

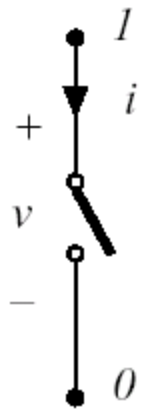
EEL 5245 POWER ELECTRONICS I
Lecture #4: Chapter 2
Switching Concepts and Semiconductor Overview

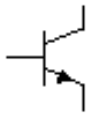
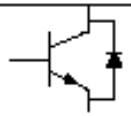


Objectives of Lecture

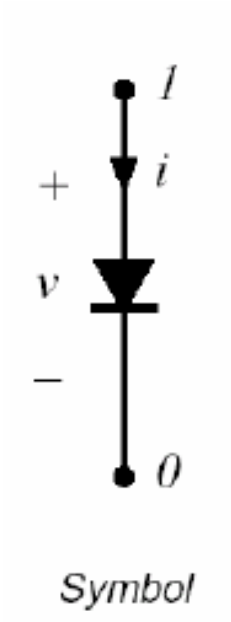
- Switch realizations
- Objective is to focus on terminal characteristics
  - Blocking capability
  - Conduction direction
- Device loss mechanisms
- Qualitative relationships between
  - On state resistance
  - Breakdown Voltage
  - Switching Time
- Survey of some commonly available commercial products
- Comparison of Switching Devices

Switch Classifications

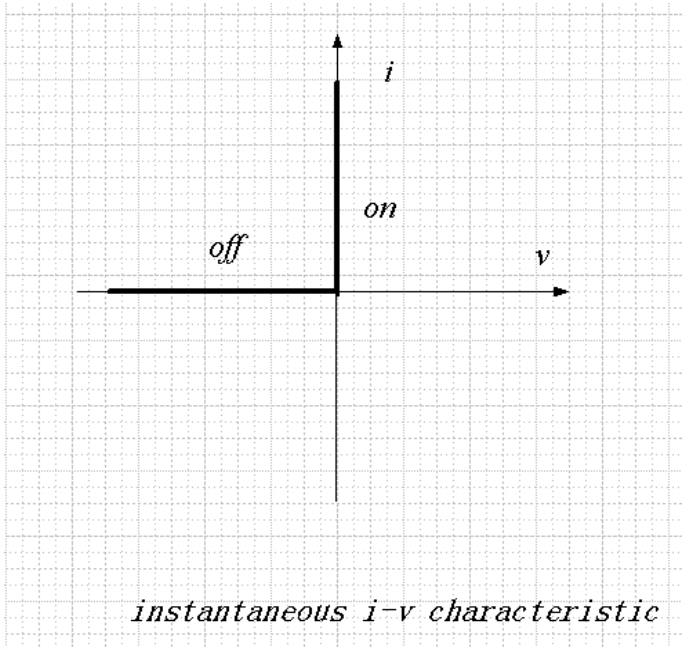


Type	Current Flow	Voltage Blocking	Switch implementation
1	Forward	Reverse	 Diod
2	Forward	Forward	 Transistor
3	Forward	Bi-directional	 SCR
4	Bi-directional	Forward	 Transistor with flyback Diod
5	Bi-directional	Bi-directional	 Triac

