Discrete Semiconductor Devices

**Bipolar Junction Transistor (BJT)**

NPN: Current flows into Base, and a proportional current flows into Collector, these combine and flow out of the Emitter

NPN: Current flows into Emitter, some current flows out of the Base, and a proportional current flows out of the Collector

**Regions:**

<table>
<thead>
<tr>
<th>Mode</th>
<th>Emitter-Base Junction</th>
<th>Collector-Base Junction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cutoff</td>
<td>Reverse</td>
<td>Reverse</td>
</tr>
<tr>
<td>Active</td>
<td>Forward</td>
<td>Reverse</td>
</tr>
<tr>
<td>Saturation</td>
<td>Forward</td>
<td>Forward</td>
</tr>
</tbody>
</table>

**Active Region Formulae**

\[ i_c = \beta i_b \]

\[ i_c = (\beta + 1)i_b \]

\[ i_C = I_{Sat} e^{\frac{qE}{V_T}} \quad \text{or} \quad i_C = I_{Sat} e^{\frac{qE}{V_T}} \left( 1 + \frac{V_{CE}}{V_A} \right) \]  

with early voltage effect

\[ i_c = \text{Collector current} \]

\[ i_{sat} = \text{Saturation Current} \]

Where:

\[ V_T = \text{Thermal Voltage} = \frac{kT}{q} \]

\[ q = \text{electron charge} \left( 1.602 \times 10^{-19} \text{ coulombs} \right) \]

\[ k = \text{Boltzmann Constant} \left( 1.3805 \times 10^{-23} \text{ Joules} / ^\circ \text{K} \right) \]

\[ T = \text{Temperature} \left( ^\circ \text{K} \right) \]

**Small Signal**

\[ g_m = \frac{I_C}{V_T} \quad r_\pi = \frac{V_T}{I_B} = \frac{\beta}{g_m} \quad r_o = \frac{V_A}{I_C} \]

Where:

\[ g_m = \text{Transconductance of BJT} \left( \text{A} \cdot \text{V}^{-1} \right) \]

\[ r_\pi = \text{Base to Emitter Small Signal Resistance} \left( \Omega \right) \]

\[ r_o = \text{Output Resistance} \left( \Omega \right) \]

\[ I_B = \text{DC bias base current} \left( \text{A} \right) \]

\[ I_C = \text{DC bias collector current} \left( \text{A} \right) \]
### Junction Field Effect Transistor (JFET)

**N Channel:**
- Apply a negative voltage to the gate to deplete the channel of carriers – Drain to Source Voltage must be positive – when \( v_{GS} = V_P \) then the channel is pinched off – no current flows

**P Channel:**
- Apply a positive voltage to the gate to deplete the channel of carriers – Drain to Source Voltage must be negative – when \( v_{GS} = V_P \) then the channel is pinched off – no current flows

**Equations for N channel**
- For P channel: \( V_P \geq 0, \ V_{DS} \leq 0, \ \lambda = \frac{1}{V_A} \leq 0 \)

**Cutoff Region:**
- \( V_{GS} \leq V_P, \ i_D = 0 \)

**Triode Region:**
- \( V_p \leq V_{GS} \leq 0 \) \& \( V_{DS} \geq V_{GS} - V_P \)

\[
i_D = I_{DSS} \left[ 2 \left( 1 - \frac{V_{GS}}{V_P} \right) \left( \frac{V_{DS}}{V_P} \right) - \left( \frac{V_{DS}}{V_P} \right)^2 \right]
\]

**Saturation Region**
- \( V_p \leq V_{GS} \leq 0 \) \& \( V_{DS} \geq V_{GS} - V_P \)

\[
i_D = I_{DSS} \left( 1 - \frac{V_{GS}}{V_P} \right)^2 \left( 1 + \lambda V_{DS} \right)
\]

- \( V_{GS} \) = Gate to Source Voltage (V)
- \( V_{DS} \) = Drain to Source Voltage (V)
- \( V_P \) = Pinchoff Voltage (V)

Where:
- \( i_D \) = Drain Current (A)
- \( I_{DSS} \) = Drain to source current with gate & source shorted together (A)
- \( \lambda = \frac{1}{V_A} \), \( V_A \) = Early Voltage (V)

**Small Signal**

\[
g_m = \frac{2I_{DSS}}{V_P} \left( 1 - \frac{V_{GS}}{V_P} \right) \quad \text{or} \quad g_m = \left( \frac{2I_{DSS}}{V_P} \right) \frac{I_D}{I_{DSS}}
\]

\[
r_o = \frac{V_A}{I_D}
\]

