Chapter 4. Switch Realization

4.1. Switch applications

Single-, two-, and four-quadrant switches. Synchronous rectifiers

4.2. A brief survey of power semiconductor devices

Power diodes, MOSFETs, BJTs, IGBTs, and thyristors

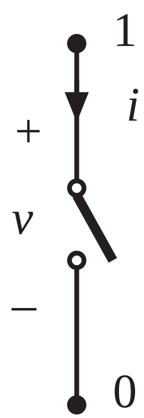
4.3. Switching loss

Transistor switching with clamped inductive load. Diode recovered charge. Stray capacitances and inductances, and ringing. Efficiency vs. switching frequency.

4.4. Summary of key points

SPST (single-pole single-throw) switches

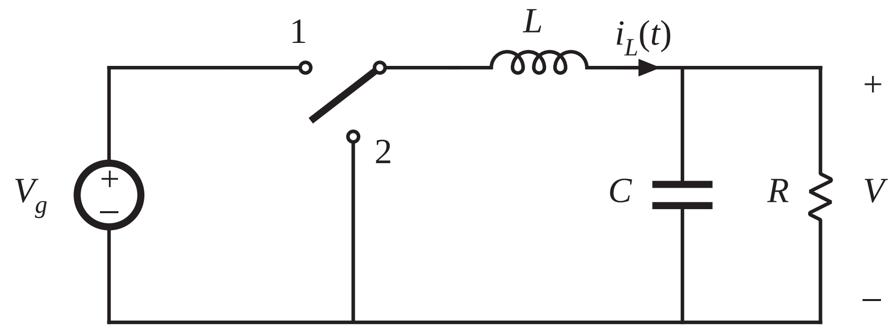
SPST switch, with voltage and current polarities defined



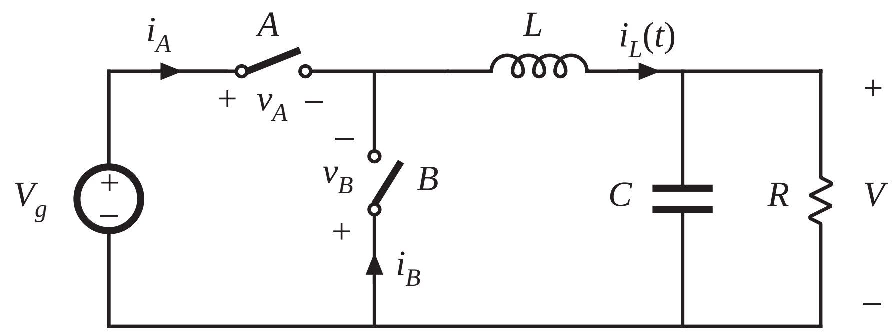
All power semiconductor devices function as SPST switches.

Buck converter

with SPDT switch:



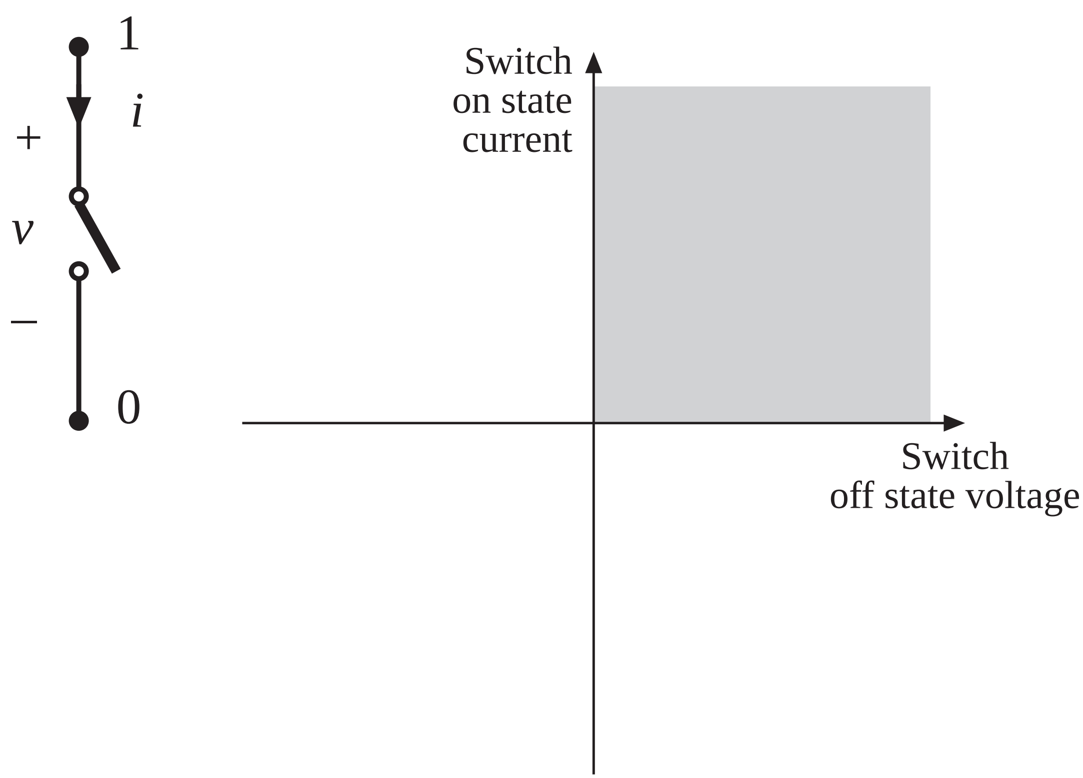
with two SPST switches:



Realization of SPDT switch using two SPST switches

- A nontrivial step: two SPST switches are not exactly equivalent to one SPDT switch
- It is possible for both SPST switches to be simultaneously ON or OFF
- Behavior of converter is then significantly modified
—discontinuous conduction modes (chapter 5)
- Conducting state of SPST switch may depend on applied voltage or current —for example: diode

Quadrants of SPST switch operation



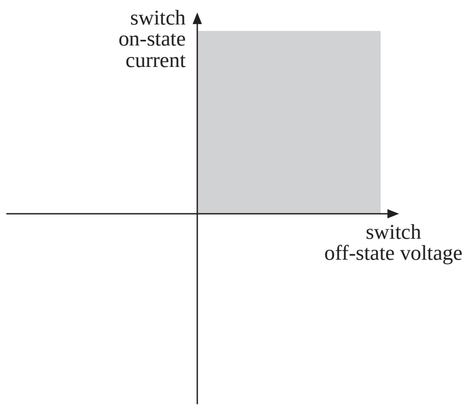
A single-quadrant switch example:

ON-state: $i > 0$

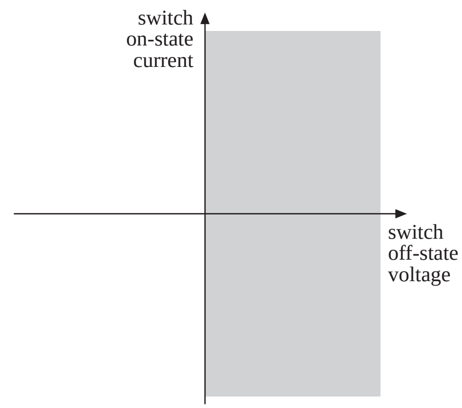
OFF-state: $v > 0$

Some basic switch applications

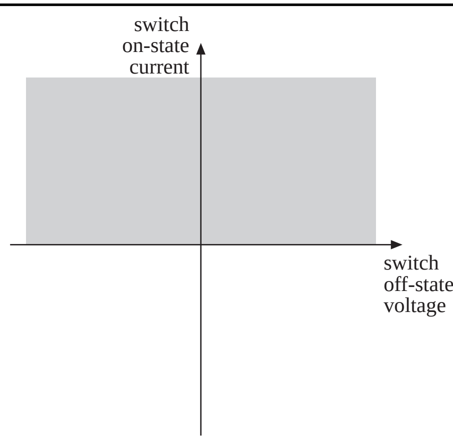
Single-quadrant switch



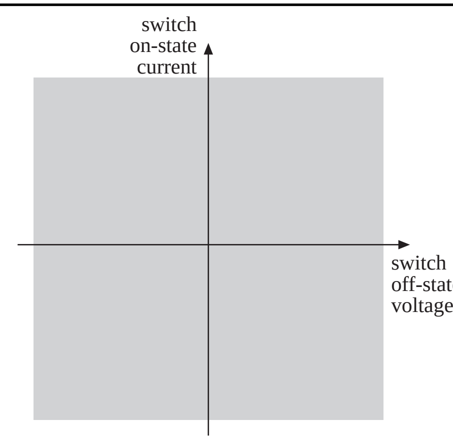
Current-bidirectional two-quadrant switch



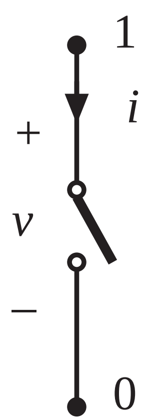
Voltage-bidirectional two-quadrant switch



Four-quadrant switch



4.1.1. Single-quadrant switches



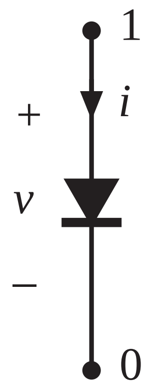
Active switch: Switch state is controlled exclusively by a third terminal (control terminal).

Passive switch: Switch state is controlled by the applied current and/or voltage at terminals 1 and 2.

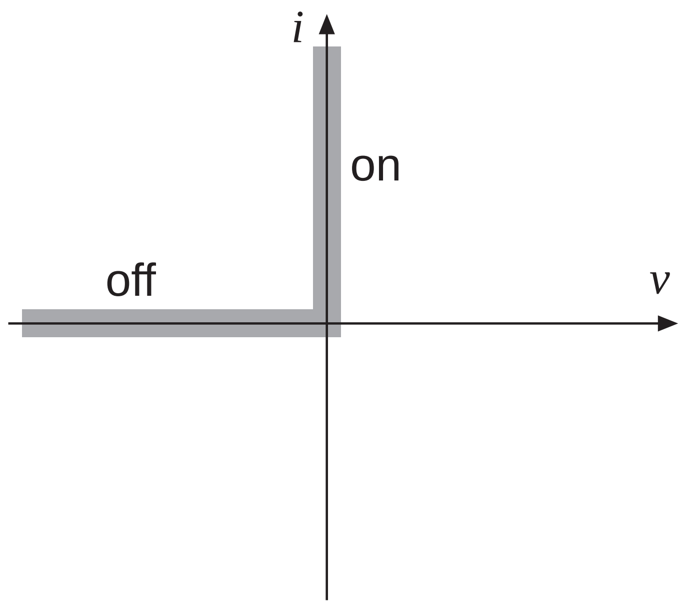
SCR: A special case — turn-on transition is active, while turn-off transition is passive.

Single-quadrant switch: on-state $i(t)$ and off-state $v(t)$ are unipolar.

The diode



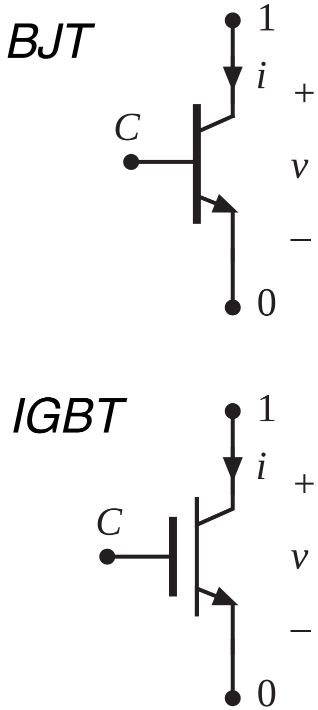
Symbol

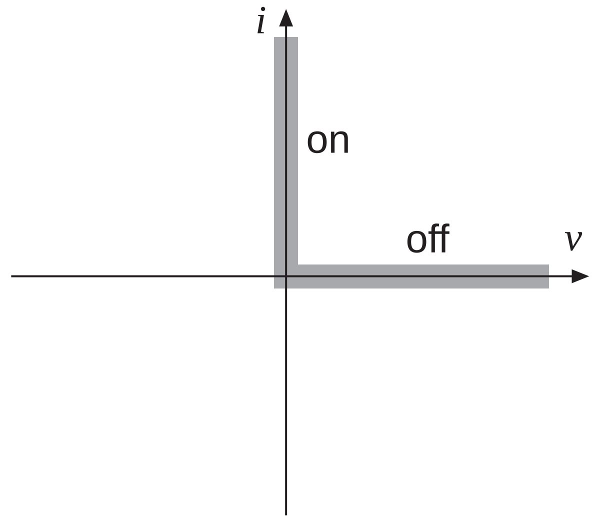


instantaneous i-v characteristic

- *A passive switch*
- *Single-quadrant switch:*
- *can conduct positive on-state current*
- *can block negative off-state voltage*
- *provided that the intended on-state and off-state operating points lie on the diode i-v characteristic, then switch can be realized using a diode*

The Bipolar Junction Transistor (BJT) and the Insulated Gate Bipolar Transistor (IGBT)

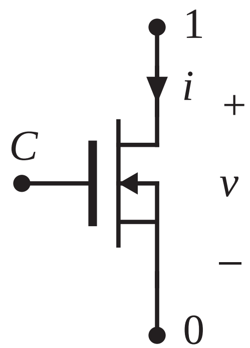


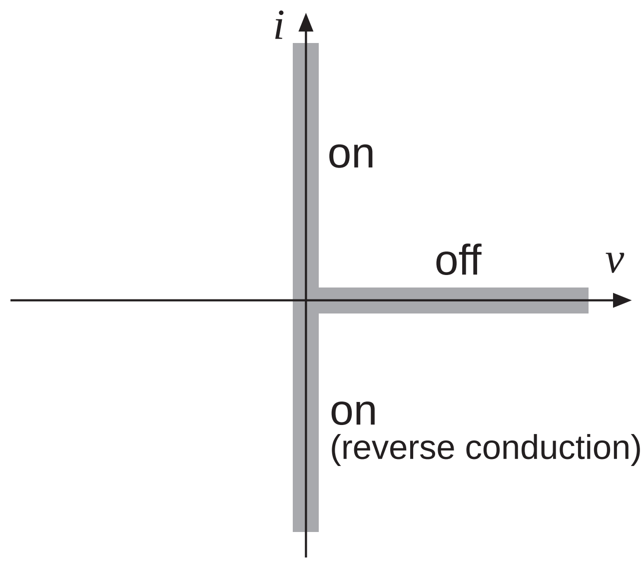


instantaneous i-v characteristic

- *An active switch, controlled by terminal* C
- *Single-quadrant switch:*
- *can conduct positive on-state current*
- *can block positive off-state voltage*
- *provided that the intended on-state and off-state operating points lie on the transistor* i-v *characteristic, then switch can be realized using a BJT or IGBT*

The Metal-Oxide Semiconductor Field Effect Transistor (MOSFET)



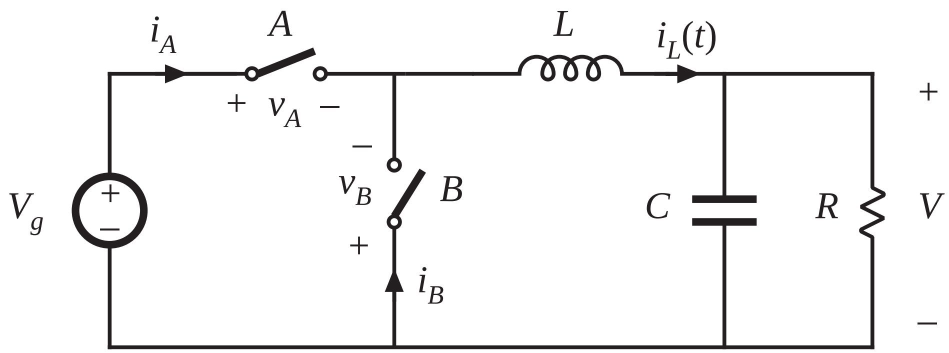


Symbol *instantaneous i-v characteristic*

- *An active switch, controlled by terminal C*
- *Normally operated as single-quadrant switch:*
- *can conduct positive on-state current (can also conduct negative current in some circumstances)*
- *can block positive off-state voltage*
- *provided that the intended on-state and off-state operating points lie on the MOSFET i-v characteristic, then switch can be realized using a MOSFET*

Realization of switch using transistors and diodes

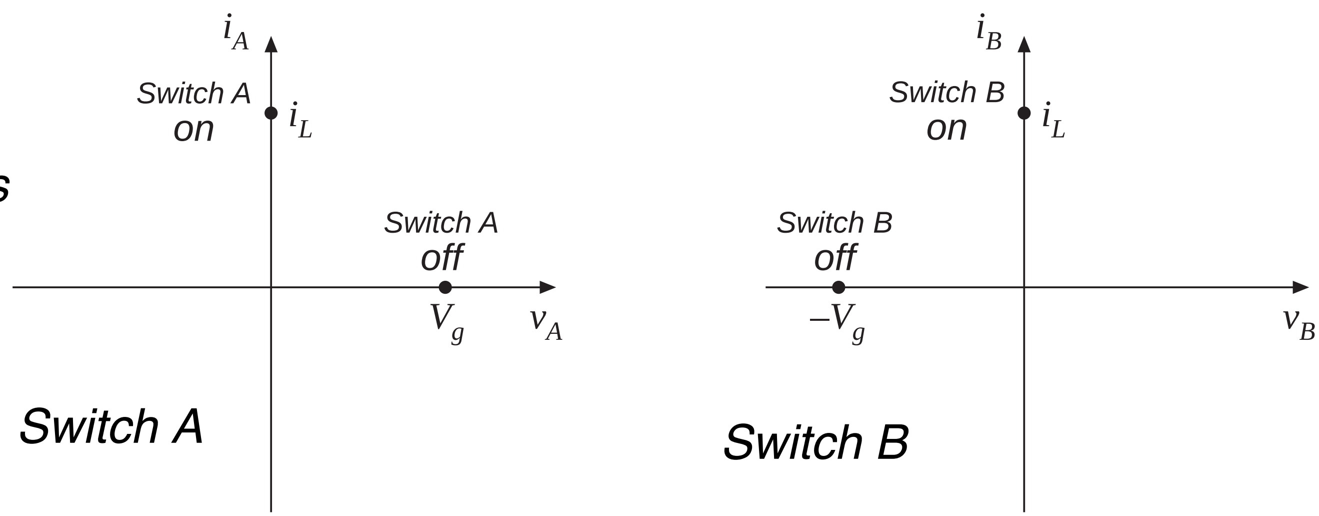
Buck converter example



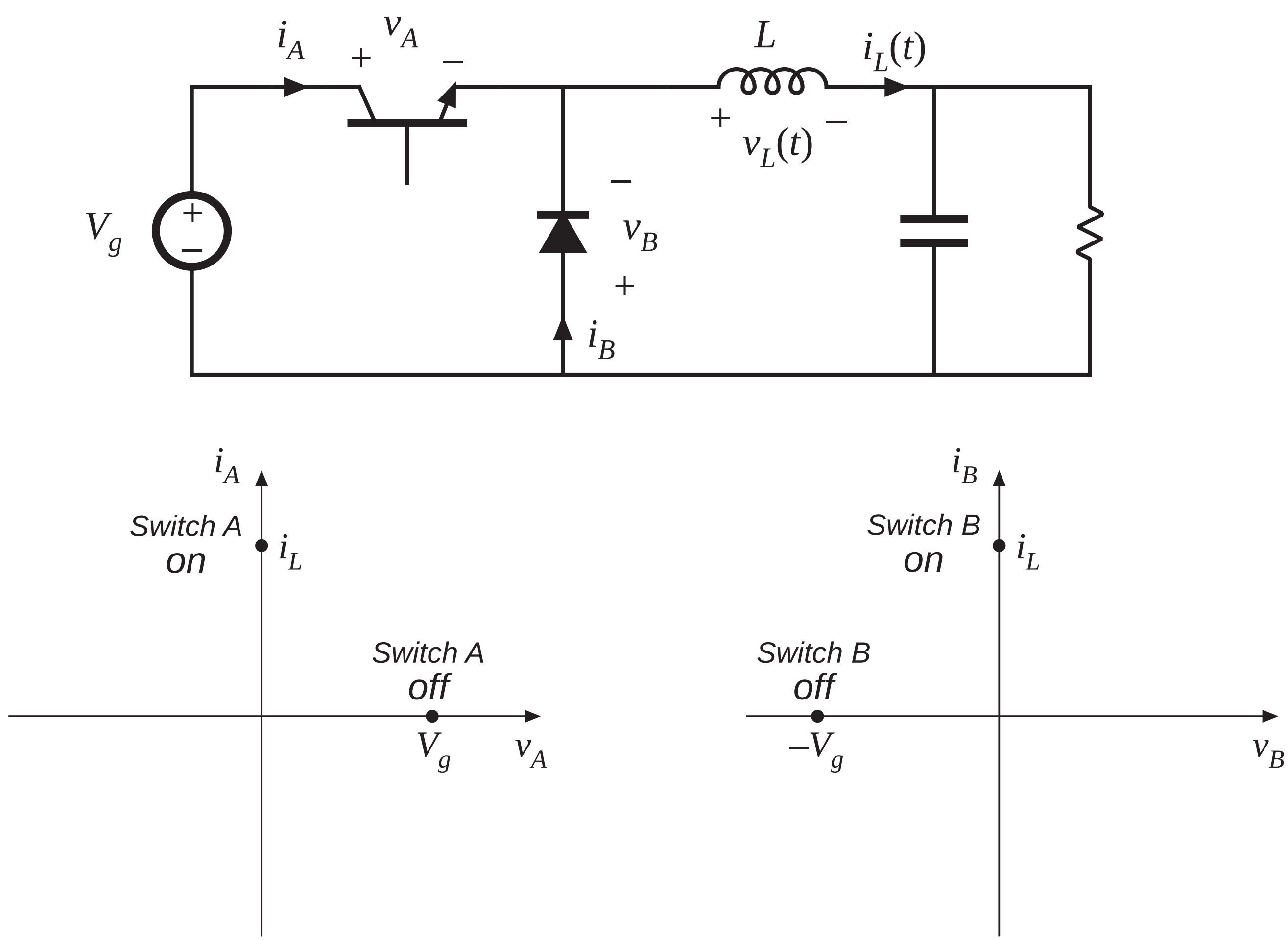
Switch A: transistor

Switch B: diode

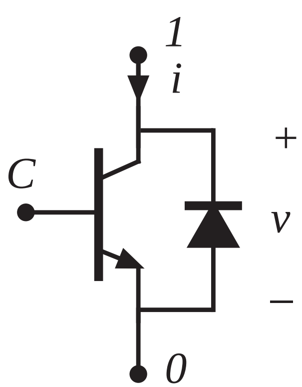
SPST switch operating points



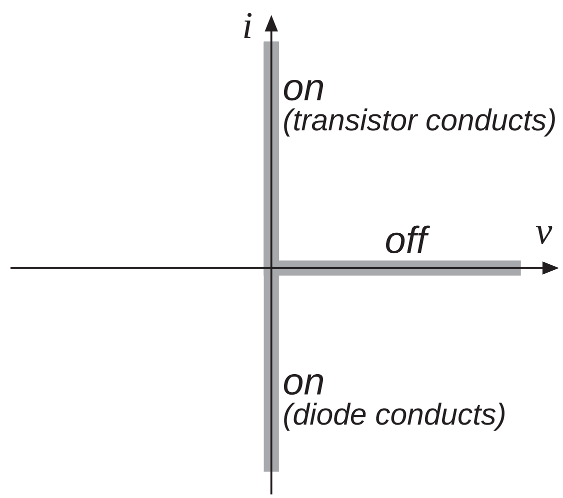
Realization of buck converter using single-quadrant switches



