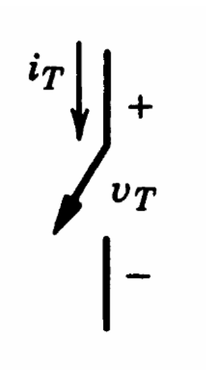
Chapter 1

Power Devices

Idealized Characteristics of Power Devices:

1. Controlled turn-on or/and –off
2. Zero gate firing power requirement
3. When on, current usually flows only in one direction
4. Zero conduction and block losses ($v_{on\text{-}state}=0$, $i_{leakage}=0$)
5. Unlimited current and voltage ratings
6. Instant turn-on and –off times
7. Low cost



Ideal Power Device Symbol

Idealized Characteristics

for analyzing the circuit topology

Real Characteristics of Power Devices:

Switch States

* **on state (static)**

current ratings (average, RMS, peak values)

on-state volt-drop or resistance

* **off state (static)**

voltage ratings (forward and reverse peak values)

* **commutation states (dynamic)**

dv/dt、di/dt rating – turn-off time

dv/dt、di/dt rating – turn-on time

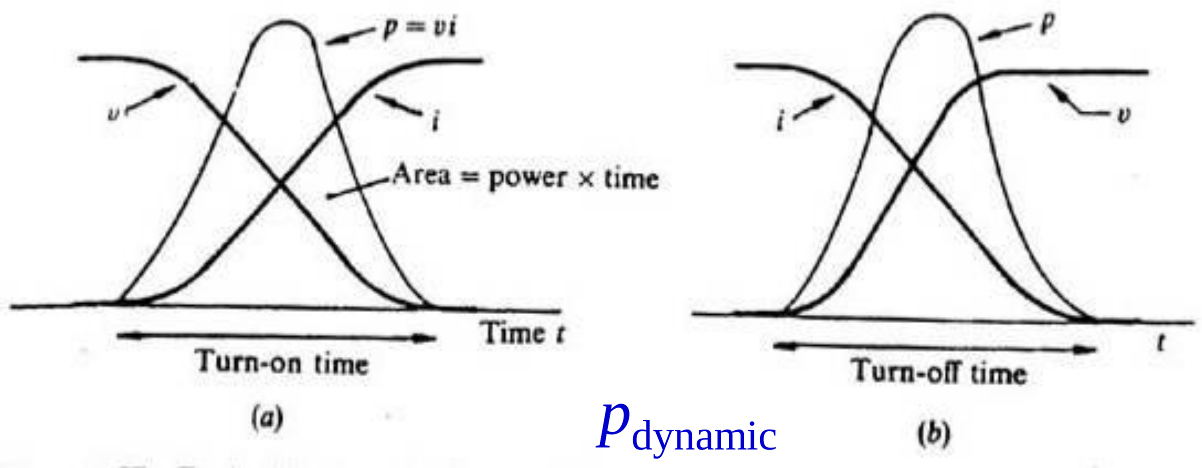
Real Characteristics

for the actual circuit design

Real Switch Energy Losses

$$\mathbf{W_{static}} = \mathbf{W_{on}} + \mathbf{W_{off}}$$
$$= \int_{\text{on-time}} i_{on}(t)\, v_{on\text{-}state}(t)\, dt + \int_{\text{off-time}} i_{leakage}(t)\, v_{off}(t)\, dt$$

$$\mathbf{W_{dynamic}} = \int_{\textbf{turn-on}} \mathbf{i(t)\, v(t)\, dt} + \int_{\textbf{turn-off}} \mathbf{i(t)\, v(t)\, dt}$$



$p_{dynamic}$

$$\mathbf{P_{average} = (W_{static} + W_{switch})/T}$$

$\mathbf{P_{static}}$--- major loss at lower-frequency operation

$\mathbf{P_{switch}}$--- significant at high-frequency operation

Study Focuses

uncontrolled device: power diode

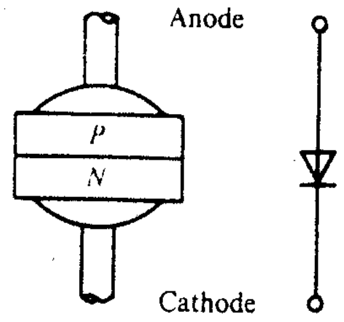
semi-controlled device: SCR

controllable devices: BJT, MOSFET, IGBT

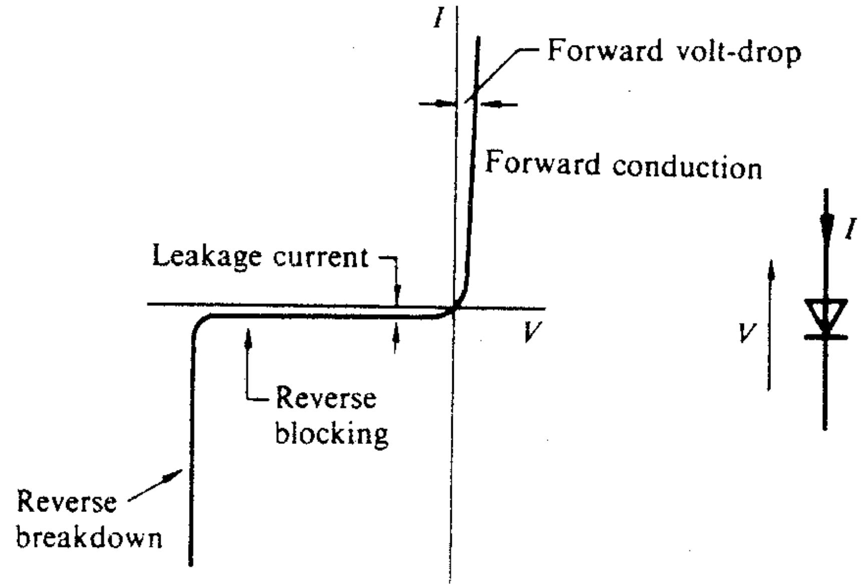
terminal characteristics, rather than the internal physics

current, voltage and switching speed capabilities

1-1. Power diode

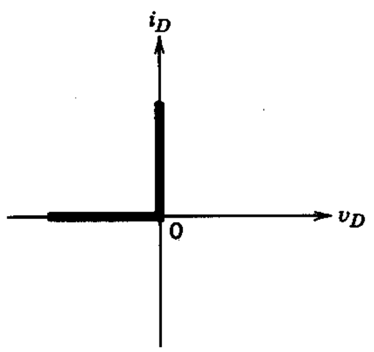


Structure and symbol



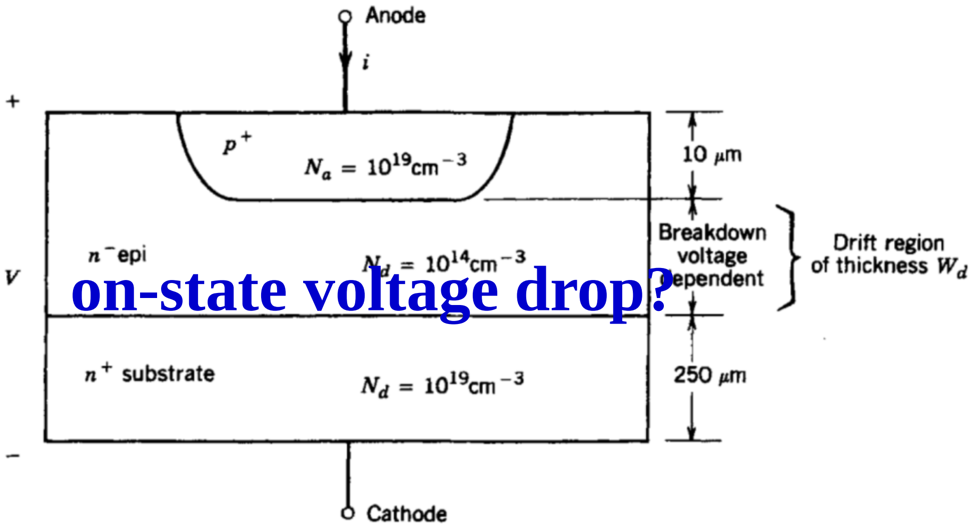
Output Characteristics --- $V_{on\text{-}state} \sim 1\text{-}3V$

