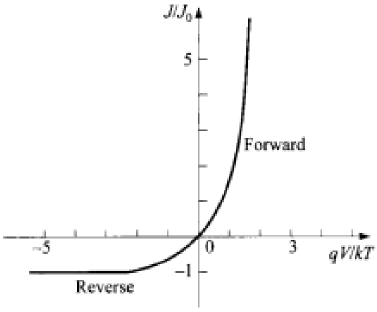
Lab 2: I/V characteristics [70]

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 last 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)



Part (A) Circuit Design

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:

1) The astable multi-vibrator 1kHz square wave circuit is a prerequisite (you must reuse that simulation. Some components may need to be added on)
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.
3) A crucial feature of the astable multi-vibrator circuit as built is that it is powered by a 9V battery. Hence the output swings between ~9V and ~0V. There is a triangular 'gnd' symbol we put into the LTSpice simulation to allow KVL to be computed. But this 0V is NOT an absolute ground!
4) The only 'absolute ground' in the circuit will be the black terminal of the DSO probe wherever you choose to connect it later.
5) 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)

There are three levels of design possible, each of which allows you to examine the behavior of the actual I/V characteristic of the diode 1N4148 in great time dependent detail, even though you're working at a fixed 1kHz frequency.

Please give your design, circuit simulation and experimental results in the spaces provided below:

In all the designs, please make sure to NOT tweak anything within the design of the astable multivibrator circuit done before. That 1kHz square waveform generator should be kept as a fixed baseline input for this and all future labs.

Level 1: Basic circuit design for measurement of I/V characteristic of diode 1N4148 characteristic

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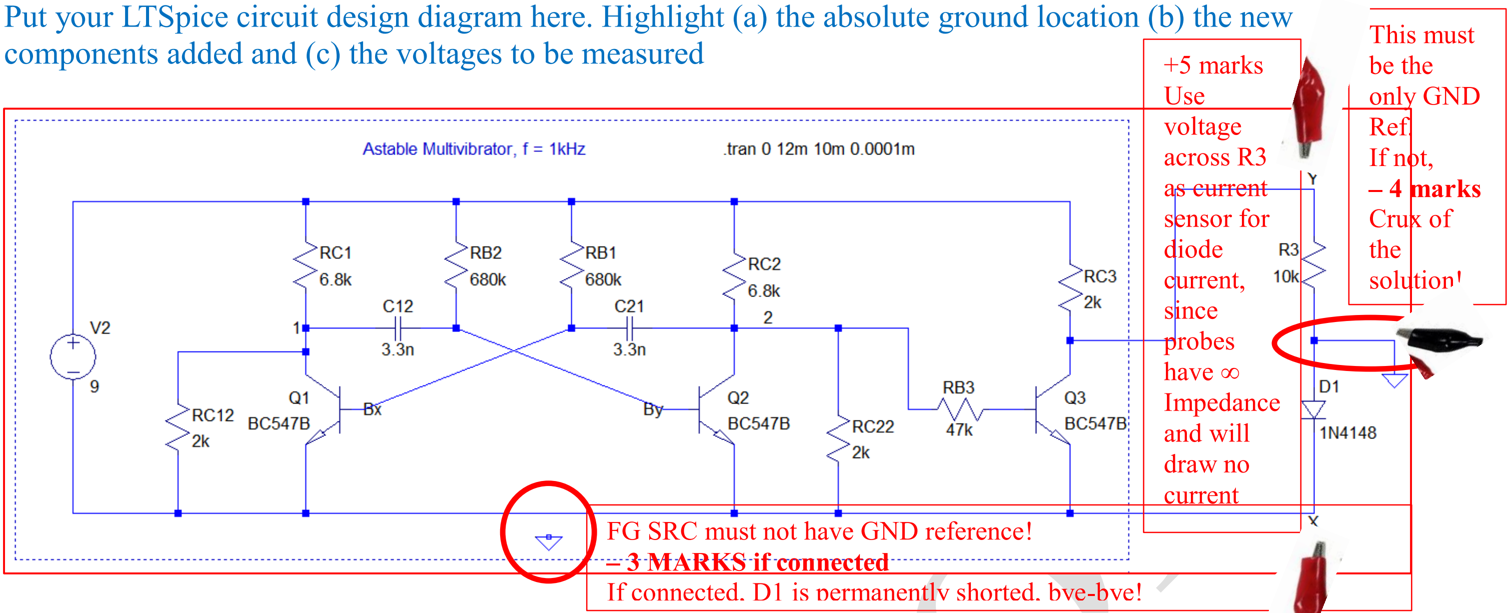
Put your LTSpice circuit design diagram here. Highlight (a) the absolute ground location (b) the new components added and (c) the voltages to be measured



