S03-022 *6.002 lecture* #6 Notes

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Semiconductor Diodes

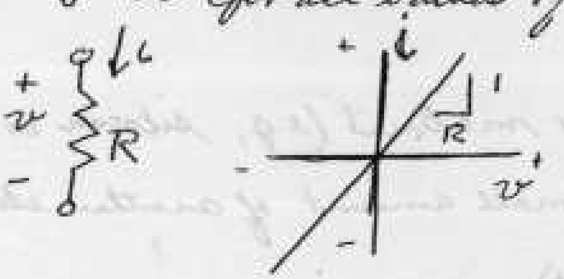
I What are they?

A Nonlinear device made from specially prepared semiconducting materials

1. Linear versus nonlinear devices

a Linear elements

$i \propto v$ for all values of v; $i = kv$



$i = \frac{1}{R} v$

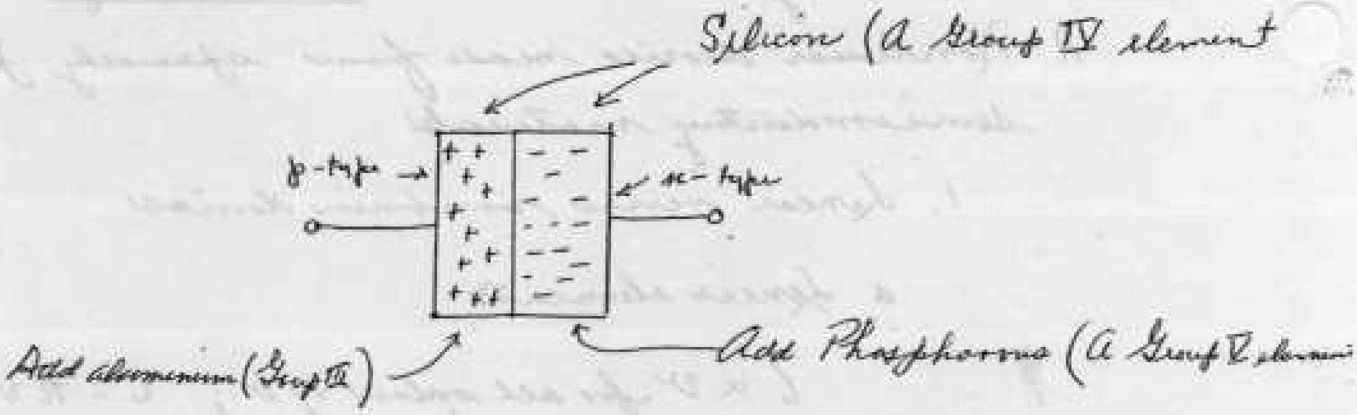
(b) Nonlinear element

$i \neq kv$ for all values of v

A Semiconductor diode is an example of a nonlinear element

II Before we get into the use of a semiconductor diode as part of an electrical circuit, we'll discuss briefly how the device is made. Note that it is not our intention to delve extensively into semiconductor physics -- there are other subjects devoted to that topic -- but it is worthwhile to say a few words about

A How they are made

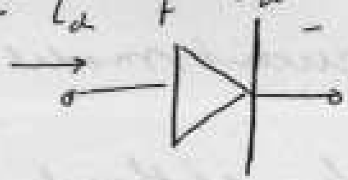


A semiconductor material (e.g., silicon or Germanium) is injected with a small amount of another element (about 1 part per million, by weight).

In the above diagram, when phosphorous is added to Silicon, a dramatic change in the electrical properties of the Silicon occurs. Originally there were very few free electrons in the pure semiconductor material. After injection (doping) of the silicon, an abundance of free electrons become available. Similarly, after the second silicon wafer is doped with aluminum, a deficiency in free electrons occurs, or in other words there is an excess of positive charges called HOLES. The wafer with excess negative charges is called an n-type material; the other wafer is called a p-type material.

