4.2.1. Power diodes

A power diode, under reverse-biased conditions:

- Low doping concentration
- Depletion region, reverse-biased
Forward-biased power diode

\[ \text{conductivity modulation} \]

\[ \text{minority carrier injection} \]
Diode in OFF state:
reversed-biased, blocking voltage

- Diode is reverse-biased
- No stored minority charge: \( q = 0 \)
- Depletion region blocks applied reverse voltage; charge is stored in capacitance of depletion region
Turn-on transient

The current $i(t)$ is determined by the converter circuit. This current supplies:

- charge to increase voltage across depletion region
- charge needed to support the on-state current
- charge to reduce on-resistance of $n^-$ region
Turn-off transient

Removal of stored minority charge $q$

$i (< 0)$

$p$  

$n^-$

$n$
Diode turn-off transient
continued

(1) Diode remains forward-biased. Remove stored charge in $n^-$ region
(2) Diode is reverse-biased. Charge depletion region capacitance.
(3) $\frac{di}{dt}$
(4) Area $-Q_r$
(5) Diode is reverse-biased. Charge depletion region capacitance.
Types of power diodes

**Standard recovery**
Reverse recovery time not specified, intended for 50/60Hz

**Fast recovery and ultra-fast recovery**
Reverse recovery time and recovered charge specified
Intended for converter applications

**Schottky diode**
A majority carrier device
Essentially no recovered charge
Model with equilibrium $i-v$ characteristic, in parallel with depletion region capacitance
Restricted to low voltage (few devices can block 100V or more)
Paralleling diodes

Attempts to parallel diodes, and share the current so that $i_1 = i_2 = i/2$, generally don’t work.

Reason: thermal instability caused by temperature dependence of the diode equation.

Increased temperature leads to increased current, or reduced voltage.

One diode will hog the current.

To get the diodes to share the current, heroic measures are required:

• Select matched devices
• Package on common thermal substrate
• Build external circuitry that forces the currents to balance
Ringing induced by diode stored charge

- Diode is forward-biased while $i_L(t) > 0$
- Negative inductor current removes diode stored charge $Q_r$
- When diode becomes reverse-biased, negative inductor current flows through capacitor $C$.
- Ringing of $L$-$C$ network is damped by parasitic losses. Ringing energy is lost.

*see Section 4.3.3*
Energy associated with ringing

Recovered charge is \[ Q_r = - \int_{t_2}^{t_3} i_L(t) \, dt \]

Energy stored in inductor during interval \( t_2 \leq t \leq t_3 \):
\[ W_L = \int_{t_2}^{t_3} v_L(t) \, i_L(t) \, dt \]

Applied inductor voltage during interval \( t_2 \leq t \leq t_3 \):
\[ v_L(t) = L \frac{di_L(t)}{dt} = -V_2 \]

Hence,
\[ W_L = \int_{t_2}^{t_3} L \frac{di_L(t)}{dt} \, i_L(t) \, dt = \int_{t_2}^{t_3} (-V_2) \, i_L(t) \, dt \]
\[ W_L = \frac{1}{2} L i_L^2(t_3) = V_2 Q_r \]
4.2.2. The Power MOSFET

- Gate lengths approaching one micron
- Consists of many small enhancement-mode parallel-connected MOSFET cells, covering the surface of the silicon wafer
- Vertical current flow
- n-channel device is shown
MOSFET: Off state

- \( p-n^- \) junction is reverse-biased
- off-state voltage appears across \( n^- \) region

![MOSFET schematic diagram]
MOSFET: on state

- $p-n^-$ junction is slightly reverse-biased
- positive gate voltage induces conducting channel
- drain current flows through $n^-$ region and conducting channel
- on resistance = total resistances of $n^-$ region, conducting channel, source and drain contacts, etc.
MOSFET body diode

- $p$-$n$ junction forms an effective diode, in parallel with the channel
- Negative drain-to-source voltage can forward-bias the body diode
- Diode can conduct the full MOSFET rated current
- Diode switching speed not optimized — body diode is slow, $Q_r$ is large
Typical MOSFET characteristics

- Off state: $V_{GS} < V_{th}$
- On state: $V_{GS} >> V_{th}$
- MOSFET can conduct peak currents well in excess of average current rating — characteristics are unchanged
- on-resistance has positive temperature coefficient, hence easy to parallel
A simple MOSFET equivalent circuit

- $C_{gs}$: large, essentially constant
- $C_{gd}$: small, highly nonlinear
- $C_{ds}$: intermediate in value, highly nonlinear
- Switching times determined by rate at which gate driver charges/discharges $C_{gs}$ and $C_{gd}$

\[
C_{ds}(v_{ds}) = \frac{C_0}{\sqrt{1 + \frac{v_{ds}}{V_0}}} = \frac{C_0}{\sqrt{V_0}}
\]

\[
C_{ds}(v_{ds}) = C_0 \sqrt{\frac{V_0}{V_{ds}}} = C_0 \sqrt{\frac{V_0}{V_{ds}}}
\]
Switching loss caused by semiconductor output capacitances