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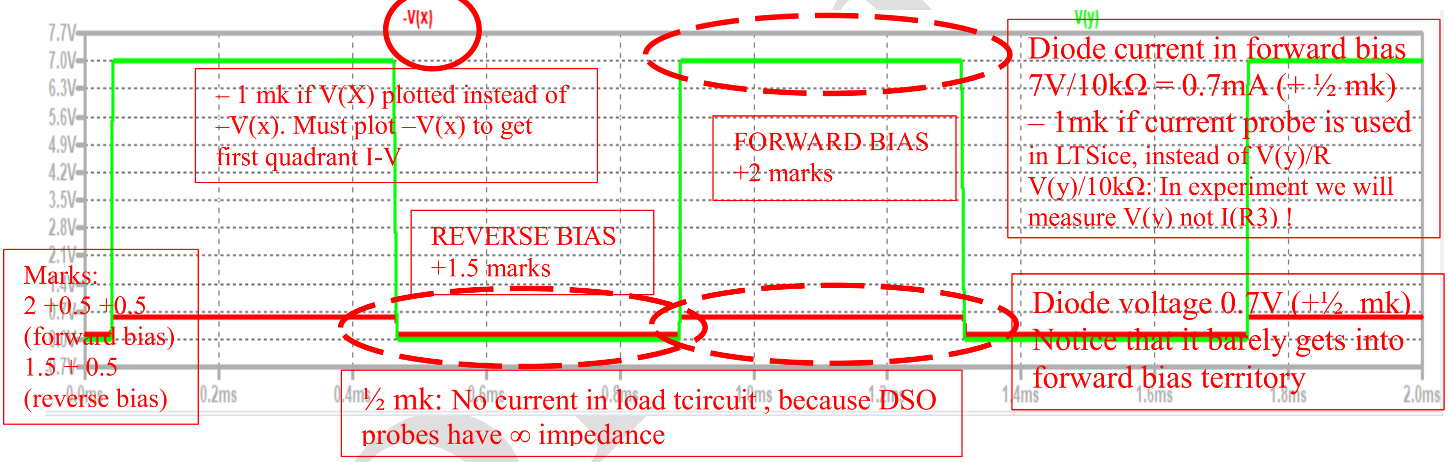
Plot the expected results from the above simulation.
Highlight using the graphics tools in Word the regions of diode going into forward/reverse bias.



Explain any unusual features observed in the simulated diode characteristic (you may have to do some advanced reading from Sze to understand this, or it may become clearer when you solve later parts

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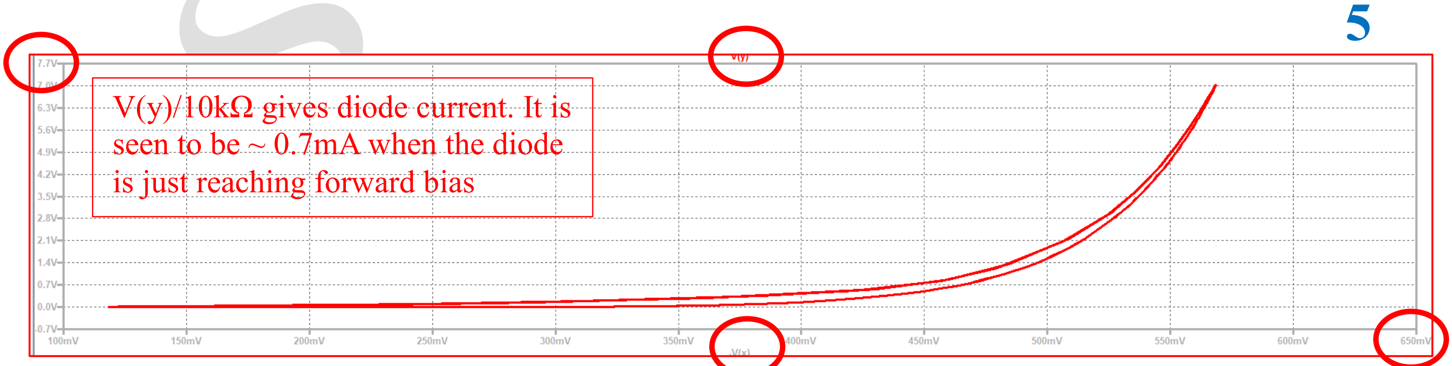