- \( g_m \) = Transconductance of JFET (A.V\(^{-1}\))
- \( r_o \) = Output resistance (\( \Omega \))
- \( V_{GS} \) = DC bias gate to source voltage (V)
- \( I_D \) = DC bias drain current (A)
Metal Oxide
Semiconductor
Field Effect
Transistor
(MOSFET)

N Channel – Current flows from drain to source when \( V_{GS} \) threshold voltage is exceeded

P Channel – Current flows from source to drain when \( V_{GS} \) threshold voltage is exceeded

Enhancement MOSFET – Positive Threshold Voltage – gate not connected = no \( I_{DS} \) current

Depletion MOSFET – Negative Threshold Voltage – gate not connected = current flows drain → source

MOSFET’s usually have reverse protection diodes between Drain and Source (opposite direction to normal current flow) and sometimes also a zener diode between the Gate and Source to stop the Gate being damaged.

![Diagram of MOSFET types and symbols]

Triode Region:

\[
i_D = (\mu_n C_{ox}) \left( \frac{W}{L} \right) \left( (V_{GS} - V_t) V_{DS} - \frac{1}{2} V_{DS}^2 \right)
\]

Saturation Region:

\[
i_D = \frac{1}{2} (\mu_n C_{ox}) \left( \frac{W}{L} \right) (V_{GS} - V_t)^2
\]

Saturation Region taking Finite Output Resistance into account:

\[
i_D = \frac{1}{2} (\mu_n C_{ox}) \left( \frac{W}{L} \right) (V_{GS} - V_t)^2 \left( 1 + \lambda V_{DS} \right)
\]

Where:

\( i_D \) = Drain Current (A)
\( \mu_n \) = Electron mobility = 580 cm²/Vs
\( C_{ox} \) = Oxide Capacitance = \( \frac{\varepsilon_{ox}}{t_{ox}} = 1.75 \text{fF} / \mu \text{m}^2 \) for \( t_{ox} = 0.02 \mu \text{m} \)
\( W \) = Width of channel (m)
\( L \) = Length of channel (m)
\( V_{GS} \) = Gate to Source Voltage (V)
\( V_t \) = Threshold Voltage (V)
\( V_{DS} \) = Drain to Source Voltage (V)
\( k' \) = Process Transconductance Parameter = \( (\mu_n C_{ox}) \)
\( \lambda = \frac{1}{V_A} \) where \( V_A \) = Early Voltage

Small Signal:

If the following equation is satisfied:

\[
v_{gs} << 2(V_{GS} - V_t) V_{gs}
\]

Then transconductance is given by:

\[
g_m = \frac{i_d}{v_{gs}} = (\mu_n C_{ox}) \left( \frac{W}{L} \right) (V_{GS} - V_t)
\]

\[
r_o = \frac{V_A}{I_D}
\]

Where:

\( g_m \) = MOSFET Transconductance (A/V)
\( r_o \) = Output Resistance (\( \Omega \))
\( i_d \) = Small Signal Drain current (A)
\( v_{gs} \) = Small Signal Gate to Source Voltage (V)
\( V_{GS} \) = Large Signal Bias Gate to Source Voltage (V)

© Evan Hunter – http://electronics.ozhiker.com
Photovoltaic Cell (Solar Cell / Panel)

$I = I_{sc} + A(1 - e^{-BV})$

where $I_{sc}$, A and B all vary with solar insolation (amount of light absorbed)

Silicon Controlled Rectifier (SCR) (Thyristor)

Constructed as a stack of PNPN silicon.

Acts as a diode which is controlled in its forward conduction by a gate pin. Injecting a current into the gate causes the device to ‘turn on’ – where it’s forward characteristic is the same as a diode. To turn the SCR off, either the device must be reverse biased, or the anode to cathode current must be brought under the holding current. Hence SCR’s are normally used for AC systems. If the ‘breakover voltage is exceeded between anode and cathode, then the device will start conducting with no gate input.

SCR Construction:  

BJT Equivalent: 

V-I Characteristic:
Triac (TRIode AC Switch) (Semistor)

A triac is similar to a SCR except that it allows controlled conduction in both directions, and can be triggered with a positive or negative pulse at the gate.

It can be seen below, that when compared to two back to back SCR’s, the gate of a Triac has an extra section of N silicon to allow triggering with both positive and negative pulses.