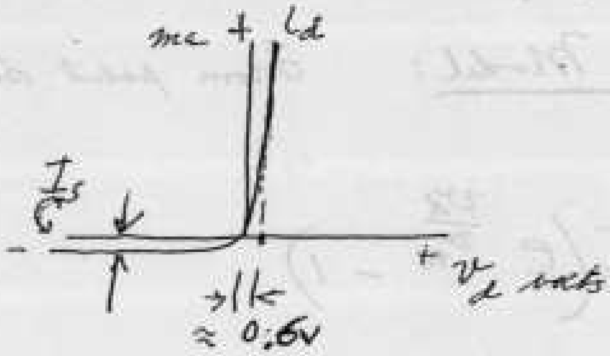
If a voltage is now applied across the sandwich so that the p-material is at a higher potential than the n-material, free electrons move freely from right to left, and holes move from left to right. However, if the polarity is reversed, there are very few free electrons available to move from left to right, and very few holes to move from right to left. In the first case the diode

SYMBOL



We said the i_d, v_d characteristic of the diode is nonlinear.

So what does the characteristic look like?



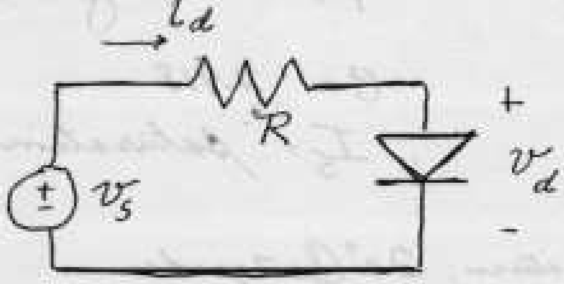
demo

↓

Explain the i_d & v_d scales

The next question is: How do we analyze a circuit when one of its elements is nonlinear.

E.G., Suppose we have this circuit



The key is to find a representation of the diode that makes the circuit easy to analyze. The representation is called a model

For the diode we can offer two types of models:

(a) Mathematical model

(b) Circuit model

4. It will turn out that the circuit model is the easier of the two to handle, although less accurate than the mathematical model

<u>Mathematical Model</u>: From solid-state physics:

$$i_d = I_S\left(e^{\frac{v_d}{v_{TH}}} - 1\right)$$

$$V_{TH} = \frac{kT}{q}$$

q = Charge on electron 1.60×10^{-19} coulomb

k = Boltzmann Constant that relates energy and temperature 1.38×10^{-23} joule/°Kelvin

T = temperature, °K

e = 2.718

I_S = saturation current $\approx 10^{-12}$ ampere

At room temperature, 20° Centigrade

$$V_{TH} \approx 25 \text{ millivolts}$$

For $v_d = 0.5v$ $i_d = 1 ma.$ $v_d = 0.6v$ $i_d = 53 ma$

Now, we have in our circuit an element that has the <u>nonlinear</u> characteristic

$$i_d = 10^{-12}\left(e^{\frac{v_d}{0.025}} - 1\right)$$

That equation must be satisfied

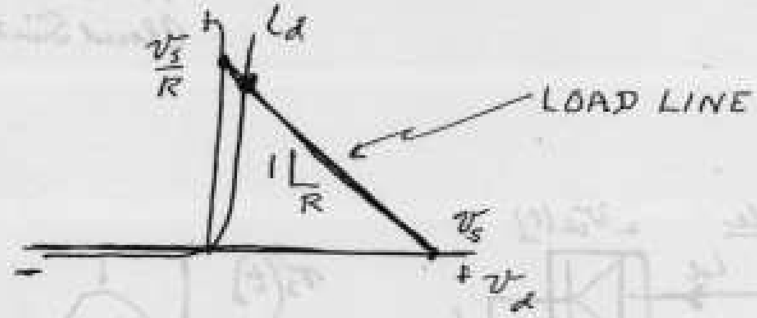
And also, by KCL

$$-v_S + i_d R + v_d = 0$$

$$i_d = -\frac{1}{R} v_d + \frac{v_S}{R}$$ linear equation (plot on i_d, v_d axes)

