GEBZE TECHNICAL UNIVERSITY ELECTRONIC ENGINEERING

ELEC-237

ELECTRONICS LABORATORY-I

EXPERIMENT 3

Junction Diode Basics

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Theorical Informations about Diodes

A diode is a semiconductor circuit element that basically functions as a one-way switch for current. It allows current to flow easily in one direction but severely restricts current from flowing in the opposite direction. The positive pole of the diode is called the anode, and the negative pole is called the cathode.

→ Diodes are basically divided into two groups:

I. **Rectifier Diodes**
II. **Signal Diodes**

Rectifier diodes are used in power supplies to convert AC currents to DC. They can carry high currents and withstand high reverse peak voltages. However, they are generally used in low frequency circuits such as 50-60 Hz.

Signal diodes are used as a logic (digital) circuit element or as a demodulator (signal splitter) in radio frequency (RF) circuits. In other words, signal diodes can operate at low voltages and currents as well as being sensitive to operating at high frequencies.

Rectifier and signal diodes can be made of silicon and germanium. When current is passed through diodes made of germanium, there is a voltage drop of about 0.2 Volts, while this value is around 0.6 to 0.7 Volts for diodes made of silicon. Because of this difference, germanium material is mostly used in the construction of signal diodes.

Simply the working principle of the diode:

Diodes are formed from PN junction by combining two separate semiconductor materials, n-type and p-type.

At the intersection of these two semiconductor materials, a depleted (neutral) region is formed. This neutral region acts as an insulator and does not allow any current to flow. When a positive voltage is applied from the positive side to the negative side, the neutral zone between the two materials disappears and the current starts to flow from the positive pole to the negative pole, that is, the diode conducts.

When a voltage is applied from the other direction, that is, from the negative side to the positive side, the neutral zone expands and resists the flow of any current, but a small amount of current flows. This current is called leakage current. If the amount of voltage applied in the reverse direction is high enough, the diode will break down, allowing the current to flow in the reverse direction as well.

Diode Action

1.1 Ideal Rectification:

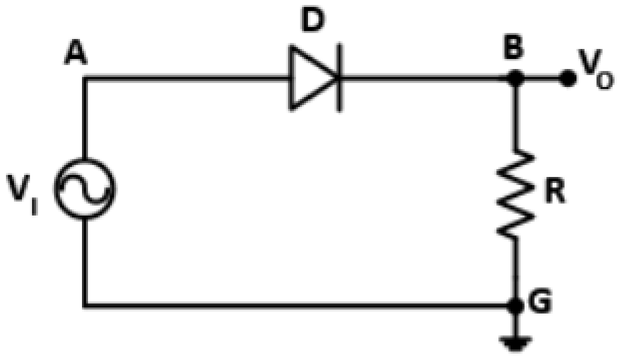


Figure 1: A circuit for the measurement of offsets.

Let's examine the working principle and operation of the above circuit:

The input signal applied to the half-wave rectifier circuit is sinusoidal and changes direction depending on time. In the positive alternans of the input sign; The diode is correctly polarized. Therefore, it is conductive. It allows current to flow through it. Positive alternans occurs on the load.

DIODE IN CONDUCTION

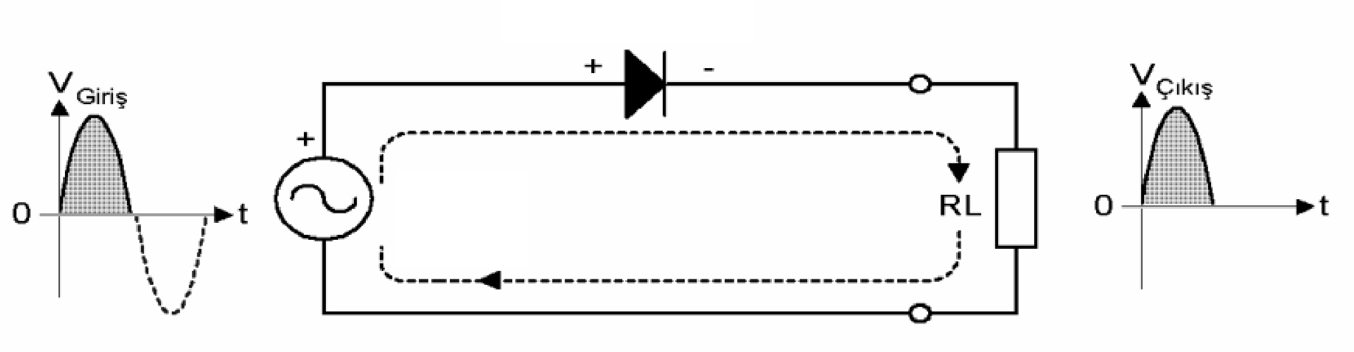


Figure 2: The operation of the circuit in the positive alternating of the input signal

Depending on the frequency of the input signal, after a while, negative alternance will be applied to the anode of the diode. Therefore, the diode is insulated in the negative alternating of the input signal. Because the diode is reverse biased. It does not allow current to flow through it. It is open circuit. The output signal received over the RL resistor becomes 0V. (Figure 3)

DIODE CUT OFF

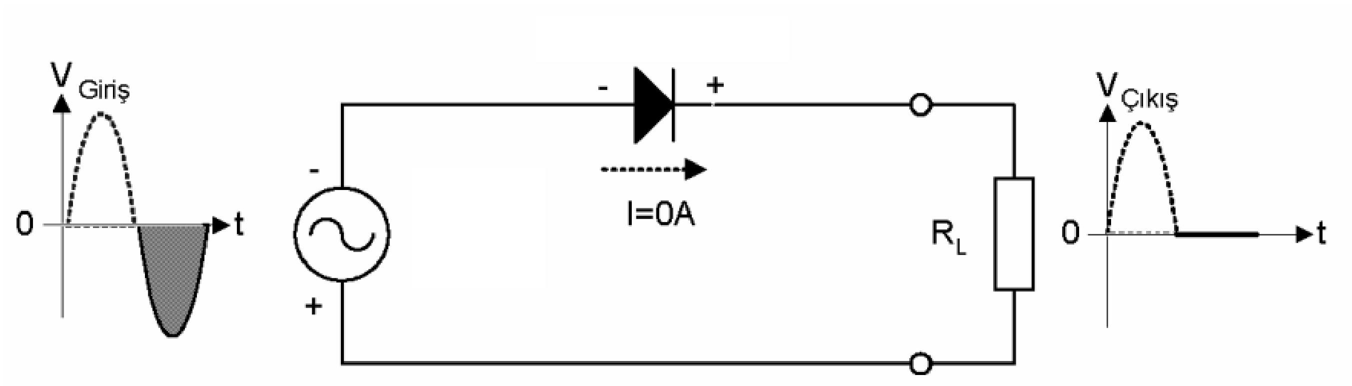


Figure 3: The operation of the circuit in the negative alternating of the input signal

The waveform of the signal obtained at the output of the half-wave rectifier circuit is given in detail in Figure 4.

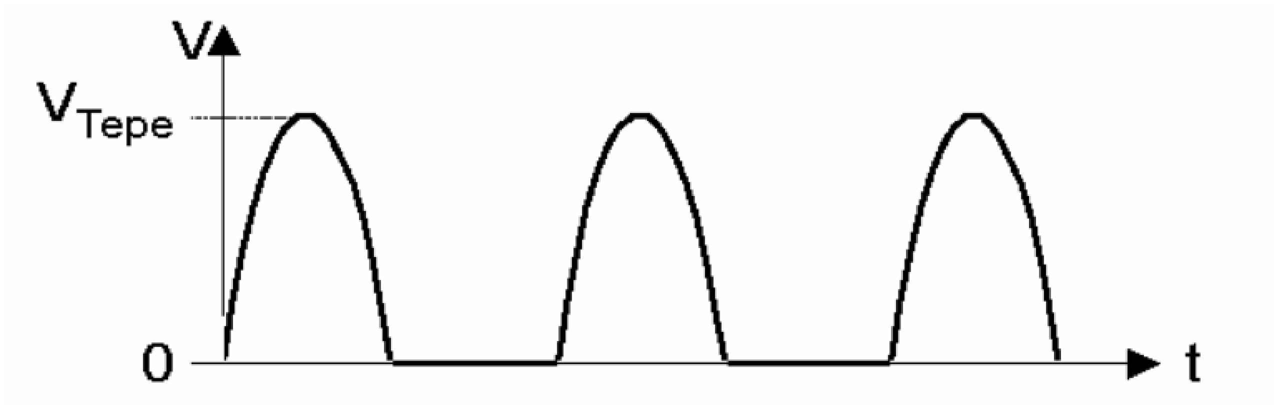


Figure 4: Output waveforms of half-wave rectifier circuit

The signal received from the output of the half-wave rectifier circuit is no longer an AC signal. Because the exit sign does not contain negative alternans. Only positive cycles are received from the rectifier output. Therefore, the output signal is not similar to the DC signal, it is wavy. This situation is undesirable. In fact, a signal should be obtained from the rectifier output at or near a full DC voltage.

a) Assemble the circuit as shown in Figure 1, using an IN4004 diode and 1kΩ resistor. Adjust the signal generator to provide a sine wave at 100 Hz with 20 Vpp amplitude. Observe and note the waveforms at nodes A and B. Indicate the voltage drop on peaks in the graph.

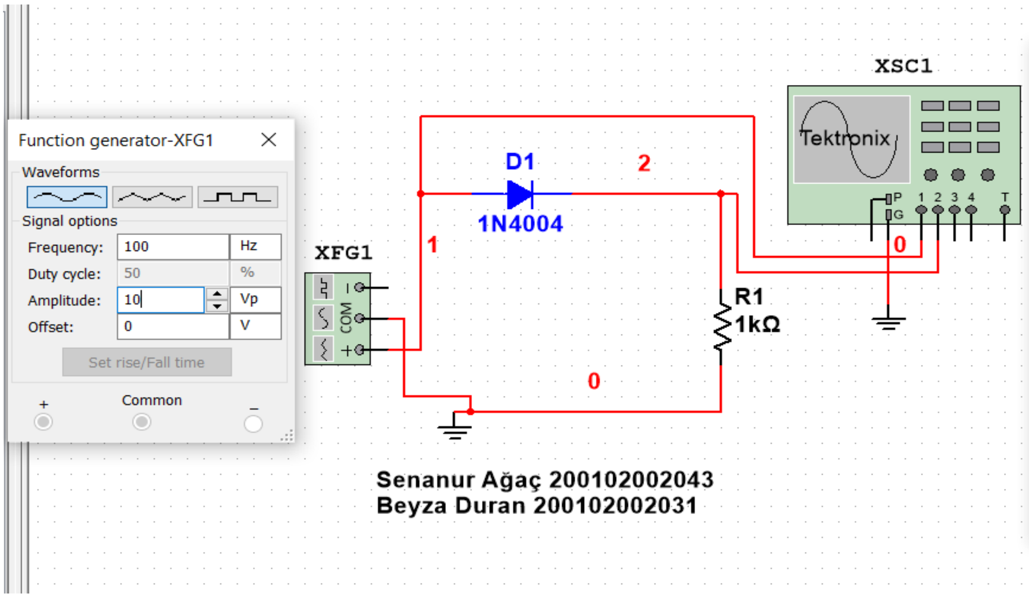


Figure 5: Setting up the circuit on MultiSim and obtaining the values

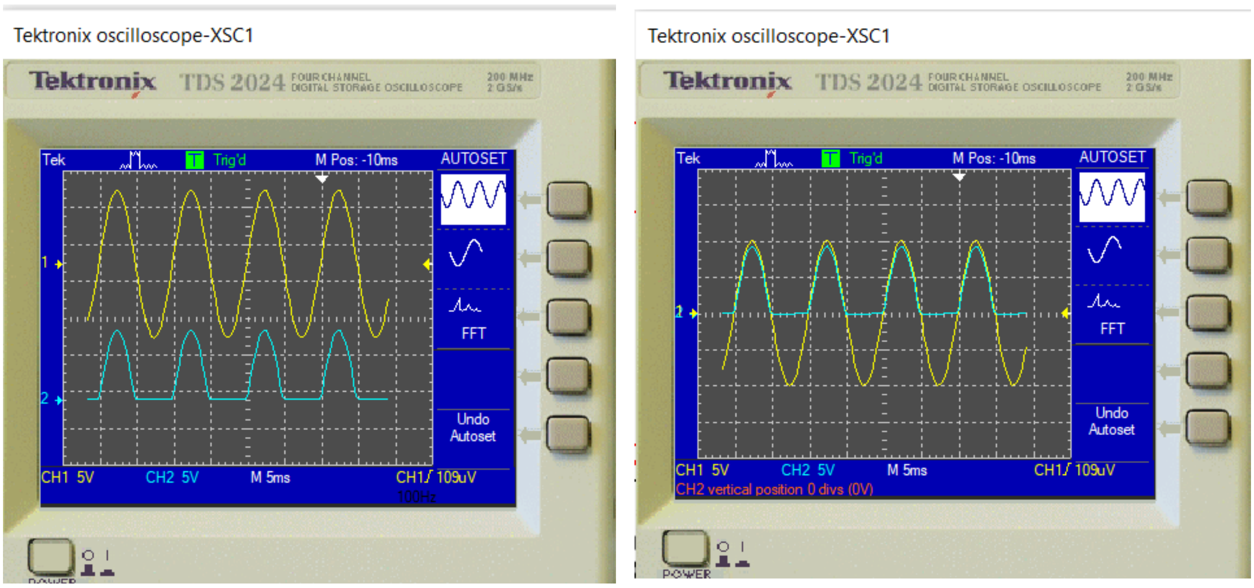


Figure 6: Obtaining the input and output voltages of points A and B on the oscilloscope