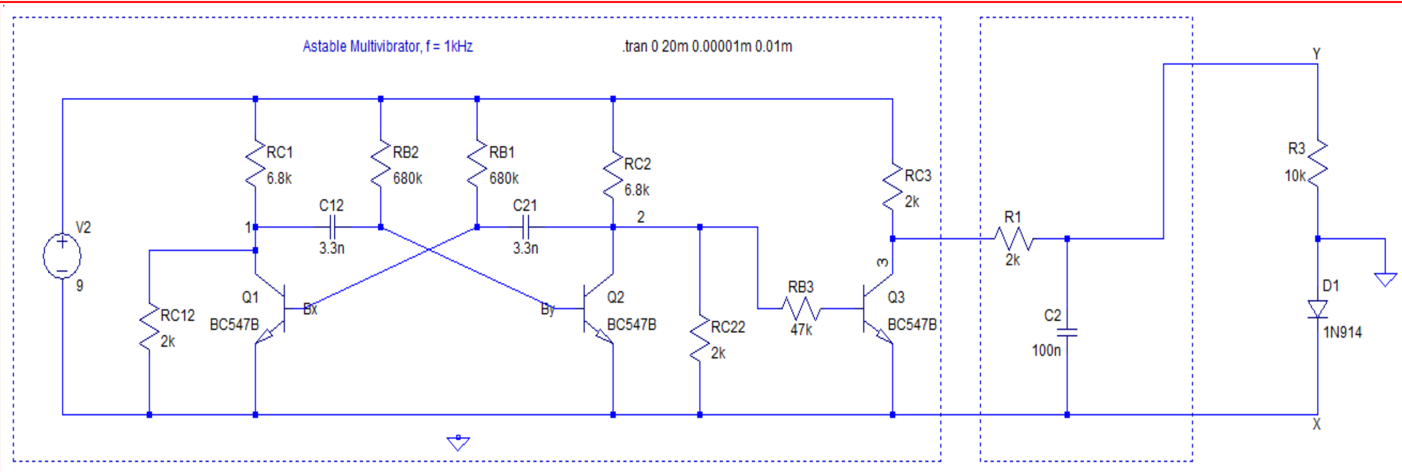
+4 marks: main trick of changing x-axis from default time to –V(x) to get direct I-V characteristic
-1 mk: if V(x) is used instead of –V(x) will get I-V in 2nd quadrant which is meaningless!
+1 mk: if 'hysteresis' behavior understood and explained. Transition with sq wave drive is too fast to discharge diode capacitance on way back from from just reaching edge of forward bias.

Level 2 Design 5

You can get an idea from the basic design that the square waveform generator is trying to slam the bias voltages across a device (diode) which has inherently finite switching time. This can cause problems… Add some basic filtering to the output of the square waveform output to get a more 'realistic' diode I/V characteristic closer to the ideal shown on pg 1.

Hint: The problem with the basic circuit setup of Level 1 is that you slam the diode voltage to full forward bias with a step function. Think about the pen-paper type of measurement: ideally you would like to increase/decrease the diode forward voltage gradually and observe the corresponding diode current (Also refer to Sze notes to understand any artefacts you observe from simulation at Level 1)

Put your circuit design and its corresponding simulated output plots here



+2 marks : Add RC integrator at output of square waveform to smooth the rate of increase/decrease of bias voltage applied to diode

Any reasonable value of R1,C2 that doesn't load the source is OK

+ 1 mark : Single point reference chosen correctly at R3,D1 – this is the crux of the solution

