ECE 3337

Electronic Circuits

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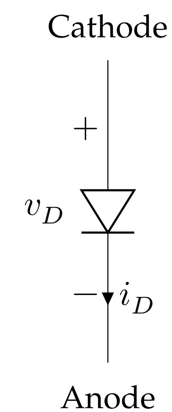
Contents

1 Introduction & Review

This course deals with analysis and design of electronic circuits, to understand the basics of this course, we will need to learn to analyze basic transistor and diode circuits, this will be reviewed below.

1.1 The Diode

A **diode** is shown in the circuit below.



An ideal diode acts as a one-way current path that only allows flow from cathode to anode.

- When $v_D > 0$ the diode acts as a **short-circuit** and is said to be **forward-biased**
- When $v_D < 0$ the diode acts as an **open-circuit** and is said to be **reverse-biased**

The **diode voltage, v_D** is defined as the voltage from anode to cathode:

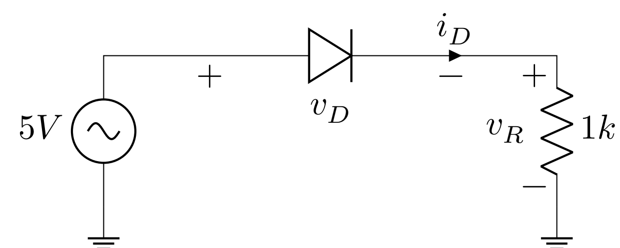
$$v_D = v_{\text{cathode}} - v_{\text{anode}}$$

1.1.1 The Constant Voltage-Drop Model

Diodes are **non-linear** elements, they actually follow an exponential i-v curve, but this makes manual analysis next to impossible, so in order to analyze circuits with diodes, we introduce the **constant voltage-drop model** where we assume that the diode voltage v_D has a fixed value if the diode is forward-biased, usually this value is assumed to be 0.7 V. This means that

- When $v_D > 0.7$ the diode is forward-biased
- When $v_D < 0.7$ the diode is reverse-biased

Lets deal with a simple example using this model, lets find v_R in the circuit below



In order to solve diode circuits, we must follow the steps below:

1. Make a guess for each diode's biasing (forward, reverse)
2. Analyze the circuit as if the guesses are correct
3. Validate the guesses to see if they are correct based on the biasing conditions

For this circuit lets assume that the diode is forward-biased and write KVL

$$
\begin{gathered}
v_{\text{src}} = v_D + v_R \\
v_{\text{src}} = v_D + 1k(i_D) \\
v_{\text{src}} - v_D = 1k(i_D) \\
i_D = \frac{v_{\text{src}} - v_D}{1k} = \frac{5 - 0.7}{1k} = 4.3\text{mA}
\end{gathered}
$$

In this case, when guessing that our diode is forward-biased, our $i_D > 0$, so our guess was correct. And the circuit operates as we guessed with 4.3 mA flowing through it If we assume that the diode is reverse-biased, we must validate that $v_D < 0.7$

1.1.2 Biasing & Non-Linear Elements

Since we are often dealing with non-linear elements in this course, a big part is modelling how they respond to **small signals** Since the i-v curve of a diode is exponential we must essentially find the point on the i-v curve where the diode is operating, this point is called a **biasing-point** or **bias**

Once we find this point, we can assume local-linearity of the i-v curve for a small enough signal.

1.1.3 The Small Signal Model

In order to find out how we can model diodes with small signal fluctuations we must derive it ourselves the exponential model of a diode can be written below.

$$i_D = I_s \left[\exp\left(\frac{v_D}{V_T}\right) - 1\right]$$

Now lets suppose we add some fluctuations in the voltage and current Δv_D and Δi_D respectively

$$i_D + \Delta i_D = I_s \left[\exp\left(\frac{v_D + \Delta v_D}{V_T}\right) - 1\right]$$

Lets also ignore the 1 term since it can be insignificant for sufficiently large values of v_D

$$i_D + \Delta i_D = I_s \left[\exp\left(\frac{v_D + \Delta v_D}{V_T}\right)\right]$$

$$i_D + \Delta i_D = I_s \exp\left(\frac{v_D}{V_T}\right) \exp\left(\frac{\Delta v_D}{V_T}\right)$$

if Δv_D is small we can use the fourier-series exapansion to approximate it: $\exp(x) = 1 + x$

$$i_D + \Delta i_D = I_s \exp\left(\frac{v_D}{V_T}\right)\left[1 + \frac{\Delta v_D}{V_T}\right]$$

$$i_D + \Delta i_D = I_s \exp\left(\frac{v_D}{V_T}\right) + \Delta v_D \cdot \frac{I_s \exp\left(\frac{v_D}{V_T}\right)}{V_T}$$