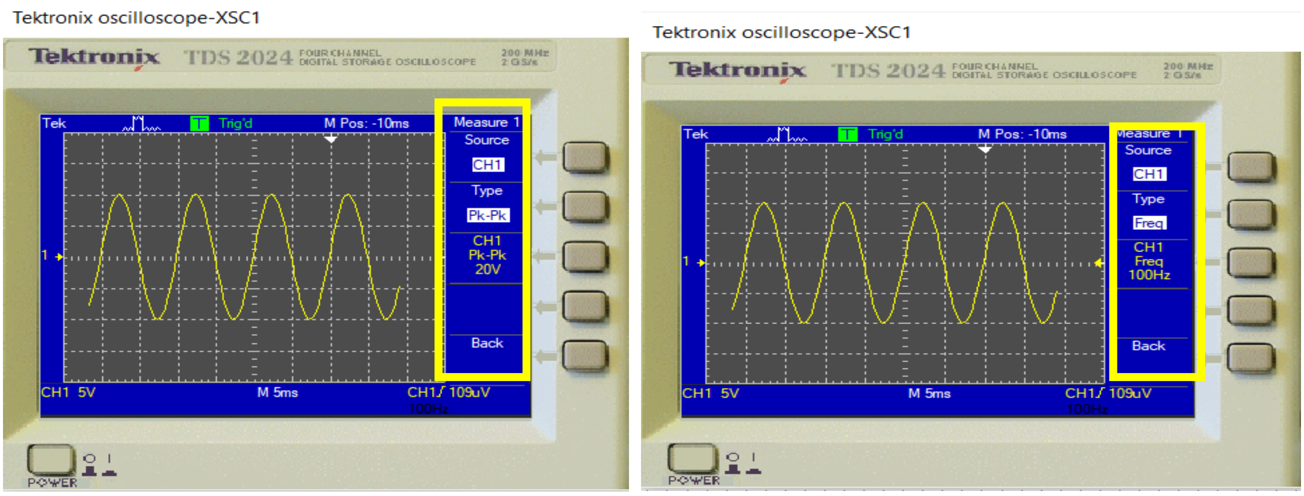


Figure 7: Display of wave frequency and peak to peak value

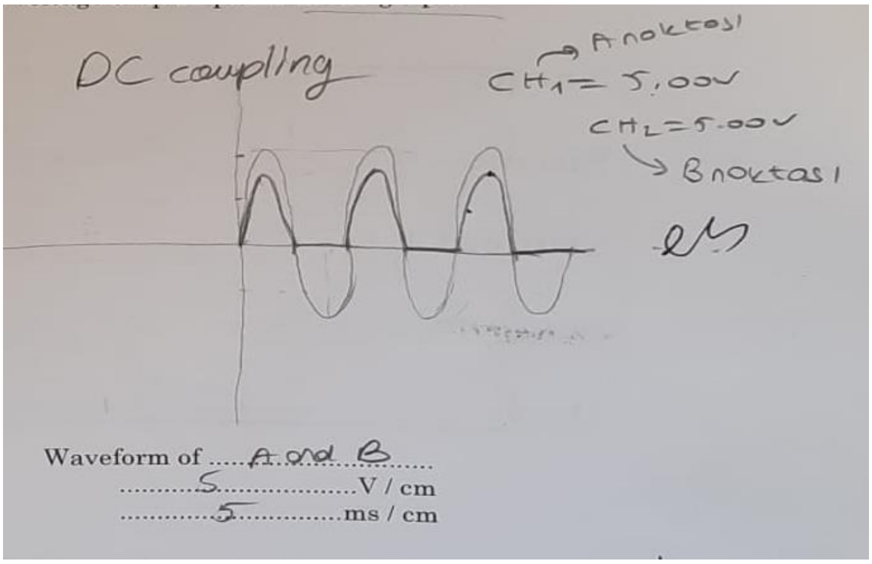
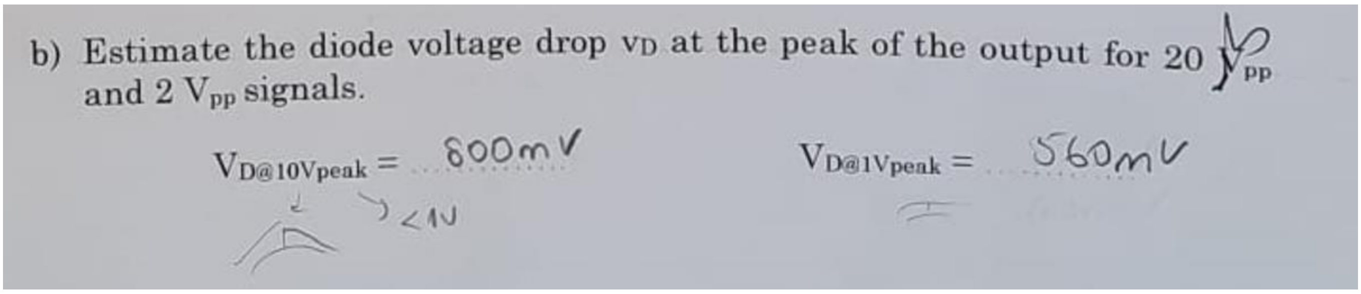


Figure 7: Graph found in the experiment

b) Estimate the diode voltage drop vD at the peak of the output for 20 Vpp and 2 Vpp signals.


b) Estimate the diode voltage drop v_D at the peak of the output for 20 V_{pp} and 2 V_{pp} signals.

$V_{D@10Vpeak}$ = 800mV $V_{D@1Vpeak}$ = 560mV

< 1V

Figure 8: Experimental values of question 1.1(b)

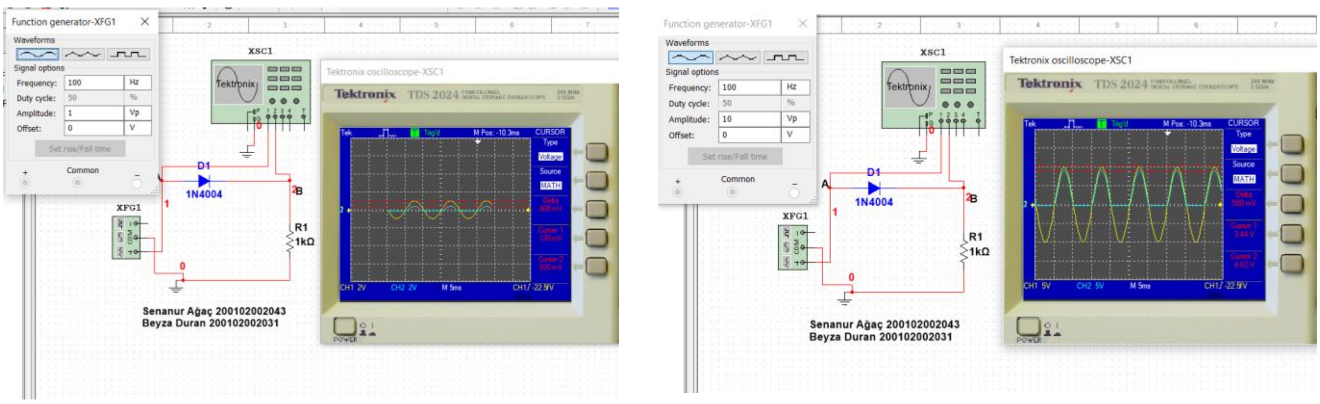


Figure 9:Arranging circui for question 1.1(b)

For this part of the experiment, the experimental values are specified and the circuit is drawn in the simulation program as above.

c) Examine the relationship between vA and vB near where vB begins to go positive. Estimate the time at which the output voltage is ½ the diode drop at the peak. Note your measurements to Table 1.

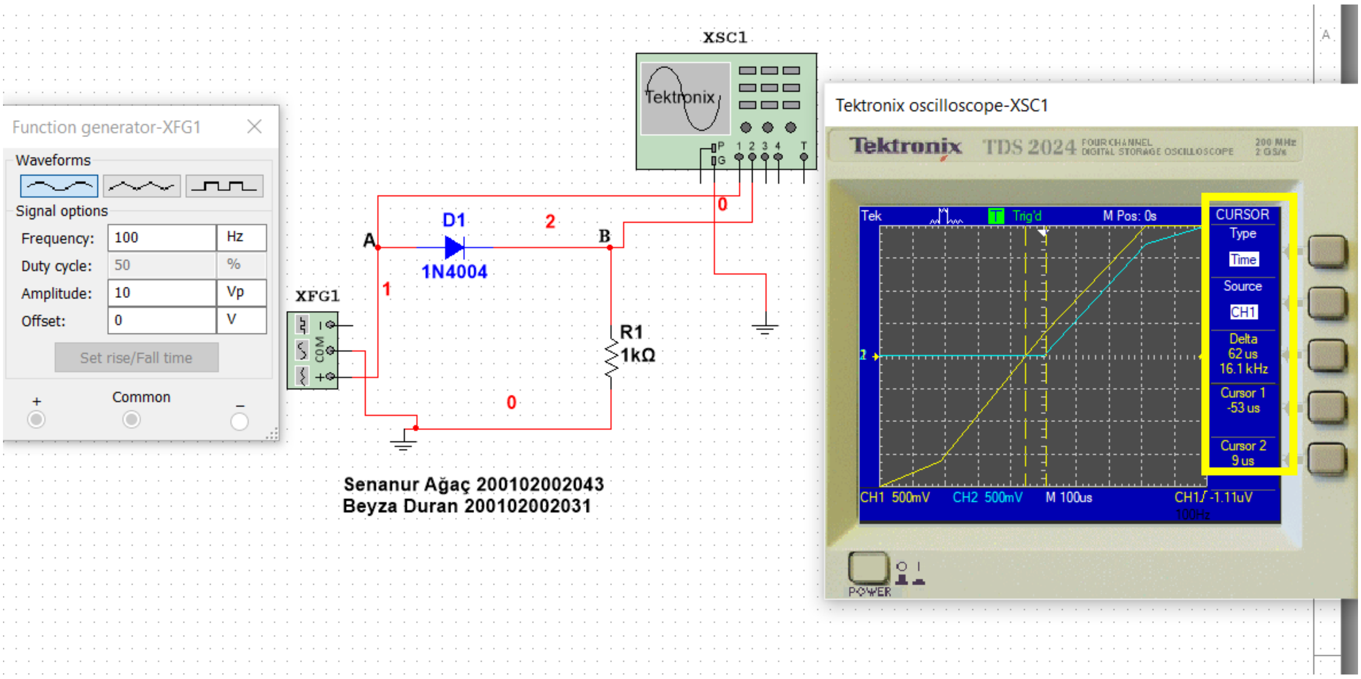


Figure 10: When VB begins rising

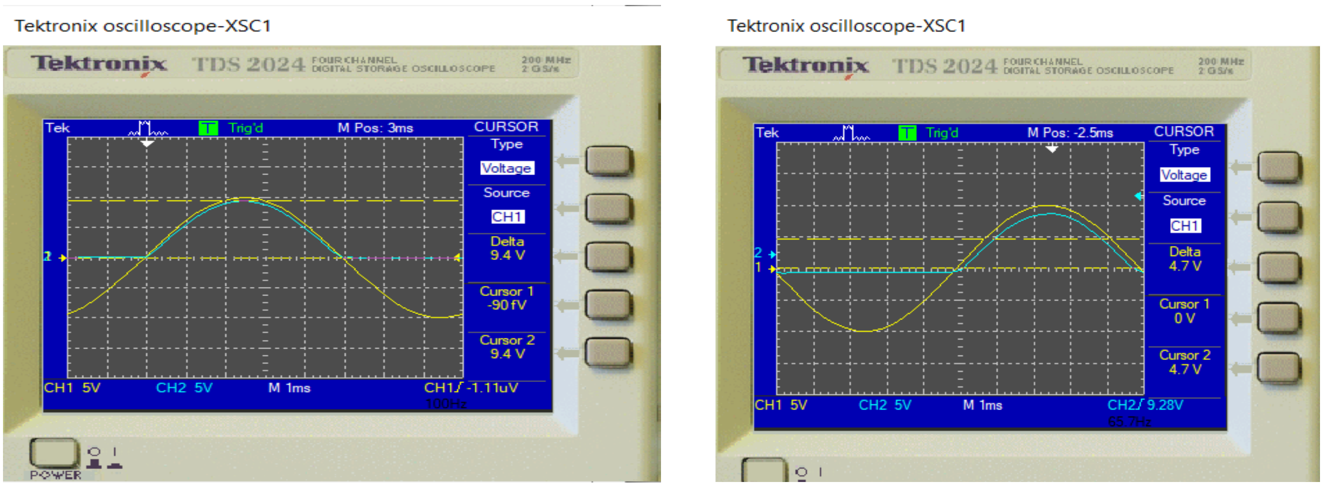


Figure 11: When VB is ½ diode drop

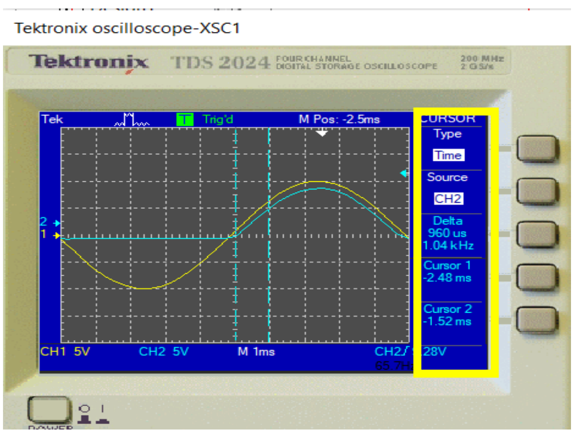


Figure 12: When VB is ½ diode drop (time)

Table 1: Time and phase measurement(MultiSim)

	When v_B begins rising	When v_B is ½ diode drop
t (ms)	62 µs	960 µs

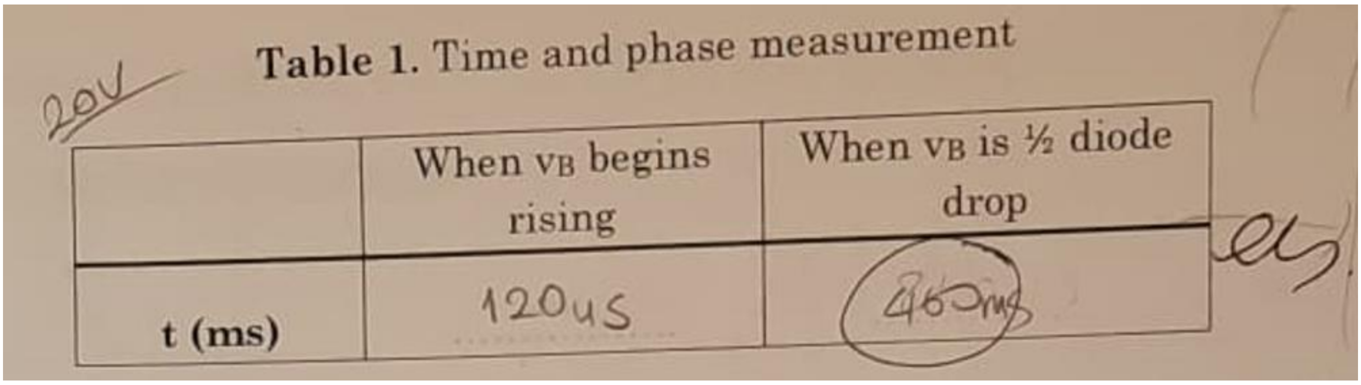


Table 1. Time and phase measurement

	When v_B begins rising	When v_B is ½ diode drop
t (ms)	120uS	460ms

Figure 13: Experiment results for Table 1

d) Switch the generator to provide a square-wave output. Notice the direct effect of the voltage drop.

