

# Chapter 4. Switch Realization

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## 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

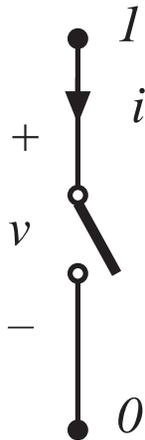
## 4.3. Switching loss

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

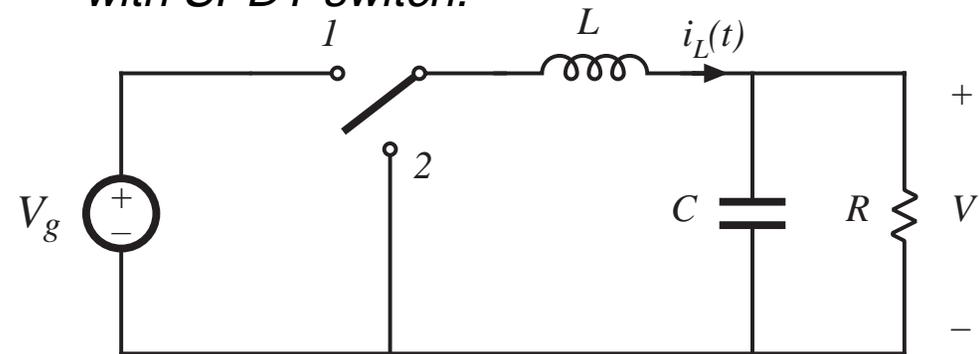
*SPST switch, with voltage and current polarities defined*



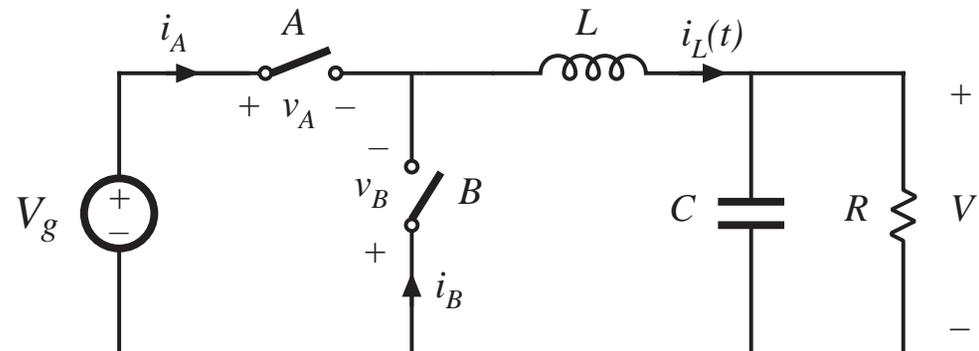
*All power semiconductor devices function as SPST switches.*

## Buck converter

*with SPDT switch:*



*with two SPST switches:*

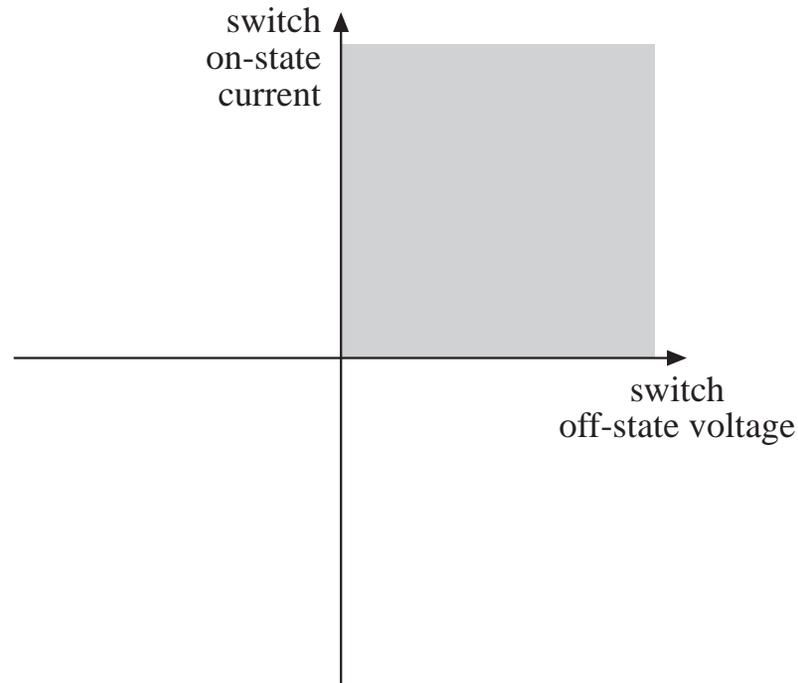
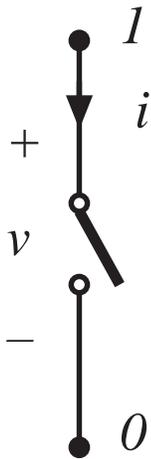


# Realization of SPDT switch using two SPST switches

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- 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 (ch. 5)
- Conducting state of SPST switch may depend on applied voltage or current —for example: diode

# Quadrants of SPST switch operation

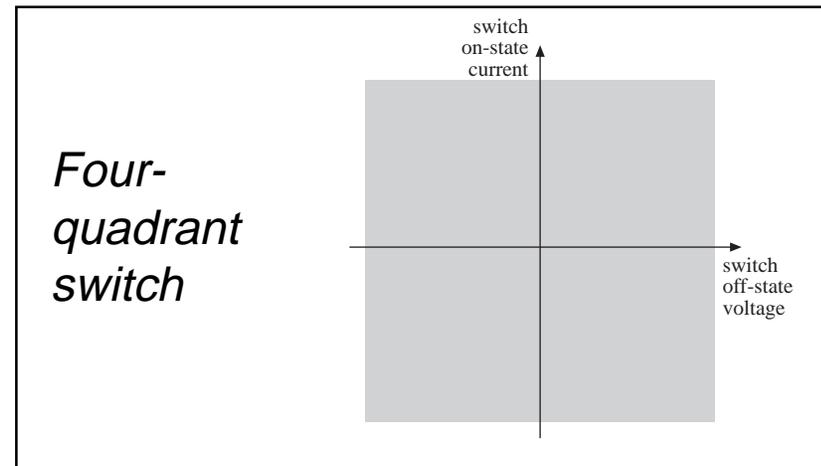
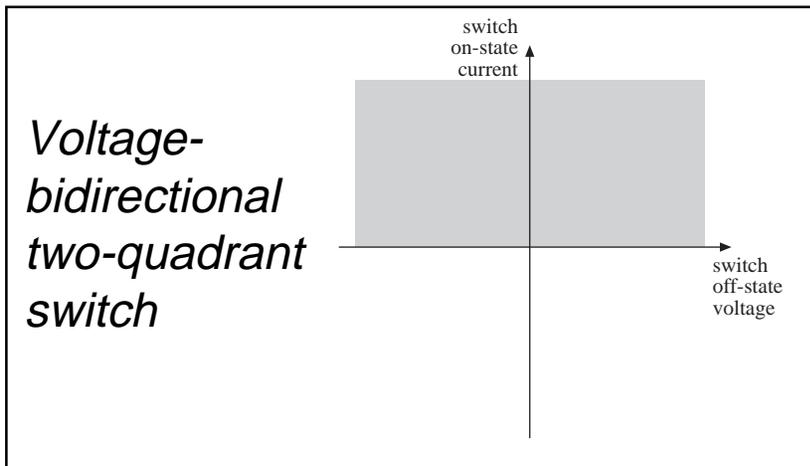
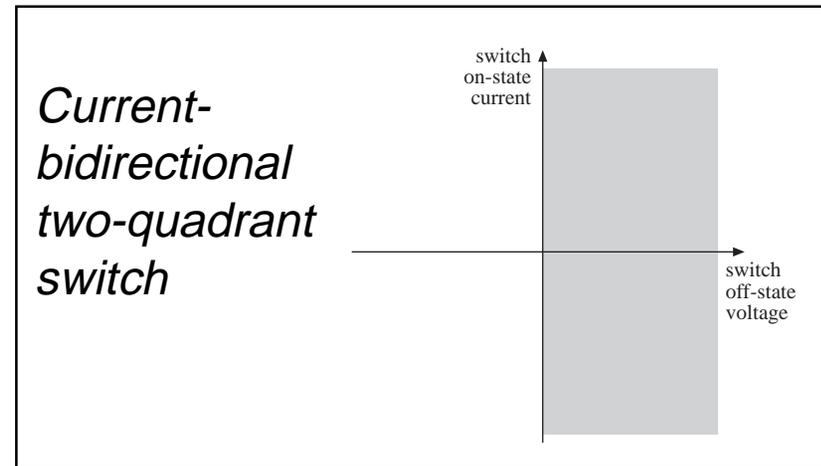
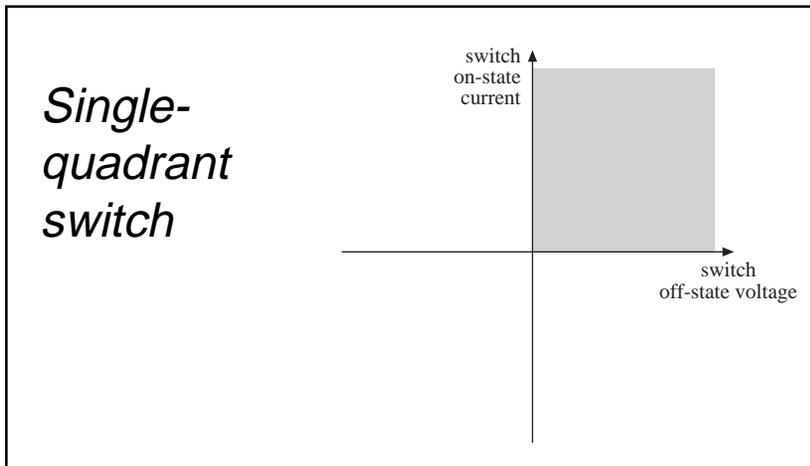


A single-quadrant switch example:

*ON-state:  $i > 0$*

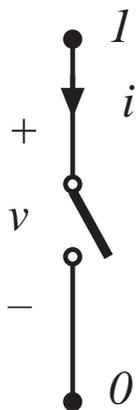
*OFF-state:  $v > 0$*

# Some basic switch applications



## 4.1.1. Single-quadrant switches

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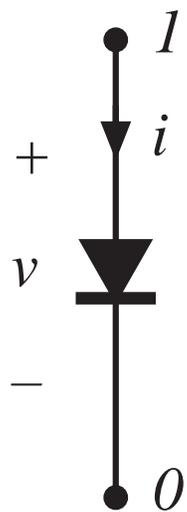
**Active switch:** Switch state is controlled exclusively by a third terminal (control terminal).

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

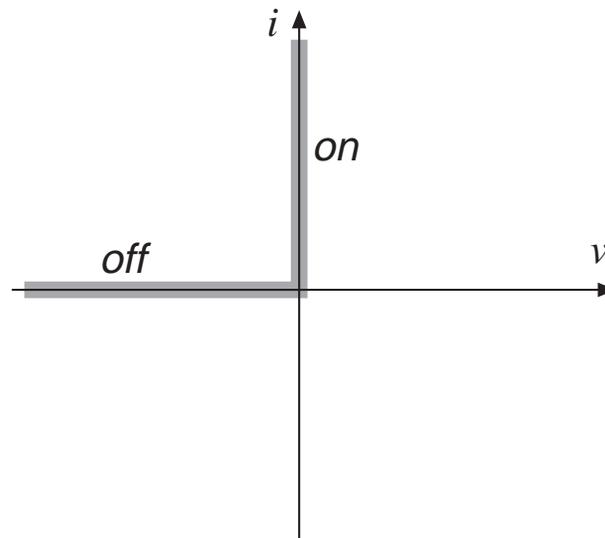
**SCR:** A special case — turn-on transition is active, while turn-off transition is passive.

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

# The diode



Symbol

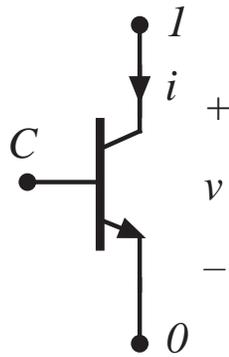


instantaneous  $i$ - $v$  characteristic

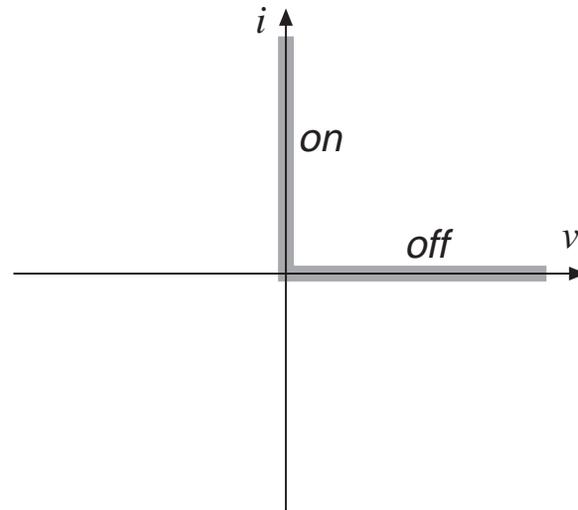
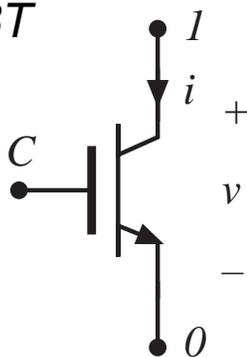
- *A passive switch*
- *Single-quadrant switch:*
- *can conduct positive on-state current*
- *can block negative off-state voltage*
- *provided that the intended on-state and off-state operating points lie on the diode  $i$ - $v$  characteristic, then switch can be realized using a diode*

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

BJT



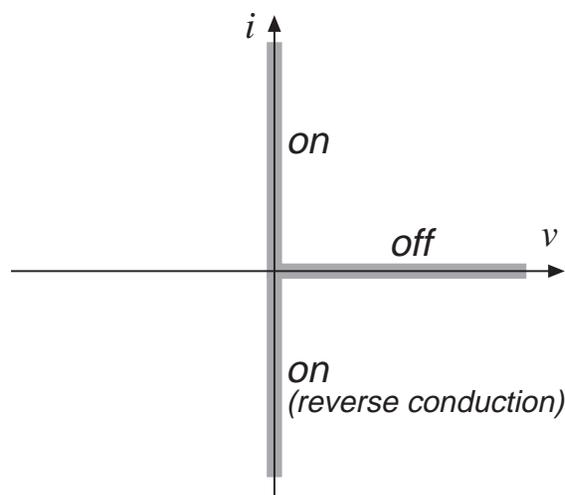
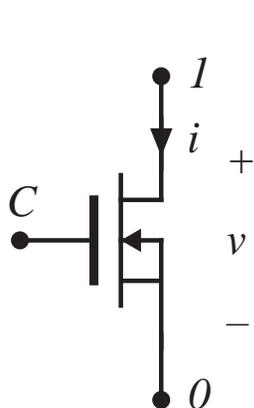
IGBT



*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)



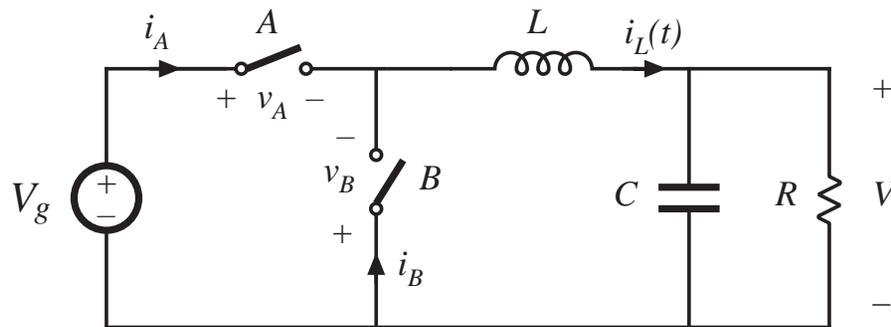
Symbol

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*

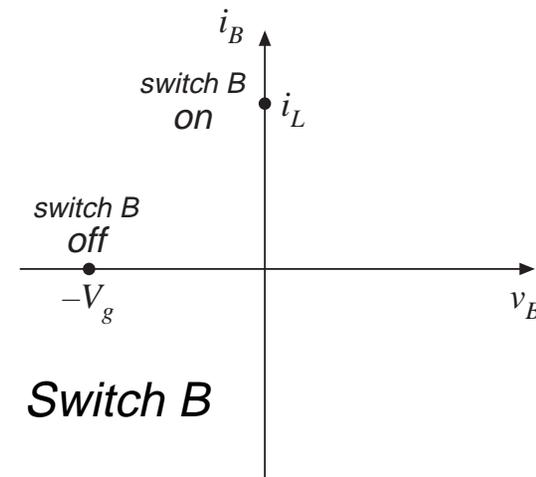
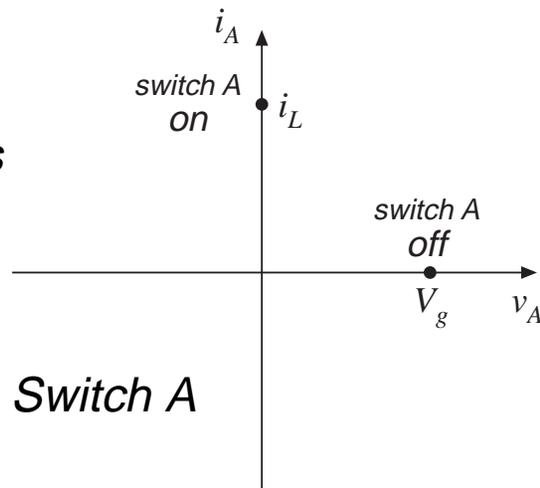
# Realization of switch using transistors and diodes

