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Three-Terminal Black Box
Lab Report 5

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Aim

- To deduce the components of a three-terminal black box
- To determine the values of the resistors, the orientation of the diodes, and the voltage and orientation of the battery, if any of the above are used in the circuit.

Experimental Setup

- A black box with three connecting terminals marked A, B, and C corresponding to three components in a star connection pattern (BB1)
- A variable DC power supply (Keltronix)
- A digital multimeter (MECO 603)
- A resistor ladder
- Connecting wires

Least count of voltage supply = 0.01 V
Least count of multimeter ammeter = 0.01 mA

Range of Voltmeter = 15 V
Range of Ammeter = 20 mA

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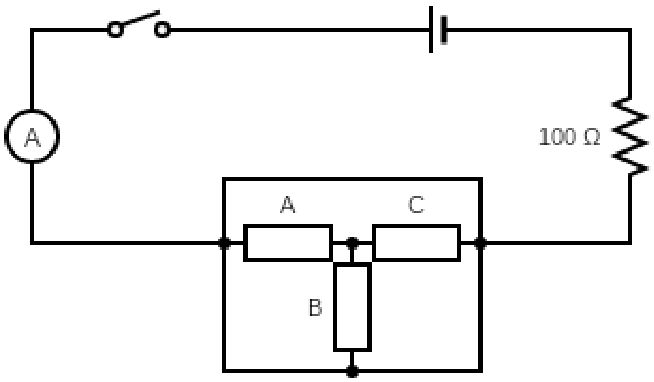

Figure 1: Experimental Setup to determine the components A, B and C in a three-terminal black box

Theoretical Background

The three-terminal black box given to us had a star connection (Figure 2). This means that any connection between a pair of terminals had two components in series. The possible components were batteries, resistors and p-n junction diodes.

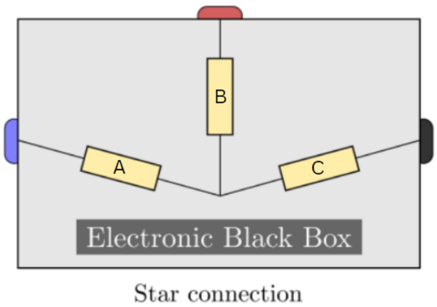

Figure 2: Schematic diagram of the star connection inside the three-terminal black box

1. **P-N Junction Diodes**: Diodes only allow current to flow through them in one direction, while they block voltage in the opposite direction. This is because a diode has a positive charge carrier and negative charge carrier part, with a layer in between without any charge carriers known as a depletion layer. The diode is said to be forward-biased when a positive voltage is applied to the anode and a negative voltage to the cathode, causing charge carriers to carry current through the diode. When the voltage is reversed (known as reverse-biasing), the current is blocked by the depletion layer.

   However, even when forward-biased, the diode only allows current to flow through it freely after a certain small positive "knee voltage" threshold has been crossed, which allows charge carriers to pass through the depletion layer. The IV graph of a diode is characterised by an exponential increase in current until the knee voltage, at which point the width of the depletion layer in the diode effectively goes to zero, causing the diode to act like a short circuit with zero resistance.

2. **Resistors**: Resistors limit the current flowing through the circuit and follow Ohm's Law (V=IR), giving a straight line in an IV graph.

3. **Batteries**: Batteries produce a potential difference across its terminals. When inserted in series in a circuit with another DC voltage supply, the voltage of the battery is added to the supply

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voltage, thereby increasing the current flowing through the circuit. However, if it is inserted in an anti-series connection (positive to positive and negative to negative), the voltage of the battery is subtracted from the supply voltage, causing the current through the circuit to reduce.

In a three-terminal black box, there are 6 possible connections - AB, BA, BC, CB, AC and CA. In a star connection box, each of these is associated with their corresponding components in series. Each of these pathways can be methodically checked to see their effect on current flow in a circuit to deduce the nature and values of each component.

