ECE360: Electronics

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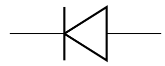
Contents

1 Diodes

A **diode** is an electronic valve that allows current to flow in one direction.

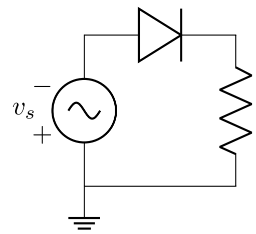


The cathode is the vertical line and typically corresponding to a black strip on the physical diode, and the triangle is the anode. Current can only flow in the direction of the arrow. Diodes are an example of a **two-terminal device,** which only has a single voltage and a single current.

The **ideal diode** has the following properties:

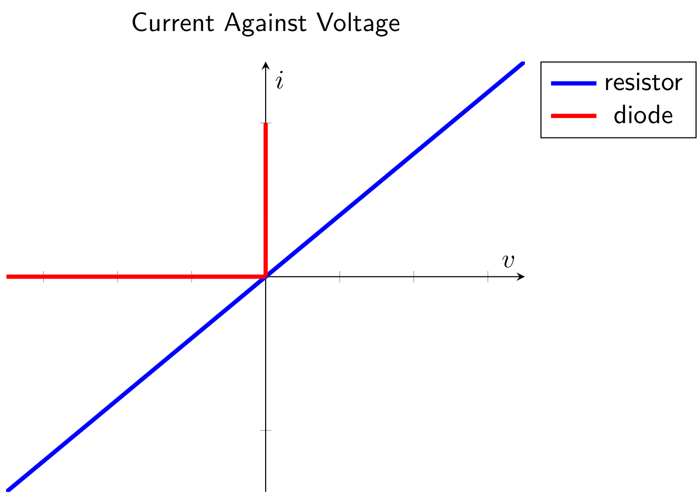
- Acts as a short-circuit when ON or conducting
- Acts as an open-circuit when OFF or not conducting

One of the most common uses is a **Half-wave rectifier,** which is used for generating a DC signal from a pure AC signal...

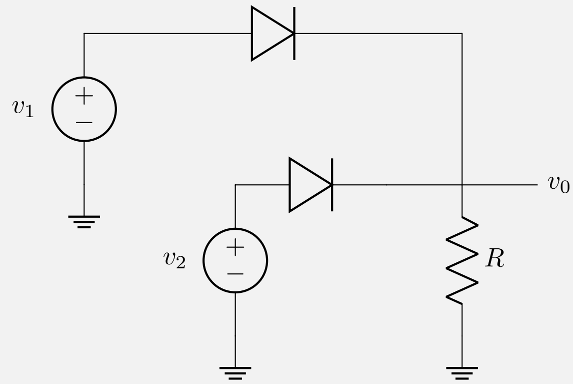


The AC source would produce a sinusoidal pattern. If $v_s > 0$, the diode is ON, and the voltage drop across the resistor is $v_0 = v_S$. IF $v_s < 0$, the diode is OFF and the voltage drop across the resistor is $v_0 = 0$.

A diode is an example of a **non-linear** component, meaning that we cannot use our standard tools of circuit analysis. Instead, we need to *assume* a state, *analyze* the circuit, then *verify* it. A helpful tool, is by looking at the graph of current against voltage:



Example 1:

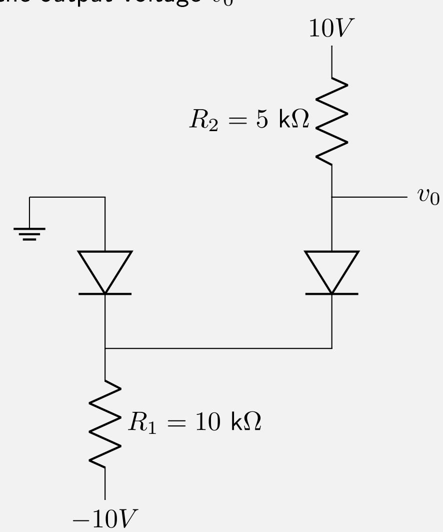


which can be described by the table

V_1	D_1	V_2	D_2	V_0
5V	ON	5V	ON	5V
5V	ON	0V	OFF	5V
0V	OFF	5V	ON	5V
0V	OFF	0V	OFF	0V

which represents an OR gate.

