DREXEL UNIVERSITY
Electrical and Computer Engineering
College of Engineering

Drexel University
Electrical and Computer Engineering Dept.
Electronic Devices Laboratory, ECE-370

TITLE: **Capacitance of PN Junctions**

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SECTION: **061**

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Objective

The objective of this lab was to analyze more characteristics of the PN junction diode. This includes describing AC characteristics as well as finding junction capacitance, doping concentration, and built in voltages.

Theory

PN junctions have an inherent characteristic in which a depletion region is formed as dopant atoms from both sides of the junction ionize and diffuse to the opposite side of the junction producing an electric field. In this electric field, all charge carriers are pushed to either side of the junction, making the depletion region essentially vacant of all charge carriers. Adding a reverse bias to this junction will increase the size of the depletion region as the applied voltage will add to the inherent electric field. Adding an AC bias to the existing DC bias will effectively add and subtract increments of charge from the n and p sides respectively. The following figure shows the energy-band diagram of reverse-bias as well as the lengths of the depletion region under AC and DC biases:

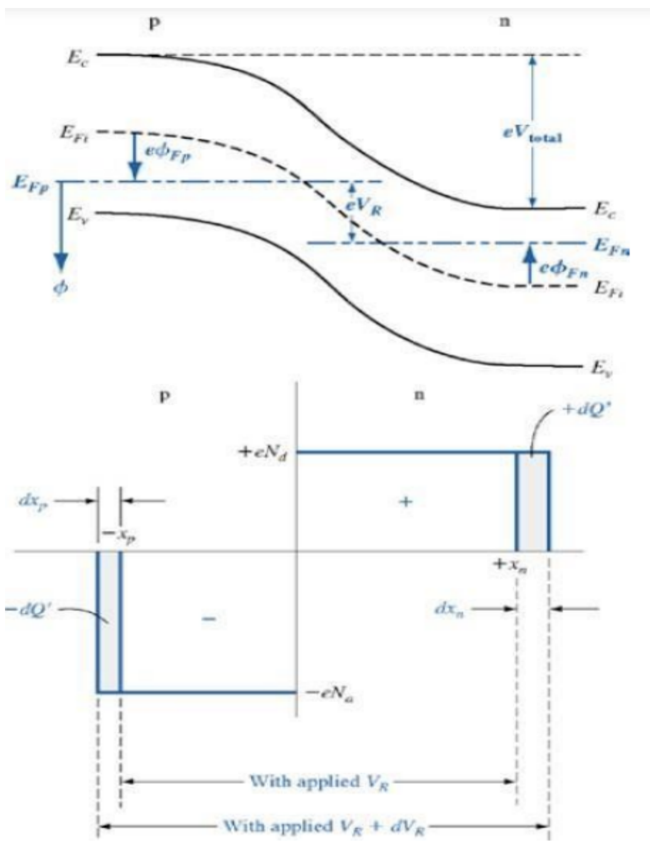


Figure 1 Energy band diagram and incremental charge storage in a PN junction under reverse bias.

As can be seen in Figure 1, the accumulation of charge on each side of the depletion region gives shape to a capacitance. Therefore, there will be a capacitance due to the buildup of charge from the ionization of the dopants. Biasing the junction will allow for the capacitance to be changed as the depletion region is altered. The capacitance follows this equation:

$$C_j = \sqrt{\frac{q\epsilon_S}{2(V_{bi}-V_a)}\frac{N_A N_D}{N_D+N_D}}$$

Equation 1

The relationships between applied voltage can be much easier observed when Na is taken to be much larger than Nd. This reduces equation 1 to:

$$\frac{1}{C_j^2} = \frac{2}{q\epsilon_S}\frac{N_A+N_D}{N_A N_D}(V_{bi} - V_a)$$

Equation 2

This equation will be extremely useful in graphical analysis. A plot of 1/Cj^2 vs. Va will yield many insights into the junction. For instance, the slop will be proportional to the inverse of the doping concentration on the lightly doped side. Also, where the line intersects the x-axis will be the built-in voltage.

Experimental Procedure

Part 1

First, the LCR meter was used to gain some insights into the capacitance of the diode's PN junction. Following the procedure written for lab 5 with respect to the LCR led the following data EC370Lab5 .

Part 2

Next, to gain a better understanding the DCIV characteristics of the diode were needed. So, voltages from -5 to 5 V were applied to the diode while recording the voltage and current through the diode. This allowed for a plot to be formed and resistances in the on and off states to be calculated.