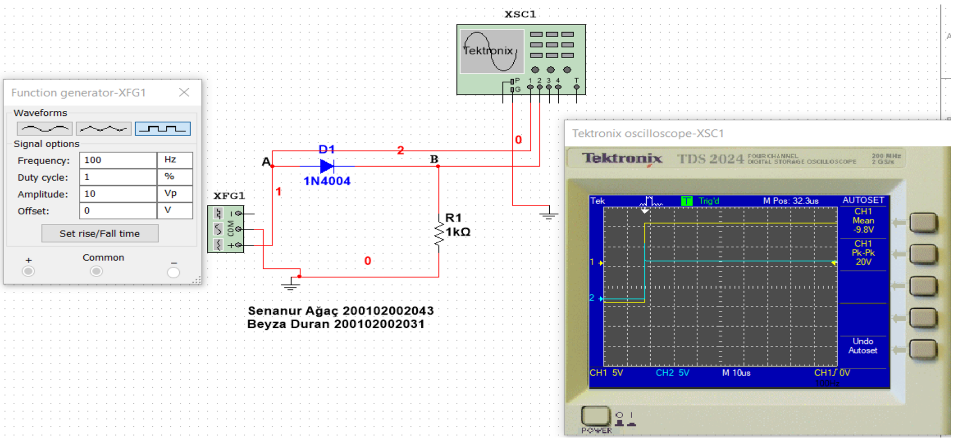


Figure 14: Providing square-wave for question 1.1(d) (MultiSim)

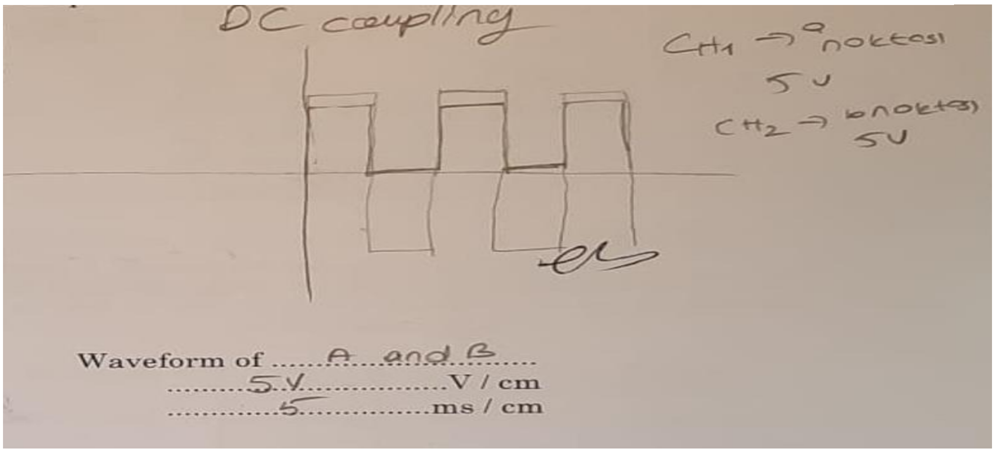


Figure 15: Providing square-wave for question 1.1(d)(Experimental results)

1.2 Rectifier Filtering:

A filter circuit is one which removes the ac component present in the rectified output and allows the dc component to reach the load.

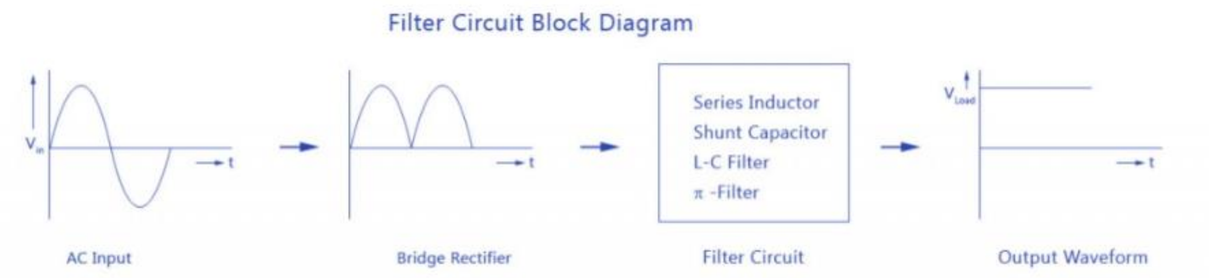


Figure 16 : Filter Circuit Block Diagram

The basic logic of the filtering operation works as shown in figure x.

Shunt Capacitor Filter :
The filter and this high value capacitor is shunted or placed across the load impedance. This capacitor, when placed across a rectifier gets charged and stores the charged energy during the conduction period. When the rectifier is not conducting, this energy charged by the capacitor is delivered back to the load. Through this energy storage and delivery process, the time duration during which the current flows through the load resistor gets increased and the ripples are decreased by a great amount. Thus for the ripple component with a frequency of 'f' megahertz, the capacitor 'C' will offer a very low impedance. The value of this impedance can be written as:
Shunt Capacitor Impedance = 1/2 fC
Thus the dc components of the input signal along with the few residual ripple components, is only allowed to go through the load resistance RLoad. The high amount of ripple components of current gets bypassed through the capacitor C.

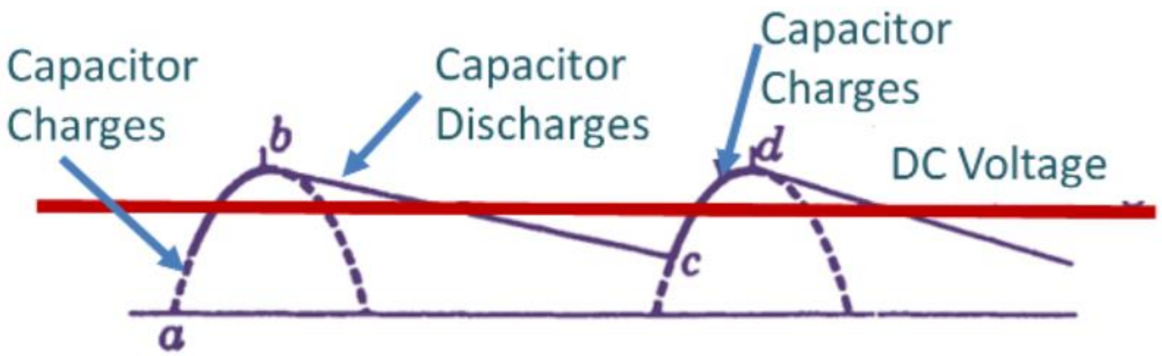


Figure 17: Rectifier output with shunt capacitor filter

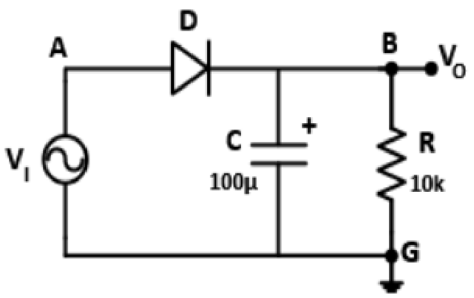


Figure 18: A Rectifier Circuit with Capacitor Filter

a) Assemble the circuit as shown in Figure 2, using an IN4004 diode. Adjust the signal generator to provide a sine wave at 100 Hz with 20 Vpp amplitude. Observe and note the waveforms at nodes A and B. Indicate the voltage drop on peaks in the graph. Estimate the time interval for which the diode is forward conducting (Note the values to the proper blanks below each graph).
b) Shunt RL by a resistor R2 = 1 kΩ. Measure vA and vB as in a).