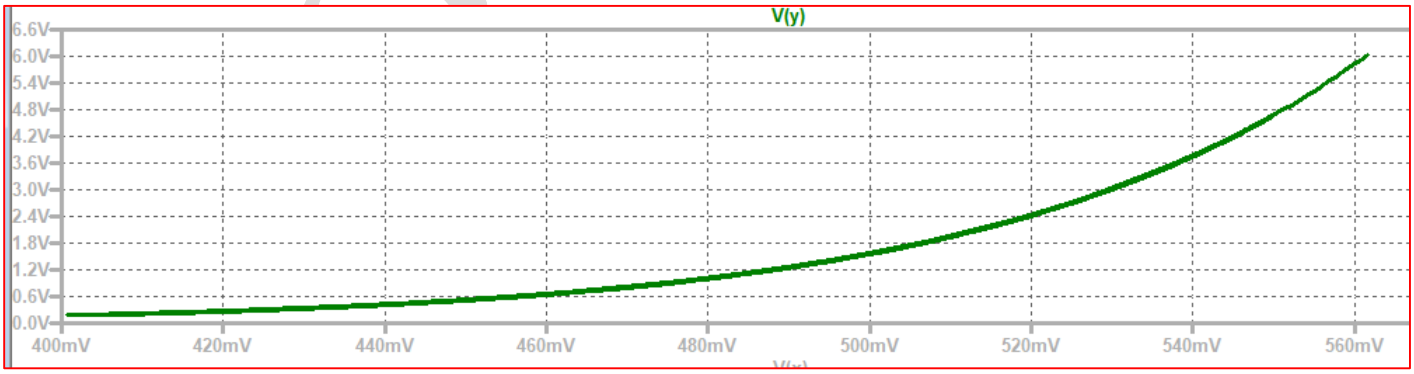
If source is separately grounded, the whole idea doesn't work!

+1mark: V_Y(t) and –V_X(t) shown correctly (sawtooth shaped) due to R1,C2 filter action

+1 mark: V(Y) v/s –V(X) mapped to **I_{D1}/V_{D1}** shown correctly as below

V(Y)/-V(X) now looks close to ideal (no hysteresis) because of slow transition of diode bias

V_Y(t), -V_X(t) needed because that's what we will be measuring directly on DSO



-1 mk if +V(X) is used instead of –V(X) – I/V characteristic in 2nd quadrant is meaningless!

Level 3 Design 5

By this level, you should have understood the full constraints of smoothly varying the diode bias voltage to measure its current as it enters/exits the different modes of operation. With this big picture in mind, design a complete end-to-end circuit you can build starting with the 1kHz square waveform generator to determine the full I/V characteristics of a two terminal diode 1N4148.

As before, highlight carefully the new parts added, and the measurement points

<u>Hint:</u> Level 3 design is expected to be slightly more complex than Level 2 (and hence Level 1): the main issue we want to attack is that we want swing the bias voltage across the diode between positive and negative bias, preferably at the *same* rate to observe experimentally the I-V characteristic in 1^{st} and 3^{rd} quadrants of the I-V plot and any time-dependent features as discussed in Sze

Put your circuit design and its corresponding simulated output plots here:

Note: Students may use different Node labels (or default n00x) labels – don't cut marks for that

