Lab 2.2: I/V characteristics of Diode [75]

Grand goal:

(a) Design and (b) perform an experiment to determine the exact I/V characteristics of the diode 1N4148 included in your parts kit.
As discussed in the intro session, the relation between current I through a diode and the "bias" voltage V applied across it is determined by the behavior of the depletion region across the internal PN junction.
The 'ideal' diode I/V characteristic is: (from Sze, Shockley Equation)

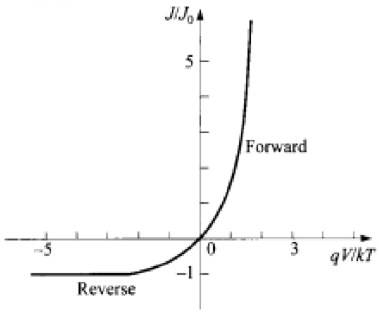


Fig 1: Shockley equation for the I/V characteristic of a diode

Part (A) Circuit Design (to be simulated in LTSpice)

In a simple minded design, you could apply a voltage across the diode, measure the current, make a column-wise table and plot on graph paper. However, we hope you are not so simple minded! Many detailed time-dependent features of the device behavior are easily missed in this old-fashioned method.

Design a clever circuit that allows you to get the I/V characteristic of the diode as a direct plot by plugging it into two nodes in your circuit. Here are some detailed hints:

Practical guidelines:
INPUT:

1) The astable multi-vibrator based 1kHz function generator (FG) circuit from Lab 1+2.1 is a prerequisite (you must reuse that simulation) Successfully building a working FG circuit on your breadboard is a prerequisite for performing this lab experiment.
2) As discussed, current through a two terminal (or any device, for that matter) is rather difficult to measure – it requires breaking the circuit, inserting a current probe in series etc.
   the DSO is our only measuring device, and it only measures voltages. Hence think of a method to *indirectly* measure current through the diode. You can take advantage of the fact that the DSO probes measuring voltage have effectively ∞ input impedance and will not take any current out of your circuit.

GROUND REFERENCE (EXPLAINED IN DETAIL IN THE LAB KICKOFF SESSION):

1) A crucial feature of the FG circuit is that it is powered by a 9V battery. The potential difference across the battery terminals is 9V. In the circuit design, we have explicitly set the negative battery terminal as a 0V reference to solve KVL/KCL. There is a triangular 'GND' symbol we put into the LTSpice simulation corresponding to this 0V reference. It is a program limitation of LTSpice that requires us to put this triangular symbol indicating 0V reference. The output swings between $+V_{out}$ and $-V_{out}$ *with reference to this chosen 0V reference.*
   In practice, the circuit would work fine if there was no such abstract symbol indicating 0V. However, when you practically try to measure the voltage at any node (with DSO or DMM), that voltage is w.r.t. some 0V. The only 'absolute' 0V reference in the circuit is the one defined by the readout device: the black terminal of the DMM or DSO probe wherever you choose to connect it later.

SIMULATION TIPS:

By default, LTSpice plots probe voltages as a function of time. However, you can replace the time axis by right-clicking on it and setting it to some other node voltage. Thus you get a plot of voltage at node 1 v/s voltage at node 2 (the solution is obvious once you crack what is 1 and 2)

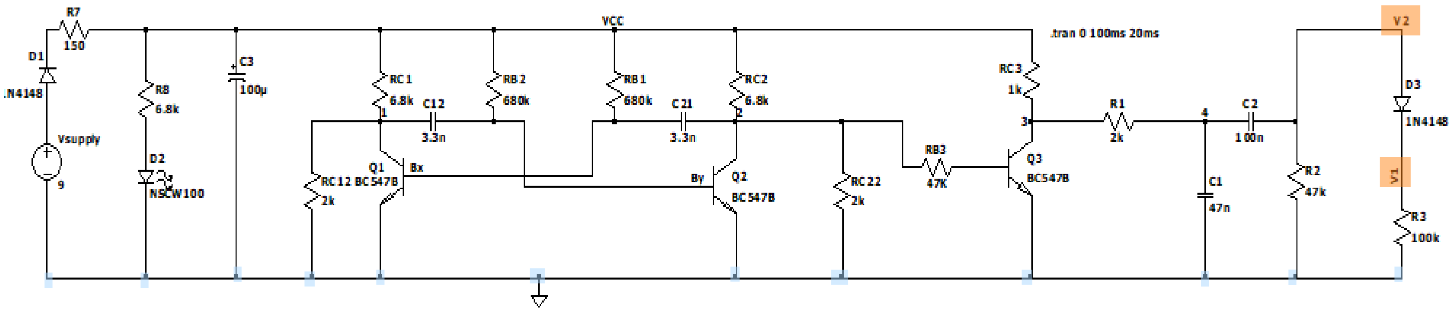
Please make sure to NOT tweak anything within the design of the astable multivibrator circuit done before. That 1kHz FG should be kept as a fixed baseline input for this and all future labs.
For this lab, you can omit BLOCK_5 (the resistor divider). You will get the maximum swing of VOUT allowed by the FG. This is required for performing this experiment to sweep V over as large a range as possible and obtain the I/V characteristic shown in Fig 1