Waveform of A&B for R = 10 kΩ
A = 5v/div B= 50mv/div
t = 887.097 us

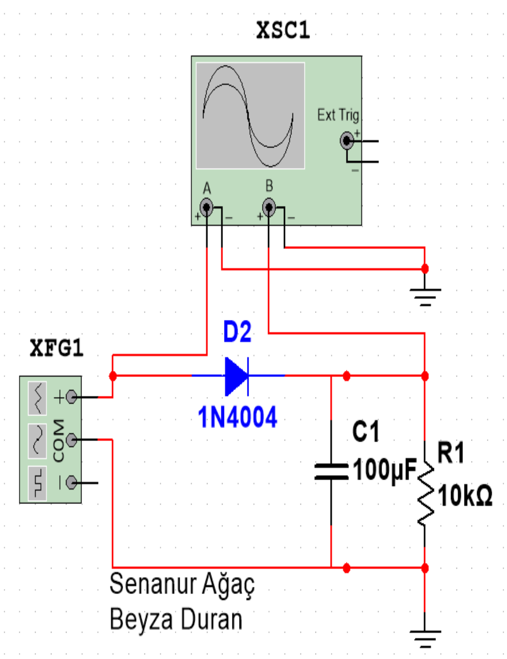


Figure 19 : Circuit of A&B for R = 10 kΩ

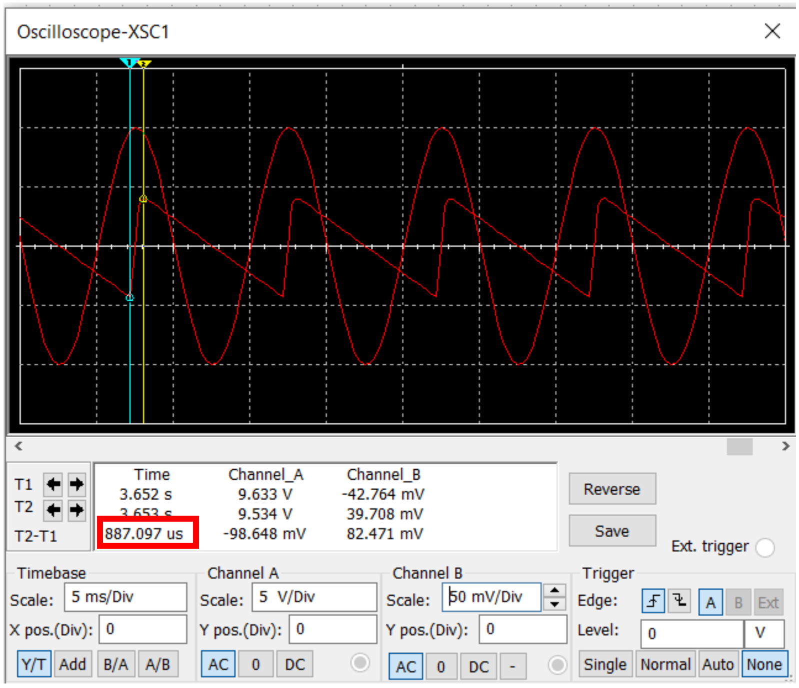


Figure 20 : Waveform of A&B for R = 10 kΩ

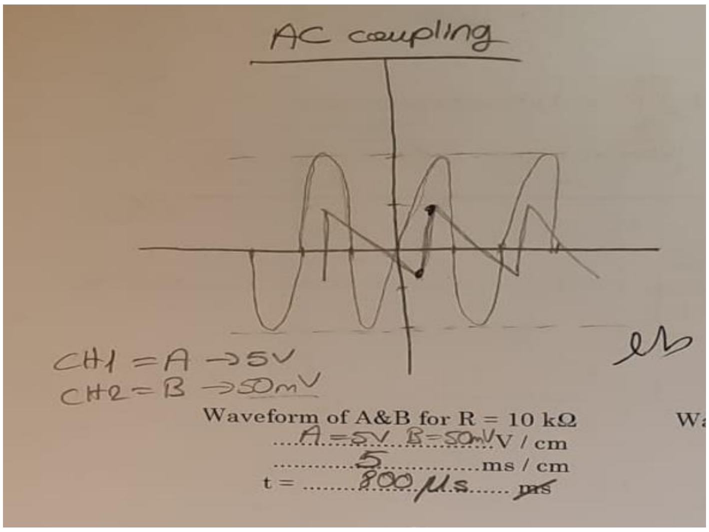


Figure 21 : Experiment result

Waveform of A&B for R = (10//1) kΩ
A = 5v/div B= 500mv/div
t = 1.290 ms

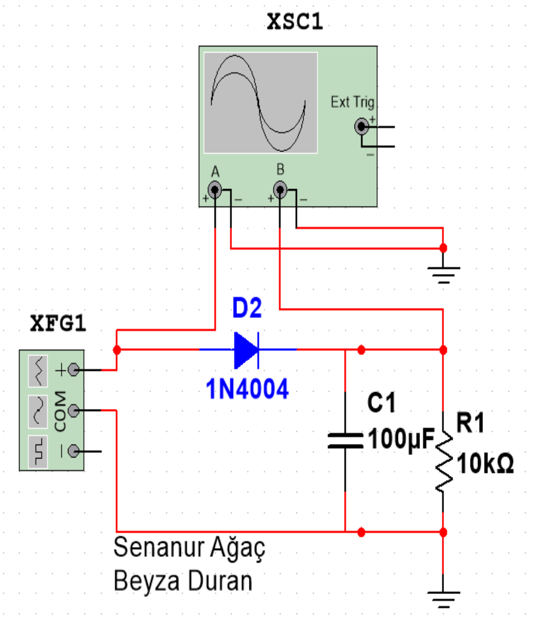


Figure 22 : Circuit of A&B for R = (10//1) kΩ

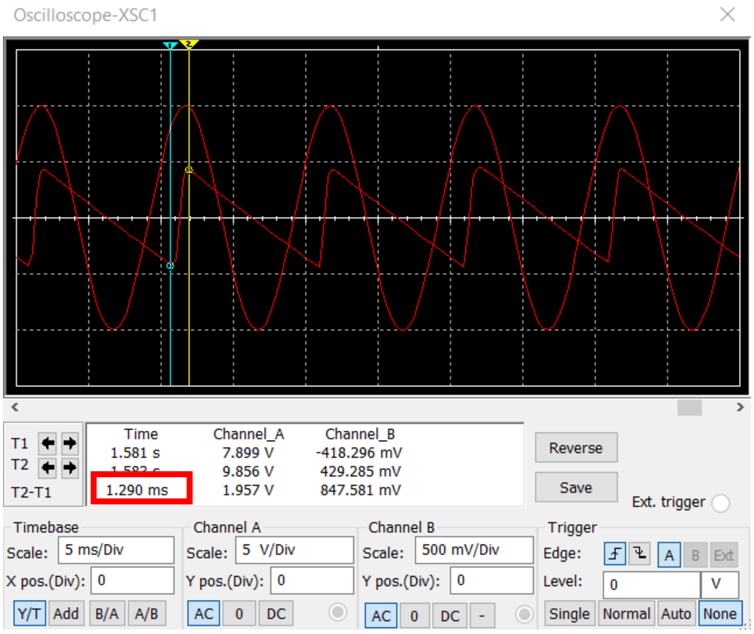


Figure 23 : Waveform of A&B for R = 10 kΩ

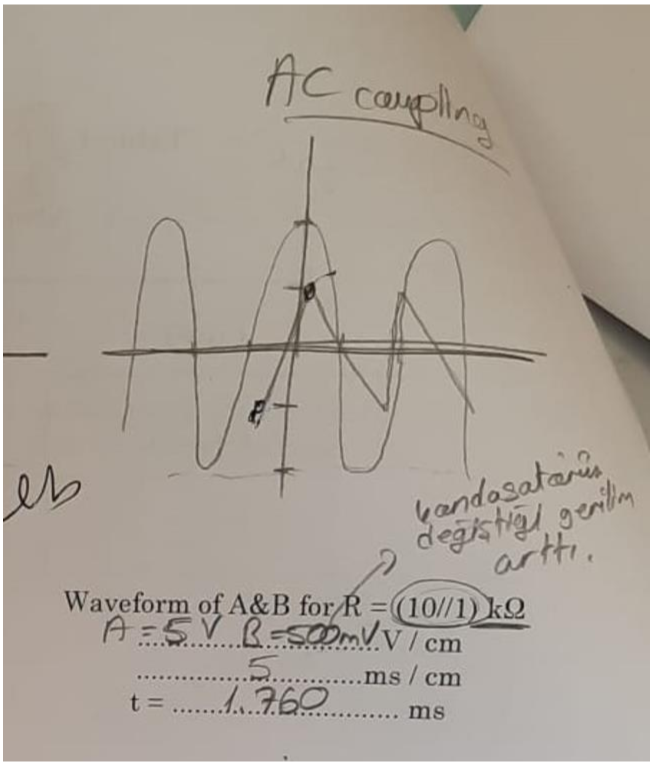


Figure 24:: Experiment result

c) Switch the generator to provide a square wave output. Repeat a), b) above with load Req = 10 kΩ and lkΩ // 10kΩ = 0.909 kΩ

Waveform of A&B for R = (10//1) kΩ
A = 5v/div B= 50mv/div
t = 4.9190 ms

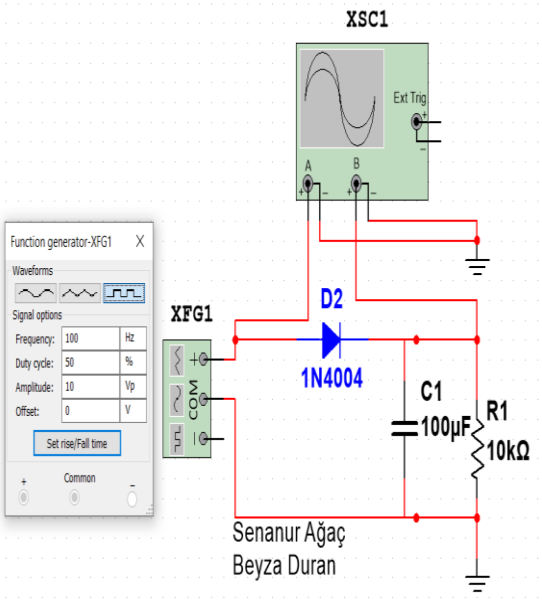


Figure 25 : Circuit of A&B for R= (10//1) kΩ

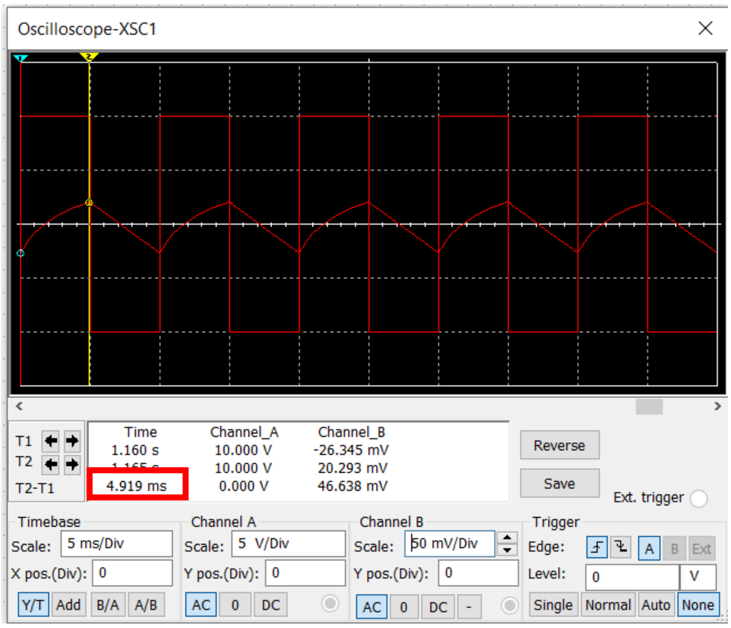


Figure 26 : Waveform of A&B for R = (10//1) kΩ

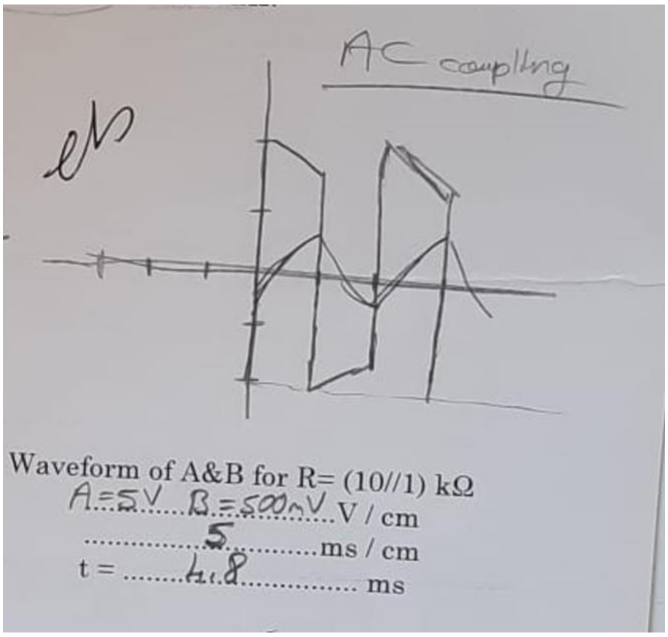


Figure 27 : Experiment result

Waveform of A&B for R = 10 kΩ
A = 5v/div B= 500mv/div
t = 4.919 ms

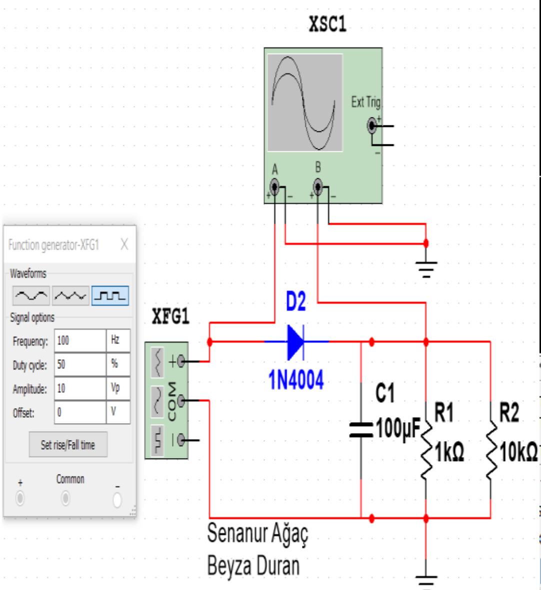


Figure 28 : Circuit of A&B for R = 10 kΩ

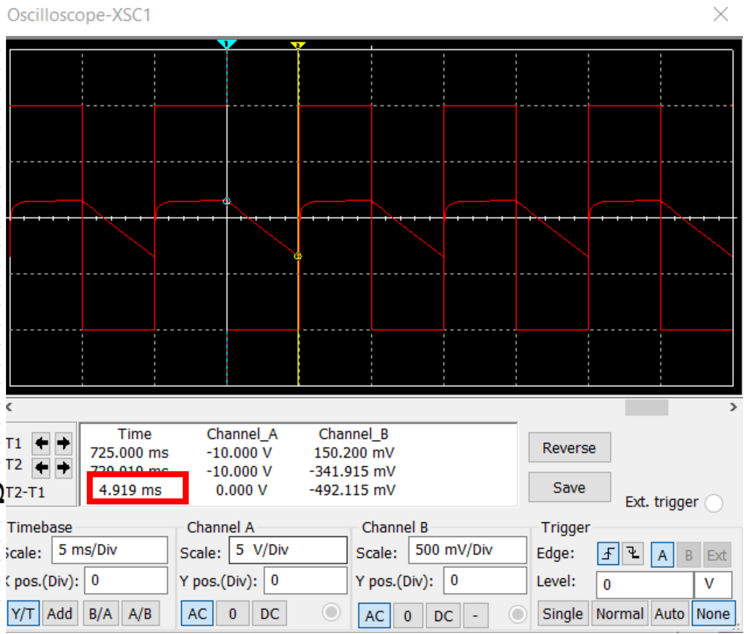
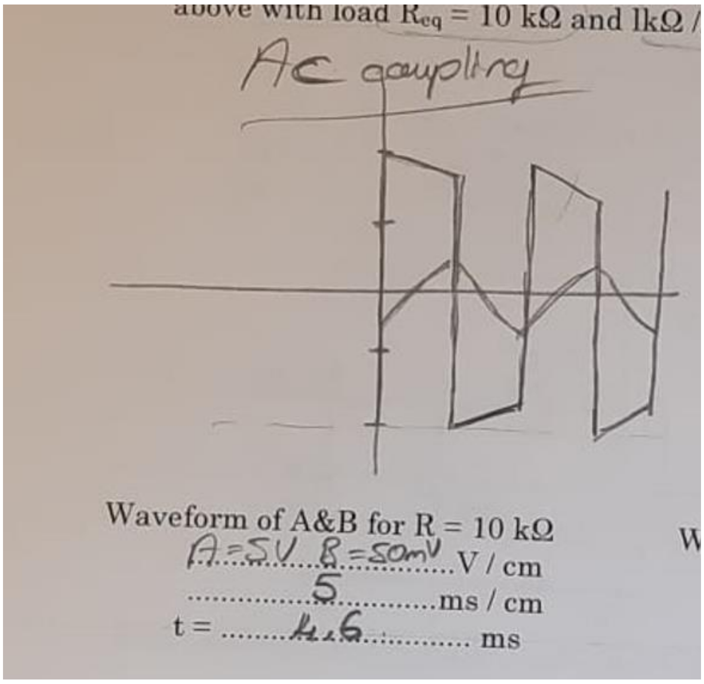


Figure 29 : Waveform of A&B for R = 10 kΩ



In this section, when a 1k resistor is connected in parallel with the 10k resistor, it is observed that there is not much change in the t value, but a change in the v/cm value of the wave measured from the b point is observed.

Figure 30 : Experiment result

2.Diode Conduction – The Forward Drop
2.1 Basic Measurements:

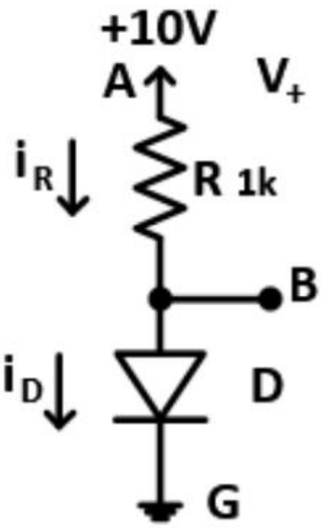
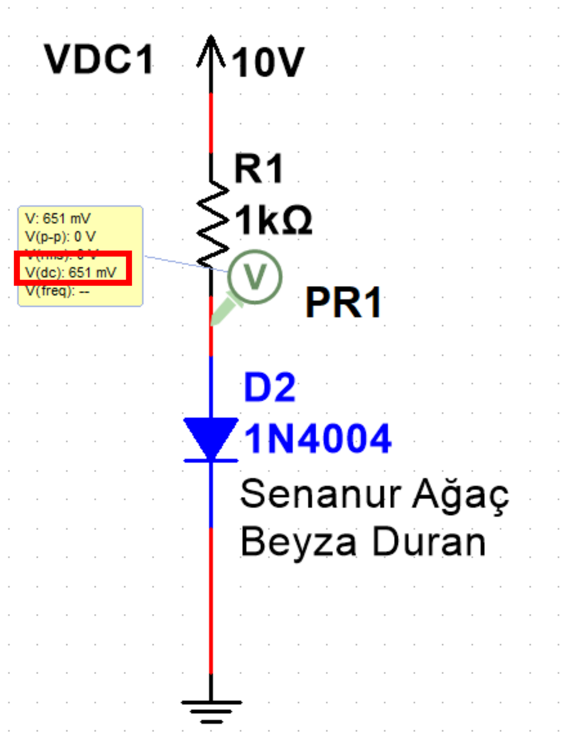


Figure 31 : : A Diode Forward-Drop Test Circuit

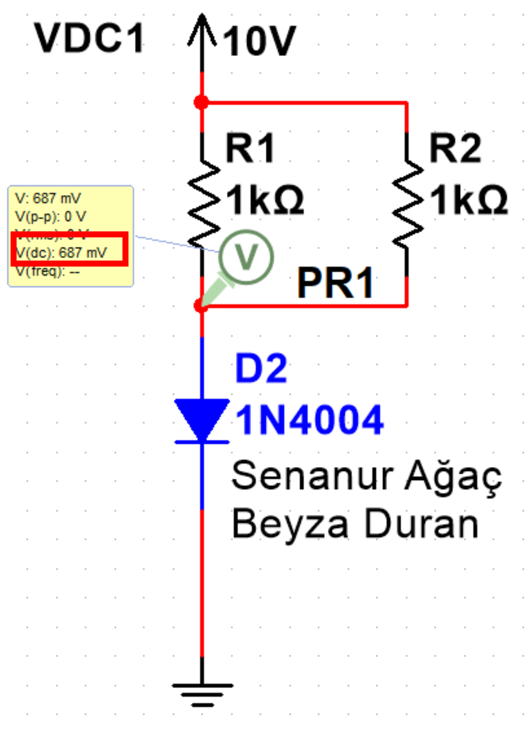
Assemble the circuit shown in Figure 3, using a IN4004 diode, a l kΩ resistor and a 10 V de supply. Note that the circuit is essentially the same as that in Figure 1, but with a dc signal source, and the location of circuit ground redefined.
a) Measure vB. Adjust the supply to 10.0(0) V (for convenience). Find iD .