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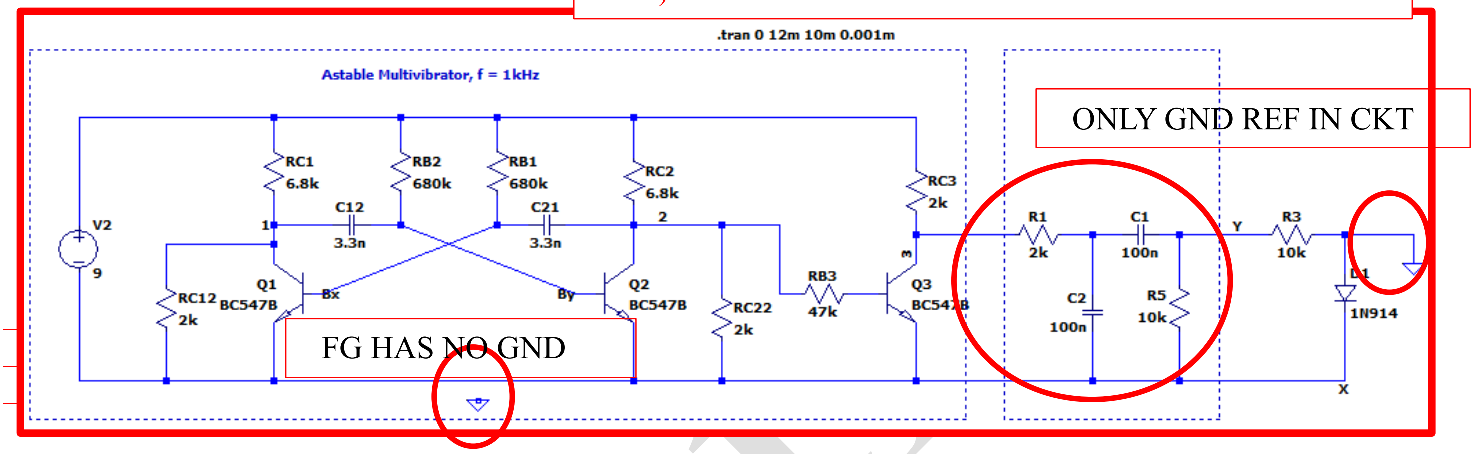
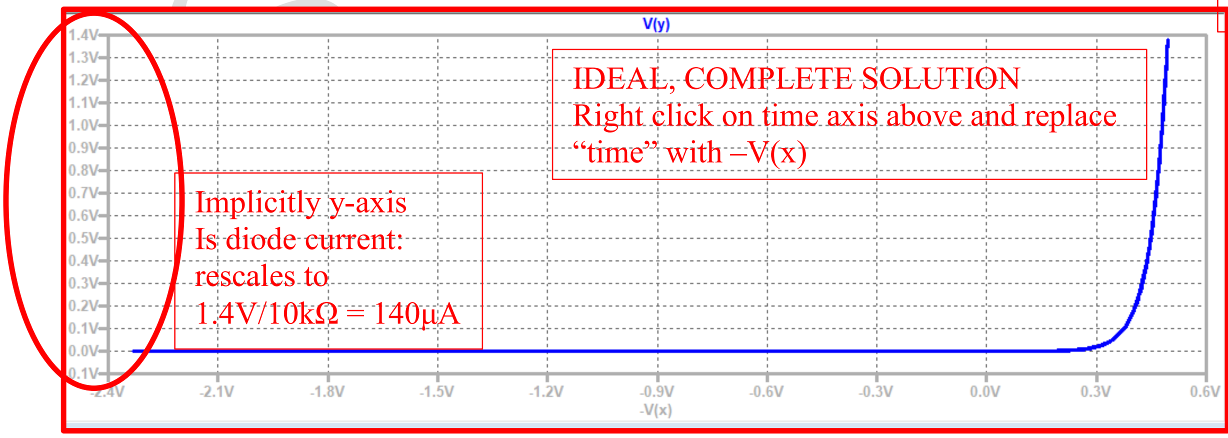


Time domain waveforms: Note there is initial charging transients in first 10ms due to C2.
Best solution sets simulation cmd to run for 12ms, and save/display data only after 10ms to get 1 diode cycle

+3 MARKS: R1,C2 + C1,R5 filters used to get both positive and negative bias to D1
+1 mark each for time domain and I/V characteristic result



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.
You should already have the 1kHz square waveform generator from Lab 1 built-up on your breadboard.

B.1) Put a photo of your breadboard with built up astable multi-vibrator circuit from Lab 1 with the measured output 1kHz on DSO **10**

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

This is basically the circuit building exercise of putting Lab 1 into practice
Breadboard configurations may vary among students

Picture MUST have student's ID card in the frame

– 2 marks if the breadboard looks like a 'rat's nest'

– 2 marks if ID card is missing

B.2) As in B.2, provide a photo of filtered output from circuit you have built based on design Level 3 of Part A to drive the I/V characterizer **5**

Expected output of standardized circuit put up for students has $f = 1.17\ kHz$
Exact value of f may vary depending on component tolerances and amplitude will depend on choice of R1,C2 + C1,R5 filter components