4.1.2. Current-bidirectional two-quadrant switches



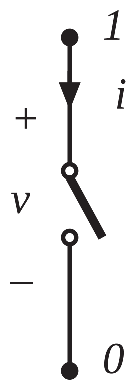
BJT / anti-parallel diode realization

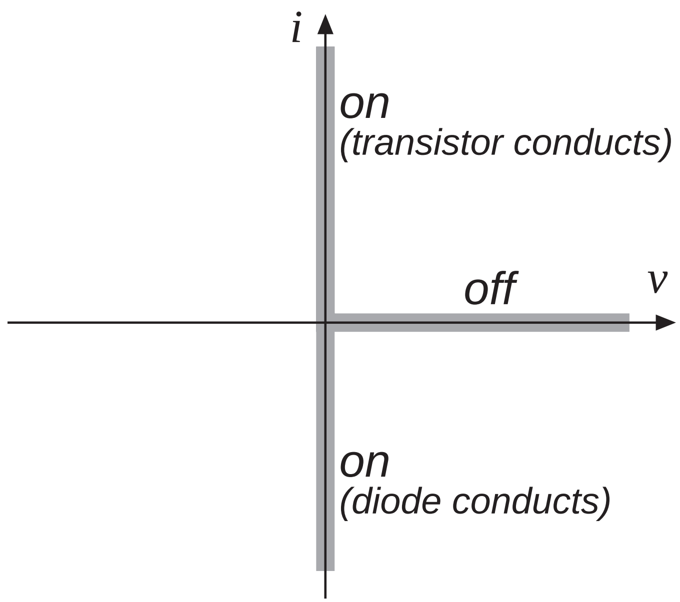


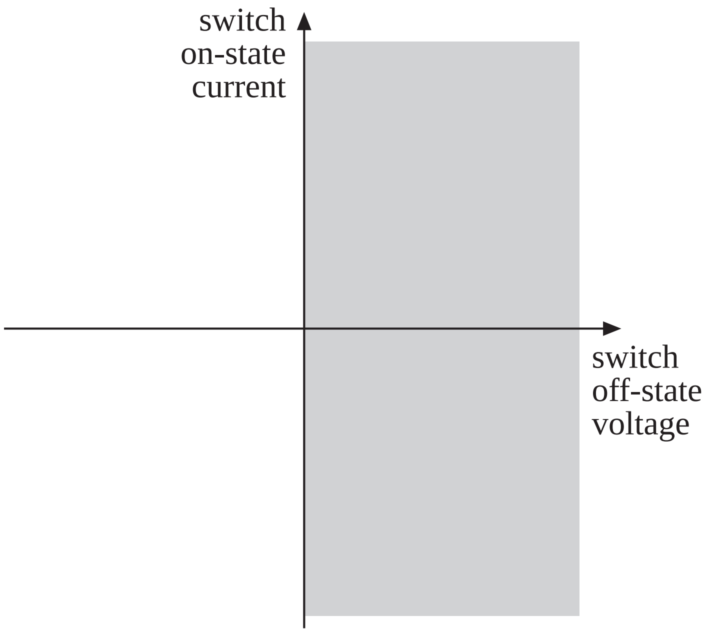
instantaneous i-v characteristic

- *Usually an active switch, controlled by terminal C*
- *Normally operated as two-quadrant switch:*
- *can conduct positive or negative on-state current*
- *can block positive off-state voltage*
- *provided that the intended on-state and off-state operating points lie on the composite i-v characteristic, then switch can be realized as shown*

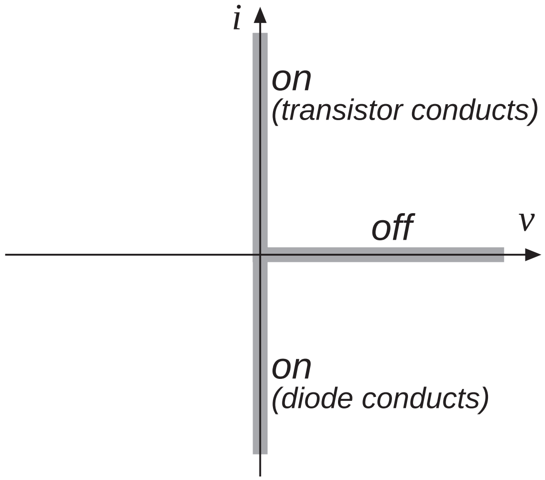
Two quadrant switches



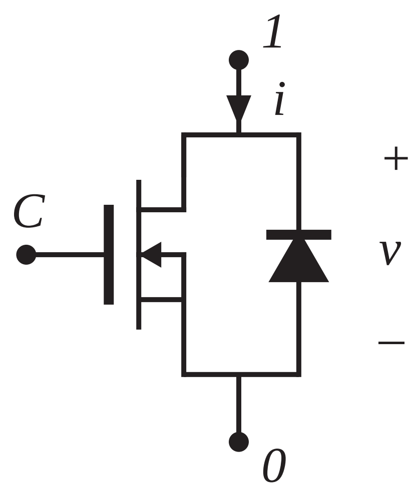




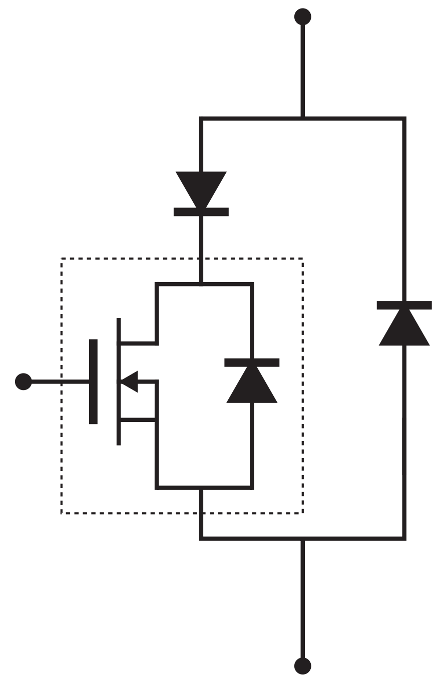
MOSFET body diode



Power MOSFET characteristics

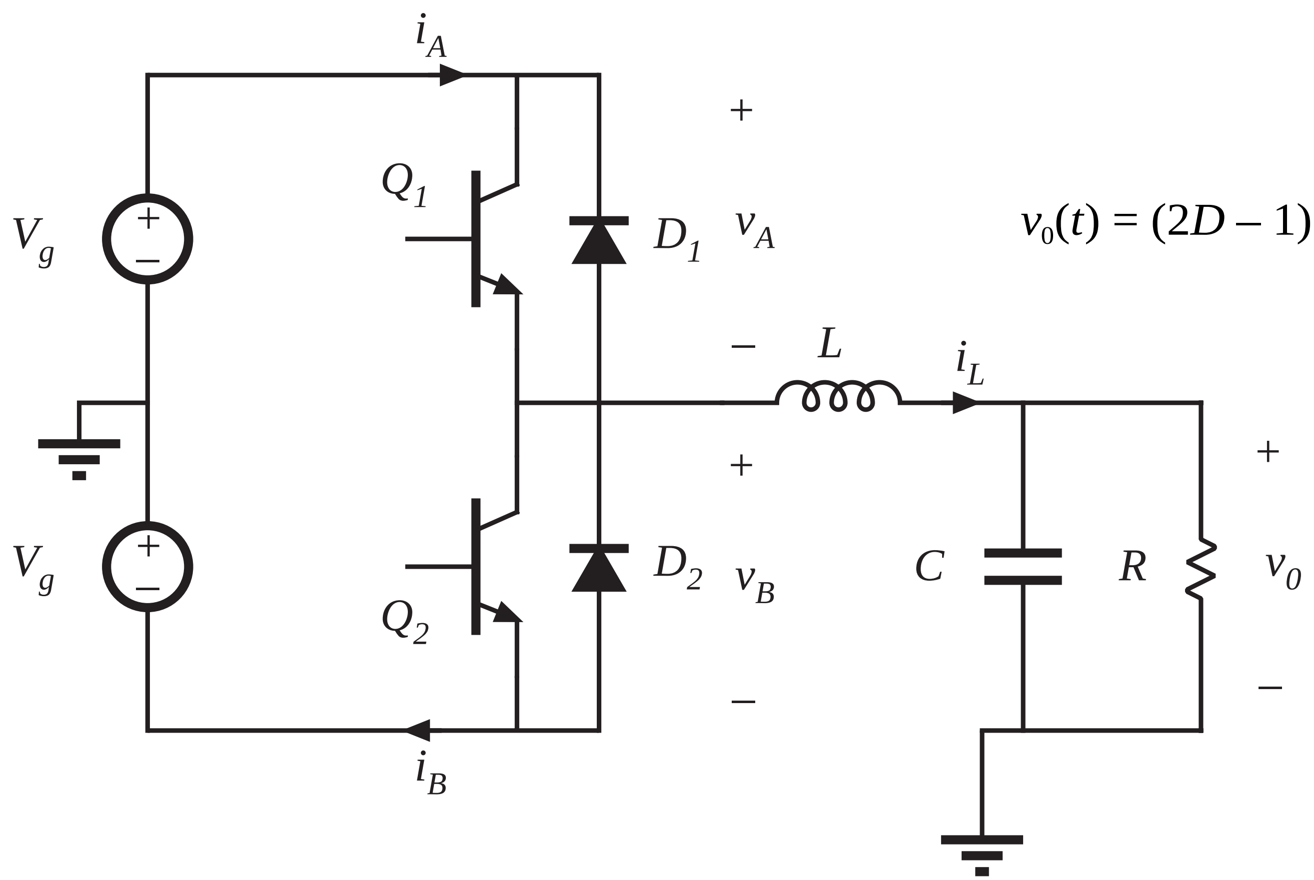


Power MOSFET, and its integral body diode



Use of external diodes to prevent conduction of body diode

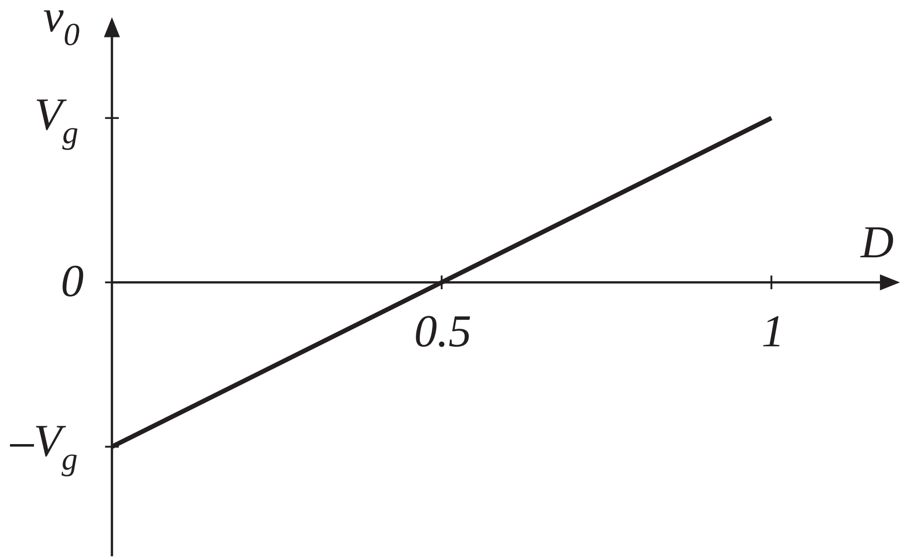
A simple inverter



$$v_0(t) = (2D - 1)\, V_g$$

Inverter: sinusoidal modulation of D

$$v_0(t) = (2D - 1)\, V_g$$



Sinusoidal modulation to produce ac output:

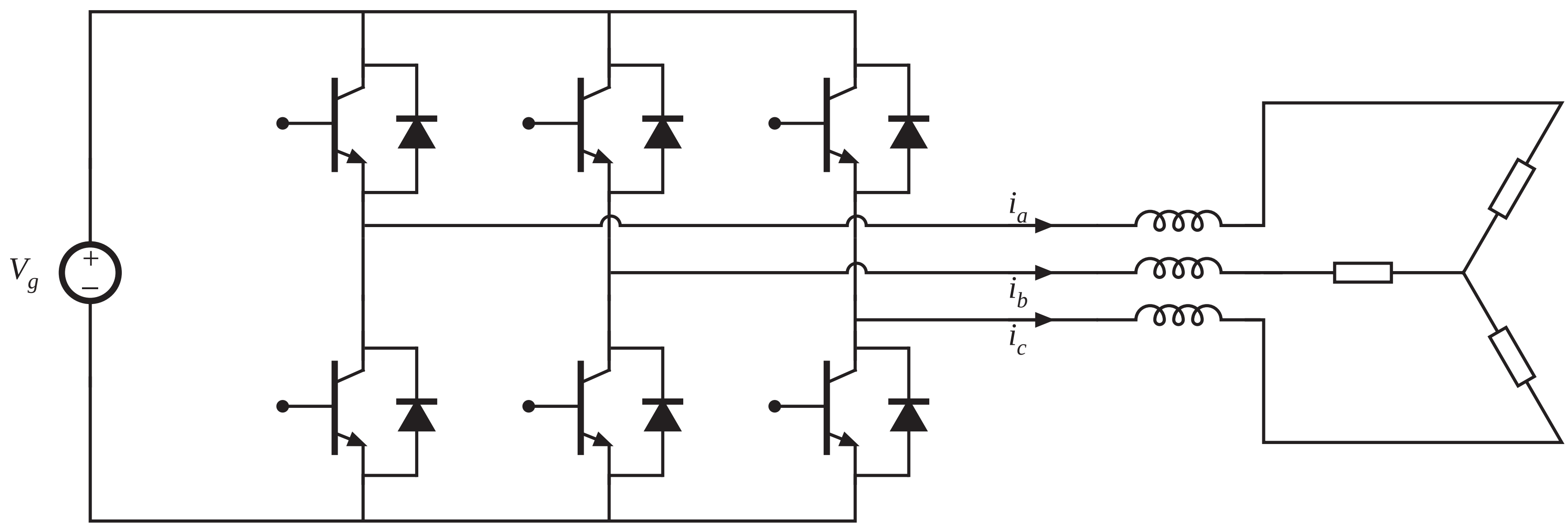
$$D(t) = 0.5 + D_m \sin(\omega t)$$

The resulting inductor current variation is also sinusoidal:

$$i_L(t) = \frac{v_0(t)}{R} = (2D - 1)\,\frac{V_g}{R}$$

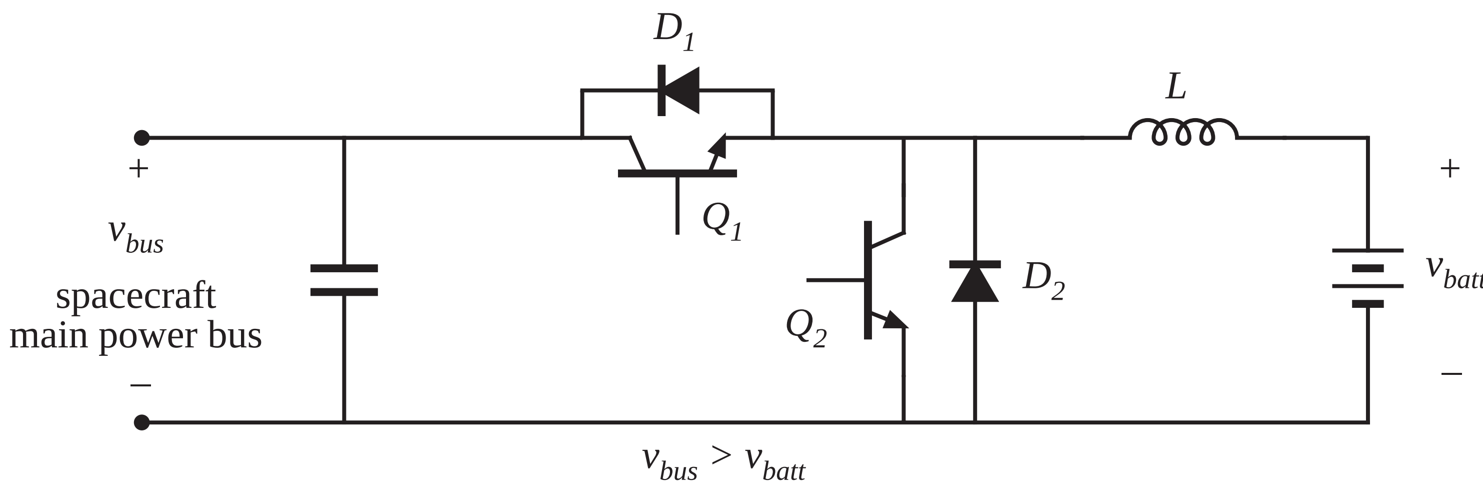
Hence, current-bidirectional two-quadrant switches are required.

The dc-3øac voltage source inverter (VSI)



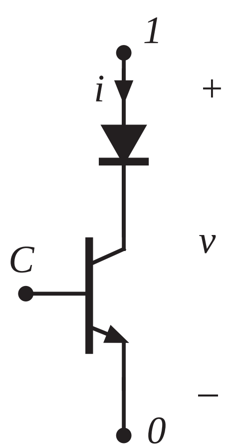
Switches must block dc input voltage, and conduct ac load current.

Bidirectional battery charger/discharger

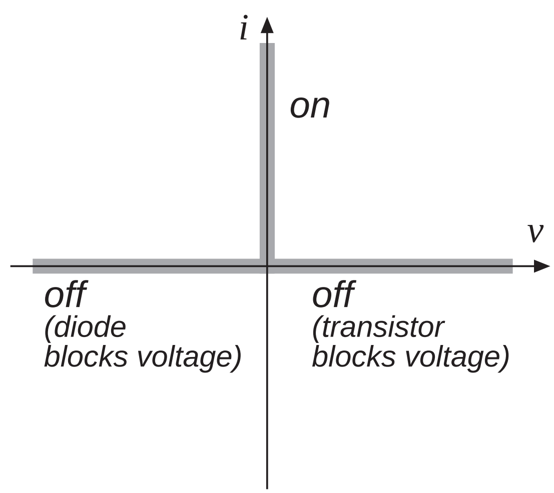


A dc-dc converter with bidirectional power flow.

4.1.3. Voltage-bidirectional two-quadrant switches



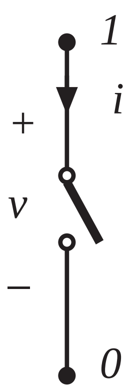
BJT / series diode realization

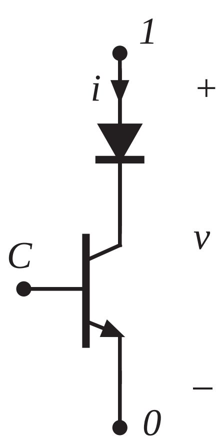


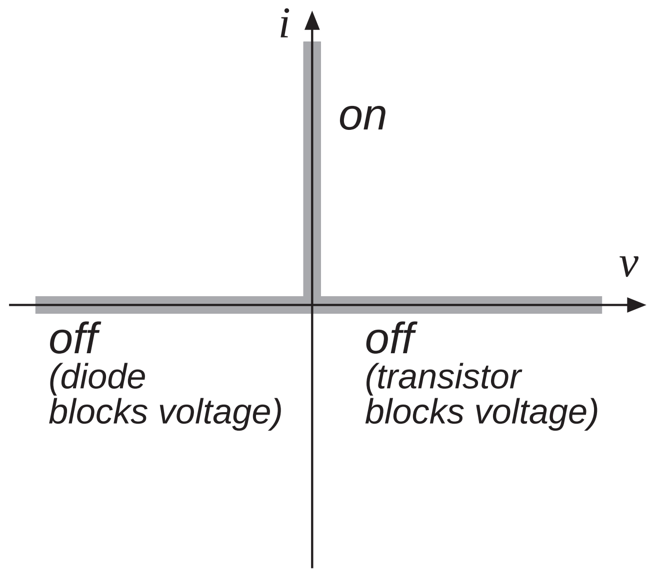
instantaneous i-v characteristic

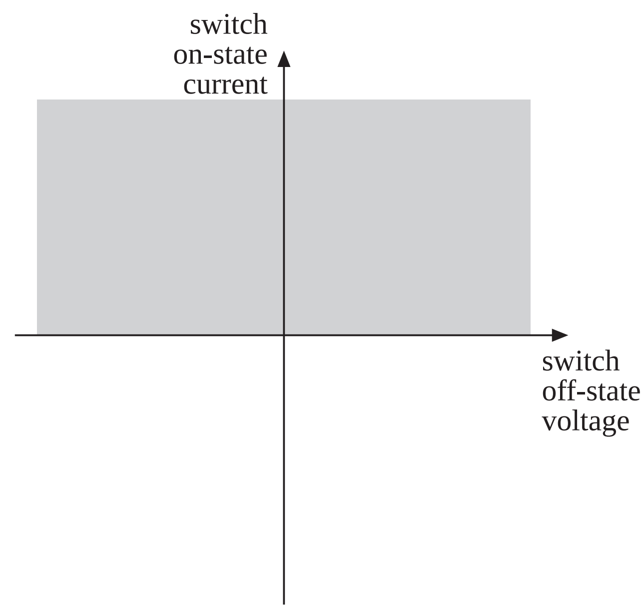
- *Usually an active switch, controlled by terminal C*
- *Normally operated as two-quadrant switch:*
- *can conduct positive on-state current*
- *can block positive or negative off-state voltage*
- *provided that the intended on-state and off-state operating points lie on the composite i-v characteristic, then switch can be realized as shown*
- *The SCR is such a device, without controlled turn-off*

Two-quadrant switches

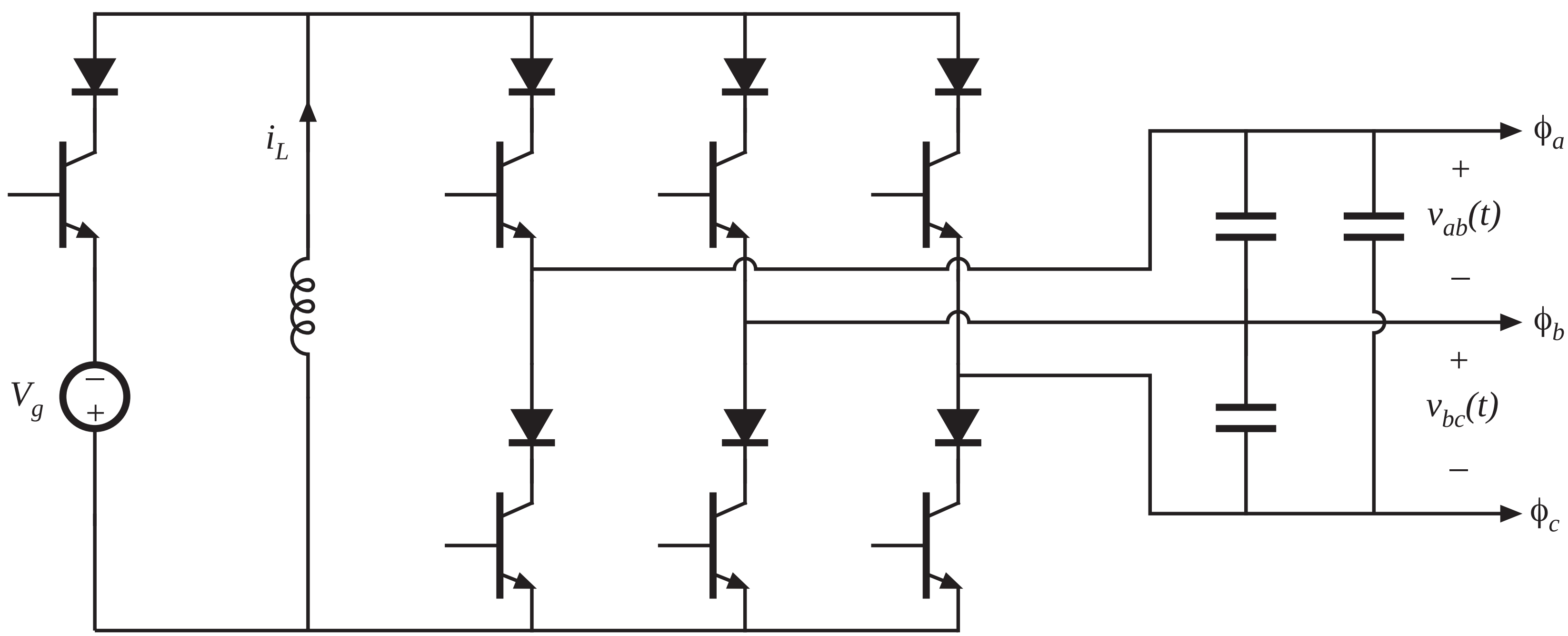








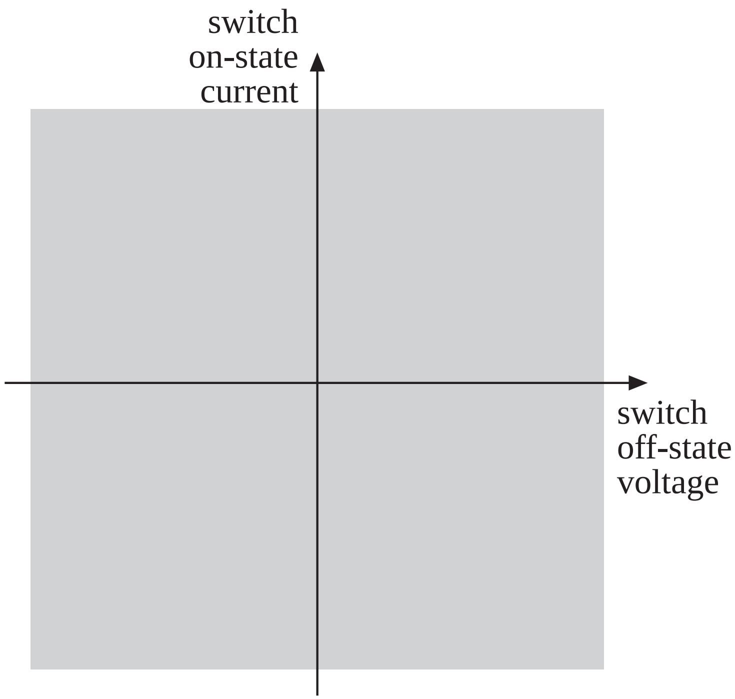
A dc-3øac buck-boost inverter



Requires voltage-bidirectional two-quadrant switches.