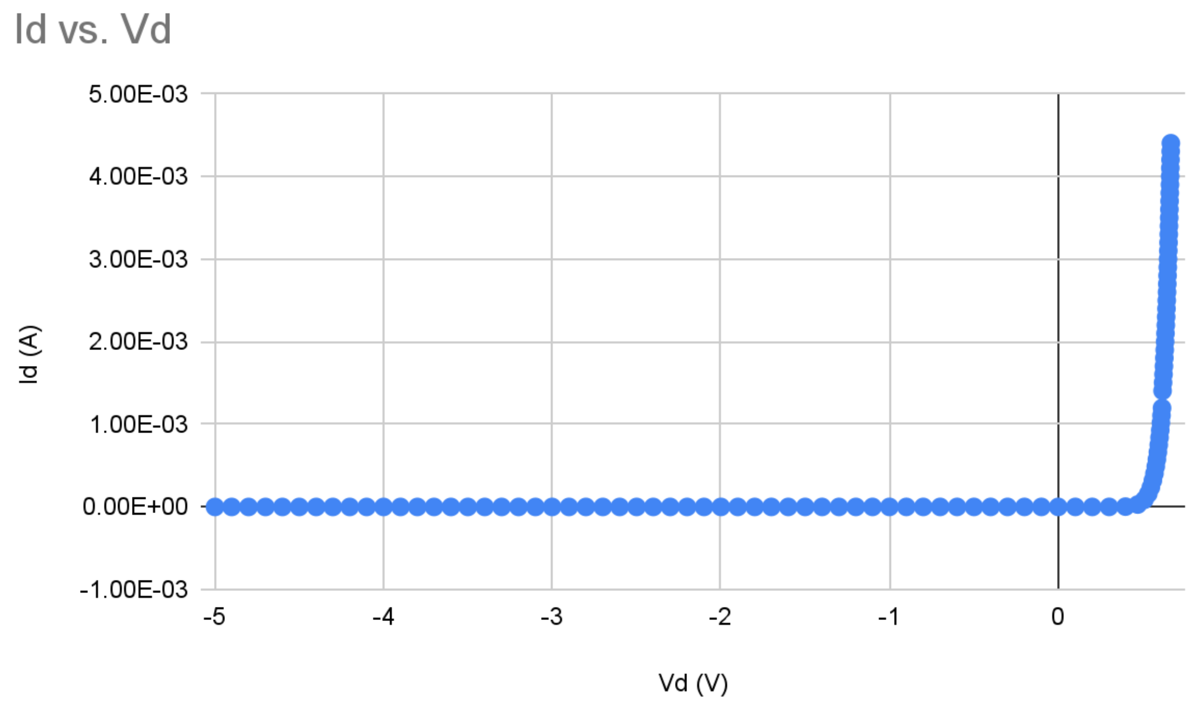


Figure 2

From this graph the on and off resistances can be calculated as it is obvious which points correspond to each state.. Namely, the on resistance was calculated using Ohm's law and yielded $R = V/I$; $(0.589963)/(6.63 * 10^{-4}) = 890\ \Omega$. As for the off resistance, the same approach was used and yielded $(-4.7)/(-4.68 * 10^{-7}) = 10 * 10^{6}\Omega$.

With the resistance established, it also became of interest to analyze the capacitance of this diode, as in how long it takes the diode to discharge after reaching the negative cycle of the 1kHz square wave applied to the diode. An oscilloscope was used to measure the voltage as a function of time over the resistor in the resistor-diode configuration. The plot obtained is:

