I-V characteristics of three diodes, and investigating the influence of annealing to a B doped Si Schottky-diodes doping profile

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1 I-V characteristics

The Shockley ideal diode equation,

$$I = I_0 \left[e^{\left(\frac{qV}{nk_BT}\right)} - 1 \right] \underbrace{\approx I_0 e^{\left(\frac{qV}{nk_BT}\right)}}_{\text{Because } V \gg nk_BT/q} , \qquad (1)$$

where k_B is the Boltzmann-constant, q is the charge of an electron and T the temperature. Taking the natural logarithm on both sides and rearranging yields

$$\ln(I) = \underbrace{\frac{q}{nk_BT}}_{\text{Slope}} V - \ln(I_0). \qquad (2)$$

At room temperature ($\approx$ 300 K) we measure each diode's current at voltage intervals specified in table 1. We plot equation (2) for our measurements in figure 1 and determine the ideality factor n, saturation current I_0 and cut-in voltage for each diode. The values are summarized in table 1.

Name: Type:	BYS21-45 Schottky	1N4148 P-N	BZX55C10 Zener
n	≈ 1	1.860	1.634
I_0 [μA]	1050	1.51	0.028
Cut-in [V]	0.1	0.5	0.6
Start at V [V]	0.0	0.0	0.0
To max V [V]	0.6	1.2	1.0
To min V_R [V]	-60.0	-100.0	-11.0

Table 1: Summarization of measurements points for both bias, and ideality results for each diode.

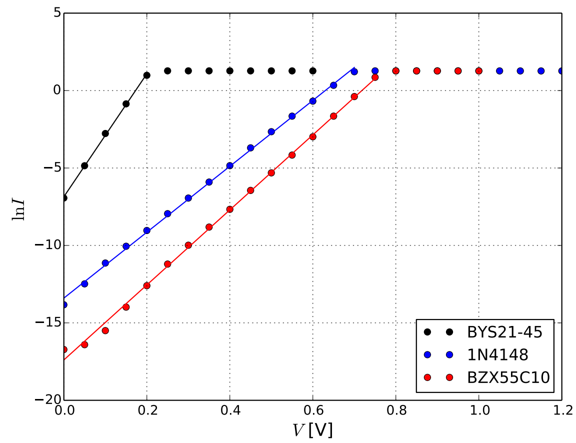

Figure 1: The natural logarithm of the injected current plotted versus increasing forward bias voltage, giving information about the diodes ideality.

1.1 The ideality factor

Forward bias generally reduces the built in energy barrier at diode junctions, enabling more charge carriers to pass through. The majority carriers in Zener & P-N diodes cross their respective junctions and become minority carriers. Once there, they tend to recombine after - on average - the minority carrier lifetime τ has elapsed. τ depends on the recombination rate and is related to majority carrier concentration in both P & N materials. The reason that n is lower in Zener diodes is a higher concentration of majority carriers and a higher effective recombination rate. Schottky diodes generally have lower V_{bi} and thus requires less bias to be turned on, at the expense of higher I_0.

1.2 Reverse bias behaviour

1.2.1 Schottky diode, a metal-semiconductor junction

In the case of the Schottky diode, the *saturation current* I_0 is due to thermal emission of electrons that have high enough energy to overcome the energy barrier ϕ_B, defined as the difference between the metal's work function ϕ_m (energy required to liberate an electron from the metal) and the electron affinity χ_s (energy released when an electron negatively ionizes a neutral atom), namely $\phi_B = \phi_m - \chi_s$, both ϕ_m and χ_s are constants associated with diode materials, consequently ϕ_B is also a material constant. A second order effect is present in Schottky diodes that affects the reverse bias current, an effect not present in Zener or P-N diodes. The electric field E, across the Schottky junction, can be treated like one of an abrupt P-N junction. The electric field is proportional to the depletion layer width on the semiconductor side of the junction w_n. The depletion width on the metal side is neglectable due to high abundance of majority carriers, so we can assume $w_p \simeq 0$. The depletion width turns out to be proportional to the square root of the reverse bias current V_R, that is

