Consider the effect of irradiating a p-n junction with light. Let’s only look at the reverse bias saturation current:
Finally, the total diode current is the sum of the hole and electron currents across the p-n junction and is given by:

\[ I = I_p(x_n = 0) - I_n(x_p = 0) = \frac{qAD_p}{L_p} \Delta p_n + \frac{qAD_n}{L_n} \Delta n_p \]

\[ I = qA \left( \frac{D_p}{L_p} p_n + \frac{D_n}{L_n} n_p \right) \left( e^{\frac{qV}{kT}} - 1 \right) = I_0 \left( e^{\frac{qV}{kT}} - 1 \right) \]

\[ L = \sqrt{D \tau} \]

Can also be substituted for L
Instead of a light source, we can also use a forward biased p-n junction to inject carriers into a reverse biased junction. In this case, we can use the forward biased (emitter-base) junction current to modulate the reverse biased (base-collector) current.
Definition of common terms which define the performance of a bipolar transistor

Emitter efficiency:

$$\gamma = \frac{I_{Ep}}{I_E} = \frac{I_{Ep}}{I_{Ep} + I_{En}}$$

Base transport factor:

$$\alpha_T = \frac{I_{Cp}}{I_{Ep}}$$
Common Base Current Gain

\[ I_C = \alpha_{dc} I_E + I_{CB0} \]

\[ I_{CP} = \alpha_T I_{EP} = \gamma \alpha_T I_E \]

\[ I_C = I_{CP} + I_{CN} = \gamma \alpha_T I_E + I_{CN} \]

\[ \alpha_{dc} = \gamma \alpha_T \]

\[ I_{CB0} = I_{CN} \]

Collector current when \( I_E \) is zero... this is usually negligible.

\[ \alpha_T = \frac{I_{CP}}{I_{EP}} \]

\( \ldots pnp \) BJT

This is the dc common base current gain.
Common emitter current gain

We rearrange above equation

\[ I_C = \beta_{dc} I_B + I_{CE0} \]

This term is the collector current when base current is zero (usually negligible)

\[ I_C = \alpha_{dc} (I_C + I_B) + I_{CB0} \]

This is the definition of the current gain

\[ \beta_{dc} = \frac{\alpha_{dc}}{1 - \alpha_{dc}} \]

\[ I_{CE0} = \frac{I_{CB0}}{1 - \alpha_{dc}} \]

\[ \beta_{dc} = \frac{I_C}{I_B} \]
On the emitter/base junction:

\[ \Delta p_E = p_n(e^{qV_{EB}/kT} - 1) \]

On the collector/base junction:

\[ \Delta p_C = p_n(e^{qV_{CB}/kT} - 1) \]

These concentrations reduce to simpler expressions if the emitter junction is strongly forward biased and the collector junction is strongly reverse biased:

\[ \Delta p_E \approx p_n e^{qV_{EB}/kT} \]

\[ \Delta p_C \approx -p_n \]
Silicon controlled rectifier (SCR)

Schematic representation of the dopant concentrations and device terminal configuration

SCR devices typically have three junctions, and at least one of these is reverse biased under normal conditions.
Device characteristics of a SCR
An equivalent diode model for a SCR under different biasing conditions:
Figure 11-3
Three bias states of the p-n-p-n diode:
(a) the forward-blocking state; (b) the forward-conducting state; (c) the reverse-blocking state.
Reverse bias saturation current for J12 or J34

Expected diode model response for SCR

Reverse bias saturation current for J23
The two-transistor model for a SCR:

Diagram and equivalent circuit
The use of the two-transistor model to describe the regenerative process that leads to switching:

1. Initial carrier injection,
2. Diffusion across the quasineutral base
3. Injected carriers enter the base of the other transistor
4. Additional injection induced by the majority carrier excess in the base
The total current from the anode to the cathode can be described as a function of the junction currents which we can remember from the transistor models.

\[ I_{AK} = \alpha_1 I_{AK} + I_{R01} + \alpha_2 I_{AK} + I_{R02} \]

\[ I_{AK} = \frac{I_{R01} + I_{R02}}{1 - (\alpha_1 + \alpha_2)} \]
Simplified large signal equivalent circuits for (a) and active-mode biased pnp and npn transistors.

Corresponding model for a SCR in blocking mode with $I_g$ and $V_{AK} = 0$.

$$\alpha_{dc} = M \gamma \alpha_T$$
Turn-on considerations:

Triggering can be accomplished by:

a) biasing beyond the breakdown voltage
b) light irradiation
c) heating
d) rapid changes in the voltage applied
Figure 11-8
A high-current SCR, fabricated by the alloy-diffused method of Fig. 11-7: (a) mounting of the anode and cathode regions to tungsten disks; (b) cutaway view of the encapsulated device. (Illustrations courtesy of General Electric Company.)

