Semiconductor Technology from A to Z

Compound Semiconductors

Fundamentals & Material System

Why Compound Semiconductors for Power Electronics?

Silicon has dominated power electronics for decades, but it runs into physical limits: at high blocking voltages, a Si device needs a thick, lightly doped drift region to safely support the electric field – which costs on-resistance and therefore losses. Compound semiconductors such as silicon carbide (SiC) and gallium nitride (GaN) have a significantly higher breakdown field strength than silicon. This allows thinner, more highly doped drift regions at the same blocking voltage – and thus noticeably lower conduction losses combined with a smaller chip area.

Material Comparison: SiC, GaN and Silicon

A direct comparison shows clear differences: silicon has a bandgap of 1.12 eV, 4H silicon carbide reaches 3.26 eV, and gallium nitride 3.4 eV – both compound semiconductors are clearly wider-gap materials. The critical breakdown field strength rises from about 0.3 MV/cm for silicon to roughly 2.8 MV/cm for SiC and 3.3 MV/cm for GaN. SiC additionally stands out with high thermal conductivity (about 4.9 W/cmK versus 1.5 W/cmK for silicon), which makes heat dissipation at high power levels easier. GaN, in turn, reaches a very high electron saturation velocity, enabling especially high switching frequencies.

Property	Silicon	4H-SiC	GaN
Bandgap (eV)	1.12	3.26	3.4
Crit. field strength (MV/cm)	0.3	2.8	3.3
Thermal conductivity (W/cmK)	1.5	4.9	1.3
Saturation velocity (10^7 cm/s)	1.0	2.0	2.5
Electron mobility (cm^2/Vs)	1400	900	1200

Values for 4H-SiC and silicon at room temperature, intrinsic bulk material. GaN electron mobility in the 2DEG (AlGaN/GaN heterostructure) can be significantly higher.

The Baliga Figure of Merit

To objectively compare semiconductor materials for power switches, B. Jayant Baliga defined a figure of merit: $BFOM = \varepsilon r \cdot \mu \cdot Ec^3$, formed from permittivity, carrier mobility and the critical field strength raised to the third power. It indicates how small the specific on-resistance can theoretically become at a given blocking voltage. Because the critical field strength enters to the third power, the material advantage of SiC and GaN has an especially strong effect: both exceed silicon by more than two orders of magnitude in the Baliga figure of merit.

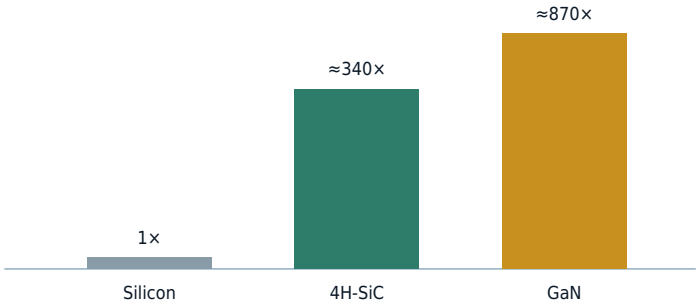
Baliga Figure of Merit (BFOM)

Material figure of merit for the minimum achievable on-resistance

$$BFOM = \varepsilon r \cdot \mu \cdot Ec^3$$

εr: permittivity · μ: carrier mobility · Ec: critical breakdown field strength

BFOM relative to Si



Positioning: Where Is Each Material Used?

SiC plays to its strengths mainly at high voltages and power levels – for example in traction inverters for e-mobility or in industrial applications. GaN, on the other hand, excels at high switching frequencies and medium voltages, for example in chargers and fast-charging infrastructure, where compact form factor and low switching losses matter most. The following chapters first cover crystal growth and substrates, then the devices of both material systems in detail.

Crystal Growth & Substrates

SiC Crystal Growth: Physical Vapor Transport

Unlike silicon, SiC cannot be pulled from a melt – at the temperatures required, SiC sublimes rather than melting. Instead, the PVT process (Physical Vapor Transport, also known as the modified Lely method) is used: a supply of SiC powder is heated above 2000 °C and sublimes, the vapor phase travels along a temperature gradient to a cooler SiC seed crystal and crystallizes there epitaxially. The process runs for days to weeks and grows a cylindrical boule, from which wafers are subsequently sawn.

Polytypes: Why 4H-SiC?