$$E \propto w_n \propto \sqrt{V_R}.$$

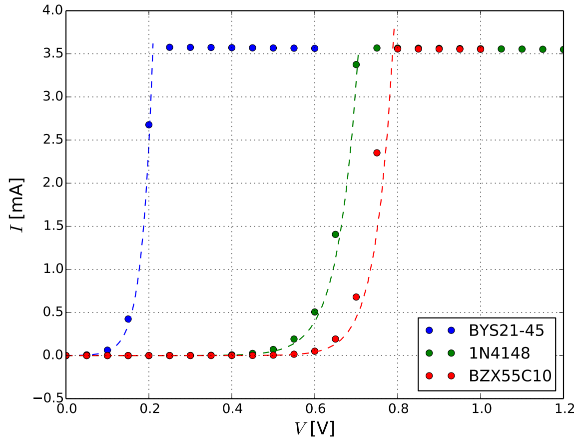

Figure 2: Our Shockley ideal diode equation graphed on the measured points

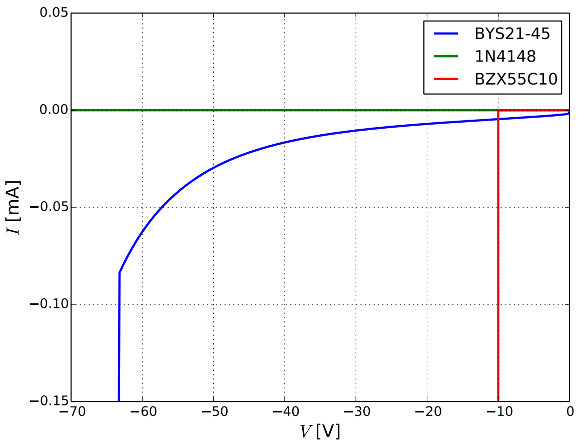

Figure 3: Current through the three diodes plotted against reverse bias voltage. Evidently, breakdown was not reached for the P-N diode.

Due to the metal's high conductivity, electrons on the semiconductors side experience mirror charge forces, that in turn reduces the barrier height ϕ_B by an amount $\Delta\phi_B \propto \sqrt{E}$. This mechanism enables increase in reverse bias current in proportion to V_R. This effect is evident in figure 3, displaying gradual increase in reverse bias current.

1.2.2 P-N & Zener diode

No bias ($V_R = 0$ V) across the junction means that the junction is in thermal equilibrium, and its Fermi level is constant through the system. As reverse bias voltage V_R is applied across the diode, the Fermi level of the P & N materials will be separated by an amount qV_R. Also, the diode's depletion layer width $w = w_n + w_p$ will increase, consequently increasing the electric field across the junction.
The reverse bias current will remain small, up to an certain extent. There are mainly two phenomena that are responsible for this reverse bias current. Usually, the prevailing contribution comes from the so-called *generation current* which is dependent on the average time a R-G (**R**ecombination-**G**eneration) center takes to generate an electron-hole pair. Intuitively, it thus depends on the density of said R-G centers as well, along with the junction width times the depletion layer width.
The other contribution is due to steady diffusion of minority carriers across the junction via acceleration by the E-field due to V_R. This current is not in proportion to V_R, though an increase in E will surely make it more favorable for these minority carriers to travel across the junction, but the current is limited by their low abundance near the junction, thus pretty much remaining constant under varying V_R.
Eventually, when V_R becomes sufficiently large, the E-field can accelerate the minority carriers to the point that their kinetic energy is great enough to break a covalent bond in the depleted region of the semiconductor lattice, in turn generating a electron-hole pair. This effect known as *avalanche breakdown*. As the temperature is increased, the V_R required to reach avalanche breakdown becomes larger. This is due to increase in phonon scattering and consequently a shorter mean free path. Likewise, highly doped diodes have a relatively larger built in E-field, so less voltage is required to reach the breakdown point.
One more important source of reverse currents in P-N diodes is due to a quantum mechanical phenomenon know as *tunnelling*. There's a finite chance that a minority carrier can appear on the other side of the junctions energy barrier, even though its energy was less than of the barrier. Reverse bias voltage reduces the barriers width, leading to increased chance of tunnelling. The chance of a single electron tunnelling is usually very small, but due to huge numbers of electrons in the valence band, tunnelling can be considerable. That being said, tunnelling is exceptionally rare unless the depletion layer is very narrow, which is often the case when both the P and N materials have high doping levels, like in the case of Zener diodes. In fact, the doping level determines whether tunnelling or avalanche breakdown occurs first. Also, an increase in temperature give the charge carriers more energy and increase their tunnelling probabilities, whereas in contrast to avalanche breakdown where increase in temperature means a relatively larger V_R is needed to achieve breakdown.
So in the case of our experiment, the Zener diode experiences breakdown due to tunnelling of carriers and the P-N diode should break down due to avalanche, but as figure 3 shows, we did not have a voltage source that could deliver the bias needed to reach breakdown.

2 C-V analysis of a Schottky diode

Near the surface of a P-doped semiconductor, the acceptors atoms (e.g. B, Al, In & Ga) can get occupied by unwanted H, making said acceptor atoms unable to carry charges. We explore how annealing affects the doping profile. We start with a disc-shaped B doped Si Schottky diode, with an approximately 1.5 mm radius. The diode is placed in a crystostat for a series of three C-V measurements from 0 to -10 V in the following order:

1. C-V is measured at room temperature $\approx 27°$C.
2. The diode is heat treated at 120°C for 10 minutes at -5 V bias, then cooled back to room temperature before the bias is set to 0 and finally measuring its C-V.
3. Step 2. is now repeated at 150°C for 30 minutes.