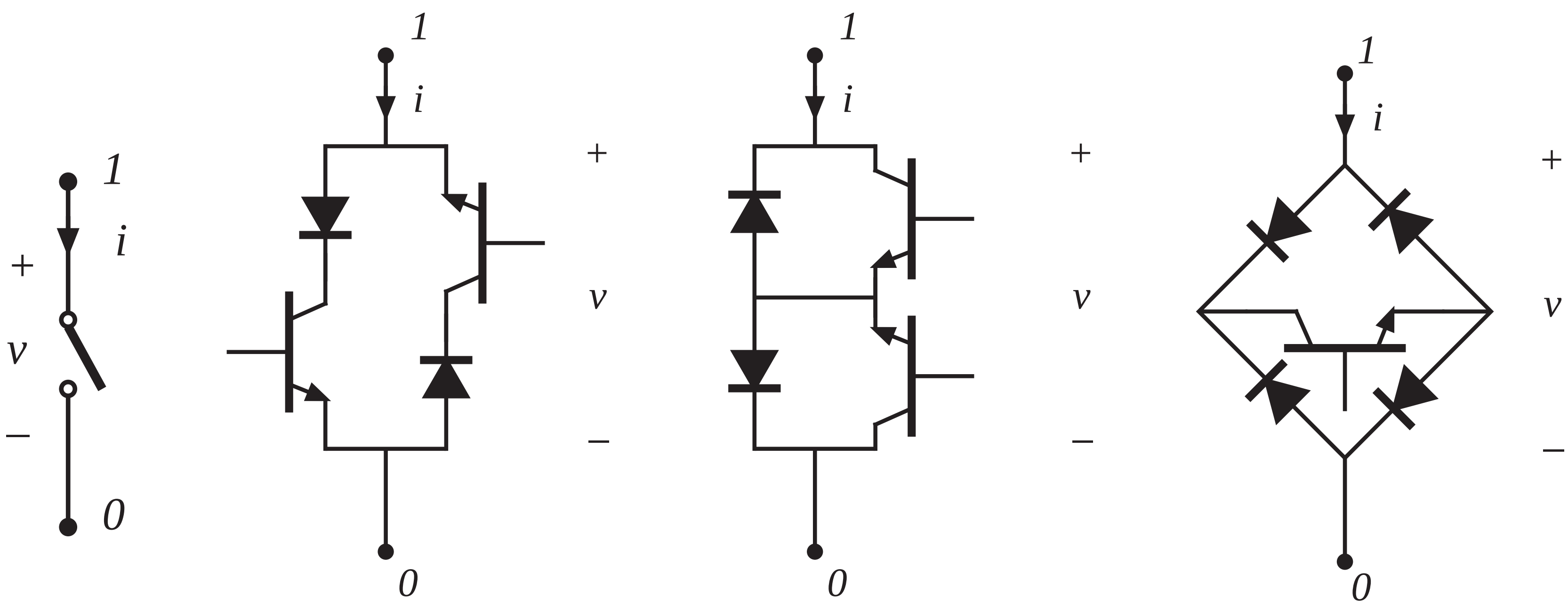
Another example: boost-type inverter, or current-source inverter (CSI).

4.1.4. Four-quadrant switches

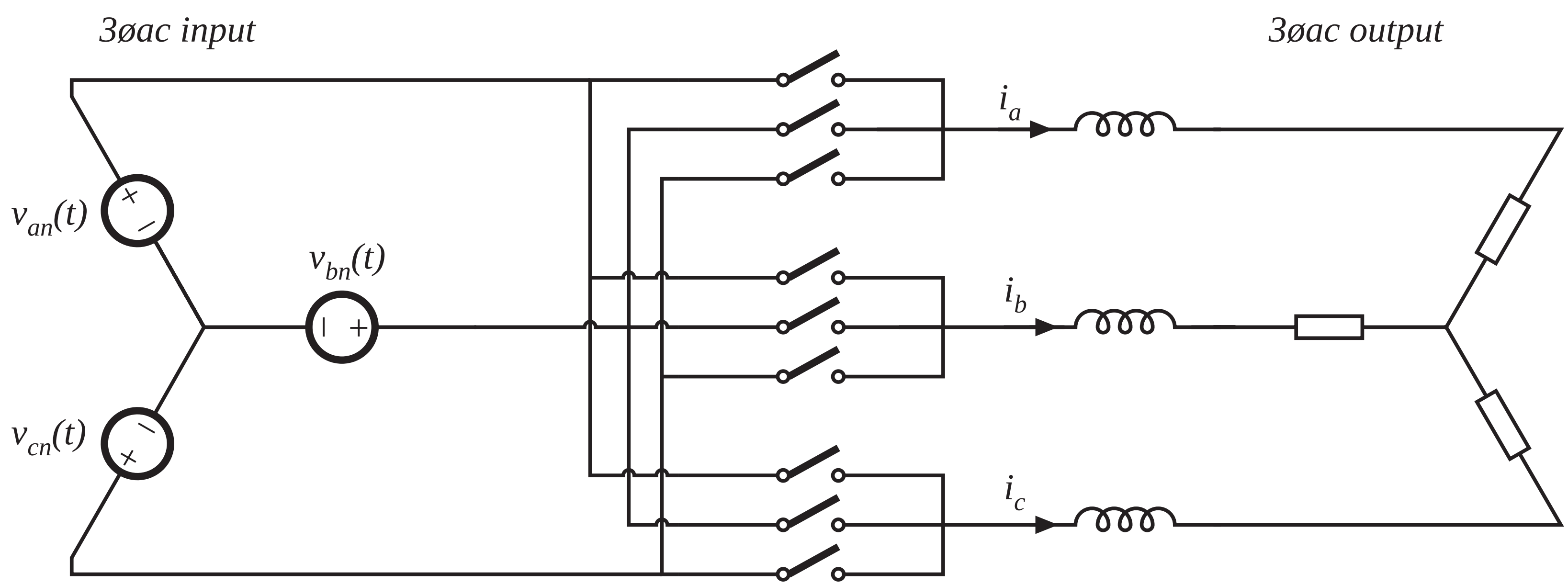


- *Usually an active switch, controlled by terminal C*
- *can conduct positive or negative on-state current*
- *can block positive or negative off-state voltage*

Three ways to realize a four-quadrant switch



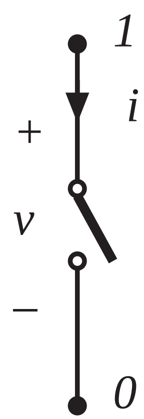
A 3øac-3øac matrix converter



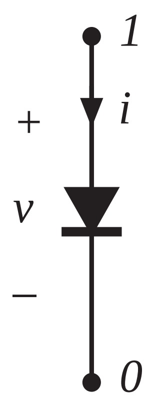
- All voltages and currents are ac; hence, four-quadrant switches are required.
- Requires nine four-quadrant switches

4.1.5. Synchronous rectifiers

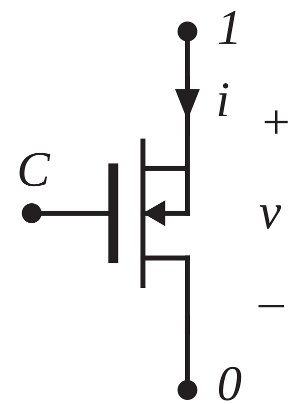
Replacement of diode with a backwards-connected MOSFET,
to obtain reduced conduction loss



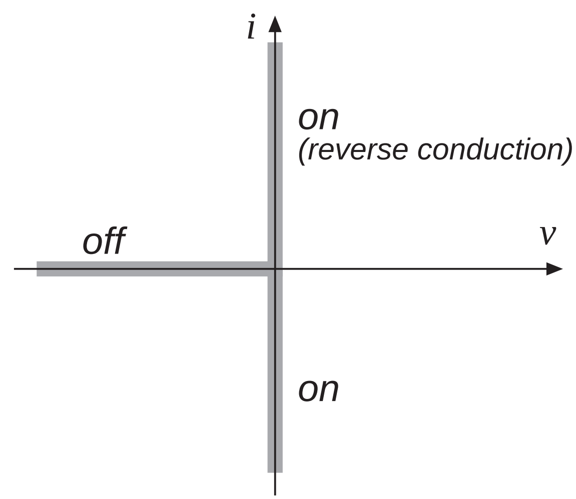
ideal switch



conventional diode rectifier

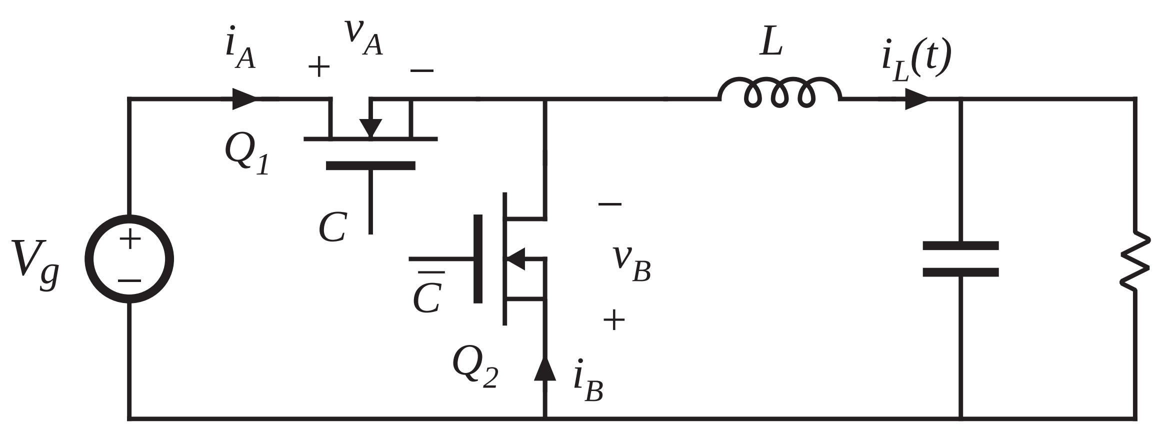


MOSFET as synchronous rectifier



instantaneous i-v *characteristic*

Buck converter with synchronous rectifier



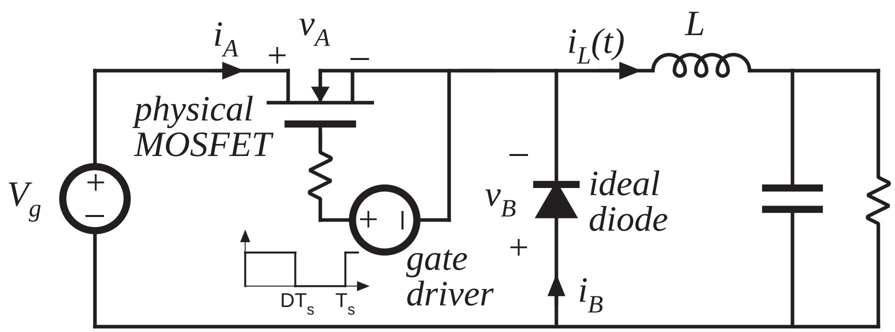
- MOSFET Q_2 is controlled to turn on when diode would normally conduct
- Semiconductor conduction loss can be made arbitrarily small, by reduction of MOSFET on-resistances
- Useful in low-voltage high-current applications

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

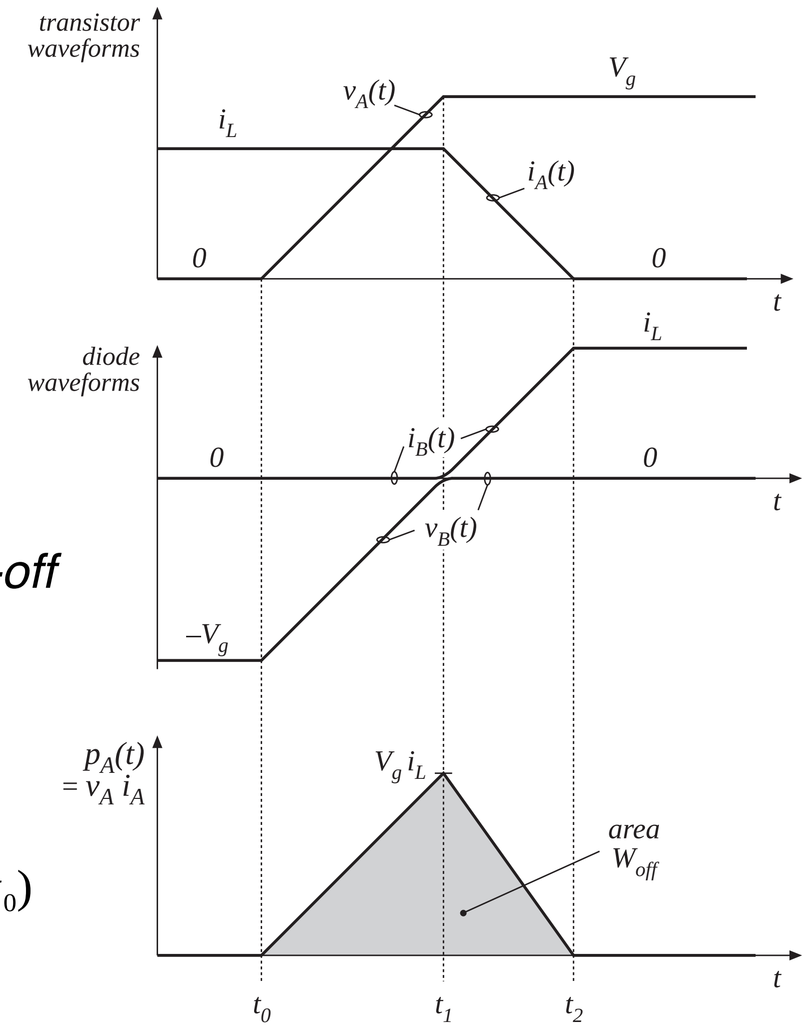
4.3.1. Transistor switching with clamped inductive load



Buck converter example

$$v_B(t) = v_A(t) - V_g$$
$$i_A(t) + i_B(t) = i_L$$

transistor turn-off transition



$$W_{off} = \frac{1}{2} V_g i_L \,(t_2 - t_0)$$

Switching loss induced by transistor turn-off transition

Energy lost during transistor turn-off transition:

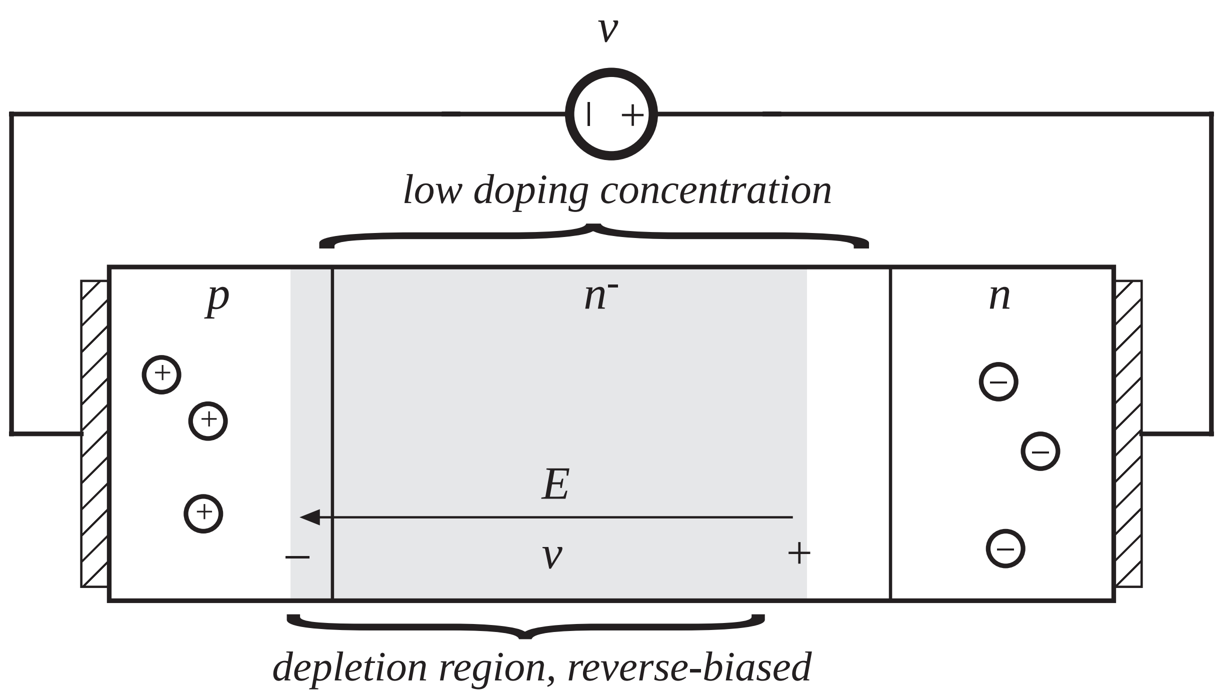
$$W_{off} = \frac{1}{2} V_g i_L \left(t_2 - t_0\right)$$

Similar result during transistor turn-on transition.
Average power loss:

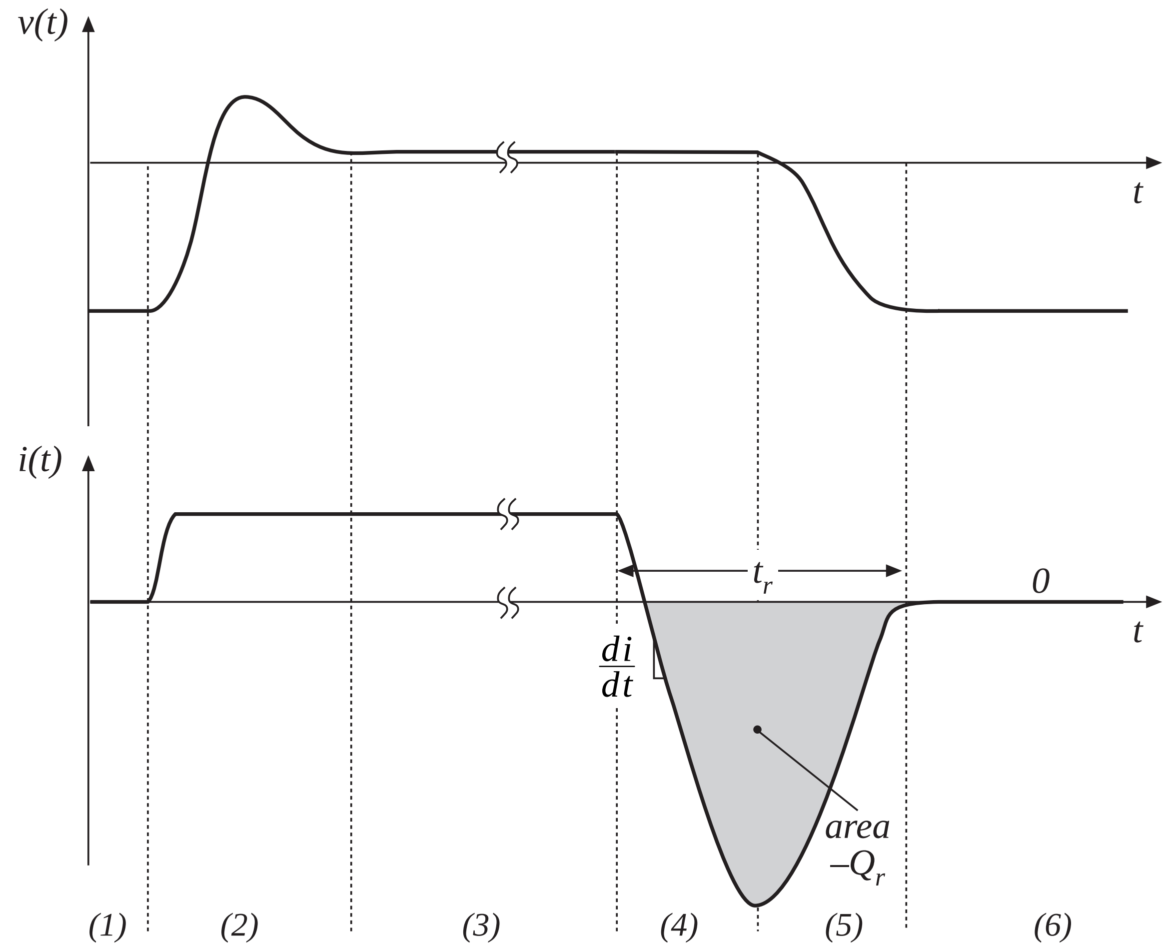
$$P_{sw} = \frac{1}{T_s} \int_{\substack{\text{switching} \\ \text{transitions}}} p_A(t)\, dt = \left(W_{on} + W_{off}\right) f_s$$

4.2.1. Power diodes

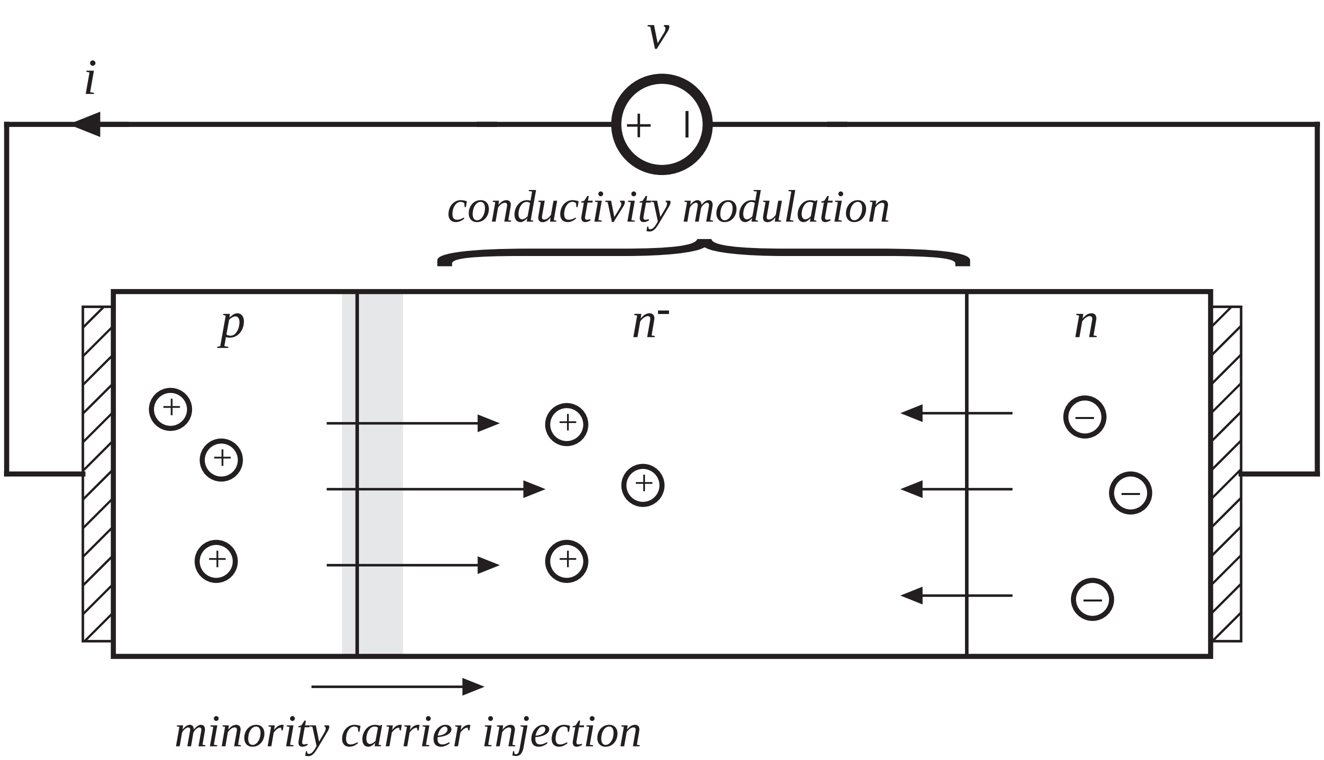
A power diode, under reverse-biased conditions:



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:

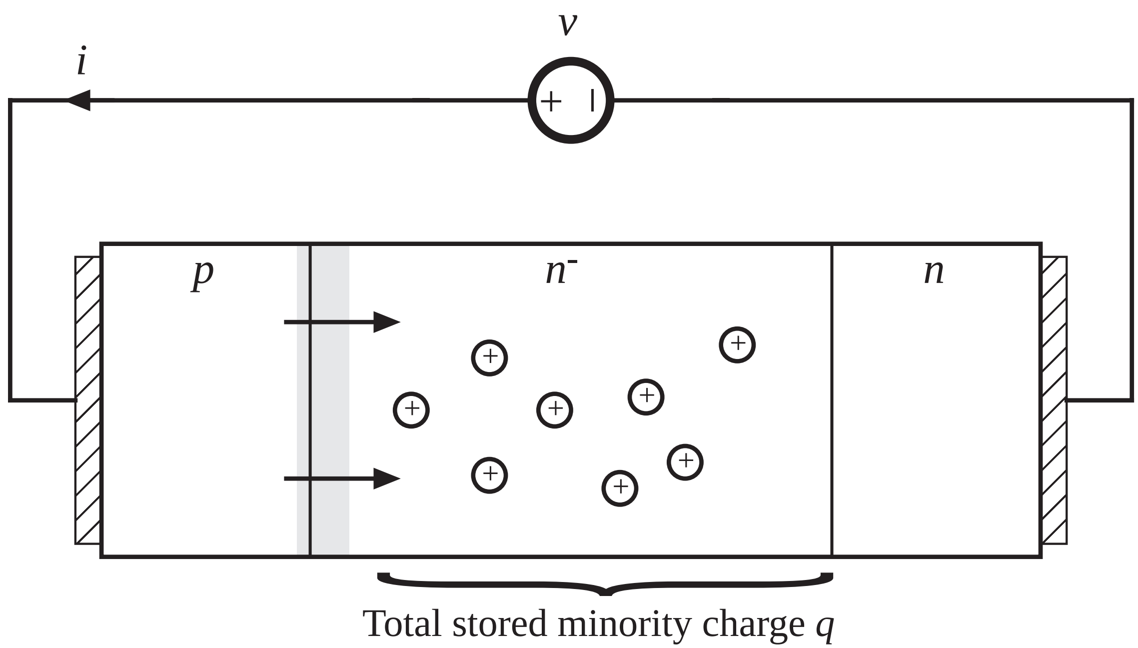
$$\frac{dq(t)}{dt} = i(t) - \frac{q(t)}{\tau_L}$$

With:

λ= 1/(26 mV) at 300 K

τ_L = minority carrier lifetime

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



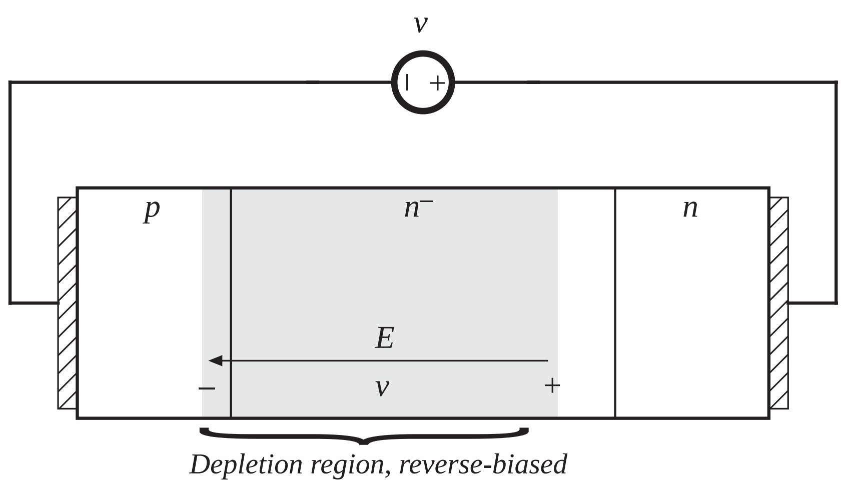
In equilibrium: $dq/dt = 0$, and hence

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

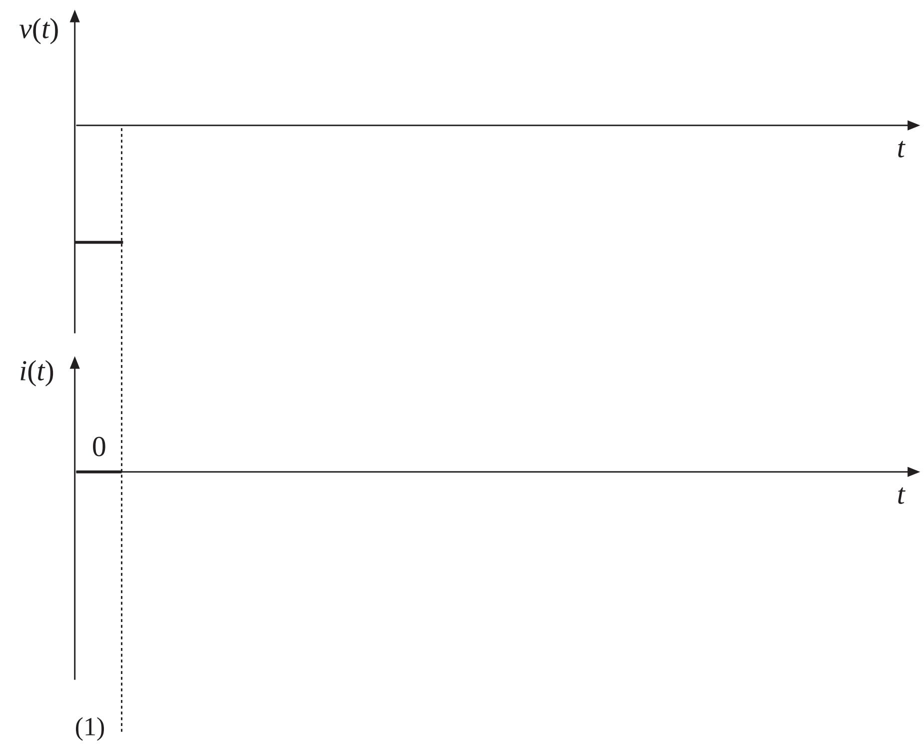
Charge-control in the diode: Discussion

- 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

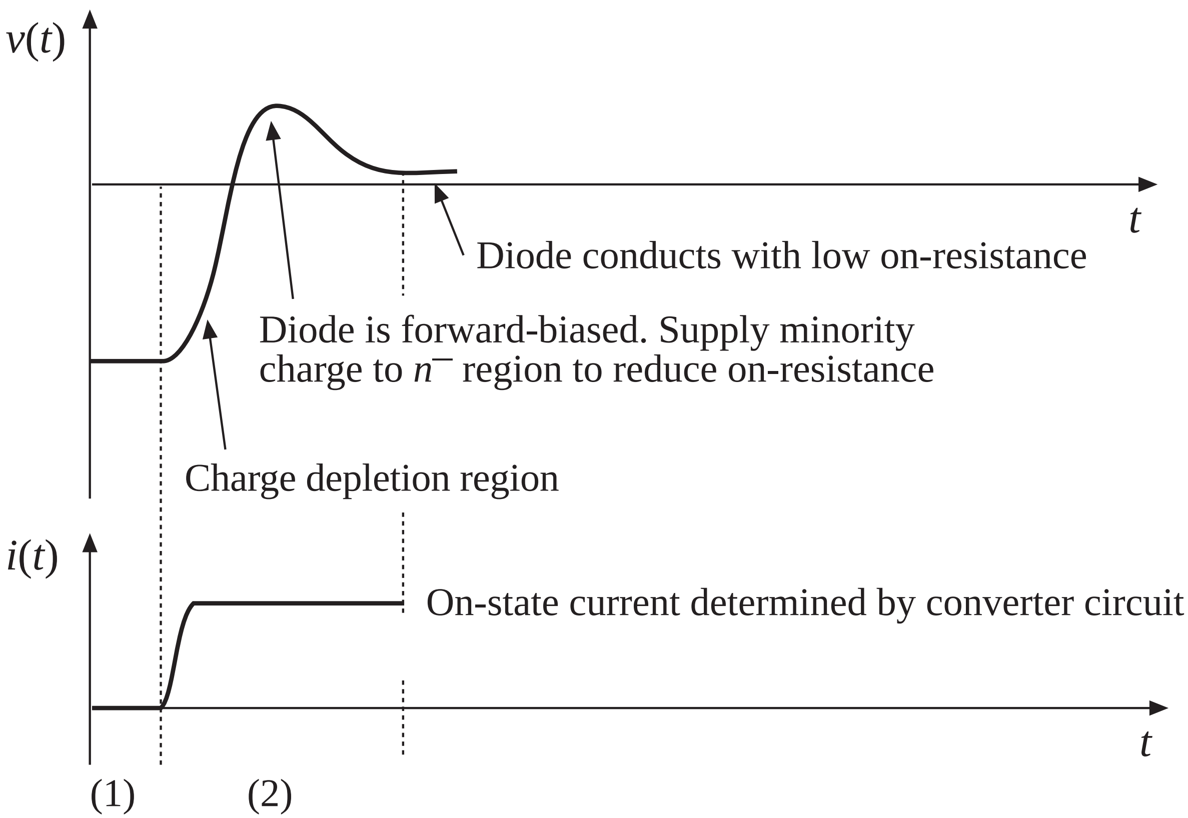
Diode in OFF state: reversed-biased, blocking voltage



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



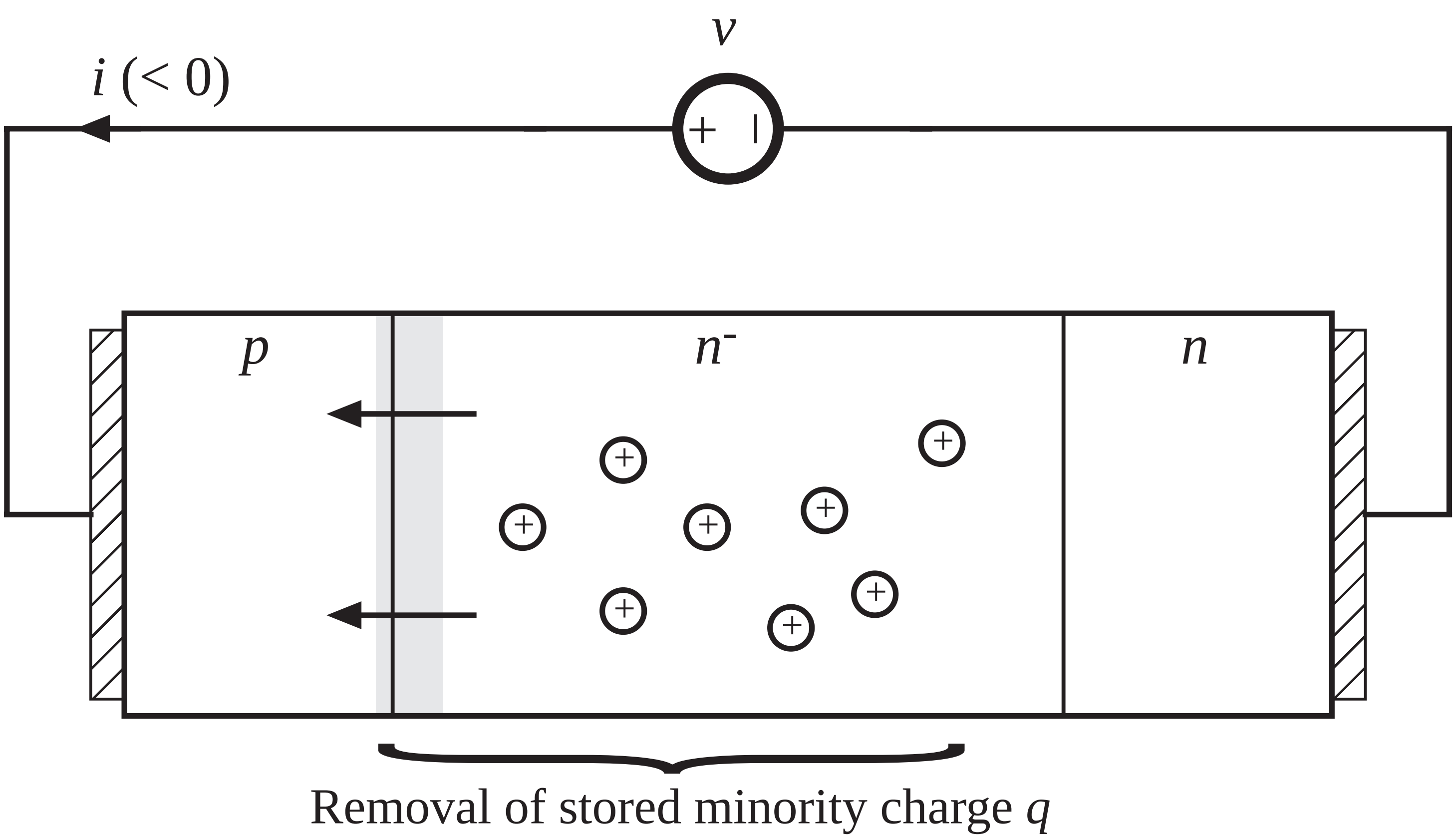
Turn-on transient



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

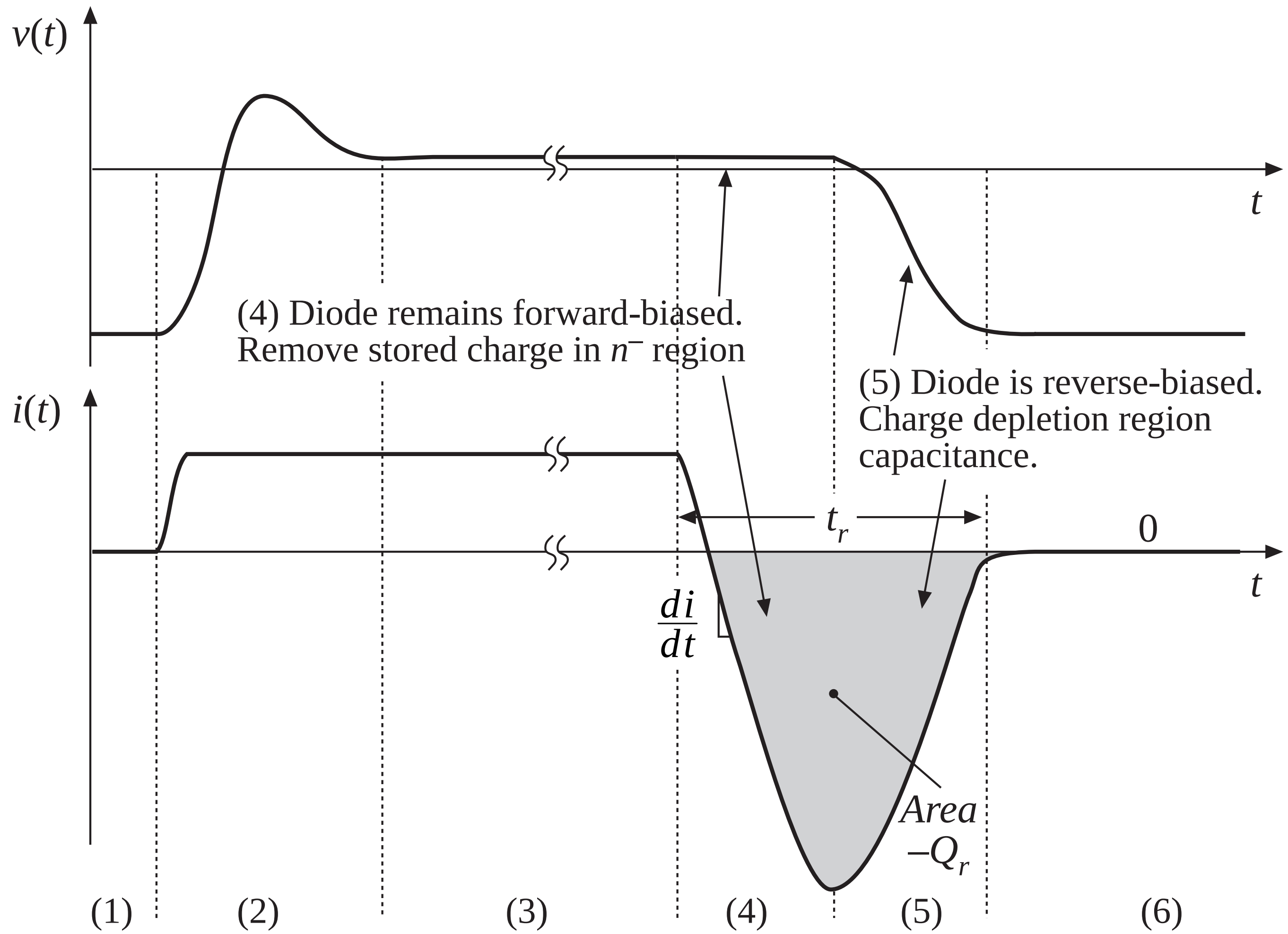
- charge to increase voltage across depletion region
- charge needed to support the on-state current
- charge to reduce on-resistance of n^- region

Turn-off transient

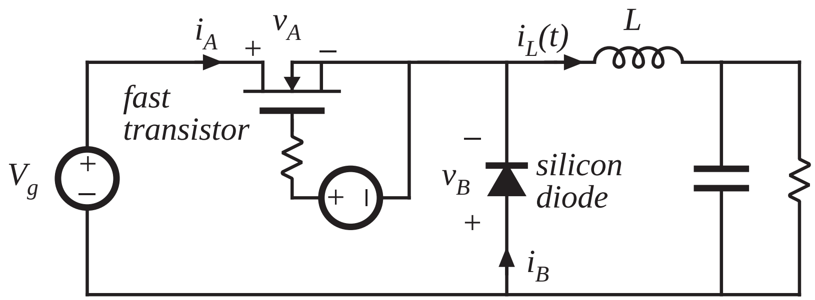


Diode turn-off transient

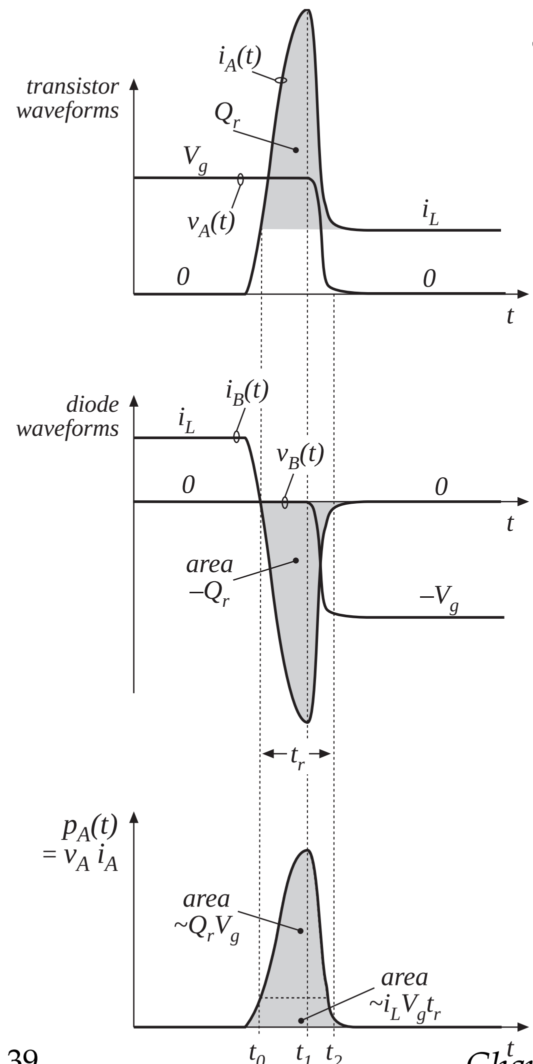
continued



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

Switching loss calculation

Energy lost in transistor:

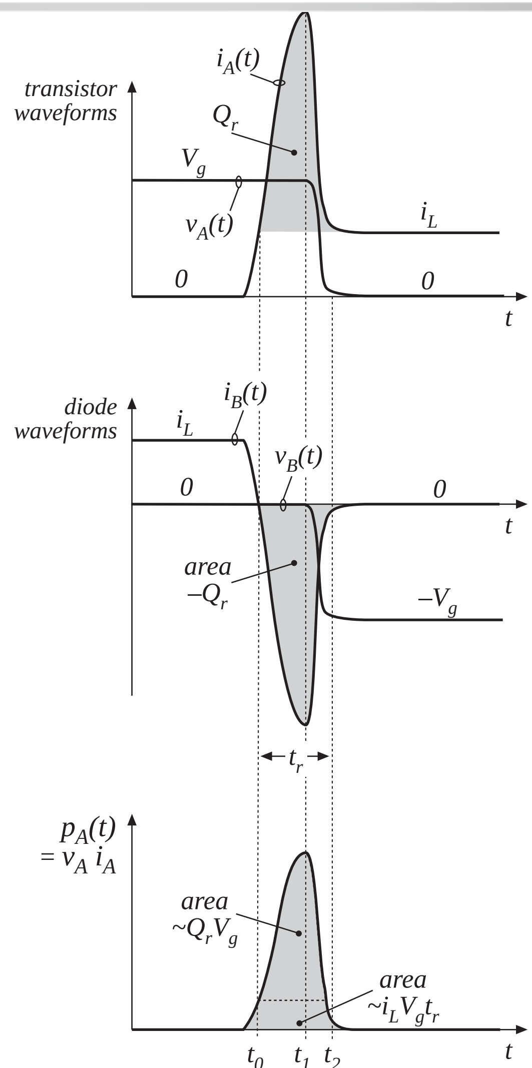
$$W_D = \int_{\substack{\text{switching}\\ \text{transition}}} v_A(t)\, i_A(t)\, dt$$

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.

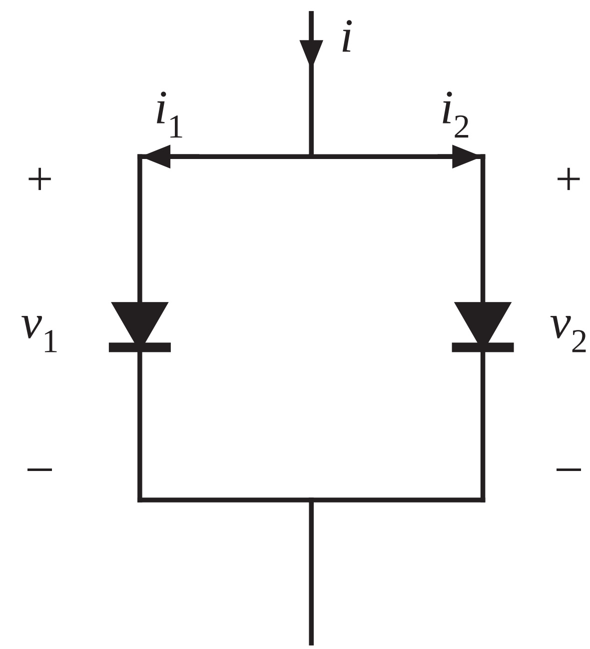
Reason: thermal instability caused by temperature dependence of the diode equation.

Increased temperature leads to increased current, or reduced voltage.

One diode will hog the current.

