Lecture 6: Semiconductor Device Implementation

ECE 481: Power Electronics

Prof. Daniel Costinett
Department of Electrical Engineering and Computer Science
University of Tennessee Knoxville
Fall 2013

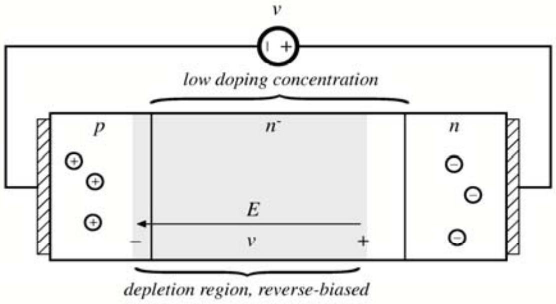
4.2. A brief survey of power semiconductor devices

- Power diodes
- Power MOSFETs
- Bipolar Junction Transistors (BJTs)
- Insulated Gate Bipolar Transistors (IGBTs)
- Thyristors (SCR, GTO, MCT)

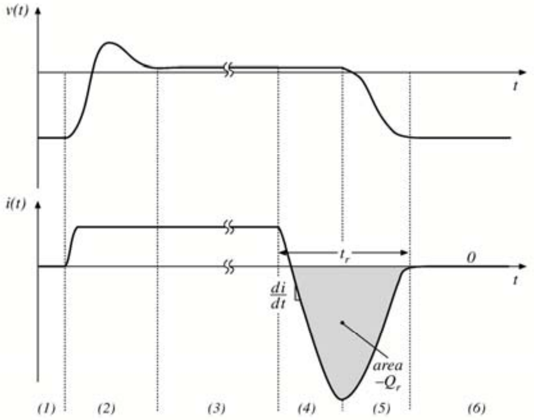
- On resistance vs. breakdown voltage vs. switching times
- Minority carrier and majority carrier devices

4.2.1. Power diodes

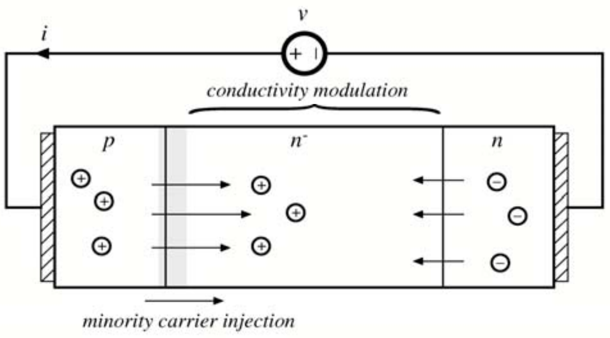
A power diode, under reverse-biased conditions:



Typical diode switching waveforms



Forward-biased power diode



Charge-controlled behavior of the diode

The diode equation:

$$q(t) = Q_0\left(e^{\lambda v(t)} - 1\right)$$

Charge control equation:

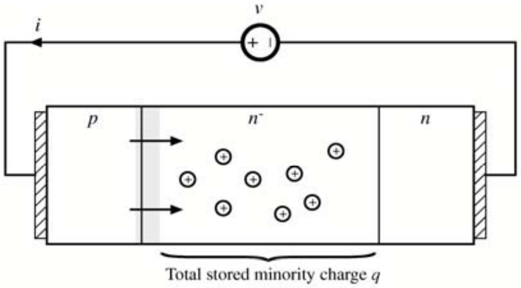
$$\frac{dq(t)}{dt} = i(t) - \frac{q(t)}{\tau_L}$$

With:

λ= 1/(26 mV) at 300 K

τ_L = minority carrier lifetime

(above equations don't include current that charges depletion region capacitance)



