Diodes

Simple two-terminal electronic devices.

Made of semiconducting materials: silicon, gallium arsenide, indium phosphide, gallium nitride, etc. (EE 332 stuff.)

Semiconductors are interesting because their electrical properties can be varied over many order of magnitude: resistivity as high as $10^7 \, \Omega \cdot m$ (almost an insulator) or as low as $10^{-6} \, \Omega \cdot m$ (almost a conductor).

Also, semiconductors can be made in two different “varieties”: either *n*-type in which current is carried by electrons (as usual) or *p*-type which current is carried by positive charges called holes.

A diode consists of a *p*-type layer of semiconductor joined to a *n*-type layer, and so is also known as a *p-n junction*. Current flowing across this junction exhibits a very asymmetric, non-linear i-v characteristic.

The non-linearity will force us to change the way we analyze circuits.
Diode applications

- Rectification – cutting off the top half or bottom half of a voltage signal.
- Voltage regulation – providing a steady voltage reference in a circuit.
- Light-emitting diodes – for indicators
- Light-emitting diodes – for illumination
- Lasers - DVD players, fiber-optic communication, surgery
- Photodetectors – sense presence of light, especially low levels or fast pulses
- Photovoltaics (solar cells) – “green” electrical power generation
- Building block for transistors
rectifying diode (switching or small-signal)

made of silicon

LEDs – various materials (not silicon). Different material = different colors.

LED lighting – usually gallium nitride (UV light) that excites a phosphor.
Diode

think “funnel” – it flows in one direction
ideal diode equation

\[ i_D = I_S \left[ \exp \left( \frac{v_D}{kT/q} \right) - 1 \right] \]

Extremely non-linear. Will cause lots of problems in analyzing, but offers many opportunities for applications.

\( I_S \) is a parameter of the diode, known as saturation current or scale current. Different for every diode. (Like \( R \) for a resistor.) Typical: \( I_S \approx 10^{-14} \text{ A} \).

\( kT \) is the thermal energy. \( k \) (Boltzmann’s constant = 1.38x10^{-23} \text{ J/K}), \( T \) = temperature in kelvin (K).

\( q \) is the charge on one electron; \( kT/q \) is the thermal voltage.

At 300K (= 27°C, approximately room temperature), \( kT/q = 25.8 \text{ mV} \).
diode: forward and reverse conduction

\[ i_D = I_S \left[ \exp \left( \frac{v_D}{kT/q} \right) - 1 \right] \]

If \( v_D \) is positive, \( v_D \gg kT/q \).

\[ i_D \approx I_S \exp \left( \frac{v_D}{kT/q} \right) \]

Lots of current can flow. Increases rapidly as \( v_D \) increases. Forward bias or forward conduction.

If \( v_D \) is negative.

\[ i_D \approx -I_S \]

A very small trickle of current flows, almost zero. Independent of the voltage. Reverse bias or reverse conduction.

The asymmetry between forward and reverse conduction is the basis for rectification – current can flow only one way (essentially). (Again, think funnel.)
Diode $i-v$

$I_s = 10^{-14}$ A

$T = 300$ K

Same diode

Forward voltage only

semi-log plot
diodes in circuit

The non-linear behavior has some significant effects.

Basic notions are still valid: KCL and KCL, energy and power

Some techniques are invalid with non-linear elements: superposition, Thevenin.

Node-voltage and mesh-current techniques are still applicable, but the result is a set of non-linear equations, which are difficult to solve.

With non-linear elements, we will rely on:

• Approximating the device behavior with linear elements. This requires some guessing and then checking of the results. Of course, it is only approximate.

• SPICE
Important: When working with diodes, don’t EVER apply a forward voltage directly across the diode. The result is usually a dead diode.

\[ V_s = 1.5 \text{ V} \]

\[ i_D \]

\[ v_D = V_s \]

\[ i_D \approx I_s \exp \left( \frac{v_D}{kT/q} \right) \]

\[ = \left( 10^{-14} \text{ A} \right) \exp \left( \frac{1.5 \text{ V}}{0.0258 \text{ V}} \right) = 1.8 \times 10^{12} \text{ A} \]

This is absolutely absurd. Of course, what really happens is that the diode would burn up (due to instant heating) when the current hits 1 A or so. There must always be a current-limiting resistor in series.
\[ i_D = I_S \left[ \exp \left( \frac{v_D}{kT/q} \right) - 1 \right] \]

\[ v_D = \frac{kT}{q} \ln \left( \frac{i_D}{I_S} + 1 \right) \]

\[ V_S = v_R + v_D \]

\[ V_S = i_D R + \frac{kT}{q} \ln \left( \frac{i_D}{I_S} + 1 \right) \]

Can’t be solved in closed form. Transcendental equation. Must use iteration. (Trial-and-error.)

\[ i_D = \frac{V_S}{R} - \frac{kT}{q} \ln \left( \frac{i_D}{I_S} + 1 \right) = 1.5 \text{mA} - (0.0258 \text{mA}) \ln \left( \frac{i_D}{10^{-11} \text{mA}} + 1 \right) \]