*Buck converter example*

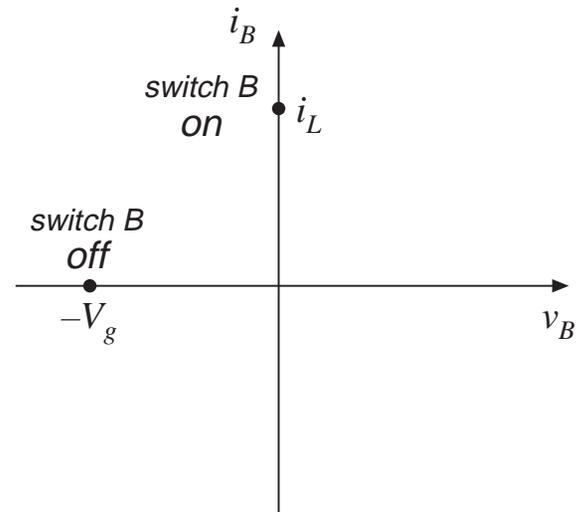
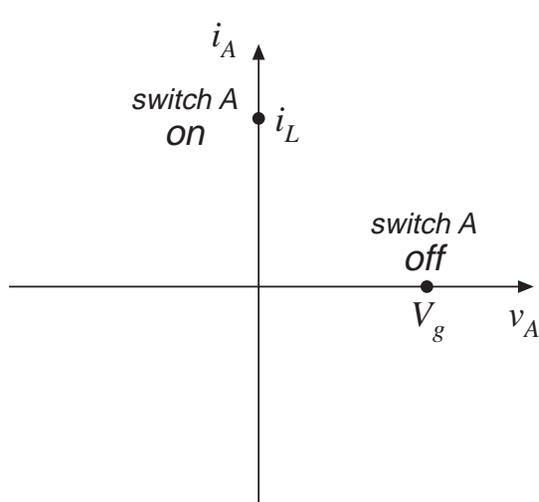
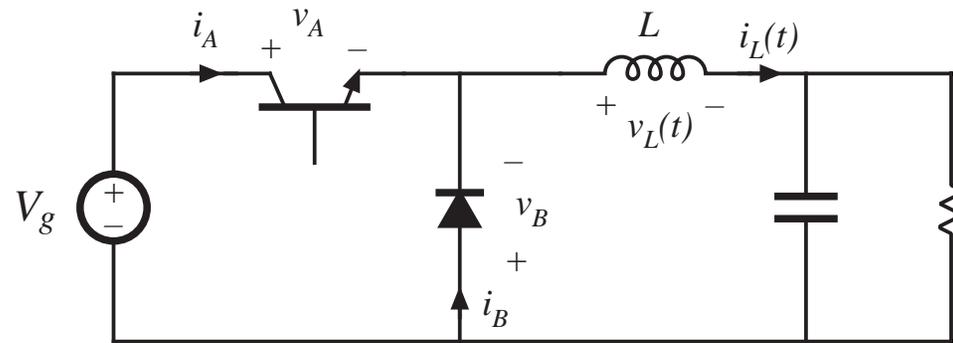


*Switch A: transistor*  
*Switch B: diode*

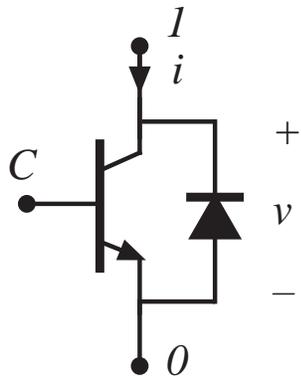
*SPST switch operating points*



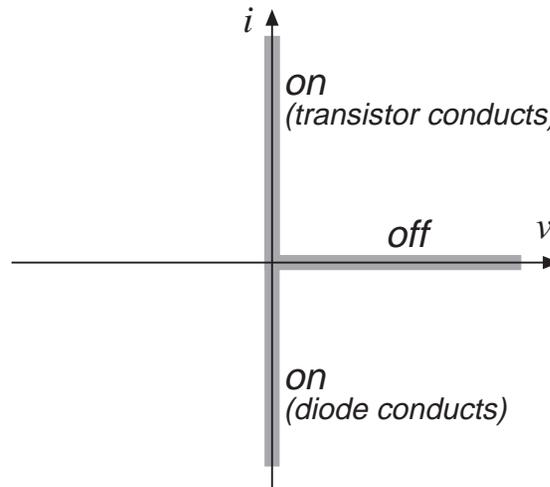
# Realization of buck converter using single-quadrant switches



## 4.1.2. Current-bidirectional two-quadrant switches



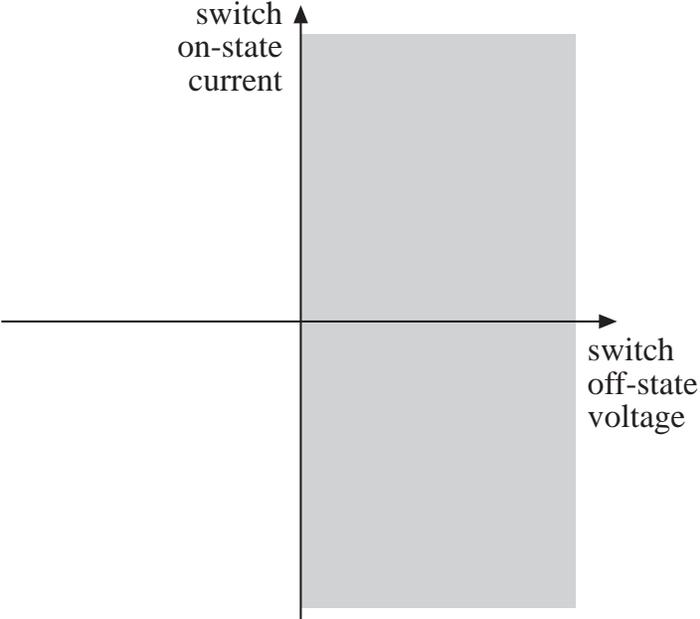
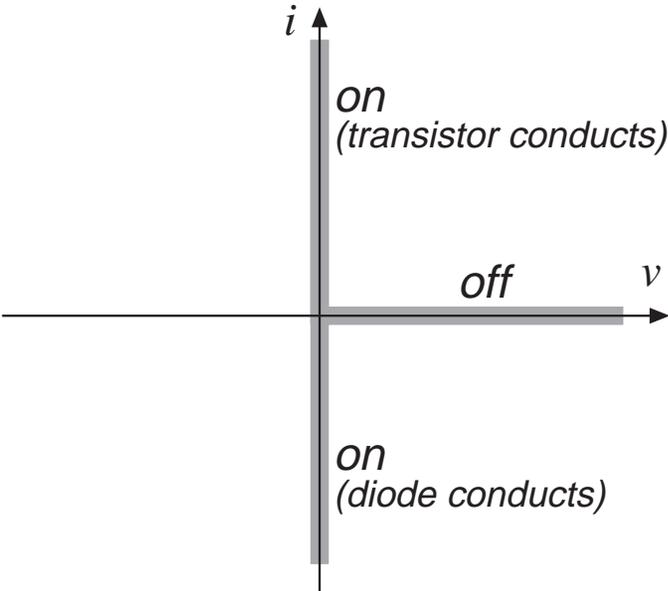
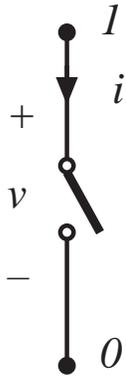
*BJT / anti-parallel diode realization*



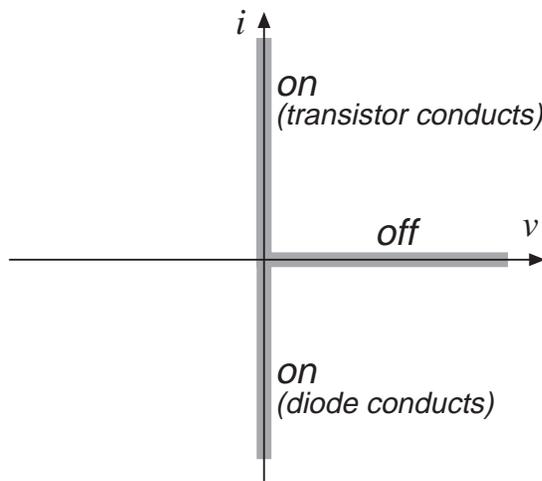
*instantaneous  $i$ - $v$  characteristic*

- *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*

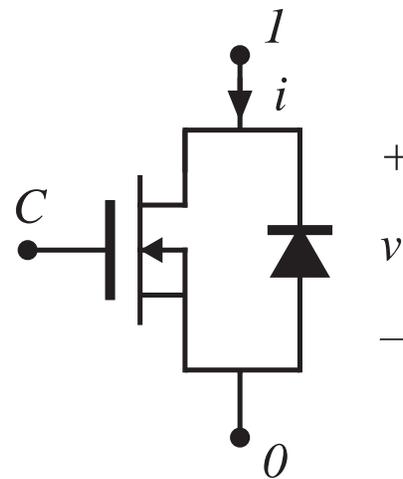
# Two quadrant switches



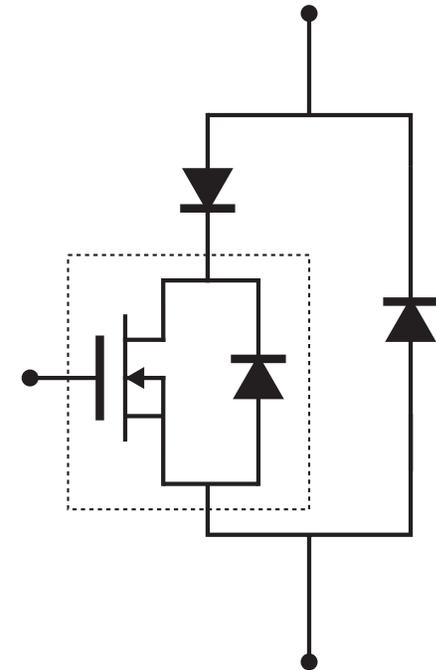
# MOSFET body diode



*Power MOSFET characteristics*

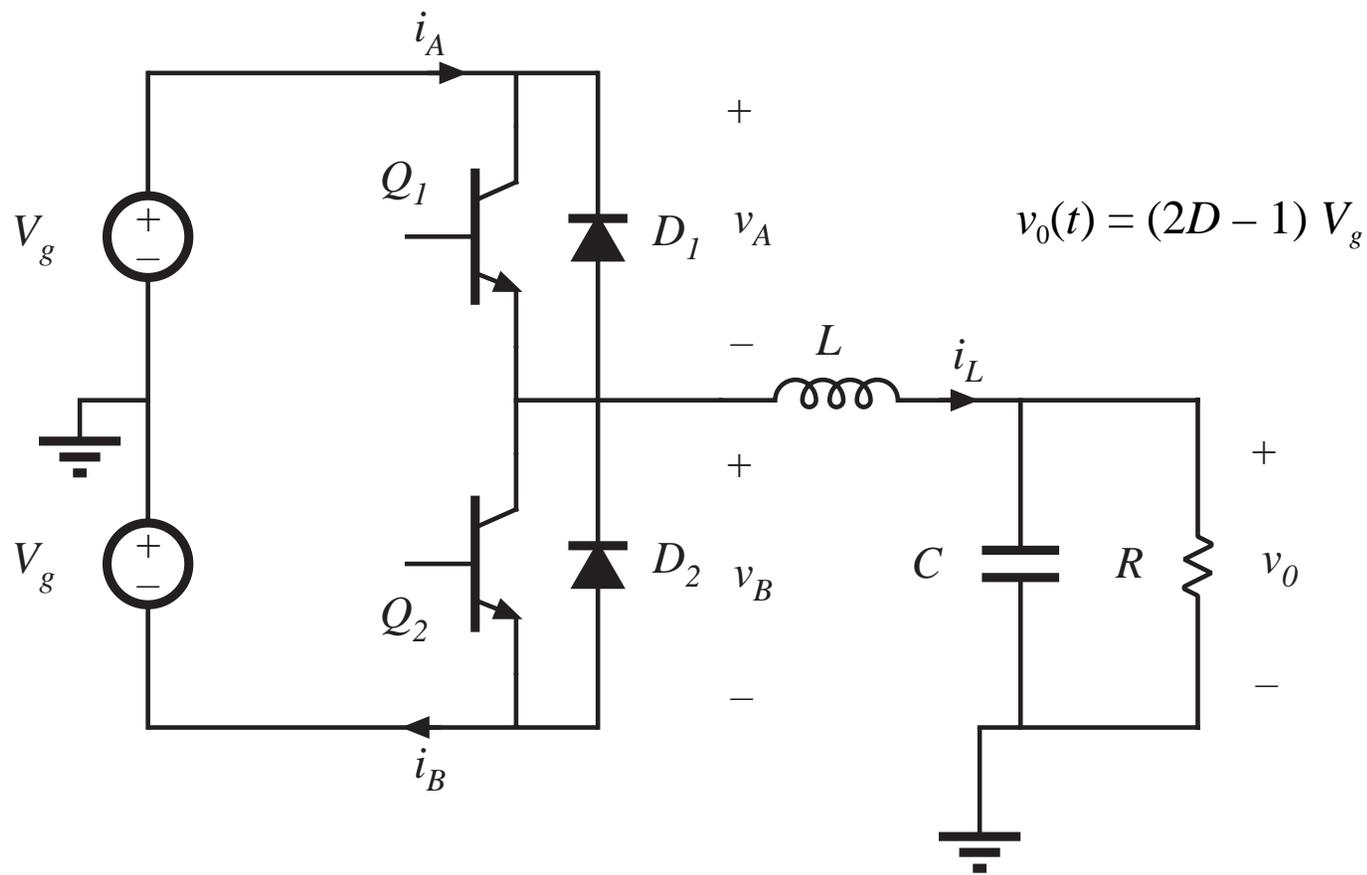


*Power MOSFET, and its integral body diode*



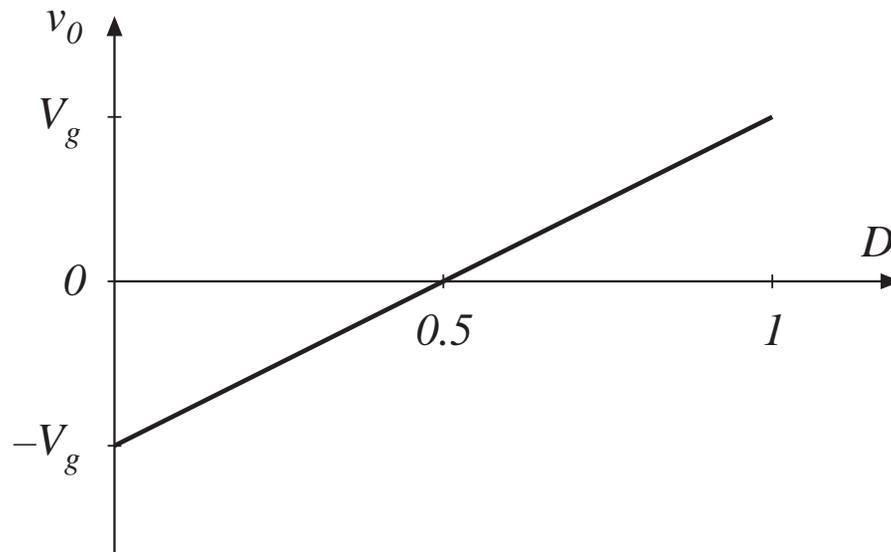
*Use of external diodes to prevent conduction of body diode*

# A simple inverter



# Inverter: sinusoidal modulation of $D$

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



Sinusoidal modulation to produce ac output:

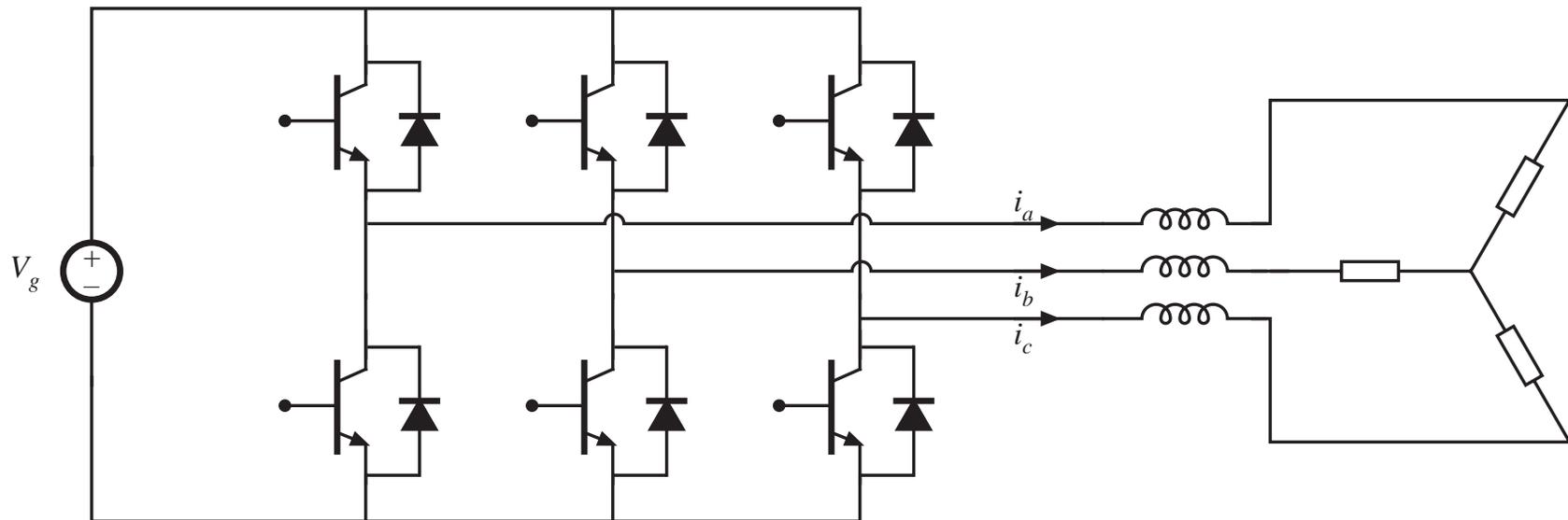
$$D(t) = 0.5 + D_m \sin(\omega t)$$

The resulting inductor current variation is also sinusoidal:

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

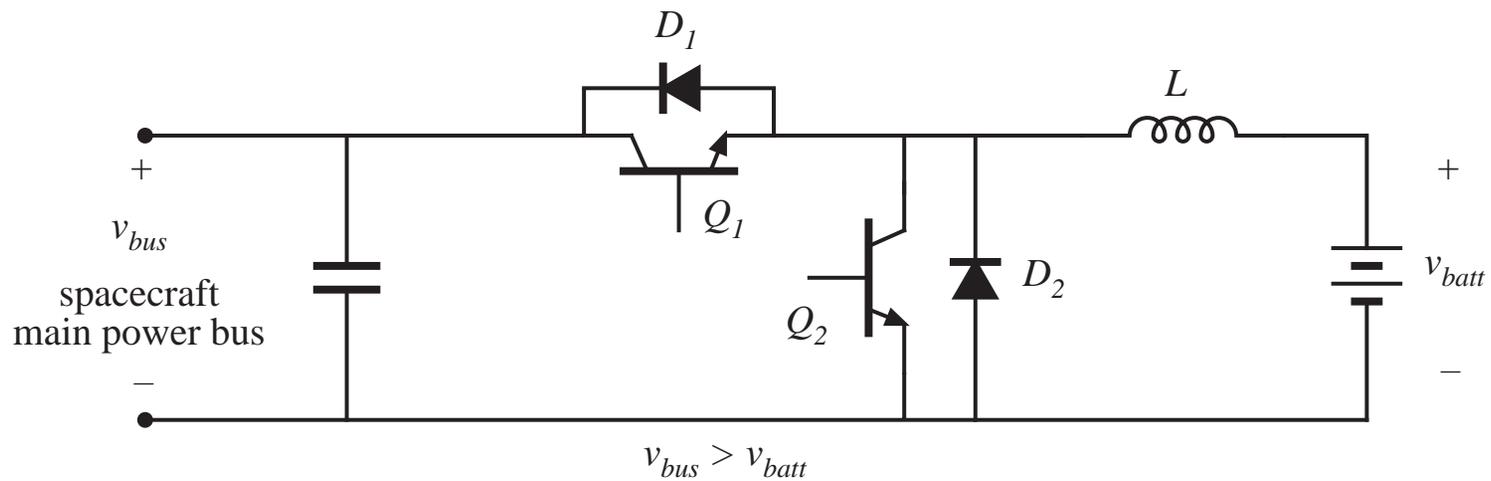
Hence, current-bidirectional two-quadrant switches are required.