In equilibrium: $dq/dt = 0$, and hence

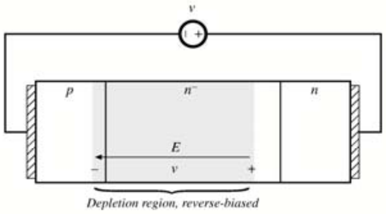
$$i(t) = \frac{q(t)}{\tau_L} = \frac{Q_0}{\tau_L}\left(e^{\lambda v(t)} - 1\right) = I_0\left(e^{\lambda v(t)} - 1\right)$$

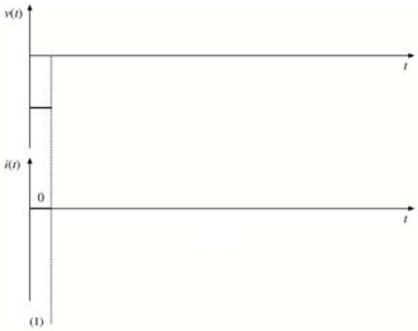
Charge-control in the diode: Discussion

- The familiar *i–v* curve of the diode is an equilibrium relationship that can be violated during transient conditions
- During the turn-on and turn-off switching transients, the current deviates substantially from the equilibrium *i–v* curve, because of change in the stored charge and change in the charge within the reverse-bias depletion region
- Under forward-biased conditions, the stored minority charge causes "conductivity modulation" of the resistance of the lightly-doped n^- region, reducing the device on-resistance

---

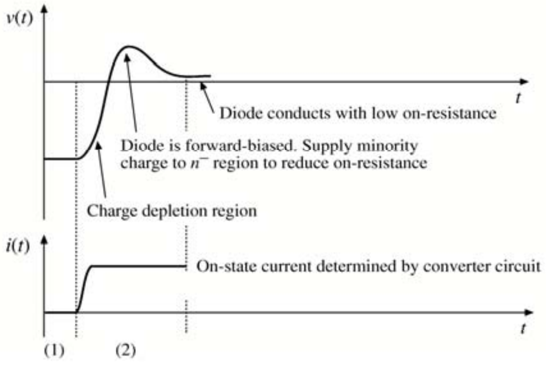
Diode in OFF state: reversed-biased, blocking voltage





- Diode is reverse-biased
- No stored minority charge: $q = 0$
- Depletion region blocks applied reverse voltage; charge is stored in capacitance of depletion region

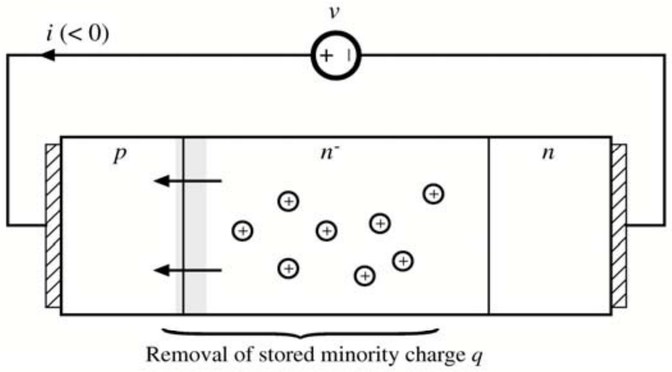
Turn-on transient



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

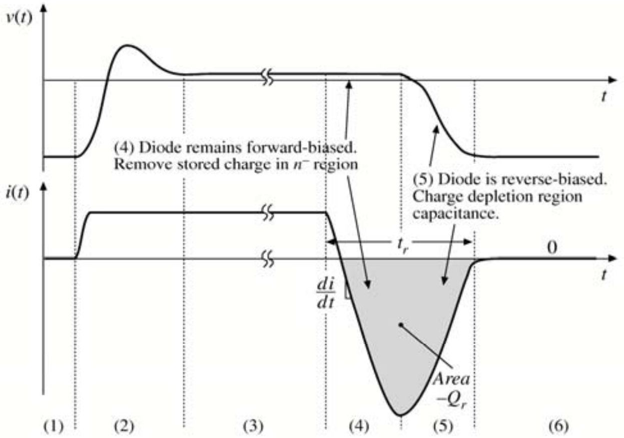
- charge to increase voltage across depletion region
- charge needed to support the on-state current
- charge to reduce on-resistance of n^- region