Results of these three measurements are shown in figure 4, indicating that annealing affects the C-V behaviour. The junction capacitance C_J can be related

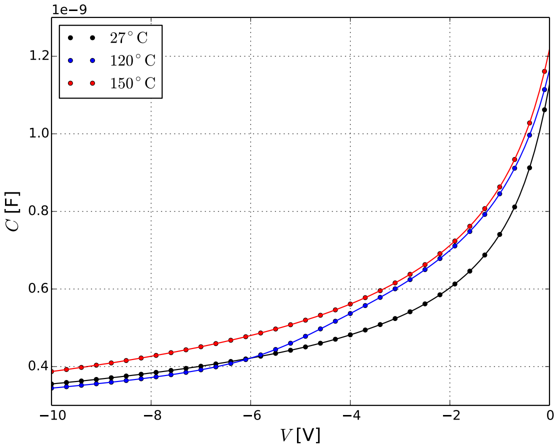

Figure 4: The diodes capacitance plotted as a function of reverse bias voltage after annealings.

to the reverse bias voltage V_R by

$$\frac{1}{C_J^2} = \frac{2(V_{bi} + V_R)}{qN_B\varepsilon A^2}, \tag{3}$$

where $\varepsilon = \varepsilon_r\varepsilon_0$ is the permittivity of Si, V_{bi} is its thermal equilibrium built-in voltage, N_B is carrier density and the junction area is A. We plot equation (3) against the reverse bias voltage V_R for each of the three annealings. The results are shown in figure 5. From the C-V measurements we can directly compute the doping profile $N_B(x)$, as a function of the distance x in to the B doped Si junction.

$$N_B(x) = \frac{2}{q\varepsilon A^2|d(1/C_J^2)/dV_R|} \quad \text{where} \quad x = \frac{\varepsilon A}{C_J}, \tag{4}$$

Now, in order to calculate $|d(1/C_J^2)/dV_R|$ we did a 6th degree polynomial regression on the datapoints in figure 5, whose derivative can then be obtained directly. A graph of equation (4) for our measurements can be seen in figure (6) It's evident from figure 6 that $N_B(x)$ changes dramatically after annealings. The source of this change can be related to H. At the first measurement (no annealing) we see N_B is small first, but gradually rises as x gets larger. This indicates that the

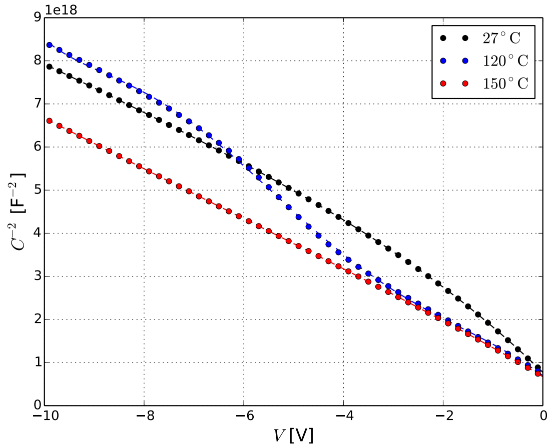

Figure 5: $1/C_J^2$ plotted against the reverse bias voltage. We note the behaviour for the first two measurements are not very linear. The dotted lines are 6th degree polynomial regressions of the datapoints.

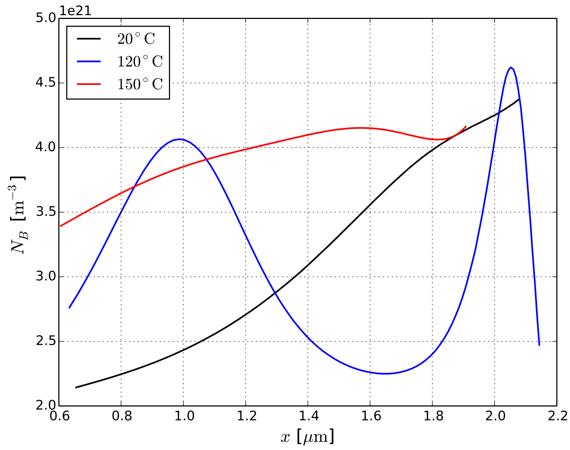

Figure 6: $N_B(x)$ plotted for different annealings

concentration of unwanted H is greatest at the surface and reducing as x gets larger. After the first annealing, it looks like some H atoms gained enough energy to liberate and diffuse further into the semiconductor before reoccupying a B atom. Finally, after the third annealing we can see a much more steady concentration of available charge carriers. This time the H didn't just diffuse further into the semiconductor. At this temperature, some H atoms are able to form H_2, a very stable bond which does not bind to B, so in effect, relatively more acceptor atoms are available to carry charge.

References

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