$I_{leakage} \sim$ negligible



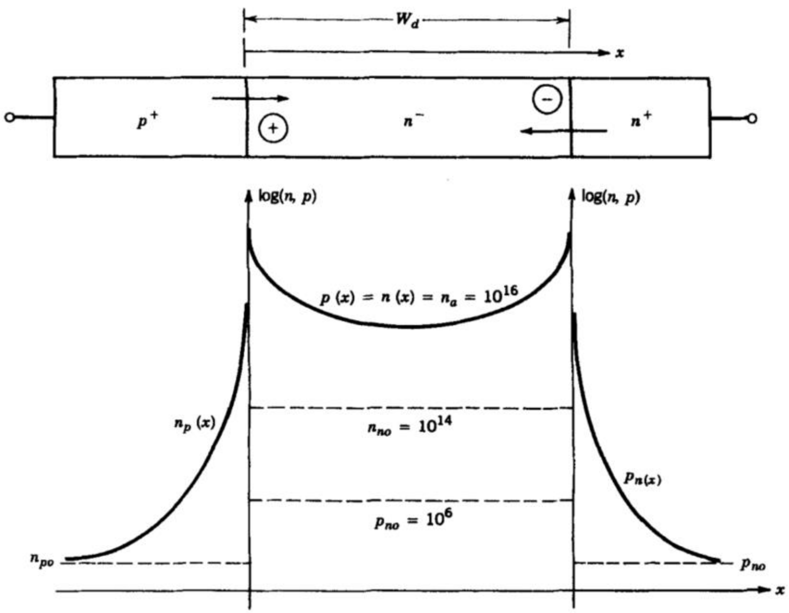
Idealized Characteristics

Most of power diodes are PiN diodes!



on-state voltage drop?

Structure of PiN diode

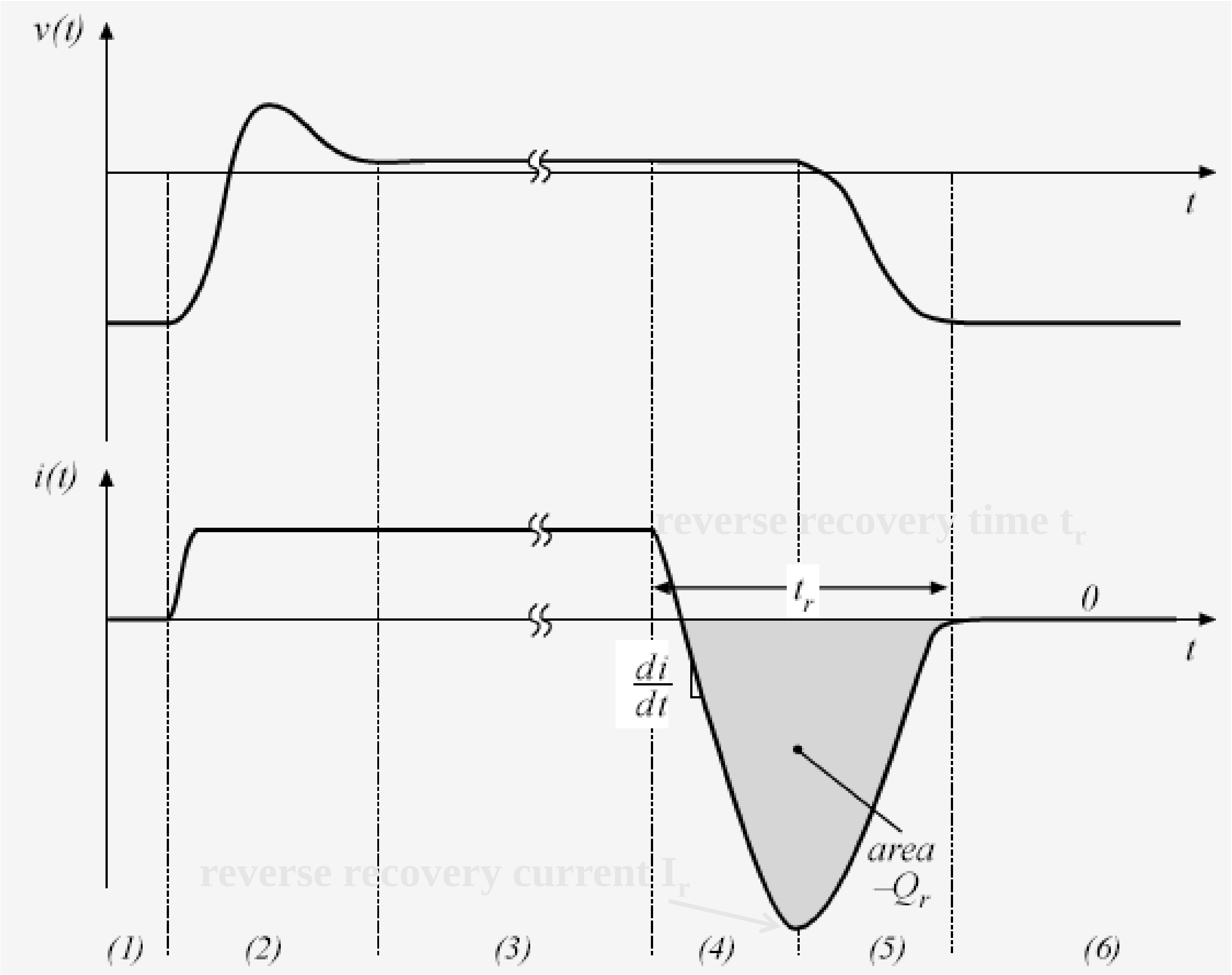


Excess carrier injection in n- region

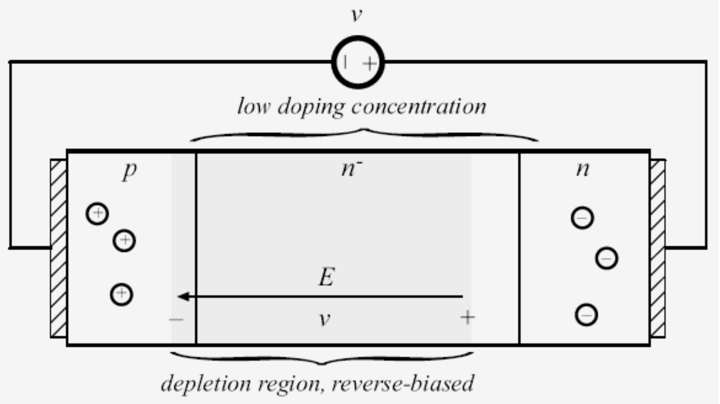
Conductivity modulation: ***on-state resistance is highly reduced due to carrier injection***