Switch Realizations-Power Diode



Symbol

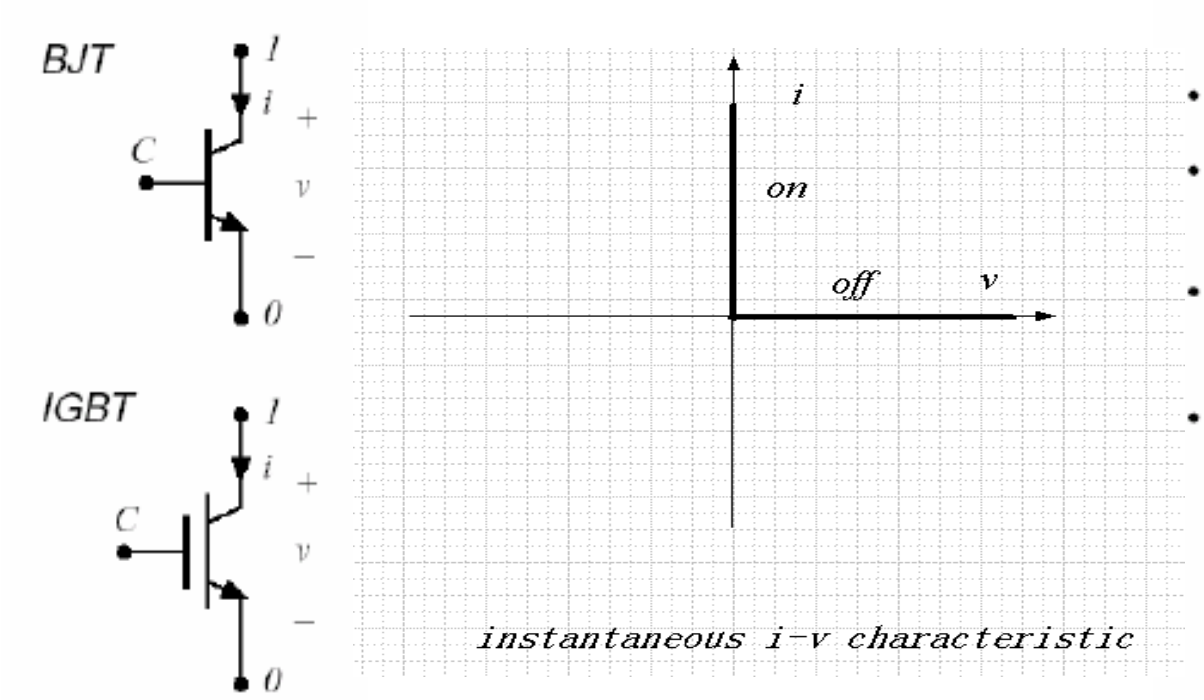


instantaneous i-v characteristic

- *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*

- **Passive means no active means of control**
- **Device conducts in forward direction in response to positive forward voltages**
- **Devices turns off with negative forward voltage**

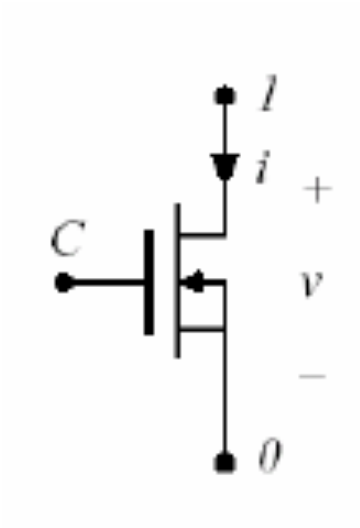
Switch Realizations-BJT/IGBT

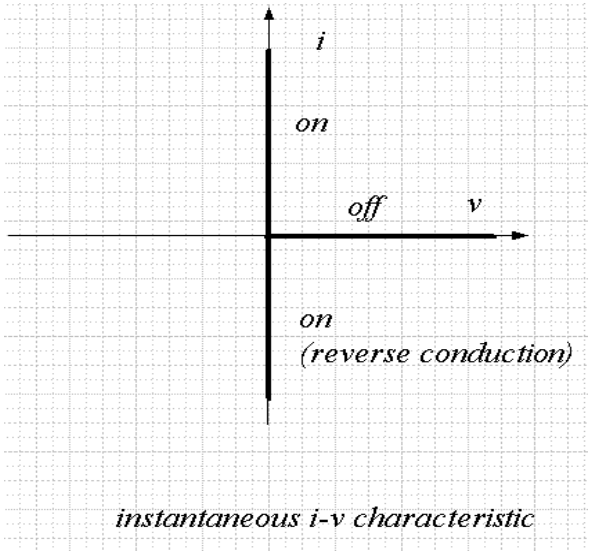


- *An active switch, controlled by terminal C*
- *Single-quadrant switch:*
- *can conduct positive on-state current*
- *can block positive off-state voltage*
- *provided that the intended on-state and off-state operating points lie on the transistor i-v characteristic, then switch can be realized using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

- **Active-controlled turn on and turn off**
- **BJT conduct in forward direction in response to control current at C**
- **IGBT conduct in forward direction in response to control voltage at C (wrt terminal 0)**
- **Devices turns off when control signal removed**

