

Semiconductor Technology from A to Z

Devices

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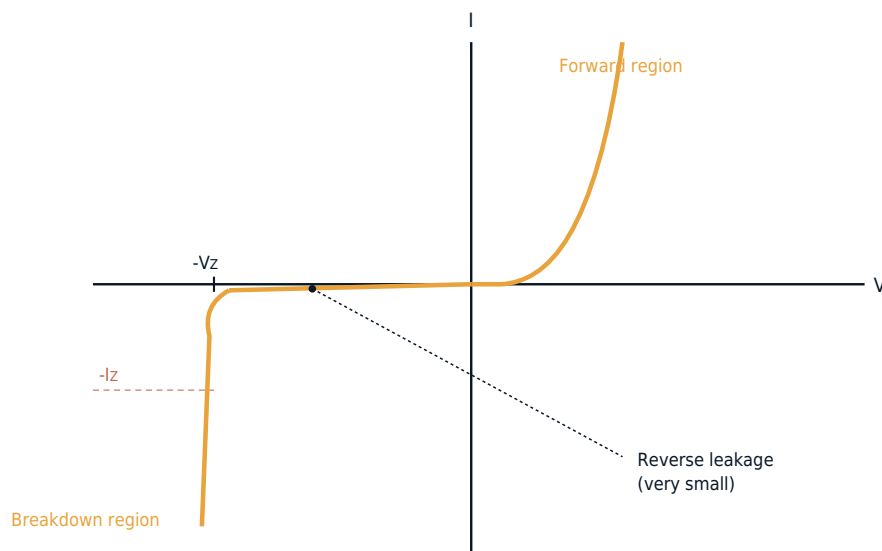
Zener and Avalanche Diodes

Controlled Breakdown as the Operating Principle

While ordinary diodes are always operated so that breakdown in the reverse direction is avoided under all circumstances – such a breakdown would normally destroy an ordinary rectifier diode through excessive heating – Zener and avalanche diodes are specifically designed to operate in a controlled, reversible, and non-destructive manner within the breakdown region. The diode is deliberately operated in reverse bias, and the characteristically very steep curve in the breakdown region makes it a nearly ideal voltage limiter: across a wide current range, the voltage across the device stays almost constant.

Zener/Avalanche Diode I-V Characteristic

Steep, reversible breakdown at the voltage V_Z



V_Z : breakdown/Zener voltage – I_Z : test current used to specify V_Z

Depending on the doping level of the p-n junction, two different physical mechanisms can dominate, differing markedly in their field-strength dependence: for heavily doped junctions with breakdown voltages below about 5 V, the Zener effect dominates, while for more lightly doped junctions with higher breakdown voltages of a few volts up to several hundred volts, the avalanche effect dominates. Confusingly, nearly all commercially available devices are sold and referred to as "Zener diodes" regardless of which mechanism actually dominates – most types above about 6 V actually operate via

the avalanche mechanism despite the name, while true Zener diodes in the strict physical sense only cover the lower voltage range.

The Zener Effect versus the Avalanche Effect

In the Zener effect, extremely heavy doping on both sides of the junction (typically above 10^{18} cm^{-3}) creates a very narrow space-charge region, often only a few nanometers wide. Even at moderate reverse voltage, field strengths above 10^6 V/cm already occur there – strong enough for valence electrons to tunnel directly through the narrow band gap quantum-mechanically, without needing to gain additional kinetic energy from acceleration in the electric field. This Zener tunneling is essentially the same quantum-mechanical mechanism underlying the tunnel diode discussed in the following chapter, only used here in reverse operation rather than forward operation.

In the avalanche effect, by contrast, the lower doping produces a wider space-charge region in which free carriers can be accelerated over a longer distance by the electric field. If they gain sufficient kinetic energy, they release additional electron-hole pairs upon colliding with lattice atoms (impact ionization); these newly generated carriers are themselves accelerated and generate further pairs in turn, so that the current multiplies in an avalanche-like fashion, similar to a chain reaction.

The two mechanisms also differ fundamentally in their temperature behavior: the Zener effect has a negative temperature coefficient – the breakdown voltage decreases with rising temperature, since the semiconductor band gap narrows with temperature, making tunneling easier –, while the avalanche effect has a positive temperature coefficient, since the mean free path of carriers between collisions shortens with rising temperature, requiring a higher field strength for the same impact ionization rate. Diodes with a breakdown voltage around 5 to 6 V, where both mechanisms contribute roughly equally, therefore largely cancel out their opposing temperature coefficients and achieve a largely temperature-independent breakdown – an effect deliberately exploited in precision voltage references, before modern circuits mostly moved to the bandgap references discussed in the previous chapter.

Applications: Voltage Reference and Overvoltage Protection

Commercial Zener and avalanche diodes cover breakdown voltages from about 2.4 V up to 200 V, at power ratings from a few hundred milliwatts in small packages up to several watts in power versions. With a simple current-limiting series resistor, a basic shunt voltage regulator can be built from one: the load current varies, but as long as a minimum current continues to flow through the

diode, the output voltage stays approximately constant. For higher precision requirements, however, modern integrated circuits generally prefer the bandgap reference, which offers better temperature stability along with lower noise contributions and a lower, more chip-compatible operating voltage.

Avalanche diodes have greater practical importance today mainly in overvoltage protection: avalanche diodes specifically designed for high pulse power, marketed as transient voltage suppressors (TVS), can absorb short energy pulses in the range of several hundred watts up to a few kilowatts and clamp voltage spikes – caused for example by electrostatic discharge, inductive switch-off of motors and relays, or lightning effects on long cables – to a safe level within nanoseconds. This protects downstream, more sensitive integrated circuits whose own ESD protection structures are not designed for such high energies.