Figure 11-9
Example of the use of an SCR to control the power delivered to a load: (a) schematic diagram of the circuit; (b) waveforms of the delivered signal and the phase-variable trigger pulse.
An SCR short-cathode configuration. This configuration is used to obtain reproducible switching characteristics (i.e., use a gate to control the switching voltage.)
Switching (triggering) time depends on the average time taken by minority carriers to diffuse across a quasineutral base region.

This time is given by \( t_1 = \frac{W^2}{2D_B} \).

So, for two base regions, we can assume:

\[
t_{ON} \approx \sqrt{t_1 t_2} = \frac{W_2 W_3}{2 \sqrt{D_P D_N}}
\]
Switching advantages:

1. SCR requires very little gate current to turn on very large anode-cathode currents

2. The SCR can block both polarities of an a-c signal

3. The SCR has a very high blocking voltage capability combined with a low voltage drop in the conducting mode.

4. Unlike the BJT, the SCR is not subject to current crowding when operated in the conducting mode
Disadvantages:

- The SCR cannot operate at high frequencies
- The SCR are prone to turn on by noise voltage spikes
- The SCR have limited temperature range
- The SCR cannot be turned off by setting Ig=0
The dual-gate SCR or SCS (silicon-controlled switch)
The DIAC: idealized crosssection and device characteristics

The TRIAC (triode AC) crosssection and the device characteristics
Programmable unijunction transistor structure and I-V characteristics
The “N-shaped” I-V characteristic

While the applied voltage is between $V_{\text{peak}}$ and $V_{\text{valley}}$, as shown, the semiconductor exhibits distinctly nonlinear behaviour. This behaviour is due to the superposition of the markedly different I-V characteristics, resulting from the large difference in effective electron mass, of the two valleys within the conduction band. This gives the Negative Differential Resistance (NDR) behaviour shown in the Figure, where, between $V_{\text{peak}}$ and $V_{\text{valley}}$, $[dI/dV]$ becomes negative. It is this negative differential resistance (usually termed just negative resistance) that is harnessed by the Gunn Diode.

- Resonant Tunnel Diode
- Gunn Diode
The Dispersion Diagram of GaAs
Concept of Domain
Example of an X-band Gunn Diode

The Gunn diode mounted to its timing circuit: the adjustment screw is mounted on the left hand side of the waveguide assembly.

The Gunn diode with its timing circuit attached, and mounted to a waveguide T connector. The two isolators to the left and right of the Gunn diode carry power in from the reference signal to phase lock the diode output (grey),
Typical Circuit of a Gunn Diode

Figure 6 - The subcircuit topology and example netlist for the Gunn diode.

.SUBCKT GUNNDIODE 1 2
*Vp=3V Ip=350mA Vv=6.5V
*Iv=50mA Vf=9V Rb=0.5Ω Cj=0.1P
*L1 1 100 0.2nH ; optional lead inductance
R1 1 3 .5
D1 3 2 DIODE
J1 4 2 3 NKANALJFET
J2 4 3 2 PKANALJFET
.MODEL NKANALJFET NJF (VTO=-4V BETA=.07 CGS=.05P)
.MODEL PKANALJFET PJF (VTO=-4V BETA=.07 CGS=.05P)
.MODEL DIODE D (RS=6 N=9)
.ENDS
Examples of Gunn Diodes

GUNN OSCILLATOR WITH 1/4 WAVE GROUND PLANE

SOLFAN GUNN DIODE OSCILLATOR
Resonant Tunneling Diode

Conduction band diagrams for different voltages and the resulting current flow.

12 different I-V curves: 2 wafers, 3 mesa sizes, 2 bias directions

- 50nm: $1 \times 10^{18}$, InGaAs
- 7 ml, nid: InGaAs
- 7 ml, nid: AlAs
- 20 ml, nid: InGaAs
- 7 ml, nid: AlAs
- 7 ml, nid: InGaAs
- 50 nm, $1 \times 10^{18}$: InGaAs
Optically Gated Resonant Tunneling Response

Current $I$ [$\mu$A] vs Bias Voltage $V_{dc}$ [V]

- $T=300K$
- $f=1.4$THz
- $V_{ac} = 32$mV
- Without THz: 74mV
- With THz: 122mV

Basic RTD Structure:

- Emitter
- n-GaAs
- $E_c$
- TB
- AlGaAs
- QW
- GaAs
- TB
- AlGaAs
- C
- n-GaAs
- Collector
- n-GaAs substrate

Absorption

Dip at Center

Stimulated Emission
CaF$_2$/CdF$_2$ RTDs
Explore the potential of tunnel diode/transistor technology for increasing speed and reducing power beyond what can be achieved with transistors alone. The circuit concepts are explored through design, fabrication, and testing of InP-based heterojunction bipolar transistor (HBT) and resonant tunneling diode (RTD) integrated circuits.
Time-resolved Response of RTDs
Impact Avalanche Transit Time diodes