Switch Realizations-MOSFET



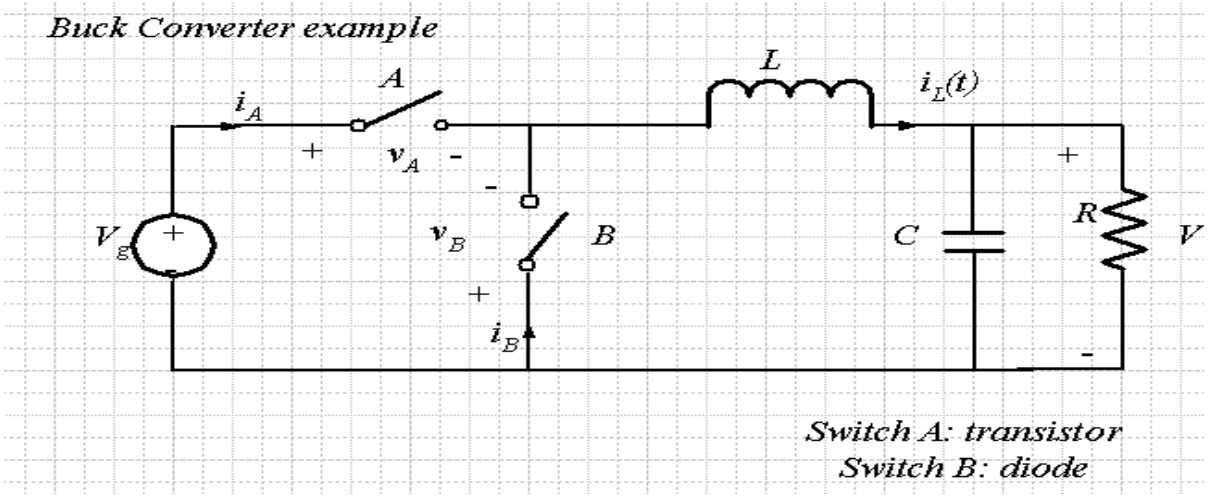


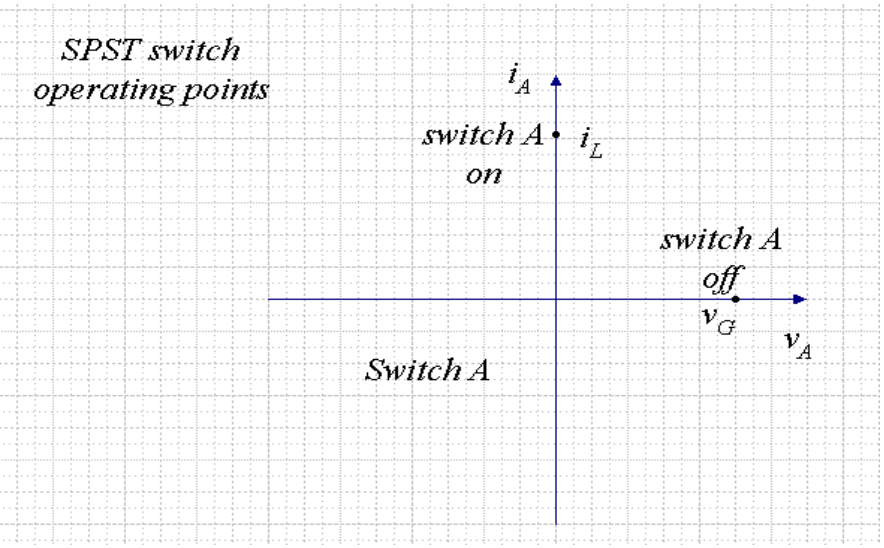
instantaneous i-v characteristic

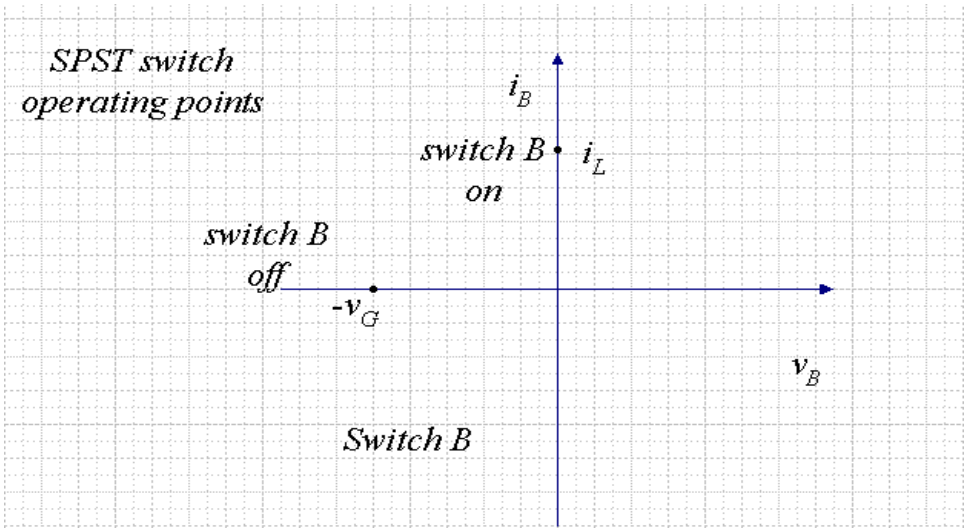
- *An active switch, controlled by terminal C*
- *Normally operated as single-quadrant switch:*
- *can conduct positive on-state current (can also conduct negative current in some circumstances)*
- *can block positive off-state voltage*
- *provided that the intended on-state and off-state operating points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

- **Active-controlled turn on and turn off**
- **MOSFETs conduct in forward direction in response to control voltage at C (wrt terminal 0)**
- **Devices turns off when control signal removed**