Turn-off transient



Diode turn-off transient

continued

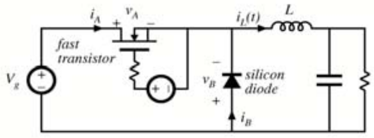


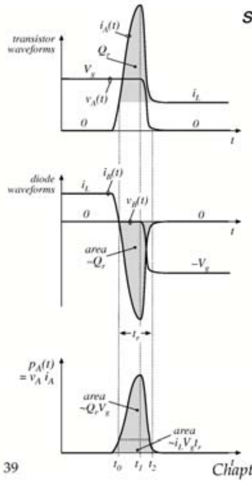
(4) Diode remains forward-biased. Remove stored charge in n^- region

(5) Diode is reverse-biased. Charge depletion region capacitance.

The diode switching transients induce switching loss in the transistor

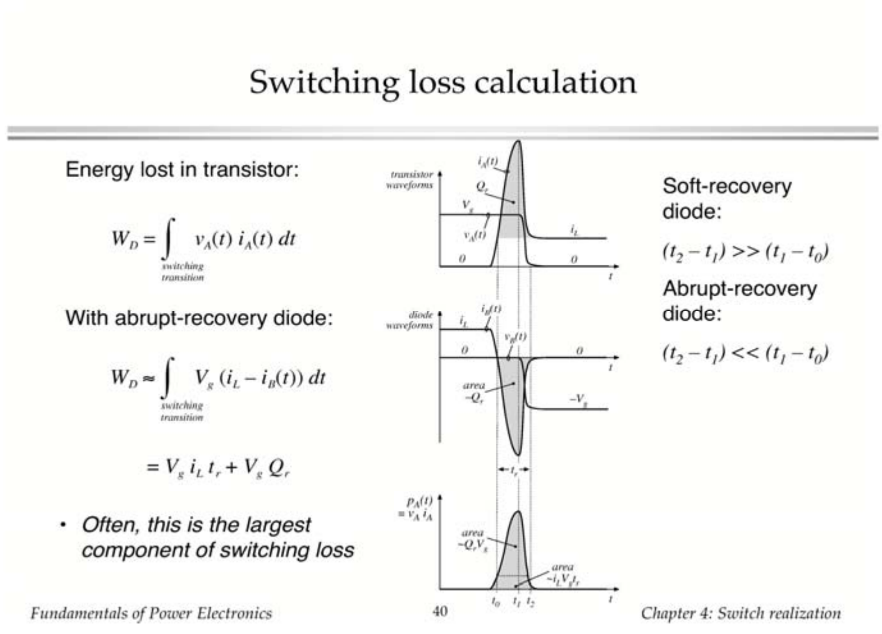
see Section 4.3.2





- Diode recovered stored charge Q_r flows through transistor during transistor turn-on transition, inducing switching loss
- Q_r depends on diode on-state forward current, and on the rate-of-change of diode current during diode turn-off transition

Reverse Recovery Loss



Switching loss calculation

Energy lost in transistor:

$$W_D = \int_{\substack{\text{switching}\\\text{transition}}} v_A(t)\, i_A(t)\, dt$$

With abrupt-recovery diode:

$$W_D \approx \int_{\substack{\text{switching}\\\text{transition}}} V_g\, (i_L - i_B(t))\, dt$$

$$= V_g\, i_L\, t_r + V_g\, Q_r$$

- *Often, this is the largest component of switching loss*

Soft-recovery diode:

$(t_2 - t_1) >> (t_1 - t_0)$

Abrupt-recovery diode:

$(t_2 - t_1) << (t_1 - t_0)$

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)