A.1) Basic circuit design for measurement of diode I/V characteristic diode **10**

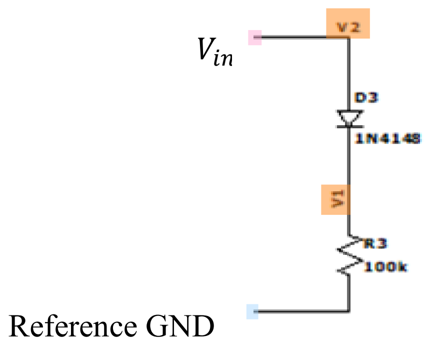
Put your LTSpice circuit design diagram here. Highlight (a) the absolute ground location (b) the new components added and (c) the voltages to be measured. Note that two quantities are to be measured to obtain the I/V characteristic: Current through the diode, and the voltage across the diode.

You can only use the voltage probe in LTSpice:  because that's all you can do with your DSO

Usage of the current probe is **not allowed**: 
For simplicity, you can enclose the entire FG circuit from Lab 2.1 into one box, and magnify the parts relevant to this Lab 2.2



Block being analyzed-Magnified:



(a) The nodes highlighted in blue are the reference ground. These need not be at 0V but all other voltage measurements are done relative to these.
(b) The new components are separately cropped out and shown above. They are the diode to be studied in series with a high resistance.
(c) The voltage across the resistance is what will allow the indirect current measurement. Thus, the voltages to be measured relative to the reference GND are V1 and V2 (highlighted in orange).

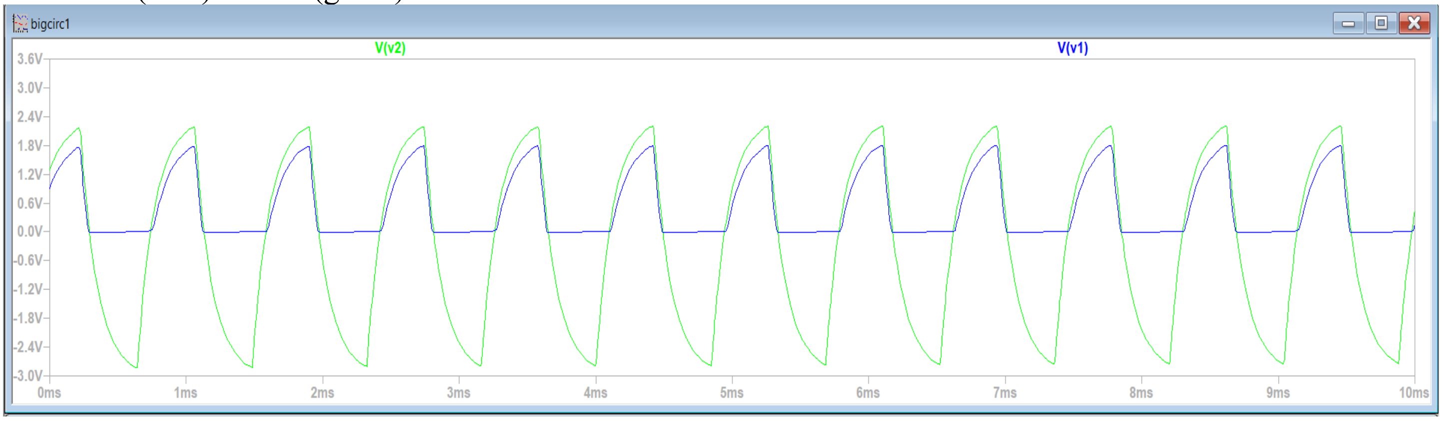
A.2) Plot the expected results from the above simulation.

Provide two simulation result plots:

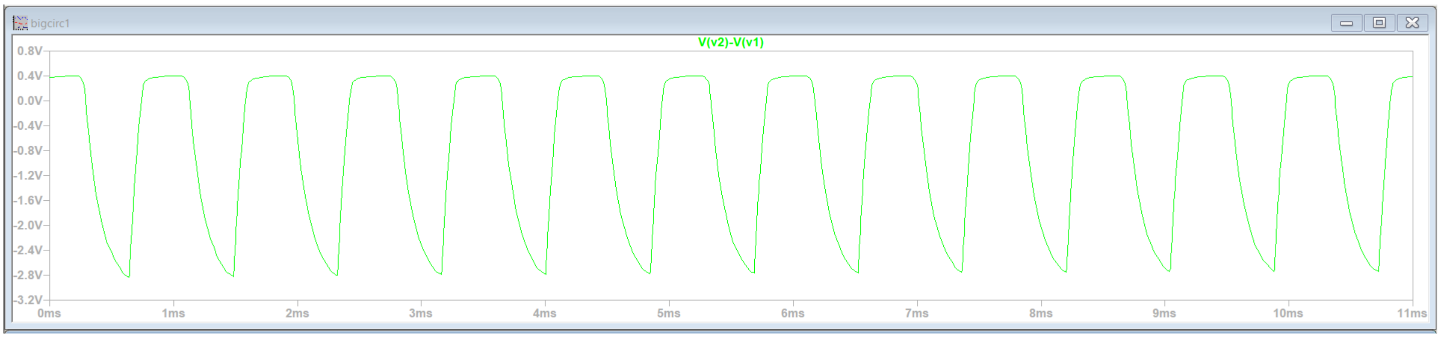
A.2.1) Basic time domain analysis: two measured voltages plotted as a function of time **5**