Bipolar devices: conduction with both holes and electrons

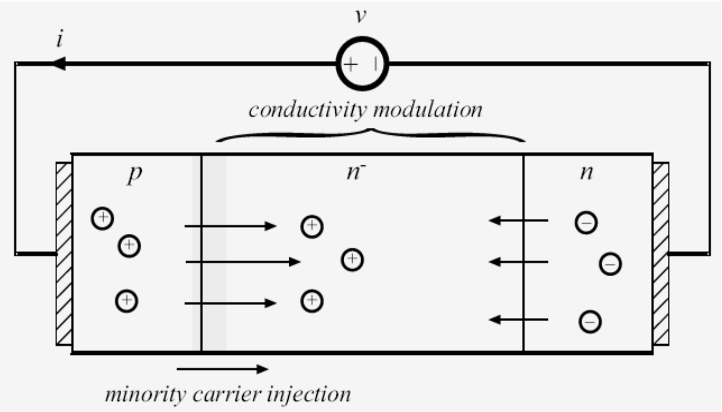
Typical diode switching waveforms



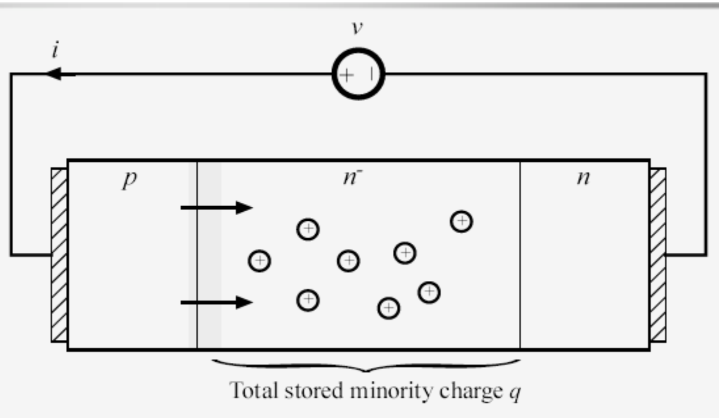
Turn-on transient of a diode



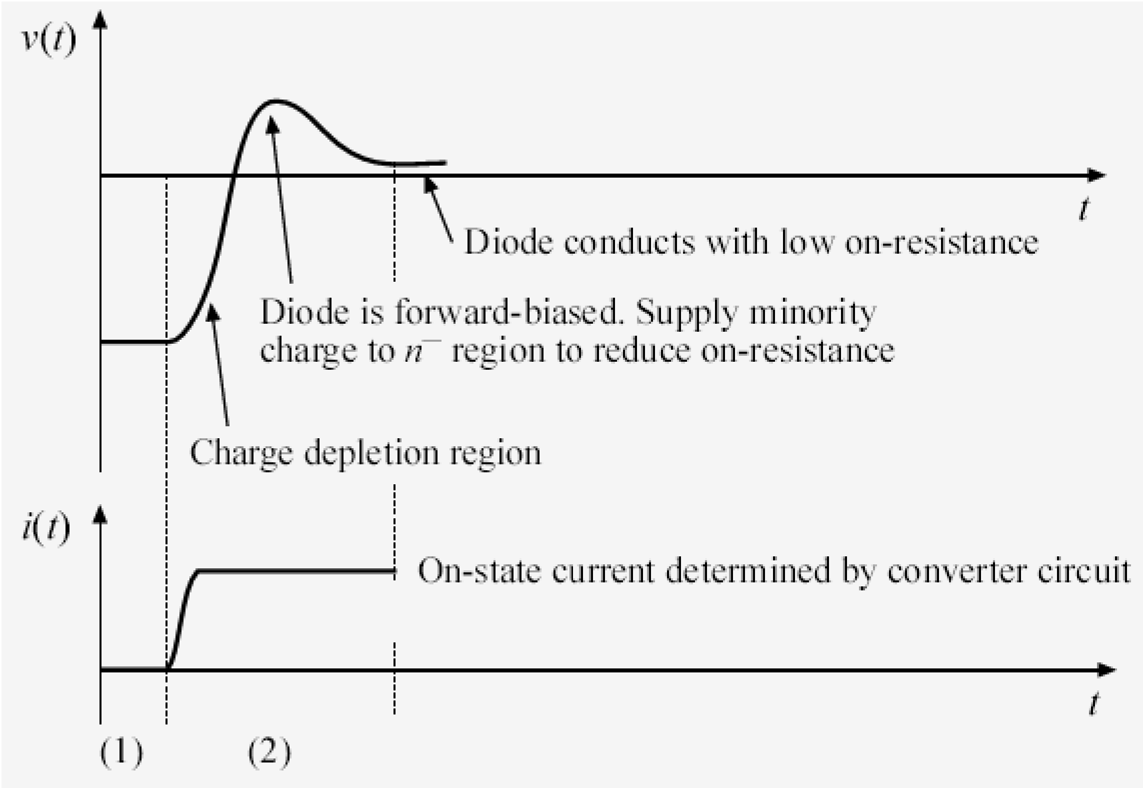
under reverse-biased



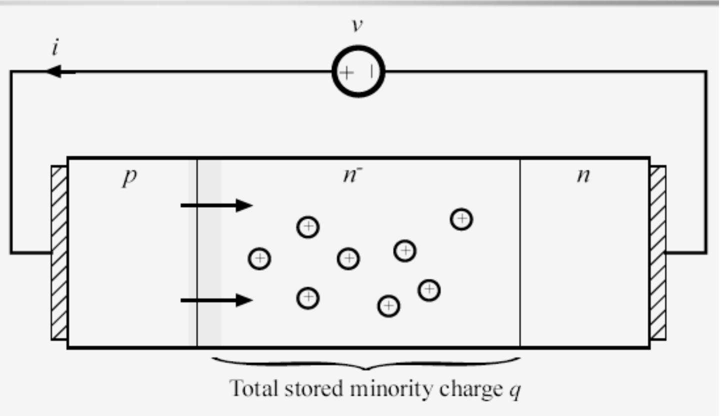
forward-biased



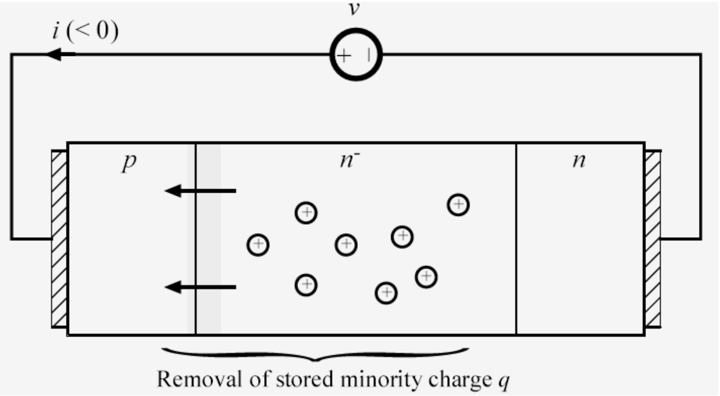
forward-conduction



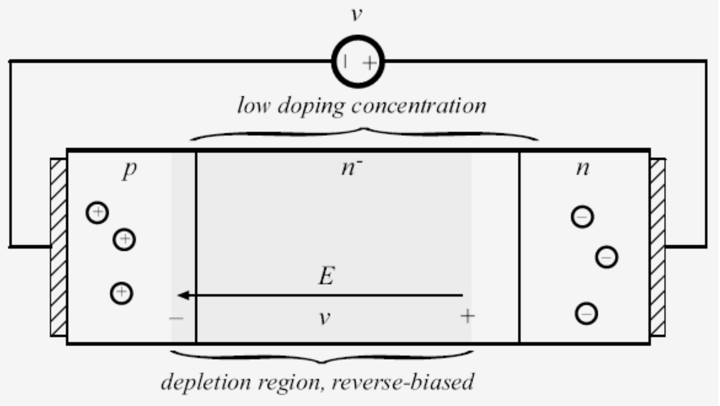
Turn-off transient of a diode



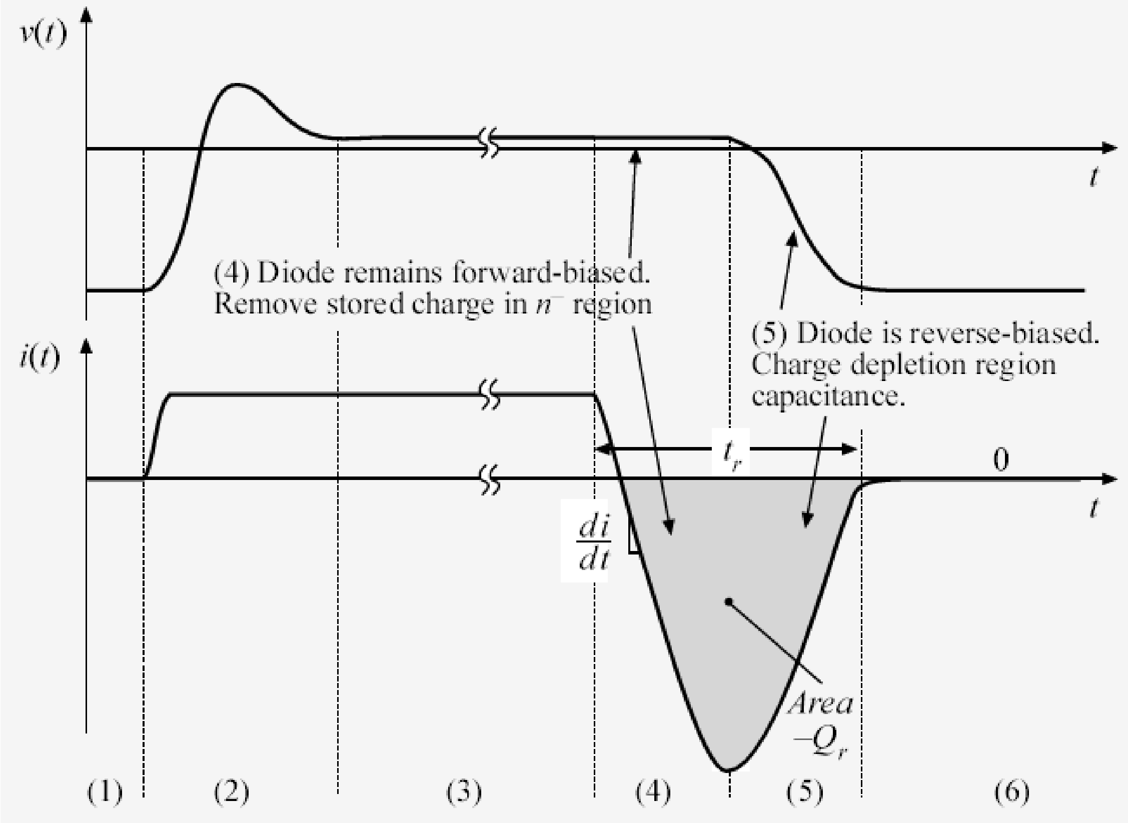
forward-conduction



reverse-biased



under reverse-biased



Power diode : conclusions

- Passive device
- Can conduct positive on-state current
- Turns-off if current tries to reverse