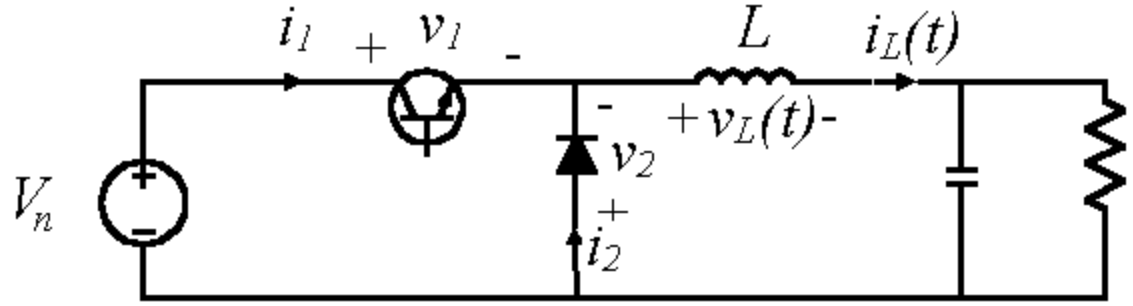
Switch Realizations-SPST

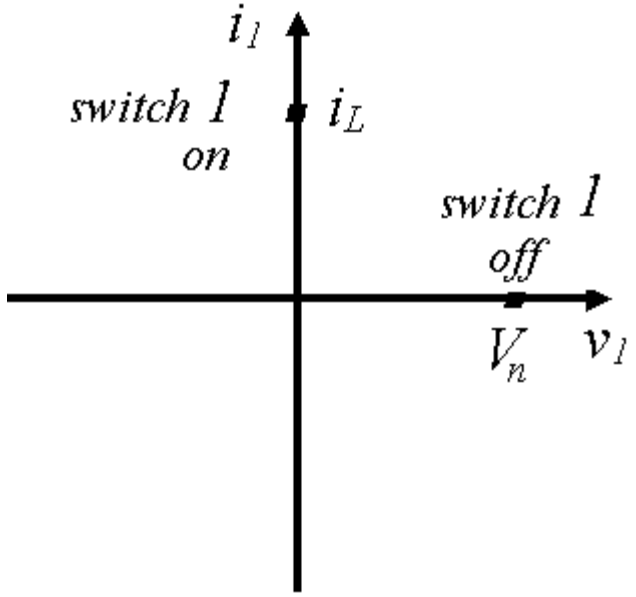


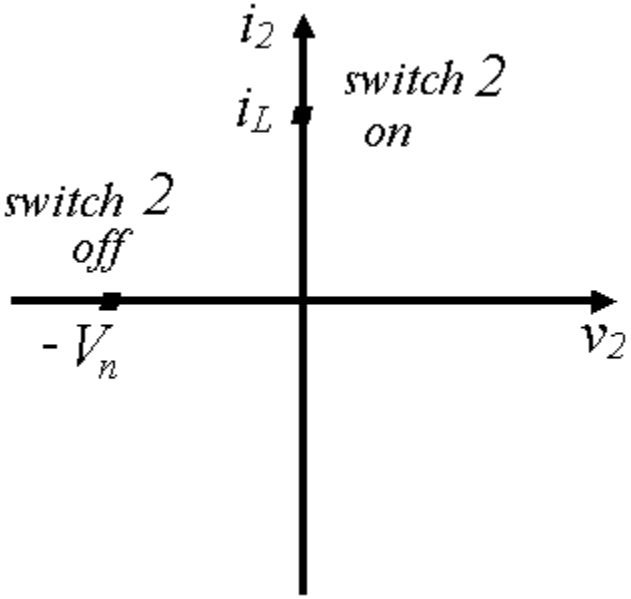




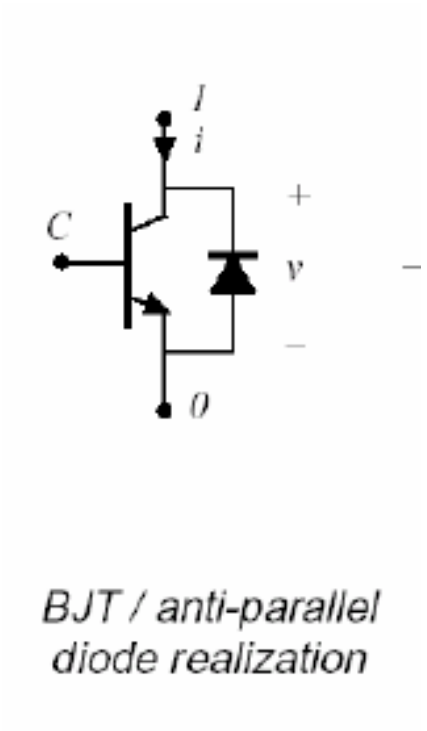
Switch Realizations-BJT and Diode

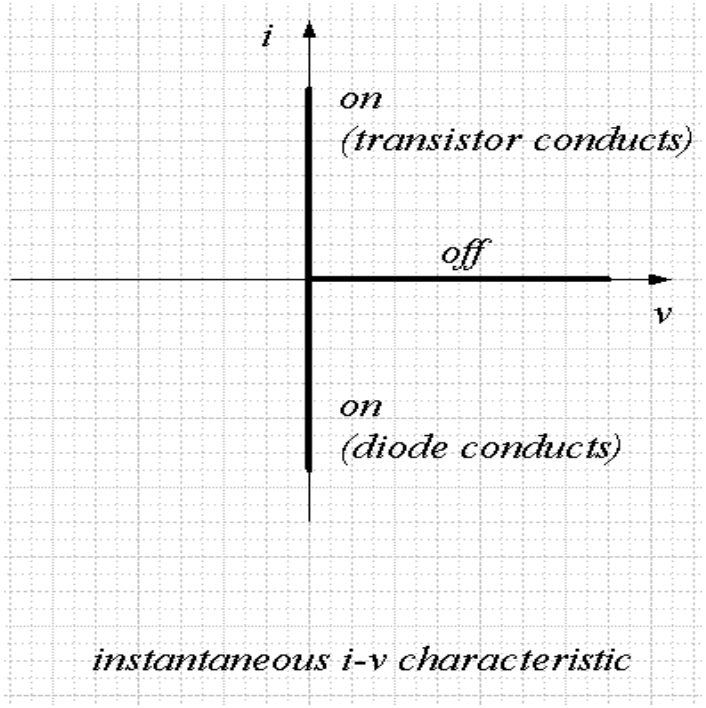






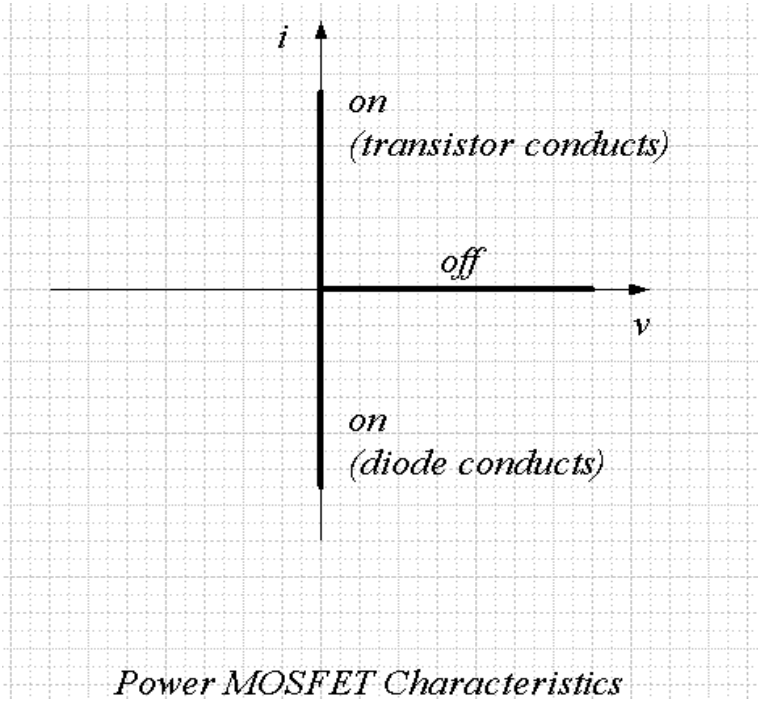
Switch Realizations- Anti-parallel Diode



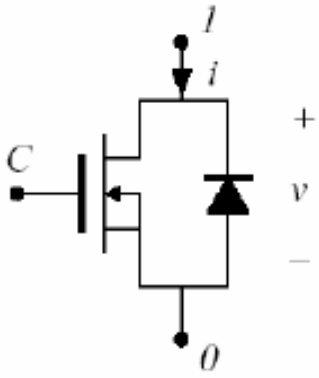


- **Usually an active switch, controlled by terminal C**
- **Normally operated as two-quadrant switch :**
- **Can conduct positive or negative on-state current**
- **can block positive off-state voltage**
- **provided that the intended on-state and the off-state operating points lie on the composite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