$$\mathrm{Id} = \frac{10\mathrm{V}-651\mathrm{mV}}{1\mathrm{k}\Omega} = 9.349mA$$

Figure 32 : simulation result for a

a) Shunt R with a resistor of equal value 1 kΩ. Measure vB =vD. Find iD.



$$\boxed{\mathrm{Id} = \frac{10\mathrm{V} - 687\mathrm{mV}}{0.5\mathrm{k}\Omega} = 18.626mA}$$

Figure33: simulation result for b

b) With two 1 kΩ resistors connected, shunt D with a second IN4004 diode (assumed to be matched). What does vD become?

$$\boxed{\mathrm{Id} = \frac{10\mathrm{V} - 651\mathrm{mV}}{0.5\mathrm{k}\Omega}/2 = 9.349mA}$$

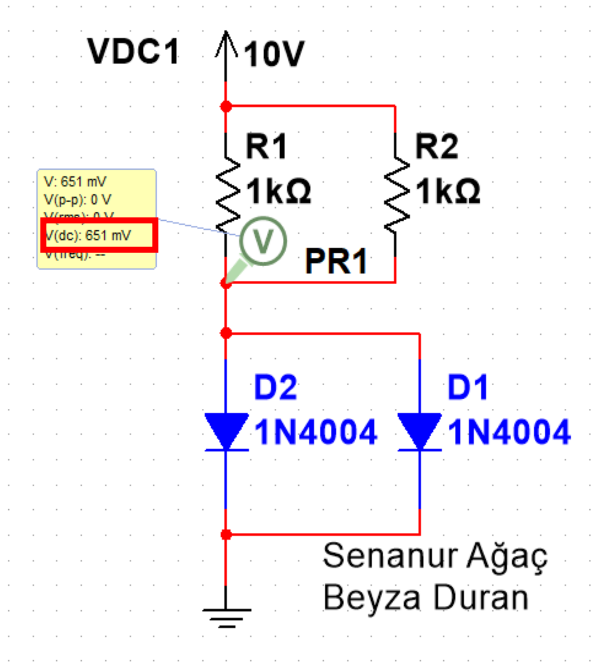
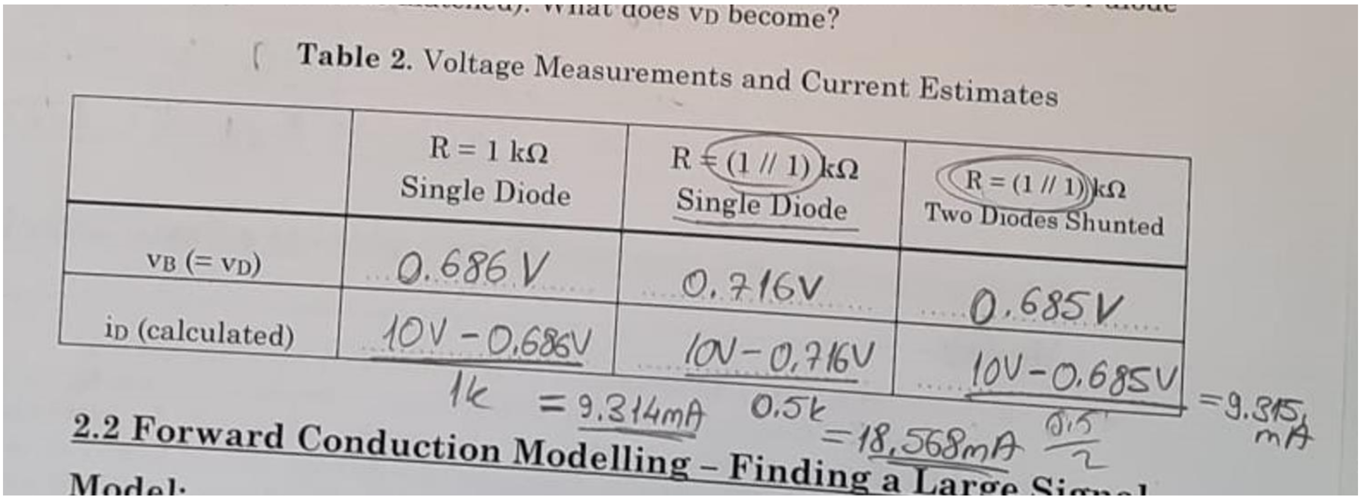


Figure34: simulation result for c

	R = 1 kΩ Single Diode	R = (1 // 1) kΩ Single Diode	R = (1 // 1) kΩ Two Diodes Shunted
vB (= vD)	651mV	687mV	651mV
iD (calculated)	9.349mA	18.626mA	9.349mA

Table 2: . Voltage Measurements and Current Estimates



...). What does v_D become?

Table 2. Voltage Measurements and Current Estimates

	R = 1 kΩ Single Diode	R = (1 // 1) kΩ Single Diode	R = (1 // 1) kΩ Two Diodes Shunted
v_B (= v_D)	0.686 V	0.716V	0.685V
i_D (calculated)	$\frac{10V - 0.686V}{1k} = 9.314mA$	$\frac{10V - 0.716V}{0.5k} = 18,568mA$	$\frac{10V - 0.685V}{\frac{0.5}{2}} = 9.315\ mA$

2.2 Forward Conduction Modelling – Finding a Large Sig

Model:

Figure 35 : EXPERIMENT RESULTS

2.2 Forward Conduction Modelling – Finding a Large Signal Model:

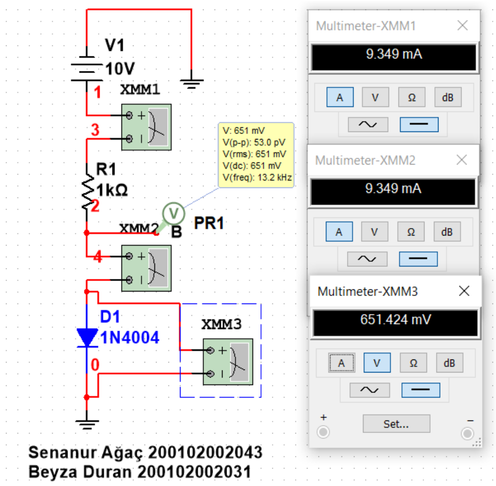
c) **Return to the circuit in Figure 3, but use four wide-ranging values for R, namely 1 kΩ, 10 kΩ, 100 kΩ, and l MΩ and a IN4004 diode. Experimentally, ground the cathode of the diode to be tested, and connect all four resistors to its anode with one end of each open, and to which the 10 V supply will be connected in turn. For a supply voltage of 10 V, measure VD as each resistor is connected to the supply in turn. Approximate the corresponding current. Note that if the supply is raised slightly, to 10.7 or so, the values of current become somewhat "friendlier", being easier to estimate (or calculate)! (Hint: Observe the exponential relation between VD and ID.)**

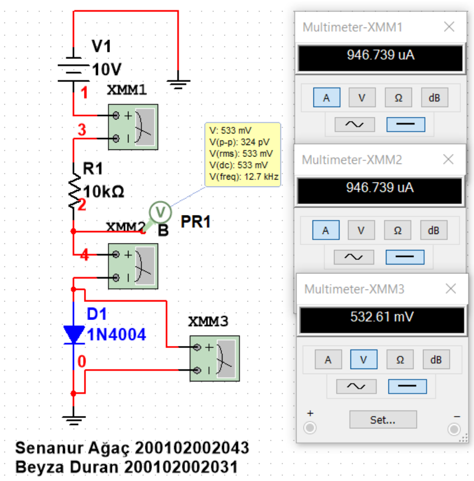
Theorical Informations about Large Signal Model:

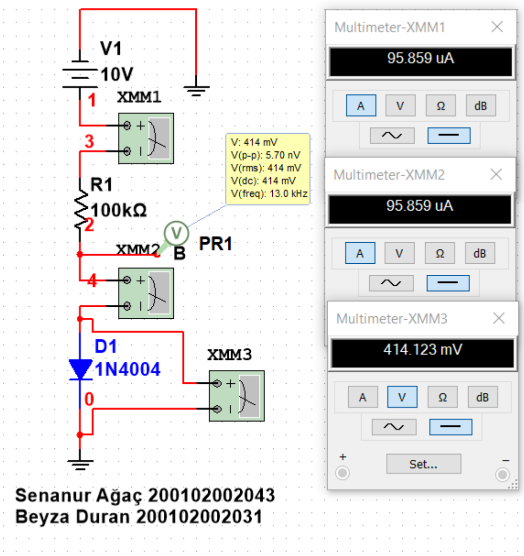
The small signal model accounts for the behavior which is linear around an operating point. When the signal is large in amplitude (say more than 1/5 of VCC, a rule of thumb) the behavior becomes non linear and we have to use the model which accounts for non-linearity , and thus called large signal model.

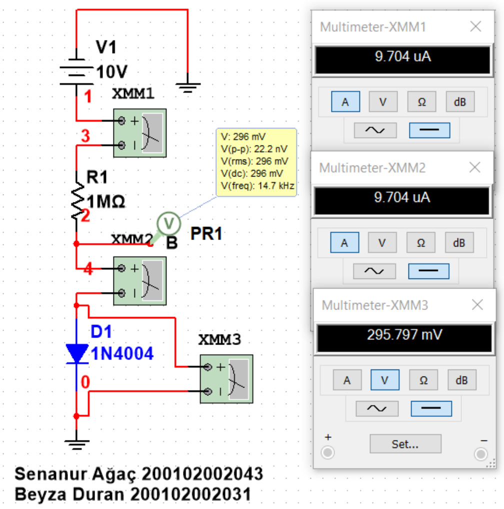
"Large signal" is the opposite of "small signal", which means that the circuit can be reduced to a linearized equivalent circuit around its operating point with sufficient accuracy

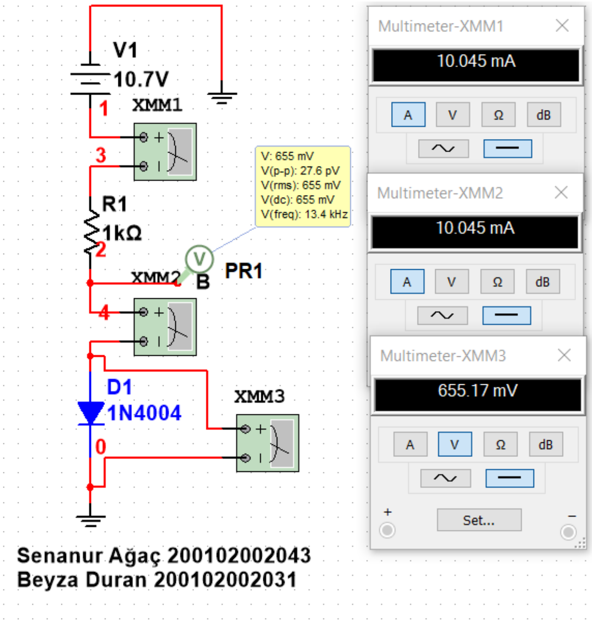
A large signal model, on the other hand, takes into account the fact that the large signal actually affects the operating point, as well as that elements are non-linear and circuits can be limited by power supply values to avoid variation in operating point. A small signal model ignores simultaneous variations in the gain and supply values.

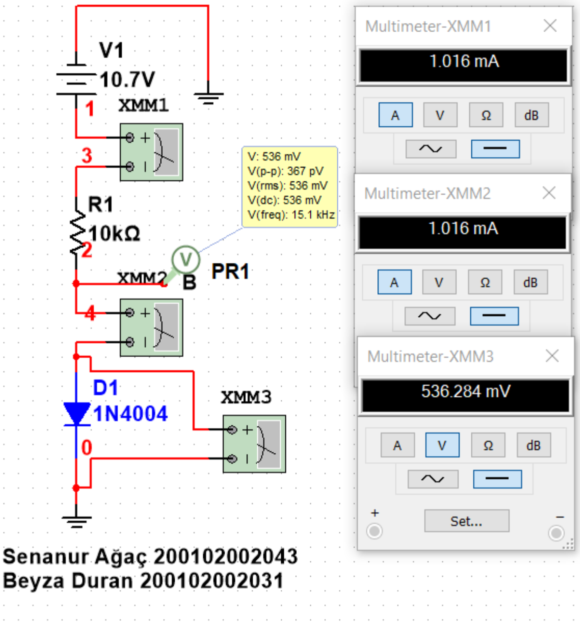


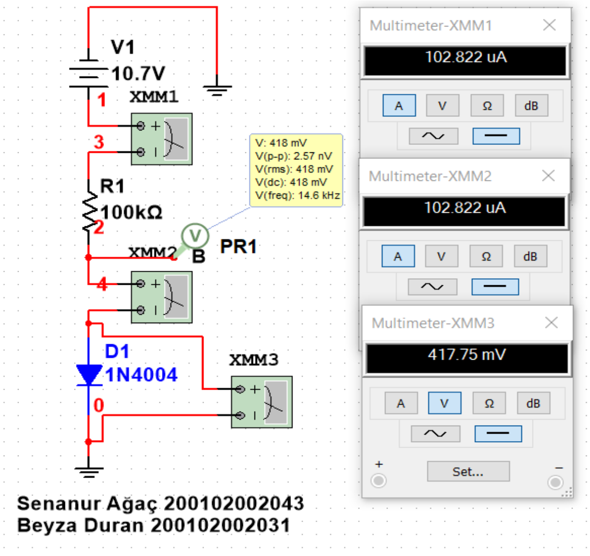


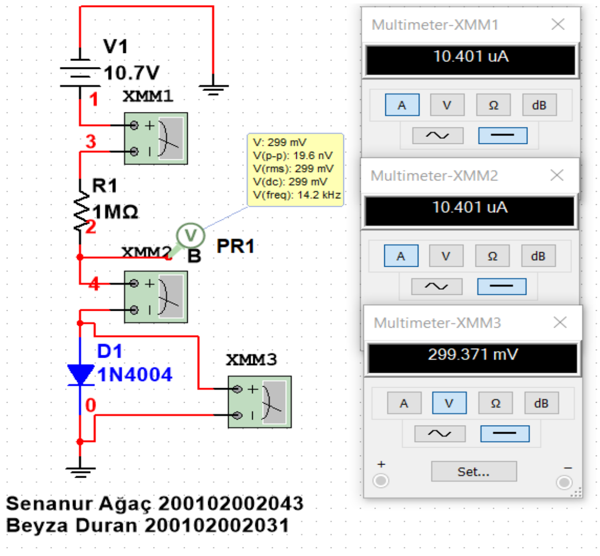




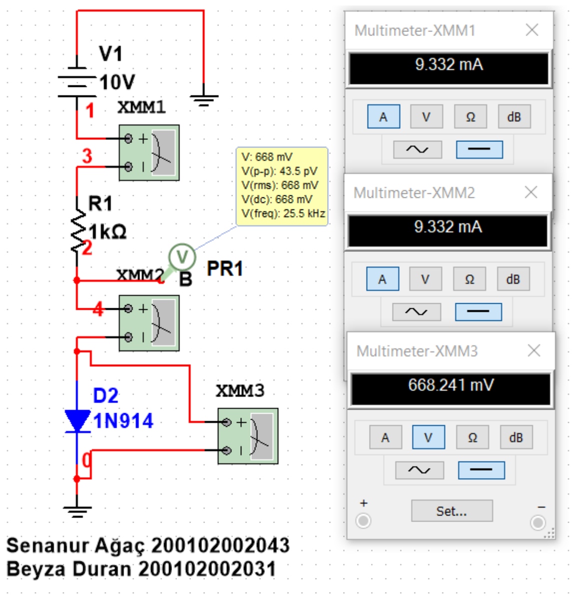

V1
10.7V
XMM1
R1
1kΩ
XMM2
PR1
D1
1N4004
XMM3
V: 655 mV
V(p-p): 27.6 pV
V(rms): 655 mV
V(dc): 655 mV
V(freq): 13.4 kHz
Multimeter-XMM1
10.045 mA
Multimeter-XMM2
10.045 mA
Multimeter-XMM3
655.17 mV
Set...
Senanur Ağaç 200102002043
Beyza Duran 200102002031