Example 2: Suppose we wish to find the output voltage v_0



Suppose both diodes are ON, i.e. they act as short circuits. Then $v_0 = 0V$. However, if we compute the currents through D_1 and D_2, we'll see that D_1 has current flowing in the opposite direction! This means that we have to repeat, assume a different diode configuration, and verify again.

If the right diode was ON, then the current through both resistors would be 1.33 mA, setting $v_0 = 3.33$ V. The voltage across the left diode is negative, so everything agrees.

1.1 Terminal Characteristics of a PN-Junction

In an actual PN-junction, there are three regions we will discuss, highlighted in yellow below. However, in this course, we will only be focusing on the forward and reverse regions.

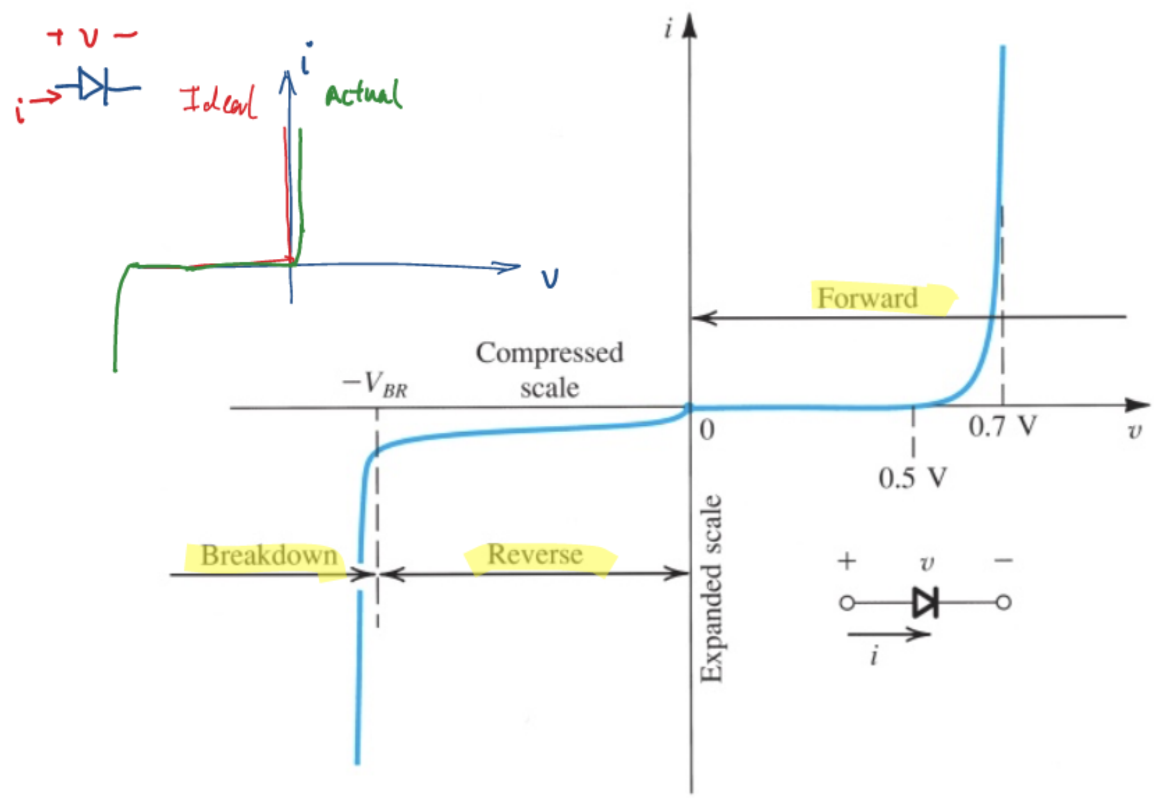


Figure 4.8 The silicon diode i–v relationship with some scales expanded and others compressed in order to reveal details.

Forward Bias ($v > 0$): The current has an exponential relationship, given by

$$i = I_s \left(e^{v/v_T} - 1 \right), \tag{1.1}$$

where v_T is the **thermal voltage,** given by

$$v_T = \frac{kT}{q} \approx 25 \text{ mV} \tag{1.2}$$

where k is Boltzmann's constant, T is the temperature, and q is the charge of an electron. I_s is the **saturation current,** which is a tiny number (on the scale of nanoamperes). The saturation current doubles roughly every $+5°$C increase in temperature and is proportional to the cross-section of the diode. Because $v \gg v_T$ typically, we can ignore the -1 constant. This means we can write the voltage drop as

$$v = v_T \ln(i/I_s) = 2.303 v_T \log(i/I_s).$$

Suppose we have two diodes where the currents are i_1, i_2 and voltages are v_1, v_2. Then:

$$\frac{i_2}{i_1} = e^{\frac{v_2 - v_1}{v_T}}$$
$$v_2 - v_1 = v_T \ln(i_2/i_1) = (60 \text{ mV}) \log(i_2/i_1).$$

Writing everything in terms of logarithms is important in practice and engineering because we are often interested in the *order of magnitude* of currents and voltages.