Characteristics of several commercial power rectifier diodes

Part number	*Rated max voltage*	*Rated avg current*	V_F *(typical)*	t_r *(max)*
Fast recovery rectifiers				
1N3913	400V	30A	1.1V	400ns
SD453N25S20PC	2500V	400A	2.2V	2μs
Ultra-fast recovery rectifiers				
MUR815	150V	8A	0.975V	35ns
MUR1560	600V	15A	1.2V	60ns
RHRU100120	1200V	100A	2.6V	60ns
Schottky rectifiers				
MBR6030L	30V	60A	0.48V	
444CNQ045	45V	440A	0.69V	
30CPQ150	150V	30A	1.19V	

Paralleling diodes

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

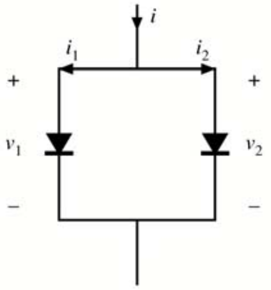
Reason: thermal instability caused by temperature dependence of the diode equation.

Increased temperature leads to increased current, or reduced voltage.

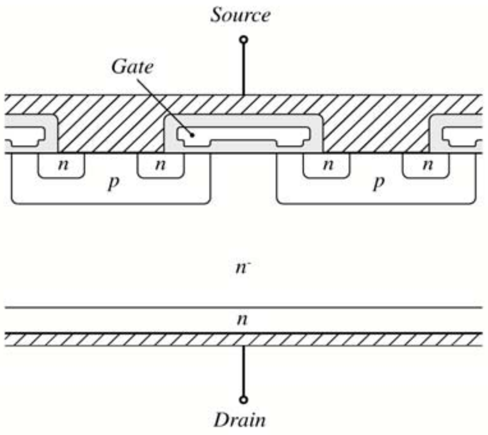
One diode will hog the current.

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

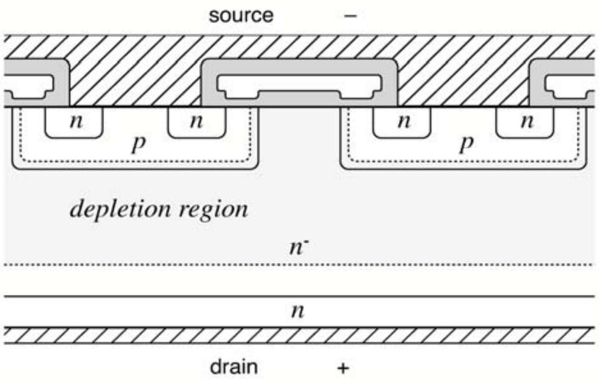


4.2.2. The Power MOSFET



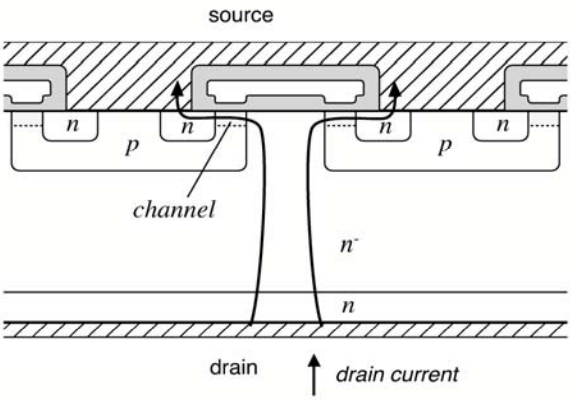
- Gate lengths approaching one micron
- Consists of many small enhancement-mode parallel-connected MOSFET cells, covering the surface of the silicon wafer
- Vertical current flow
- n-channel device is shown

MOSFET: Off state



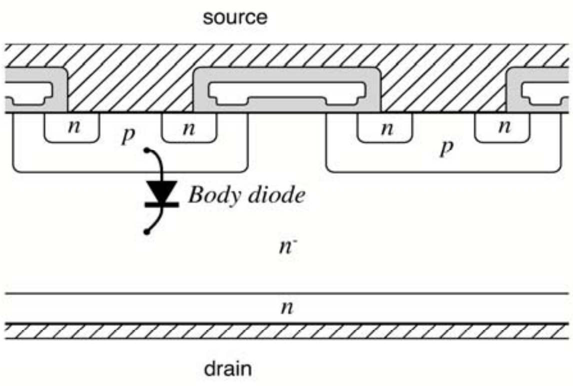
- p-n^- junction is reverse-biased
- off-state voltage appears across n^- region

MOSFET: 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.