Using the DSO we can measure V1 and V2 individually with respect to reference GND. We can also measure V2-V1 which is the potential drop across the diode.

Plot of V1(blue) and V2(green)



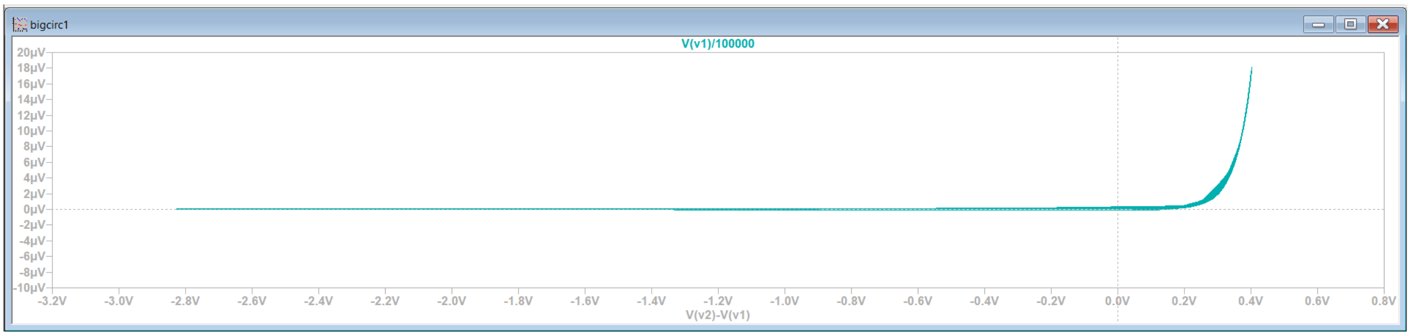
Plot of V2-V1



A.2.2) Use the trick mentioned above to plot one voltage against the other. Rescale the relevant axis to get a direct I/V measurement **5**

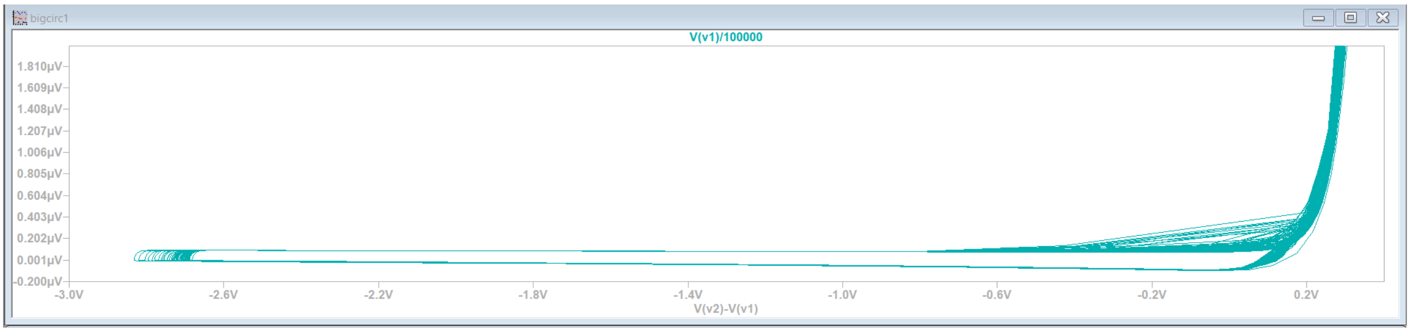
Note: I/V characteristic obtained from LTSpice must be plotted in the 1st and 3rd quadrants, else -3 marks.

The graph of V1 v/s diode voltage V2-V1 gives the I-V characteristic. Next, applying Ohm's law we rescale the y-axis: (then the numerical values shown on y-axis must be written with unit ampere to give current) The diode current $I_d = \frac{V2}{R3}$. Here, $R3 = 100k\Omega$. Thus, the rescaled y-axis must plot $\frac{V2}{10^5}$.



A.2.3) Do you observe any deviation from the expected Shockley equation I/V characteristic (Fig 1) in your simulated circuit measurement of Q2.2? If so, explain the reasons for the deviation.

