Wide Bandgap Semiconductor Devices

Why wide bandgap semiconductor materials can significantly improve the tradeoff between breakdown voltage, forward voltage drop, and switching speed

Silicon Carbide (SiC) power devices

- Schottky diode
- MOSFET

Gallium Nitride (GaN) power devices

- HEMT

Specific on-resistance R_{on} as a function of breakdown voltage V_B

Majority-carrier device: $$AR_{on} = \frac{k}{\mu_n \varepsilon_s E_c^3} V_B^2$$

A	device area
V_B	device breakdown voltage
E_c	critical electric field for avalanche breakdown
μ_n	electron mobility
ε_s	semiconductor permittivity

Comparison of Power Semiconductor Materials

Material	**Bandgap [eV]**	**Electron mobility μ_n [cm^2/Vs]**	**Critical field E_c [V/cm]**	**Thermal conductivity [W/m°K]**
Si	1.12	1400	3×10^5	130
SiC	2.36-3.25	300-900	**$1.3\text{-}3.2 \times 10^6$**	**700**
GaN	3.44	**1500-2000** (AlGaN/GaN 2DEG)	**$3.0\text{-}3.5 \times 10^6$**	110

Wide-bandgap device advantages

- Much larger E_c, hence much lower specific R_{on} at high breakdown voltages
- Majority carrier devices: no current tail, no reverse recovery
- Capability of operation at increased junction temperature

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But:

- SiC is inferior to Si at sub-600V voltages because of lower electron mobility
- GaN devices are lateral (not vertical), more difficult to scale to higher voltages and currents
- GaN substrate issues: GaN-on-Si

The SiC Schottky Diode

Available at 600 V, 1200 V, and higher

No reverse recovery

Forward voltage drop 1.5 V – 2 V

Comparison with *p–n* Si diode at same voltage:

- Much lower switching loss
- Higher conduction loss
- Overall higher efficiency
- More expensive

Note that silicon Schottky diodes are restricted to < 100V

The SiC MOSFET

We have silicon MOSFETs at up to 600-700 V

SiC MOSFETs now are available at 600V – 10kV

- Properties are similar to Si MOSFETs, but with low R_{on} at these higher voltages
- *p–n* body diode has V_F of 3-4 V
- Allows much higher switching frequency than Si IGBT

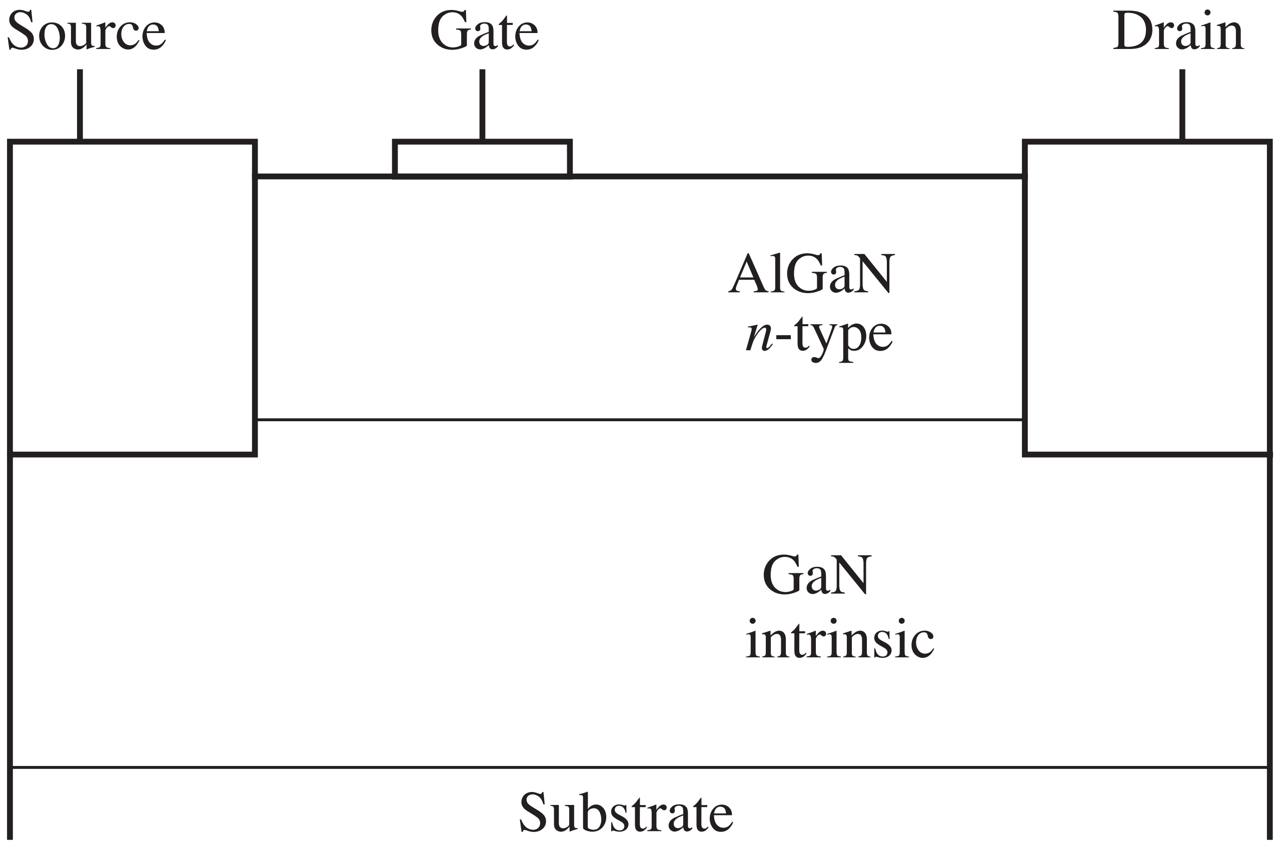
Table 4.4 Characteristics of several commercial SiC MOSFETs