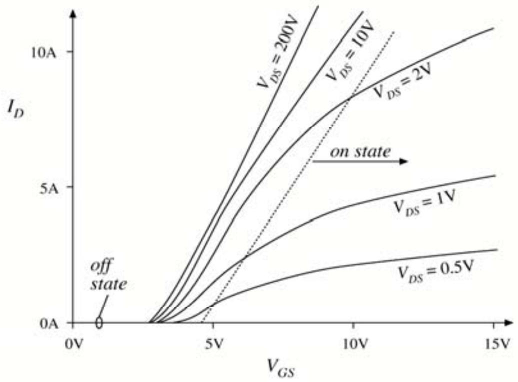
MOSFET body diode



- 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

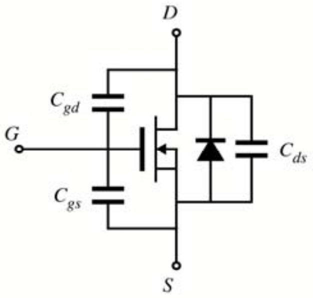
---

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

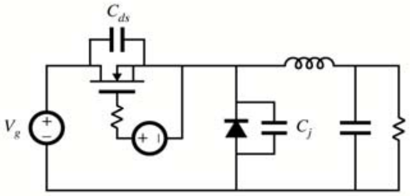


- C_{gs} : large, essentially constant
- C_{gd} : small, highly nonlinear
- C_{ds} : intermediate in value, highly nonlinear
- switching times determined by rate at which gate driver charges/discharges C_{gs} and C_{gd}

$$C_{ds}(v_{ds}) = \frac{C_0}{\sqrt{1+\frac{v_{ds}}{V_0}}} \qquad C_{ds}(v_{ds}) \approx C_0\sqrt{\frac{V_0}{v_{ds}}} = \frac{C_0'}{\sqrt{v_{ds}}}$$

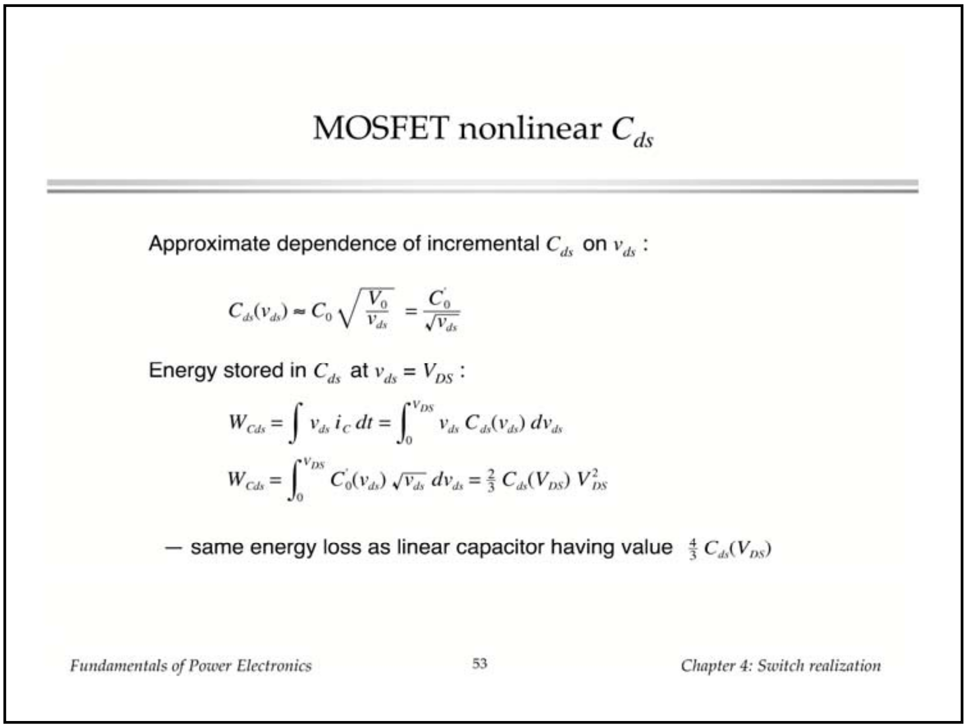
Switching loss caused by semiconductor output capacitances