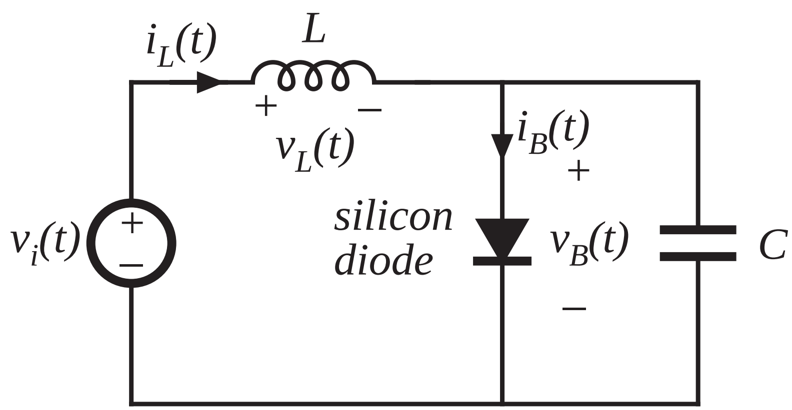
To get the diodes to share the current, heroic measures are required:

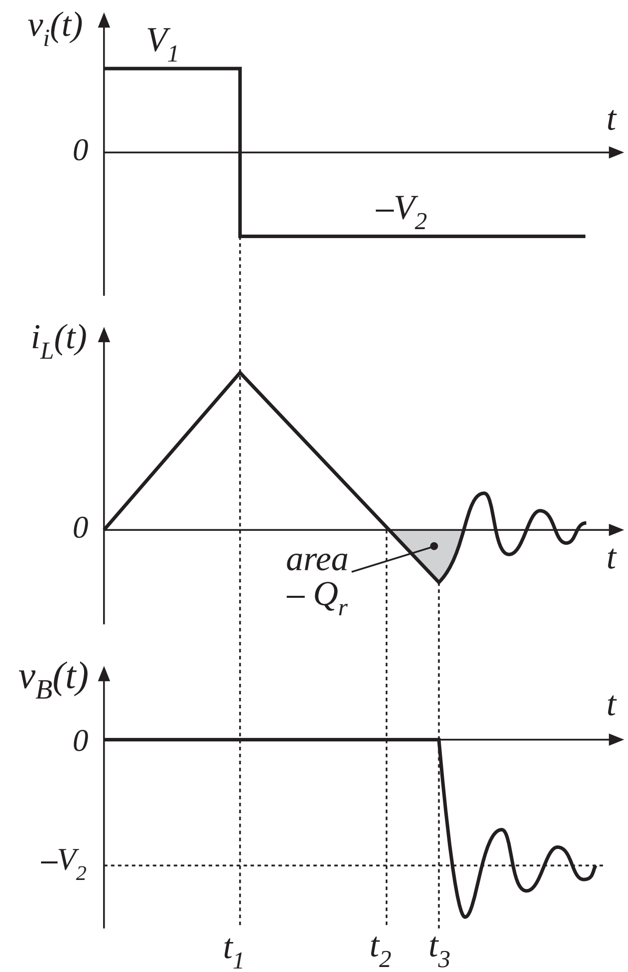
- Select matched devices
- Package on common thermal substrate
- Build external circuitry that forces the currents to balance



Ringing induced by diode stored charge

see Section 4.3.3





- 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.

Energy associated with ringing

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

Energy stored in inductor during interval $t_2 \le t \le t_3$:

$$W_L = \int_{t_2}^{t_3} v_L(t)\, i_L(t)\, dt$$

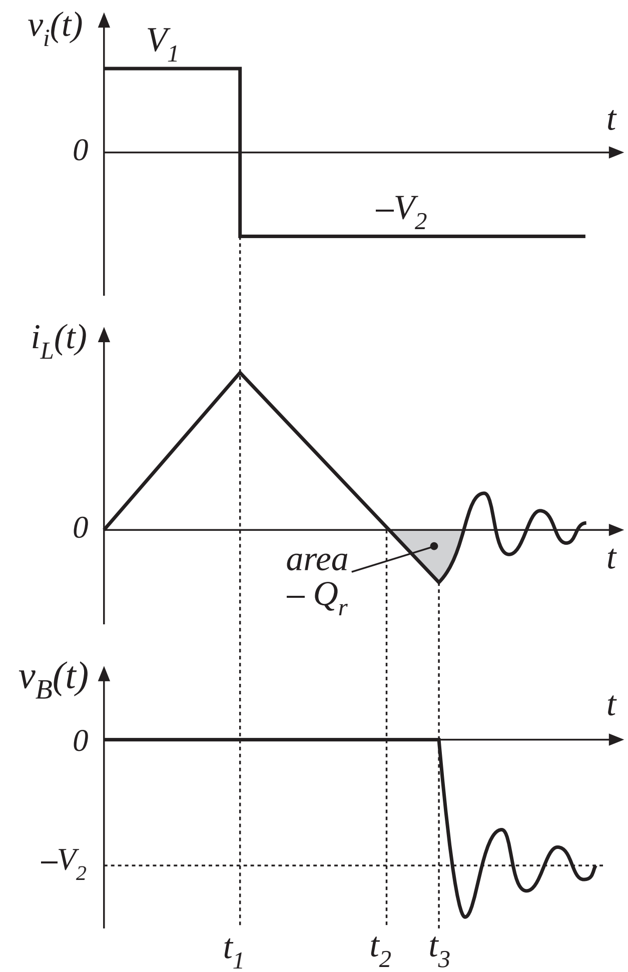
Applied inductor voltage during interval $t_2 \le t \le t_3$:

$$v_L(t) = L\,\frac{di_L(t)}{dt} = -V_2$$

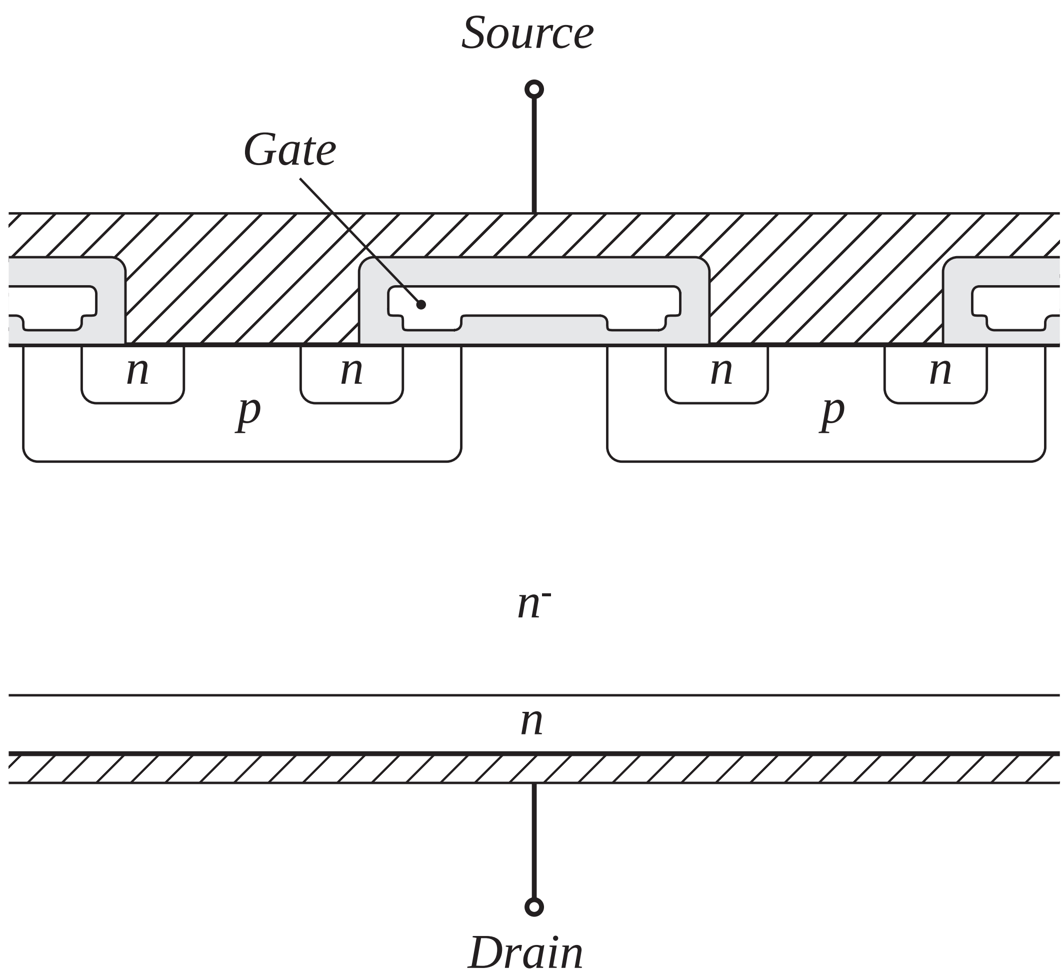
Hence,

$$W_L = \int_{t_2}^{t_3} L\,\frac{di_L(t)}{dt}\, i_L(t)\, dt = \int_{t_2}^{t_3} (-V_2)\, i_L(t)\, dt$$

$$W_L = \tfrac{1}{2} L\, i_L^2(t_3) = V_2\, Q_r$$

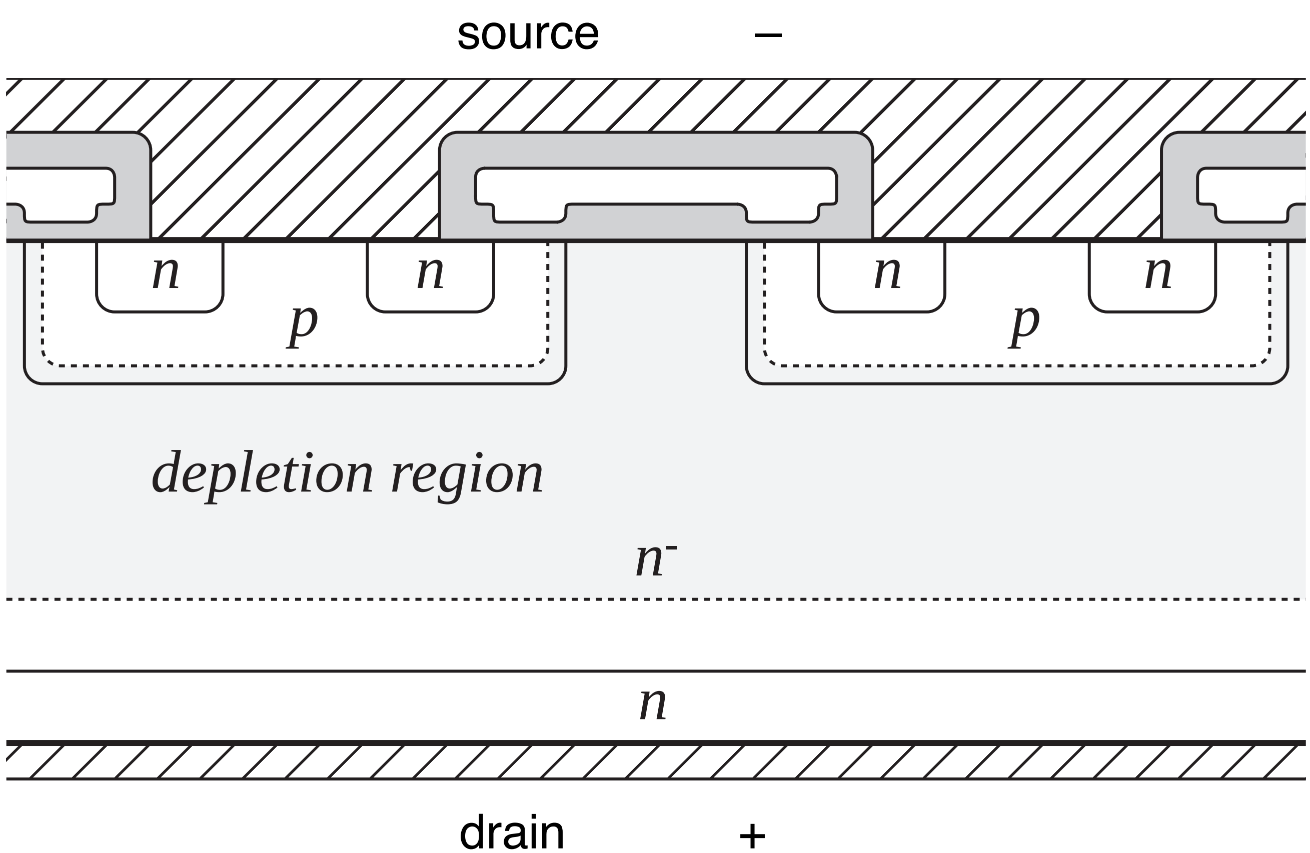


4.2.2. The Power MOSFET



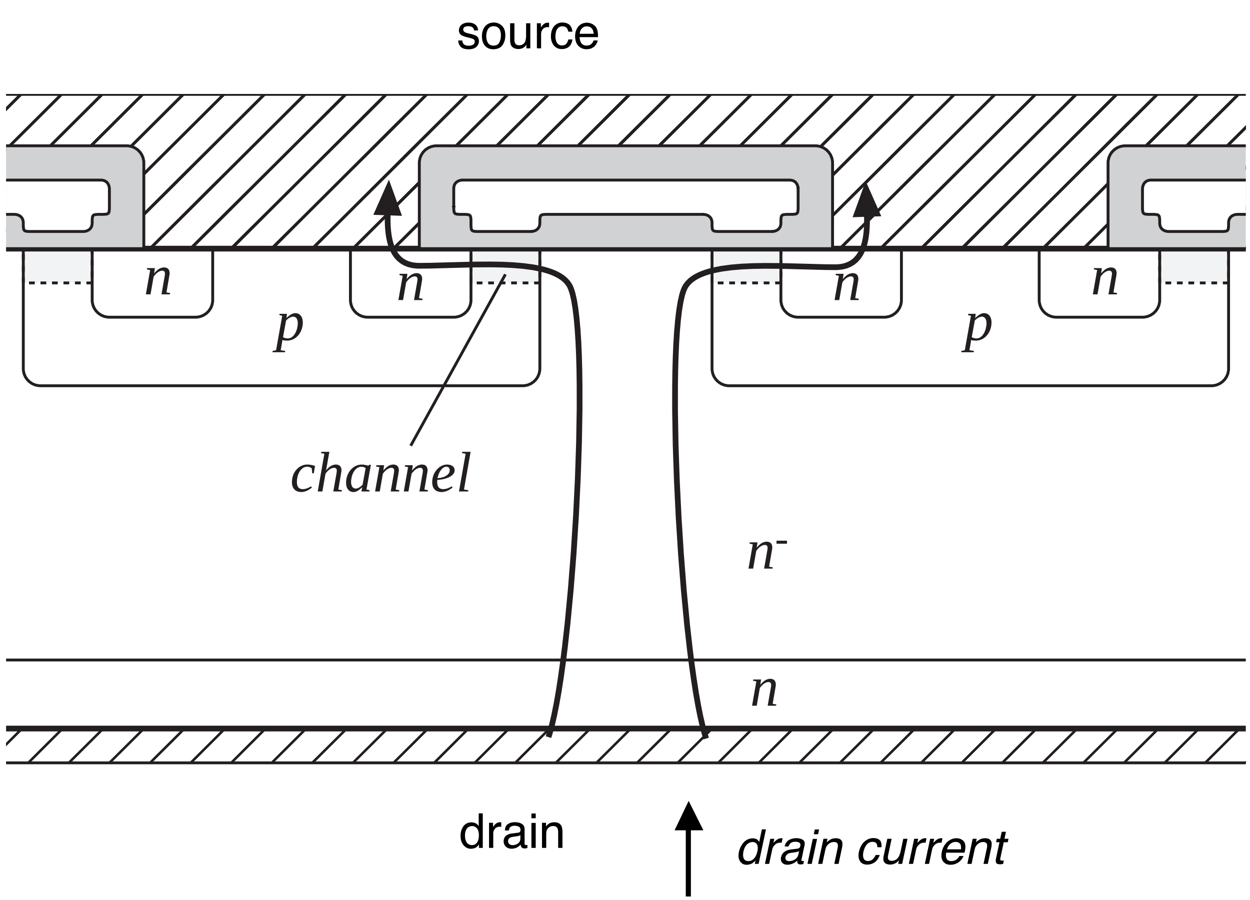
- Gate lengths approaching one micron
- Consists of many small enhancement-mode parallel-connected MOSFET cells, covering the surface of the silicon wafer
- Vertical current flow
- n-channel device is shown

MOSFET: Off state



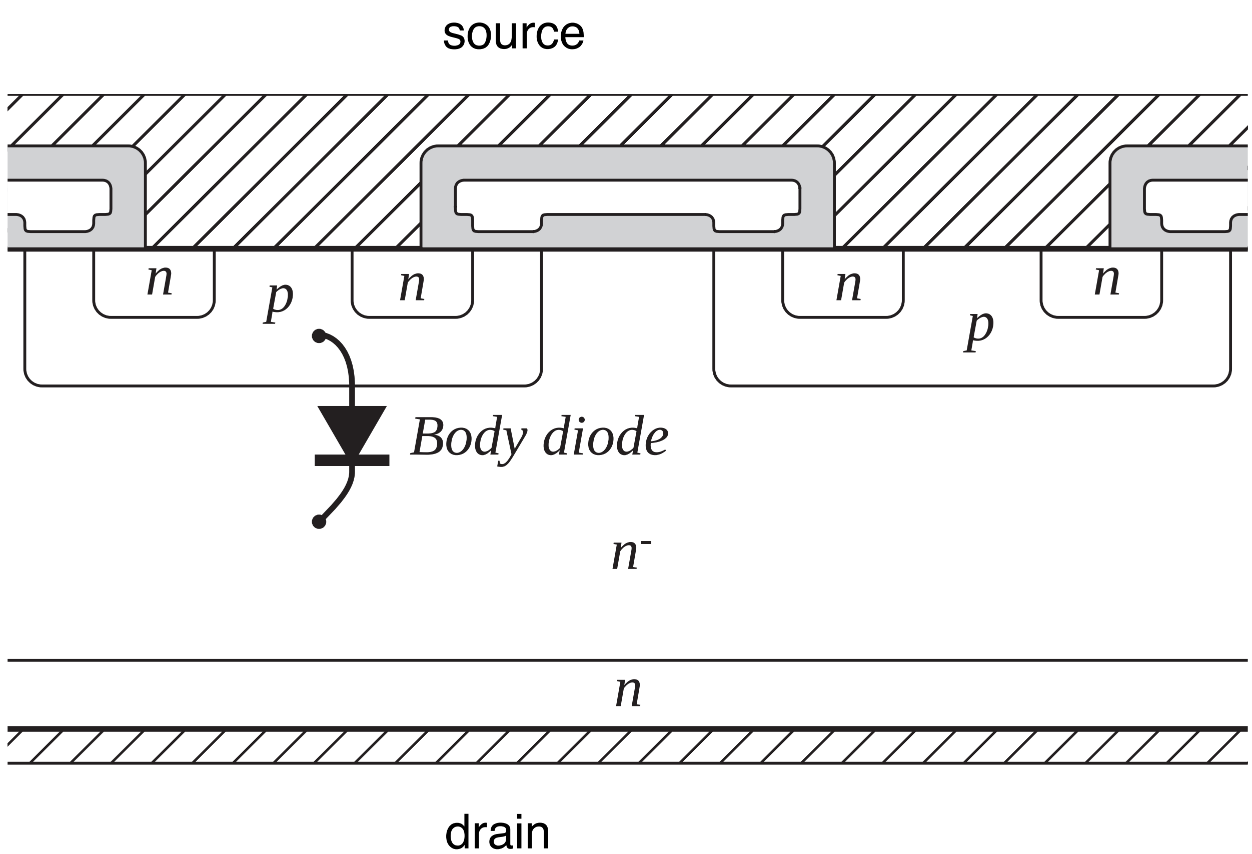
- p-n^- junction is reverse-biased
- off-state voltage appears across n^- region

MOSFET: on state



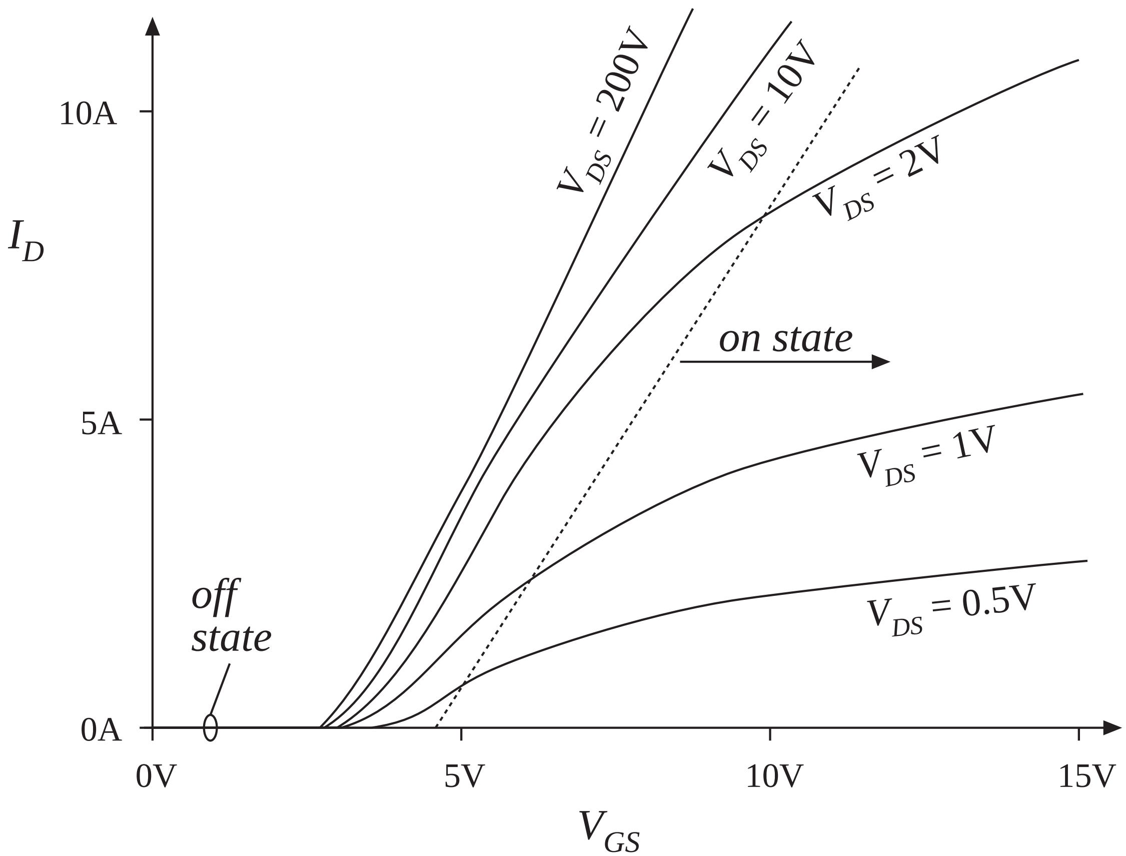
- p-n^- junction is slightly reverse-biased
- positive gate voltage induces conducting channel
- drain current flows through n^- region and conducting channel
- on resistance = total resistances of n^- region, conducting channel, source and drain contacts, etc.

