Report on silicon lab and homework

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1 From exercise session

Here the result from the investigations of the pn-junction and the Schottky contact shall be presented.

1.1 Simulation of pn-junction

For these exercises an 3-by-3 μm n-bulk is doped with $p+$ and $n+$ on opposite sides.

In order to compare to some theoretical prediction, the following equation will be used to determine the potential difference in the junction,

$$\phi = \frac{k_\mathrm{B}T}{q} \ln\left(\frac{N_\mathrm{A}N_\mathrm{D}}{n_\mathrm{i}^2}\right), \tag{1}$$

where N_A and N_D is the concentration of the acceptor and donor dopant, respectively. The intrinsic concentration of the bulk n_i, depend both on specific conditions of the material and the temperature T in a non-trivial way. So this will be found in the literature.

The width of the space charge can be determined as

$$d = \sqrt{\frac{2\epsilon_0\epsilon_r}{q}\left(\frac{1}{N_\mathrm{A}} + \frac{1}{N_\mathrm{D}}\right)\phi}, \tag{2}$$

If nothing else is noted the doping is 10^{16} for both, a temperature of 300K is used, and the material is Si, without any bias voltage.

In Table 1 the effect of varying the temperature is presented. The theoretical predictions are also added, and one can see that the junction potential shows a fairly good comparison. However, the space charge width, is somewhat off, but does not change much, which is also what is observed for the simulation.

Table 1: Effect of changing the temperature on the pn-junction in simulation.

Temperature [K]	273	300	330	400
Junction potential [V]	0.76	0.71	0.65	0.51
Electron density 1e16 minus	8.5e1	1.2e4	1.1e6	3.7e9
Width of space charge region [μm]	1.6	1.6	1.6	1.6
Theoretical junction potential [V]	-	0.73	-	0.53
Theoretical width of space charge region [μm]	-	0.43	-	0.37

In Table 2 the effect of varying the donor concentration is presented Again the theoretical prediction for the junction potential is agreeing fairly well with the simulation. The width shows

the same behavior of deminishing wdith for higher concentration. Only for a concentration of 1e14 is the model i trouble, as the width is predicted to be wider than the size of the chip.

Table 2: Effect of changing the doping concentration of the pn-junction in simulation.

Dopant concentration	1e14	1e15	1e16	1e17	1e18
Junction potential [V]	0.46	0.59	0.71	0.82	0.92
Electron density minus this	1.2e6	1.2e5	1.2e4	1.3e3	3.6e2
Width of space charge region [μm]	3.0 (FULL)	(FULL)	1.6	0.6	0.4
Theoretical junction potential [V]	0.49	0.61	0.73	0.85	0.96
Theoretical width of space charge region [μm]	3.54	1.25	0.43	0.15	0.05

In Table 3 the effect of varying the ratio of the donor/acceptor concentration Here the donor concentration is fixed at 1e16, and only the acceptor concentration is modified. At the precision read off for the junction potential the model seem to describe the behaviour quite well. The width changes from the previous experiments, in as it is no longer symmetric for the cases with different acceptor and donor concentrations, and is therefore noted as a range. With the theoretical value for the width again showing the right trend, but having values much smaller.

Table 3: Effect of changing the ratio of the acceptor/donor concentration of the pn-junction in simulation.

Acceptor/donor ratio	1e-1	1e0	1e1	1e2
Junction potential [V]	0.6	0.7	0.7	0.8
Electron density 1e16 minus this	1.2e5	1.2e4	1.3e3	1.2e2
Width of space charge region, 0 at donor [μm]	1.8-3.0	1.6	0.6-1.2	0.6-1.1
Theoretical junction potential [V]	0.67	0.73	0.79	0.85
Theoretical width of space charge region [μm]	0.97	0.43	0.33	0.33

In Table 4 the effect of changing material is presented. It is exemplified that Ge gives a weaker potential, though about the same width of the space charge region as in Si.

Table 4: Effect of changing the material of the pn-junction in simulation.

Material	Si	Ge
Junction potential [V]	0.71	0.32
Electron density 1e16 minus this	1.2e4	5.1e10
Width of space charge region, 0 at donor [μm]	1.6	1.4
Height of space charge region	3.1e4	1.6e4
Theoretical junction potential [V]	0.73	0.32
Theoretical width of space charge region [μm]	0.43	0.33

p-type?

A larger pn-junction was also investigated. A 100x50 micron thick sensors with 3 micron thick implants of a concentration of 10^{15} on a n-type bulk with a concentration of 10^{13}. Both implants were implemented with a Gaussian trail-off into the bulk, adjusted with Y.MARG = 1.

A DC sweep is run to determine the IV-curve, which shall be used to determine the depletion voltage. (note to self: next time, do not start by turning the chip upside down, because then what should be a bias, is actually a reverse bias) On Figure 1 the IV-curves for Si and Ge is presented. One observes the very small current, indicating that the bias is reversed (otherwise one would see a current of order mA).