Buck converter example



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

$$W_C = \frac{1}{2}\left(C_{ds} + C_j\right) V_g^2$$



MOSFET nonlinear C_{ds}

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

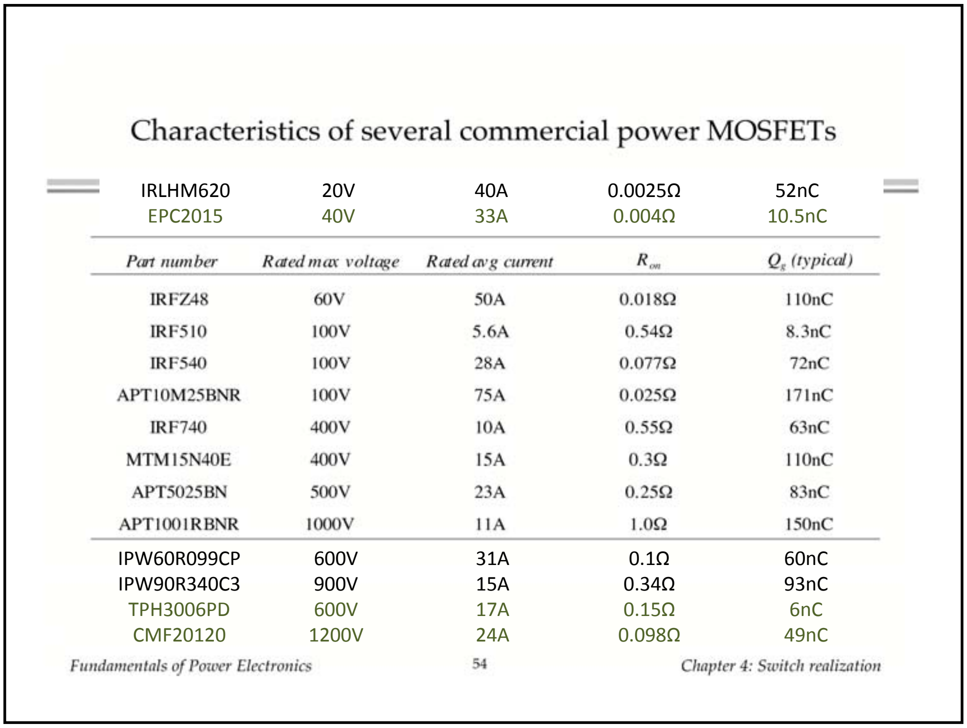
$$C_{ds}(v_{ds}) \approx C_0 \sqrt{\frac{V_0}{v_{ds}}} = \frac{C_0'}{\sqrt{v_{ds}}}$$