SiC occurs in more than 200 crystal structures (polytypes), which differ only in the stacking sequence of the Si-C double layers. 4H-SiC has become the

standard for power electronics because it offers higher and more isotropic electron mobility than, for example, 6H-SiC. Growth is usually performed off-axis (typically a 4° miscut from the c-axis) to force step-flow growth during homoepitaxy and avoid polytype inclusions.

GaN Epitaxy: Heteroepitaxy Instead of Native Substrates

Native GaN substrates are expensive and available only in small diameters, because GaN does not melt congruently at normal pressure. In practice, GaN is therefore deposited heteroepitaxially on foreign substrates – usually silicon (GaN-on-Si, low cost, large diameters up to 200 mm) or silicon carbide (GaN-on-SiC, better heat dissipation, but more expensive). A thin AlN nucleation layer along with step-graded AlGaN buffer layers absorb the lattice and thermal expansion mismatch before the actual GaN layer grows.

Lattice Matching, Strain and Defect Density

The lattice constants of GaN and silicon differ by about 17%, and their thermal expansion coefficients by more than 50% – without buffer layers, the GaN layer would crack on cooling. Even with a buffer strategy, a significant dislocation density remains (typically 10^8–10^9 cm^{-2} for GaN-on-Si, versus 10^3–10^4 cm^{-2} for native SiC substrates). This explains the industry trade-off: GaN-on-Si for cost- and area-driven applications, GaN-on-SiC or native SiC substrates where reliability and thermal management take priority.

SiC Power Devices

The SiC Power MOSFET

The SiC power MOSFET adopts the planar DMOS base structure of its silicon counterpart (see the fundamentals chapter "The MOSFET"), but exploits the much higher breakdown field strength of SiC to make the drift region significantly thinner and more highly doped at the same blocking voltage. This lowers the specific on-resistance R_on·A by more than an order of magnitude compared to an equivalent Si MOSFET – while simultaneously allowing a higher blocking voltage (600 V to over 3.3 kV) and a noticeably smaller chip area per ampere.

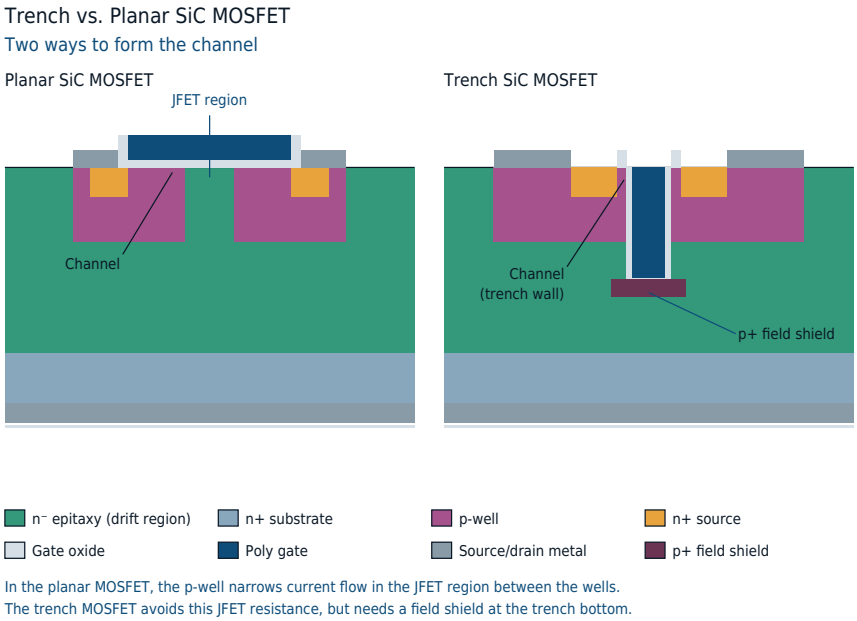
The SiC Schottky Diode

A Si pn diode needs time when switching off to clear the minority charge stored during conduction – the so-called reverse recovery time, which causes switching losses that become more significant at higher frequencies. A SiC Schottky diode, by contrast, is a pure majority-carrier device: there is virtually no stored charge and therefore almost no reverse recovery current. This only becomes practical

with SiC, because its high breakdown field strength allows Schottky contacts to sustain high blocking voltages with acceptable conduction losses – with silicon, Schottky diodes are only practical up to a few hundred volts.

Trench vs. Planar SiC MOSFET

In the planar SiC MOSFET, the channel lies horizontally at the wafer surface, similar to the Si DMOS. Trench SiC MOSFETs instead place the channel along the vertical wall of an etched trench. This avoids the JFET resistance of the planar structure (the constriction between two neighboring p-wells) and increases channel density – at the cost of more complex fabrication and higher demands on field shielding at the trench bottom, where locally elevated electric fields would otherwise threaten gate oxide reliability.