This equation must also be satisfied

Graphical Solution

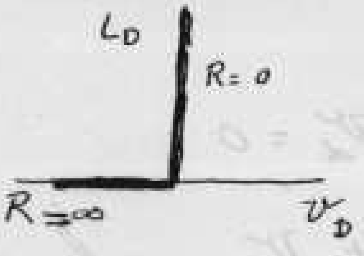


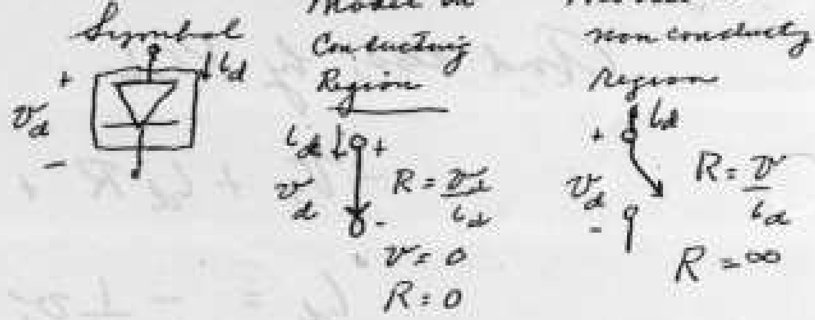
Explain the common point is where the circuit operates. Also, explain what happens when v_S is changed, and when the value of R is changed, holding v_S constant

CIRCUIT MODELS

Principle: we break the nonlinear characteristic into linear segments, analyze each segment using linear-circuit analysis methods, then piece together the several solutions. This is called piecewise linear analysis and the models are called piecewise linear models

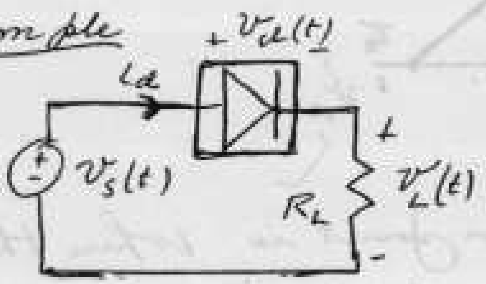
5. Ideal diode



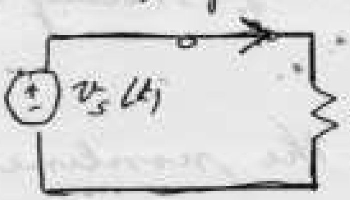


$v_d = 0$	$i_d = 0$
i_d positive	v_d negative
$R = 0$	$R = \infty$
Closed Switch	open switch

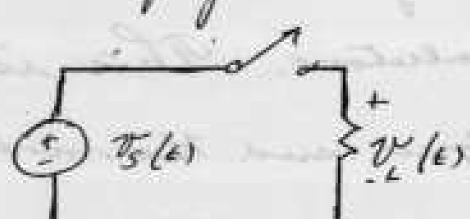
Example



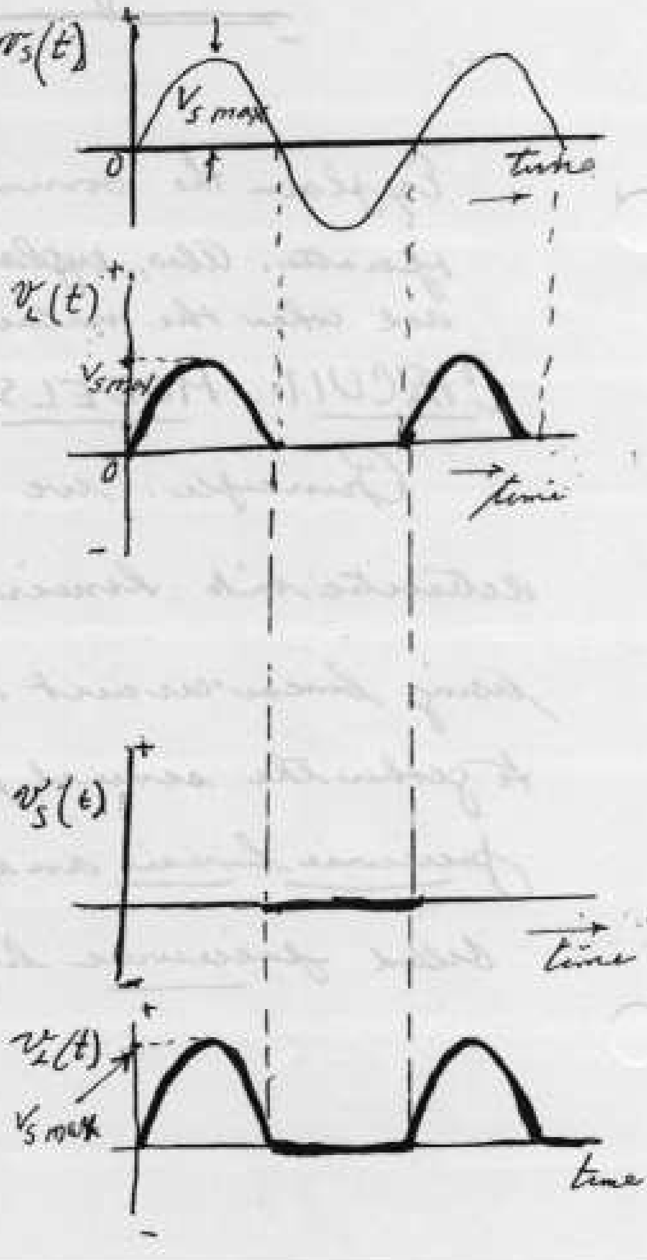
Positive half cycle:



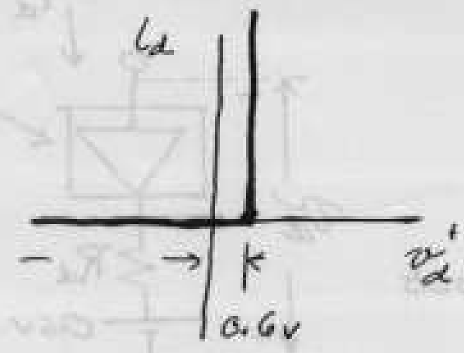
Negative half cycle



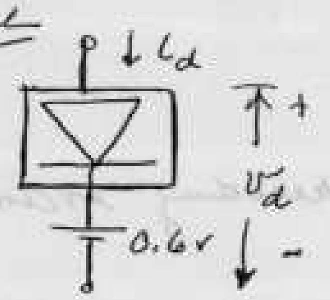
Combine

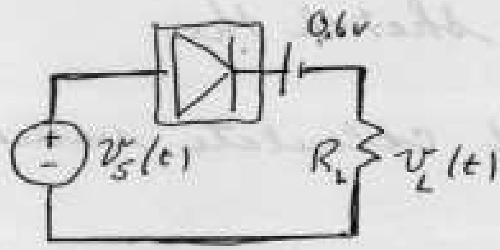


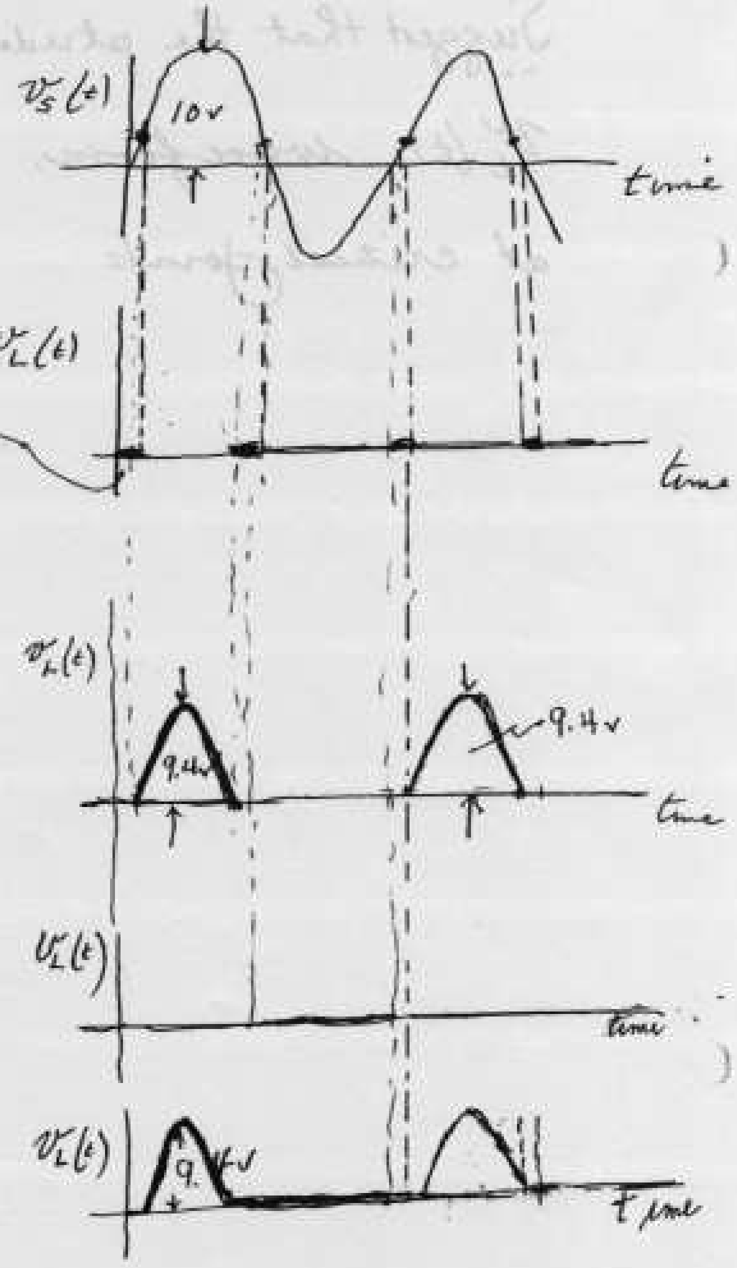
7. A more accurate piecewise linear model