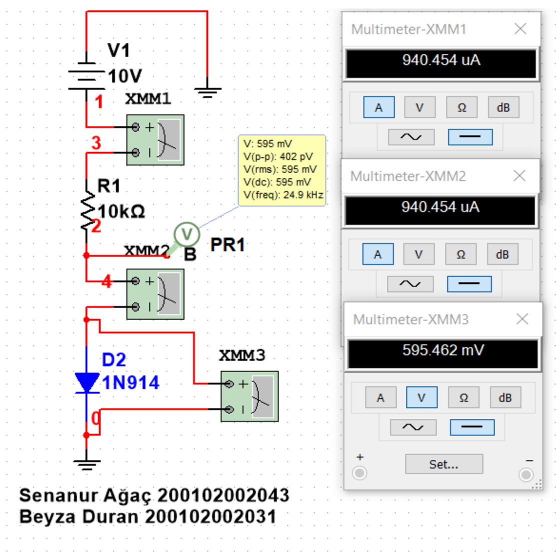

V1
10.7V
XMM1
R1
10kΩ
XMM2
PR1
D1
1N4004
XMM3
V: 536 mV
V(p-p): 367 pV
V(rms): 536 mV
V(dc): 536 mV
V(freq): 15.1 kHz
Multimeter-XMM1
1.016 mA
Multimeter-XMM2
1.016 mA
Multimeter-XMM3
536.284 mV
Set...
Senanur Ağaç 200102002043
Beyza Duran 200102002031

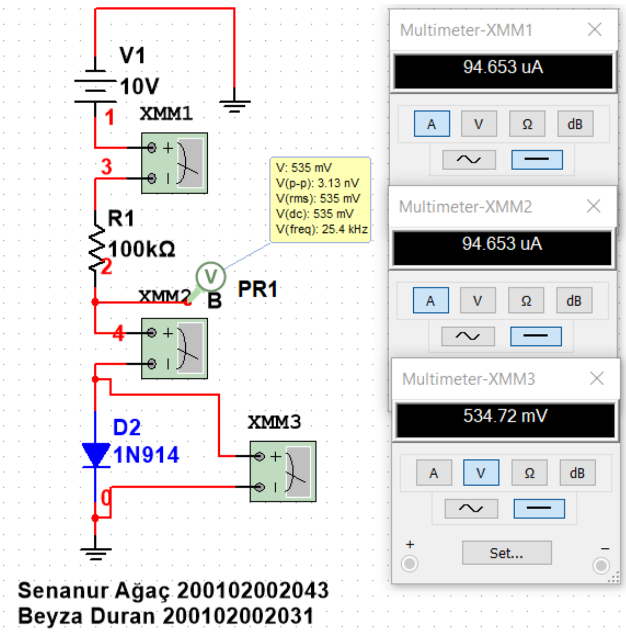

V1
10.7V
XMM1
R1
100kΩ
XMM2
PR1
D1
1N4004
XMM3
V: 418 mV
V(p-p): 2.57 nV
V(rms): 418 mV
V(dc): 418 mV
V(freq): 14.6 kHz
Multimeter-XMM1
102.822 uA
Multimeter-XMM2
102.822 uA
Multimeter-XMM3
417.75 mV
Set...
Senanur Ağaç 200102002043
Beyza Duran 200102002031

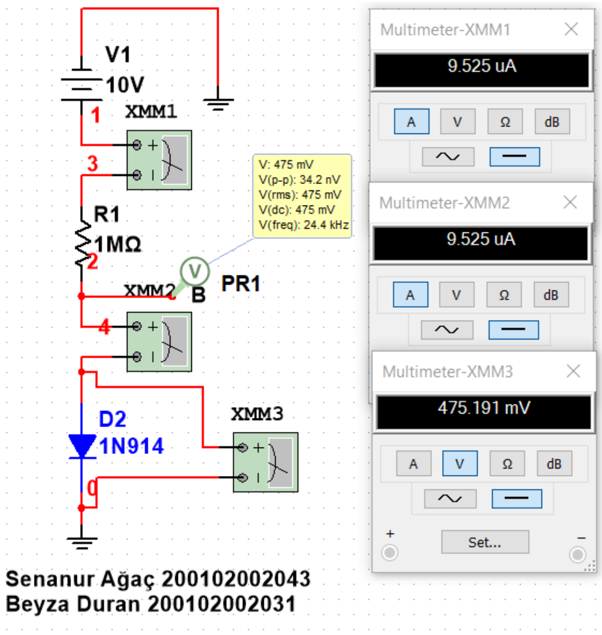

V1
10.7V
XMM1
R1
1MΩ
XMM2
PR1
D1
1N4004
XMM3
V: 299 mV
V(p-p): 19.6 nV
V(rms): 299 mV
V(dc): 299 mV
V(freq): 14.2 kHz
Multimeter-XMM1
10.401 uA
Multimeter-XMM2
10.401 uA
Multimeter-XMM3
299.371 mV
Set...
Senanur Ağaç 200102002043
Beyza Duran 200102002031

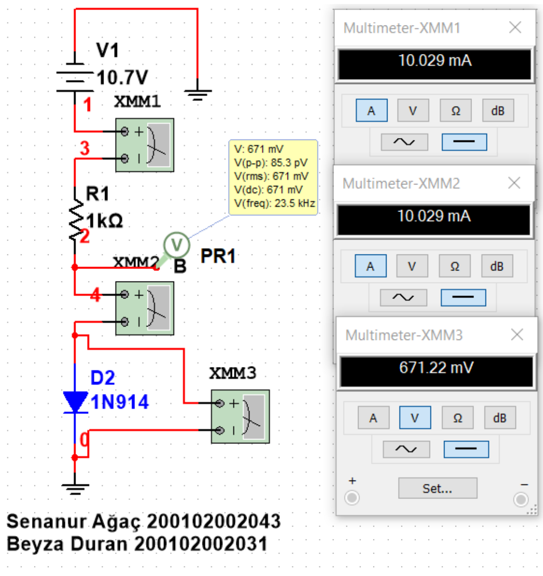
IN914

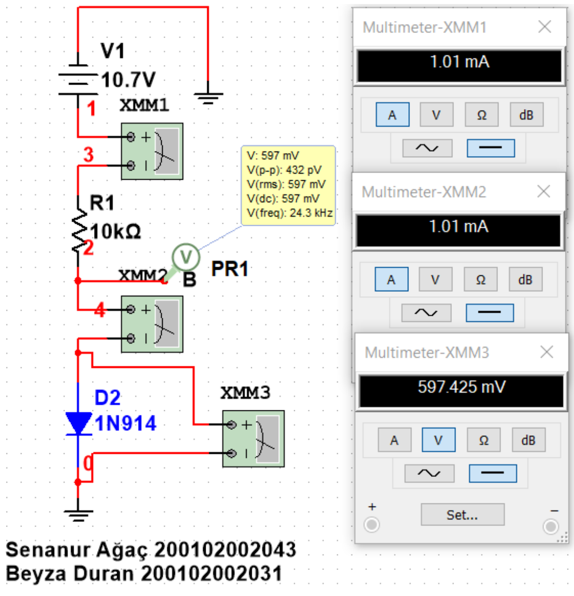

V1
10V
XMM1
R1
1kΩ
XMM2
PR1
D2
1N914
XMM3
V: 668 mV
V(p-p): 43.5 pV
V(rms): 668 mV
V(dc): 668 mV
V(freq): 25.5 kHz
Multimeter-XMM1
9.332 mA
Multimeter-XMM2
9.332 mA
Multimeter-XMM3
668.241 mV
Set...
Senanur Ağaç 200102002043
Beyza Duran 200102002031

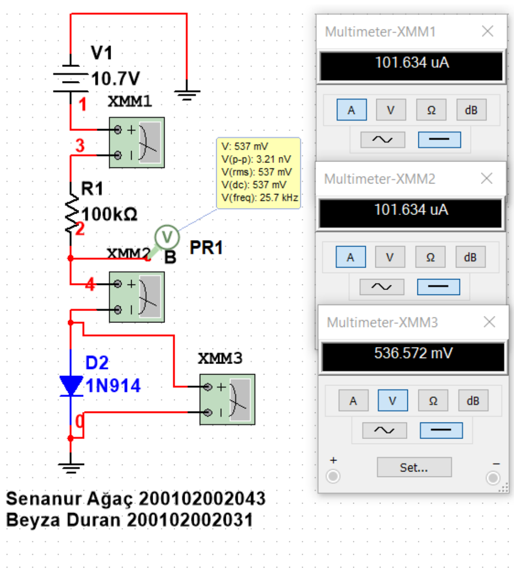

V1
10V
XMM1
R1
10kΩ
XMM2
PR1
D2
1N914
XMM3
V: 595 mV
V(p-p): 402 pV
V(rms): 595 mV
V(dc): 595 mV
V(freq): 24.9 kHz
Multimeter-XMM1
940.454 uA
Multimeter-XMM2
940.454 uA
Multimeter-XMM3
595.462 mV
Set...
Senanur Ağaç 200102002043
Beyza Duran 200102002031

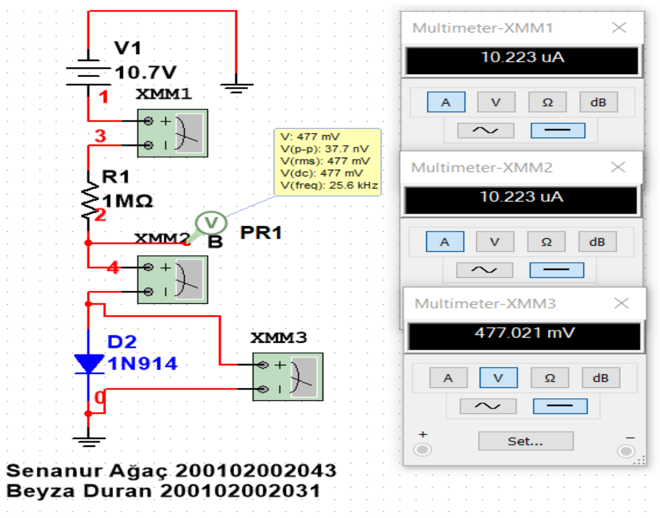

V1
10V
XMM1
R1
100kΩ
XMM2
PR1
D2
1N914
XMM3
V: 535 mV
V(p-p): 3.13 nV
V(rms): 535 mV
V(dc): 535 mV
V(freq): 25.4 kHz
Multimeter-XMM1
94.653 uA
Multimeter-XMM2
94.653 uA
Multimeter-XMM3
534.72 mV
Set...
Senanur Ağaç 200102002043
Beyza Duran 200102002031


V1
10V
XMM1
R1
1MΩ
XMM2
PR1
D2
1N914
XMM3
V: 475 mV
V(p-p): 34.2 nV
V(rms): 475 mV
V(dc): 475 mV
V(freq): 24.4 kHz
Multimeter-XMM1
9.525 uA
Multimeter-XMM2
9.525 uA
Multimeter-XMM3
475.191 mV
Set...
Senanur Ağaç 200102002043
Beyza Duran 200102002031


V1
10.7V
XMM1
R1
1kΩ
XMM2
PR1
D2
1N914
XMM3
V: 671 mV
V(p-p): 85.3 pV
V(rms): 671 mV
V(dc): 671 mV
V(freq): 23.5 kHz
Multimeter-XMM1
10.029 mA
Multimeter-XMM2
10.029 mA
Multimeter-XMM3
671.22 mV
Set...
Senanur Ağaç 200102002043
Beyza Duran 200102002031


V1
10.7V
XMM1
R1
10kΩ
XMM2
PR1
D2
1N914
XMM3
V: 597 mV
V(p-p): 432 pV
V(rms): 597 mV
V(dc): 597 mV
V(freq): 24.3 kHz
Multimeter-XMM1
1.01 mA
Multimeter-XMM2
1.01 mA
Multimeter-XMM3
597.425 mV
Set...
Senanur Ağaç 200102002043
Beyza Duran 200102002031


V1
10.7V
XMM1
R1
100kΩ
XMM2
PR1
D2
1N914
XMM3
V: 537 mV
V(p-p): 3.21 nV
V(rms): 537 mV
V(dc): 537 mV
V(freq): 25.7 kHz
Multimeter-XMM1
101.634 uA
Multimeter-XMM2
101.634 uA
Multimeter-XMM3
536.572 mV
Set...
Senanur Ağaç 200102002043
Beyza Duran 200102002031