With our approximation from earlier we can sub in i_D to get the following

$$i_D + \Delta i_D = i_D + \frac{i_D}{V_T} \cdot \Delta v_D$$

This means that

$$\Delta i_D = \frac{i_D}{V_T} \cdot \Delta v_D$$

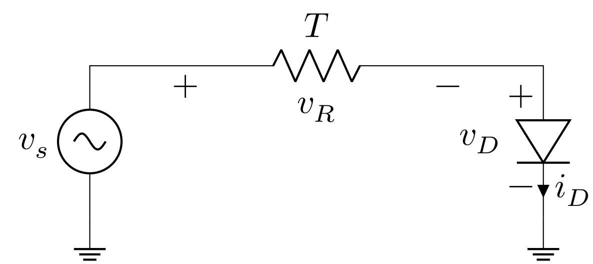
Giving us a simple linear small-signal model of a resistor, so during ac-analysis we can swap out our forward-biased diodes for resistors of value r_D

$$r_D = \frac{V_T}{i_D}$$

1.1.4 Small Signal Model: Example

Now lets do an example, where we need to find the diode voltage v_D

- $v_s = 10 + \sin \omega t$ V
- $R = 10$ k
- $V_T = 25$ mV



As always we start with DC analysis to find the bias point of the diode.

Assume diode is forward-biased:

$$v_s = v_R + v_D$$

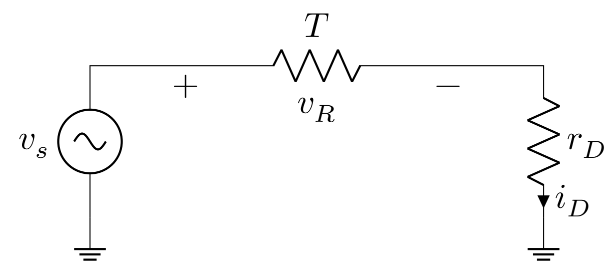
$$v_s = R(i_D) + 0.7$$

$$i_D = \frac{v_s - 0.7}{R} = \frac{10 - 0.7}{10k} = 0.93\text{mA}$$

So our guess was correct since $i_D > 0$, this gives a bias-point of $(0.7\text{V}, 0.93\text{mA})$

Now lets look at the AC part, with the small signal model, replacing the diode with the resistor

$$r_D = \frac{V_T}{i_D} = \frac{25mV}{0.93mA} = 27\Omega$$



This gives the AC part of our v_D as

$$v_D = \left(\frac{r_D}{r_D + R}\right) \cdot v_s$$

$$v_D = \left(\frac{27}{27 + 10k}\right) \cdot \sin \omega t = 2.7m \cdot \sin \omega t \text{V}$$

In order for the small signal model to be accurate we require that the small signal voltage fulctuation $v_D < V_T$ Here $2.7mV < 25mV$ so this is quite accurate of an approximation.

All in all our complete $v_D(t)$ becomes the sum of the DC and AC points:

$$v_D(t) = 0.7 + 2.7\text{m} \cdot \sin \omega t \, \text{V}$$

1.1.5 The Flowchart for Diode Analysis

Now with a bunch under our belt we can create a basic flowchart for diode circuit analysis

1. DC Analysis, make assumptions for each diode's operating mode
2. Validate the assumptions
    1. Forward-Biased $\rightarrow i_D > 0$
    2. Reverse-Biased $\rightarrow v_D < 0.7$
3. Find small-signal resistance $r_D = \frac{V_T}{i_D}$

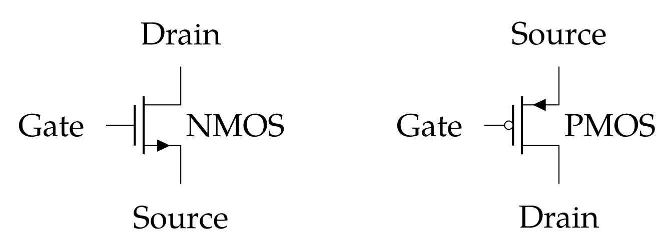
4. AC analysis, replcae forward biased diodes with a resistor r_D and reverse-biased with open circuits
5. Combine DC and AC analysis answers for the total voltages

1.2 Transistors

A **transistor** is a three terminal device. At a high-level it functions as an electrically controlled switch. There are many flavours of transistors but the most basic ones are the **MOSFET** and the **BJT**. MOSFET is an acronym for Metal Oxide Semiconductor Field-Effect Transistor, BJT is an acronym for Bipolar Junction Transistor. This chapter will cover the basics of each device, and basic circuit analysis with them.