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

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

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

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



Characteristics of several commercial power MOSFETs

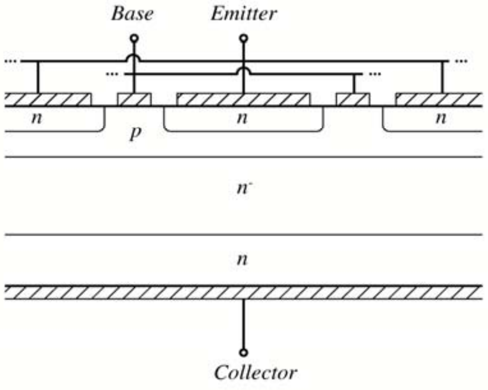
IRLHM620	20V	40A	0.0025Ω	52nC
EPC2015	40V	33A	0.004Ω	10.5nC
Part number	*Rated max voltage*	*Rated avg current*	R_{on}	Q_g *(typical)*
IRFZ48	60V	50A	0.018Ω	110nC
IRF510	100V	5.6A	0.54Ω	8.3nC
IRF540	100V	28A	0.077Ω	72nC
APT10M25BNR	100V	75A	0.025Ω	171nC
IRF740	400V	10A	0.55Ω	63nC
MTM15N40E	400V	15A	0.3Ω	110nC
APT5025BN	500V	23A	0.25Ω	83nC
APT1001RBNR	1000V	11A	1.0Ω	150nC
IPW60R099CP	600V	31A	0.1Ω	60nC
IPW90R340C3	900V	15A	0.34Ω	93nC
TPH3006PD	600V	17A	0.15Ω	6nC
CMF20120	1200V	24A	0.098Ω	49nC

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

---

4.2.3. Bipolar Junction Transistor (BJT)



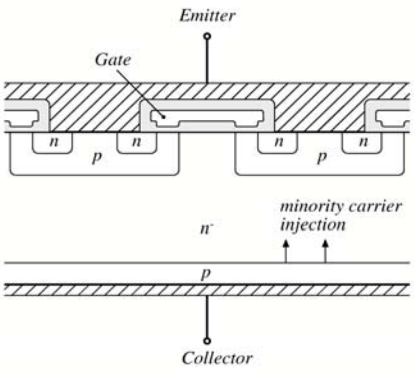
- Interdigitated base and emitter contacts
- Vertical current flow
- npn device is shown
- minority carrier device
- on-state: base-emitter and collector-base junctions are both forward-biased
- on-state: substantial minority charge in p and n^- regions, conductivity modulation

Conclusions: BJT

- 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

---

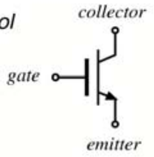
4.2.4. The Insulated Gate Bipolar Transistor (IGBT)



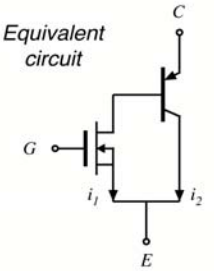
- A four-layer device
- Similar in construction to MOSFET, except extra p region
- On-state: minority carriers are injected into n^- region, leading to conductivity modulation
- compared with MOSFET: slower switching times, lower on-resistance, useful at higher voltages (up to 1700V)