Procedure

1. Setup the circuit to match the diagram in Figure 1. Calculate the resistance from the resistor ladder that must be added in series with the circuit to limit the current passing through the ammeter to avoid fusing it.
   For our ammeter, the maximum load was 250 mA, for which a minimum resistance of 60 Ω was needed to limit current upto 15 V. Hence, we used a 100 Ω resistor to ease calculations.

2. Set the ammeter to a range that can detect current in the given circuit. We used the 20 mA range, which gave us a least count of 0.01 mA.

3. First check for diodes in the circuit by running current through each pair of connections. If current flows through only one direction (for instance, if AB shows current flowing but not BA), then the arm must have a diode in it. *[Precaution: Slowly increase the voltage while checking to ensure that the knee voltage of the diode is surpassed.]*

4. If two paths with a common component do not allow current to flow through them, say AB and CB, then the common component, in this case B, is the diode. The direction in which the current does not flow indicates the reverse-bias direction of the diode.

5. Next, check for batteries by noting the difference in the current flowing one way through a path as opposed to the opposite direction. The direction in which the current increases is when the battery is in series, while the lower current orientation indicates an anti-series connection. *[Precaution: Since the black box may contain a battery, always use a resistor that is significantly greater than the minimum resistance required to avoid fusing the ammeter to account for additional current flow.]*

6. Any connections that give the same current reading in both directions indicate two resistors in series. To detect a single resistor, note any deviation from the expected current due to the single 100 Ω resistor.

7. For a given connection through the black box, gradually vary the voltage from the supply and record how the current changes. *[Precaution: The DC voltage supply box may not display the accurate voltage supplied. By connecting the ammeter with a known resistor to the DC supply, check the true voltage supplied for every reading using V=IR.]*

8. In connections which contain a diode, take a fine set of readings for the first 2 V to confirm its presence and determine the knee voltage of the diode.

9. Plot the IV graphs for every pair of connections to determine the nature and values of each component in the black box. An exponential curve in the beginning of an IV graph confirms the presence of a diode in the circuit. A straight line indicates the presence of a resistor. The slope of the straight line in a VI graph gives the value of resistance. A difference in the current flowing in one direction and the opposite direction implies the presence of a battery.

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Part A: Deducing the Circuit

Observations

Using the circuit in Figure 1, each connection was systematically checked for current flow.

Black Box used: BB1
Voltage = 1 V

Connection	AB	BA	AC	CA	BC	CB
Current (mA)	0.89	0.89	0.00	0.66	0.00	0.77

Table 1: Current flow through every pair of connections in the three terminal black box

Analysis

From the data in Table 1, we can deduce that:

- A and B are both resistors since the current flow through AB and BA is the same.
- C is a diode since there is no current flow through AC and BC, where C is the common component.
- C is directed inwards (towards the junction of the star connection) since current only flows from C to A or B, but not the other way.
- The black box does not have any batteries.

This leads us to the following diagram of the black box:

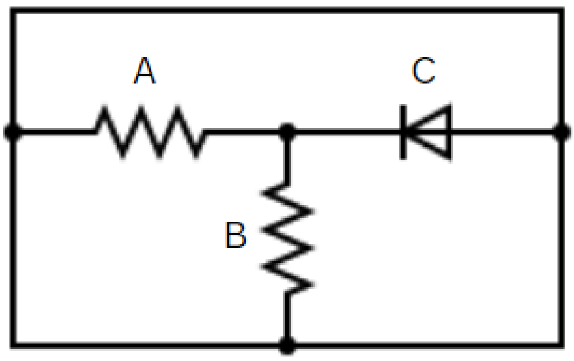

Figure 3: Schematic circuit diagram of the deduced components inside the three-terminal black box

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Part B: Determining component information

0.1 Path AB

Since A and B are both resistors, the circuit diagram for path AB can be simplified as:

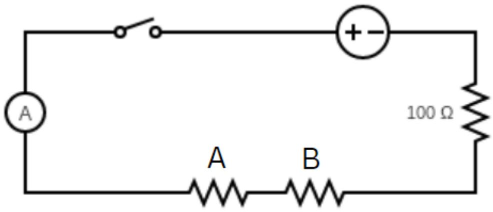

Figure 4: Schematic circuit diagram of the circuit through AB

Observations

The IV data for path AB is plotted in the graph below:

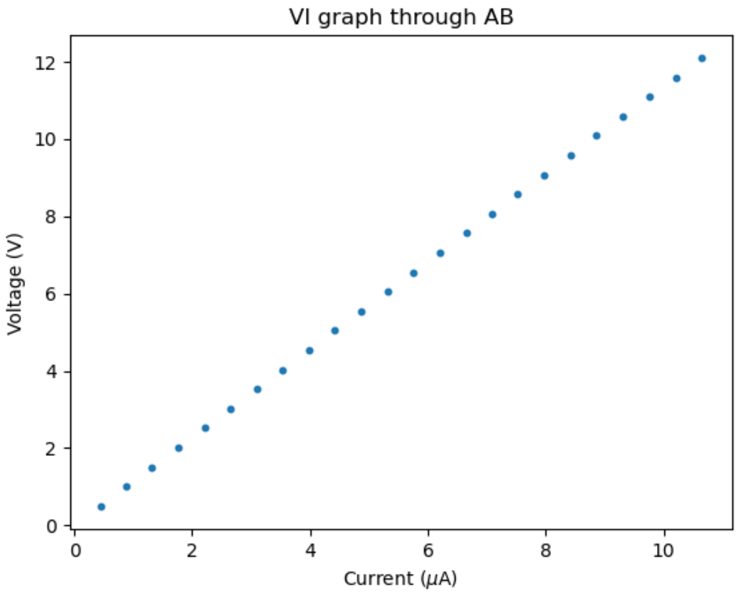

Figure 5: The purely linear trend confirms that AB is composed of only resistors

The data for figure 5 is tabulated in the appendix.

Analysis

Since we know that A and B are both resistors in series, their collective resistance is simply the sum of their individual resistances. From Ohm's law we know that $R = V/I$, so the slope of Figure 5 will give us the equivalent resistance of A+B+100, since the 100 Ω resistor is also in series with it.

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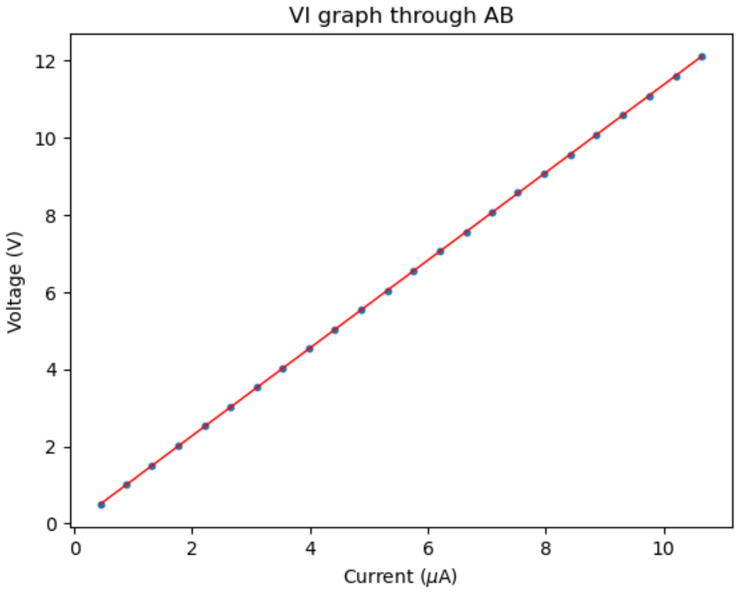