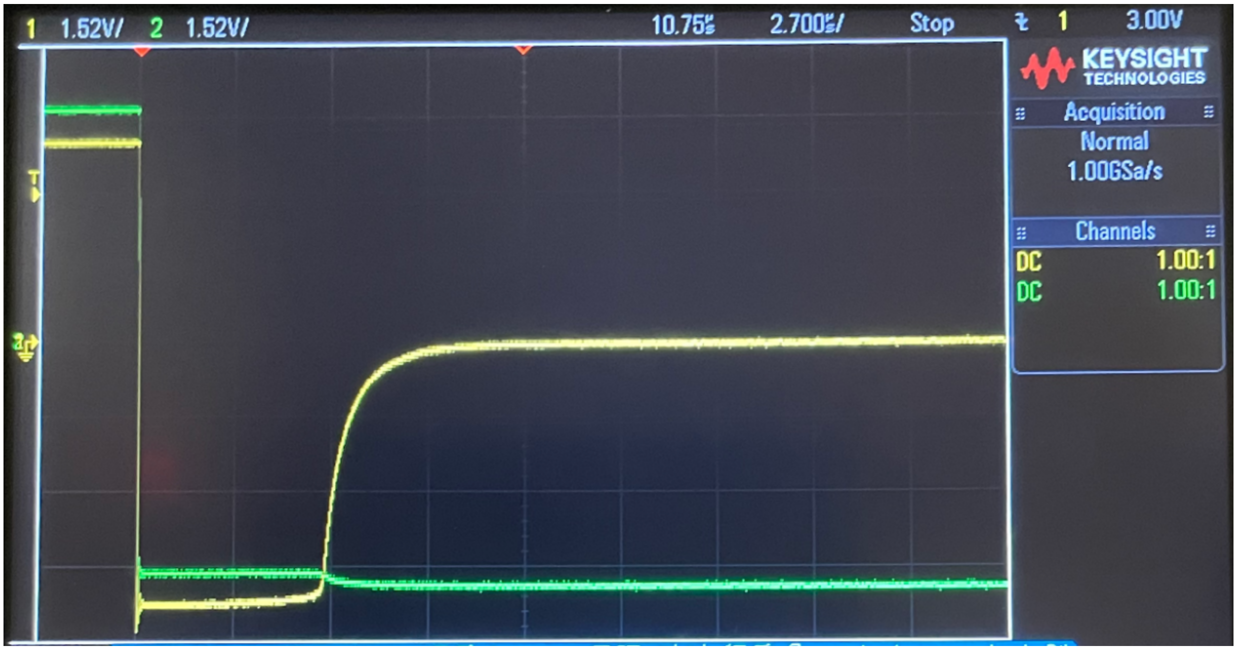


Figure 3

From this graph, it can be seen that each box is 10.75 microseconds, and 0 voltage across the resistor is when the voltage reaches a steady value after the drop. Taking the beginning of the discharge to be the 0 time point, the RC value can be found by looking for when the voltage is 1/e of its peak. This yields a number of squares of approximately 0.25. 0.25 times 10.75 gives 2.69 microseconds. 2.69 microseconds=RC, $2.69/1000 = 0.00269$ microfarads for the diffusion capacitance.

Part 3

For this section of the experiment it became necessary to use nanohub as it has the features where one can select the dopings to use in the semiconductor. The specific simulation used was Nanohub's bulk Silicon transport characteristics. The silicon in the simulation was doped with a concentration of 1e16 cm-3 donor atoms. For this particular doping, there was a majority carrier of electrons with an associated mobility of 1106.8 cm2/V-s, and a minority carrier of holes with an associated mobility of 498.46 cm2/V-s. The majority electron also had a mobility of 1.0965e+07 cm/s.

The simulation also gave access to resistivity data for concentrations, so to get better insights it was changed into a conductivity vs. concentration graph. This yielded the following graph:

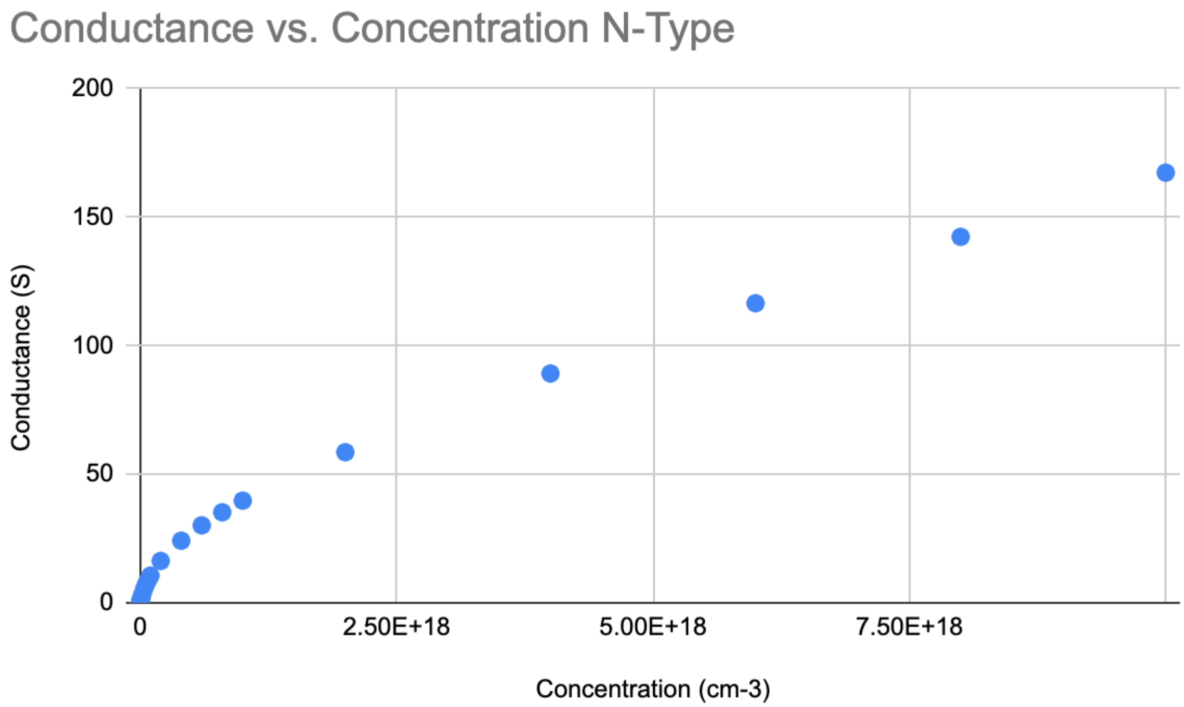


Figure 4

A doped semiconductor with excess acceptor atoms were also taken into account. This semiconductor also had 1e16 cm-3 dopants, but rather they were acceptor dopants. The majority carriers in this scenario were the holes and they had an associated mobility of 406.43 cm2/V-s as well as a drift velocity of 7.9498e+06 cm/s. The minority electron had a mobility of 1254.6 cm2/V-s. The corresponding conductance vs. concentration graph is as follows:

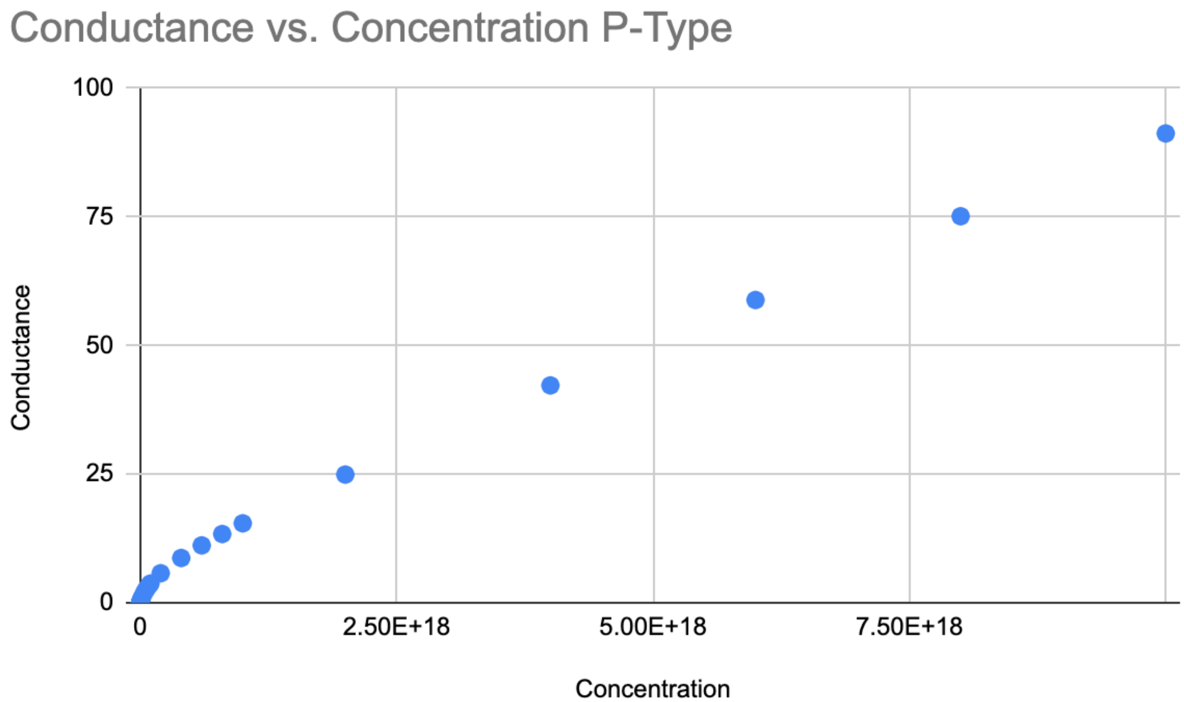


Figure 5

It is important to note the drift velocity and that it saturates when the electric field passes a certain value. The primary mechanism for this saturation is phonon scattering. Phonons are a collective excitation in a periodic arrangement of atoms or particles. This makes sense that this phenomenon would apply to semiconductors with crystalline structures. Essentially, phonons are a type of quasi particle used as a quantum mechanical description of vibrations in which a lattice of atoms vibrate. As the electric field increases, the phonons amplitude increases because of the greater force on the ions.

