Semiconductor Technology from A to Z

Devices

The Tunnel Diode

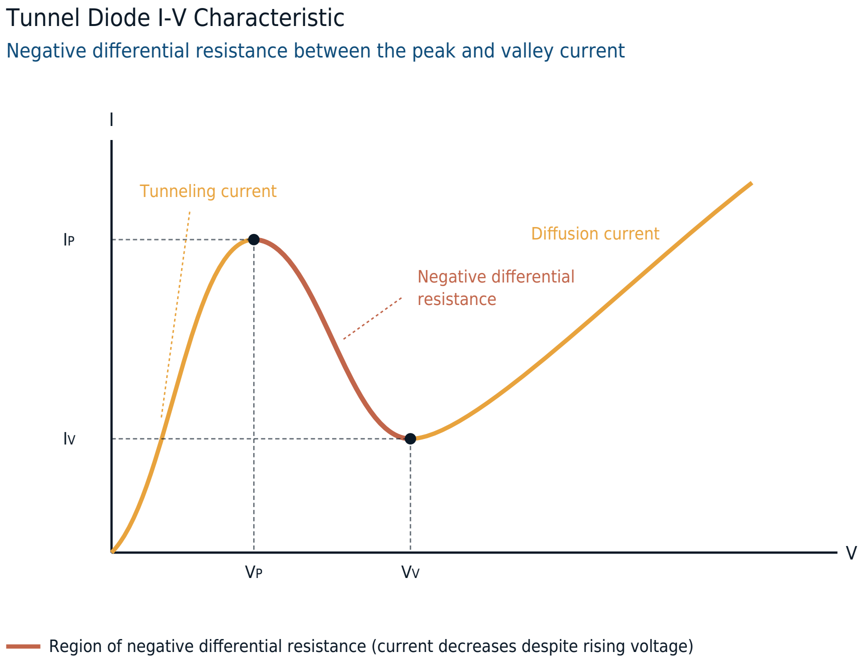
Extreme Doping Creates a Degenerate Junction

The tunnel diode, also known as the Esaki diode after its discoverer, is doped exceptionally heavily on both sides of the p-n junction – typically in the range of 10^{19} to 10^{20} cm^{-3}, several orders of magnitude higher than in ordinary p-n diodes, where doping concentrations of 10^{15} to 10^{17} cm^{-3} are typical. At such high doping levels, both semiconductor regions become degenerate: the Fermi level then no longer lies within the forbidden band gap, as in normally doped semiconductors, but shifts into the conduction band on the n-side and into the valence band on the p-side.

The resulting extremely thin space-charge region, only a few nanometers wide – considerably narrower than in any ordinary diode –, enables direct quantum-mechanical tunneling of charge carriers between the bands, without them having to classically overcome the band gap energetically. This tunneling mechanism already occurs at very small applied voltages, in the range of a few tens to a few hundred millivolts, well below the usual threshold voltage of a normal p-n diode.

Negative Differential Resistance

At small forward voltage, a tunneling current initially grows with voltage, since occupied states in the conduction band on the n-side and empty, available states in the valence band on the p-side overlap in energy, allowing electrons to tunnel through unimpeded. As the voltage rises further, however, the energy bands on both sides shift increasingly against each other, so that the region of energetic overlap – and therefore the number of state pairs available for tunneling – decreases again even as the applied voltage continues to increase.



In this intermediate voltage range, the current therefore decreases as the voltage increases: the diode exhibits negative differential resistance, a behavior that is rare in semiconductor devices and very useful for many analog circuits, usually only achievable with active amplifying devices or feedback circuits. Only at even higher voltage, once the bands have shifted so far apart that no energetic overlap remains, does the ordinary thermal diffusion current across the remaining residual barrier take over, and the characteristic curve returns to the usual, exponentially rising diode behavior. Overall, this produces a characteristic N-shaped current-voltage curve with a local maximum (peak current) followed by a local minimum (valley current), unlike any other conventional diode type.

Niche Applications Despite Being Superseded

The tunnel diode was historically significant as one of the first semiconductor devices exhibiting negative differential resistance, enabling extremely fast switching as well as remarkably simple oscillator circuits: since an inductor or resonant circuit combined with negative differential resistance can already generate sustained oscillations without any additional active amplifying elements, tunnel diodes made possible very simple and potentially very fast oscillators. Its inventor, Leo Esaki, received the Nobel Prize in Physics in 1973 for this discovery, first published in 1957.

Because transistor-based circuits have since completely displaced the tunnel diode in most classic applications – amplifiers, switches, digital logic –, mainly because transistors provide genuine power gain, while the tunnel diode, as a purely two-terminal device, only acts passively, the tunnel diode today survives only in a few niche applications in RF and microwave technology. There, its negative differential resistance continues to be used for particularly simple, robust oscillators and amplifier stages in the gigahertz to terahertz range, where its extremely short tunneling time, on the order of a few picoseconds, can still outperform other devices.