- Can block negative off-state voltage
- Low forward volt-drop, high power ratings, simple construction
- High switching loss, limited switching frequency

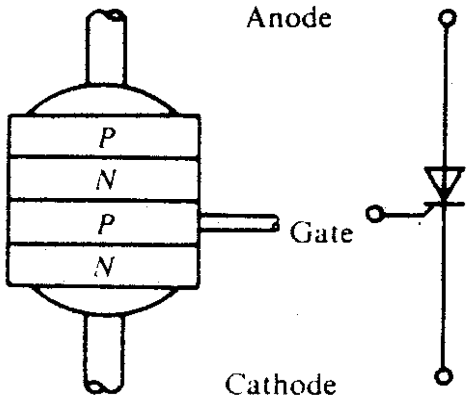
Line-frequency Diodes:

Ratings	up to	9000V, 8400A
Switching time		~ 100μs

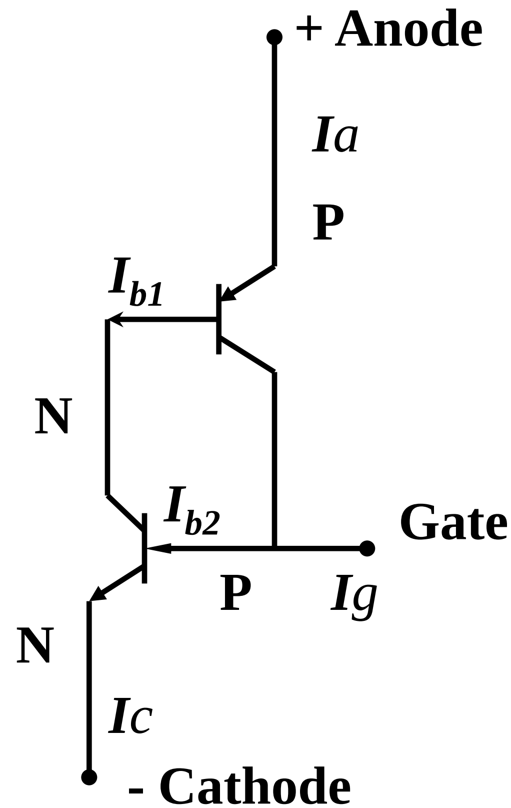
Fast Recovery Diodes:

reverse-recovery time		***< 1μs***
Ratings	up to	4500V, 1000A

1-2. Thyristor (SCR)



Structure and Symbol

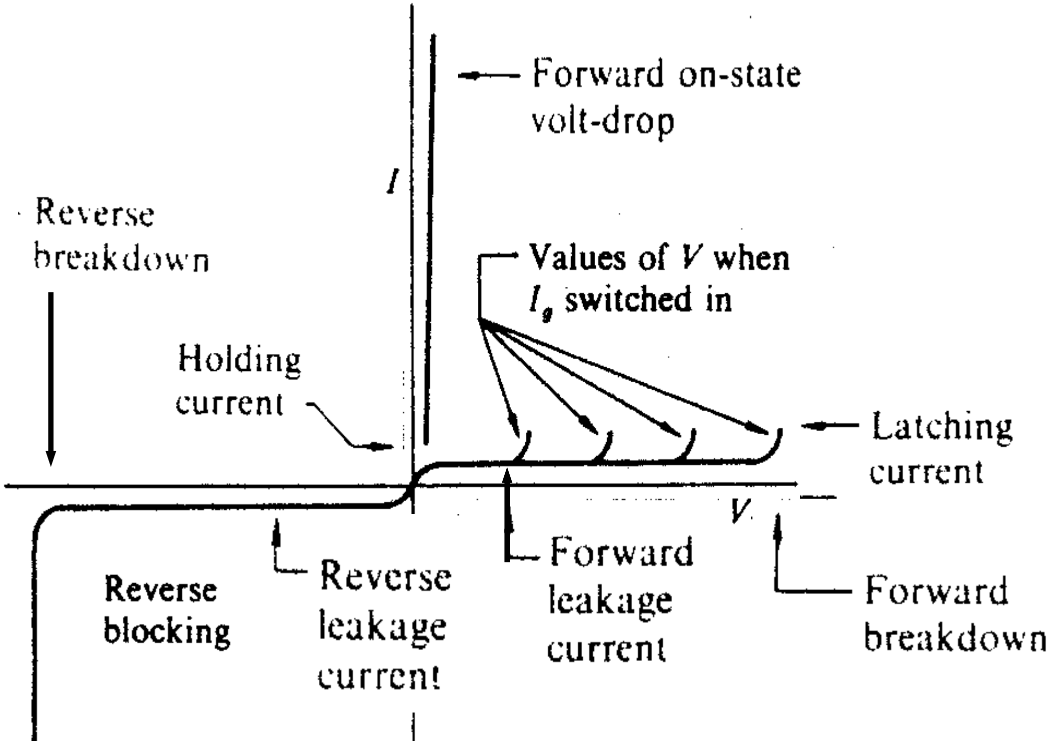


V_{AC} positive

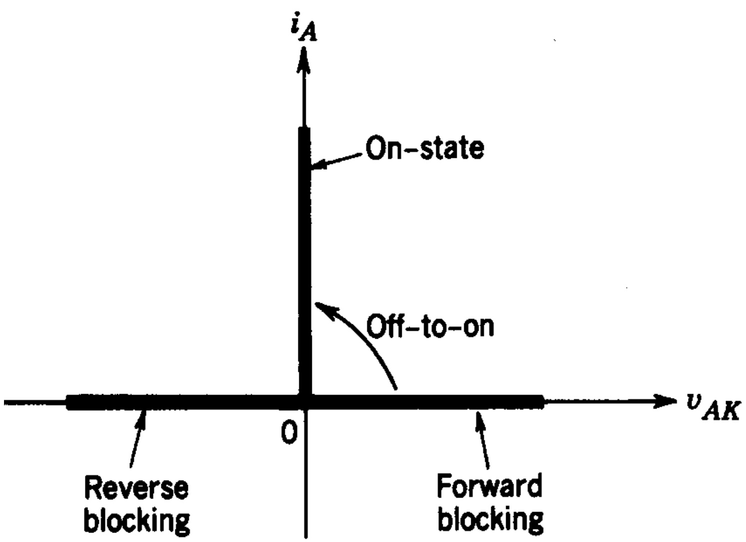
Equivalent Circuit

$$Ig\uparrow \rightarrow I_{b1}\uparrow \rightarrow Ia, Ic\uparrow \rightarrow I_{b2}\uparrow$$

