Schematics of Transit-time NDR diode.
A packet of carriers (e.g., electrons) is generated in a confined and narrow zone (generation region) and injected into the adjacent fully depleted zone (drift region). The current density in the external circuit is given by *Ramo-Schokley theorem*:

\[
J_{\text{ind}} = \frac{Q}{W} \left( v_Q - \frac{W_c}{W} \frac{dW}{dt} \right)
\]

\(v_Q\) is the charge velocity

If \(W=\text{const}\) (full depletion) and electric field is high (\(v_Q = v_s\))

\[
J_{\text{ind}} = \frac{Q}{W} v_s
\]
The current pulse is represented by the injection phase angle $\Theta_M$ and the width angle $\Theta_W$ of the pulse. The induced current pulse is represented by the current density $J_{max}$ and the transit angle in the drift region $\Theta_D = \omega W/v_S$.

The generated RF power is given by

$$V_T = V_{DC} + V_{RF} \sin(\omega t)$$

$$P_{RF} = \frac{A}{2\pi} \int_0^{2\pi} J_{\text{ind}}(\omega t) V_{RF} \sin(\omega t) \, d(\omega t)$$

$$P_{RF} = A V_{RF} J_{DC} \frac{\sin(\Theta_W/2)}{\Theta_D} \cos(\Theta_M + \Theta_D) - \cos \Theta_M$$
\[ P_{RF} = A V_{RF} J_{DC} \frac{\sin(\Theta_w/2)}{(\Theta_w/2)} \frac{\cos(\Theta_M + \Theta_D) - \cos \Theta_M}{\Theta_D} \]
To find the conversion efficiency we estimate the DC current:

\[ J_{DC} = \frac{1}{2\pi} \int_0^{2\pi} J_{ind}(\omega t) \, d(\omega t) = \frac{J_{max}}{2\pi} \Theta_D \]

\[ P_{RF} = A V_{RF} J_{DC} \sin(\Theta_W/2) \cos(\Theta_M + \Theta_D) - \cos \Theta_M \]

\[ \Theta_W/2 \Theta_D \]

\[ \eta = \frac{P_{RF}}{P_{DC}} = \frac{V_{RF} \sin(\Theta_W/2) \cos(\Theta_M + \Theta_D) - \cos \Theta_M}{V_{DC} \Theta_W/2 \Theta_D} \]
Injection mechanisms in Transit-Time Diodes

1. Thermionic emission over a barrier: This barrier can be formed by a $p-n$ junction or Schottky junction in forward bias or by a heterojunction of a layer with a wider bandgap than in the neutral and drift regions. This would result in a BARITT diode.

2. Tunneling through a barrier: At very high electric fields, electrons can tunnel from the valence band to the conduction band of a reverse-biased $p^+-n^+$ junction if the distance is short and energy states are available. Also, tunneling through a thin heterojunction barrier or resonant tunneling through a double barrier can be employed. This would result in a TUNNETT diode or QWITT device, respectively.

3. Avalanche multiplication through impact ionization: Electrons or holes at high-enough energy levels in a strong electric field create new electron–hole pairs. This would result in an IMPATT diode.

*Any mechanism with the injection angle $\Theta_M > \pi/2$ may result in NDR*
IMPATT Diode

(IMpact ionization Avalanche Transit Time Diode)
IMPATT diode operation principles

1. The DC voltage applied is high enough to initiate the avalanche breakdown in the p⁺-n junction.

2. The total voltage is the sum of DC voltage and AC (the diode is in high-Q cavity)

3. The generation rate $G$ is a strong function of the maximum electric field.

4. $G$ is proportional to the number of carriers.

5. The rate of the current increase is proportional to the $G$

6. Hence the current continues to rise, reaching the peak when the AC voltage goes to zero

$$Q_M \sim \frac{\pi}{2}$$
High-power double-drift IMPATT diodes

Schematics of double-drift TT Diode

Ideal field profile
Realistic field profile
State of the art Transit time diodes
NDR Diodes based on Quantum Tunneling Effects

I. Tunnel Diode (TD)

- A tunnel diode is a PN junction where both P- and N-type regions are degenerately doped.
- As a result, the Fermi level in the N-type material is above the minimum of the conduction band and the Fermi level in the P type material is below the maximum of the valence band.
- The doping concentrations are so high that the width of the space-charge region at the junction is extremely thin and usually measures less than 10 nm.

A: zero bias at the p-n junction;
B: small forward bias;
C: larger forward bias.
Tunnel Diode: principle of operation

A: Zero applied bias. In that case the Fermi level is uniform, and the tunneling current is equal to zero.

B: If a forward bias, is applied the quasi-Fermi level and the energy bands in the N-type region move up with respect to the P-type region. As a result there are empty states in the P-side valence band which have the same energy as occupied states in the N-side conduction band. The tunneling current take place. This current increases with increased applied bias, until a maximum is reached. The maximum current occurs when the number of states in the N-conduction band having the same energy as empty states in the P-valence band is maximum.

C: If the applied bias, is further increased the number of empty valence states having the same energy as occupied conduction states decreases until the tunneling current eventually vanishes. A "valley" point of the I-V characteristics is reached when tunneling ceases.

D: In addition to the band-to-band tunneling current a "regular" PN junction current flows through the diode.

In the part of the curve between the peak and the valley the tunnel diode has a negative resistance characteristics \( R = dV/dI < 0 \).
A thin layer (< 20 nm) of a semiconductor material with a lower bandgap (e.g., GaAs, InAs, and InGaAs), the so-called quantum well, is sandwiched and confined between two very thin (< 10 nm) layers of a semiconductor material with a wider bandgap (e.g., AlGaAs or AlAs, AlSb, and AlAs).
Resonant Tunneling Diode (RTD) principles

If the thickness of the quantum well approaches the order of the de Broglie wavelength of electrons, electrons in the well are confined to discrete energy levels \( (E_i, E_2, \text{etc.}) \)

(A) As the applied bias voltage is increased, an accumulation region forms near the barrier at the cathode side and a depletion region forms near the barrier at the anode side. Only a few electrons can tunnel through the double barrier.

(B) Once the bias reaches a value where the conduction band's occupied energy states on the cathode side line up with empty states at \( e_i \) in the well, resonance occurs. At this point, many electrons can tunnel through the left barrier into the well and subsequently through the right barrier into unoccupied states in the conduction band of the anode side.

(C) At higher bias the current drops as there is no lineup level in the well
TD and RTD circuit operation

Large-signal conductance per unit area:

\[ G_D = \frac{J_v - J_p}{V_v - V_p} \]

Susceptance per unit area:

\[ B_D = \omega C_D = \omega \frac{\varepsilon_s}{W} \]

The RF power:

\[ P_{RF} = \frac{1}{8} A (J_p - J_v) (V_v - V_p) \]

RF to DC conversion efficiency

\[ \eta = \frac{P_{RF}}{P_{DC}} = \frac{1}{2} \frac{(J_p - J_v)(V_v - V_p)}{(J_p + J_v)(V_v + V_p)} = \frac{1}{2} \left( \frac{J_p}{J_v} - 1 \right) \left( \frac{V_v}{V_p} - 1 \right) \]
NDR Diode (two-terminal device) based oscillators

The oscillation conditions:

\[ R_D + R_s + R_L = 0 \quad \text{(real part)} \]
\[ \frac{-1}{\omega_0 C_d} + \omega_0 L_L = 0 \quad \text{(imaginary part)} \]