In the planar MOSFET, the p-well narrows current flow in the JFET region between the wells.
The trench MOSFET avoids this JFET resistance, but needs a field shield at the trench bottom.

The SiC/SiO2 Interface as a Challenge

Unlike with silicon, thermal oxidation of SiC leaves part of the carbon behind as interface defects. This elevated defect density at the SiC/SiO2 interface reduces the effective channel electron mobility to a fraction of the bulk value – a key reason why SiC MOSFETs long lagged behind their theoretical potential despite superior material properties. Process improvements such as NO or N2O post-oxidation annealing (nitrogen passivation) have significantly improved interface quality and therefore channel mobility in recent years.

GaN Power Devices

The 2DEG: Foundation of the HEMT

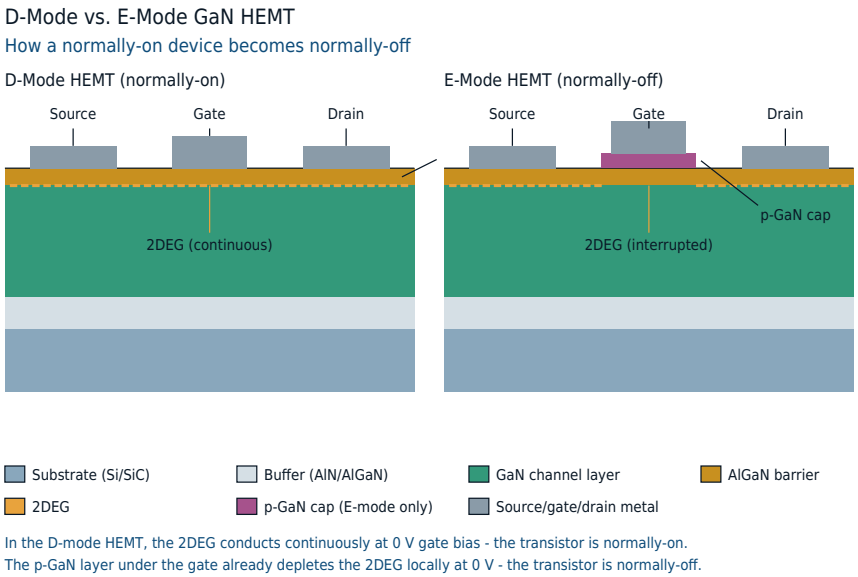
When a thin AlGaN layer is grown on GaN, spontaneous and piezoelectric polarization at the interface creates an extremely thin, highly mobile electron gas – the two-dimensional electron gas (2DEG). Unlike in a Si MOSFET, this conductive channel needs no doping at all: it arises purely from the polarization charge at the AlGaN/GaN heterointerface and reaches electron mobilities well above those of doped bulk material. This structure forms the basis of the HEMT (High Electron Mobility Transistor).

The GaN HEMT as a Power Switch

A gate electrode on the AlGaN barrier controls the 2DEG beneath it: applying a sufficiently negative gate voltage locally depletes the channel under the gate and the transistor turns off. Because no pn junction and no stored minority carriers are involved, the GaN HEMT switches extremely fast and with very low losses – ideal for high-frequency switch-mode power supplies and fast chargers, where switching losses increasingly limit Si and even SiC devices.

E-Mode vs. D-Mode and the Cascode Configuration

An untreated AlGaN/GaN HEMT is normally-on (D-mode): the 2DEG already conducts with no gate voltage applied, which is undesirable in power electronics for safety reasons (fail-safe behavior if gate drive is lost). True E-mode devices (normally-off) are achieved, for example, with a p-GaN gate layer that locally depletes the 2DEG under the gate at rest. Physically, this relies on a shift of the band edge: the ionized acceptors (usually magnesium) in the p-GaN layer create a built-in electric field that pushes the conduction band edge at the AlGaN/GaN interface directly beneath the gate above the Fermi level – at rest, no free electrons accumulate there, so the 2DEG is locally interrupted. Outside the gate, where there is no p-GaN layer, the band edge stays below the Fermi level and the channel continues to exist unimpeded. Only a positive gate voltage above the threshold voltage pushes the band edge locally back below the Fermi level and restores the channel. A common alternative is the cascode configuration: a normally-on GaN HEMT in series with a low-voltage Si MOSFET, which imposes normally-off behavior on the combined device from the outside.