The IGBT

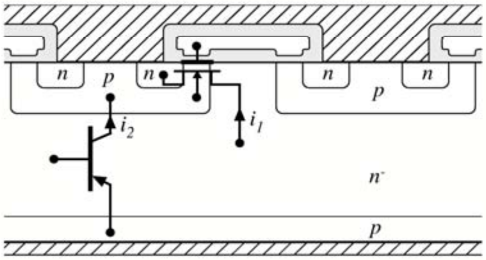
Symbol



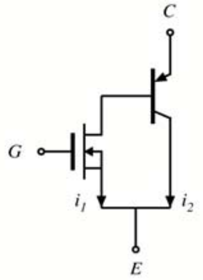
Equivalent circuit

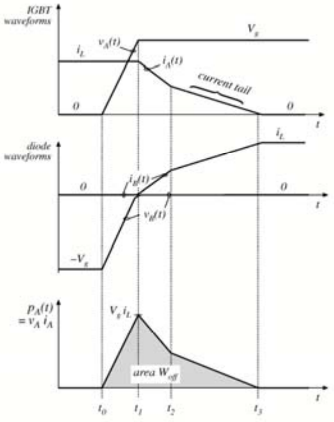


Location of equivalent devices

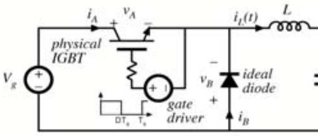


Current tailing in IGBTs

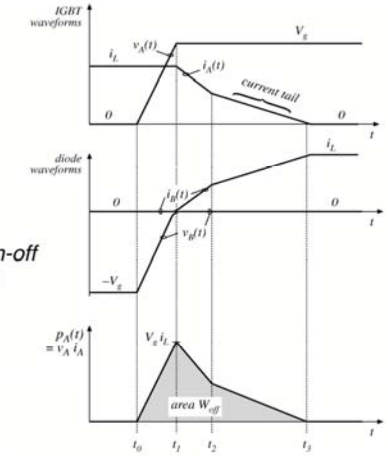




Switching loss due to current-tailing in IGBT



Example: buck converter with IGBT



transistor turn-off transition

$$P_{sw} = \frac{1}{T_s}\int_{\substack{\text{switching}\\ \text{transitions}}} p_A(t)\,dt = (W_{on} + W_{off})\, f_s$$

Characteristics of several commercial devices

Part number	*Rated max voltage*	*Rated avg current*	*V_F (typical)*	*t_f (typical)*
Single-chip devices				
HGTG32N60E2	600V	32A	2.4V	0.62μs
HGTG30N120D2	1200V	30A	3.2A	0.58μs
Multiple-chip power modules				
CM400HA-12E	600V	400A	2.7V	0.3μs
CM300HA-24E	1200V	300A	2.7V	0.3μs

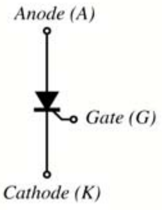
Conclusions: IGBT

- 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

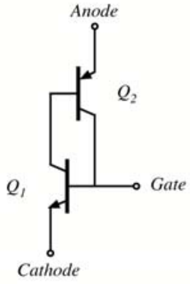
4.2.5. Thyristors (SCR, GTO, MCT)

The SCR

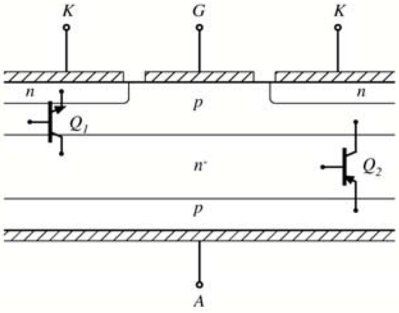
symbol



equiv circuit

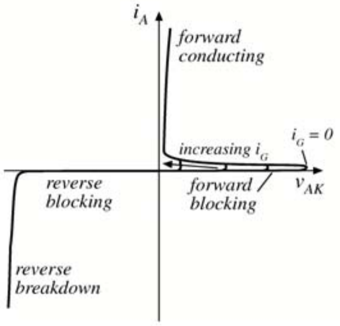


construction



The Silicon Controlled Rectifier (SCR)

- Positive feedback —a latching device
- A minority carrier device
- Double injection leads to very low on-resistance, hence low forward voltage drops attainable in very high voltage devices
- Simple construction, with large feature size
- Cannot be actively turned off
- A voltage-bidirectional two-quadrant switch
- 5000-6000V, 1000-2000A devices



4.3. Switching loss

- Energy is lost during the semiconductor switching transitions, via several mechanisms:
  - Transistor switching times
  - Diode stored charge
  - Energy stored in device capacitances and parasitic inductances
- Semiconductor devices are *charge controlled*
- Time required to insert or remove the controlling charge determines switching times

Some other sources of this type of switching loss

Schottky diode

- Essentially no stored charge
- Significant reverse-biased junction capacitance

Transformer leakage inductance

- Effective inductances in series with windings
- A significant loss when windings are not tightly coupled

Interconnection and package inductances

- Diodes
- Transistors
- A significant loss in high current applications