Unijunction Transistor

Silicon between Base 1 and Base 2 acts as a resistor. At some point along this resistor is the Emitter. When a positive voltage is applied at base 2 with respect to base 1, a voltage gradient along the internal resistance is created. If the voltage at the Emitter becomes higher than the adjacent voltage gradient, then the transistor will start to conduct from the Emitter to Base 1 with almost a short circuit, this also pulls Base two down.

©Evan Hunter – http://electronics.ozhiker.com
## Diodes

| Junction Diode (also applies to Schottky diodes & Light Emitting Diodes - LED’s) | These diodes consist of a single P-N junction. Schottky diodes use a schottky barrier metal in their construction and have much lower forward voltage, and are much faster than junction diodes. LED’s are similar to junction diodes but emit light. 

\[ I_F = I_{Sat} \left[ e^{\frac{V_F}{nV_F}} - 1 \right] \]

where:

- \( I_F \) = Forward Current (A)
- \( V_F \) = Forward Voltage (V)
- \( I_{Sat} \) = Reverse Saturation Current (A)
- \( n \) = Emission Coefficient (1 ≤ n ≤ 2)

\[ V_T = \text{Thermal Voltage} = \frac{q}{kT} \]

- \( q \) = electron charge \((1.602 \times 10^{-19} \text{coulombs})\)

\[ k = \text{Boltzmann Constant} \left(1.3805 \times 10^{-23} \text{Joules/°K} \right) \]

\[ T = \text{Temperature} \left(°K \right) \]

| Varicap diodes (Varactor) | Varactors have a junction capacitance which changes according to the applied reverse voltage. They are used mainly for RF tuning and modulation |

| Transient Voltage Supressor diodes (Protection diodes) | Transient Voltage Suppressor (TVS) diodes are similar to zener diodes, except that they are extremely fast acting, have a small conduction resistance, and are designed for power dissipation. They protect a circuit against overvoltage conditions by conducting when the rated voltage is exceeded, hence clipping the voltage. Bi-Directional TVS diodes are simply two single direction TVS diodes back to back. |

©Evan Hunter – http://electronics.ozhiker.com
<table>
<thead>
<tr>
<th>Sidac (Sidac, Sidactor)</th>
<th>Consists of two shockley diodes back to back, and provides overvoltage protection by going into a regeneration region allowing high current flow once the device has been ‘turned on’ by first reaching the breakover voltage, then reaching the switching current. To turn off the device, the current must be reduced below the holding current.</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Tunnel Diode</th>
<th>Tunnel diodes have a region before the normal conduction region which allows conduction through quantum tunneling. The diodes are extremely fast (picoseconds) but are seldom used. The tunnel diode is made with a heavily doped PN junction. The tunneling current creates a region of negative resistance useful for oscillators.</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Gunn Diode</th>
<th>Galium Arsenide Diodes used as Microwave &amp; Millimeter wave oscillators</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pin Diode</td>
<td>(Positive-Intrinsic-Negative doping) Photodiode normally reverse biased for light detection.</td>
</tr>
<tr>
<td>Back Diode</td>
<td>A Back Diode is a tunnel diode with a suppressed tunneling current suppressed, and is only useful between −0.2V and +0.3V since it conducts heavily outside this region.</td>
</tr>
<tr>
<td>Zener diode</td>
<td>A zener diode conducts with almost constant voltage in the reverse direction. Diodes with a variety of reverse voltages are available, hence they are often used in shunt regulators. The equation for the V-I characteristic of a Zener diode is extremely complicated since it is controlled by the quantum mechanical properties of the junction which are controlled by the geometry and doping concentrations. The response of the zener diode in the zener breakdown region can be approximated by a resistance $R_Z$. This resistance can be obtained from finding the slope of the V-I characteristic curve at the operating point.</td>
</tr>
</tbody>
</table>

©Evan Hunter – http://electronics.ozhiker.com
### Shockley diode (Four-Layer Diode)

A shockley diode is effectively a Silicon Controlled Rectifier (SCR) with no gate. When the forward voltage is below the threshold voltage, the shockley diode blocks current, but when the voltage is raised above the threshold voltage, the diode switches on, and conducts heavily. After the diode has turned on, it will stay on until the current is reduced to below the holding current.

**Construction:**

- Equivalent circuit:

**Circuit current**

**Applied voltage**

### Diac (Diode AC Switch)

Diacs are effectively two shockley diodes in inverse parallel, or a triac with no gate pin. They operate in the same way as a shockley diode except that they also allow conduction in the reverse direction. Diacs are usually used as a trigger for a triac in AC phase control systems such as dimmers or speed controllers.

**Equivalent circuit:**