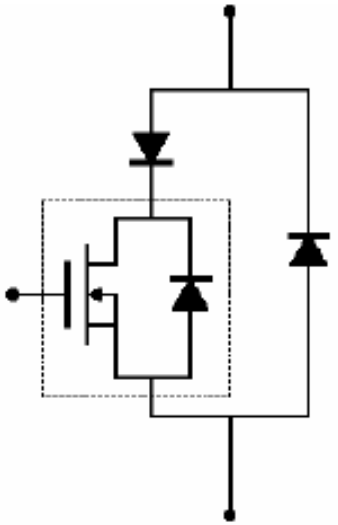
Switch Realizations- MOSFET Body Diode



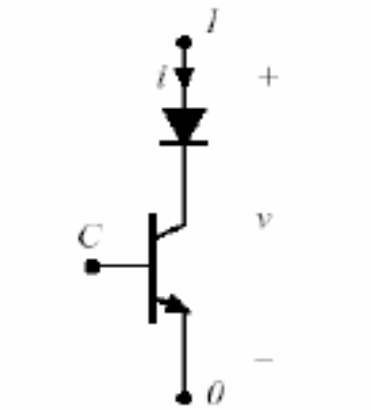
Power MOSFET Characteristics



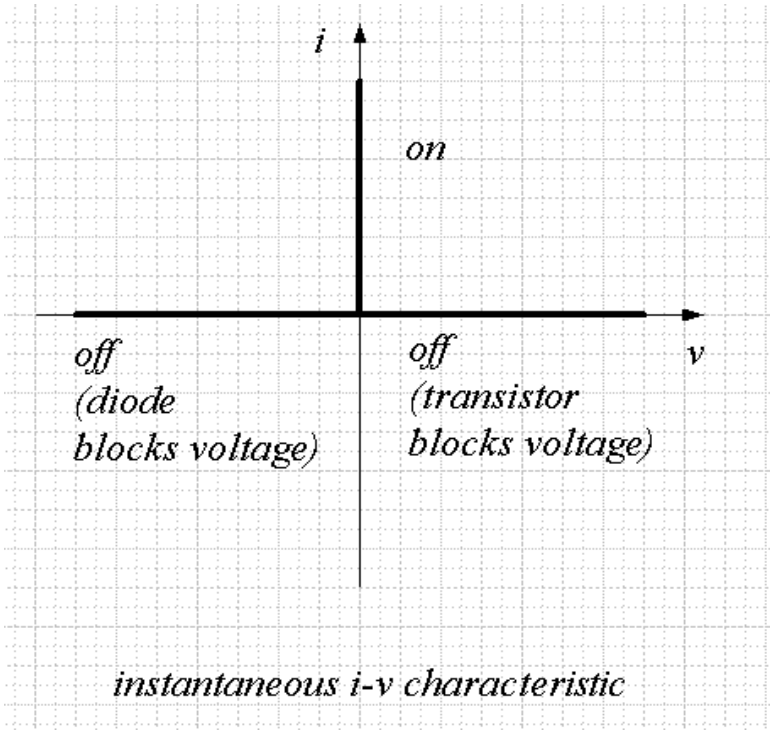
Power MOSFET, and its integral body diode


Use of external diodes to prevent conduction of body diode

Switch Realizations- Bidirectional Voltage Blocking-SCR



BJT / series diode realization

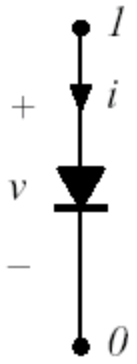


instantaneous i-v characteristic

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

- **Thyristor family also has this i-v characteristic**
  - **Silicon Controller Rectifier (SCR)**
  - **Gate Turn Off Thyristor (GTO)**

Power Diode Overview



- **Diode**
  - **Minority carrier device**
  - **Passively controlled device**
  - **Controlled by external circuitry**
    - **Forward Bias to turn on**
    - **Reverse Bias to turn off**
  - **Relatively low on state conduction losses**
  - **Turn-on is to charge the depletion capacitor across the pn-junction**
  - **Turn-off is more complex.**

Diode Switching Characteristics
Conventional

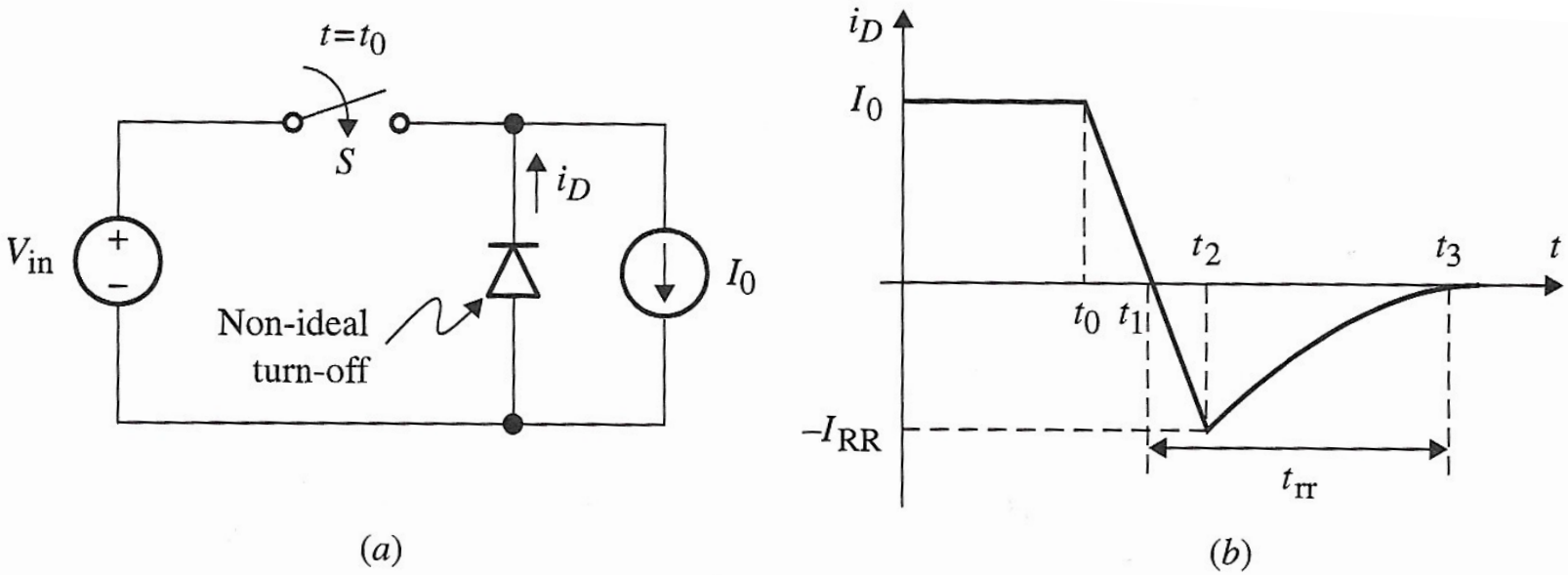
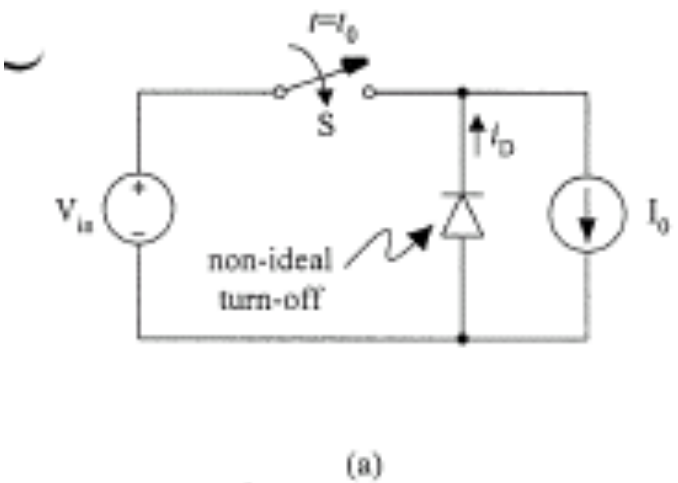