Positive Feedback



Idealized Characteristics



Thyristor Characteristics

$V_{on\text{-}state} \sim$ 1-3V,

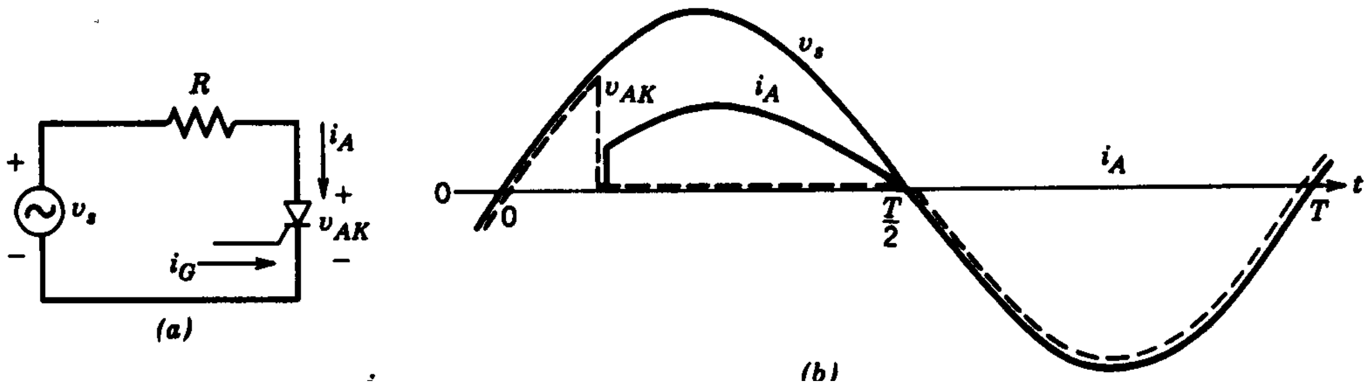
$I_{leakage} \sim$ negligible,

forward breakdown voltage

≈ reverse breakdown voltage,

2 x holding current ≈ latching current.

Thyristor in a Simple Circuit



For successful turn on,

pulse gate current required *with a fast rise and a sufficient length so that the anode current rises over the latching value.*

For successful turn-off,

reverse voltage required *for an interval greater than the turn-off interval so that the blocking junction recovers its blocking state.*

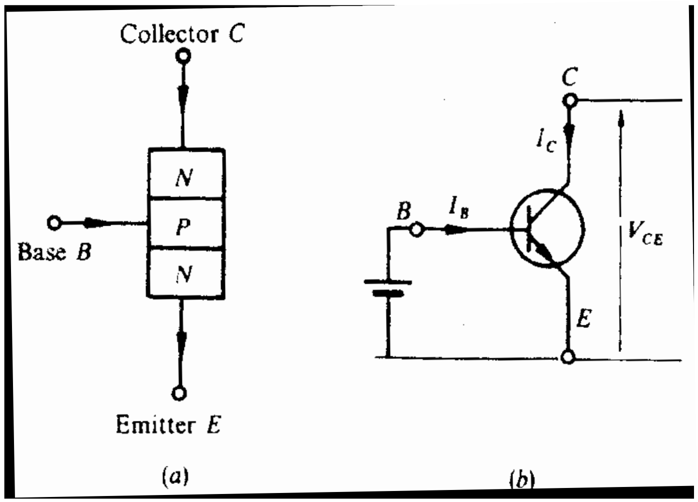
Thyristors : conclusions

- Semi-controlled device
- Latches on by a gate-current pulse if forward biased
- Turns-off if current tries to reverse like the diode
- Voltage-bidirectional blocked
- Low forward volt-drop, high power ratings, simple construction
- High switching loss, limited switching frequency

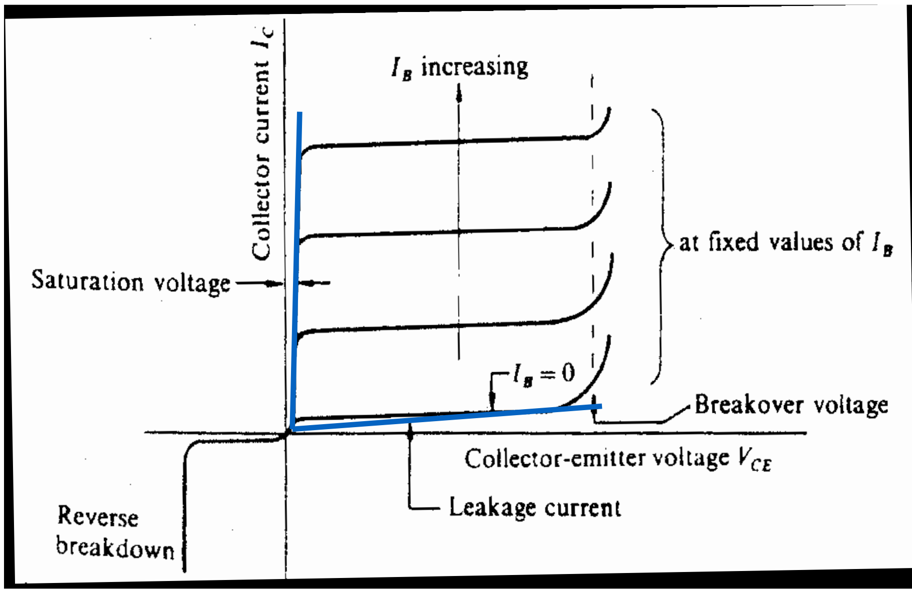
Line-frequency Thyristors

Ratings	up to	9500V, 5000A
Switching time	~	200μs

1-3. Power Transistor (GTR / BJT)

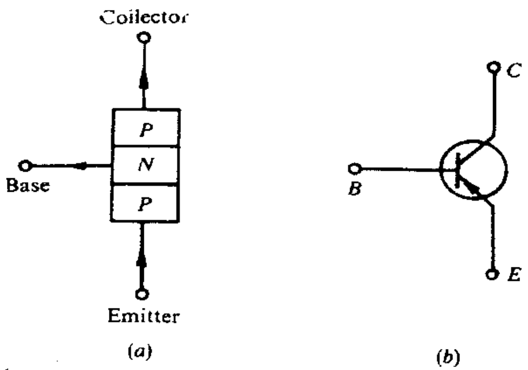


N-P-N Transistor.
(a) Structure. (b) Symbol.

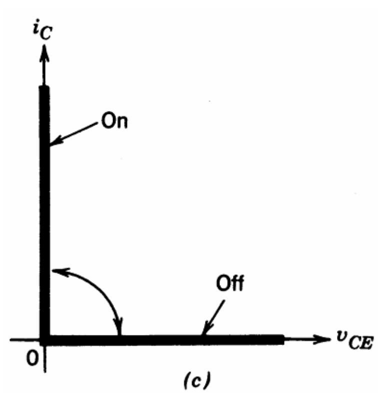


Characteristic for N-P-N Transistor

saturation voltage ($V_{on\text{-}state}$) ~ 1-2V
reverse breakdown voltage ~ small



P-N-P Transistor.
(a) Structure. (b) Symbol.



Idealized Switch Characteristics

Power Transistors

Profile of the base to the collector current

— base current just sufficient to maintain saturation

if too small amplification −V_{CE} high, second breakdown!

if too large deep saturation − turn-off too slow!

a. at turn-on, the base current high enough to give a fast turn-on

b. any change in the collector current matched by a change in the base current

c. at turn-off, the base current is negative-biased in order to speed up the carrier sweep-out