(you may have to do some advanced reading from Sze to answer this question) **5**



The diode deviates from the Shockley equation I/V characteristic. The I/V curve is not one curve but several closely placed curves. The voltage oscillates (approximately) between +2.5V to -2.5V. There is a lag between the diode current increase/decrease as the voltage increases/decreases. This is due to a combination several effects. Derivation of the Shockley model takes some assumptions which idealize (thus simplify) the model. Given below are the assumptions with a brief explanation on how the real system deviates from them:

1) The abrupt depletion layer approximation assumes that the voltages are supported by a dipole layer of with abrupt boundaries outside which the semiconductor is neutral. This is false and the finite gradient of charge carriers leads to a more diffused depletion region. This leads to slight delay in rise and fall of diode current with external voltage. This is sort of like a hysteresis effect.
2) Ignores surface currents. There are also surface effects due to ionic charges leading to the so-called surface depletion layer regions. This leads to surface leakage currents.
3) Current due to recombination-generation is ignored, which are very small compared to diffusion currents but non-zero.
4) High-injection densities of minority carriers assumed to be zero may actually become significant when the diode id forward biased.

Quantum mechanical tunneling effects and breakdown are seen at large reverse voltage so for our circuit we don't have to worry about these.

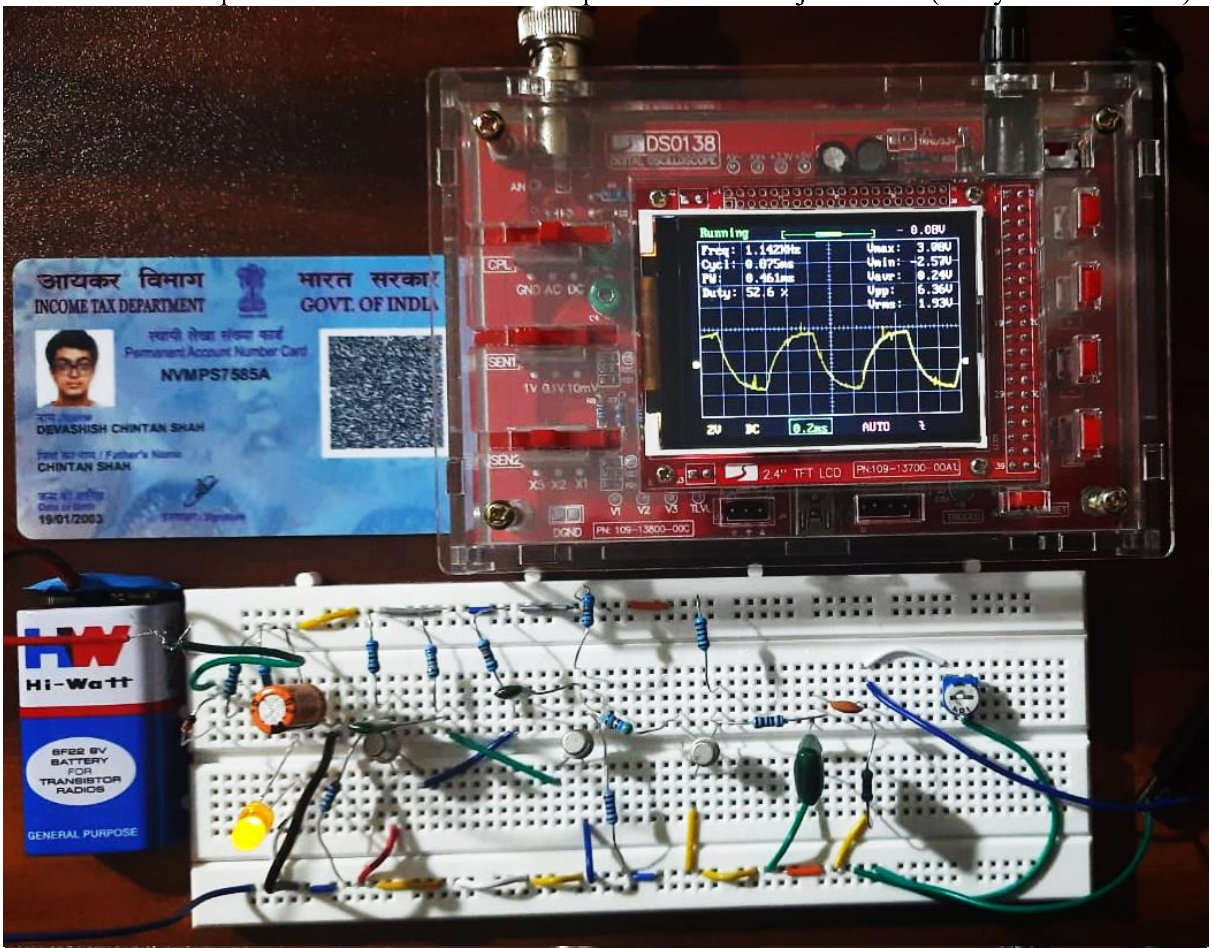
Part (B) Circuit Build and demo: I/V of diode 1N4148