B.3) Egad!! you realize that your DSO has only a single analog input, so you are only able to probe one voltage at a time! The simulated output of plotting one voltage against another was a pipe-dream! Or, was it?? **(25)**

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, ID card, omit breadboard for this one – you will need to examine details of the measured waveform on your DSO screen)

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

Level 1: V(Y) shows peak forward current 5.72V/10kΩ = 0.572mA (was 0.7mA in LTSpice)

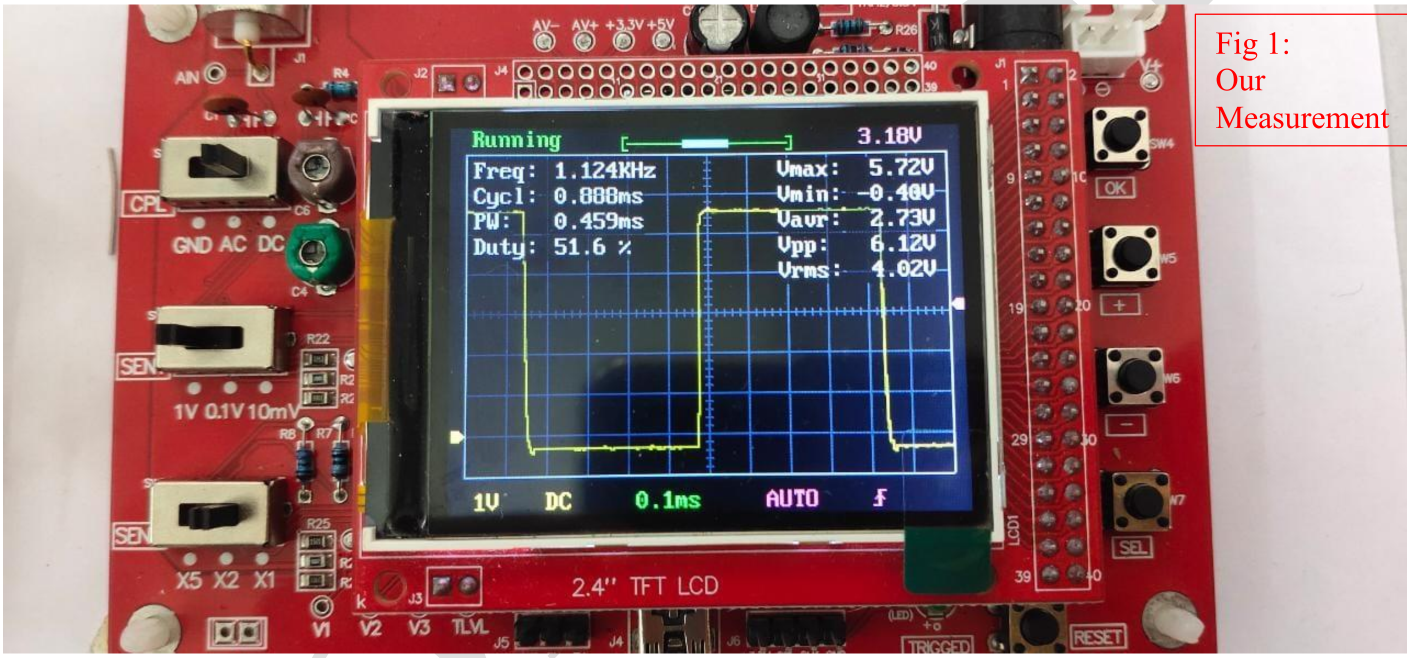


Fig 1: Our Measurement

Note: 25 marks are for showing photos of DSO measurements for Level 1 (7 marks), Level 2(7 marks) and Level 3(14 marks), with ID card in the frame.

Ideally, put a zoomed in photo of your DSO screen so that the measured values are clearly seen.

Exact values of the measurements may vary among students depending on their local setup, battery conditions, noise levels etc but should roughly match the order of magnitude of the ones seen in the photos shown here as reference. Comparison to LTSpice simulated values should roughly match, as pointed out in our measurements below. For example, currents should be in mA range, NOT µA or nA range! Voltages should be in <1V range for forward bias (obviously!)