Figure 2.9 Typical diode switching characteristics. (*a*) Switching circuit with *S* closed at $t = t_0$. (*b*) Diode current.

Diode Switching Characteristics
Conventional

Example:



(a)

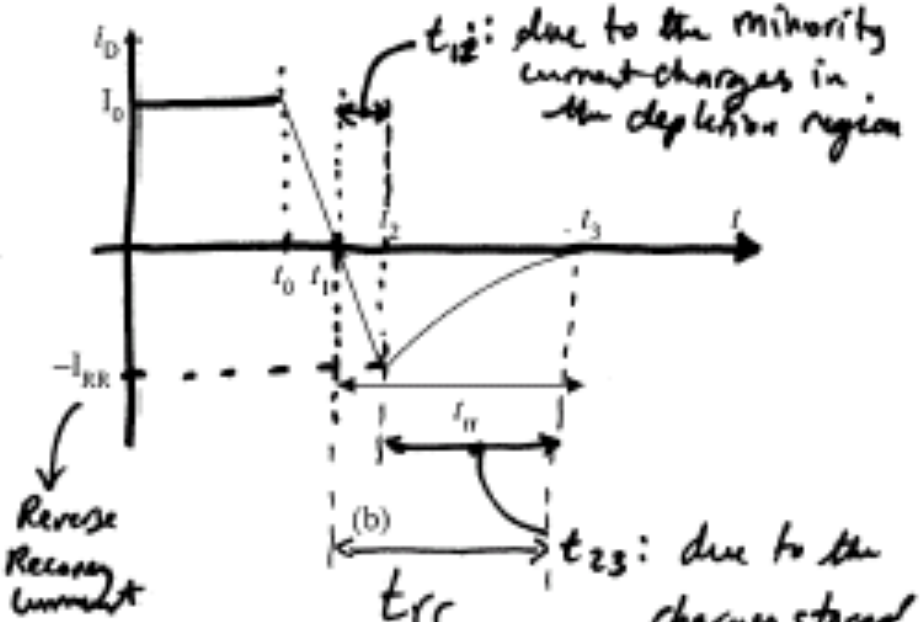


Fig. 2.9

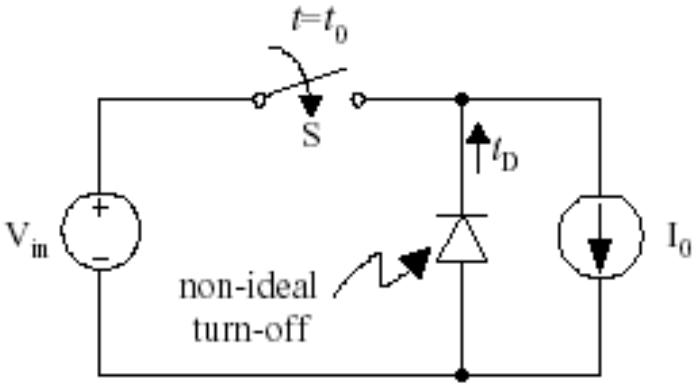
Assume
- Ideal switch
- D has finite t_{rr}
- The diode is turned off at $t=t_0$
  (S is turned ON)