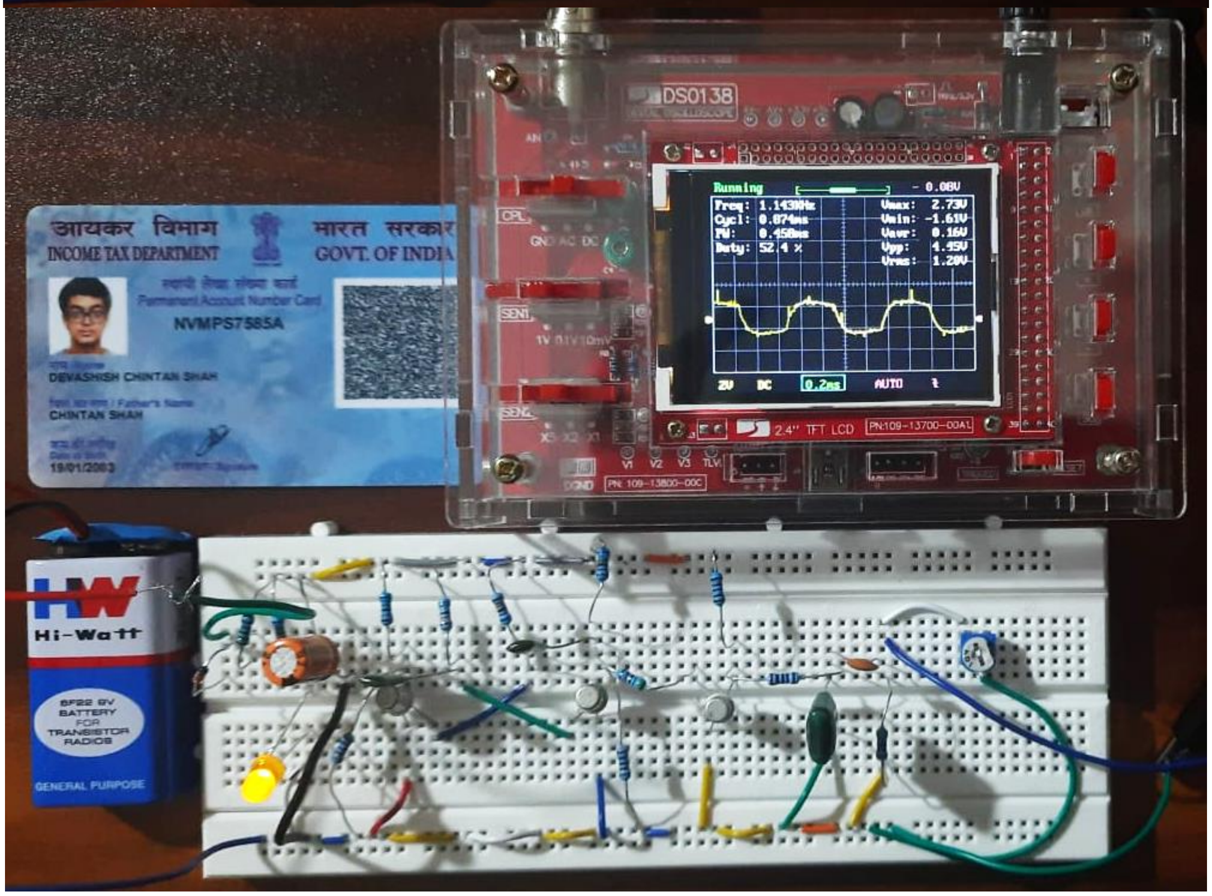
Now that you have a confidently designed circuit with a clear idea of what to measure, build your circuit on the breadboard.

B.1) Put a photo of your breadboard with built up waveform generator circuit from Lab 2.1 with the measured output 1kHz on DSO **10**

Note: your photo must include the breadboard, the battery, the DSO display showing working waveform *and your photo ID placed next to the breadboard*

Given below are two output waveforms for different potentiometer adjustments (analyzed in lab 2.1):





B.2) Oh no! you realize that your DSO has only a single analog input, so you are only able to probe one voltage at a time!

The trick of being able to measure current and voltage simultaneously has been cracked in circuit design of A.1. You have time domain simulation plots from A.2.1 – two voltages, but one of those voltages corresponds to the diode current as plotted in I-V characteristic of A.2.2 Hence it is still possible to interpret the measurements and get precise quantitative answers, including the time-domain behavior of the device that would not be possible with the old-fashioned [measure, write, plot-on-graph, fit curve] method.

Provide photos of your measurements (DSO screen, photo id, breadboard) – use as much space as required below to get zoomed in photos of the DSO screen so details of the measurement are clearly visible.