Level 2: V(Y) shows peak forward current 3.7V/10kΩ = 0.37mA
(only 1st quad I/V possible in Level 1 and Level 2

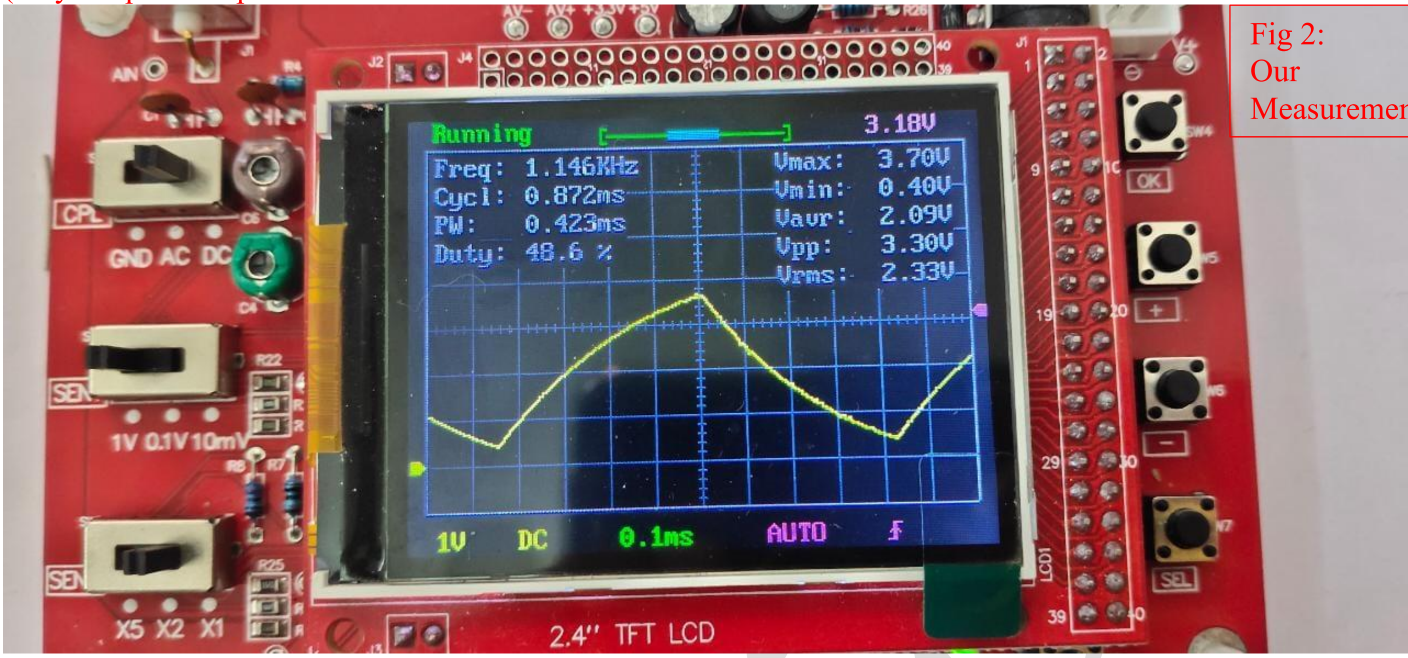


Fig 2:
Our
Measurement

Level 3: Now the diode is biased into both forward and reverse range, hence V(X) indicates peak Voltage of 0.6V (was 0.560V in LTSpice) and peak reverse voltage of 1.79V (was 2.4V in LTSpice)