# The dc-3 $\phi$ ac voltage source inverter (VSI)



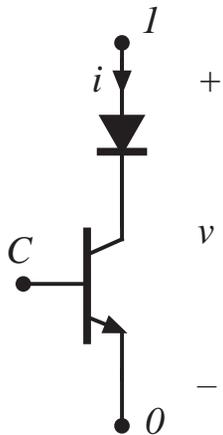
Switches must block dc input voltage, and conduct ac load current.

# Bidirectional battery charger/discharger

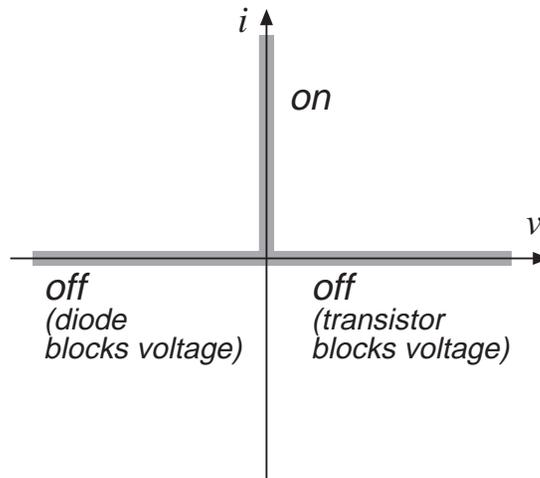


A dc-dc converter with bidirectional power flow.

## 4.1.3. Voltage-bidirectional two-quadrant switches



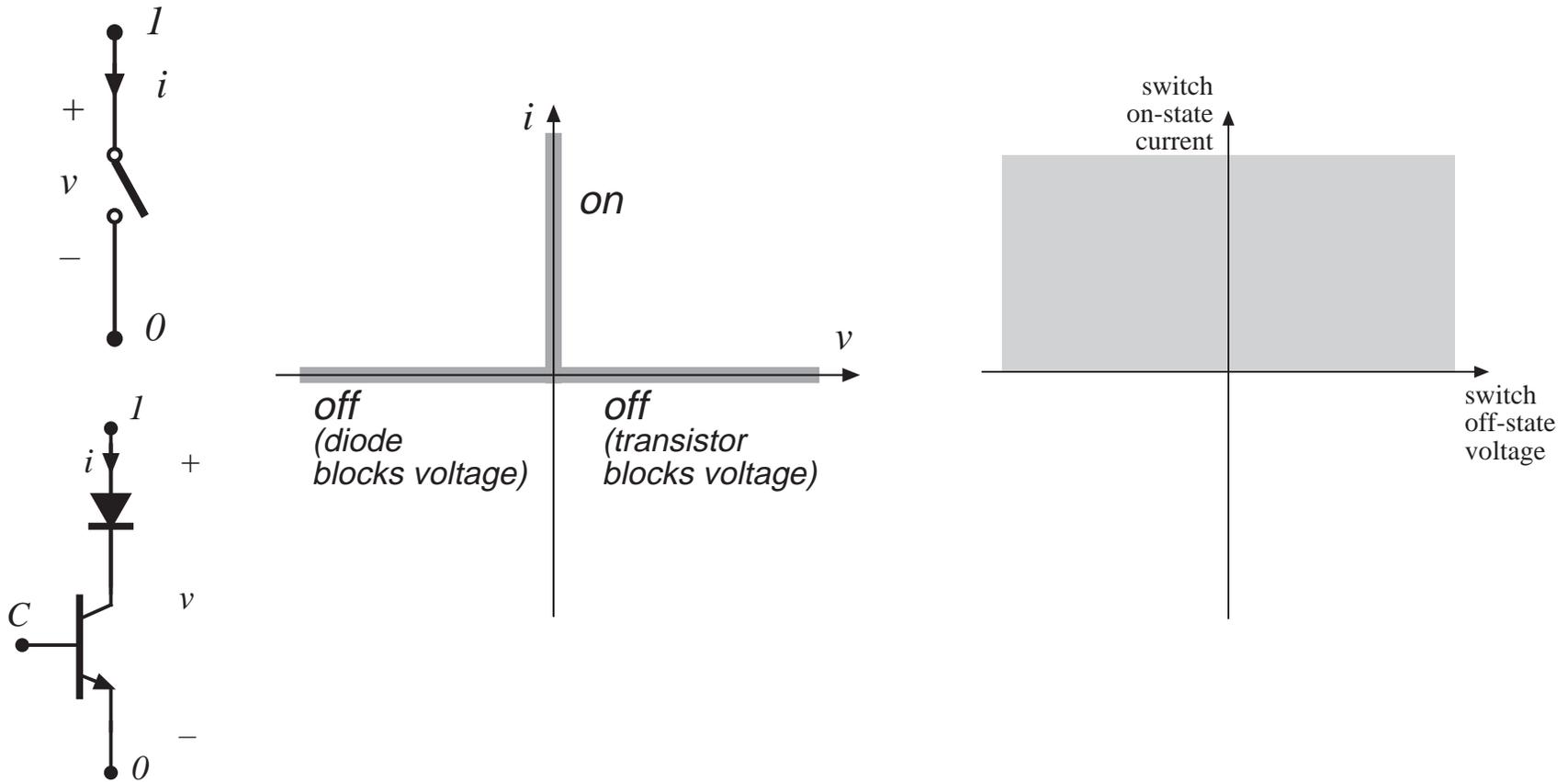
*BJT / series  
diode realization*



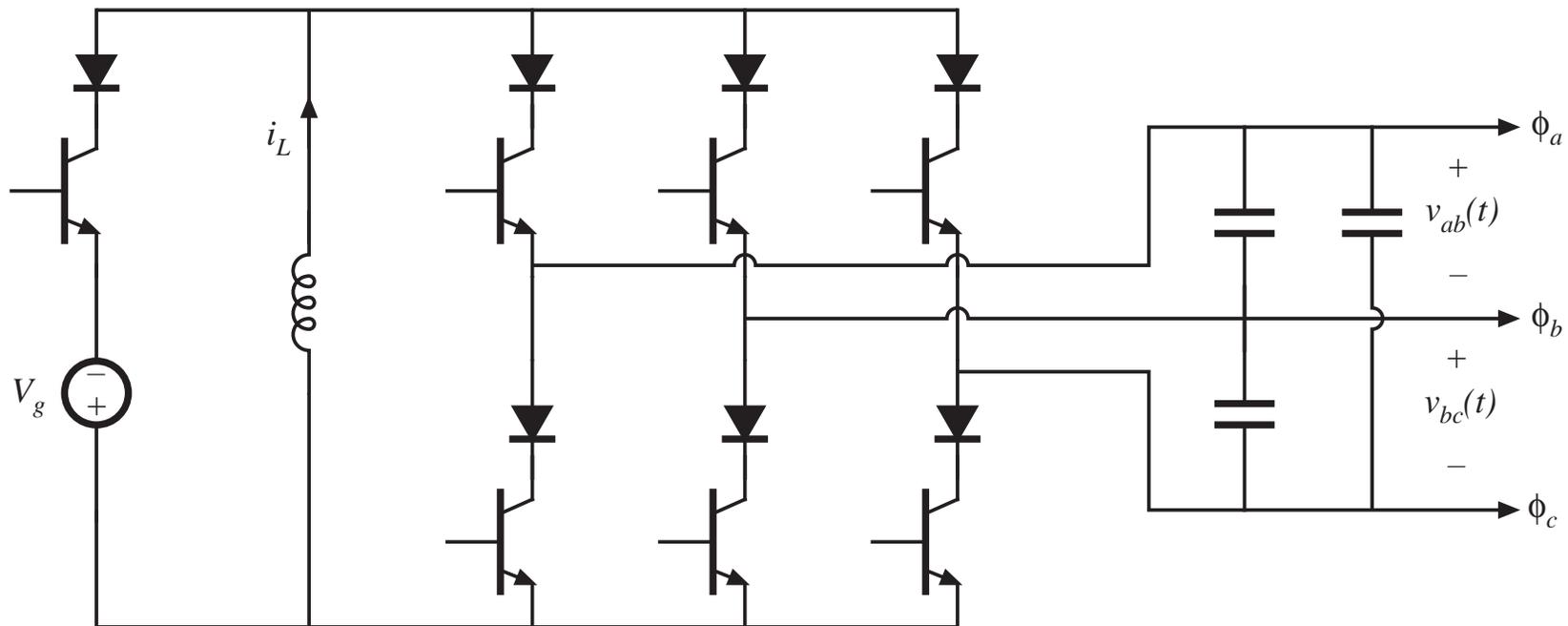
*instantaneous  $i$ - $v$   
characteristic*

- *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-3 $\phi$ ac buck-boost inverter

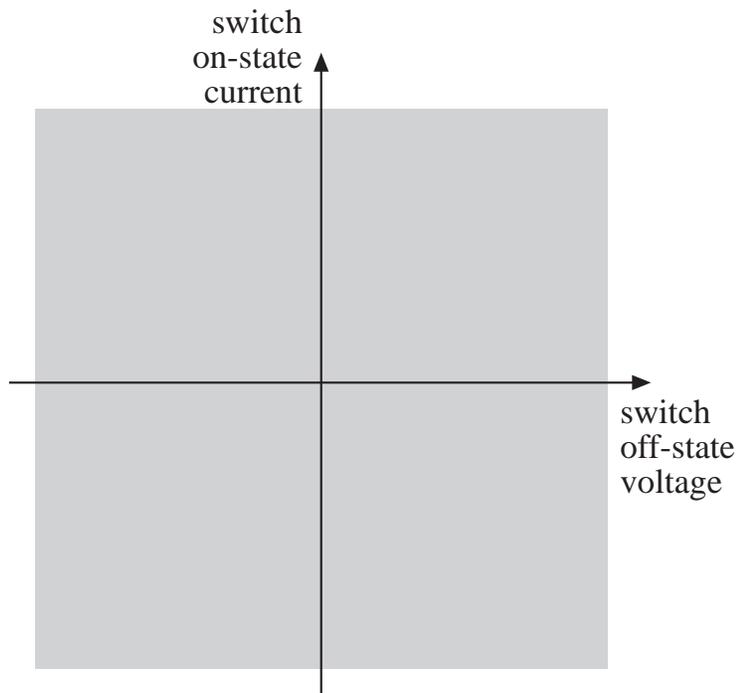


Requires voltage-bidirectional two-quadrant switches.

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

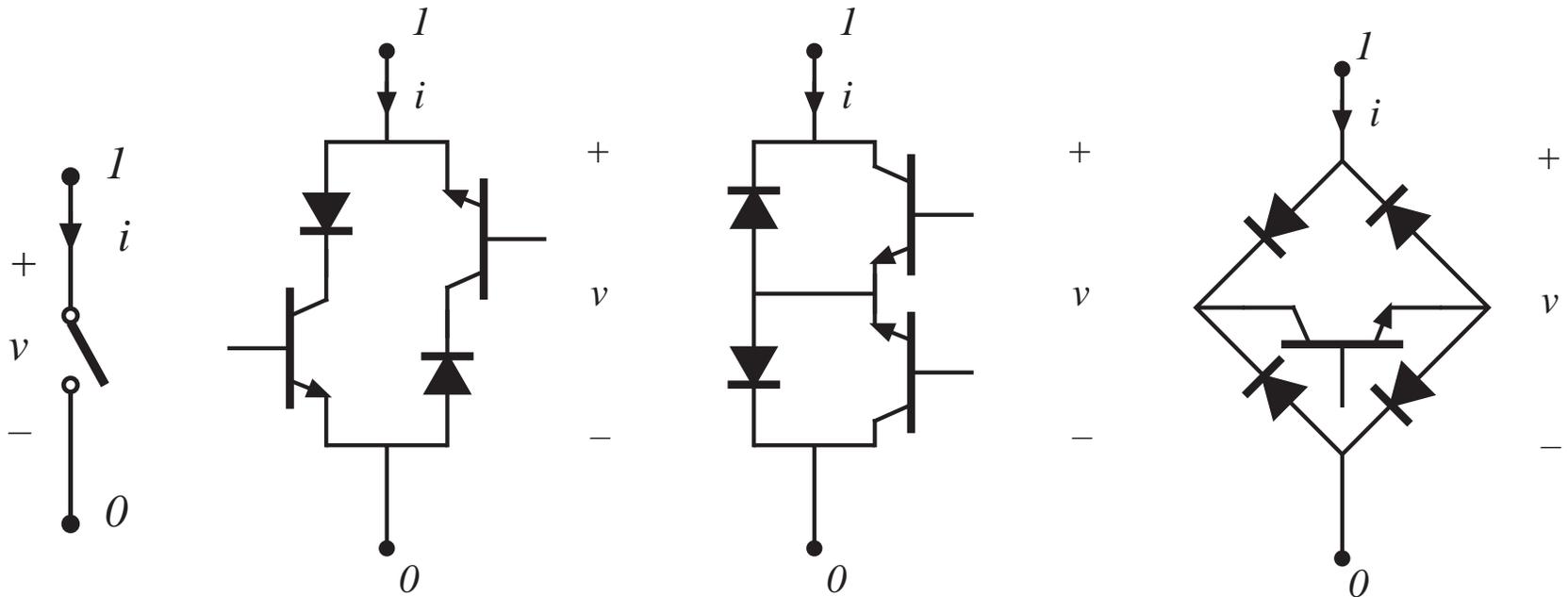
## 4.1.4. Four-quadrant switches

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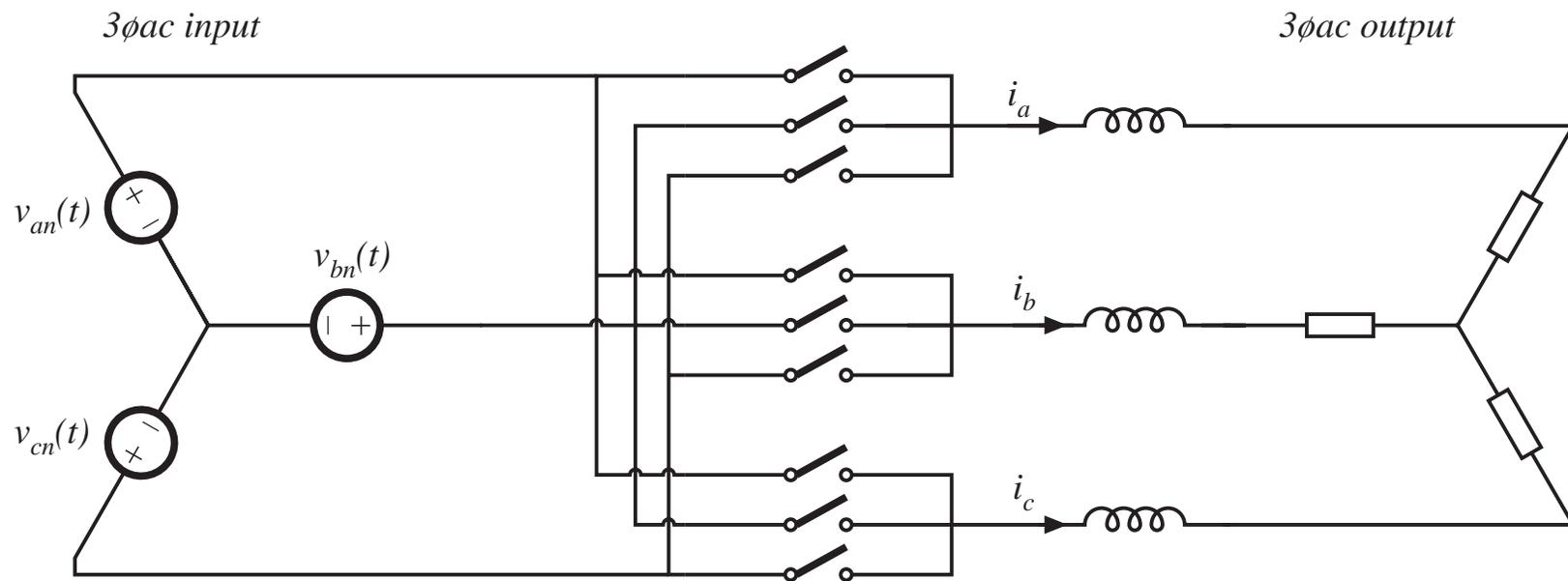


- *Usually an active switch, controlled by terminal C*
- *can conduct positive or negative on-state current*
- *can block positive or negative off-state voltage*

# Three ways to realize a four-quadrant switch



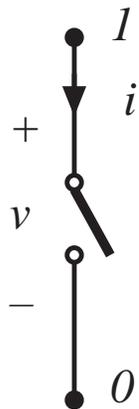
# A 3 $\phi$ ac-3 $\phi$ ac matrix converter



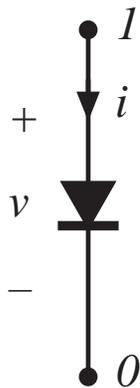
- All voltages and currents are ac; hence, four-quadrant switches are required.
- Requires nine four-quadrant switches

## 4.1.5. Synchronous rectifiers

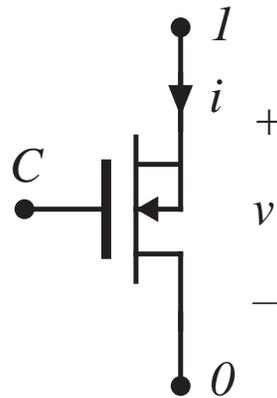
Replacement of diode with a backwards-connected MOSFET,  
to obtain reduced conduction loss



