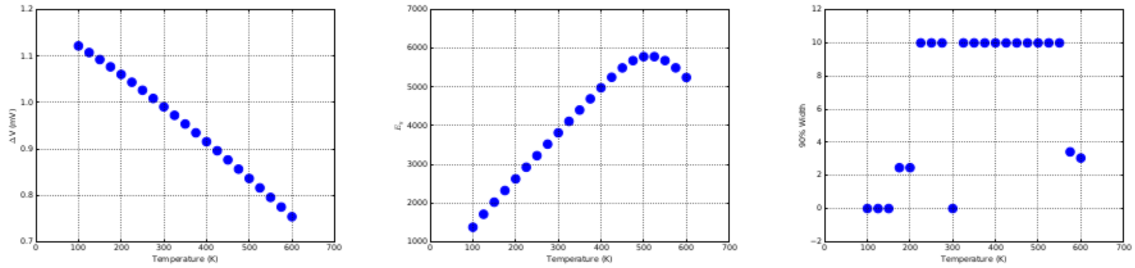


Figure 6: The effect of varying the temperature on the voltage, electric field, and width for the Schottky detector. The doping level is held at 10^{18} for all points and the work function is fixed to 4.2 eV.

very high doping for a sensor

The simulation of the Schottky device is much more unstable than the PN diode. This is clear, for example, when looking at the effect of varying the work function values in Figure 7. After many hours of investigation, during which the geometry, temperatures, doping concentrations, and other settings were varied, no clear fix was available. There seem to be three distinct regions in terms of the work function, with work functions below 3 eV producing different properties than those between 3-4 eV and above 4 eV.

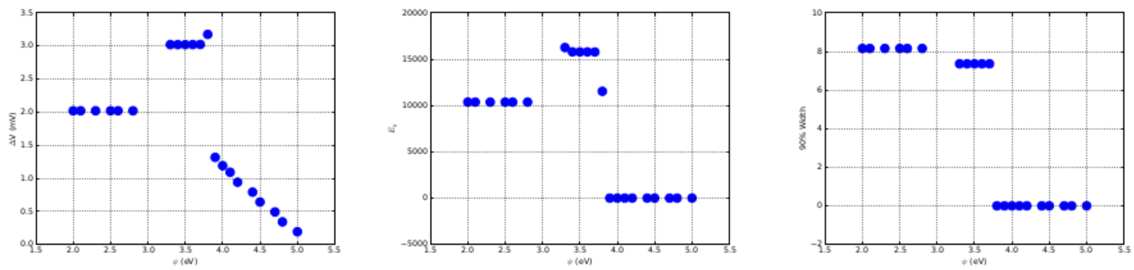


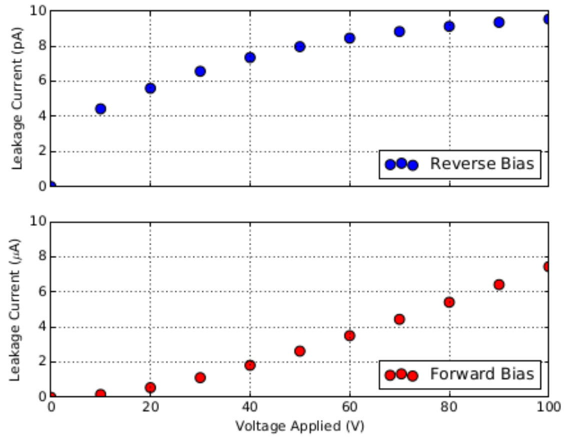
Figure 7: The effect of varying the work function on the voltage, electric field, and width for Schottky detector with doping of 10^{18} at 300 K. The instability of the simulation is clearly visible, with discrete transitions ocurring at approximately 3.0 and 3.8 eV. Detectors with work functions near 3.0 eV failed to properly converge.

Regardless of the issues with convergence, the general shapes of the plots in Figure 6 follow similar patterns as shown for the PN diode. There also exists a peak at 500 K again, mirroring the effect seen in Figure 3. The IV curves shown in Figure 8

Nice study. For furter reading have a look at http://www.znaturforsch.com/aa/v59a/s59a0795.pdf

4 Conclusions

The simulation of the PN diode compares well to the theoretical values predicted at temperatures of 300 K. The Schottky device performed adequately for general trends to be discerned and matched the behavior of the



Very low currents for a Scottky with high bulk doping.

300K?

Figure 8: The IV curve for both forward and reverse bias of the Schottky detector. The detector geometry and doping levels are identical to that of Figure 2.

IV with what work function?

PN diode for varying temperatures. The behavior of the Schottky diode behaved in odd ways for varying work functions with the values of the intrinsic potential, electric field, and depletion width taking discrete values for different ranges of values of the work function.

References

[1] Knoll, G.F, Radiation Detection and Measurement John Wiley & Sons 3nd edition, 2000.