V1
10.7V
XMM1
R1
1MΩ
XMM2
PR1
D2
1N914
XMM3
V: 477 mV
V(p-p): 37.7 nV
V(rms): 477 mV
V(dc): 477 mV
V(freq): 25.6 kHz
Multimeter-XMM1
10.223 uA
Multimeter-XMM2
10.223 uA
Multimeter-XMM3
477.021 mV
Set...
Senanur Ağaç 200102002043
Beyza Duran 200102002031

Tablo 3: Voltage Measurements and Current Estimates for IN4004 (Large Signal Model)

IN4004		R = 1 kΩ	R = 10 kΩ	R = 100 kΩ	R = 1 MΩ
V_{DD} = 10 V	V_D (meas.)	651.424 mV	532.61 mV	414.123 mV	295.797 mV
	I_D (calc.)	9.349 mA	946.739 µA	95.859 µA	9.704 µA
V_{DD} = 10.7 V	V_D (meas.)	655.17 mV	536.284 mV	417.75 mV	299.371 mV
	I_D (calc.)	10.045 mA	1.016 mA	102.822 µA	10.401 µA

Tablo 4: Voltage Measurements and Current Estimates for IN914 (Large Signal Model)

IN914		R = 1 kΩ	R = 10 kΩ	R = 100 kΩ	R = 1 MΩ
V_{DD} = 10 V	V_D (meas.)	668.241 mV	595.462 mV	534.72 mV	475.191 mV
	I_D (calc.)	9.332 mA	940.454 µA	94.653 µA	9.525 µA
V_{DD} = 10.7 V	V_D (meas.)	671.22 mV	597.425 mV	536.572 mV	477.021 mV
	I_D (calc.)	10.029 mA	1.01 mA	101.634 µA	10.223 µA

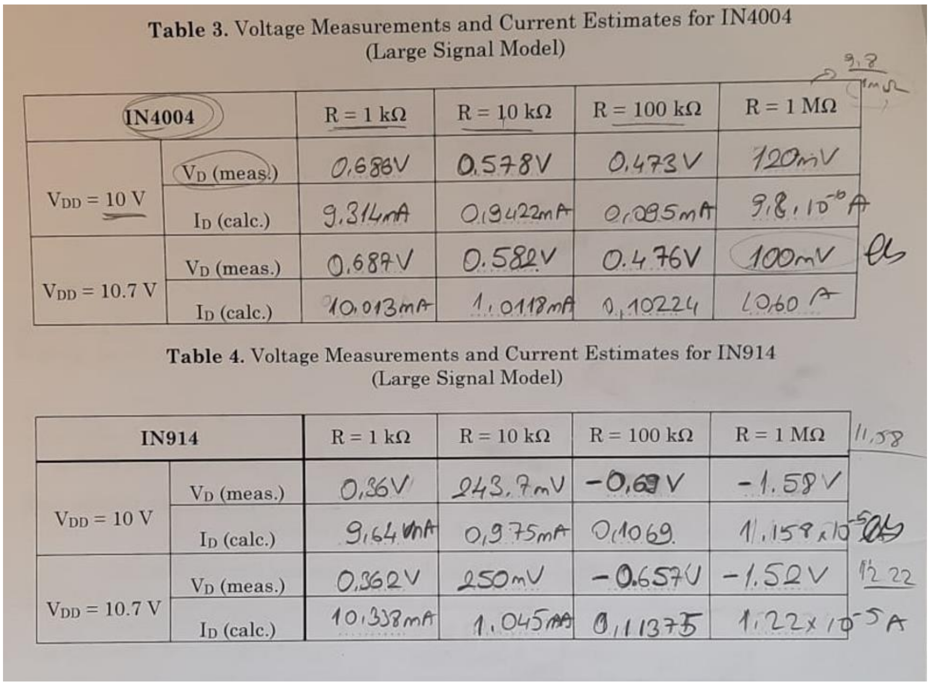


Table 3. Voltage Measurements and Current Estimates for IN4004 (Large Signal Model)

IN4004		R = 1 kΩ	R = 10 kΩ	R = 100 kΩ	R = 1 MΩ
V_{DD} = 10 V	V_D (meas.)	0,686V	0.578V	0.473V	120mV
	I_D (calc.)	9.314mA	0,9422mA	0,095mA	9,8.10⁻⁶A
V_{DD} = 10.7 V	V_D (meas.)	0.687V	0.582V	0.476V	100mV
	I_D (calc.)	10,013mA	1,0118mA	0,10224	10,60 A

Table 4. Voltage Measurements and Current Estimates for IN914 (Large Signal Model)

IN914		R = 1 kΩ	R = 10 kΩ	R = 100 kΩ	R = 1 MΩ
V_{DD} = 10 V	V_D (meas.)	0,36V	243.7mV	-0,69V	-1.58V
	I_D (calc.)	9,64mA	0,975mA	0,1069	1,158x10⁻⁵
V_{DD} = 10.7 V	V_D (meas.)	0,362V	250mV	-0.657V	-1.52V
	I_D (calc.)	10,338mA	1,045mA	0,11375	1,22x10⁻⁵A

Figure 17:Experimental results for question 2.2

2.3Forward Conduction Modelling – Finding a Small Signal Model:

Theorical Informations about Small Signal Model:

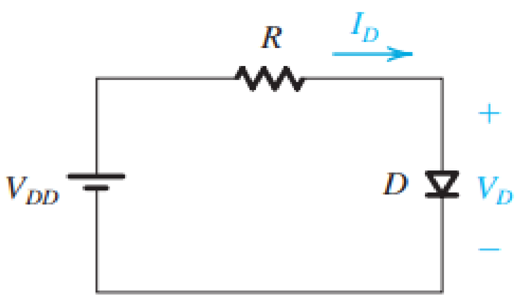


Figure 35: A simple diode circuit

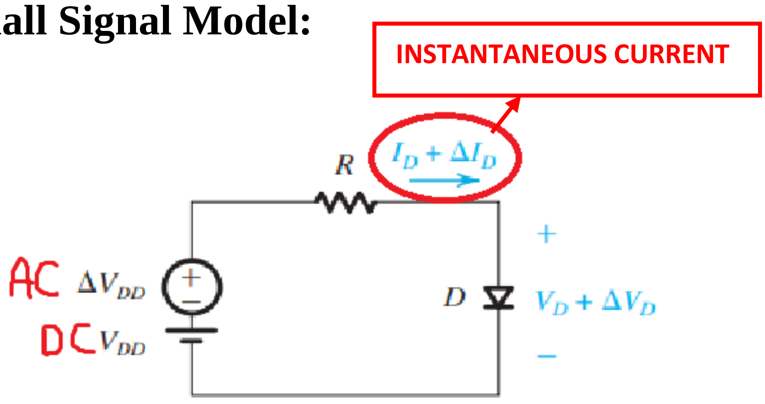
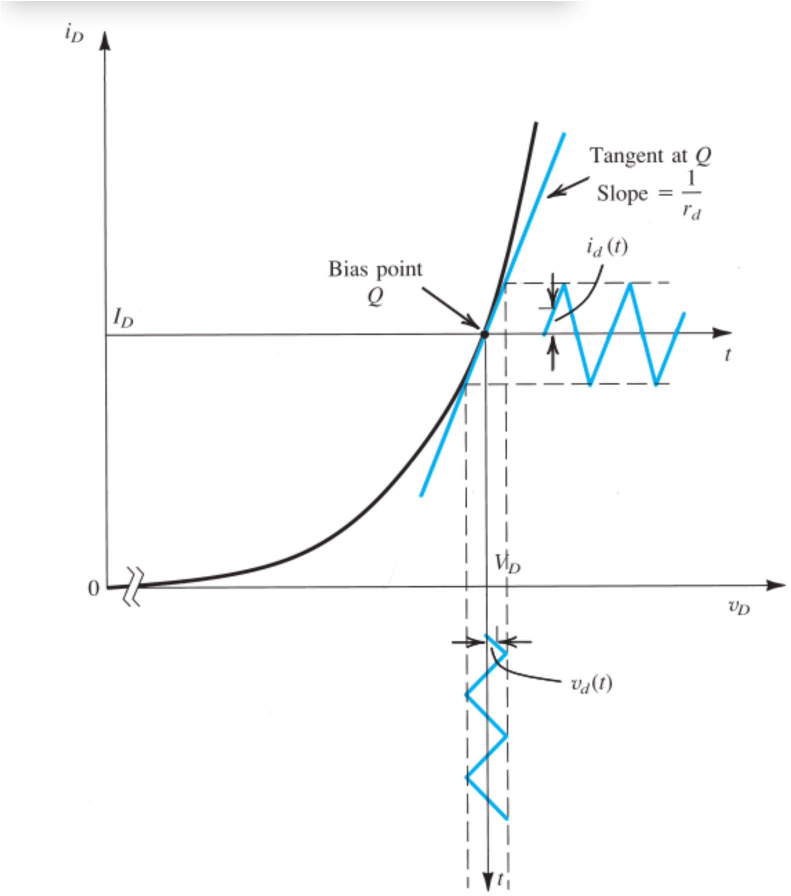


Figure 36:The situation when V_{DD} changes by ΔV_{DD}

As we can see figure 16, where a dc voltage V_{DD} establishes a dc current I_D through the series combination of a resistance R and a diode D. The resulting diode voltage is denoted V_D. As mentioned above, values of I_D and V_D can be obtained by solving the circuit using the diode exponential characteristic or, much more quickly, approximate values can be found using the diode constant-voltage-drop model.

Next, consider the situation of V_{DD} undergoing a small change ΔV_{DD}, as shown in Figure 17.As indicated, the current I_D changes by an increment ΔI_D, and the diode voltage V_D changes by an increment ΔV_D. We wish to find a quick way to determine the values of these incremental changes. Toward that end, we develop a "small-signal" model for the diode.



Purpose: To make analysis easier by linearizing the nonlinear curve using the small signal model (basically the derivative operation).

NOTATION:

$$v_D(t) = V_D + v_d(t)$$

↓ ↓ ↓

AC+DC DC AC

(superimpose)

Figure 37: Development of the diode small-signal model

Accordingly, the total instantaneously diode current $(i_D(t))$ will be :

$$i_D(t) = I_S . e^{\frac{v_D}{V_T}} \rightarrow i_D(t) = I_S . e^{\frac{V_D + v_d(t)}{V_T}}$$

which can be rewritten

$$i_D(t) = \underbrace{I_S . e^{\frac{V_D}{V_T}}}_{I_D} \underbrace{. e^{\frac{v_d}{V_T}}}_{i_d}$$

$i_D(t)$ **can be expressed as**

$$i_D(t) = I_D . e^{\frac{v_d}{V_T}}$$

Since our goal is to linearize the expression, it would make sense to somehow get rid of the exponential expression. For this, the exponential expression expands to the Taylor series. For this, $\frac{v_d}{V_T}$<<1 must be set so that it can be expanded to the series properly.

$$i_D(t) \cong I_D . (1 + \frac{v_d}{V_T})$$

$$i_D(t) \cong \underbrace{I_D}_{\text{DC}} + \underbrace{\frac{v_d}{V_T} I_D}_{\text{AC}}$$

$$i_D(t) = I_D + i_d$$

$$i_d = \frac{I_D}{V_T} V_D$$

$$\frac{V_D}{i_d} = \frac{V_T}{I_D} \rightarrow r_d = \frac{V_T}{I_D}$$

DIODE SMALL SIGNAL RESISTANCE

From the preceding we conclude that superimposed on the quantities V_D and I_D that define the dc bias point, or quiescent point, of the diode will be the small-signal quantities v_d(t) and i_d(t), which are related by the diode small-signal resistance rd evaluated at the bias point .

The small-signal analysis can be performed separately from the dc bias analysis, a great convenience that results from the linearization of the diode characteristics inherent in the small-signal approximation. Specifically, after the dc analysis is performed, the small-signal equivalent circuit is obtained by eliminating all dc sources (i.e., short-circuiting dc voltage sources and open-circuiting dc current sources) and replacing the diode by its small-signal resistance.

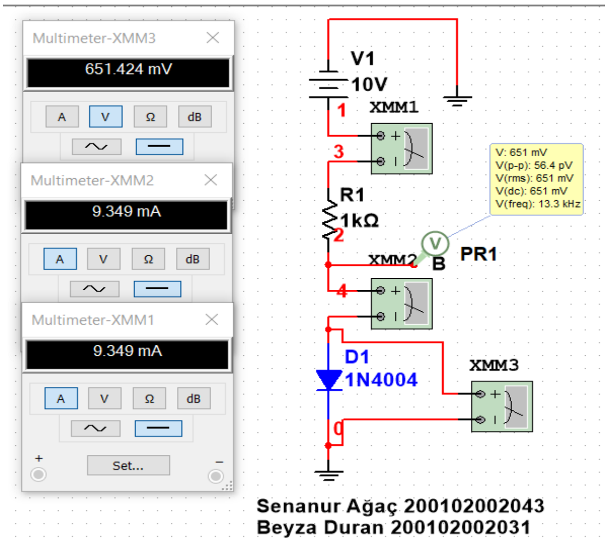


Figure 38: IN4004/ 1kΩ/with no R shunting

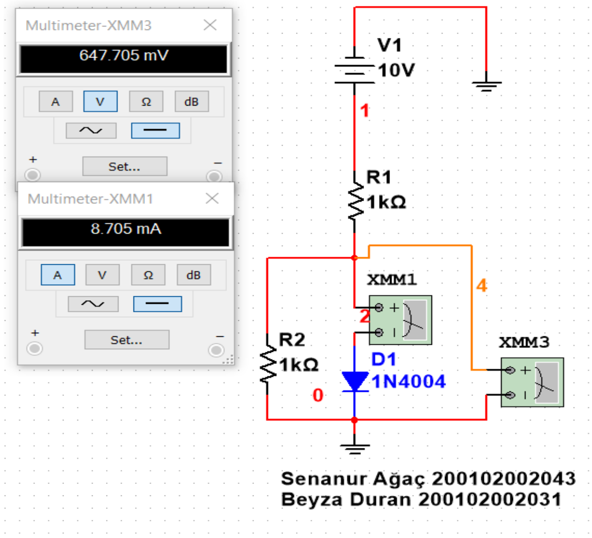


Figure 39: IN4004/1kΩ/with R = 1kΩ shunting

$$r_d = \frac{651.424\ mV - 647.705\ mV}{9.349\ mA - 8.705\ mA} = 5.77\ \times 10^{-3}\ k\Omega = 5.77\Omega$$