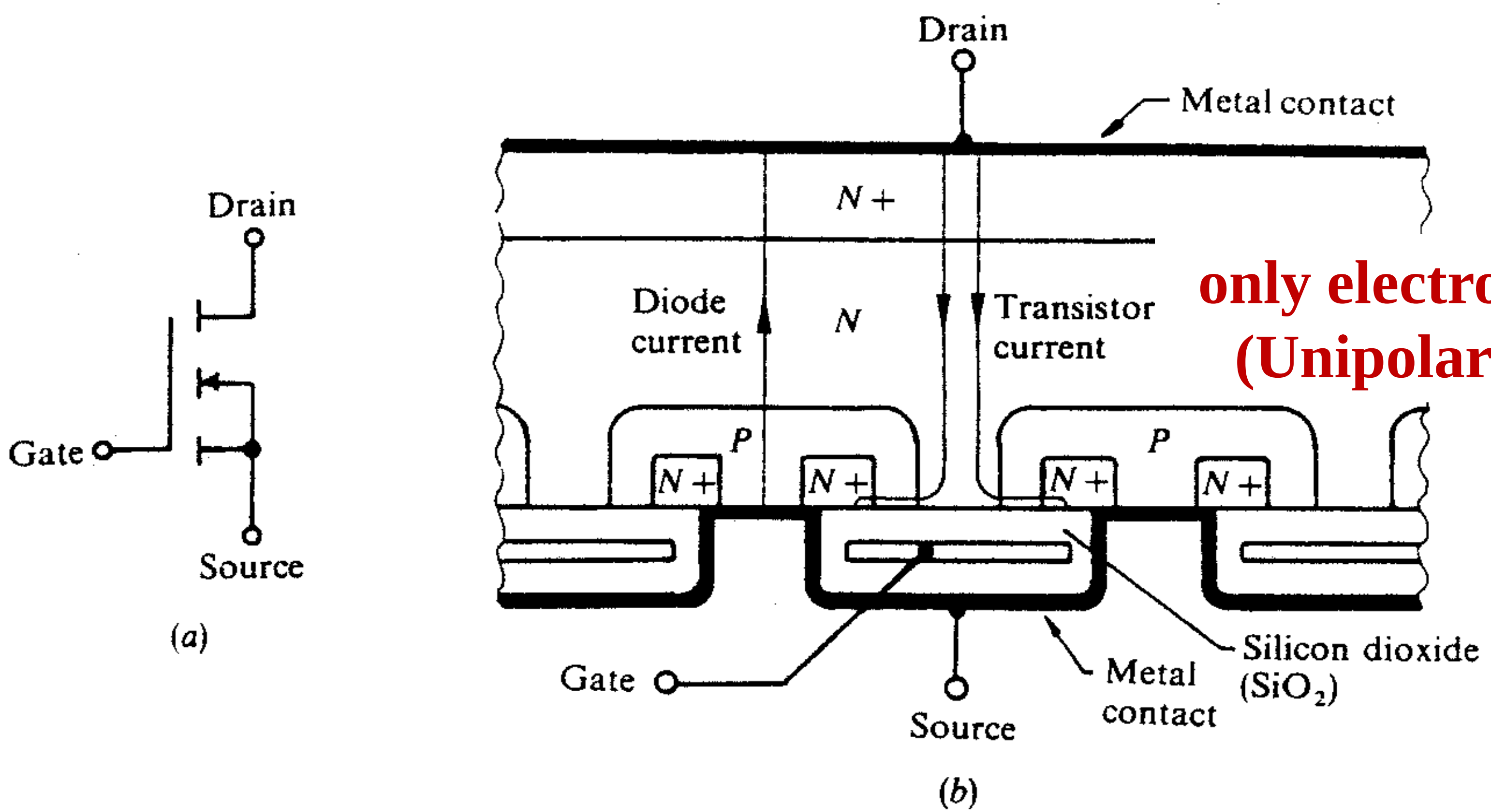
Power Transistors: conclusions

- Complicated base control − high switching loss
- Used commonly in the past
- Now used in specific applications
- Replaced by MOSFETs and IGBTs

Power Transistors

Ratings	up to	1400V, 400A
Switching frequency	up to	10 kHz

1-4. Power MOSFET

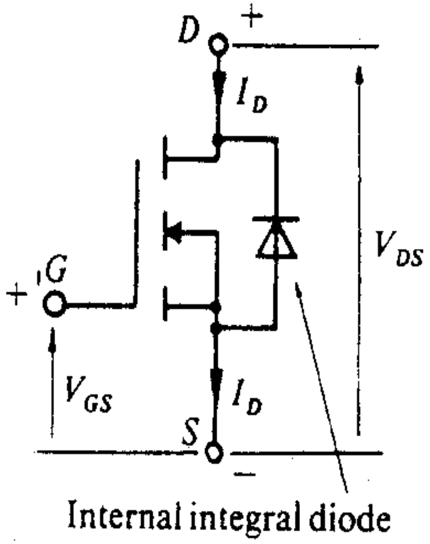


only electrons (Unipolar)

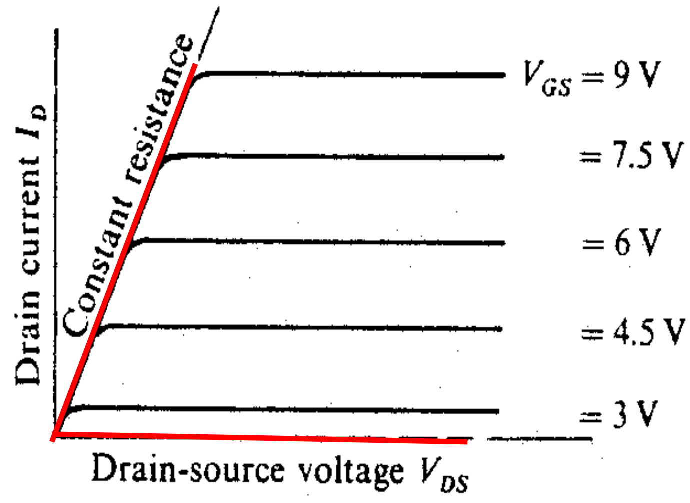
(a) Symbol. (b) Simplified cross-sectional structure.

MOSFET body diode

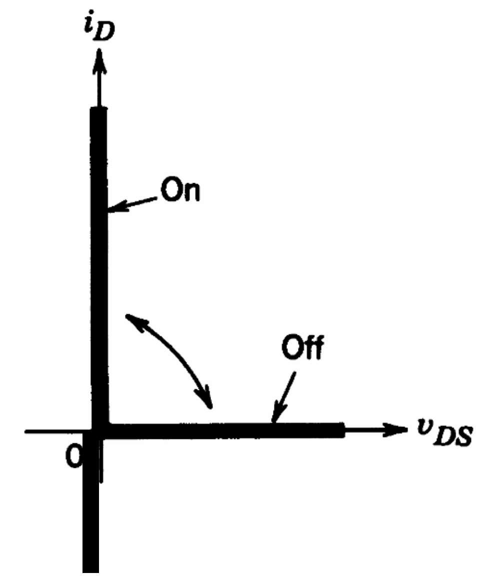
- p-n- junction forms an effective diode, in parallel with the channel
- negative drain-to-source voltage can forward-bias the body diode
- diode can conduct the full MOSFET rated current
- diode switching speed not optimized—body diode slow, Qr large



Electrical circuit.



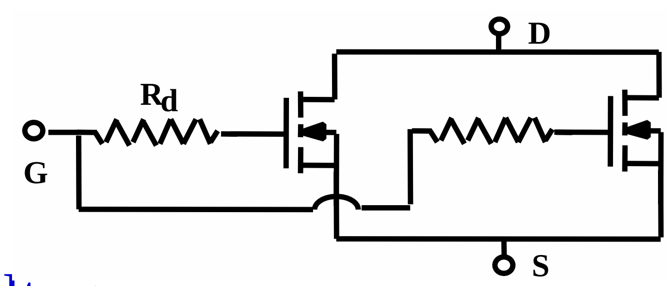
Output characteristic.



Idealized Switch Characteristics

Power MOSFET

* **Very fast switching**
  voltage controlled without any stored charge
* **High conduction loss**
  high constant resistance
* **Low power rating**
  hard to achieve both high current and voltage
* **Positive temperature coefficient for resistance**
  simple paralleling of devices