Figure 6: The slope of the VI graph gives the resistance of A+B+100

Slope of AB graph = 1.137 V/mA = 1137 Ω

Resistance (A+B) = 1037 Ω

0.2 Path CB

Since C is a diode and B is a resistor, only CB will allow current to flow through it due to the orientation of the diode. The circuit can be simplified as:

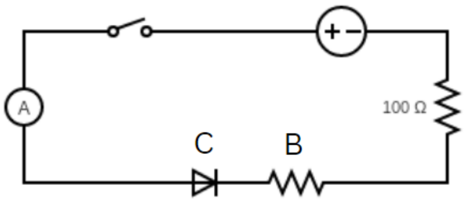

Figure 7: Schematic circuit diagram of the circuit through AB

Observations

The IV data for path CB is plotted in the graph below:

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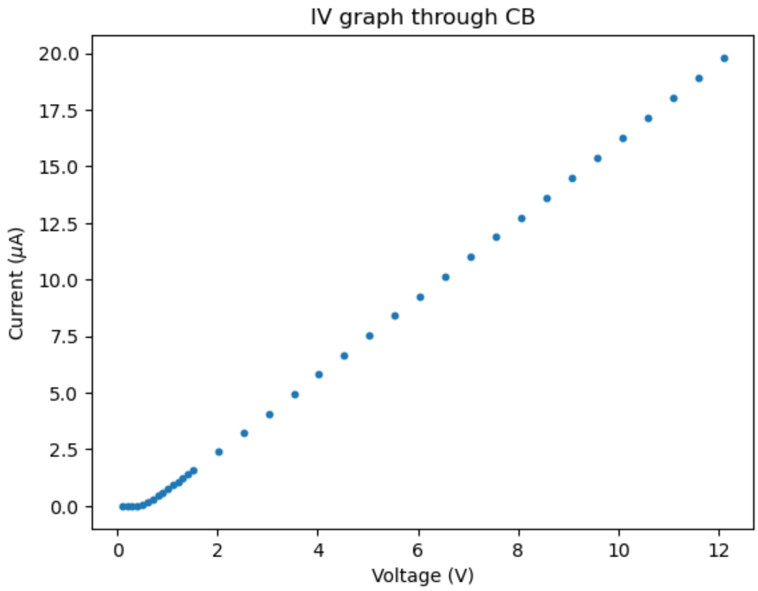

Figure 8: The initially non-linear curve confirms the presence of a diode in path CB

The data for figure 8 is tabulated in the appendix.

Analysis

The non-linear trend of the data for small values of voltage confirms the presence of a diode in path CB. The slope of the linear part indicates the resistance B+100, since the diode effectively has zero resistance past its knee voltage.

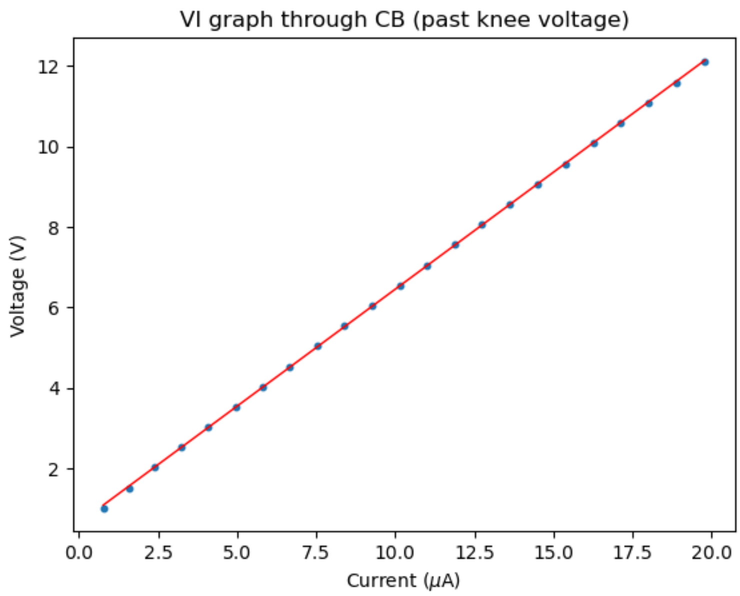

Figure 9: The slope of the VI graph gives the resistance of B+100

Slope of CB graph = 0.580 V/mA = 580 Ω

Resistance B = 480 Ω

We can also determine the knee voltage of the diode by closely looking at the start of the graph.