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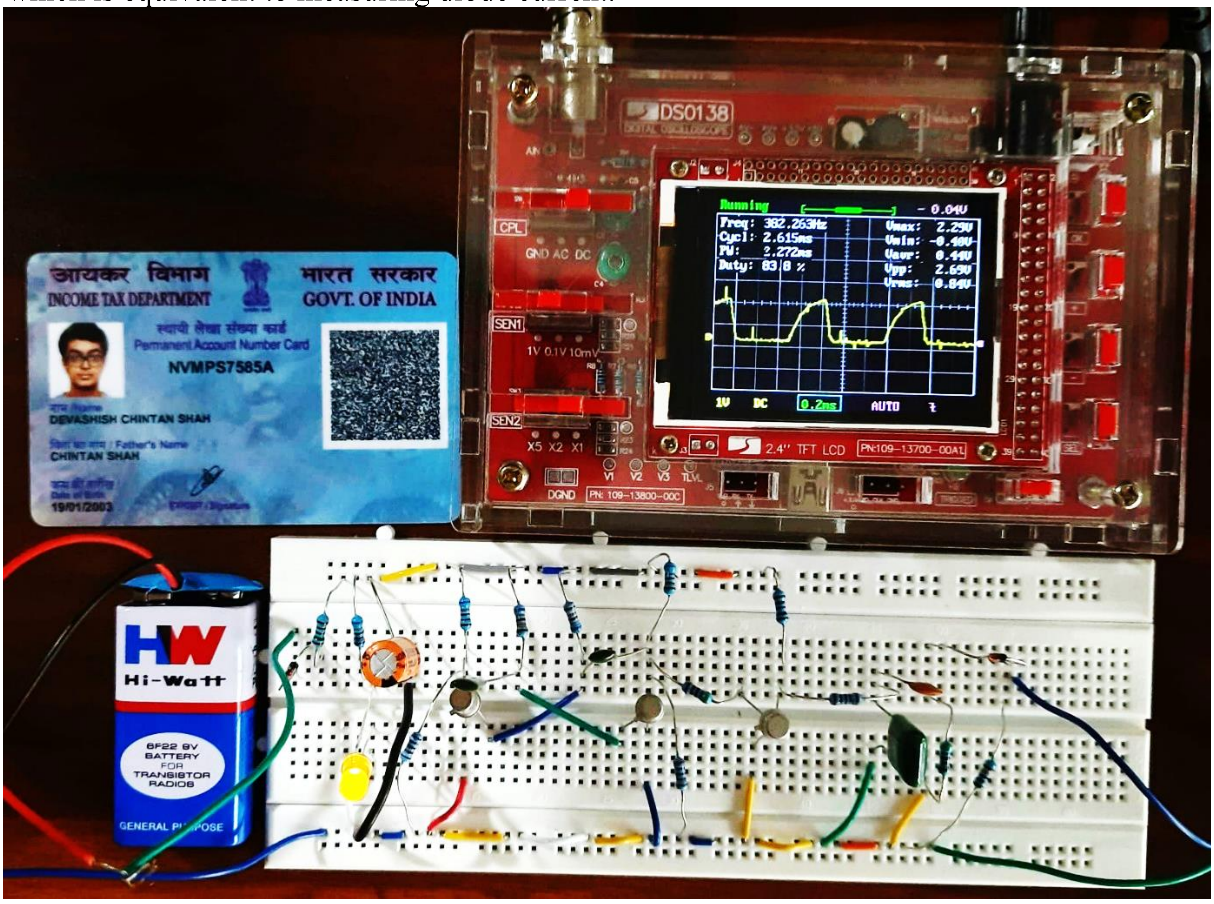
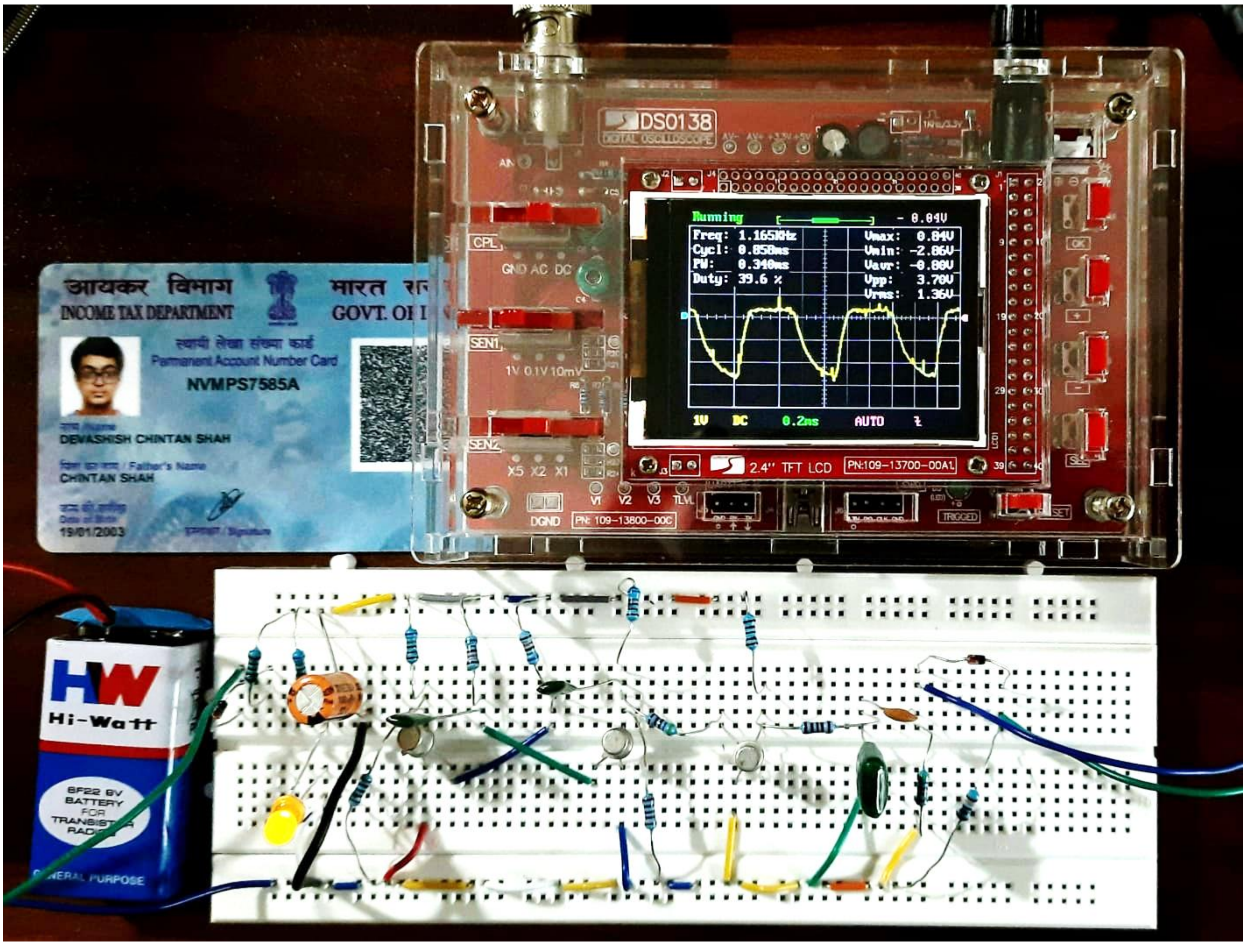
*DSO only measures voltages as a function of time you will have to fine tune the trigger settings to get a stable measurement. Highlight on your photos, the region where the diode is in forward and reverse bias. We are primarily interested in the **diode current** as it's terminal voltages swing back and forth between forward and reverse bias.*