- Transit time devices can convert dc to microwave ac signals
- The current lags behind the voltage applied due to
  - A delay due to the avalanche process
  - A delay due to the transit time of the carriers across the drift region

\[ E(x) \]
Time dependence of the growth and drift of holes during a cycle of applied voltage

Critical field for avalanche

The hole pulse is sketched as a line on the field diagram
SiC IMPATT Diode

Because of its high breakdown field, silicon carbide is an ideal semiconductor for the fabrication of high-power microwave devices. One device, in particular, that benefits from the high breakdown field of SiC is the IMPact ionization Avalanche Transit-Time (IMPATT) diode oscillator. IMPATT diodes deliver the highest RF power of any semiconductor microwave oscillator, and are used to produce carrier signals for microwave transmission systems, particularly airborne and ground-based radar. Depending upon the design, IMPATT diodes can operate from a few GHz to a few hundred GHz.
Time-resolved response for IMPATT
IMPATT diode response

<table>
<thead>
<tr>
<th>Parameter</th>
<th>33 – 37</th>
<th>38 – 78</th>
<th>92 – 96</th>
<th>120 – 140</th>
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<tbody>
<tr>
<td>Operating frequency range, GHz</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diode capacitance (at a reverse voltage $U_r=10 , \text{V}$), pF</td>
<td>0.3 – 0.4</td>
<td>0.25 – 0.35</td>
<td>0.12 – 0.15</td>
<td>0.1 – 0.13</td>
</tr>
<tr>
<td>Switching time, ns</td>
<td>2 – 5</td>
<td>2 – 5</td>
<td>3 – 10</td>
<td>3 – 10</td>
</tr>
<tr>
<td>Forward loss resistance (at a $I_{FOR}=10 , \text{mA}$), $\Omega$</td>
<td>1 – 3</td>
<td>1 – 3</td>
<td>1 – 3</td>
<td>1 – 3</td>
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<tr>
<td>Breakdown voltage, V</td>
<td>50</td>
<td>50</td>
<td>70</td>
<td>70</td>
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<tr>
<td>Continuous operating current, mA</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
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<tr>
<td>Package capacitance, pF</td>
<td>0.2</td>
<td>0.16</td>
<td>0.08</td>
<td>0.08</td>
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<td>Ruby sleeve dimensions, mm</td>
<td>1.2×0.7×0.4</td>
<td>0.9×0.55×0.3</td>
<td>0.4×0.2×0.15</td>
<td>0.4×0.2×0.15</td>
</tr>
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</table>
Cavity-stabilized IMPATT diode

<table>
<thead>
<tr>
<th>Model Number</th>
<th>CIDO - 28</th>
<th>CIDO - 22</th>
<th>CIDO - 19</th>
<th>CIDO - 15</th>
<th>CIDO - 12</th>
<th>CIDO - 10</th>
<th>CIDO - 8</th>
<th>CIDO - 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency Band and Range, GHz</td>
<td>Ka</td>
<td>Q</td>
<td>U</td>
<td>V</td>
<td>E</td>
<td>W</td>
<td>F</td>
<td>D</td>
</tr>
<tr>
<td>26.5-40</td>
<td>33-50</td>
<td>40-60</td>
<td>50-75</td>
<td>60-90</td>
<td>75-110</td>
<td>90-140</td>
<td>110-150</td>
<td></td>
</tr>
<tr>
<td>Maximum Power Output*</td>
<td>150</td>
<td>150</td>
<td>120</td>
<td>120</td>
<td>120</td>
<td>100</td>
<td>60</td>
<td>40</td>
</tr>
<tr>
<td>Frequency Stability, 1/°C (typ)</td>
<td>10⁻⁵</td>
<td>8x10⁻⁶</td>
<td>8x10⁻⁶</td>
<td>6x10⁻⁶</td>
<td>5x10⁻⁶</td>
<td>5x10⁻⁶</td>
<td>5x10⁻⁶</td>
<td>5x10⁻⁶</td>
</tr>
<tr>
<td>Amplitude Stabil., dB/°C (typ)</td>
<td>0.01</td>
<td>0.01</td>
<td>0.015</td>
<td>0.015</td>
<td>0.015</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>DC Power (IMPATT Bias), V/A (max)</td>
<td>+50/0.15</td>
<td>+45/0.15</td>
<td>+45/0.15</td>
<td>+35/0.15</td>
<td>+35/0.2</td>
<td>+27/0.2</td>
<td>+24/0.26</td>
<td>+24/0.26</td>
</tr>
</tbody>
</table>
Optical Generation of THz signals

Two lasers with slightly different frequencies are heterodyned to generate THz radiation.