1.2.1 The MOSFET

The MOSFET is a type of transistor, and it features three terminals. The **Gate** G, **Source** S, and **Drain** D. It also comes in two flavours NMOS and PMOS, the circuit symbols for each are shown below, with their terminals labelled



An easy way to differ the two is to use the arrow, the arrow always denotes the Source terminal, and the N in NMOS means "Not pointing inwards".

The Gate essentially acts as the transistors control input, The N and P in PMOS and NMOS signify the logic level required to close the switch, This means the following:

- NMOS transistors are "turned-on" when their gate voltage v_G is high
- PMOS transistors are "turned-on" when their gate voltage v_G is low

In reality its a little more complicated, but this makes it easy to remember which is which.

1.2.2 Operating Regions of a FET

Unsurprisingly FETs are also non-linear devices, and they actually have a very similar approach to diodes for circuit analysis. We first make an assumption about the operating region of the device, these three regions, **Cutoff**, **Triode**, and **Saturation** will be introduced now.

Note that for NMOS, v_{th} is a positive value, and it is a negative value for PMOS, this is why we have the flipped sign convention here.

Operating Region	Conditions (NMOS)	Conditions (PMOS)	Drain Current (i_D)
Cutoff	$v_{GS} < v_{th}$	$v_{GS} > v_{th}$	$i_D = 0$
Triode	$v_{GS} > v_{th}$ and $0 \leq v_{DS} \leq v_{GS} - v_{th}$	$v_{GS} < v_{th}$ and $0 \geq v_{DS} \geq v_{GS} - v_{th}$	$i_D = k\left[(v_{GS} - v_{th})v_{DS} - \frac{1}{2}(v_{DS})^2\right]$
Saturation	$v_{GS} > v_{th}$ and $v_{DS} > v_{GS} - v_{th}$	$v_{GS} < v_{th}$ and $v_{DS} < v_{GS} - v_{th}$	$i_D = \frac{1}{2}k(v_{GS} - v_{th})^2$

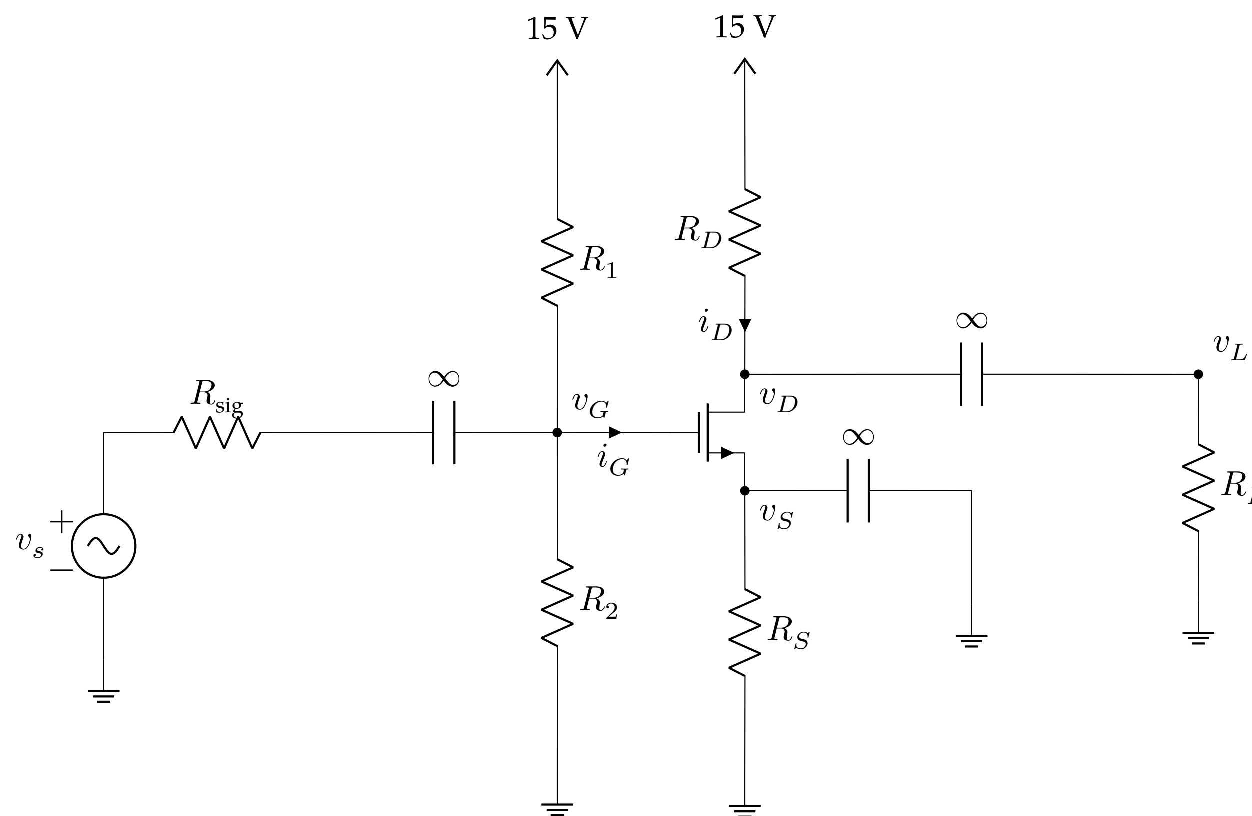
In the table above, the value k is a predefined quantity in units of $\frac{\text{A}}{\text{V}^2}$ There is also another thing, the drain current i_D should always be positive in Triode or Saturation Regions, this means that in NMOS current flows *out* of the source, and flows *into* the source for PMOS.