Buck converter example

Energy lost during MOSFET turn-on transition (assuming linear capacitances):

\[ W_c = \frac{1}{2} (C_{ds} + C_j) V_g^2 \]
MOSFET nonlinear $C_{ds}$

Approximate dependence of incremental $C_{ds}$ on $v_{ds}$:

$$C_{ds}(v_{ds}) = C_0 \sqrt{\frac{V_0}{v_{ds}}} = C_0 \sqrt{\frac{v_{DS}}{v_{ds}}}$$

Energy stored in $C_{ds}$ at $v_{ds} = V_{DS}$:

$$W_{C_{ds}} = \int v_{ds} i_C \, dt = \int_0^{V_{DS}} v_{ds} C_{ds}(v_{ds}) \, dv_{ds}$$

$$W_{C_{ds}} = \int_0^{V_{DS}} C_0(v_{ds}) \sqrt{\frac{v_{DS}}{v_{ds}}} \, dv_{ds} = \frac{2}{3} C_{ds}(V_{DS}) \, V_{DS}^2$$

— same energy loss as linear capacitor having value $\frac{4}{3} C_{ds}(V_{DS})$
MOSFET: conclusions

- A majority-carrier device: fast switching speed
- Typical switching frequencies: tens and hundreds of kHz
- On-resistance increases rapidly with rated blocking voltage
- Easy to drive
- The device of choice for blocking voltages less than 500V
- 1000V devices are available, but are useful only at low power levels (100W)
- Part number is selected on the basis of on-resistance rather than current rating
Main switch $Q_1$
Synchronous rectifier $Q_2$

Gate driver circuitry:
- Source of $Q_2$ is connected to ground
- Source of $Q_1$ is connected to switch node
Half-bridge gate driver:
• Gate of $Q_2$ is driven by low-side driver
• Gate of $Q_1$ is driven by high-side driver
• High-side driver is powered by bootstrap power supply circuit
• High voltage integrated circuit

Logic input:
• Commands ON/OFF state of MOSFETs
• When $Q_1$ is on, $Q_2$ must be off, and vice-versa
• High-side control signal must be level-shifted
• Non-overlapping control: insert dead times
A simple Thevenin-equivalent circuit:

- $v_{th}(t)$ is open-circuit voltage produced by gate driver.
- $R_{th}$ is effective output resistance of driver, approximately given by on-resistance of output-stage transistors within the driver.
- For a driver rated at 12 V and 1 A, $R_{th} = (12 \text{ V})/(1 \text{ A}) = 12 \Omega$. 

MOSFET, with capacitances and body diode explicitly shown.
Switching transitions

\[ \text{v}_{\text{th}}(t) \]

\[ \text{v}_{gs}(t) \]

\[ \text{v}_{\text{vs}}(t) \]

Gate driver model

MOSFET model

+ 12 V

\[ Q_1 \]

\[ D_1 \]

\[ \text{L} \]

\[ i_L \]

\[ R_{th} \]

\[ C_{gd} \]

\[ C_{gs} \]

\[ v_s(t) \]

\[ t \]
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
- \( \mu_n \): electron mobility
- \( \varepsilon_s \): semiconductor permittivity
## Comparison of Power Semiconductor Materials

<table>
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<tr>
<th>Material</th>
<th>Bandgap [eV]</th>
<th>Electron mobility $\mu_n$ [cm²/Vs]</th>
<th>Critical field $E_c$ [V/cm]</th>
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<td>1500-2000 (AlGaN/GaN 2DEG)</td>
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**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
Power MOSFET technology advanced rapidly and replaced power BJTs relatively quickly (in spite of cost disadvantages)

- Majority carrier device, much faster, much lower switching losses
- Sufficiently low on-resistance can be achieved economically (up to 600-900V)
- Easier to drive and control
- Power MOSFETs led to significant efficiency and power density improvements
Transition from Si MOSFET to GaN in sub-600V applications?

Si MOSFET

GaN HEMT

Similar transitions: from Si to SiC at 600+ V

Si IGBT  $\rightarrow$  SiC MOSFET  Si Diode  $\rightarrow$  SiC Schottky
## State of the Art Device Comparison Example

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<td>184 pF</td>
<td>177 pF</td>
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<tr>
<td>$C_{oss}$ (time eq.)</td>
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<td>284 pF</td>
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<td>$V_{SD}$</td>
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<td>4 V</td>
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<td>$Q_{rr}$</td>
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Si MOSFET body diode reverse recovery: $Q_{rr} V_{DS} f_s = 350$ W at 400V, 100 kHz