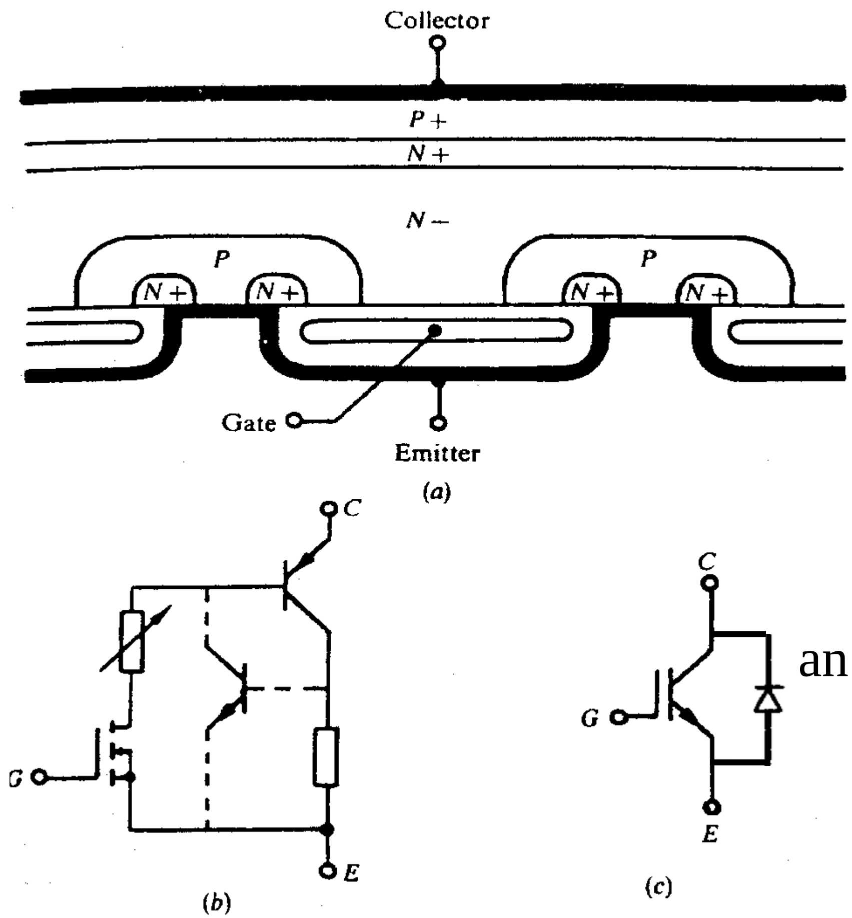
Power MOSFETs: conclusions

- Use gate voltage for control (Easy to drive)
- Forward conduction or blocking, but reverse conduction
- A unipolar device: fast switching speed
- On-resistance increases rapidly with rated blocking voltage

Power MOSFET

Ratings	up to	1200V, 300A
Switching frequency	up to	100 kHz

1-5. IGBT (Insulated Gate Bipolar Transistor)

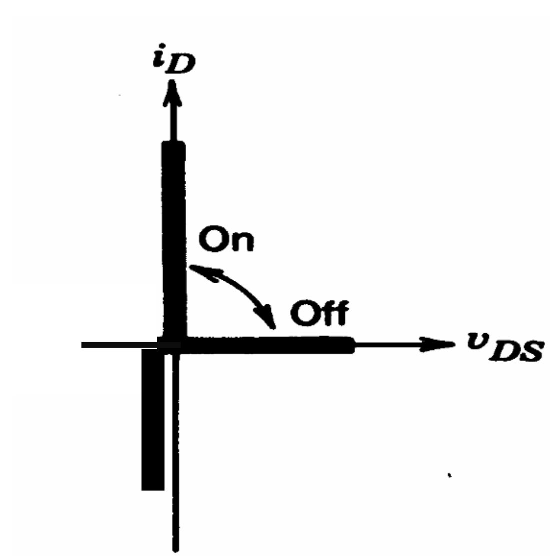


an external diode

(a) Simplified cross-section.

(b) Equivalent electric circuit. (c) Symbol.

The collector-emitter characteristics are similar to those of the power transistor but the control features are those of the MOSFET



Idealized Characteristics

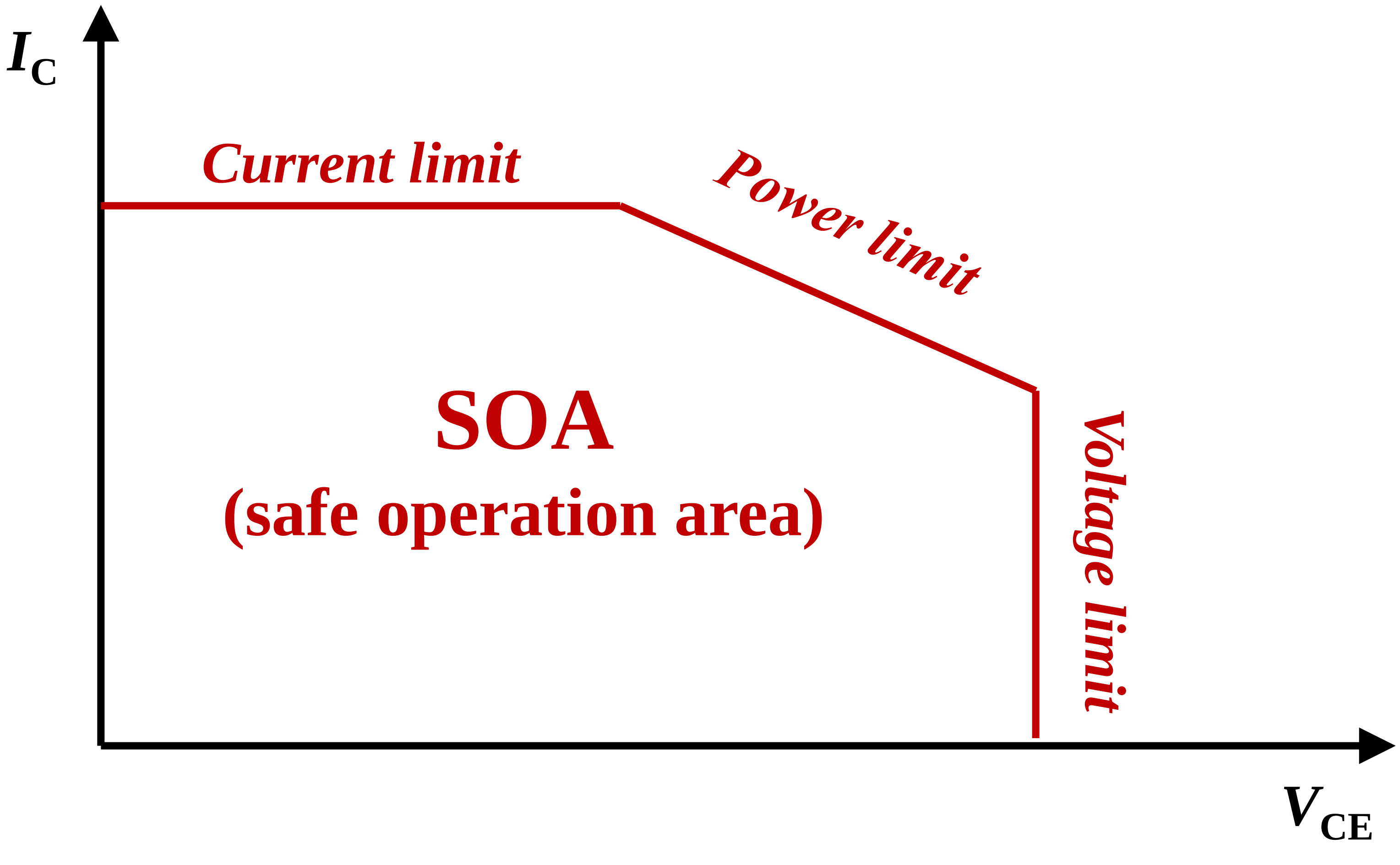
IGBTs: conclusions

- used most widely nowadays in low and medium power applications
- Low forward voltage drop: 2-4V typical
- Easy to drive —similar to MOSFET
- Slower than MOSFET, but faster than BJT

IGBTs (insulated-gate bipolar transistors)

Ratings	up to	6500V, 3600A
Switching frequency	up to	20 kHz

Safe Operating Area of Power Semiconductors



1-6. Device Comparisons

Based on the ideal characteristics:

1. Controlled turn-on and –off

voltage-controlled: MOSFET、IGBT

current-controlled: BJT

SCR (semi-controlled)

2. Zero gate firing power requirement

low : MOSFET、IGBT

medium: SCR、 BJT

3. Zero conduction loss

low : SCR

medium: BJT 、 IGBT

high : MOSFET

(Continued)