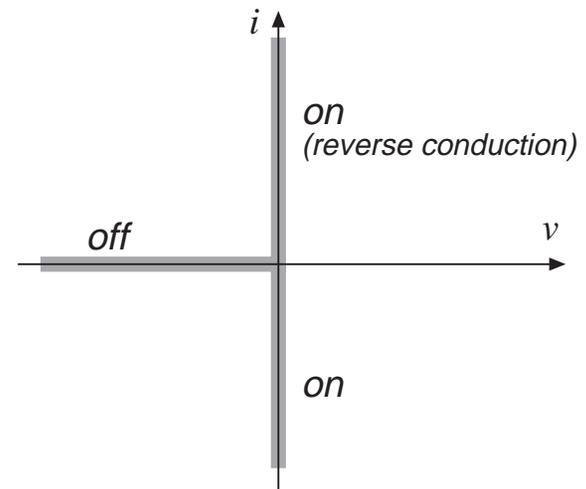
*ideal switch*



*conventional  
diode rectifier*

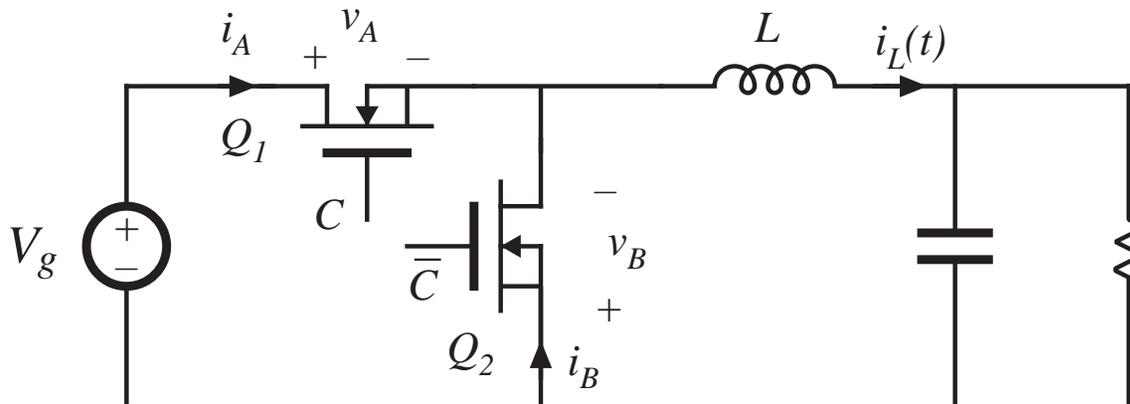


*MOSFET as  
synchronous  
rectifier*



*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

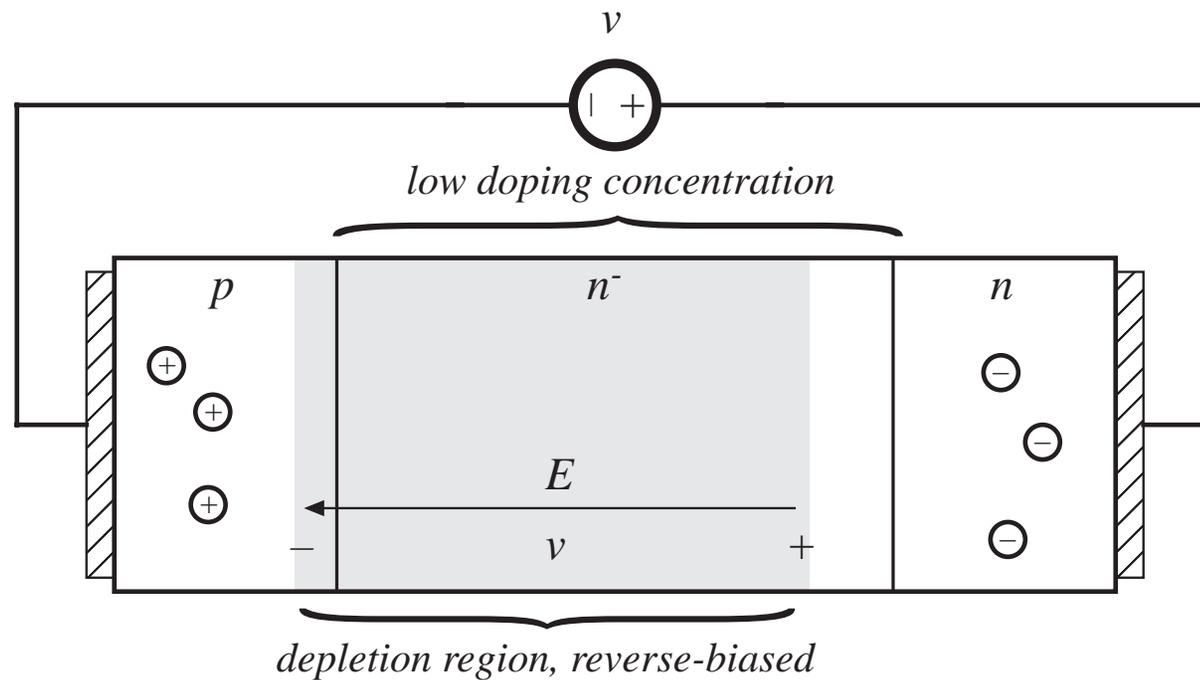
## 4.2. A brief survey of power semiconductor devices

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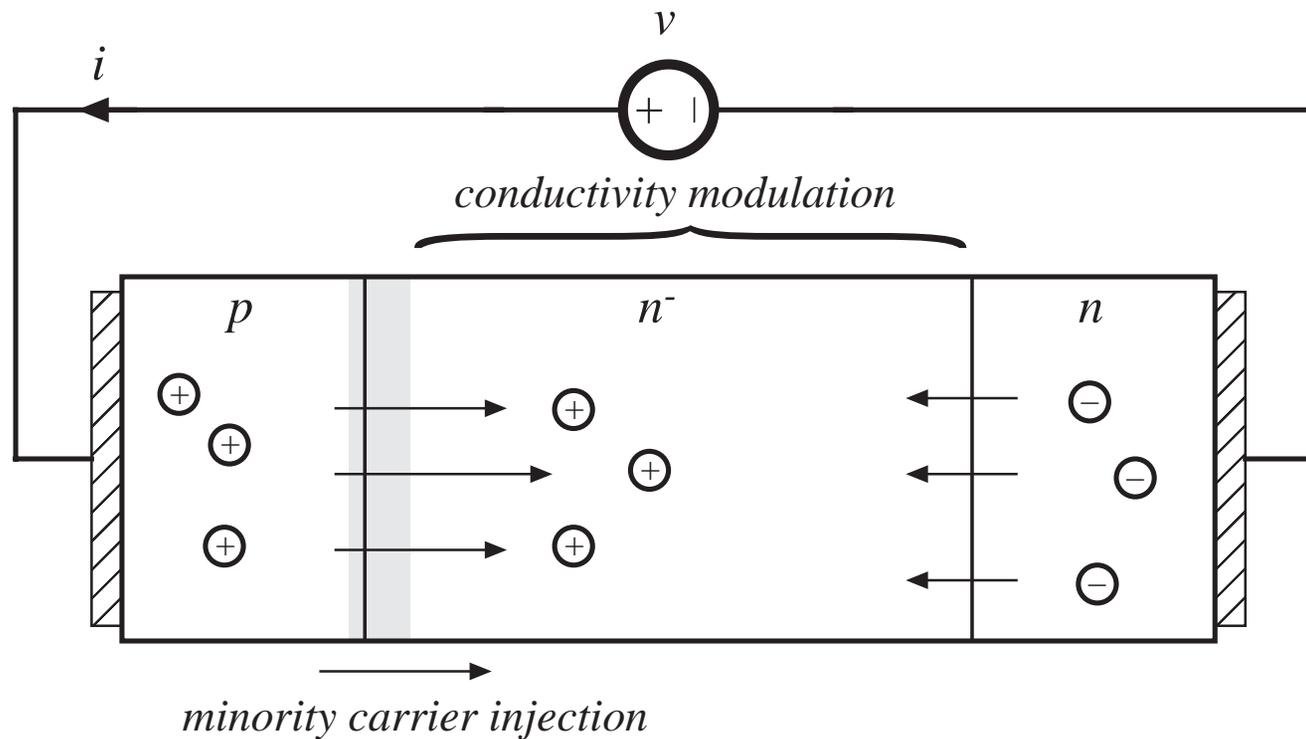
- Power diodes
  - Power MOSFETs
  - Bipolar Junction Transistors (BJTs)
  - Insulated Gate Bipolar Transistors (IGBTs)
  - Thyristors (SCR, GTO, MCT)
- 
- On resistance vs. breakdown voltage vs. switching times
  - Minority carrier and majority carrier devices

## 4.2.1. Power diodes

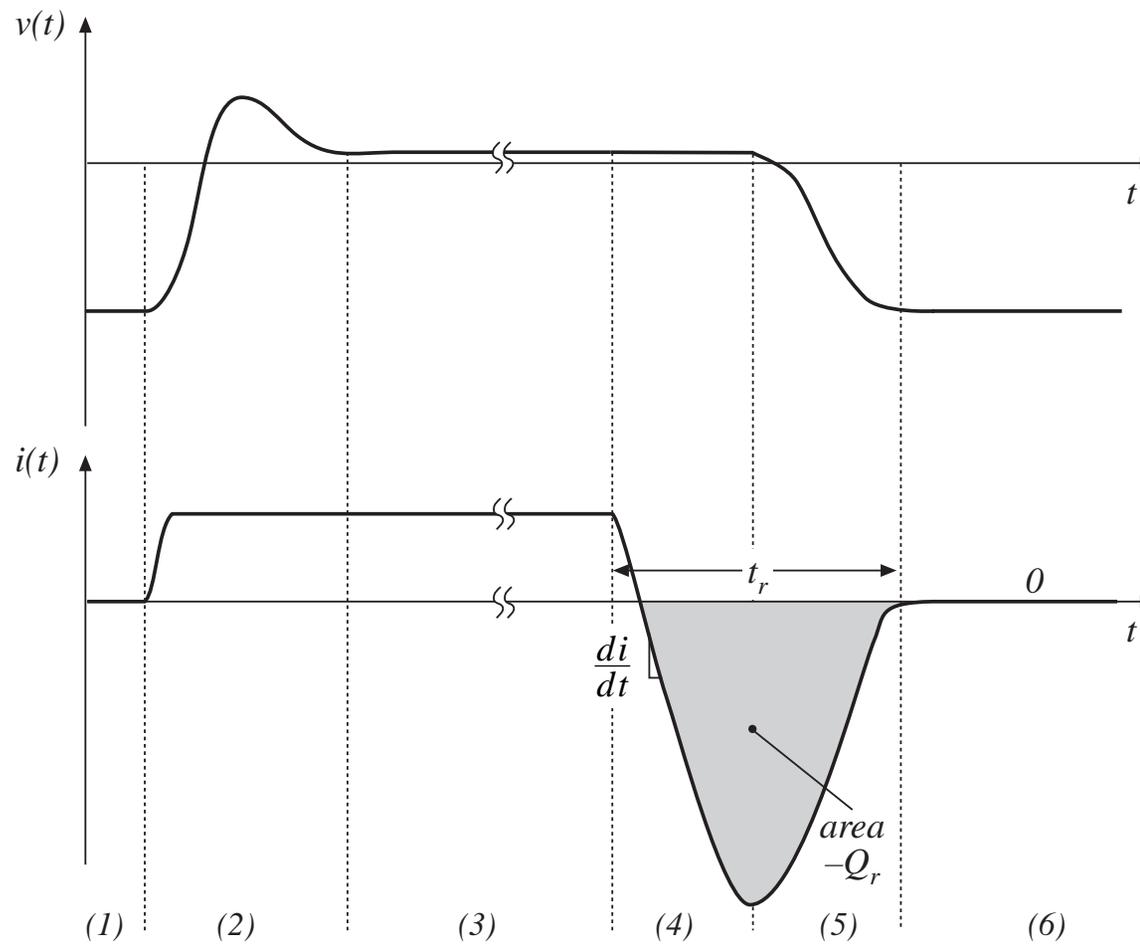
A power diode, under reverse-biased conditions:



# Forward-biased power diode



# Typical diode switching waveforms



# Types of power diodes

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## *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

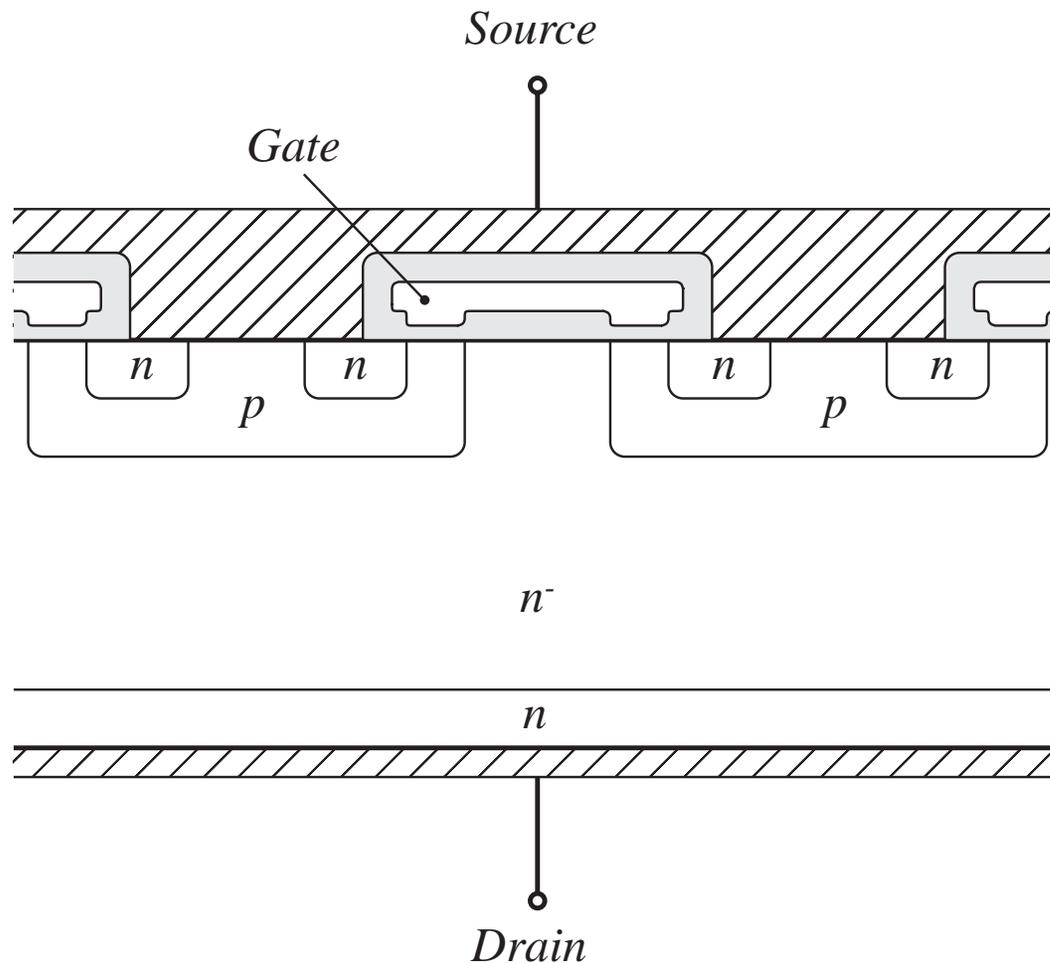
Model with equilibrium  $i-v$  characteristic, in parallel with depletion region capacitance

Restricted to low voltage (few devices can block 100V or more)

# Characteristics of several commercial power rectifier diodes

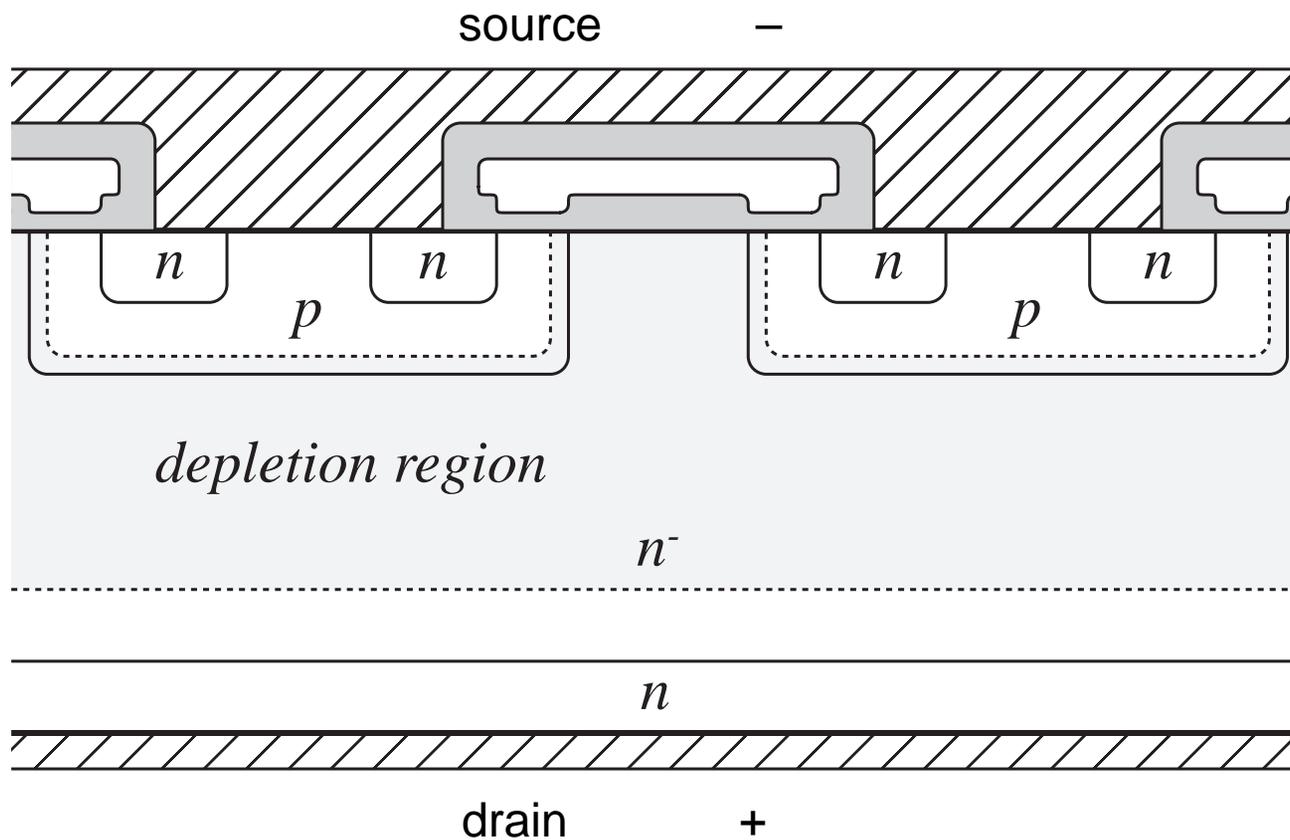
<i>Part number</i>	<i>Rated max voltage</i>	<i>Rated avg current</i>	$V_F$ (typical)	$t_r$ (max)
<b><i>Fast recovery rectifiers</i></b>				
1N3913	400V	30A	1.1V	400ns
SD453N25S20PC	2500V	400A	2.2V	2 $\mu$ s
<b><i>Ultra-fast recovery rectifiers</i></b>				
MUR815	150V	8A	0.975V	35ns
MUR1560	600V	15A	1.2V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