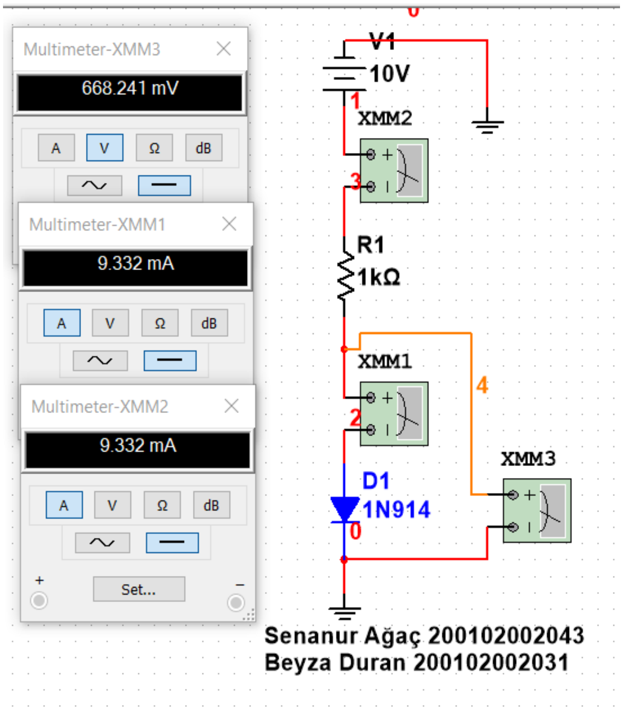


Figure 40: IN914/ 1kΩ/with no R shunting

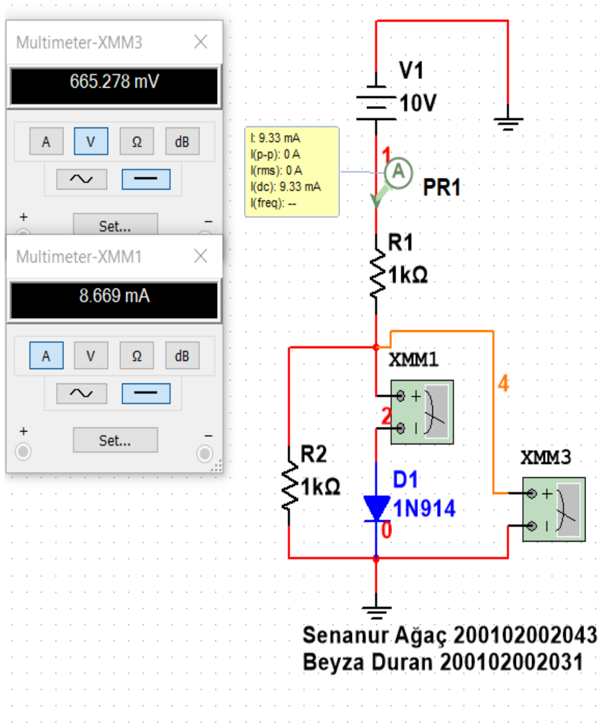


Figure 41: IN914/1kΩ/with R = 1kΩ shunting

$$r_d = \frac{668.241\ mV - 665.278\ mV}{9.332\ mA - 8.669\ mA} = 4.47\ \times 10^{-3}\ k\Omega = 4.47\Omega$$

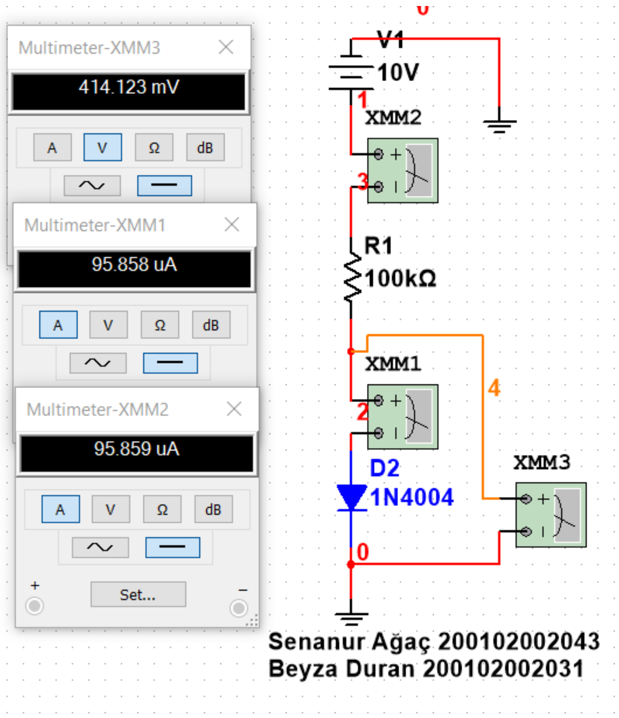


Figure 42: IN4004/ 100kΩ/with no R shunting

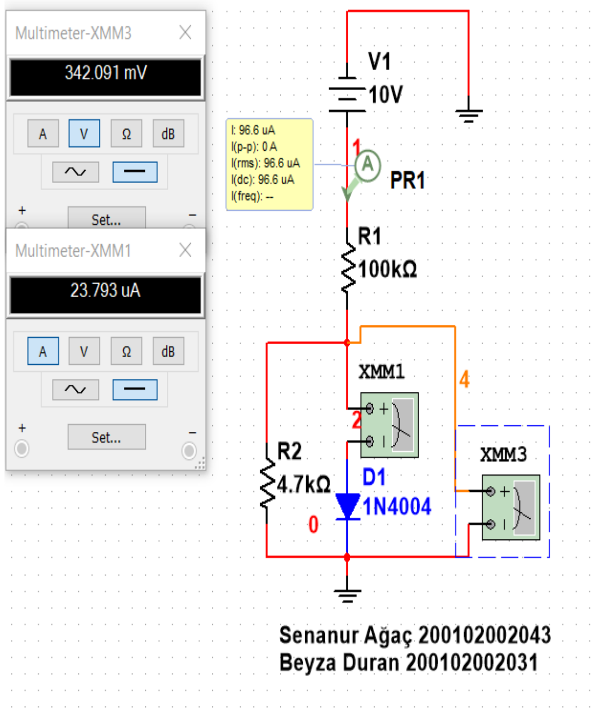


Figure 43: IN4004 / 100kΩ / with R = 4.7kΩ shunting

$$r_d = \frac{414.123\ mV - 342.091\ mV}{95.858\ \mu A - 23.793\ \mu A} = 0.99\ k\Omega$$

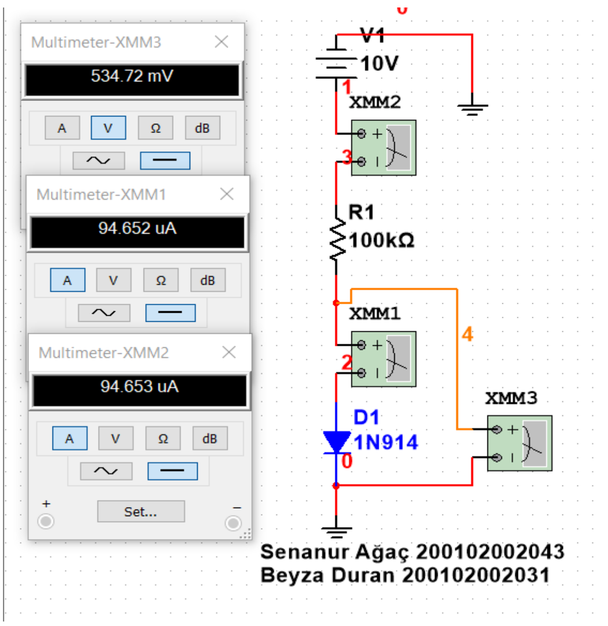


Figure 44: IN914/ 100kΩ/ with no R shunting

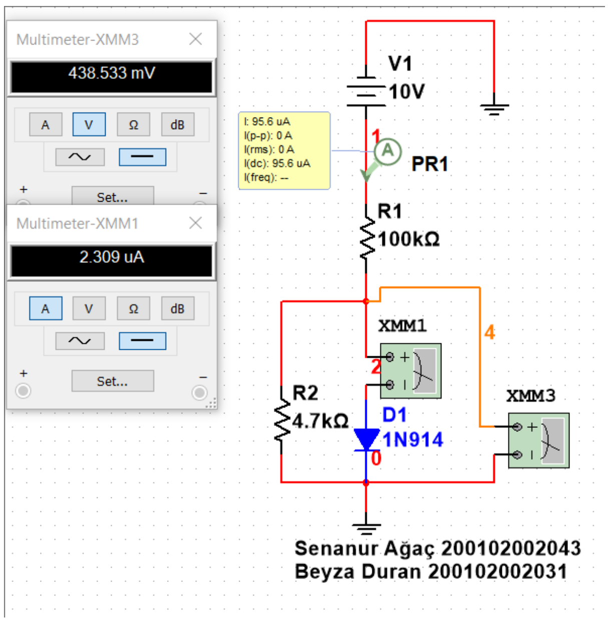


Figure 45: IN914/100kΩ/with R = 4.7kΩ shunting

$$r_d = \frac{534.72\ mV - 438.533\ mV}{94.652\ \mu A - 2.309\ \mu A} = 1.042\ k\Omega$$

Tablo 2: Voltage Measurements and r_D Estimates for IN914 and IN4004 (Small Signal Model)

	R = 1 kΩ			R = 100 kΩ		
	V_D with no R shunting	V_D with R shunting	r_D @ ~10 mA	V_D with no R shunting	V_D with R shunting	r_D @ ~0.1 mA
IN4004	I_D=9.349 mA 651.424 mV	I_D=8.705 mA 6470.705 mV	5.77 Ω	I_D=95.858 μA 414.123 mV	I_D=23.793 μA 342.091 mV	0.99 kΩ
IN914	I_D=9.332 mA 668.241 mV	I_D=8.669 mA 665.278 mV	4.47 Ω	I_D=94.652 μA 534.72 mV	I_D=2.309 μA 438.533 mV	1.042 kΩ

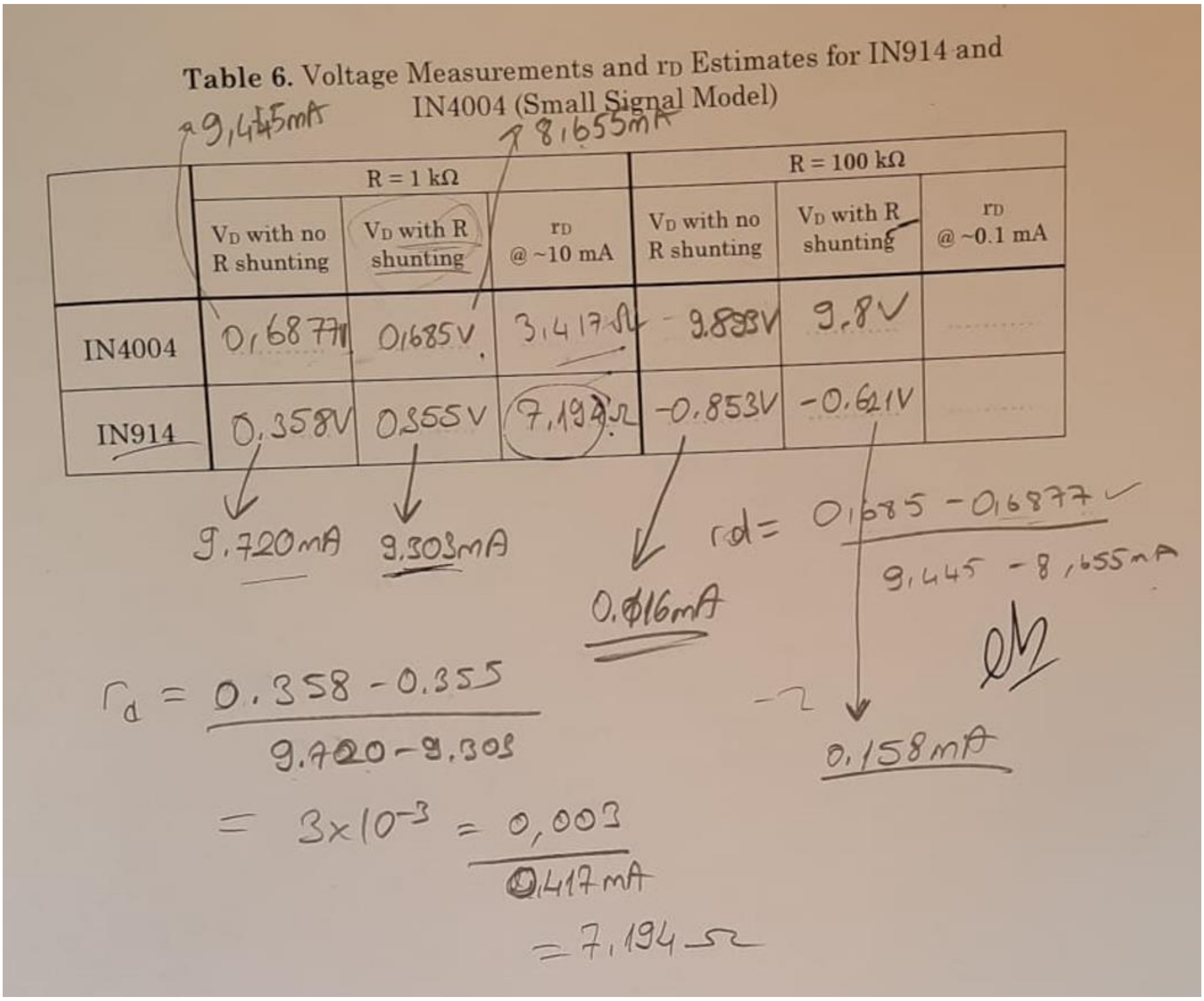


Table 6. Voltage Measurements and r_D Estimates for IN914 and IN4004 (Small Signal Model)

≈9,445mA ≈8,655mA

	R = 1 kΩ			R = 100 kΩ		
	V_D with no R shunting	V_D with R shunting	r_D @ ~10 mA	V_D with no R shunting	V_D with R shunting	r_D @ ~0.1 mA
IN4004	0,6877V	0,685V	3,417Ω	9.893V	9.8V	
IN914	0,358V	0,355V	7,194Ω	-0.853V	-0.621V	

9.720mA 9.303mA 0.016mA 0,158mA

$r_d = \frac{0,685 - 0,6877}{9,445 - 8,655\ mA}$

$r_d = \frac{0.358 - 0.355}{9.720 - 9.303} = 3\times10^{-3} = \frac{0,003}{0,417\ mA} = 7,194\ \Omega$

Figure 46:Experimental results for question 2.3