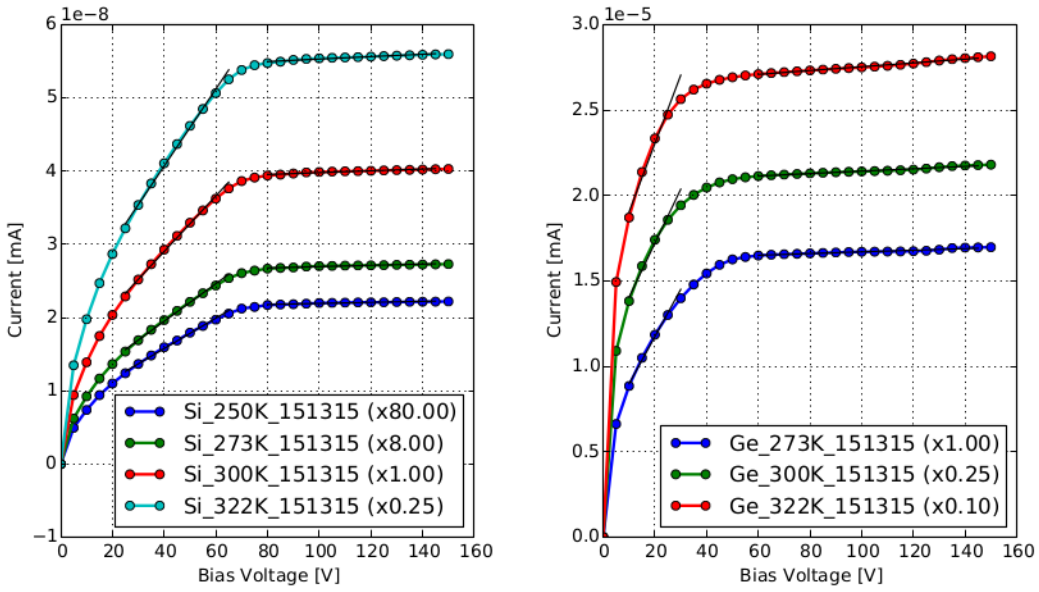

Figure 1: The IV-curves for a pn-junction in Si (left) and Ge (right), for various temperatures. The straight lines used to determine the depletion voltage is plotted as well.

The depletion voltage is determined as the crossing point of two straight lines fitted to the two regions of the IV-curve. The plateau is fairly simple to follow, but it is not as obvious which part of the ramp up to use for the fit, and the depletion voltage naturally depends on which point to use for the fit. On Figure 1, the lines used for determining the depletion voltage is plotted as well. The points that seemed to form the most straight line have been chosen for the fit. In Table 5 the depletion voltage is listed for the temperatures simulated. One sees that the effect of changing the temperature is much larger for Ge, though one still see an effect in Si.

Table 5: Depletion voltage of pn-junctions of different materials at various temperaturs.

Temperature [K]	Depletion voltage [V]	
	Si	Ge
250	68.5	-
273	68.0	36.8
300	67.3	31.8
322	66.7	29.2

Theoretically we can use that bulk concentration to determine for which voltage, the depletion width is 100μm, the full width of the detector. For Si and Ge at 300 K that will happen for a reverse bias of 387 V and 283 V repectively. Either the discrepancy between these numbers and the numbers in Table 5, is due to the model not describing the simulation, or because the numbers in Table 5 refer to when the depletion starts, and not when the chip is 'fully' depleted, as that might happen for higher voltages.

1.2 Simulation of Schottky contact

The Schottky contact is quite different from the pn-junction, as it has a metal contact on one side of the chip. And the rest of the diode is acceptor doped material. The electron density is VERY narrowly concentrated in the Schottky diode. Compared to the pn-junction the E-field is fairly flat over the diode, except at the contact where it drops to 0. Investigating the effect of variation it is observed that the E-field gets lower with lower acceptor density.

Strange, I would expect a rather high field region at the metal-silicon junction

No big change with temperature. The potential shows a more smooth change, and then a sharp drop by the contact. The electric density is always the same as those stem from the metallic contact, and only the hole density changes with acceptor density.

On Figure 2 the IV-curve is plotted for a diode similar to the one used to simulate the pn-junction. A size of 50x100 μm, now only an acceptor bulk with a 1e16 concentration as anode (as it was not possible to make one with only a 1e15 concentration). One sees a quite different behaviour of the current, it is an order of magnitude lower, and it does not reach a plateau as smoothly as for the pn-junction. Instead it have this step-wise behavior, for which the cause is not obvious.

What work function was used in the simulation?

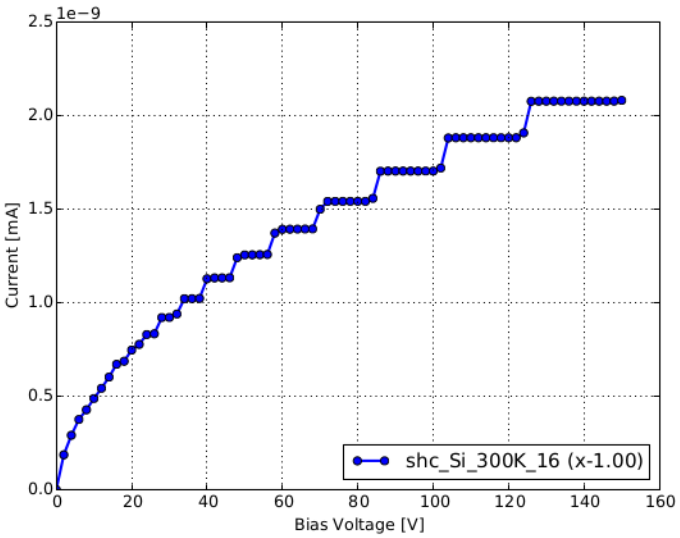

Figure 2: The IV-curve for a Schottky contact on a acceptor dopant with a concentration of 1e16, at a temperature of 300 K.