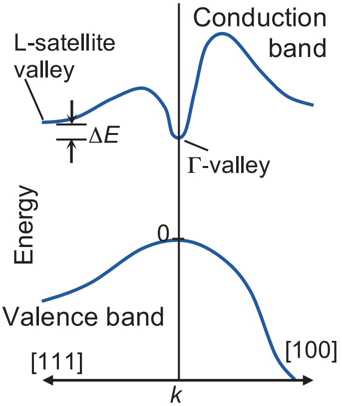
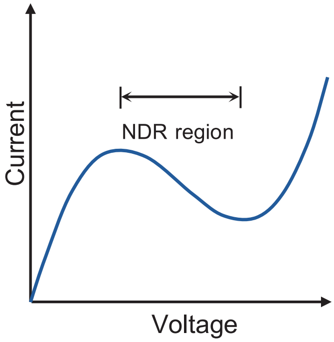
Gunn Diodes

Gunn diodes are two-terminal negative differential resistance (NDR) devices that, when coupled to a suitably tuned ac resonator, generate RF power. Typically, a Gunn diode consists of a uniformly doped n-type III-V material (e.g., GaAs, InP) sandwiched between heavily doped regions at each terminal.

The lowest conduction band in, for example, a GaAs crystal has distinct valleys in certain orientations, two of which are labeled Γ and L. If they reside in the lower Γ-valley, electrons exhibit a small effective mass and very high mobility, whereas in the L-valley, they have a large effective mass and low mobility. The two valleys are separated by a small energy gap ΔE.

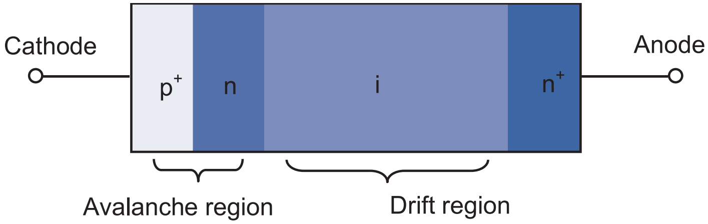




As the bias voltage across the diode is increased, electrons gain sufficient energy to be transferred to the L-valley. (A Gunn diode is also known as a **transferred-electron device**.) These electrons have a lower drift velocity because of the increase in their effective mass; the current decreases with increasing bias voltage, and the diode exhibits a region of NDR. If biased in this region, small local perturbations in the net charge give rise to ac current oscillations at the contacts. If the diode is placed in a cavity or resonant circuit so that its negative resistance cancels the resistance of the resonator, then the circuit oscillates without attenuation and emits electromagnetic radiation.

IMPATT Diodes

An **impact ionization avalanche transit time** (or **IMPATT**) **diode** is an NDR device with relatively high power capability. Its basic structure is based on a reverse-biased p–n junction and an intrinsic (high-resistivity) layer.

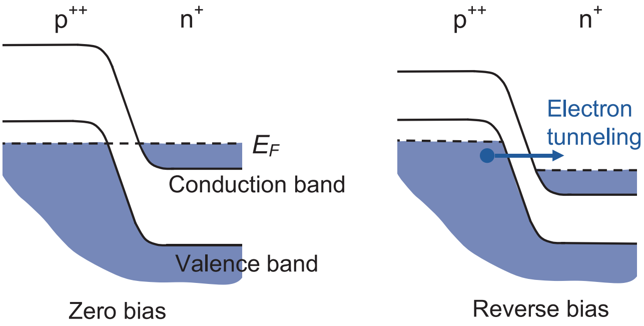


When a reverse bias across the p–n junction exceeds a certain threshold value, then avalanche breakdown (due to impact ionization) occurs, resulting in a large number of carriers in what is called the avalanche region. In the example above, electrons move through the drift region (intrinsic doping) to the n^+ contact in a time known as the transit time delay.

An ac signal with a mean value just below avalanche breakdown is applied to the diode. As the voltage increases above threshold, carriers are generated; however, since the rate of carrier generation at avalanche depends not only on the electric field but also on the number of carriers already in existence, the current continues to rise even as the ac voltage decreases (it lags the voltage by 90 deg, known as the injection delay). The length of the diode can be chosen so that the transit time delay results in a further 90-deg phase lag in current and therefore a negative differential resistance device. An external resonant circuit can then be used to sustain the oscillations. Like other devices based on the random avalanche process, IMPATT diodes tend to suffer from phase noise.

TUNNETT Diodes

As the operating frequency of an IMPATT diode increases, the dominant carrier injection mode changes from an avalanche to a mixed avalanche–tunnel mechanism. The exploitation of the injection of charge by tunneling led to the development of **tunnel injection transit time** or **TUNNETT diodes**.