MOSFET body diode



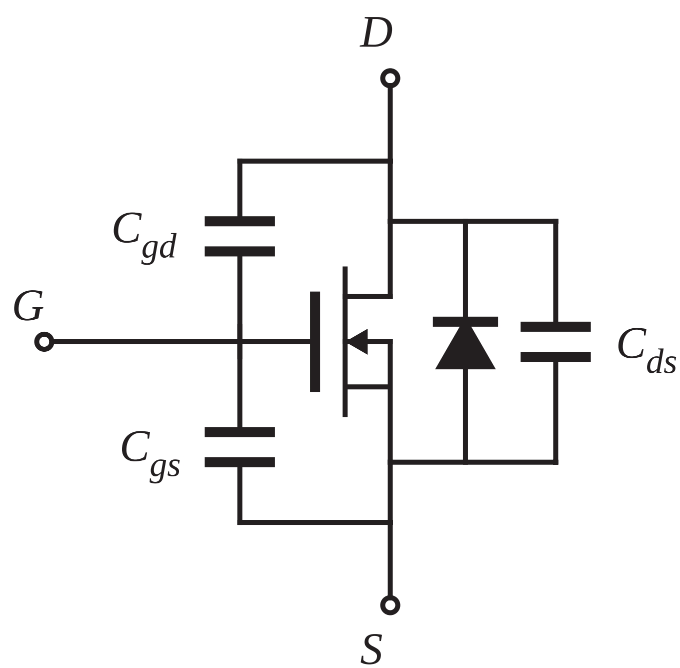
- p-n^- junction forms an effective diode, in parallel with the channel
- negative drain-to-source voltage can forward-bias the body diode
- diode can conduct the full MOSFET rated current
- diode switching speed not optimized —body diode is slow, Q_r is large

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



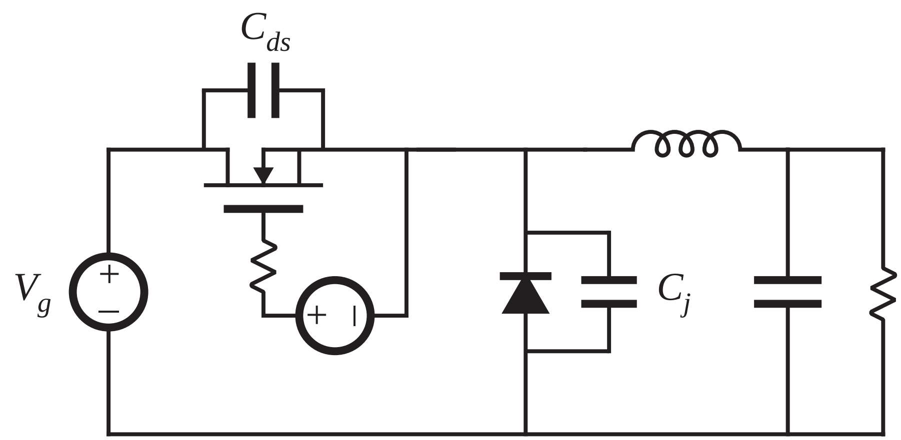
- C_{gs} : large, essentially constant
- C_{gd} : small, highly nonlinear
- C_{ds} : intermediate in value, highly nonlinear
- switching times determined by rate at which gate driver charges/discharges C_{gs} and C_{gd}

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

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

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 $\frac{4}{3}\, C_{ds}(V_{DS})$

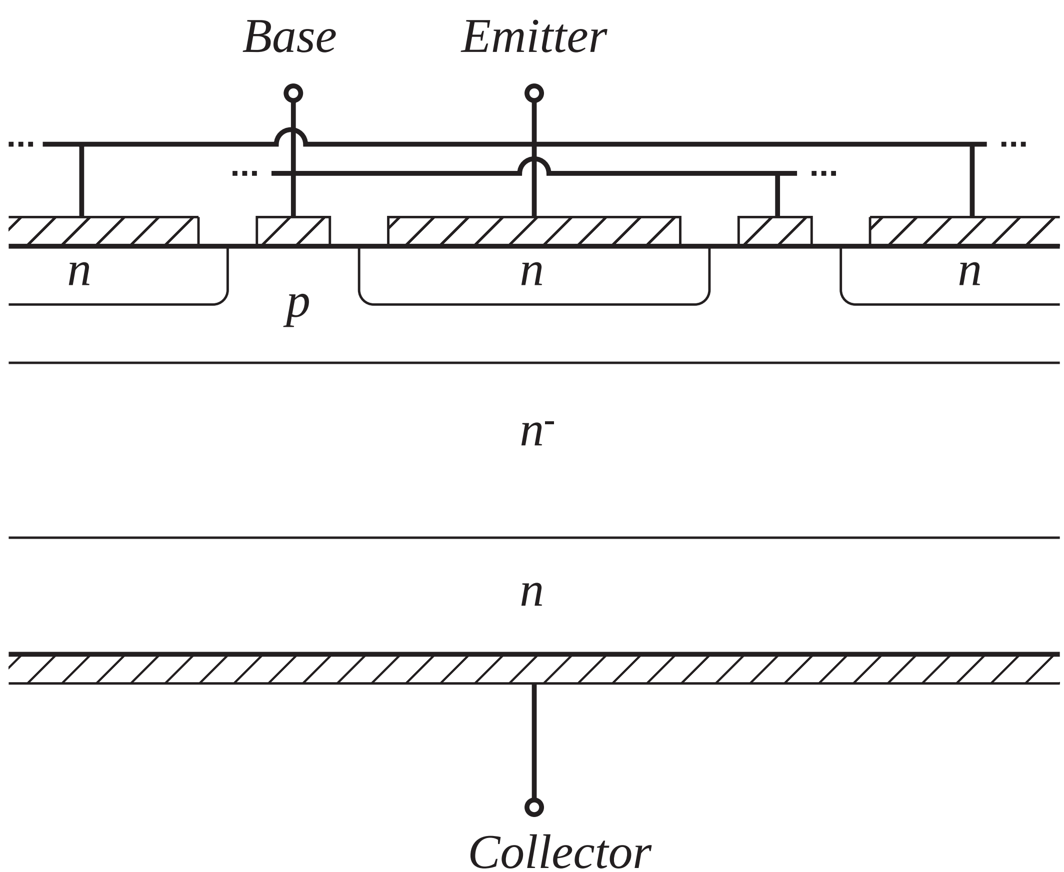
Characteristics of several commercial power MOSFETs

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

MOSFET: conclusions

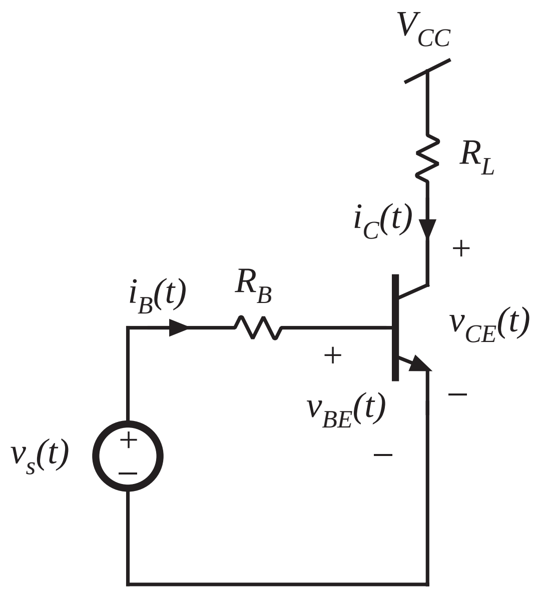
- A majority-carrier device: fast switching speed
- Typical switching frequencies: tens and hundreds of kHz
- On-resistance increases rapidly with rated blocking voltage
- Easy to drive
- The device of choice for blocking voltages less than 500V
- 1000V devices are available, but are useful only at low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

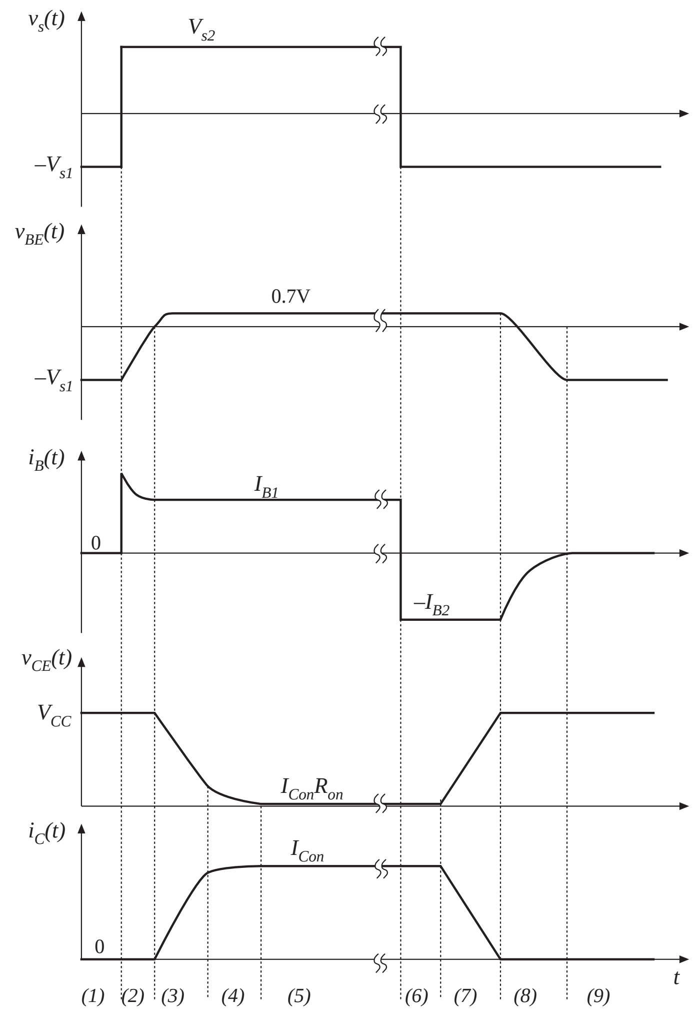
4.2.3. Bipolar Junction Transistor (BJT)



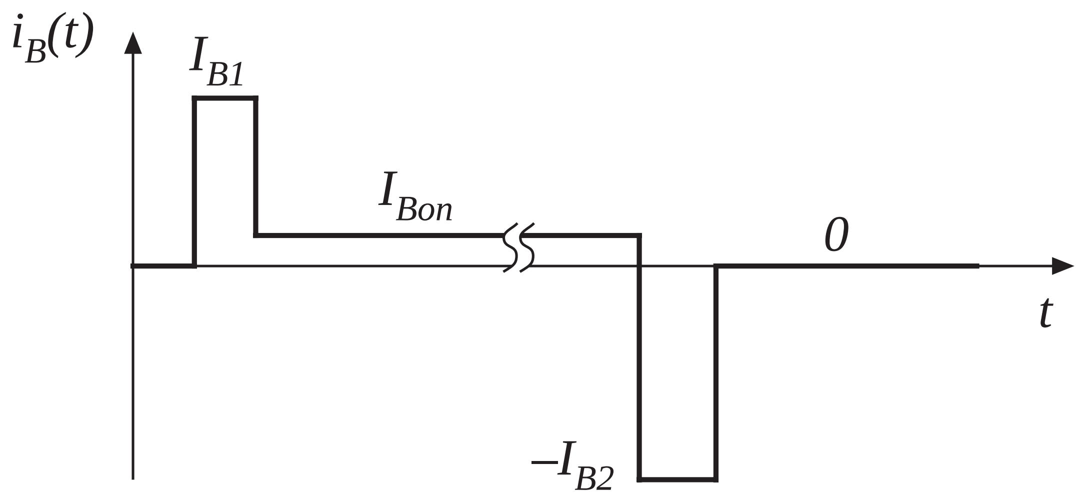
- Interdigitated base and emitter contacts
- Vertical current flow
- npn device is shown
- minority carrier device
- on-state: base-emitter and collector-base junctions are both forward-biased
- on-state: substantial minority charge in p and n^- regions, conductivity modulation

BJT switching times

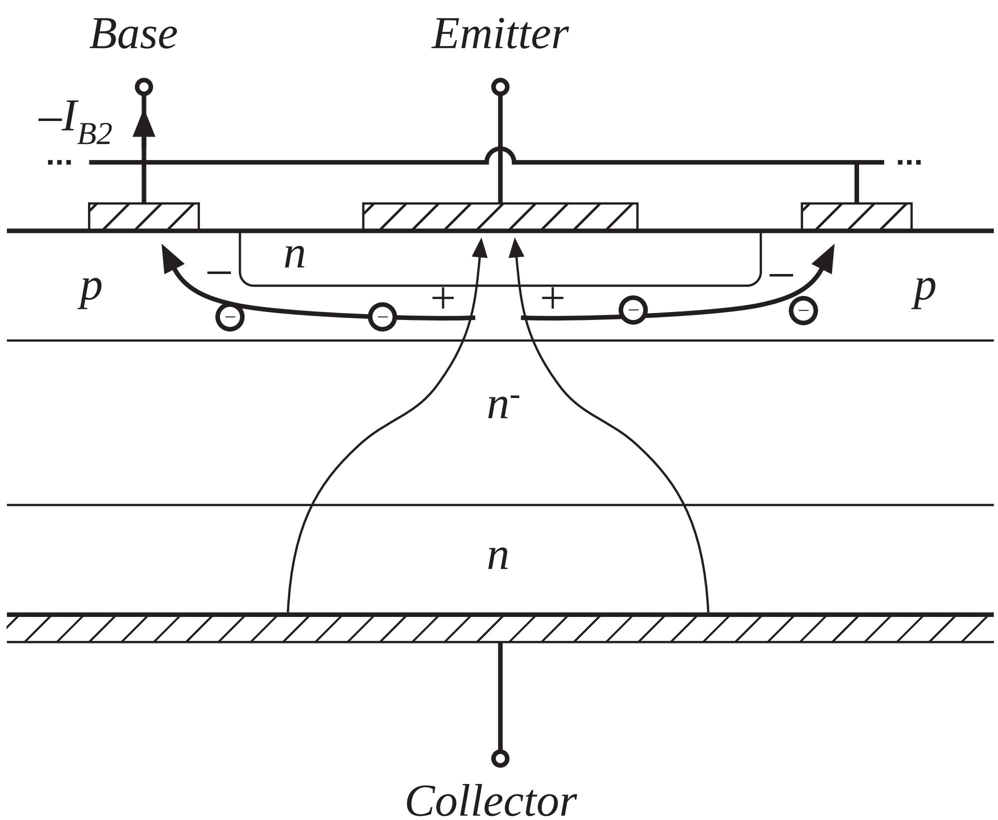




Ideal base current waveform

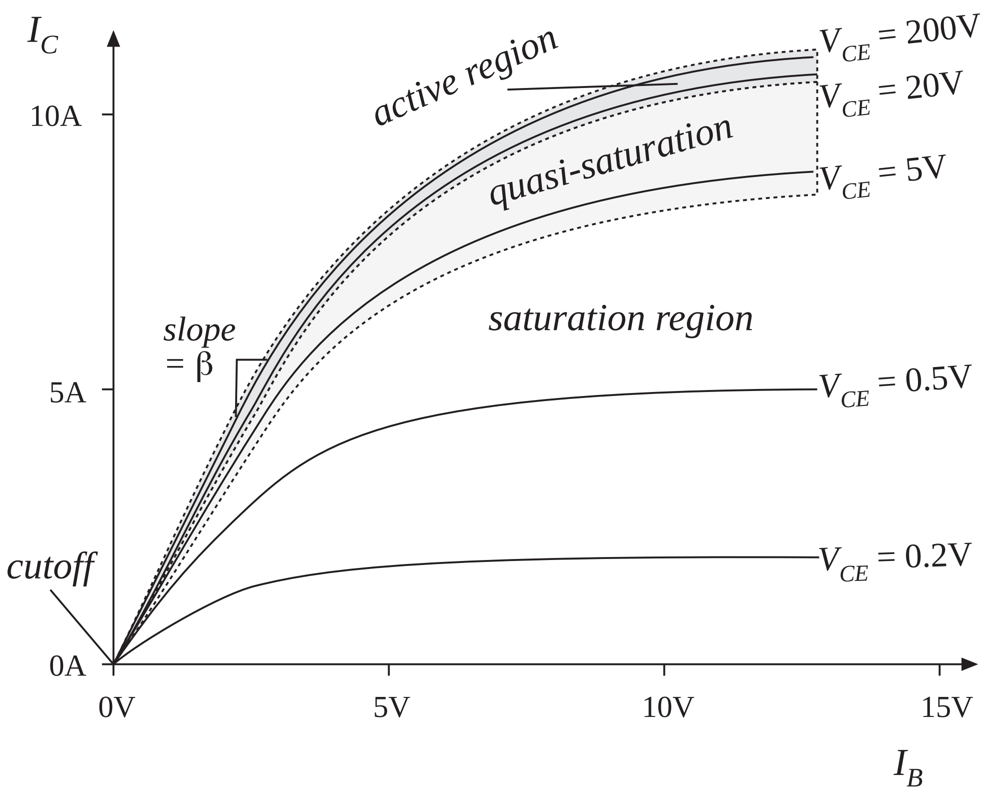


Current crowding due to excessive I_{B2}



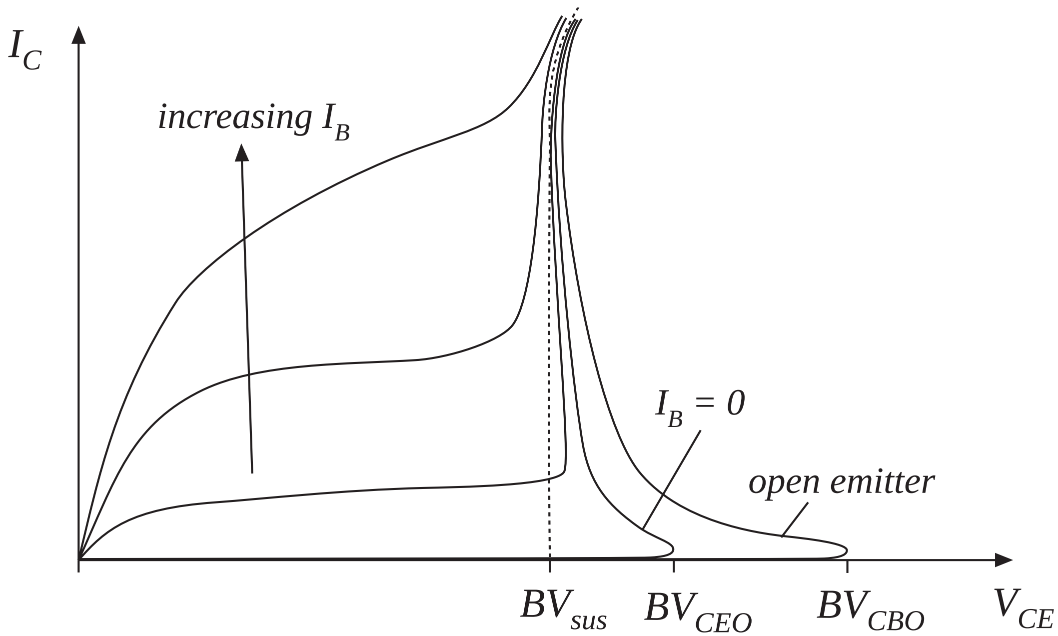
can lead to formation of hot spots and device failure

BJT characteristics



- Off state: $I_B = 0$
- On state: $I_B > I_C / \beta$
- Current gain β decreases rapidly at high current. Device should not be operated at instantaneous currents exceeding the rated value

Breakdown voltages



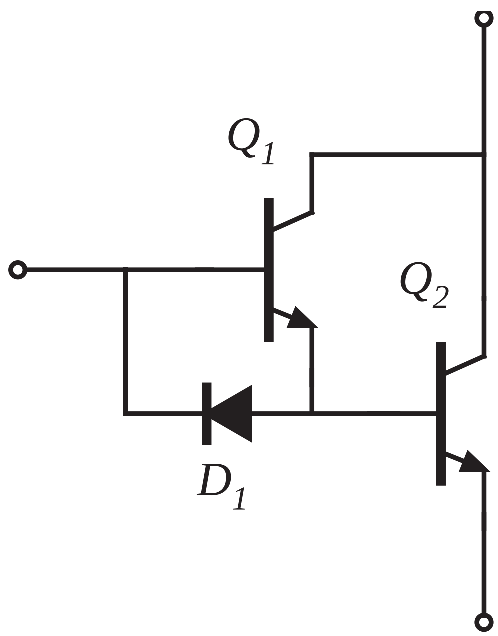
BV_{CBO}: avalanche breakdown voltage of base-collector junction, with the emitter open-circuited

BV_{CEO}: collector-emitter breakdown voltage with zero base current

BV_{sus}: breakdown voltage observed with positive base current

In most applications, the off-state transistor voltage must not exceed BV_{CEO}.

Darlington-connected BJT

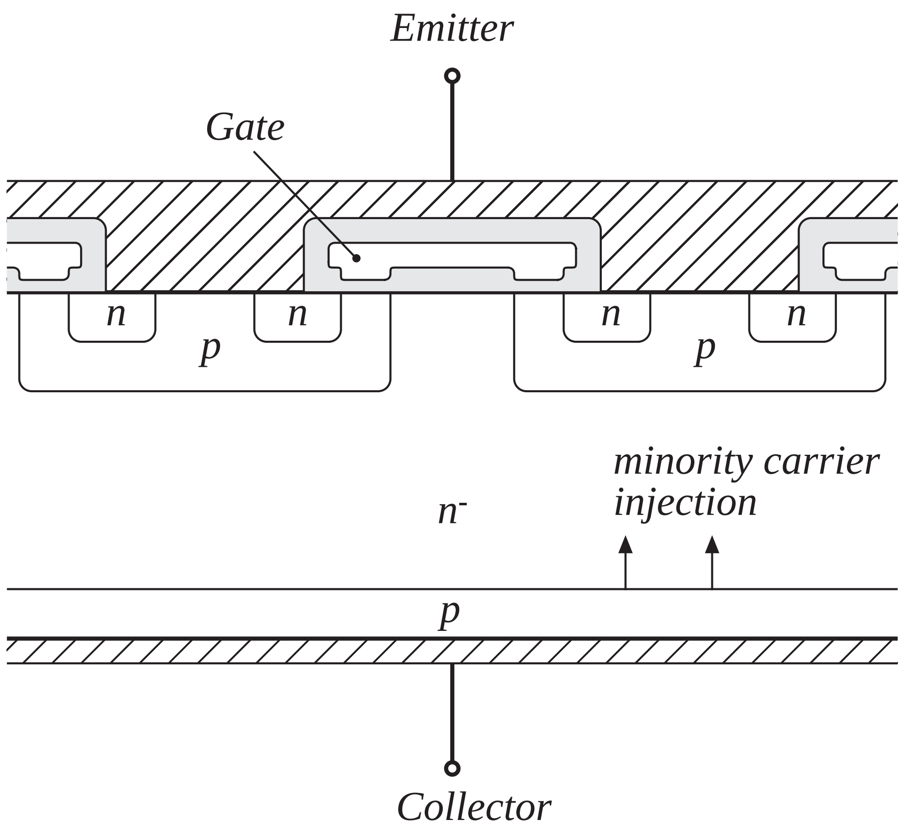


- Increased current gain, for high-voltage applications
- In a monolithic Darlington device, transistors Q_1 and Q_2 are integrated on the same silicon wafer
- Diode D_1 speeds up the turn-off process, by allowing the base driver to actively remove the stored charge of both Q_1 and Q_2 during the turn-off transition

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

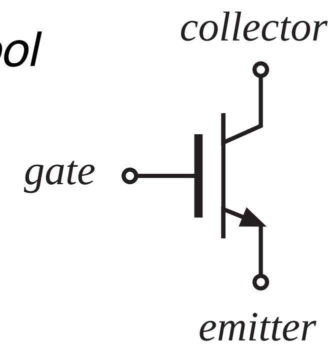
4.2.4. The Insulated Gate Bipolar Transistor (IGBT)



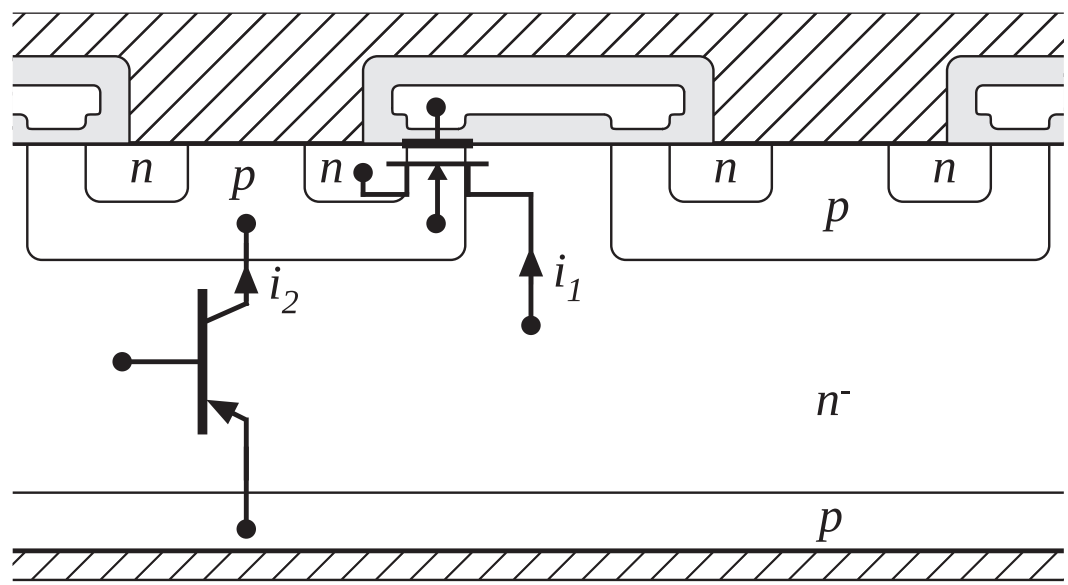
- A four-layer device
- Similar in construction to MOSFET, except extra p region
- On-state: minority carriers are injected into n^- region, leading to conductivity modulation
- compared with MOSFET: slower switching times, lower on-resistance, useful at higher voltages (up to 1700V)