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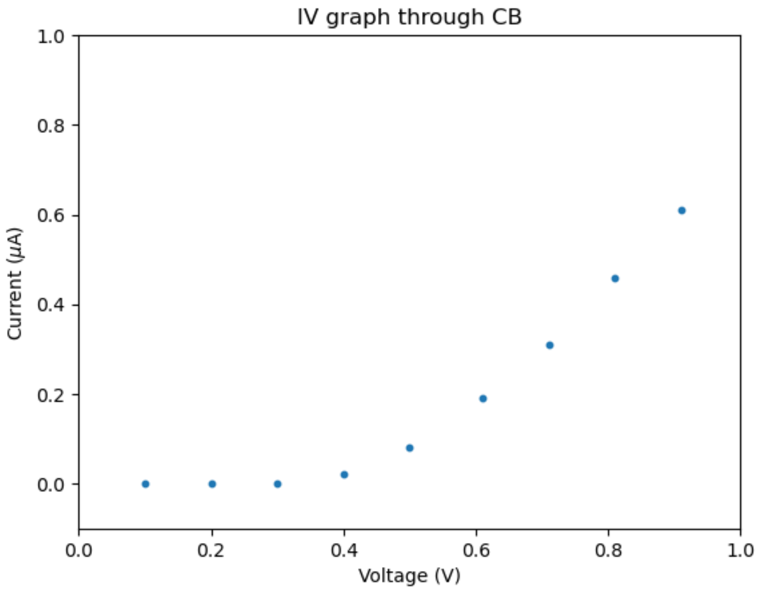

Figure 10: The point after which the graph becomes linear indicates the knee voltage of the diode

The knee voltage is the point at which the width of the depletion layer effectively goes to zero, and the diode acts like a short circuit with zero resistance. It is 0.3 V for germanium semiconductors and 0.7 V for silicon semiconductors. From figure 10 we can see that the trend becomes linear after about 0.6-0.8 V, which means that the diode likely contains silicon semiconductors.

0.3 Path CA

Since C is a diode and A is a resistor, only CA will allow current to flow through it due to the orientation of the diode. The circuit can be simplified as:

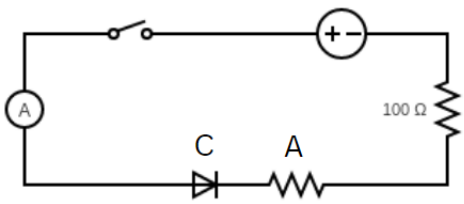

Figure 11: Schematic circuit diagram of the circuit through CA

Observations

The IV data for path CA is plotted in the graph below:

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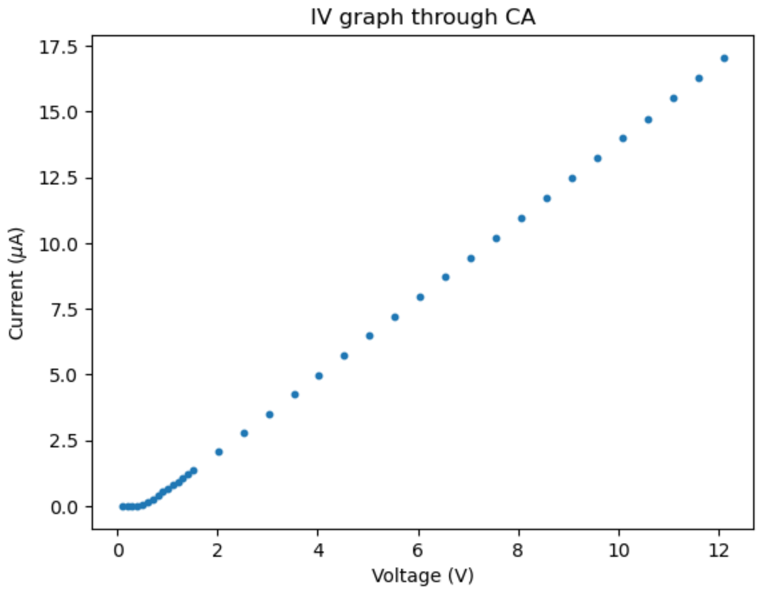