4. Unlimited voltage and current ratings

high:	SCR
medium:	IGBT、BJT
low:	MOSFET

5. Instant turn-on and –off times

high:	MOSFET
medium:	IGBT、BJT
low:	SCR

6. Low cost

low :	SCR
medium:	BJT、 IGBT
high :	MOSFET

Research and development work is constantly being undertaken to improve the present devices and to develop new devices closer to the ideal electronic switches ——

being able to handle power larger and larger

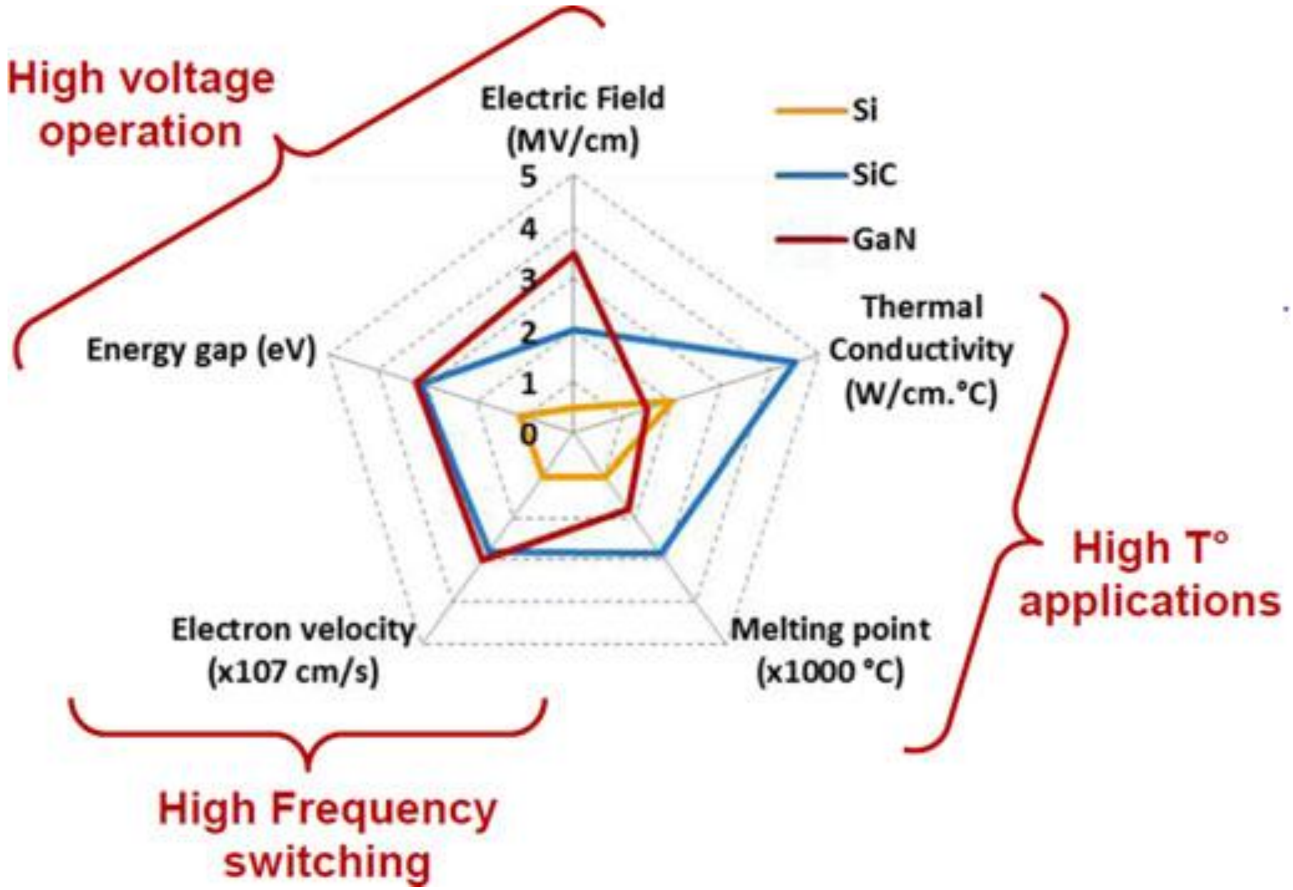
with switching speed faster and faster

by control easier and easier .

Today, the IGBT is the most important device for medium-to-high power applications. The high-power, integrated gate-commutated thyristor (IGCT) was introduced by ABB in 1997. Currently, it is a competitor to the high-power IGBT, but it is gradually losing the race.

Although silicon has been the basic raw material for current power devices, **large-bandgap materials, such as SiC and GaN, are showing great promise**. SiC devices, such as the Schottky barrier diode (1200V/50A), the power MOSFET (1200V/100A half-bridge module), and the JBS diode (600V/20A), are already on the market, and the p-i-n diode (10 kV) and IGBT (15 kV) will be introduced in the future.

Power Electronics—Historical Perspective and My Experience
by Bimal Bose (2014)

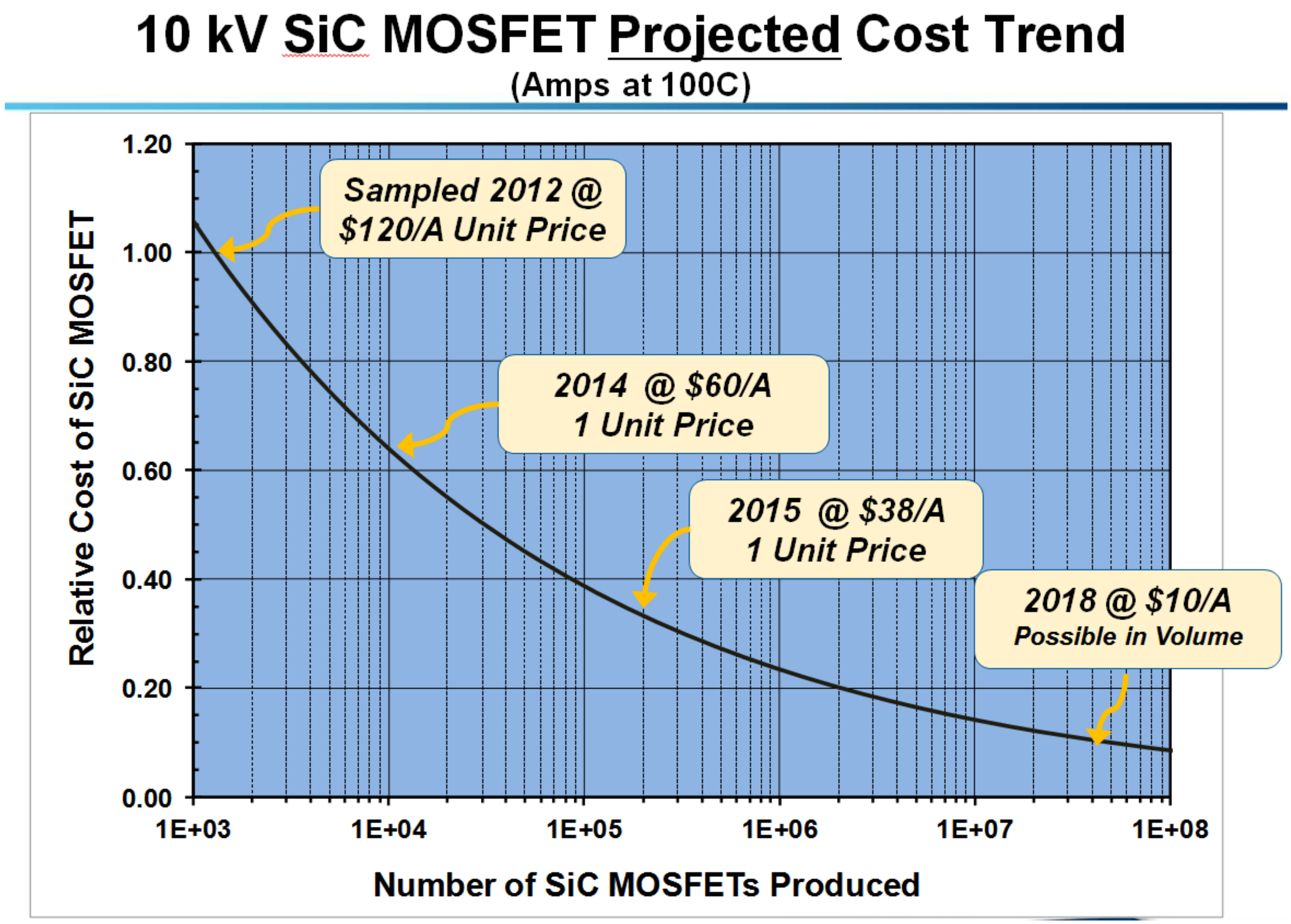


A Survey of Wide Bandgap Power Semiconductor Devices

by José Millán etc., 2014

Review of Commercial GaN Power Devices and GaN-Based Converter Design Challenges

by Edward A. Jones etc., 2016



Silicon Carbide High Voltage, High Frequency Conversion
by Raju R., 2014.

Summary:

- What are key performance of power semi.? Why are they important?
- Several types of power semi.: diode, SCR, BJT, MOSFET, IGBT
- Basic operation principles (idealized characteristics, control)
- Key characteristics including conduction and switching, etc.
- Reasons causing these characteristics

The End