The next simulation used to perform more analyses was ‘Effects of Doping on Semiconductors’. Here, the Fermi level is shown as the level of dopants changes. It is important to note how the Fermi level changes as a function of temperature and dopants. As the level of acceptors are increased, the fermi level moves toward the conduction band to balance electrons and holes as the holes increase. As the donor concentrations increase, the Fermi level will move closer to the conduction band to balance holes and electrons with the excess electrons. Increasing temperature makes the semiconductor act more as an intrinsic semiconductor and move the Fermi level closer to that of an intrinsic semiconductor.

When a semiconductor is highly doped with acceptors, the majority carrier becomes holes. Conversely, when a semiconductor is highly doped with donors, the majority carrier becomes electrons.

Report

1.

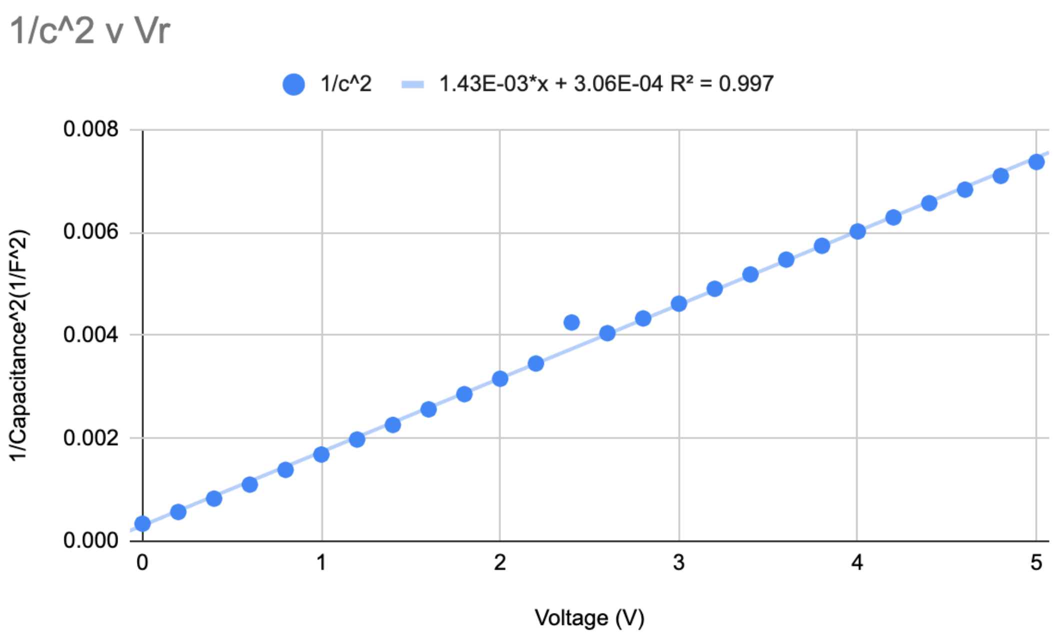


Figure 6

$$N_d = \frac{2}{e\,\epsilon_s} \cdot \frac{1}{slope} \qquad N_a = \frac{n_i^2}{N_d} \exp\left(\frac{V_{bi}}{V_t}\right)$$

Figure 7

Given: e = 1.6*10^-19,
Es = 1.03*10^-12 F/cm,
Slope(m) = 1.43*10^-3,
ni = 1.5*10^10 cm^-3,
Vbi = -0.21398 V, and
Vt = 0.0259,

We can find Nd = 8.49*10^33 m^-3. Using this value, we can calculate Na = -6.67*10^-13 m^-3. Vbi. $0 = 1.43 * 10^{-3}x + 3.06 * 10^{-4}$. Vbi = -0.21398 V.