Provide an overview photo of your experimental setup here, with diode current (measured as a voltage) here: **15**

Since we are primarily interested in diode current as a terminal voltage swings, we measure voltage across resistor which is equivalent to measuring diode current.



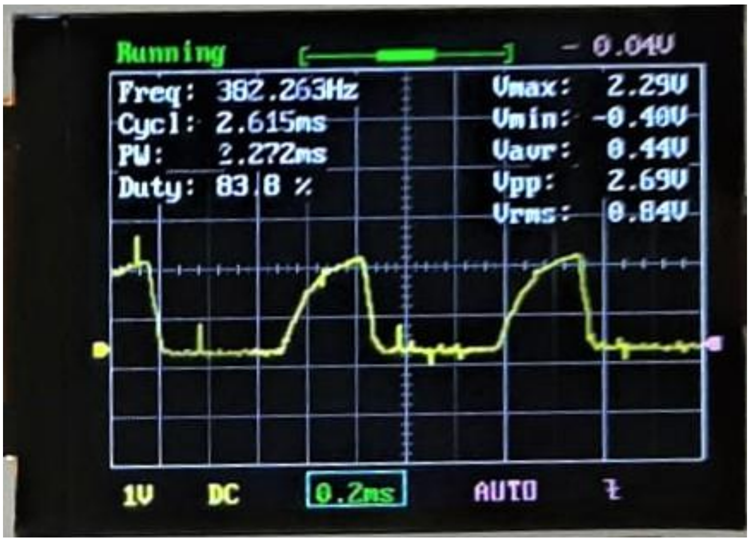
Further questions use measurements of diode voltage (V2-V1). Setup shown below.



Provide zoomed in photos of your DSO screen for the following questions.