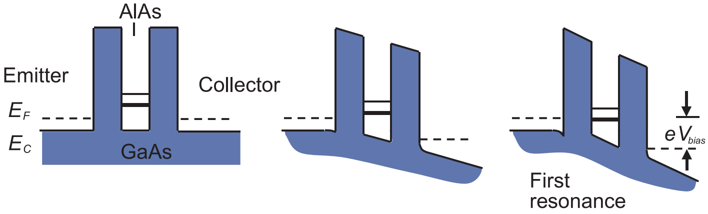
In these diodes a highly doped, narrow, $p^{++}n^{+}$ junction (in an overall $p^{++}n^{+}nn^{+}$ structure) is formed in order to change the breakdown mechanism from avalanche to tunnel injection. Since the carrier generation rate due to tunneling does not depend on the current density, there is no injection delay in this case, and negative differential resistance is achieved by the transit time of carriers through a drift region with a considerably lower electric field than in IMPATT diodes.

Tunneling is a quick, low-noise process when compared with impact ionization, so TUNNETT diodes can provide medium power at higher frequencies and with lower noise than IMPATT diodes.

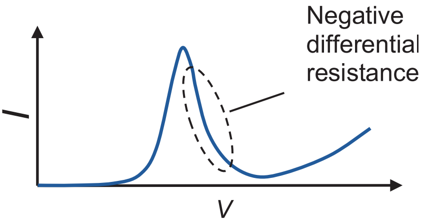
Like other NDR devices, TUNNET diodes in an external resonant circuit can be used to generate electromagnetic radiation.

Resonant Tunnel Diodes

In a **resonant tunnel diode (RTD)**, layers of undoped material are used to create a quantum well between two thin barriers. Quasi-bound, or resonant, energy states are formed in the well.



When an energy level in the quantum well is close to the energy of the electrons in the conduction band, then resonant tunneling through the double-barrier structure occurs. This gives rise to a peak in the current-voltage characteristic. The width of the peak depends on the width of the resonant state in the quantum well.



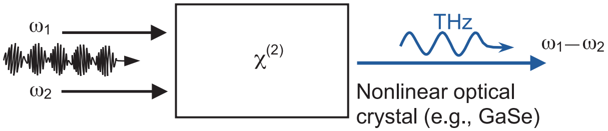
As the bias voltage is increased beyond the resonance peak, the *I*–*V* curve exhibits negative differential resistance.

Like other NDR devices, RTD diodes in an external resonant circuit can be used to generate electromagnetic radiation.

Because tunneling is inherently a very fast process, RTDs produce the highest oscillation frequencies of the NTD devices discussed here.

Difference Frequency Generation

Difference Frequency Generation (DFG) refers to a process in which two beams, at frequencies ω_1 and ω_2, interact in a medium with a second-order nonlinear **susceptibility** $\chi^{(2)}$, producing radiation at their difference frequency $\omega_1 - \omega_2$.



An electromagnetic field incident on a medium induces bound electrons to oscillate about their equilibrium position. In the linear regime, the resulting dielectric polarization is proportional to the applied electric field

$$\mathbf{P}(t) = \varepsilon_0 \chi \mathbf{E}(t)$$

where χ is the electric susceptibility, but in the nonlinear regime, when the input field is strong, for example, the polarization is described by a series of terms:

$$\mathbf{P}(t) = \varepsilon_0 \chi \mathbf{E}(t) + \varepsilon_0 \chi^{(2)} \mathbf{E}^2(t) + \varepsilon_0 \chi^{(3)} \mathbf{E}^3(t) + \ldots$$

The second-order nonlinear susceptibility tensor $\chi^{(2)}$ is nonzero in noncentrosymmetric materials; DFG makes use of this second-order term. (For simplicity we consider a lossless dispersionless medium and scalar quantities.)

If the incident optical field has two distinct frequency components $E(t) = E_1 e^{-i\omega_1 t} + E_1 e^{-i\omega_2 t}$ + c.c., then the second-order induced polarization $P^{(2)}(t) = \varepsilon_0 \chi^{(2)} E^2(t)$ has five, at frequencies 0 (**optical rectification**), $2\omega_1$, $2\omega_2$ (**second-harmonic generation**), $\omega_1 + \omega_2$ (**sum-frequency generation**), and $\omega_1 - \omega_2$ (difference-frequency generation).

The input frequencies are chosen so that an output THz radiation field is produced by the time-varying second-order polarization $E_{THz}(t) \propto \partial^2 P^{(2)}(t)/\partial t^2$.