## 4.2.2. The Power MOSFET



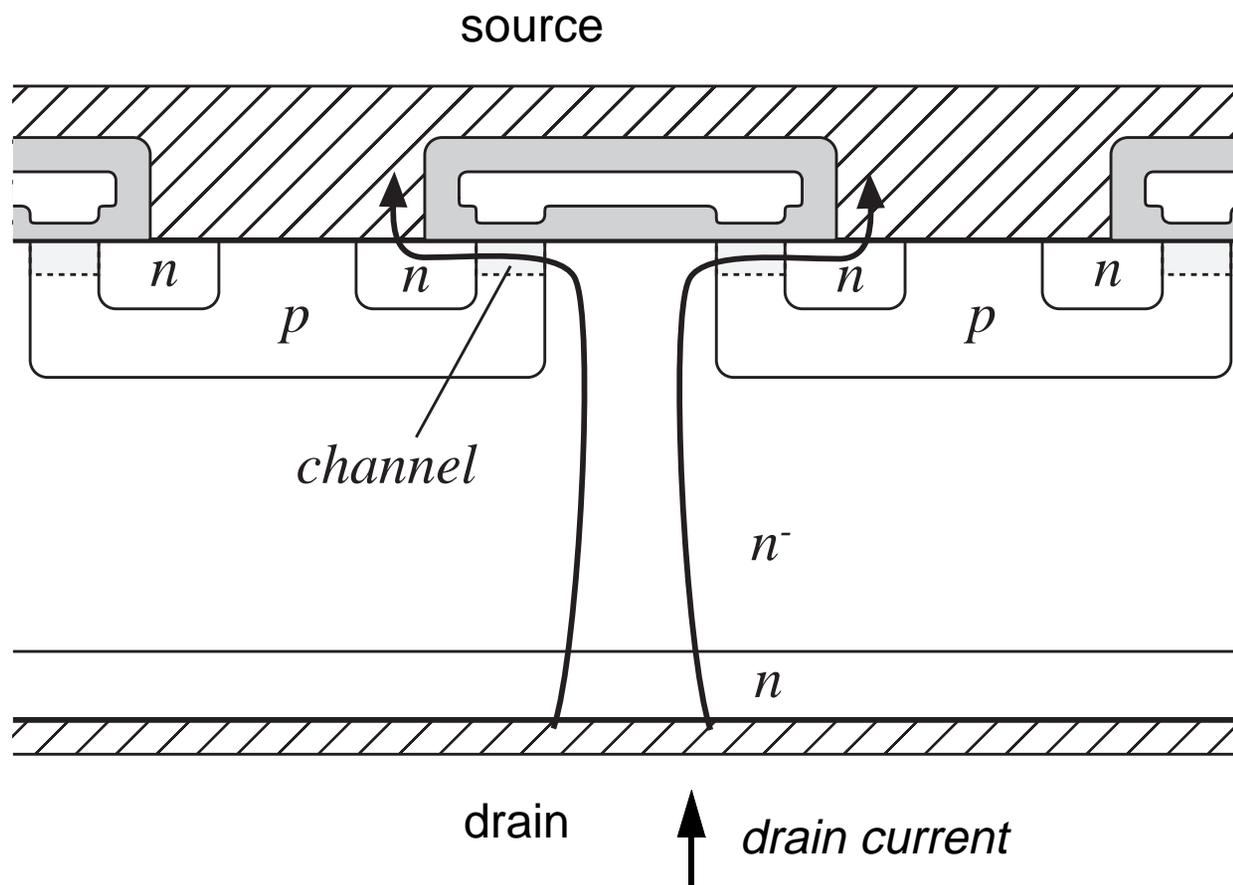
- Gate lengths approaching one micron
- Consists of many small enhancement-mode parallel-connected MOSFET cells, covering the surface of the silicon wafer
- Vertical current flow
- n-channel device is shown

# MOSFET: Off state



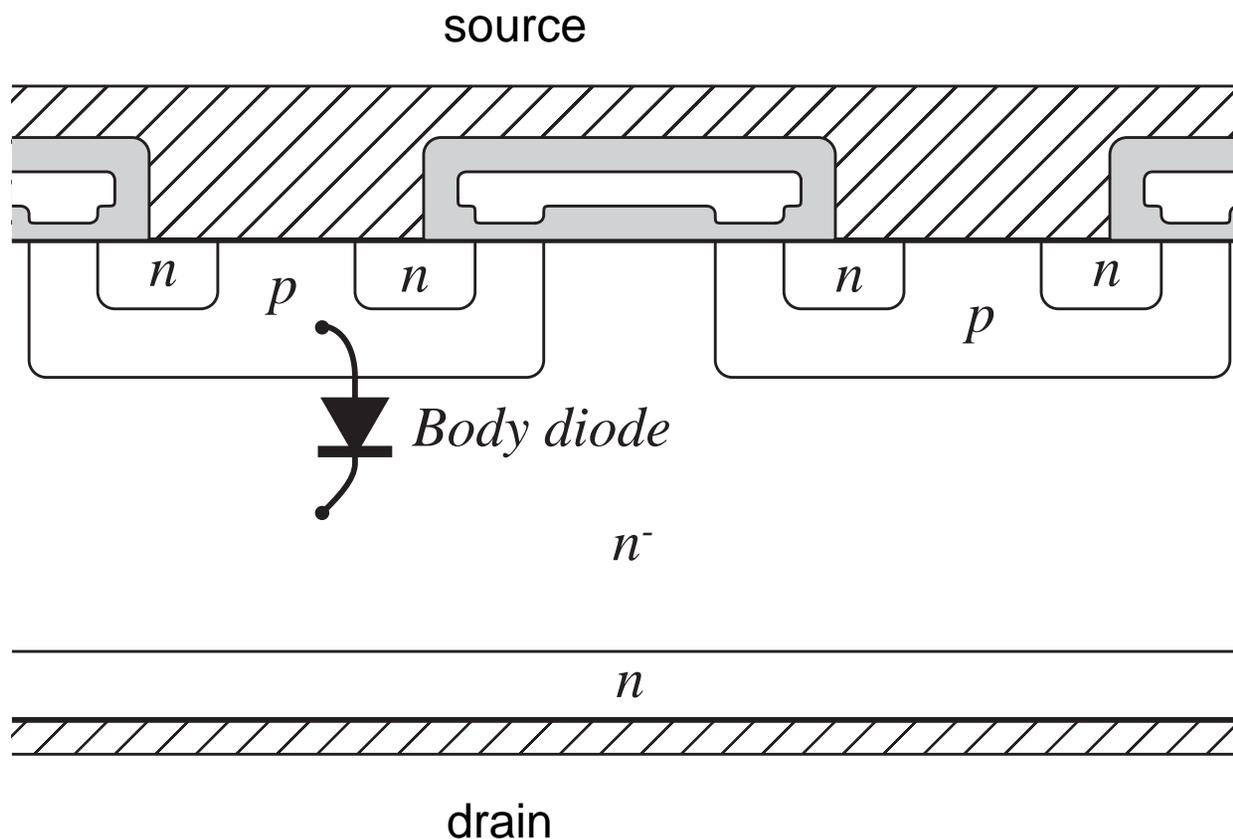
- $p-n$  junction is reverse-biased
- off-state voltage appears across  $n^-$  region

# MOSFET: on state



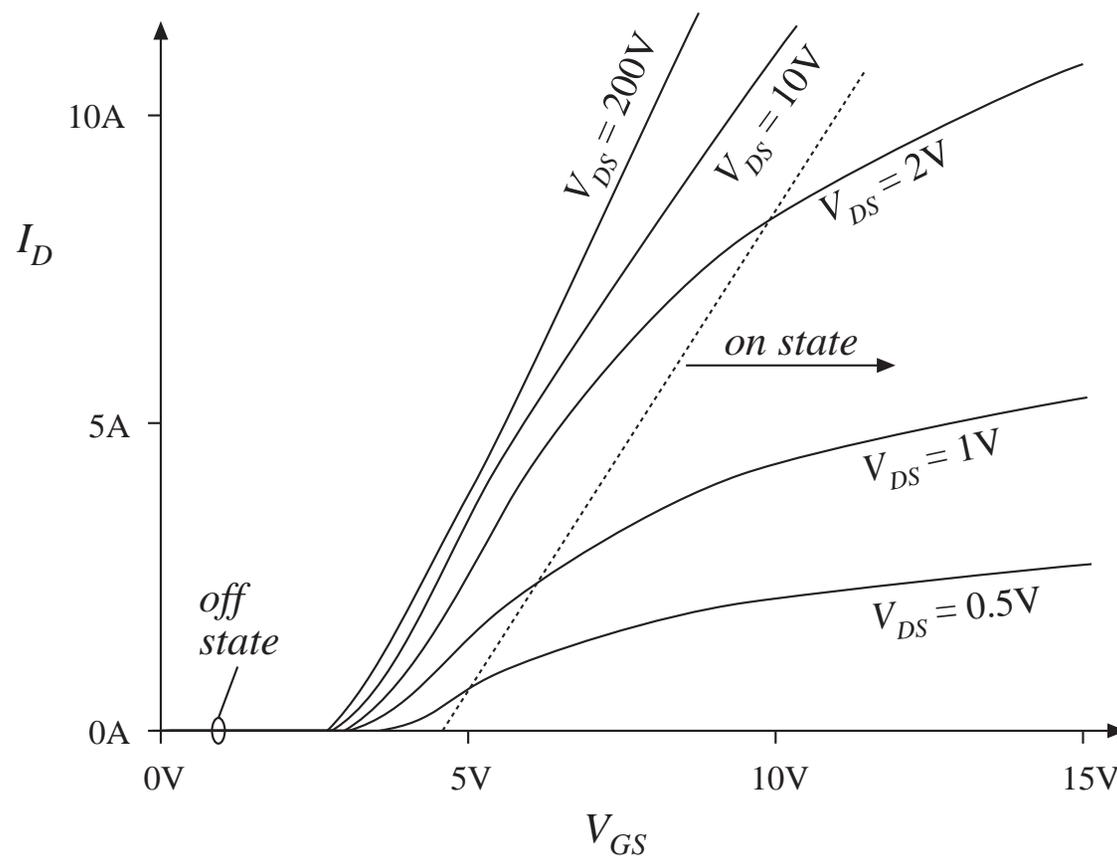
- $p$ - $n$  junction is slightly reverse-biased
- positive gate voltage induces conducting channel
- drain current flows through  $n^-$  region and conducting channel
- on resistance = total resistances of  $n^-$  region, conducting channel, source and drain contacts, etc.

# MOSFET body diode



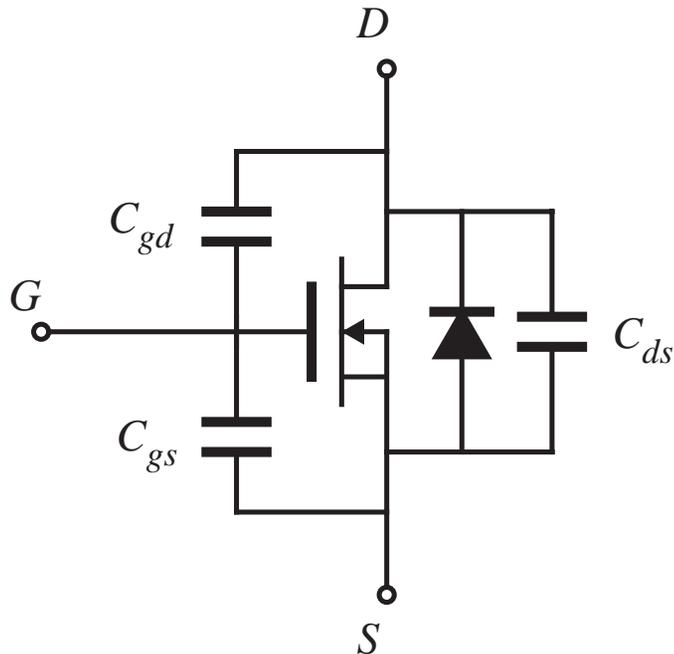
- $p$ - $n$  junction forms an effective diode, in parallel with the channel
- negative drain-to-source voltage can forward-bias the body diode
- diode can conduct the full MOSFET rated current
- diode switching speed not optimized —body diode is slow,  $Q_r$  is large

# Typical MOSFET characteristics



- Off state:  $V_{GS} < V_{th}$
- On state:  $V_{GS} \gg V_{th}$
- 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  $C_{gd}$

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

$$C_{ds}(v_{ds}) \approx C_0 \sqrt{\frac{V_0}{v_{ds}}} = \frac{C'_0}{\sqrt{v_{ds}}}$$

# Characteristics of several commercial power MOSFETs

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<i>Part number</i>	<i>Rated max voltage</i>	<i>Rated avg current</i>	$R_{on}$	$Q_g$ (typical)
IRFZ48	60V	50A	0.018 $\Omega$	110nC
IRF510	100V	5.6A	0.54 $\Omega$	8.3nC
IRF540	100V	28A	0.077 $\Omega$	72nC
APT10M25BNR	100V	75A	0.025 $\Omega$	171nC
IRF740	400V	10A	0.55 $\Omega$	63nC
MTM15N40E	400V	15A	0.3 $\Omega$	110nC
APT5025BN	500V	23A	0.25 $\Omega$	83nC
APT1001RBNR	1000V	11A	1.0 $\Omega$	150nC

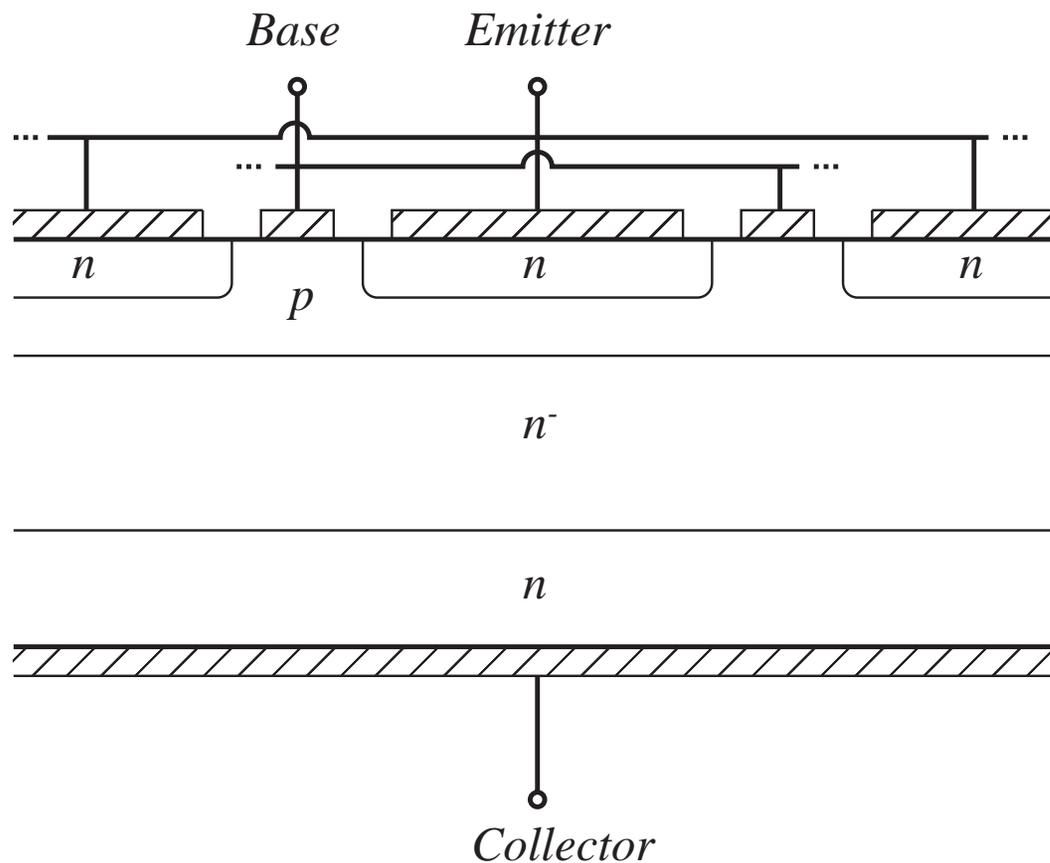
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# MOSFET: conclusions

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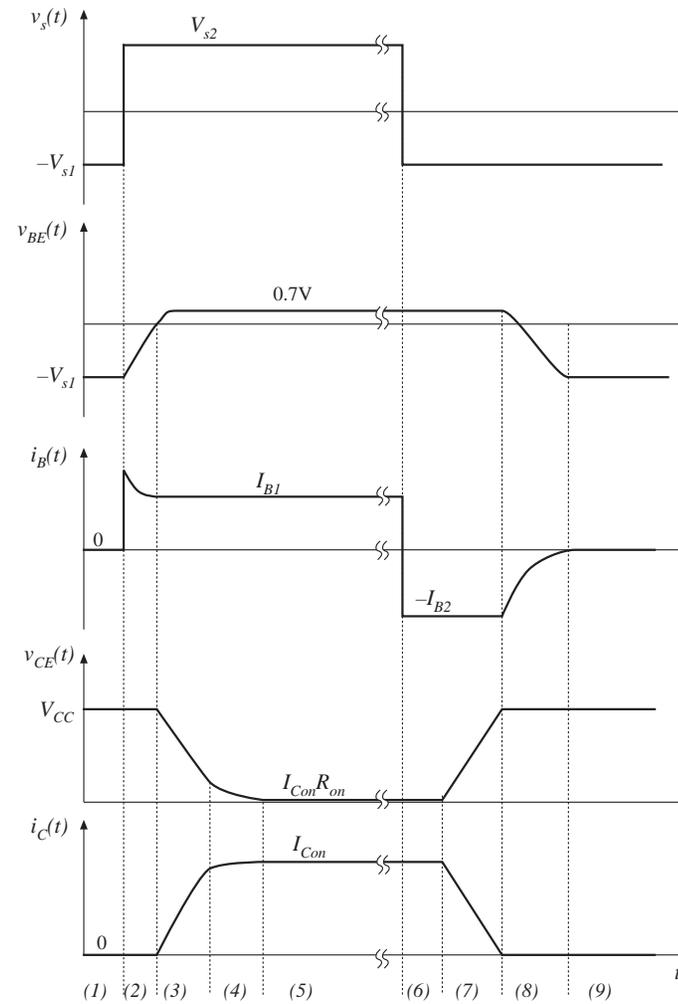
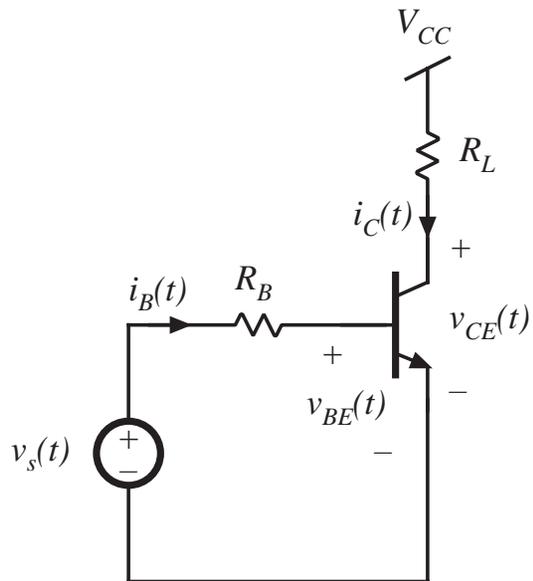
- A majority-carrier device: fast switching speed
- Typical switching frequencies: tens and hundreds of kHz
- On-resistance increases rapidly with rated blocking voltage
- Easy to drive
- The device of choice for blocking voltages less than 500V
- 1000V devices are available, but are useful only at low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