The IGBT

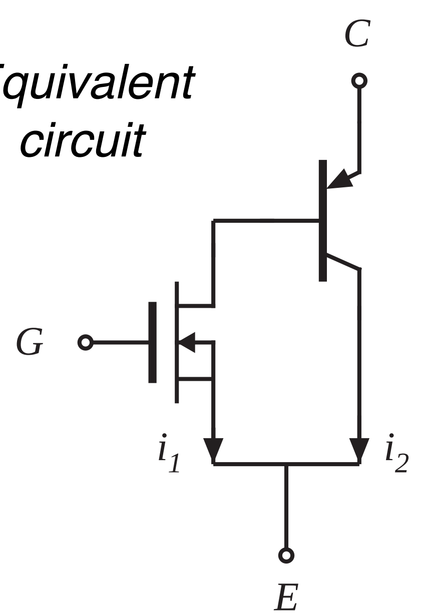
Symbol



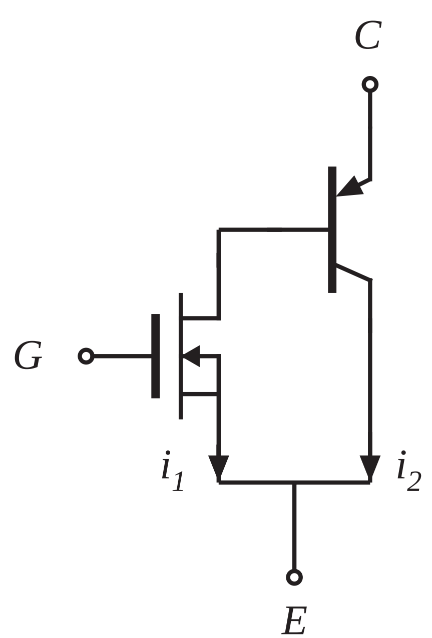
Location of equivalent devices

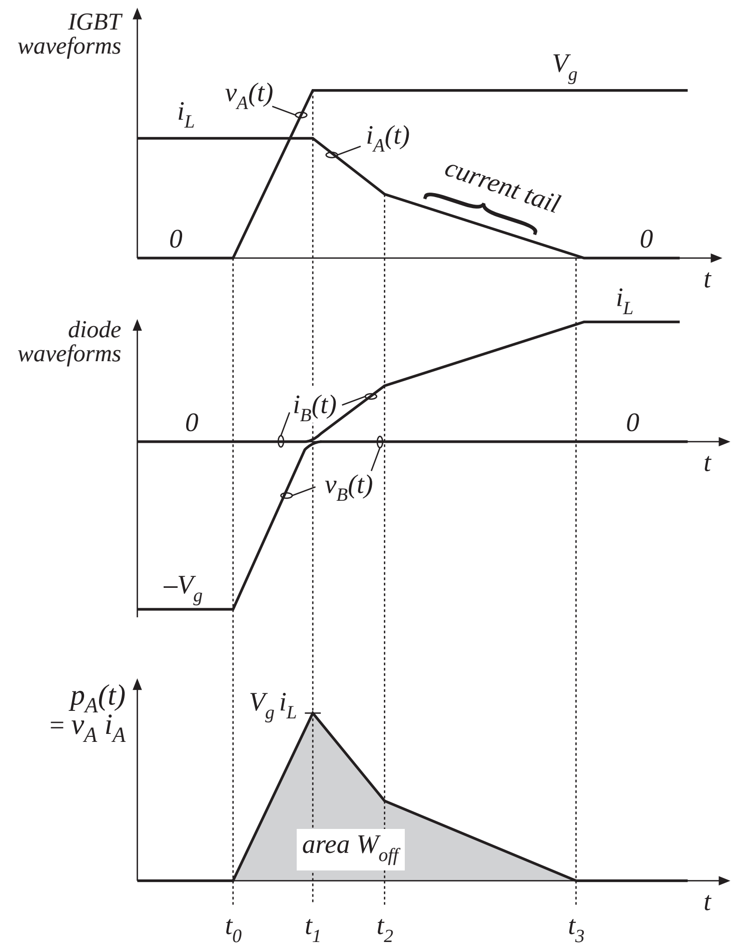


Equivalent circuit

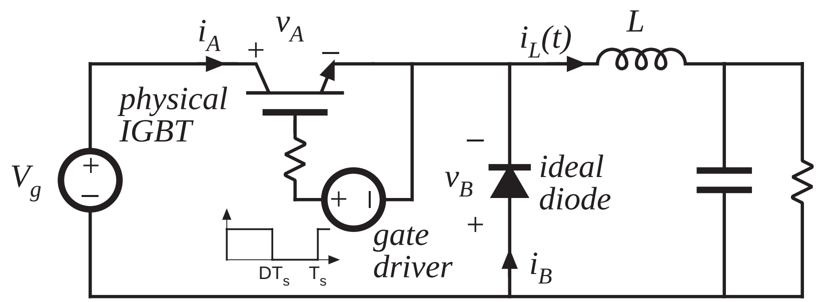


Current tailing in IGBTs

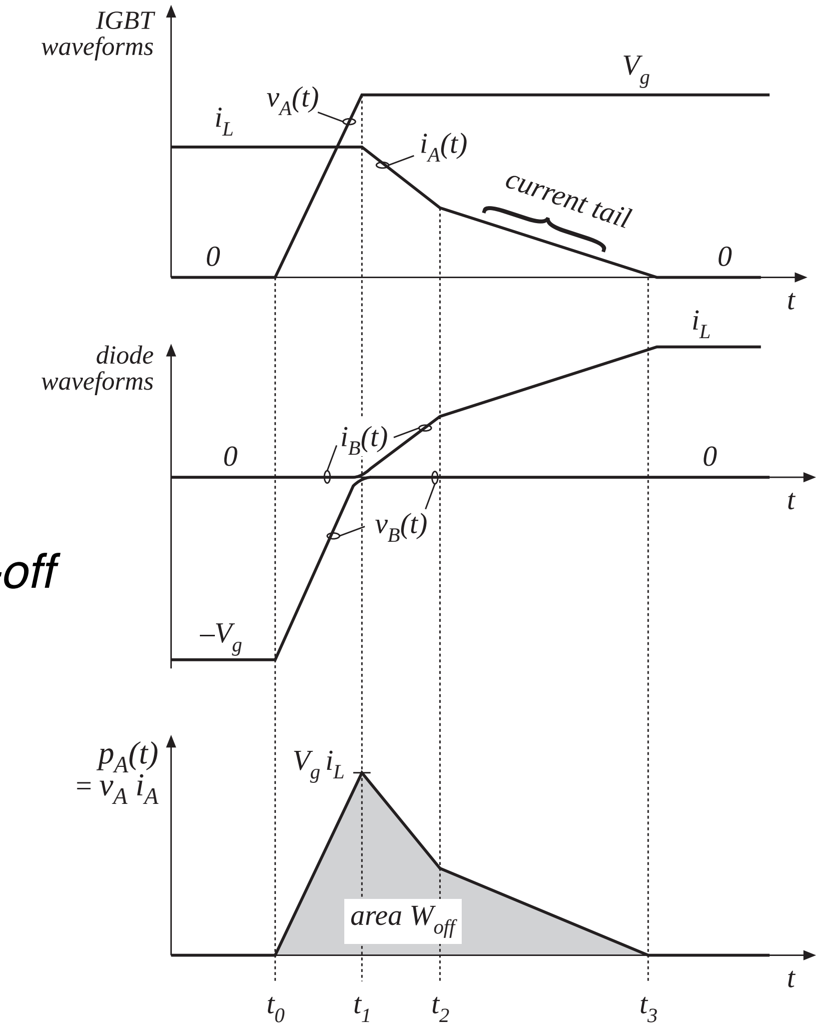




Switching loss due to current-tailing in IGBT



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

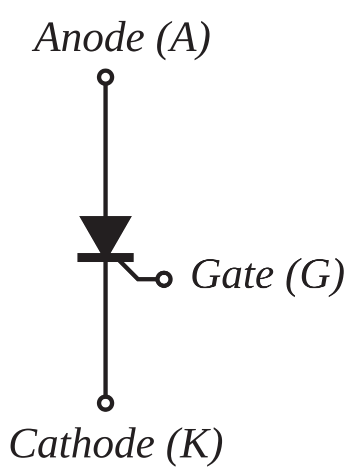
Conclusions: IGBT

- 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

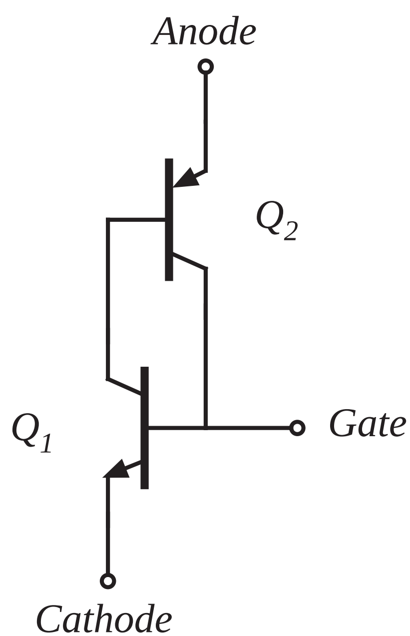
4.2.5. Thyristors (SCR, GTO, MCT)

The SCR

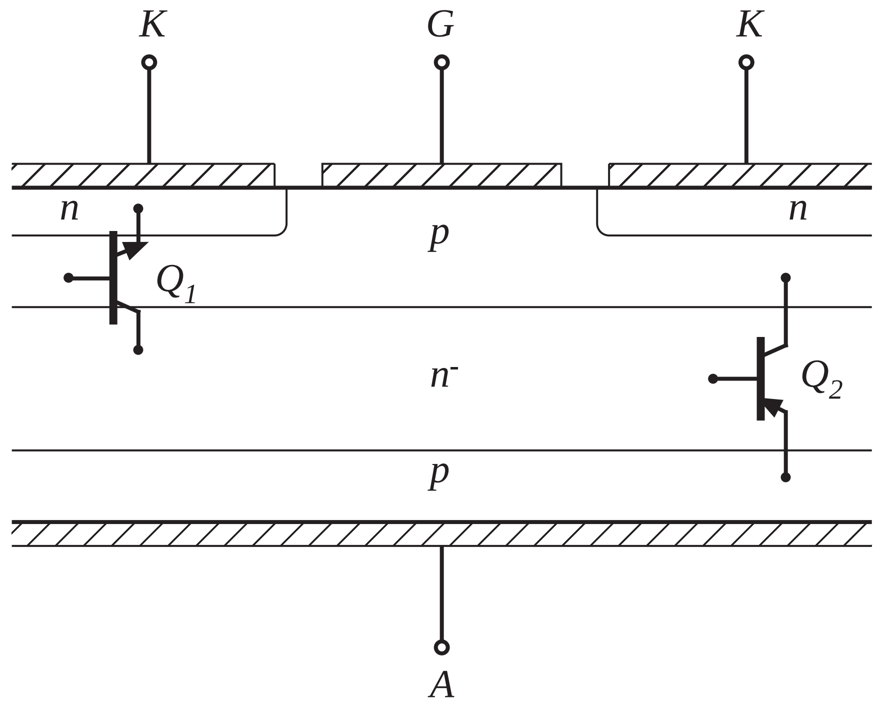
symbol



equiv circuit

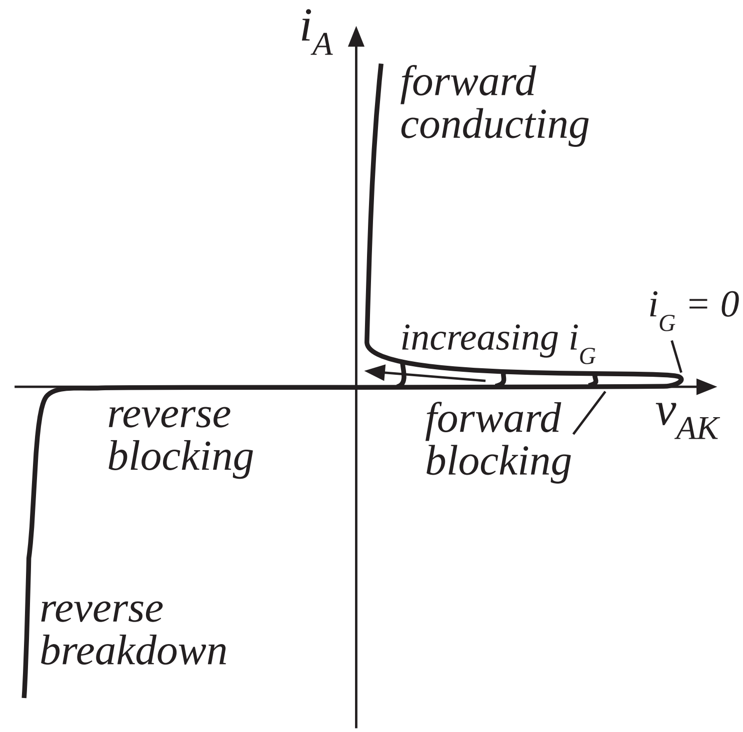


construction



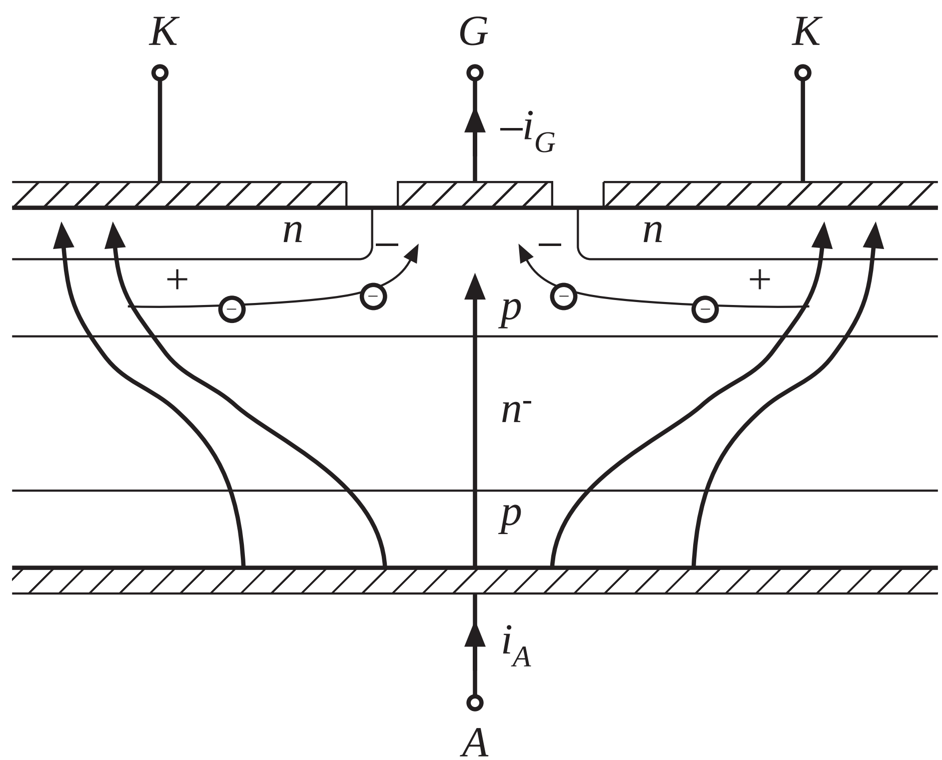
The Silicon Controlled Rectifier (SCR)

- 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



Why the conventional SCR cannot be turned off via gate control

- Large feature size
- Negative gate current induces lateral voltage drop along gate-cathode junction
- Gate-cathode junction becomes reverse-biased only in vicinity of gate contact



The Gate Turn-Off Thyristor (GTO)

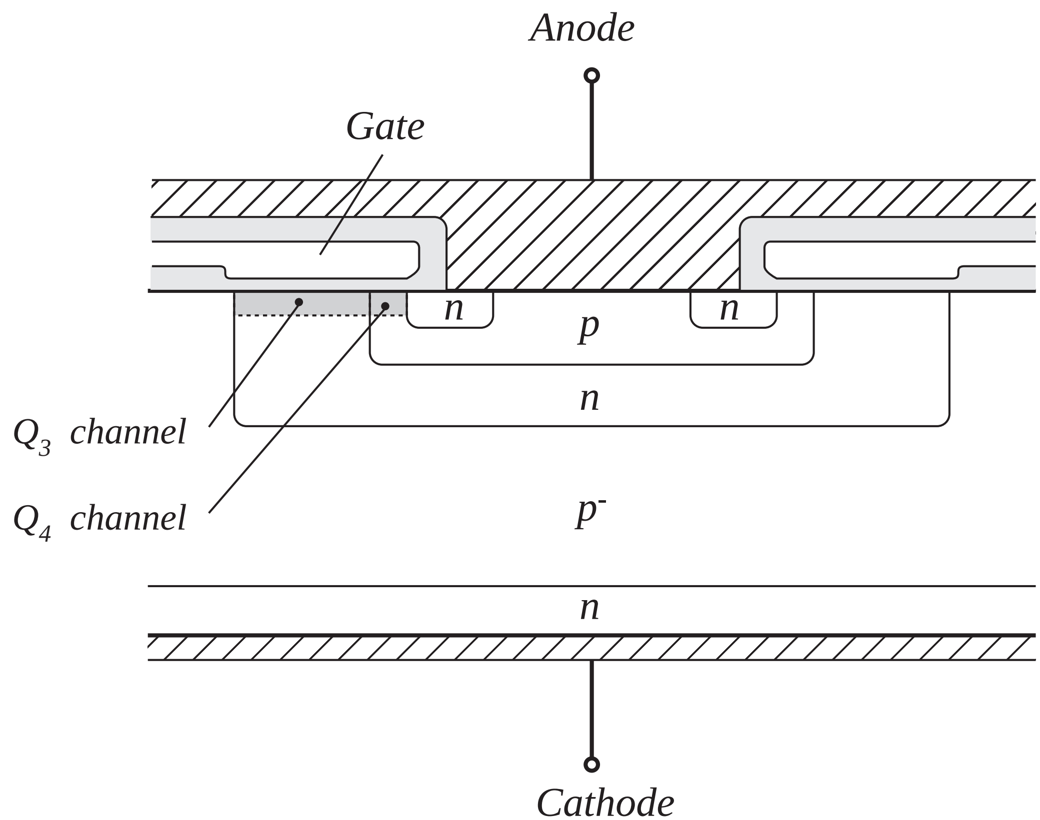
- An SCR fabricated using modern techniques —small feature size
- Gate and cathode contacts are highly interdigitated
- Negative gate current is able to completely reverse-bias the gate-cathode junction

Turn-off transition:

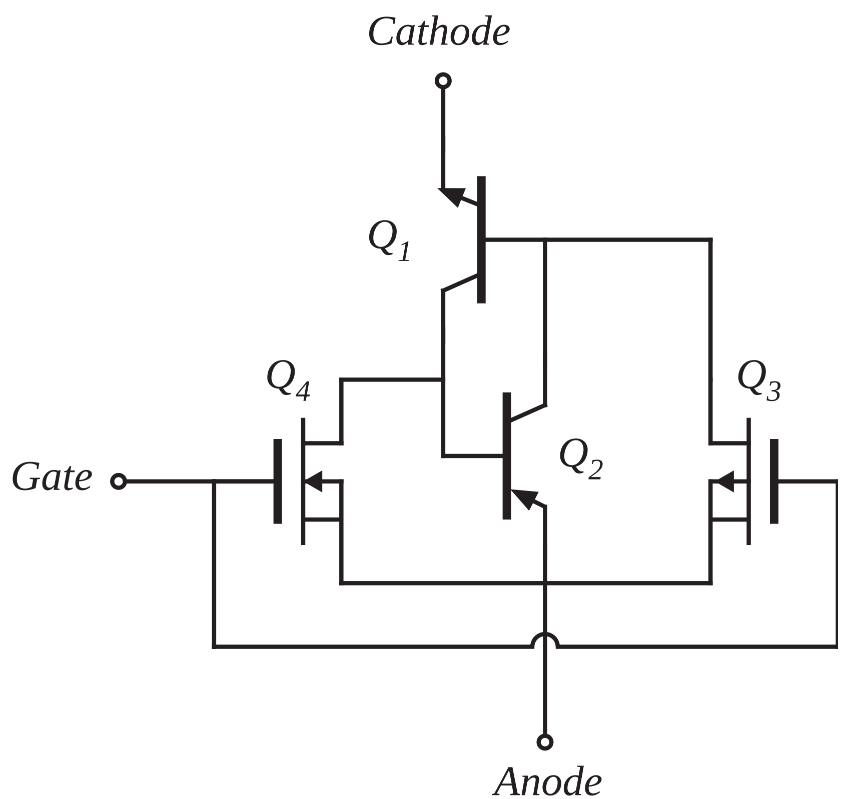
- Turn-off current gain: typically 2-5
- Maximum controllable on-state current: maximum anode current that can be turned off via gate control. GTO can conduct peak currents well in excess of average current rating, but cannot switch off

The MOS-Controlled Thyristor (MCT)

- Still an emerging device, but some devices are commercially available
- p-type device
- A latching SCR, with added built-in MOSFETs to assist the turn-on and turn-off processes
- Small feature size, highly interdigitated, modern fabrication



The MCT: equivalent circuit



- Negative gate-anode voltage turns p-channel MOSFET Q_3 on, causing Q_1 and Q_2 to latch ON
- Positive gate-anode voltage turns n-channel MOSFET Q_4 on, reverse-biasing the base-emitter junction of Q_2 and turning off the device
- Maximum current that can be interrupted is limited by the on-resistance of Q_4

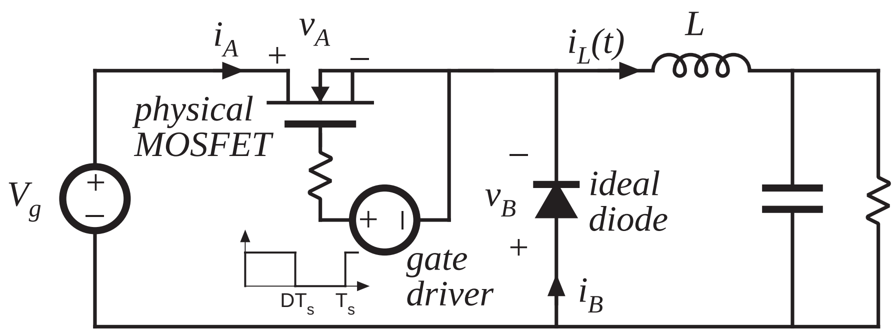
Summary: Thyristors

- The thyristor family: double injection yields lowest forward voltage drop in high voltage devices. More difficult to parallel than MOSFETs and IGBTs
- The SCR: highest voltage and current ratings, low cost, passive turn-off transition
- The GTO: intermediate ratings (less than SCR, somewhat more than IGBT). Slower than IGBT. Slower than MCT. Difficult to drive.
- The MCT: So far, ratings lower than IGBT. Slower than IGBT. Easy to drive. Second breakdown problems? Still an emerging device.