Part number	Rated maximum voltage	Rated average current	R_{on}	Q_g (typical)
C3M0030090K	900 V	63 A	30 mΩ	87 nC
C3M0075120K	1200 V	30 A	75 mΩ	51 nC
C2M0045170D	1700 V	72 A	45 mΩ	188 nC
SCT3022AL	650 V	93 A	22 mΩ	133 nC
CPM3-0900-0010A	900 V	196 A	10 mΩ	68 nC

Power GaN HEMT

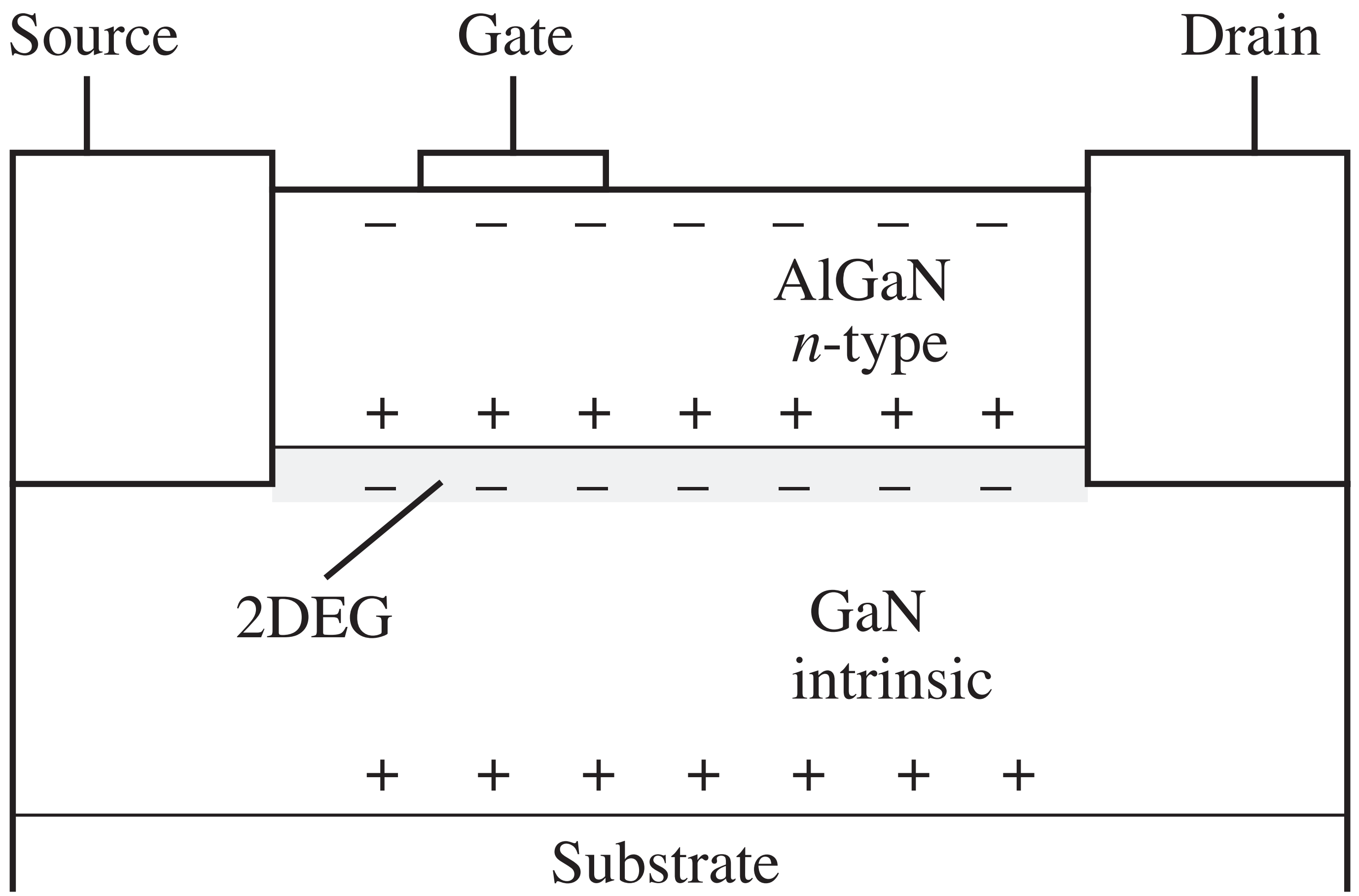
High Electron Mobility Transistor (HEMT)
A heterojunction field effect transistor