Figure 12: The initially non-linear curve confirms the presence of a diode in path CB

The data for figure 12 is tabulated in the appendix.

Analysis

The non-linear trend of the data for small values of voltage confirms the presence of a diode in path CA. The slope of the linear part indicates the resistance A+100, since the diode effectively has zero resistance past its knee voltage.

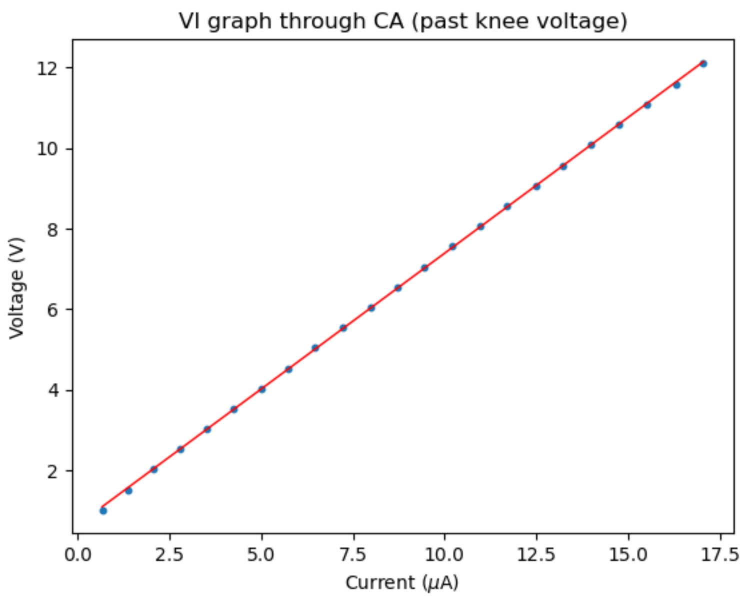

Figure 13: The slope of the VI graph gives the resistance of A+100

Slope of CA graph = 0.674 V/mA = 674 Ω

Resistance A = 574 Ω

We can also determine the knee voltage of the diode by closely looking at the start of the graph.

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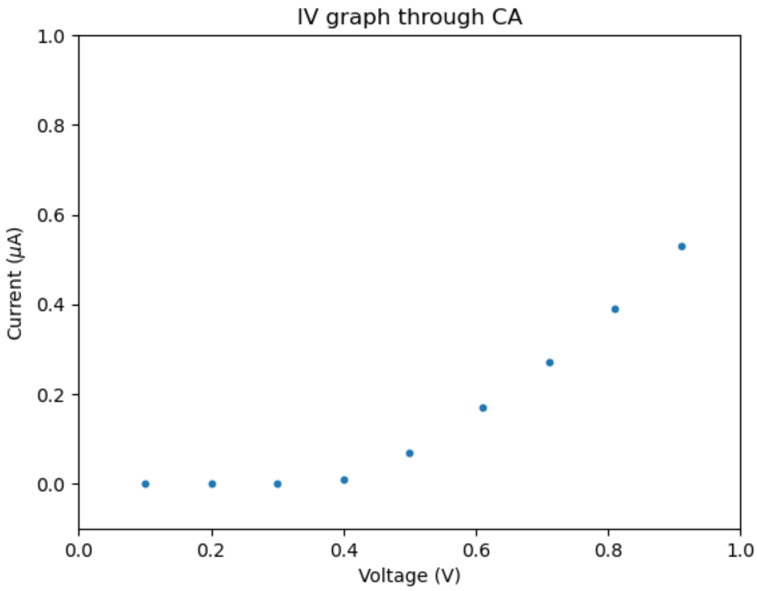

Figure 14: The point after which the graph becomes linear indicates the knee voltage of the diode

This graph also shows a linear trend after about 0.6-0.8 V, which suggests that the knee voltage of diode C is around 0.7 V and likely contains silicon semiconductors.