2. Starting with 1/c^2 vs. V, this seems to be a very good fit, which confirms at least one side is linearly doped. The graph for 1/c^3 vs. V is as follows :

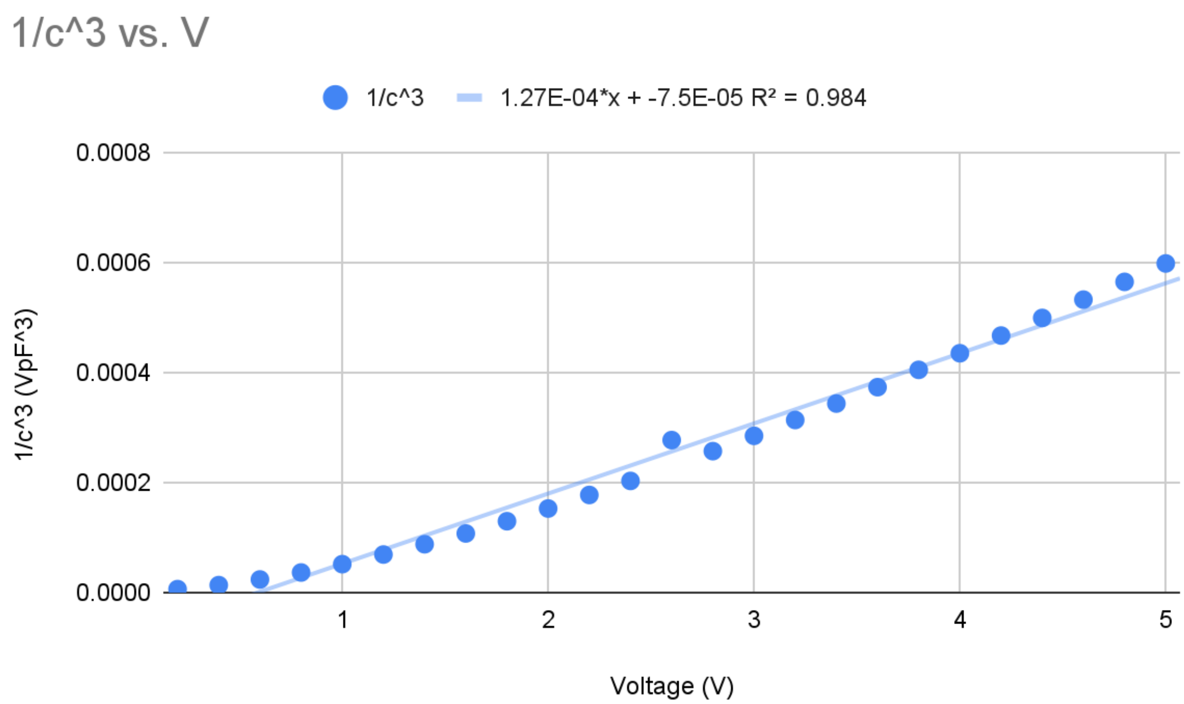


Figure 7

Here, it can be seen that the linear fit is much better for the 1/c^2 y-axis. This confirms that both sides of the PN junction aren't uniformly doped. The model being used is valid because equation 3 is shown to be derived from equation 2 in the event that Na >> Nd. The slope is linear for the 1/c^2 graph, with an R^2 value of 0.997 and an RMSE of 0.000000004352581086. This validates the model due to the almost perfect R^2 value and RMSE being very close to 0. For 1/c^3 the model shows a 0.984 R^2 value and an RMSE value of 0.0003083772041. This shows that the 1/c^2 is truly linear and verifies the use of equation 3 and consequently equation 1.

3. Compare the junction capacitance of the datasheet against what was found experimentally

   From Eq 1, we know that the junction capacitance can be found using the following formula:

$$C_j = \sqrt{\frac{q\epsilon_S}{2(V_{bi}-V_a)}\frac{N_A N_D}{N_D+N_D}}$$

   Given q =1.6*10^-19 C,
   Es = 1.03*10^-12 F/cm,
   Vbi = -0.21398 V,
   Va= 0.589963V,
   Nd=$8.49 * 10\text{^}33\, m^{-3}$, and
   Na= -6.67*10^-13 m^-3.

   We can conclude that the junction capacitance is: 1.85*10^-22 F. From the datasheet, we know that the junction capacitance of the IN4001 diode is typically 15 pF. Looking at this two values, we can tell that our Cj is far from the value we are expecting. This may be as a result of our Vbi value, or other unknown errors in the lab.

4. Plot the DCIV curve and the discharge of the switched 1N4001 diode. Annotate turn-on voltage and which points are used for calculating storage delay.