## 4.2.3. Bipolar Junction Transistor (BJT)



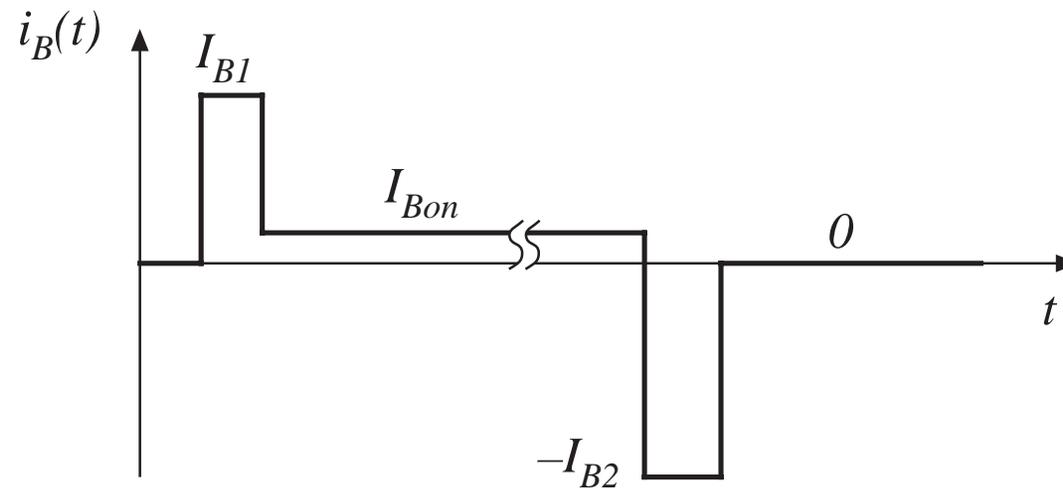
- Interdigitated base and emitter contacts
- Vertical current flow
- npn device is shown
- minority carrier device
- on-state: base-emitter and collector-base junctions are both forward-biased
- on-state: substantial minority charge in  $p$  and  $n^-$  regions, conductivity modulation

# BJT switching times

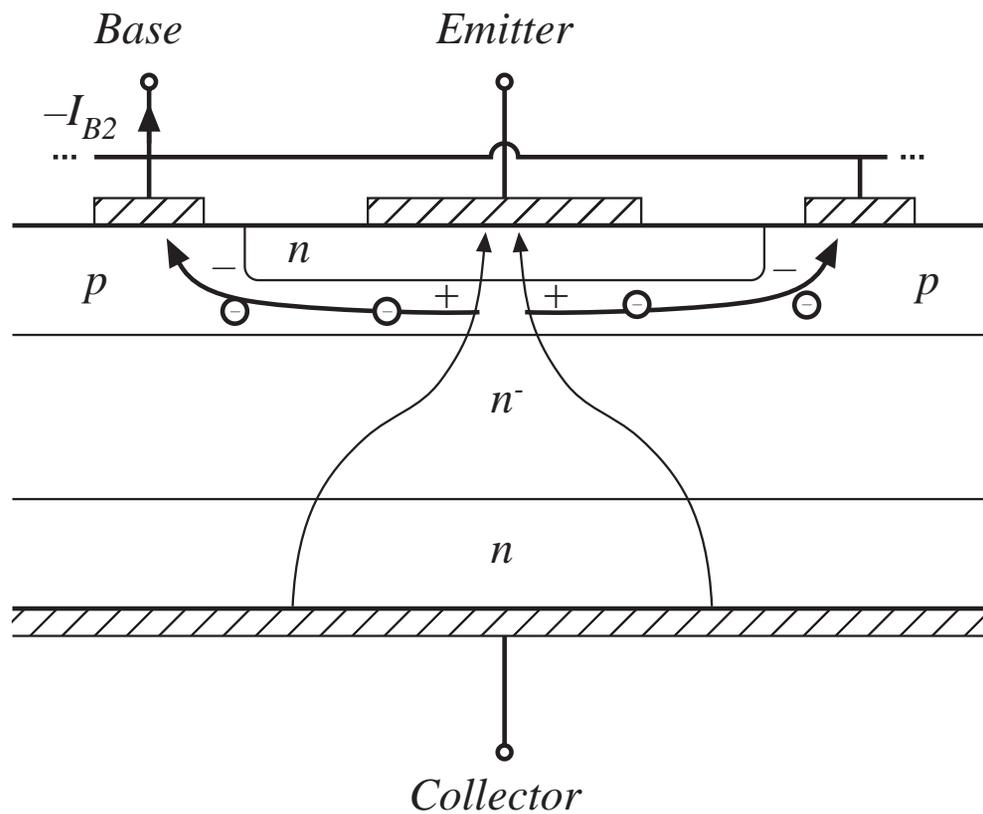


# Ideal base current waveform

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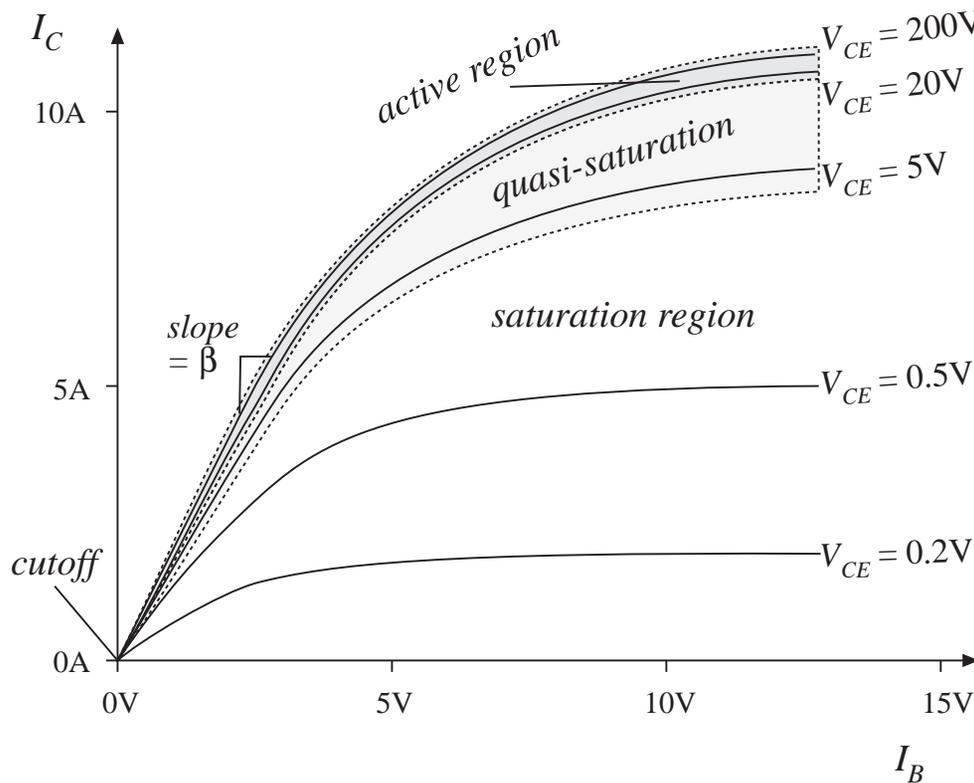


# Current crowding due to excessive $I_{B2}$



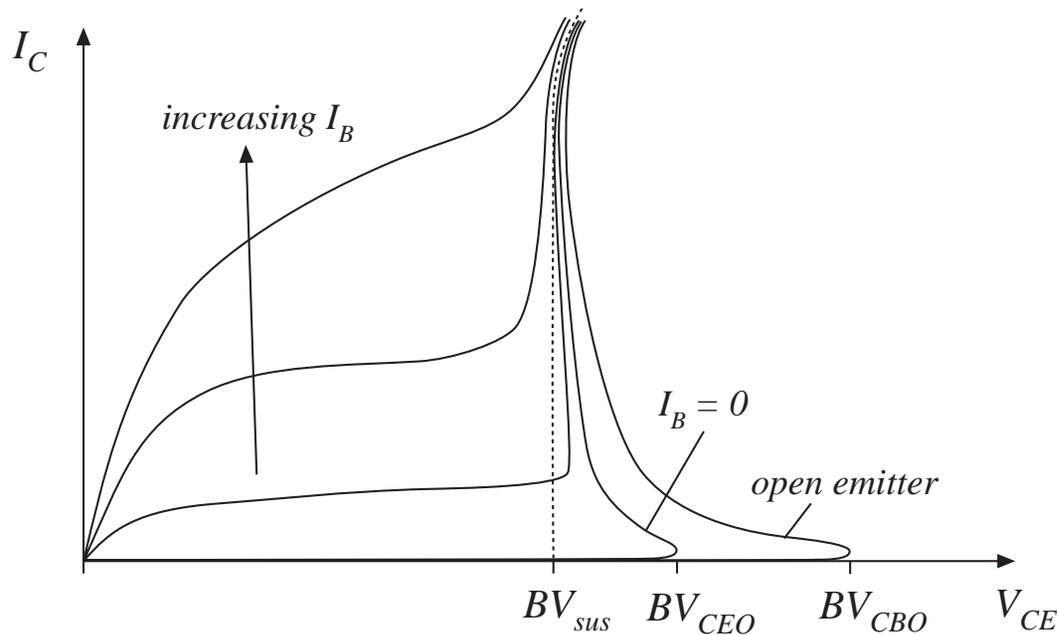
can lead to  
formation of hot  
spots and device  
failure

# BJT characteristics



- Off state:  $I_B = 0$
- On state:  $I_B > I_C / \beta$
- Current gain  $\beta$  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

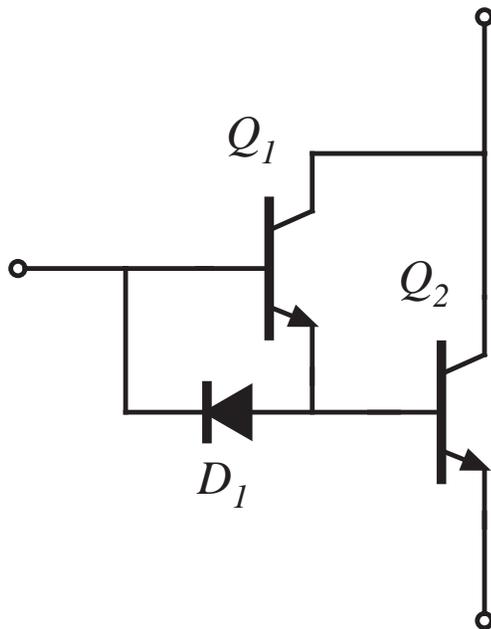
$BV_{CEO}$ : collector-emitter breakdown voltage with zero base current

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

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

# Darlington-connected BJT

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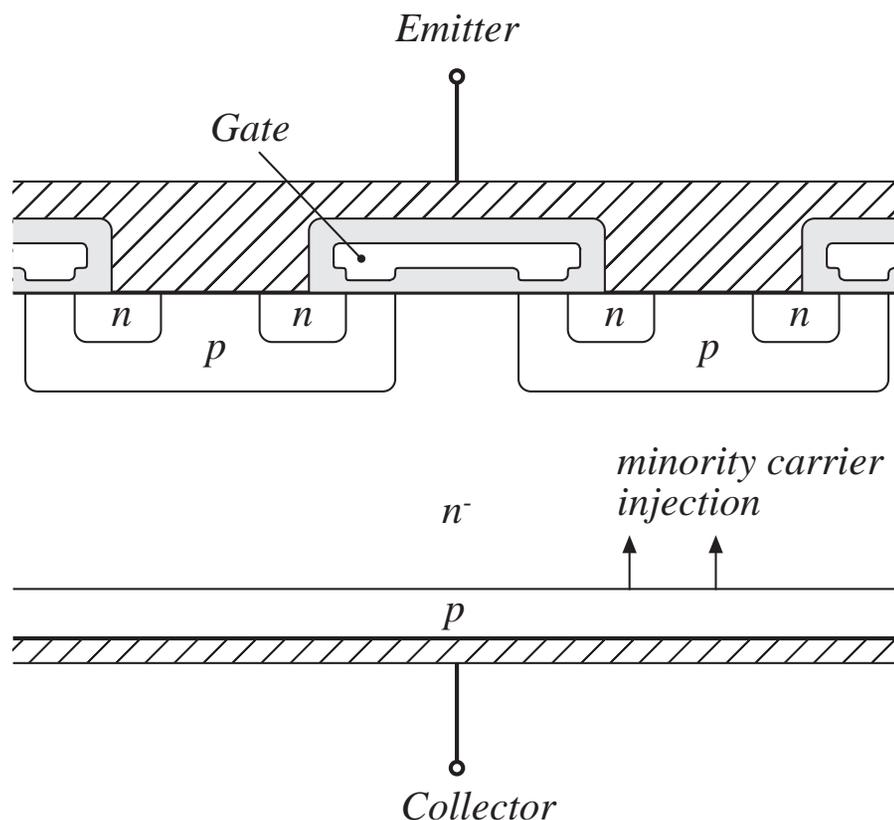
- Increased current gain, for high-voltage applications
- In a monolithic Darlington device, transistors  $Q_1$  and  $Q_2$  are integrated on the same silicon wafer
- Diode  $D_1$  speeds up the turn-off process, by allowing the base driver to actively remove the stored charge of both  $Q_1$  and  $Q_2$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

# Conclusions: BJT

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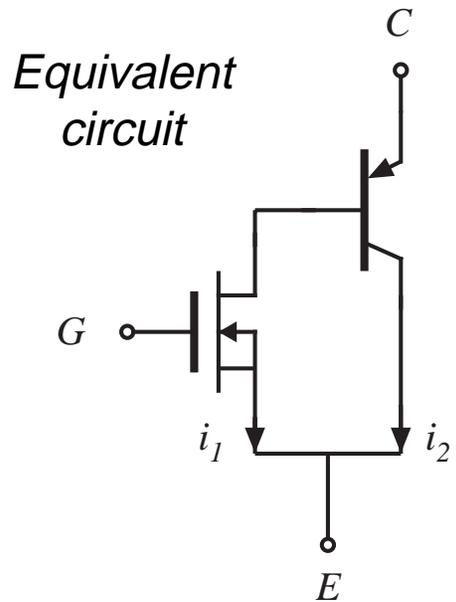
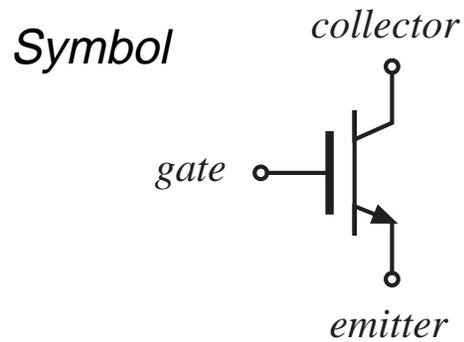
- BJT has been replaced by MOSFET in low-voltage (<500V) applications
- BJT is being replaced by IGBT in applications at voltages above 500V
- A minority-carrier device: compared with MOSFET, the BJT exhibits slower switching, but lower on-resistance at high voltages

## 4.2.4. The Insulated Gate Bipolar Transistor (IGBT)

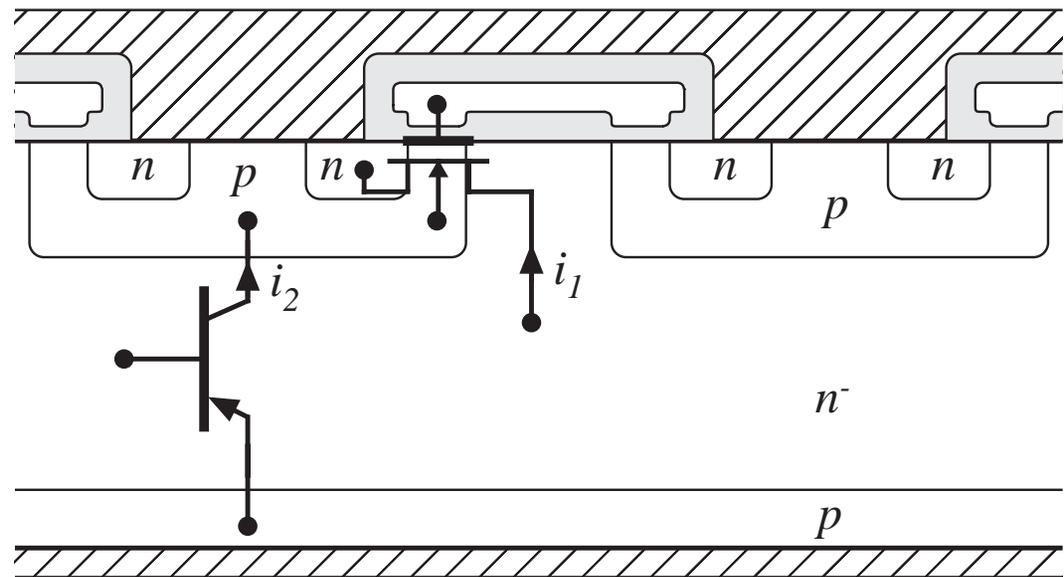


- A four-layer device
- Similar in construction to MOSFET, except extra  $p$  region
- On-state: minority carriers are injected into  $n^-$  region, leading to conductivity modulation
- compared with MOSFET: slower switching times, lower on-resistance, useful at higher voltages (up to 1700V)