Temperature Dependence:

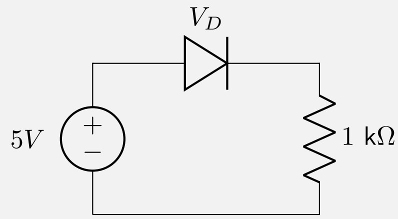
- At constant current, the voltage drop decreases by approximately 2 mV for every $1°$C increase in temperature.
- I_S doubles roughly every $5°$C increase in temperature.

Reverse Bias ($v < 0$): Since $v \ll v_T$, the exponential term can be ignored, and we have a constant:

$$i = -I_S.$$

Note that the actual reverse current is much larger than the saturation current. For example, $i_{\text{reverse}} = -1$ nA when $I_S = -1$ pA.

Example 3: Calculate the diode voltage and current in the circuit below. Assume that the diode voltage is 0.7 V at 1 mA and $v_T = 25$ mV.



Using the above information, we have:

$$1 \text{ mA} = I_s e^{(0.7V)/(25mV)}$$
$$\Longrightarrow I_s = 6.9 \times 10^{-16} \text{ A}.$$

The current through the diode is

$$I_D = I_S e^{V_D/v_T}$$

And Kirchoff's Loop Rule gives us

$$5 - V_D = I_D R.$$

Solving this using a graphing calculator, we get

$$I_D = 4.264 \text{ mA}$$
$$V_D = 0.736 \text{ V}.$$

We can also use an iterative solution. Recall that

$$v - v_0 = v_T \ln\left(\frac{i}{i_0}\right),$$

where we are given $v_0 = 0.7V$ and $i_0 = 1$ mA.

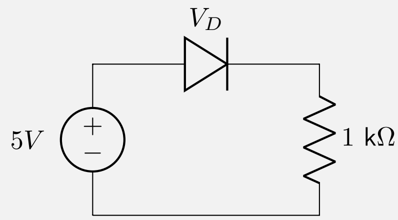
We can guess $v_1 = 0.5V$, which gives $i_1 = 4.5$ mA. Using this new current, we can compute $v_2 = 0.738V$, and get the current to be $i_2 = 4.262$ mA. In general:

$$v_{n+1} = v_0 + v_T \ln\left(\frac{i_n}{i_0}\right)$$
$$i_{n+1} = \frac{5 - v_{n+1}}{R}$$

We can build a simpler model of the diode, called the **Constant Voltage Drop** (CVD) model, which is the same as an ideal diode, except the graph is shifted $0.7V$ to the right. That is, if the voltage drop is lower than $0.7V$, the diode will be closed, otherwise the voltage drop is $0.7V$ and current is able to flow through freely.

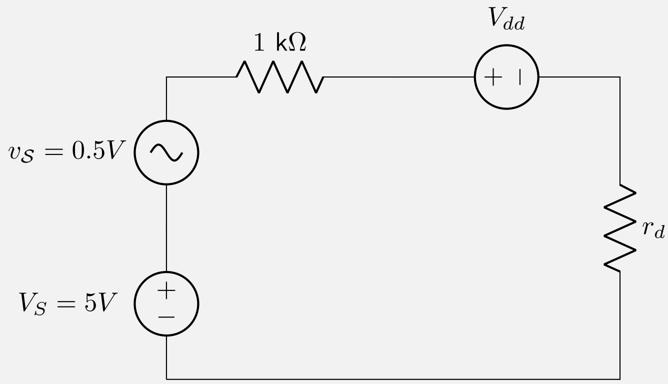
Another model is the **small signal model.** There are certain problems where the diode is in the forward bias region, but is operating in a very small range. In this case, we can approximate the diode as a linear resistor, with a voltage drop of $0.7V$. This is a good approximation for small signal diodes, but is not accurate for large signal diodes.