<table>
<thead>
<tr>
<th>1st guess</th>
<th>1.00 mA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.846526 mA</td>
</tr>
<tr>
<td></td>
<td>0.850825 mA</td>
</tr>
<tr>
<td></td>
<td>0.850694 mA</td>
</tr>
<tr>
<td></td>
<td>0.850698 mA</td>
</tr>
</tbody>
</table>

\[ i_D = 0.851 \text{mA} \]

\[ v_D = 0.649 \text{V} \]
\[ i_{D1} = \frac{v_a - v_b}{R_1} \]

\[ v_{D1} = V_S - v_a \]

\[ \frac{v_a - v_b}{R_1} = \frac{v_b}{R_2} + i_{D2} \]

\[ v_{D2} = v_b - v_c \]

\[ i_{D2} = \frac{v_c}{R_3} \]

\[ I_{S1} \left[ \exp \left( \frac{V_S - v_a}{kT/q} \right) + 1 \right] = \frac{v_a - v_b}{R_1} \]

\[ \frac{v_a - v_b}{R_1} = \frac{v_b}{R_2} + I_{S2} \left[ \exp \left( \frac{v_b - v_c}{kT/q} \right) + 1 \right] \]

\[ I_{S2} \left[ \exp \left( \frac{v_b - v_c}{kT/q} \right) + 1 \right] = \frac{v_c}{R_3} \]

3 non-linear equations in 3 unknowns

Good luck with that!!
When the diode is reverse-biased ($V_S < 0$, so $v_D < 0$), the diode behaves essentially like an open circuit, $i_D \approx 0$.

When the diode is forward-biased ($V_S > 0$, so $v_D > 0$), the diode voltage is roughly constant at 0.6 V - 0.7 V.
piecewise diode model

The results of the previous slide suggest the following approximate model.

- When the diode is reverse-biased, we can treat it as if it is an open-circuit
- When the diode is forward-biased, we treat it like an ideal source with a value of 0.7 V.

Reverse ($v_D < 0$)

\[ i_D = 0 \quad + \quad v_D < 0 \quad - \]

Forward ($v_D > 0$)

\[ i_D \quad + \quad v_D > 0 \quad - \]

\[ i_D \quad + \quad 0.7 \text{ V} \]

To use the models.

- Guess forward or reverse
- Insert the corresponding model
- Solve for voltage/current using model
- Check the result: for reverse, $v_D < 0$, for forward, $i_D$ flows in correct direction

Note that the diode is NOT a voltage source. It does not provide power to the circuit. It simply behaves as if it were a small voltage source or battery that is absorbing power.
Reverse \((v_D < 0 \text{ when } V_S < 0)\)

Forward \((v_D > 0 \text{ when } V_S > 0)\)

\[ i_D = \frac{V_S - v_D}{R} = \frac{V_S - 0.7V}{R} \]

<table>
<thead>
<tr>
<th>(V_S (V))</th>
<th>(v_D (V))</th>
<th>(i_D (mA))</th>
</tr>
</thead>
<tbody>
<tr>
<td>-10</td>
<td>-10 V</td>
<td>(\approx 0)</td>
</tr>
<tr>
<td>-8</td>
<td>-8 V</td>
<td>(\approx 0)</td>
</tr>
<tr>
<td>-6</td>
<td>-6 V</td>
<td>(\approx 0)</td>
</tr>
<tr>
<td>-4</td>
<td>-4 V</td>
<td>(\approx 0)</td>
</tr>
<tr>
<td>-2</td>
<td>-2 V</td>
<td>(\approx 0)</td>
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<tr>
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<td>0</td>
<td>0</td>
</tr>
<tr>
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<td>0.7</td>
<td>0.3</td>
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</tr>
<tr>
<td>10</td>
<td>0.7</td>
<td>9.3</td>
</tr>
</tbody>
</table>

compare to slide 12 – very similar
Example

Since $V_S$ is positive, we might guess that both diodes are forward-biased.

\[ v_a = V_S - 0.7 \, \text{V} = 4.3 \, \text{V}. \]

\[ v_c = v_b - 0.7 \, \text{V}. \]

\[ \frac{v_a - v_b}{R_1} = \frac{v_b}{R_2} + i_{D2} \]

\[ i_{D2} = \frac{v_c}{R_3} = \frac{v_b - 0.7V}{R_3} \]

\[ \frac{V_S - 0.7V - v_b}{R_1} = \frac{v_b}{R_2} + \frac{v_b - 0.7V}{R_3} \]

\[ v_b = 2.47 \, \text{V}. \]

check:

\[ i_{D1} = \frac{v_a - v_b}{R_1} = \frac{V_S - 0.7V - v_b}{R_1} = 1.83 \, \text{mA} \]

\[ i_{D2} = \frac{v_c}{R_3} = \frac{v_b - 0.7V}{R_3} = 0.591 \, \text{mA} \]

Both currents are positive, consistent with forward conducting diodes. The guesses were correct.