Note that the gate of a FET does not accept any current, in other words $i_G = 0$ in every region above. When designing electronic amplifiers, we often want to bias our FETs in the saturation region.

1.2.3 DC Analysis of a FET

Lets start with a quick example of DC analysis with a NMOS amplifier, for this problem we will assume the following

- $k = 2\ \frac{\text{mA}}{\text{V}^2}$
- $v_{th} = 1$ V
- R_1 = 10M
- R_2 = 5M
- R_D = 7.5k
- R_S = 3k
- R_L = 10k



Lets start by finding the gate voltage, since $i_G = 0$ it acts as a voltage divider, we can formulate a simple expression for it. Note that we can ignore everything on the other side of the infinite capactiors, as they will block all DC signals, these capacitors will come into play when we go through AC analysis

$$v_G = \frac{R_2}{R_1 + R_2} \cdot (15) = 5\text{V}$$

We can also find the source voltage if we know the drain current

$$v_S = R_s i_D = 3(i_D)$$

This means that our gate-source voltage v_{GS} can be found as follows:

$$v_{GS} = v_G - v_S = \frac{R_2}{R_1 + R_2} \cdot (15) - R_s i_D = 5 - 3(i_D)$$

Lets assume saturation and use the drain-current equation from the table above, plugging in $k = 2$ here as well:

$$i_D = \frac{1}{2} k (v_{GS} - v_{th})^2 = (5 - 3(i_D) - 1)^2$$

$$0 = 16 - 25(i_D) + 9(i_D)^2$$

Solving this gives two solutions:

- $i_D = 1$ mA
- $i_D = 1.78$ mA

Now we must use the conditions from the table above to see which is correct. Lets quickly rewrite the terminal voltage relations:

- $v_G = 5$
- $v_S = 3(i_D)$
- $v_D = 15 - 7.5(i_D)$

We must choose an answer that satifies the following

- $v_{GS} > v_{th}$
- $v_{DS} > v_{GS} - v_{th}$

The correct answer here is $i_D = 1$ mA as the other answer doesnt satisfy both inequalities above.

This means that we have found the DC Biasing point of our MOSFET, and since our conditions are both satisfied with $i_D = 1mA$ we are certain that our initial guess of the operating region is correct.

1.2.4 Small Signal Models of a MOSFET

There are two versions of the small-signal model of a MOSFET, the **pi-model** and the **T-model**. Both are equivalent, but analysis might be easier with one rather than another.

These models require two parameters for full use with the early-effect resistance:

$$g_m = \frac{2i_D}{v_{GS} - v_{th}}$$

$$r_o = \frac{V_A}{i_D}$$

The Pi Model is shown below