B.2.1) What is the maximum forward current $I_{max|forward}$ up to which your circuit is able to drive the diode in forward bias? **5**

$$I_{max\,|forward} = \frac{V2_{max}}{R3} = \frac{2.29V}{100k\Omega} = 22.9\mu A$$



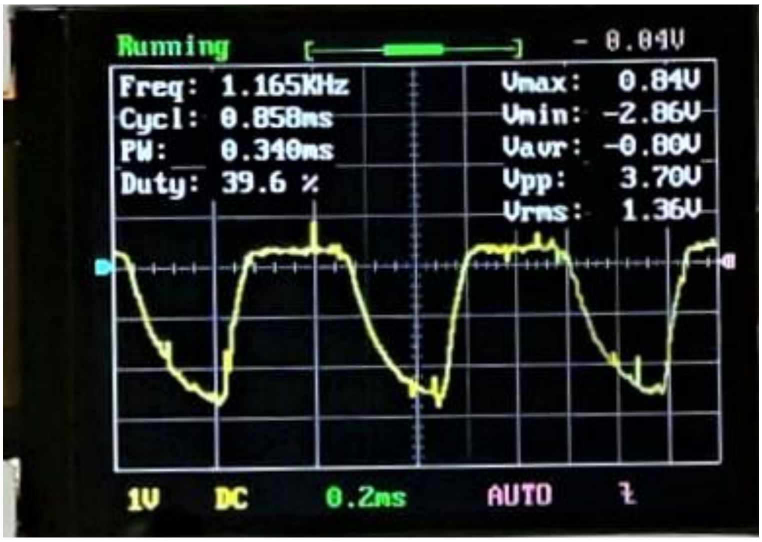
2. Correspondingly, what is the maximum forward bias voltage at $I_{max|forward}$? **5**

The DSO registers the sudden spike as max voltage:

$V_{\text{max |forward}} = 0.84V$

But the overall max voltage (height of plateau) is clearly:

$V_{\text{max |forward}} \simeq 0.4V$



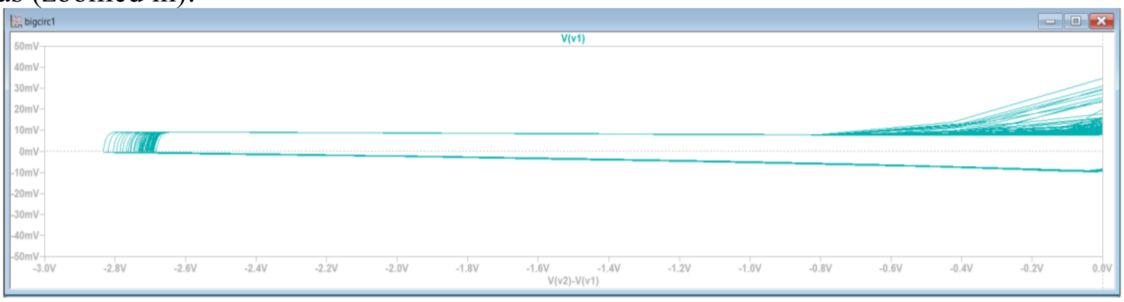
3. What is the maximum reverse bias voltage applied to the diode? **5**

$V_{\text{max |reverse}} = -2.86V$

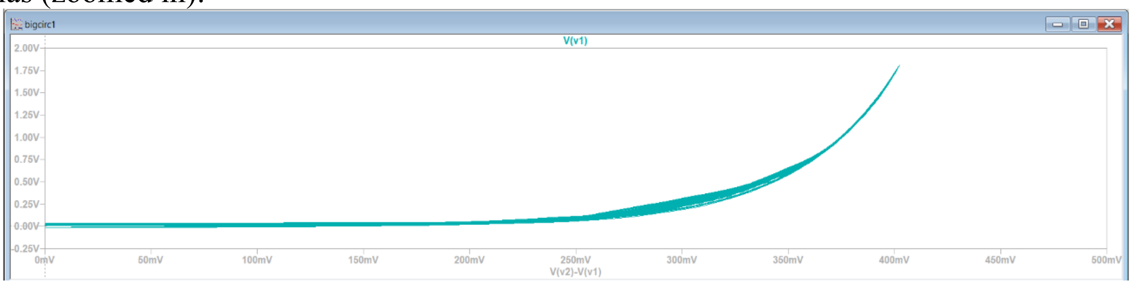
4. When the diode bias voltage falls below the turn on threshold, does the diode current fall to Immediately as expected from theory? If not, why not? When the bias voltage goes to reverse bias, do you observe opposite sign leakage current in the diode in the 3rd quadrant of I/V as shown in Fig 1 ideal Shockley diode equation? **10**

No, the diode current doesn't fall as soon as voltage falls. Unlike in the ideal case, the real depletion region doesn't have an abrupt boundary. When the diode voltage falls there is a certain delay in the diode current fall which in the ideal case is expected to be instantaneous. This is similar to a hysteresis effect due to delayed response. The diode I/V curve thus forms closely spaced loops.

Reverse bias (zoomed in):



Forward bias (zoomed in):



Yes, when the bias voltage becomes negative and diode becomes reverse biased an opposite sign leakage current is observed.