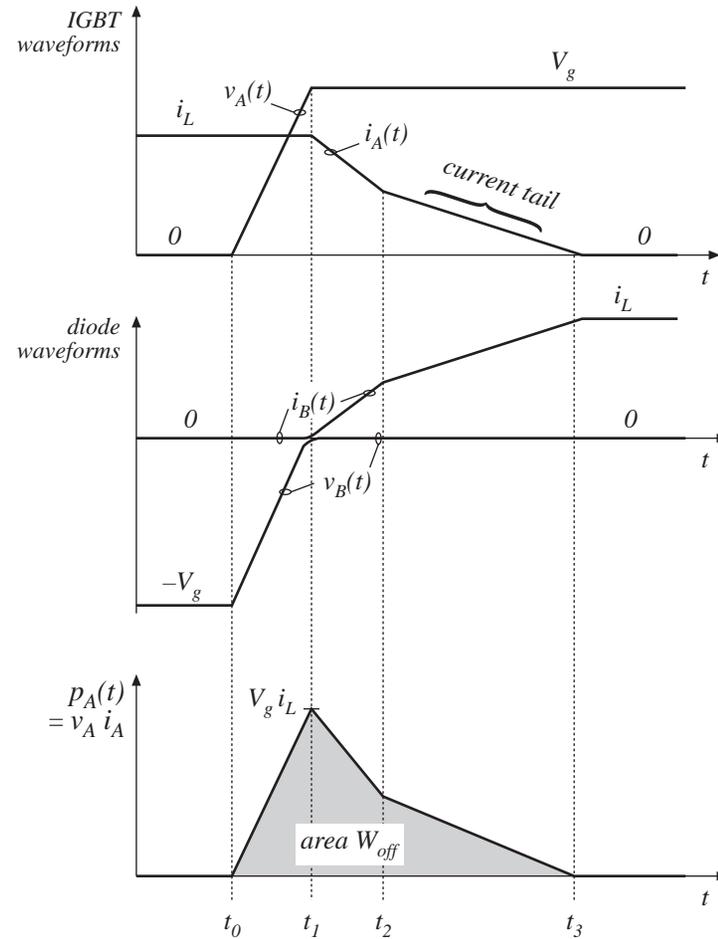
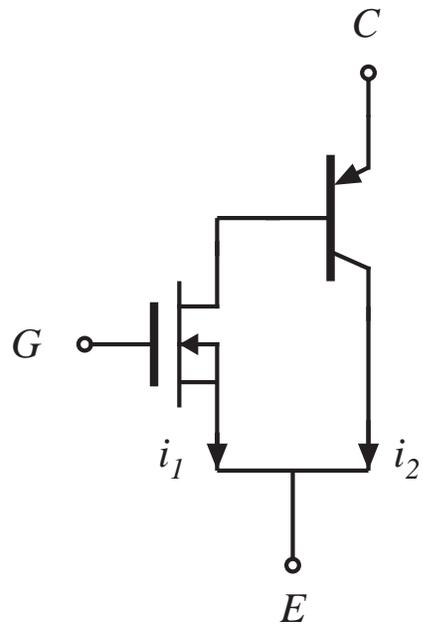
# The IGBT



*Location of equivalent devices*



# Current tailing in IGBTs



# Characteristics of several commercial devices

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

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# Conclusions: IGBT

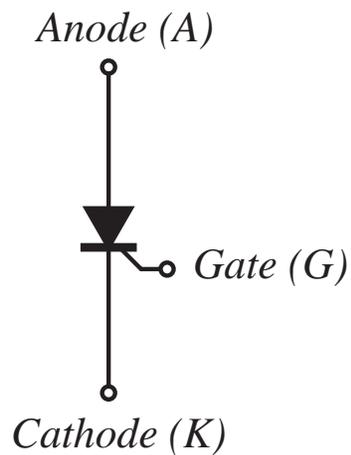
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- Becoming the device of choice in 500-1700V applications, at power levels of 1-1000kW
- Positive temperature coefficient at high current —easy to parallel and construct modules
- Forward voltage drop: diode in series with on-resistance. 2-4V typical
- 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 —next generation: 2500V

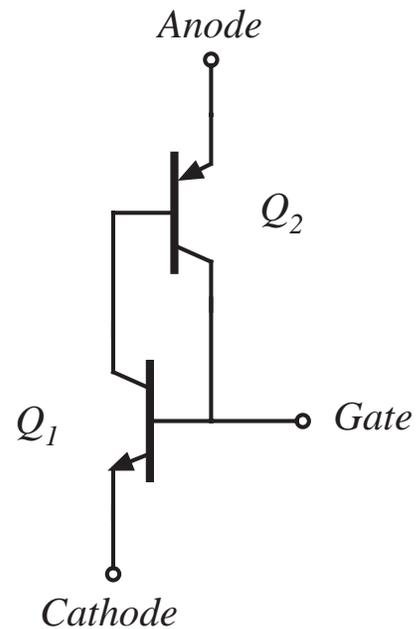
## 4.2.5. Thyristors (SCR, GTO, MCT)

### The SCR

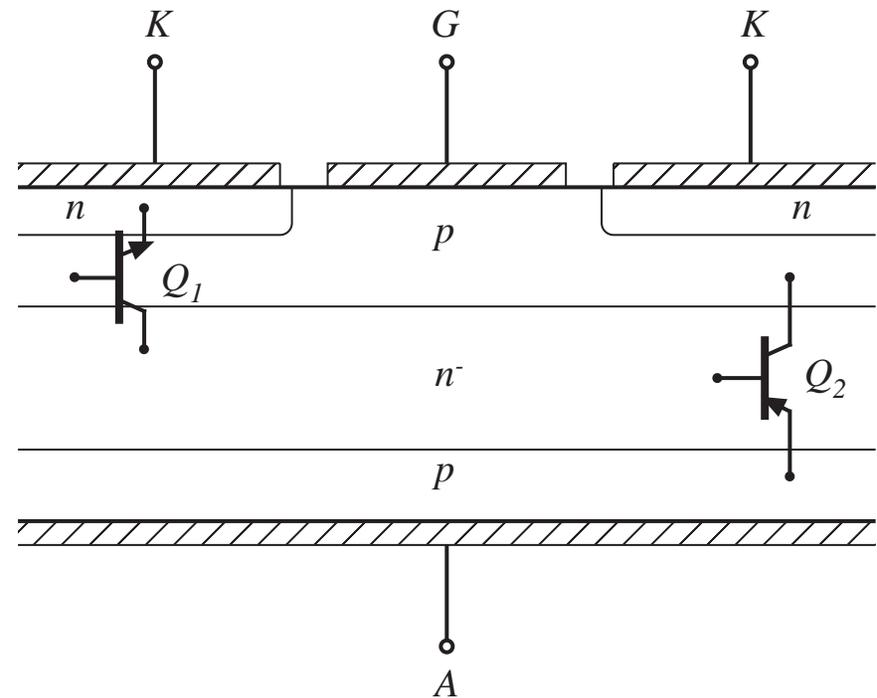
symbol



equiv circuit

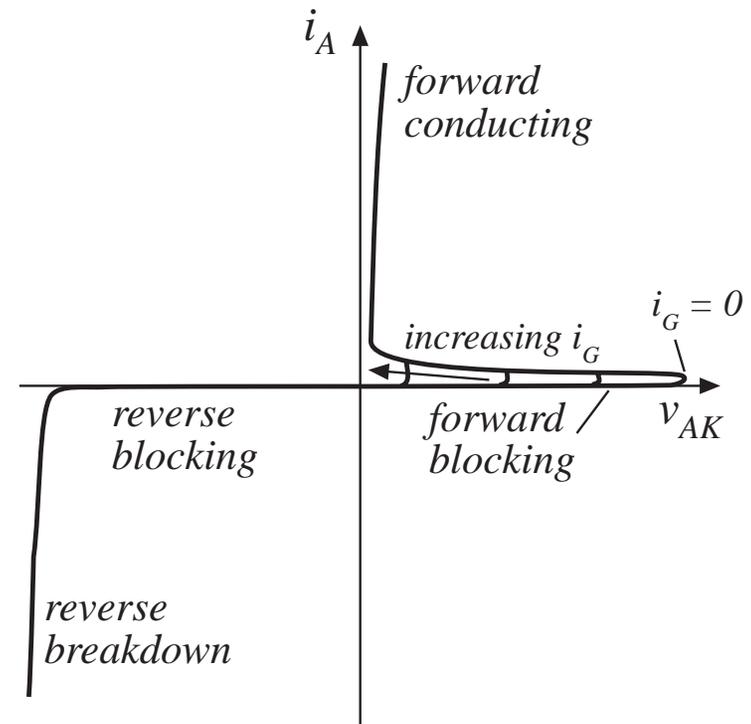


construction



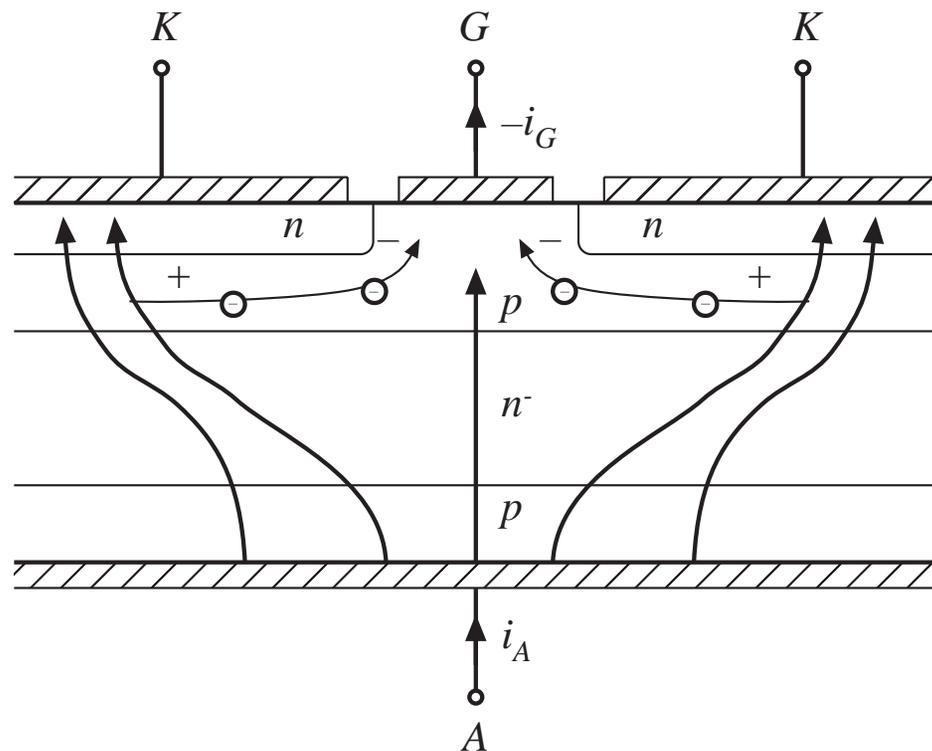
# The Silicon Controlled Rectifier (SCR)

- 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)

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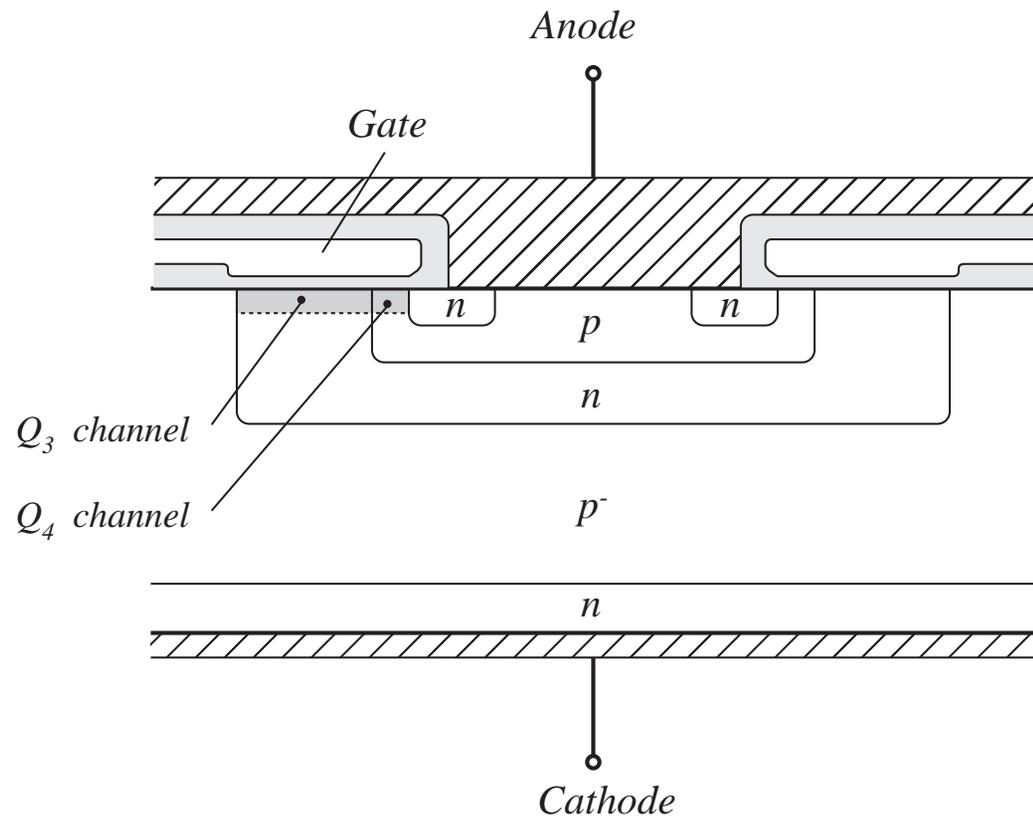
- An SCR fabricated using modern techniques —small feature size
- Gate and cathode contacts are highly interdigitated
- Negative gate current is able to completely reverse-bias the gate-cathode junction

Turn-off transition:

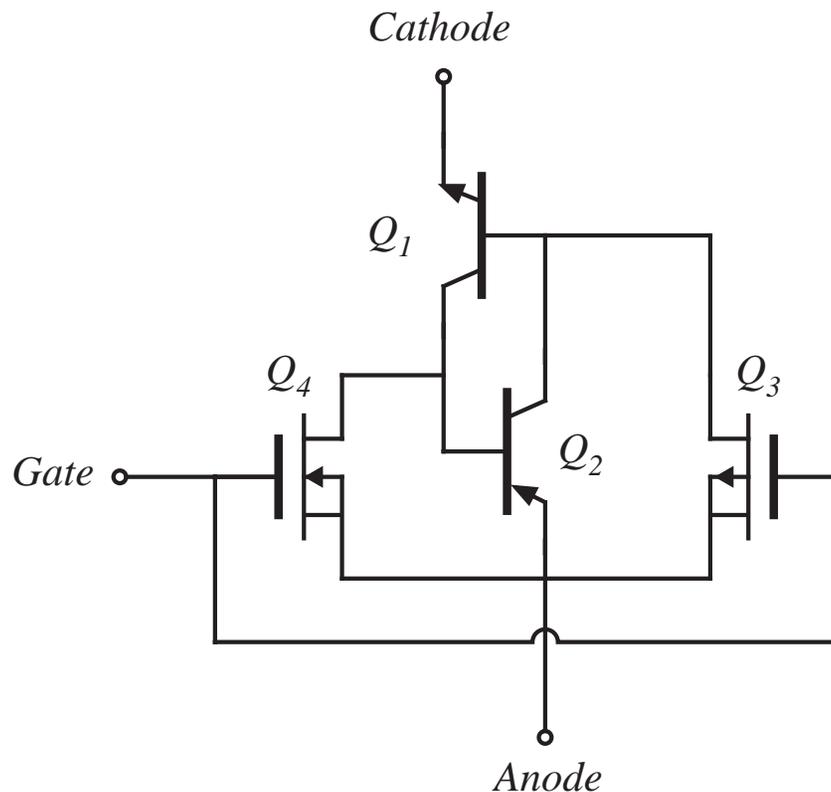
- Turn-off current gain: typically 2-5
- Maximum controllable on-state current: maximum anode current that can be turned off via gate control. GTO can conduct peak currents well in excess of average current rating, but cannot switch off

# 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

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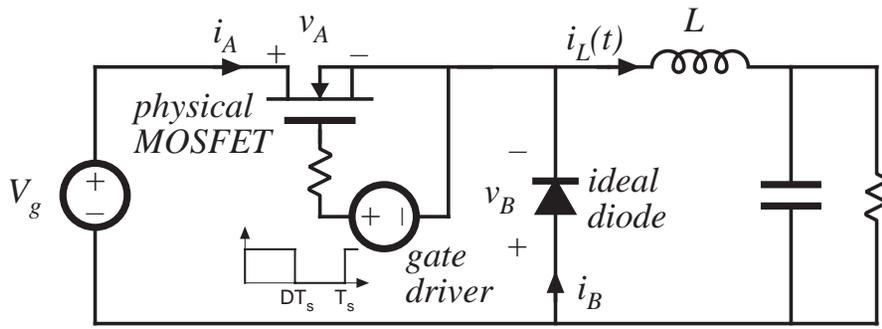
- The thyristor family: double injection yields lowest forward voltage drop in high voltage devices. More difficult to parallel than MOSFETs and IGBTs
- The SCR: highest voltage and current ratings, low cost, passive turn-off transition
- The GTO: intermediate ratings (less than SCR, somewhat more than 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

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- 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



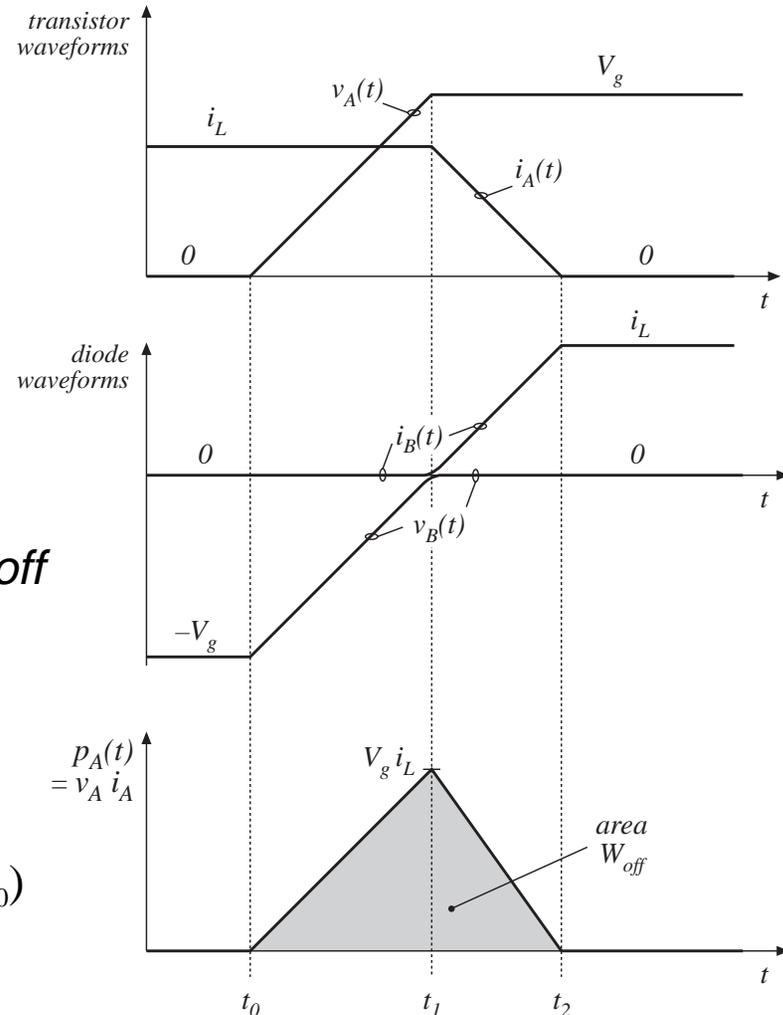
*Buck converter example*

$$v_B(t) = v_A(t) - V_g$$

$$i_A(t) + i_B(t) = i_L$$

*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

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Energy lost during transistor turn-off transition:

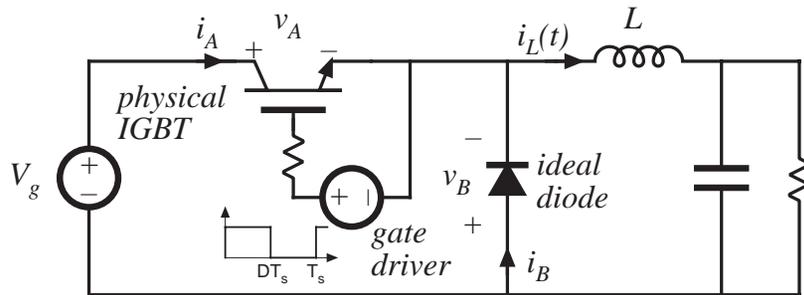
$$W_{off} = \frac{1}{2} V_g i_L (t_2 - t_0)$$

Similar result during transistor turn-on transition.