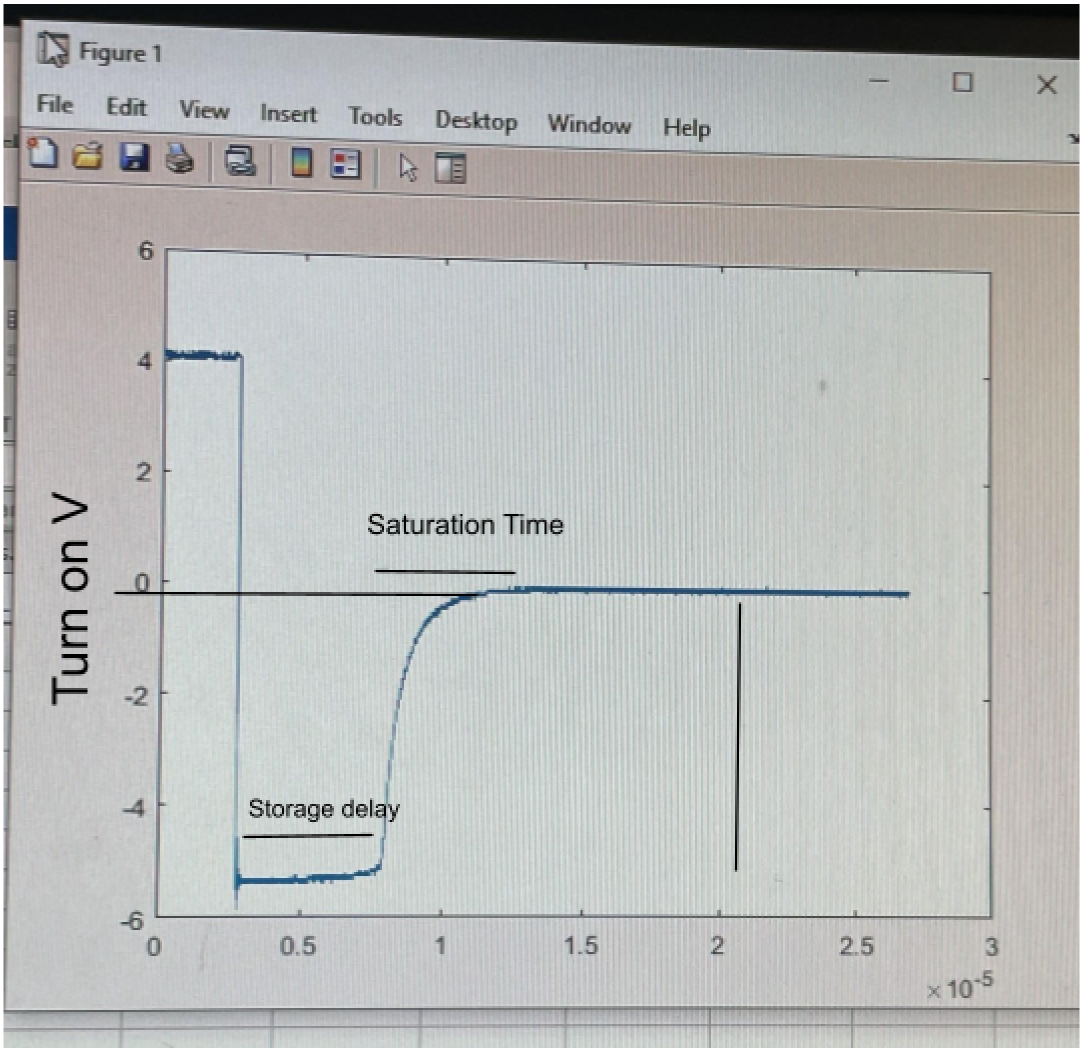


Figure 8

5. Show the small-signal equivalent models of the 1N4001 diode.

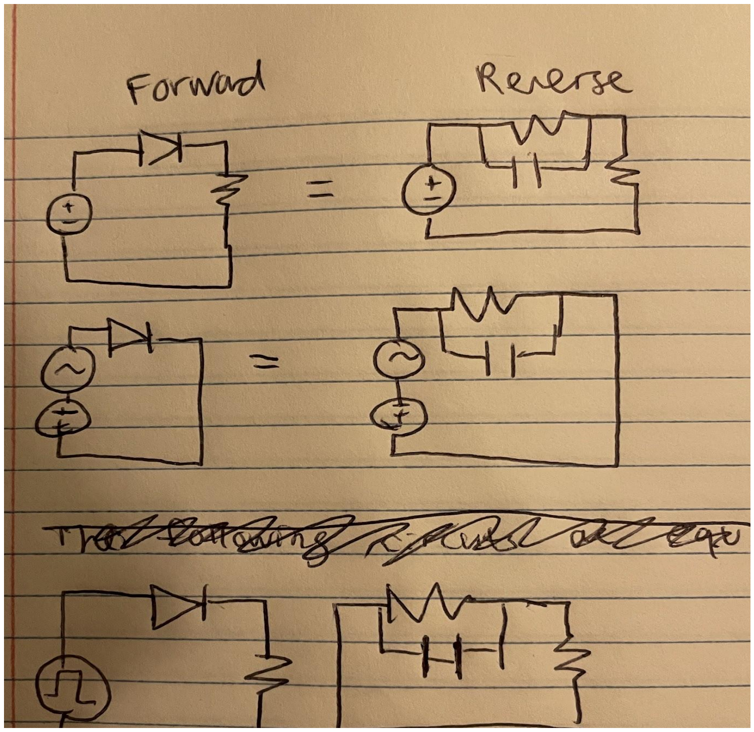


Figure 9

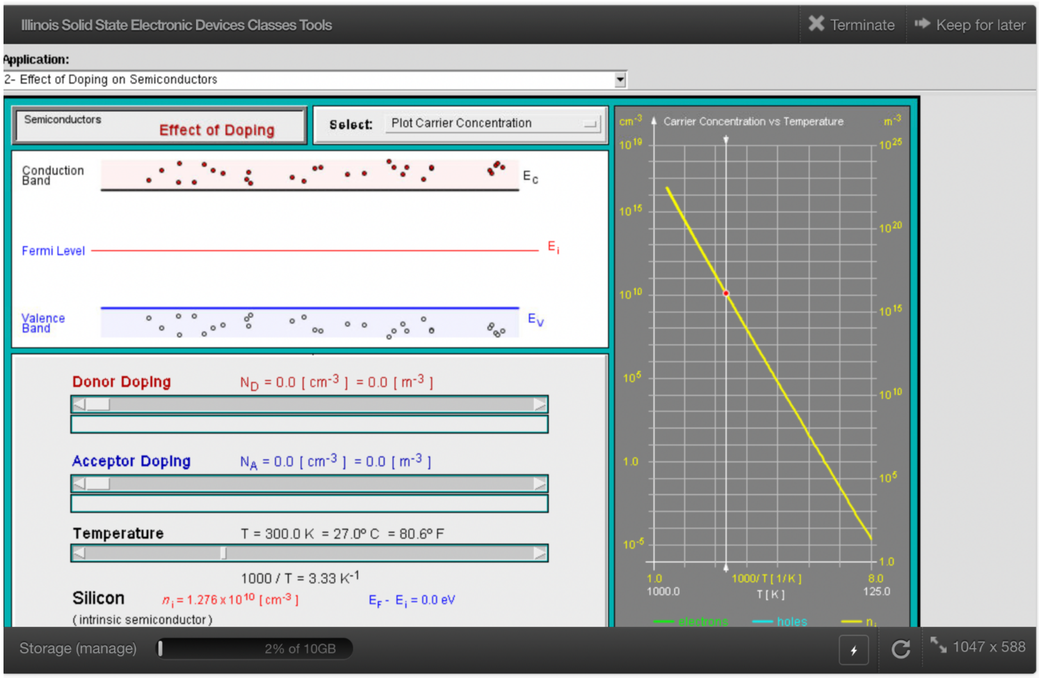
The models above display that in the reverse bias, the diode essentially acts as a resistor. When looking at the 1N4001 diode with binary states, “on” and “off”, the reverse bias in the off state becomes the bottom left circuit. The voltage source is what was stored in the capacitor.

6. How does the turn-on voltage V0 compare to the built-in potential Vbi?

Looking at Figure 8, we can determine that the turn on voltage V0 is approximately -0.3V, which is very close to our calculated built in potential, Vbi = -0.21398V. Therefore, we can conclude that V0 >Vbi.

7. Try to validate results from the experimental procedures with the plots from the NanoHub. Write your interpretation

Fig 8



With large increases in T, there is a significant drop off in the intrinsic carrier concentration as seen by the formula $n_i = E_g/k_B T$.

Works Cited

- **Phonon. *Wikipedia* (2022). Available at: https://en.wikipedia.org/wiki/Phonon. (Accessed: 12th May 2022)**
- **Velocity saturation. *Velocity Saturation - an overview | ScienceDirect Topics* Available at: https://www.sciencedirect.com/topics/computer-science/velocity-saturation#:~:text=At%20high%20fields%2C%20the%20velocity,can%20suffer%20from%20velocity%20saturation. (Accessed: 12th May 2022)**