Example 4: Find the variation on the diode voltage given the supply is $V_{dd} = 5V \pm 0.5V$.



We've already computed that $V_D = 0.736V$ when $V_S = 5V$. We can compute $V_{S,max} = 0.739V$ and $V_{S,min} = 0.736V$. But computing these numbers without a computer is difficult (since we want precision). Instead, we can use a small signal model, which approximates the diode as a resistor and a voltage source.

Specifically, we can write $V_S = 5$ V as our operating point, and v_S, allowing us to draw,

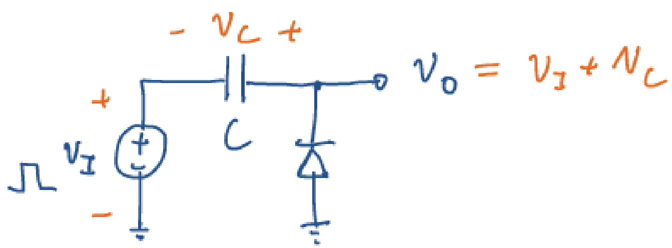


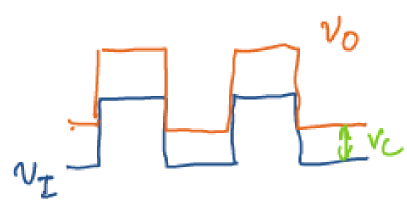
Using our above information, we can compute $r_d = 5.8\Omega$, so

$$v_d = \frac{r_d}{R + r_d} \times v_S = \pm 3 \text{ mV}$$

2 Clamping Circuits

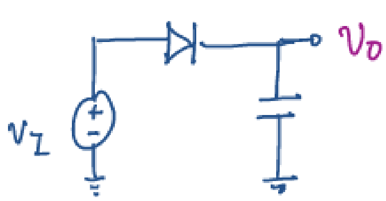
2.1 Clamped Capacitor Circuits

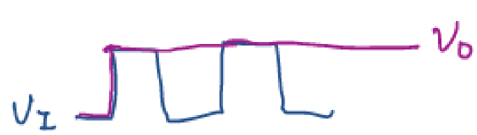




Example

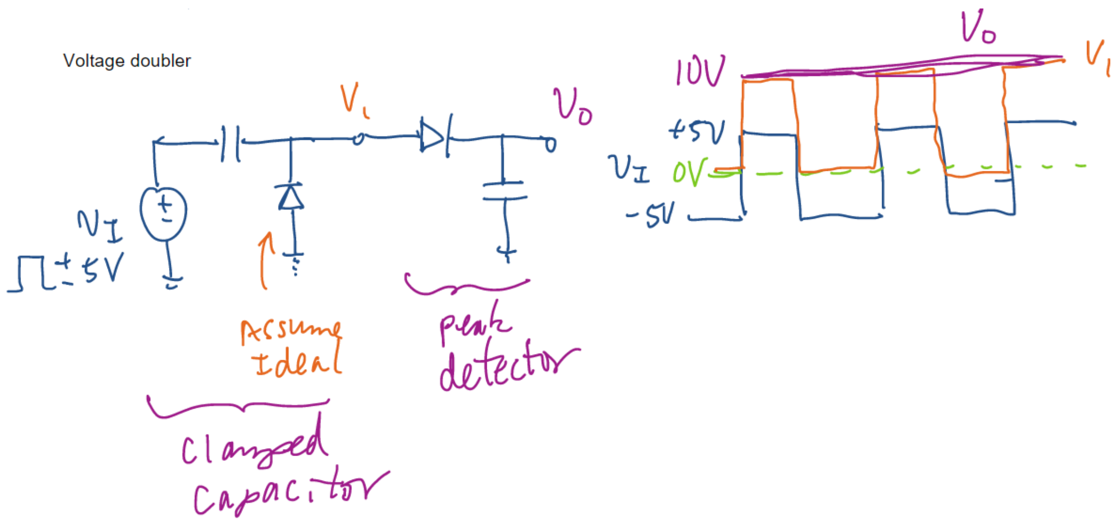
2.2 Peak Detector





2.3 Voltage Doubler

This is very useful because we can generate a voltage higher than the source that we can supply.



3 Breakdown Region

After a certain voltage is sustained across the diode in reverse bias, it can break down (avalanche effect). **Zener diodes** operate in this region and are often represented as a constant voltage source of $V_z = 5V$.