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

4.3.1. Transistor switching with clamped inductive load

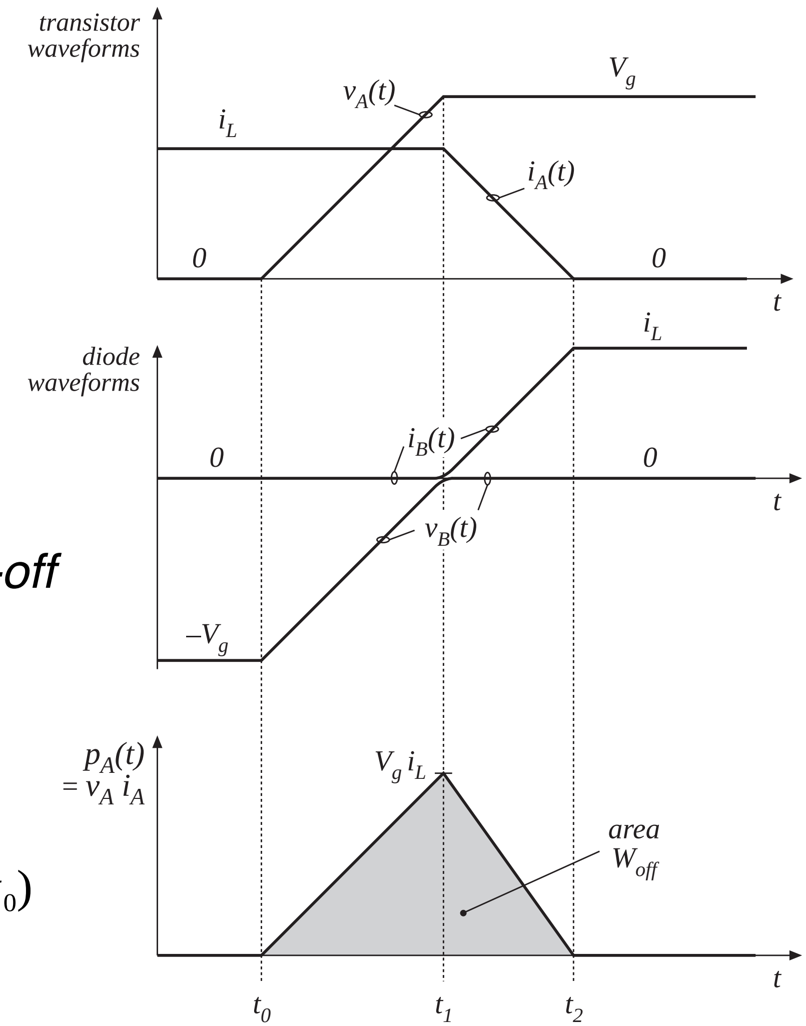


Buck converter example

$$v_B(t) = v_A(t) - V_g$$
$$i_A(t) + i_B(t) = i_L$$

transistor turn-off transition

$$W_{off} = \frac{1}{2} V_g i_L \, (t_2 - t_0)$$



Switching loss induced by transistor turn-off transition

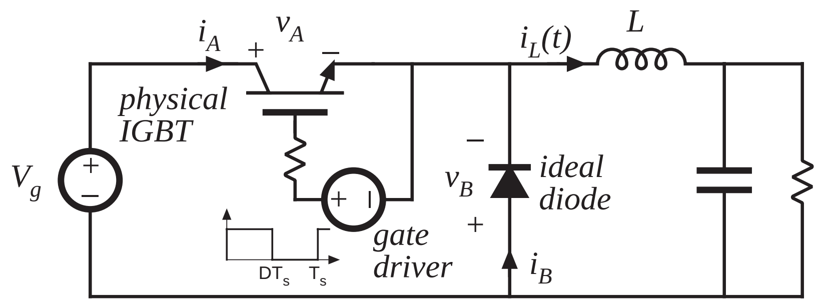
Energy lost during transistor turn-off transition:

$$W_{off} = \frac{1}{2} V_g i_L \, (t_2 - t_0)$$

Similar result during transistor turn-on transition.
Average power loss:

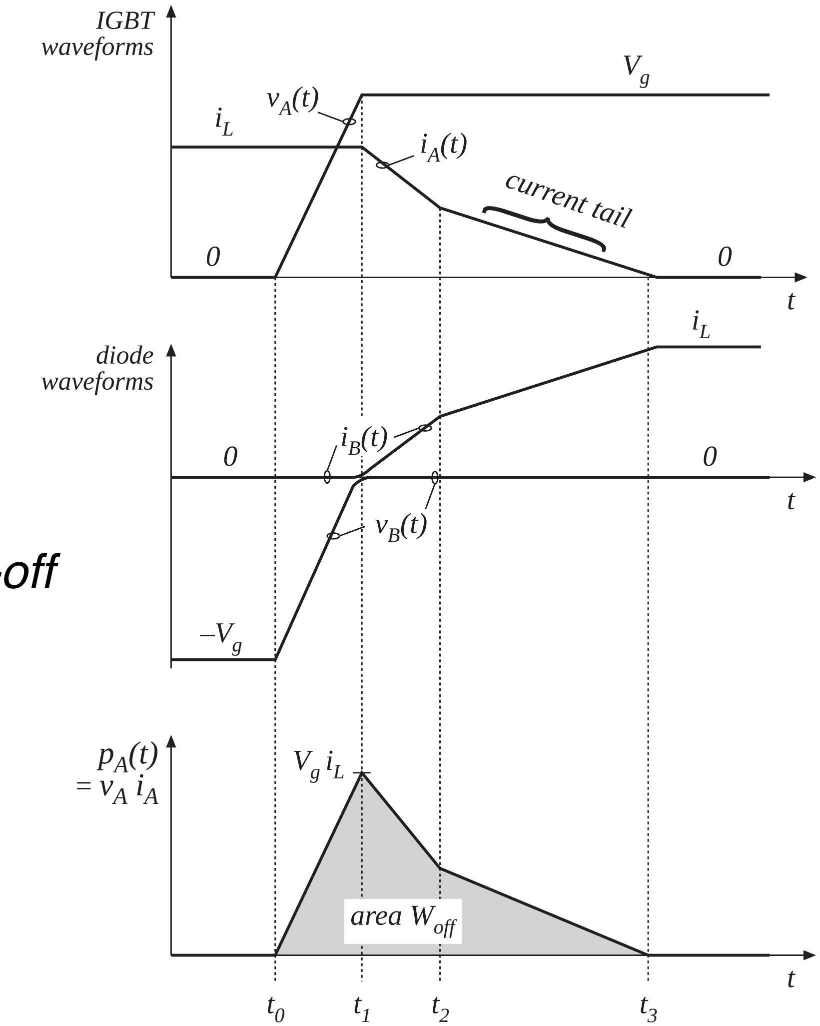
$$P_{sw} = \frac{1}{T_s} \int_{\substack{\textit{switching} \\ \textit{transitions}}} p_A(t)\, dt = (W_{on} + W_{off})\, f_s$$

Switching loss due to current-tailing in IGBT



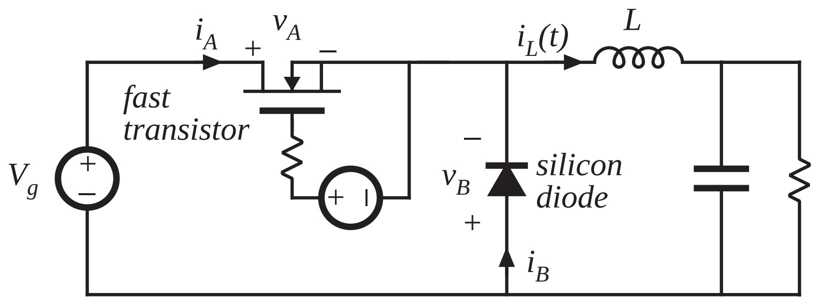
Example: buck converter with IGBT

transistor turn-off transition

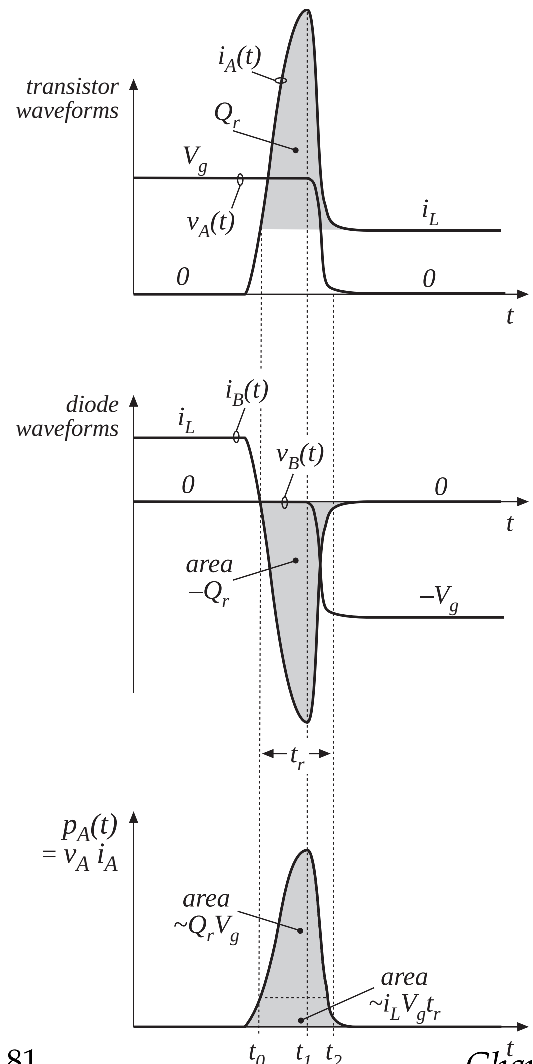


$$P_{sw} = \frac{1}{T_s} \int_{\substack{\text{switching}\\ \text{transitions}}} p_A(t)\, dt = (W_{on} + W_{off})\, f_s$$

4.3.2. Diode recovered charge



- 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



Switching loss calculation

Energy lost in transistor:

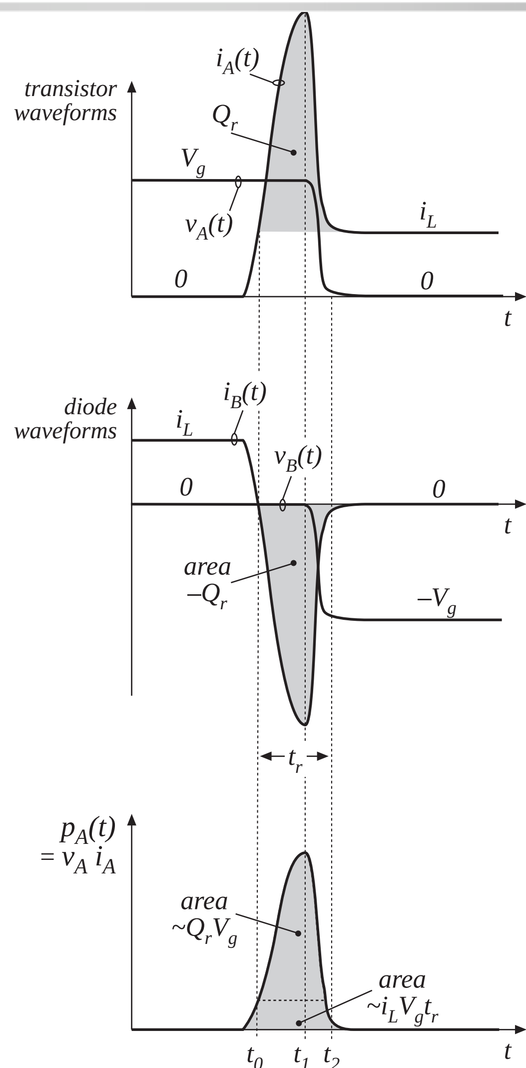
$$W_D = \int_{\substack{\text{switching}\\ \text{transition}}} v_A(t)\, i_A(t)\, dt$$

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:

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

4.3.3. Device capacitances, and leakage, package, and stray inductances

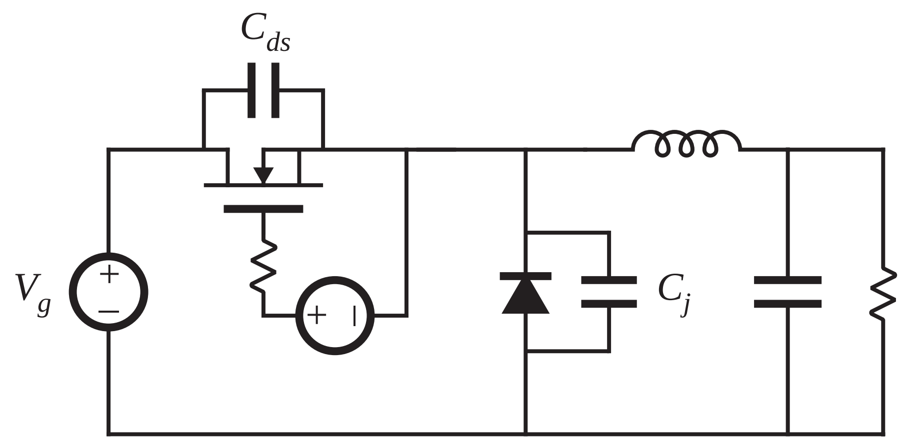
- Capacitances that appear effectively in parallel with switch elements are shorted when the switch turns on. Their stored energy is lost during the switch turn-on transition.
- Inductances that appear effectively in series with switch elements are open-circuited when the switch turns off. Their stored energy is lost during the switch turn-off transition.

Total energy stored in linear capacitive and inductive elements:

$$W_C = \sum_{\substack{\text{capacitive} \\ \text{elements}}} \tfrac{1}{2} C_i V_i^2 \qquad W_L = \sum_{\substack{\text{inductive} \\ \text{elements}}} \tfrac{1}{2} L_j I_j^2$$

Example: 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} :

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

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 $\tfrac{4}{3}\, C_{ds}(V_{DS})$

Some other sources of this type of switching loss

Schottky diode

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

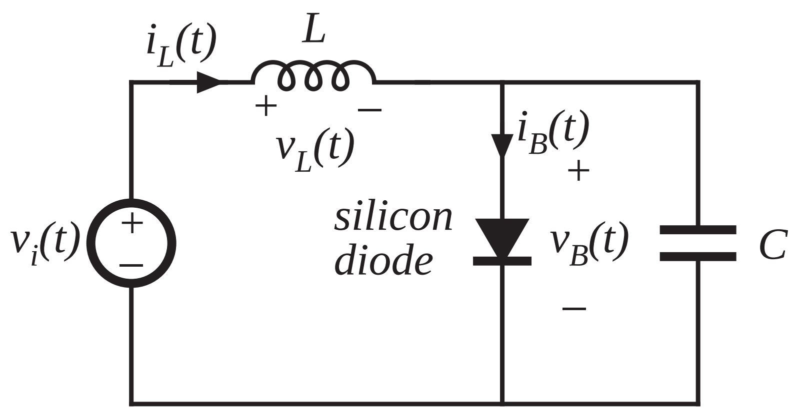
Transformer leakage inductance

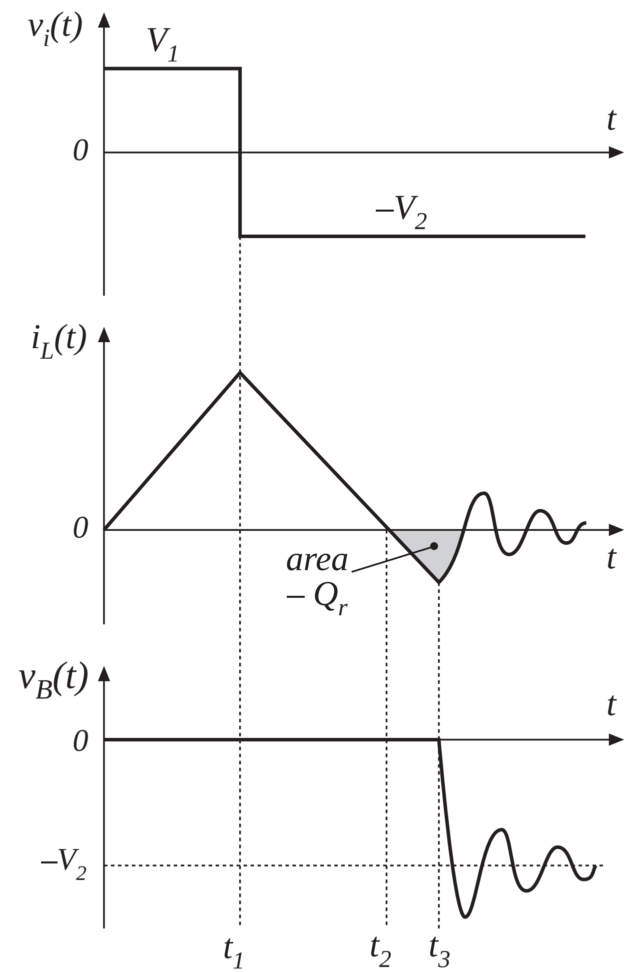
- Effective inductances in series with windings
- A significant loss when windings are not tightly coupled

Interconnection and package inductances

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

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.

Energy associated with ringing

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

Energy stored in inductor during interval $t_2 \le t \le t_3$:

$$W_L = \int_{t_2}^{t_3} v_L(t)\, i_L(t)\, dt$$

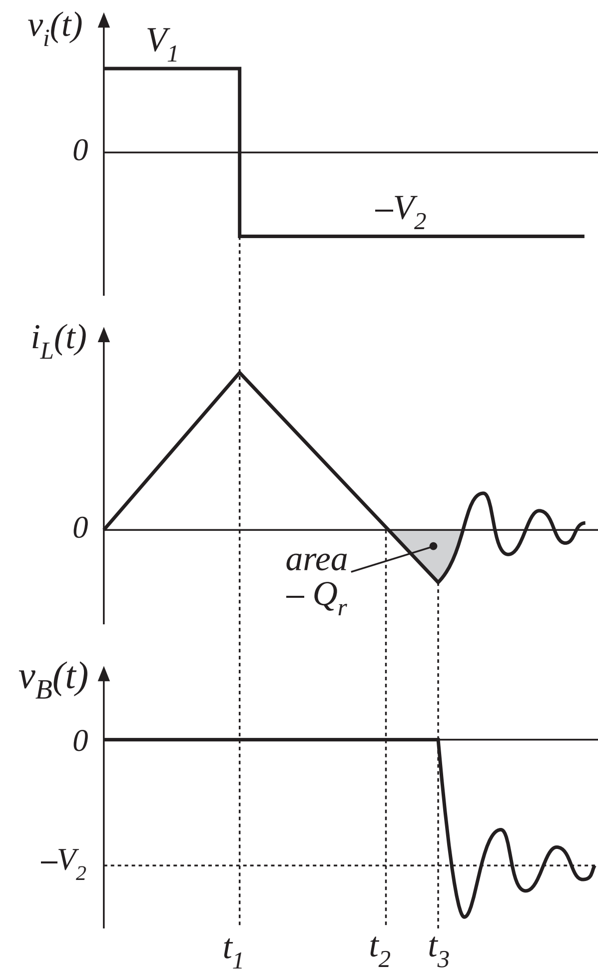
Applied inductor voltage during interval $t_2 \le t \le t_3$:

$$v_L(t) = L\,\frac{di_L(t)}{dt} = -V_2$$

Hence,

$$W_L = \int_{t_2}^{t_3} L\,\frac{di_L(t)}{dt}\, i_L(t)\, dt = \int_{t_2}^{t_3} (-V_2)\, i_L(t)\, dt$$

$$W_L = \tfrac{1}{2} L\, i_L^2(t_3) = V_2\, Q_r$$



4.3.4. Efficiency vs. switching frequency

Add up all of the energies lost during the switching transitions of one switching period:

$$W_{tot} = W_{on} + W_{off} + W_D + W_C + W_L + \ldots$$

Average switching power loss is

$$P_{sw} = W_{tot}\, f_{sw}$$

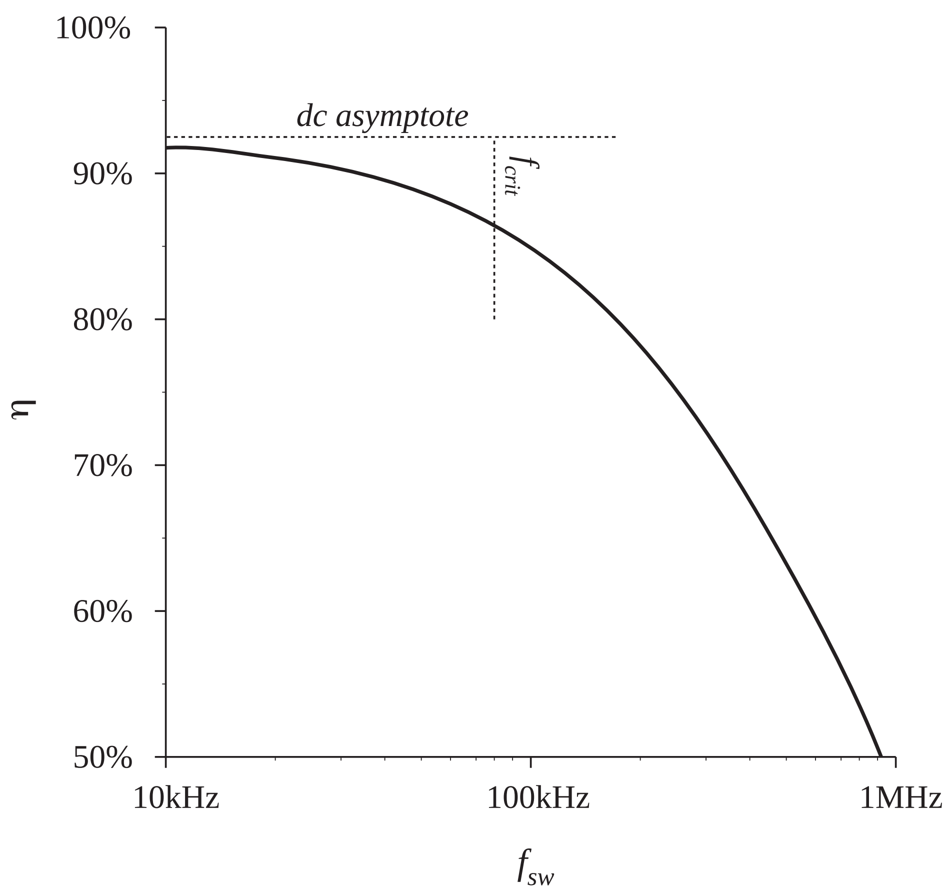
Total converter loss can be expressed as

$$P_{loss} = P_{cond} + P_{fixed} + W_{tot}\, f_{sw}$$

where P_{fixed} = fixed losses (independent of load and f_{sw})
P_{cond} = conduction losses

Efficiency vs. switching frequency

$$P_{loss} = P_{cond} + P_{fixed} + W_{tot}\, f_{sw}$$



Switching losses are equal to the other converter losses at the critical frequency

$$f_{crit} = \frac{P_{cond} + P_{fixed}}{W_{tot}}$$

This can be taken as a rough upper limit on the switching frequency of a practical converter. For $f_{sw} > f_{crit}$, the efficiency decreases rapidly with frequency.

Summary of chapter 4

1. How an SPST ideal switch can be realized using semiconductor devices depends on the polarity of the voltage which the devices must block in the off-state, and on the polarity of the current which the devices must conduct in the on-state.
2. Single-quadrant SPST switches can be realized using a single transistor or a single diode, depending on the relative polarities of the off-state voltage and on-state current.
3. Two-quadrant SPST switches can be realized using a transistor and diode, connected in series (bidirectional-voltage) or in anti-parallel (bidirectional-current). Several four-quadrant schemes are also listed here.
4. A "synchronous rectifier" is a MOSFET connected to conduct reverse current, with gate drive control as necessary. This device can be used where a diode would otherwise be required. If a MOSFET with sufficiently low R_{on} is used, reduced conduction loss is obtained.

Summary of chapter 4

5. Majority carrier devices, including the MOSFET and Schottky diode, exhibit very fast switching times, controlled essentially by the charging of the device capacitances. However, the forward voltage drops of these devices increases quickly with increasing breakdown voltage.
6. Minority carrier devices, including the BJT, IGBT, and thyristor family, can exhibit high breakdown voltages with relatively low forward voltage drop. However, the switching times of these devices are longer, and are controlled by the times needed to insert or remove stored minority charge.
7. Energy is lost during switching transitions, due to a variety of mechanisms. The resulting average power loss, or switching loss, is equal to this energy loss multiplied by the switching frequency. Switching loss imposes an upper limit on the switching frequencies of practical converters.

Summary of chapter 4

8. The diode and inductor present a “clamped inductive load” to the transistor. When a transistor drives such a load, it experiences high instantaneous power loss during the switching transitions. An example where this leads to significant switching loss is the IGBT and the “current tail” observed during its turn-off transition.
9. Other significant sources of switching loss include diode stored charge and energy stored in certain parasitic capacitances and inductances. Parasitic ringing also indicates the presence of switching loss.