Symbol

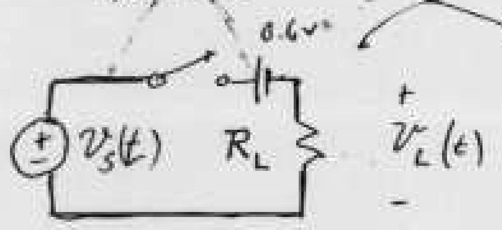


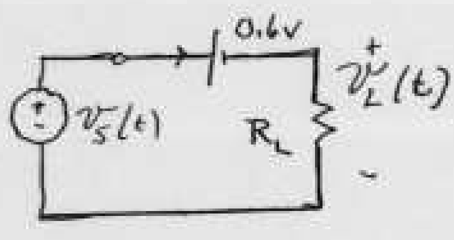


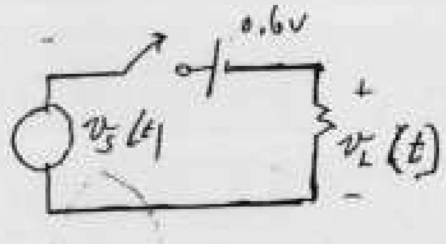


$v_S(t) = 10 \sin \omega t$

Model

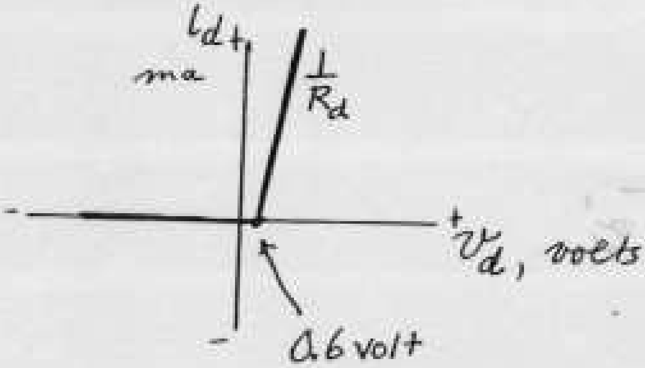


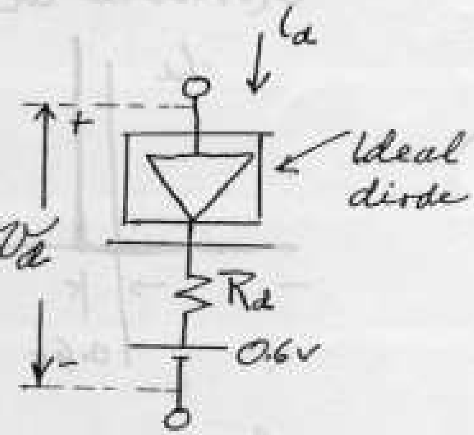




Combine:

8. Another model





Use same circuit as in preceding examples

Suggest that the student sketch the $v_L(t)$ waveform, and calculate values at critical points