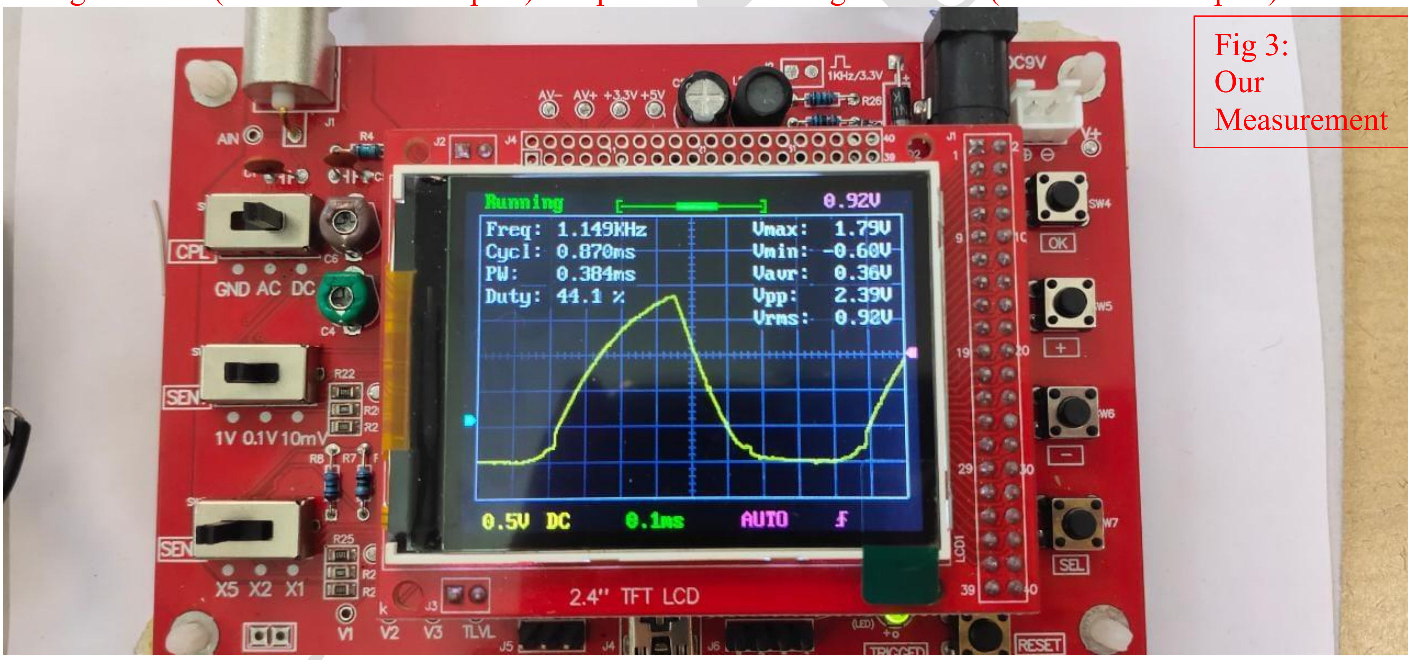


Fig 3:
Our
Measurement

Note:
In the DSO we are unable to invert the voltages displayed on screen (so easy in LTSpice!)
So the interpretations below require a negative sign to be put in explicitly. For example, in Level 3 shown above with our lab built circuit (Fig 3), the diode reaches a peak **reverse** bias of 1.79V and a **forward** bias of 0.60V

Interpret the voltages you are able to measure using single DSO probes sequentially (take separate photos to be put in above). Determine the following measurable quantities:

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**

~ 0.572mA in Level 1, expected 0.7V from LTSpice (sq wave) [Fig 1]

~ 0.37mA in Level 2, expected 0.56V in LTSpice (sawtooth)[Fig 2]

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

0.6V (our measurement, Fig 3)

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

–1.79V (our measurement, Fig 3)

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 pg 1 ideal diode characteristic? **10**

Essentially, main point is that the diode in reverse bias has a deep depletion region which effectively acts like a dynamic capacitance across the junction. The depletion zone consists of immobile atoms with opposite charge on either side of the junction. Thus sending the diode into reverse bias is like charging the junction capacitance. Bringing it back into forward bias (where the depletion zone shrinks to near zero is like discharging the capacitance. **6**

The 1N4148 is a 'small signal diode' expected to switch at ~ ns time scale so the charging/discharging effect is just barely perceptible in the X/Y LTSpice simulation plot @ 1kHz. Very difficult to observe this in the experiment! Especially on the DSO138 without the X/Y plotting capability. **2**

For comparison, you could try the other diode 1N4007 included in your kit. That is a power rectifier diode – it's main application is in a bridge rectifier to convert AC to DC voltages. So that diode is specified to operate at a slow 50/60Hz frequency. The I/V switching hysteresis should be more pronounced and observable in the 1N4007 **2**