Average power loss:

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

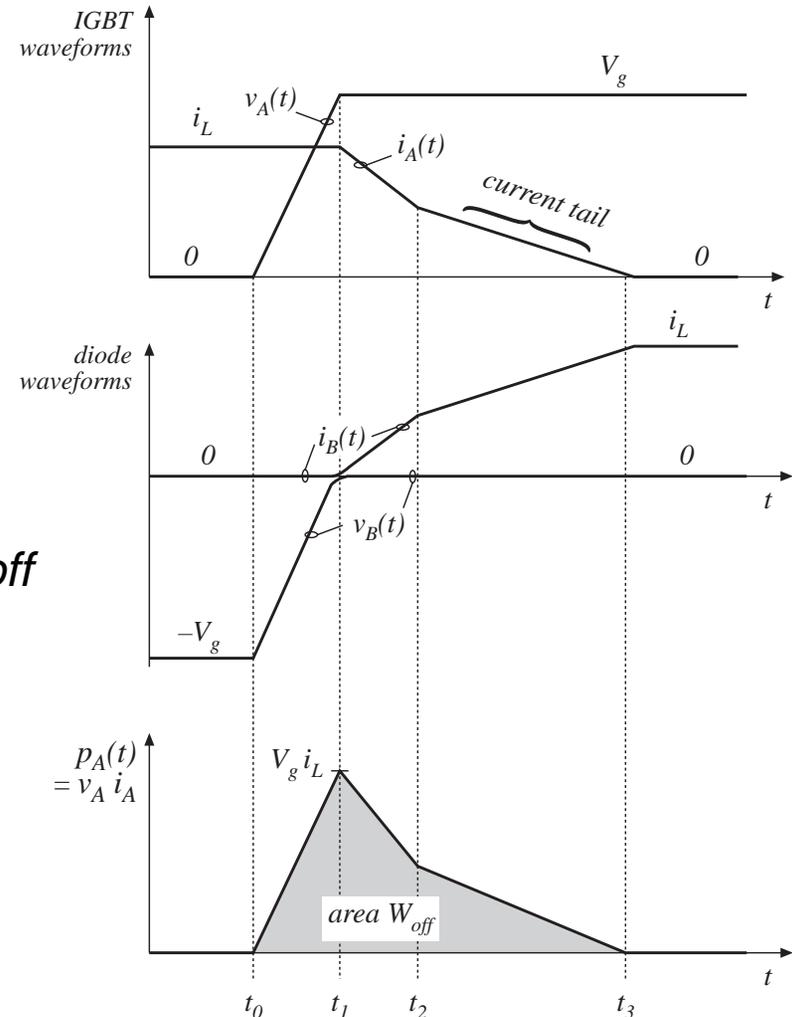
# Switching loss due to current-tailing in IGBT



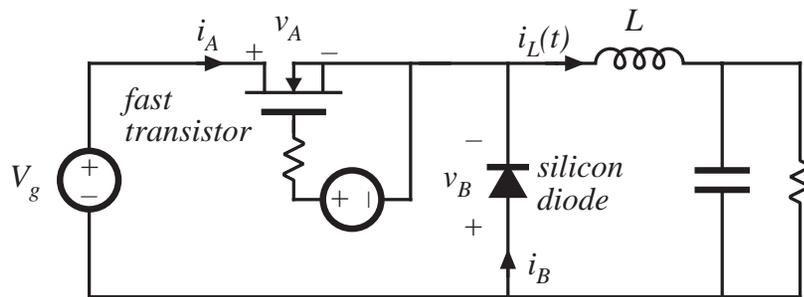
Example: buck converter with IGBT

transistor turn-off transition

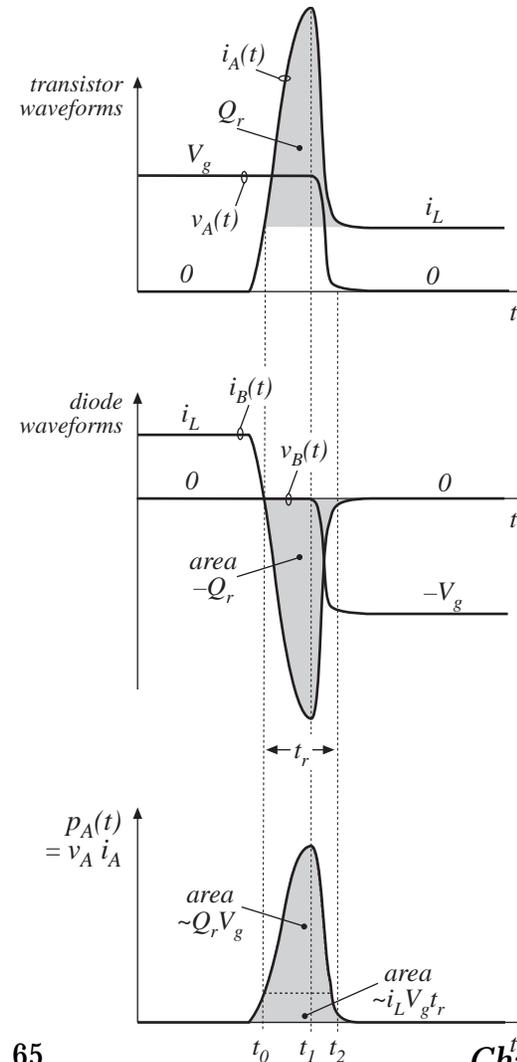
$$P_{sw} = \frac{1}{T_s} \int_{\text{switching transitions}} p_A(t) dt = (W_{on} + W_{off}) f_s$$



## 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:

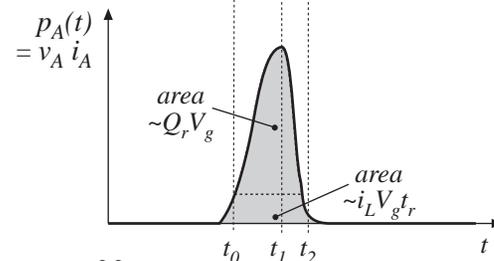
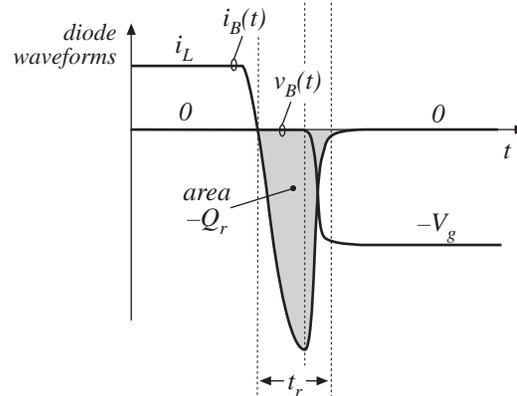
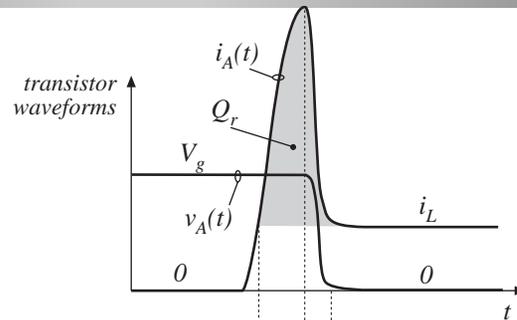
$$W_D = \int_{\text{switching transition}} v_A(t) i_A(t) dt$$

With abrupt-recovery diode:

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

$$= V_g i_L t_r + V_g Q_r$$

- Often, this is the largest component of switching loss



Soft-recovery diode:

$$(t_2 - t_1) \gg (t_1 - t_0)$$

Abrupt-recovery diode:

$$(t_2 - t_1) \ll (t_1 - t_0)$$

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

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- 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.

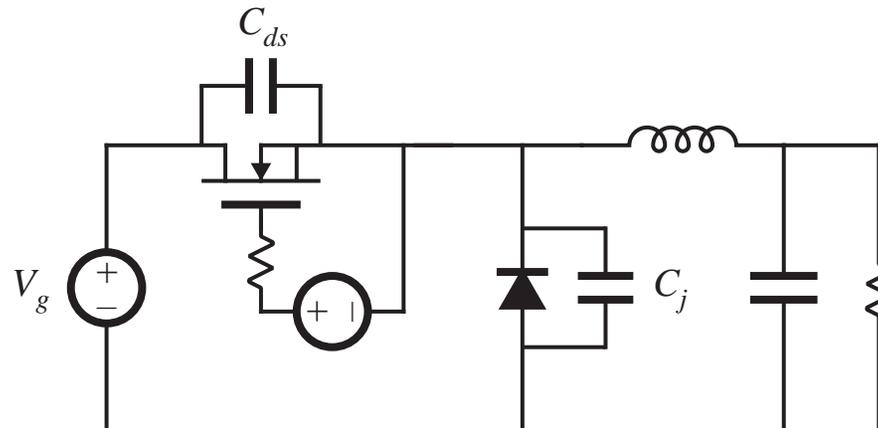
Total energy stored in linear capacitive and inductive elements:

$$W_C = \sum_{\substack{\text{capacitive} \\ \text{elements}}} \frac{1}{2} C_i V_i^2$$

$$W_L = \sum_{\substack{\text{inductive} \\ \text{elements}}} \frac{1}{2} L_j I_j^2$$

# 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  $v_{ds} = V_{DS}$  :

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

$$W_{Cds} = \int_0^{V_{DS}} C'_0(v_{ds}) \sqrt{v_{ds}} dv_{ds} = \frac{2}{3} C_{ds}(V_{DS}) V_{DS}^2$$

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

## Some other sources of this type of switching loss

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### Schottky diode

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

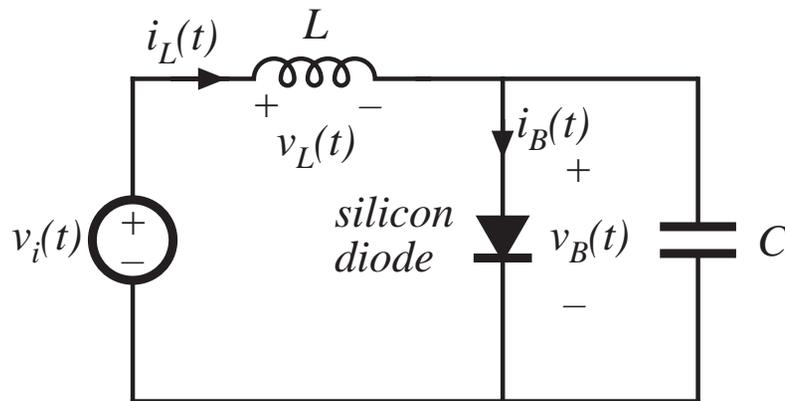
### Transformer leakage inductance

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

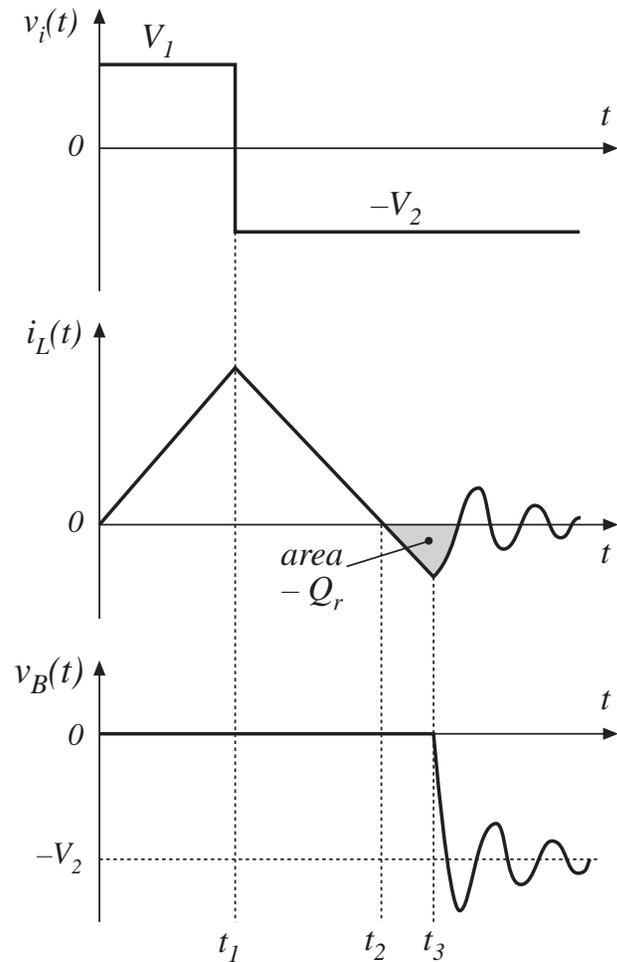
### Interconnection and package inductances

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

# Ringinduced 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  $t_2 \leq t \leq t_3$ :

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

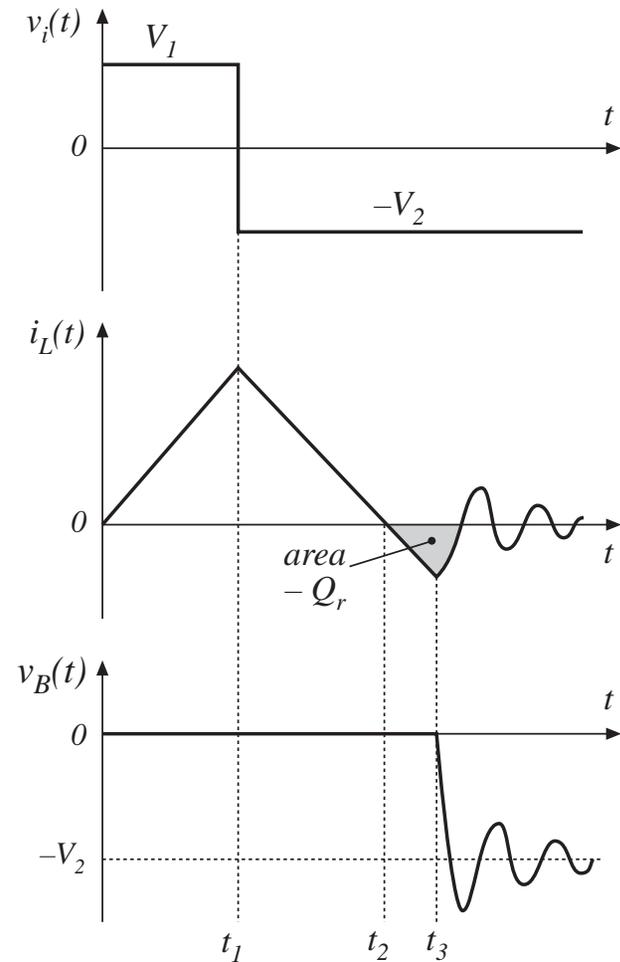
Applied inductor voltage during interval  $t_2 \leq t \leq t_3$ :

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

Hence,

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

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



## 4.3.4. Efficiency vs. switching frequency

---

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

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

Average switching power loss is

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

Total converter loss can be expressed as

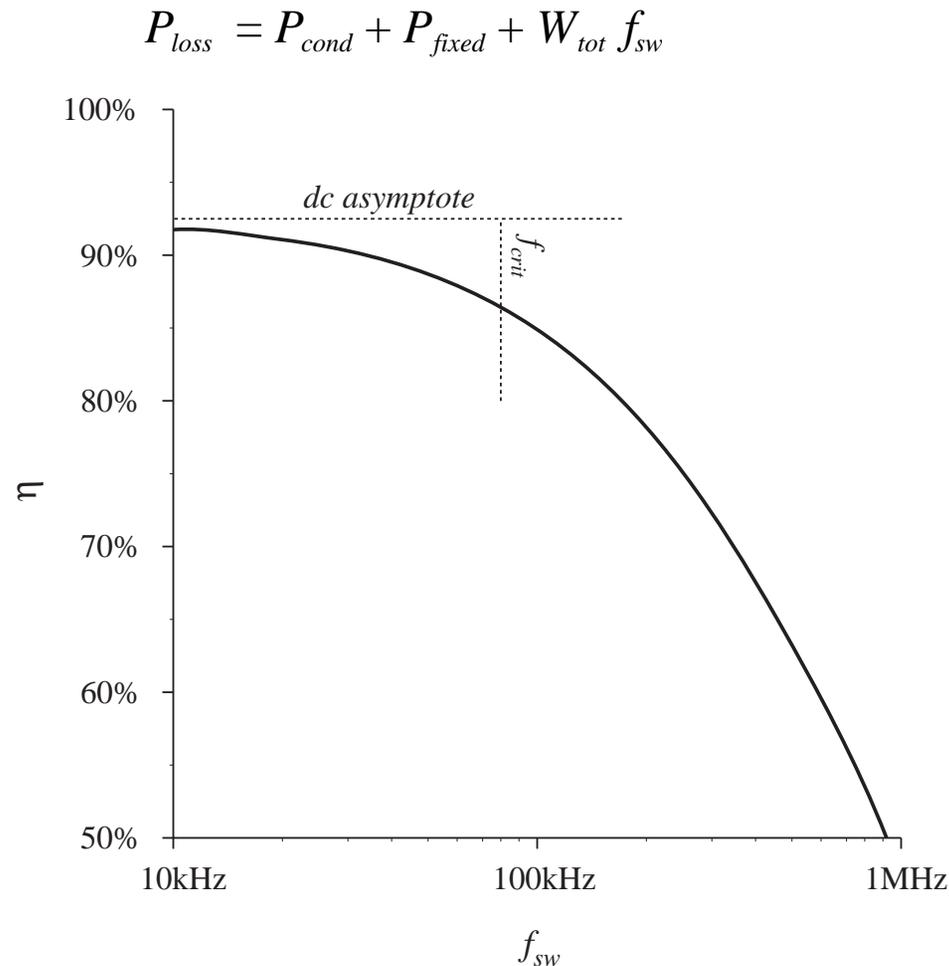
$$P_{loss} = P_{cond} + P_{fixed} + W_{tot} f_{sw}$$

where

$P_{fixed}$  = fixed losses (independent of load and  $f_{sw}$ )

$P_{cond}$  = conduction losses

# Efficiency vs. switching frequency



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

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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

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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

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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.