MOSFET Cross Section

Power MOSFET in Ohmic Region
MOSFET Static Characteristics

MOSFET Depletion capacitance
MOSFET Equivalent Circuit

Switching Losses: Output Capacitance
**Wide Bandgap Materials**

![Wide Bandgap Materials Diagram]


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**Power 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
Bipolar Junction Transistor

- Interdigitated base and emitter contacts
- Vertical current flow
- npn device is shown
- minority carrier device
- on-state: base-emitter and collector-base junctions are both forward-biased
- on-state: substantial minority charge in p and n regions, conductivity modulation

BJT: Conclusions

- BJT has been replaced by MOSFET in low-voltage (<500V) applications
- BJT is being replaced by IGBT in applications at voltages above 500V
- A minority-carrier device: compared with MOSFET, the BJT exhibits slower switching, but lower on-resistance at high voltages
**Insulated Gate Bipolar Junction Transistor**

- A four-layer device
- Similar in construction to MOSFET, except extra p region
- On-state: minority carriers are injected into n region, leading to conductivity modulation
- Compared with MOSFET: slower switching times, lower on-resistance, useful at higher voltages (up to 1700V)

**The IGBT**

![Diagram of IGBT](image-url)
IGBT: Current Tailing

Conclusions: IGBT

- Becoming the device of choice in 500 to 1700V+ applications, at power levels of 1-1000kW
- Positive temperature coefficient at high current — easy to parallel and construct modules
- Forward voltage drop: diode in series with on-resistance, 2-4V typical
- Easy to drive — similar to MOSFET
- Slower than MOSFET, but faster than Darlington, GTO, SCR
- Typical switching frequencies: 3-30kHz
- IGBT technology is rapidly advancing:
  - 3300 V devices: HVIGBTs
  - 150 kHz switching frequencies in 600 V devices
Averaged Equivalent Circuit Model – Switching Loss

- The methods of Chapter 3 can be extended to include switching loss in the converter equivalent circuit model
  - Include switching transitions in the converter waveforms
  - Model effects of diode reverse recovery, etc.
- To obtain tractable results, the waveforms during the switching transitions must usually be approximated
- Things that can substantially change the results:
  - Ringing caused by parasitic tank circuits
  - Snubber circuits

The Modeling Approach

- Sketch the converter waveforms
  - Including the switching transitions (idealizing assumptions are made to lead to tractable results)
  - In particular, sketch inductor voltage, capacitor current, and input current waveforms
- The usual steady-state relationships:
  - \( \langle v_L \rangle = 0, \langle i_C \rangle = 0, \langle i_g \rangle = I_g \)
- Use the resulting equations to construct an equivalent circuit model, as usual
Buck Converter Example

- Ideal MOSFET, p–n diode with reverse recovery
- Neglect semiconductor device capacitances, MOSFET switching times, etc.
- Neglect conduction losses
- Neglect ripple in inductor current and capacitor voltage

Assumed waveforms

- Diode recovered charge $Q_r$, reverse recovery time $t_r$
- These waveforms assume that the diode voltage changes at the end of the reverse recovery transient
  - a "snappy" diode
  - Voltage of soft-recovery diodes changes sooner
  - Leads to a pessimistic estimate of induced switching loss
**Inductor volt-second & Cap-Charge balance**

As usual: \( \langle v_L \rangle = 0 = D V_g - V \)

Also as usual: \( \langle i_C \rangle = 0 = I_L - V/R \)

**Average input current**

\[ \langle i_g \rangle = I_g = \frac{\text{area under curve}}{T_s} \]
\[ = \frac{D T_s I_L + t_i I_L + Q_r}{T_s} \]
\[ = D I_L + t_i I_L / T_s + Q_r / T_s \]
Construction of Equivalent Circuit Model

From inductor volt-second balance: \( \langle v_L \rangle = 0 = DV_g - V \)

From capacitor charge balance: \( \langle i_C \rangle = 0 = I_L - V/R \)

Input port of model

\[
\langle i_g \rangle = I_g = DI_L + t_I L / T_s + Q_r / T_s
\]
Combine for complete model

The two independent current sources consume power

\[ V_g \left( t_{IL}/T_s + Q_r/T_s \right) \]

equal to the switching loss induced by diode reverse recovery

Solution of model

Output:

\[ V = DV_g \]

Efficiency:

\[ \eta = \frac{P_{out}}{P_{in}} \]

\[ P_{out} = VI_L \quad P_{in} = V_g \left( DI_L + t_{IL}/T_s + Q_r/T_s \right) \]

Combine and simplify:

\[ \eta = 1 \left[ 1 + f_s (t_r/D + Q_r R / D^2 V_g) \right] \]
Predicted Efficiency vs Duty Cycle

- Switching frequency 100 kHz
- Input voltage 24 V
- Load resistance 15 Ω
- Recovered charge 0.75 µCoul
- Reverse recovery time 75 nsec
- (no attempt is made here to model how the reverse recovery process varies with inductor current)
- Substantial degradation of efficiency
- Poor efficiency at low duty cycle

![Buck converter with diode reverse recovery](image)

Boost Converter Example

- Model same effects as in previous buck converter example:
  - Ideal MOSFET, p–n diode with reverse recovery
  - Neglect semiconductor device capacitances, MOSFET switching times, etc.
  - Neglect conduction losses
  - Neglect ripple in inductor current and capacitor voltage

![Boost converter diagram](image)
Boost converter

As usual: \( v_L \) = 0 = \( V_g - D'V \)

Also as usual: \( \langle i_g \rangle = I_L \)
Capacitor charge balance

\[
\langle i_C \rangle = \langle i_d \rangle - \frac{V}{R} = 0
\]

\[
= -\frac{V}{R} + I_L(D'T_s - t_r)/T_s - \frac{Q_r}{T_s}
\]

Collect terms: \( V/R = I_L(D'T_s - t_r)/T_s - Q_r/T_s \)

Construct model

The result is:

\[
I_s = I_L
\]

The two independent current sources consume power

\[
V \left( t_r I_L / T_s + Q_r / T_s \right)
\]
equal to the switching loss induced by diode reverse recovery
Predicted $M$ vs duty cycle

- Switching frequency 100 kHz
- Input voltage 24 V
- Load resistance 60 Ω
- Recovered charge 5 µCoul
- Reverse recovery time 100 nsec
- Inductor resistance $R_L = 0.3$ Ω
- (inductor resistance also inserted into averaged model here)

Boost converter with diode reverse recovery

- With $R_L$ only
- With $R_L$ and diode reverse recovery