Lateral vs. Vertical: Why GaN Mostly Stays Lateral

Unlike SiC MOSFETs, commercial GaN power devices today are almost exclusively lateral – source, gate and drain all sit on the same wafer surface, and current flows horizontally rather than vertically through the chip. The reason is heteroepitaxy on foreign substrates (see Chapter 2): vertical GaN devices would need a thick, low-resistance bulk GaN layer for the return current path, which is practically not economical to produce with heteroepitaxial GaN-on-Si. Vertical GaN structures are the subject of active research but are not yet in volume production.

Applications & System Comparison

E-Mobility: SiC Dominates the Traction Inverter

The traction inverter is the power electronics component that most directly determines an electric vehicle's range and efficiency. SiC MOSFETs have become the standard here over Si IGBTs, because their lower switching losses allow higher switching frequencies – this shrinks passive components (inductors, capacitors) and typically raises efficiency by 3 to 5 percentage points over the drive cycle. In 800 V system architectures, which are increasingly becoming standard, the SiC advantage grows even further, since the higher breakdown field strength matters most at higher voltage classes.

Fast-Charging Infrastructure and Power Supplies: GaN Excels at High Frequency

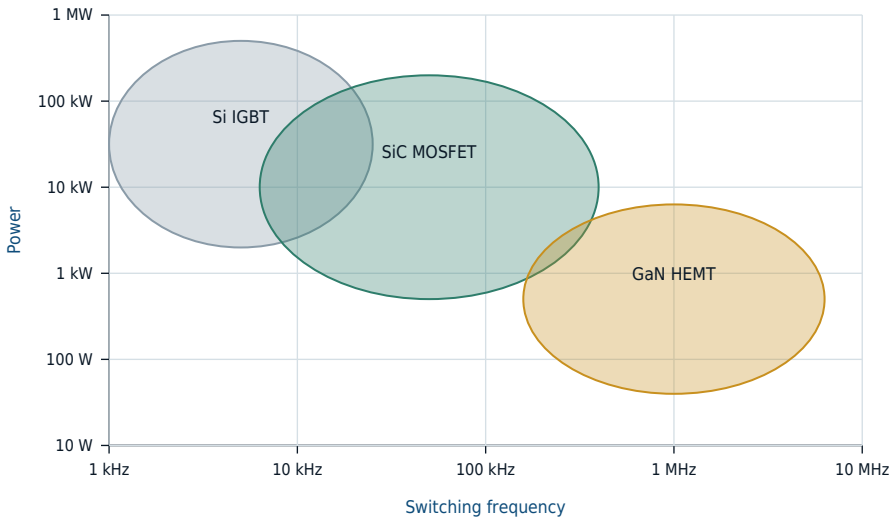
For applications with medium voltages (48 V to a few hundred volts) and a need for a compact form factor, GaN plays to its strengths: chargers for laptops and smartphones use the high switching frequency of GaN HEMTs to drastically shrink transformers and filter components – a 65 W USB-C charger today fits into a housing that, just a few years ago, was needed for a third of the power. DC fast chargers for electric vehicles are also increasingly adopting GaN in their front-end AC/DC stages.

Efficiency and Switching Frequency Comparison

Roughly speaking: Si IGBTs remain the most cost-effective option today for low switching frequencies (below 20 kHz) at very high power levels. SiC MOSFETs dominate the medium-to-high power range with frequencies reaching into the hundreds of kHz. GaN HEMTs unlock MHz frequencies at lower to medium power levels, where form factor is the dominant design driver.

Efficiency and Frequency Ranges Compared

Typical application ranges of Si IGBT, SiC MOSFET and GaN HEMT



Si IGBTs dominate low frequencies at very high power levels.
SiC MOSFETs cover the medium-to-high power range.
GaN HEMTs unlock MHz frequencies at lower to medium power levels.

Cost Trends and Outlook

Despite their clear technical advantages, SiC and GaN devices remain more expensive than comparable Si solutions – driven mainly by substrate costs and lower manufacturing volumes. That price gap, however, is shrinking steadily: 200 mm SiC substrates and larger GaN-on-Si wafers lower per-unit costs, while rising volumes in e-mobility and consumer electronics create economies of scale.

For many applications, the break-even point over the system's lifetime (lower cooling costs, smaller form factor, higher efficiency) has already been reached today, even though the raw component price is still higher.