Lateral device
No oxide layers



AlGaN: low bandgap
GaN: high bandgap

The Two-Dimensional Electron Gas (2DEG)



The energy band diagram takes a step at the heterojunction. Under the correct conditions, a 2DEG forms at the surface of the GaN layer. These electronics exhibit very low resistivity (high mobility), and can conduct current between source and drain.

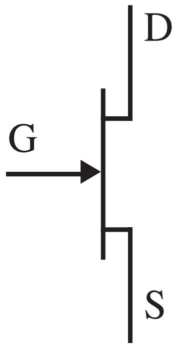
A majority carrier device having:

- High breakdown field
- Low on resistance

The HEMT is a JFET

The basic device is a depletion-mode junction field-effect transistor:

- Normally on
- To turn off, reverse-bias gate
- Gate-channel junction is a diode that can conduct current when forward-biased



Additional semiconductor design can shift threshold voltage:

- Enhancement-mode JFETs are available
- Then device is off when $v_{gs} = 0$

Electrical Considerations

On state:

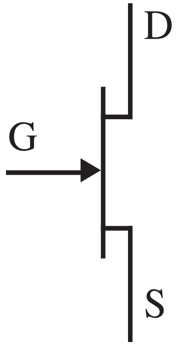
- $v_{gs} > V_{th}$ with $V_{th} \sim 3.5$ V
- But don't apply v_{gs} that is too large: gate-source diode will become forward-biased and conduct large current.

Off state:

- $v_{gs} \leq 0$

Reverse conduction:

- No body diode
- Channel can conduct current in either direction
- With $v_{gs} = 0$, a negative v_{ds} ($< -V_{th}$) can turn device on
- Behavior is similar to having a body diode, except
  - Large forward drop $\sim V_{th}$
  - No reverse recovery



State of the Art Device Comparison Example

	Si MOSFET	**GaN**
Voltage rating	600 V	650 V
R_{on} at 25°C-150°C	24-60 mΩ	25-65 mΩ
Q_g at $V_{DS} = 400$V	123 nC (10V)	12 nC (6V)
C_{oss} (energy eq.)	184 pF	177 pF
C_{oss} (time eq.)	1900 pF	284 pF
V_{SD}	0.8 V	4 V
Q_{rr}	8.7 uC	-
t_{rr}	440 ns	-

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Si MOSFET body diode
reverse recovery

$Q_{rr} V_{DS} f_s = 350\ \text{W}$
at 400V, 100 kHz