Error Analysis

The sum of resistance A and B found from the separate measurements is $574 + 480 = 1054\ \Omega$, which is 17 Ω more than the resistance found from the measurement through path AB (i.e. 1037 Ω). This discrepancy could be due to the following reasons:

- The least count errors of the voltmeter (0.01 V) and ammeter (0.01 mA).
- Non-ideal behaviour of the diode, causing it to contribute some resistance even past its knee voltage.

Results

Circuit diagram of three-terminal black box:

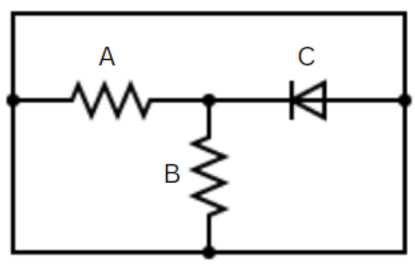

Figure 15: Schematic circuit diagram of the components inside the three-terminal black box

Resistance A = $\boxed{574\ \Omega}$

Resistance B = $\boxed{480\ \Omega}$

Knee Voltage of Diode C = $\boxed{0.6 - 0.8\ V}$ (most likely silicon)

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Appendix

Source Voltage (V)	Current (mA)
0.50	0.44
1.01	0.89
1.51	1.32
2.02	1.77
2.52	2.21
3.03	2.65
3.53	3.10
4.03	3.54
4.53	3.99
5.04	4.42
5.54	4.86
6.04	5.31
6.55	5.75
7.05	6.19
7.56	6.65
8.06	7.08
8.57	7.52
9.07	7.97
9.57	8.42
10.08	8.86
10.58	9.30
11.09	9.75
11.59	10.20
12.10	10.65

Table 2: IV data for circuit through path AB

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Source Voltage (V)	Current (mA)
0.10	0.00
0.20	0.00
0.30	0.00
0.40	0.02
0.50	0.08
0.61	0.19
0.71	0.31
0.81	0.46
0.91	0.61
1.01	0.77
1.11	0.92
1.21	1.08
1.31	1.24
1.41	1.40
1.51	1.57
2.02	2.39
2.52	3.25
3.03	4.09
3.53	4.95
4.03	5.81
4.53	6.67
5.04	7.54
5.54	8.40
6.04	9.27
6.55	10.14
7.05	11.00
7.56	11.87
8.06	12.75
8.57	13.62
9.07	14.50
9.57	15.37
10.08	16.26
10.58	17.14
11.09	18.02
11.59	18.91
12.10	19.80

Table 3: IV data for circuit through path CB

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Source Voltage (V)	Current (mA)
0.10	0.00
0.20	0.00
0.30	0.00
0.40	0.01
0.50	0.07
0.61	0.17
0.71	0.27
0.81	0.39
0.91	0.53
1.01	0.66
1.11	0.79
1.21	0.92
1.31	1.06
1.41	1.20
1.51	1.35
2.02	2.06
2.52	2.78
3.03	3.52
3.53	4.25
4.03	4.99
4.53	5.73
5.04	6.47
5.54	7.21
6.04	7.97
6.55	8.71
7.05	9.45
7.56	10.21
8.06	10.96
8.57	11.71
9.07	12.48
9.57	13.23
10.08	14.00
10.58	14.74
11.09	15.52
11.59	16.30
12.10	17.06

Table 4: IV data for circuit through path CA