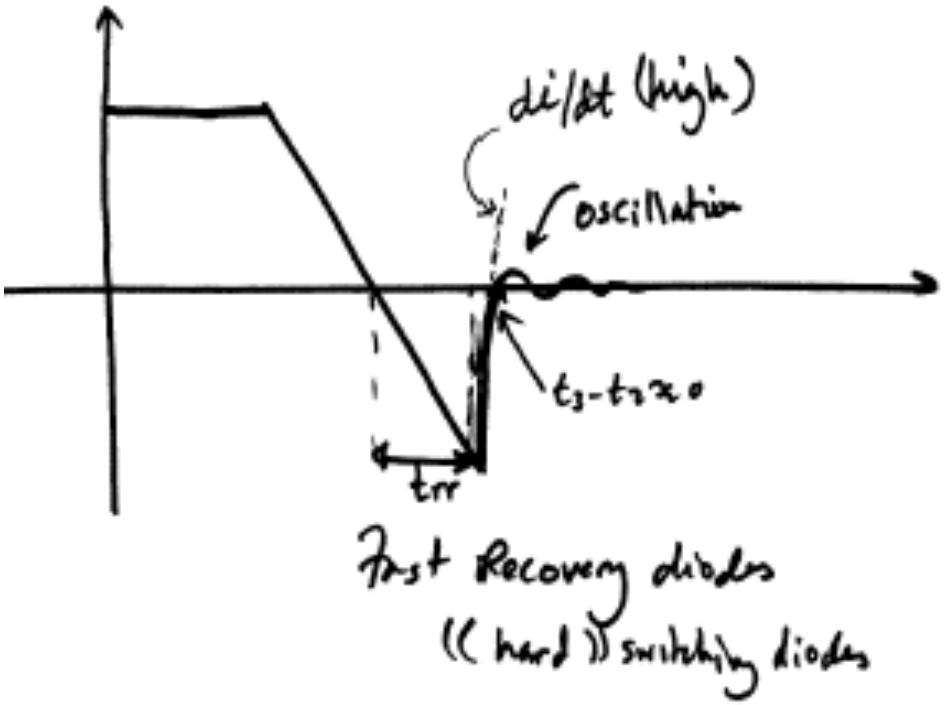
$$t_{rr} = t_{12} + t_{23}$$

t_{12}: depletion region

t_{23}: bulk region.

Diode Switching Characteristics
Fast Recovery Type





Types of Power Diodes

Standard recovery

- Reverse time not specified, intended for 50/60 Hz

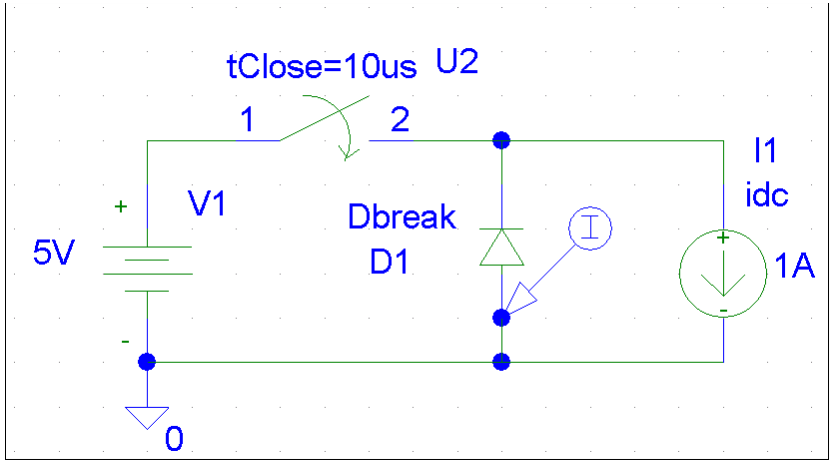
Fast recovery and ultra-fast recovery

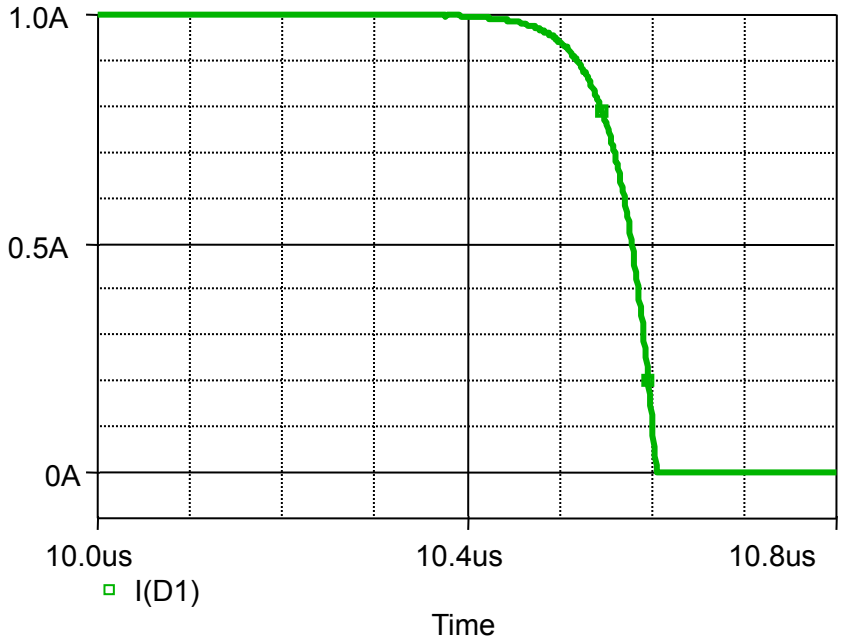
- Reverse recovery time and recovered charge specified
- Intended for converter applications

Schottky diode

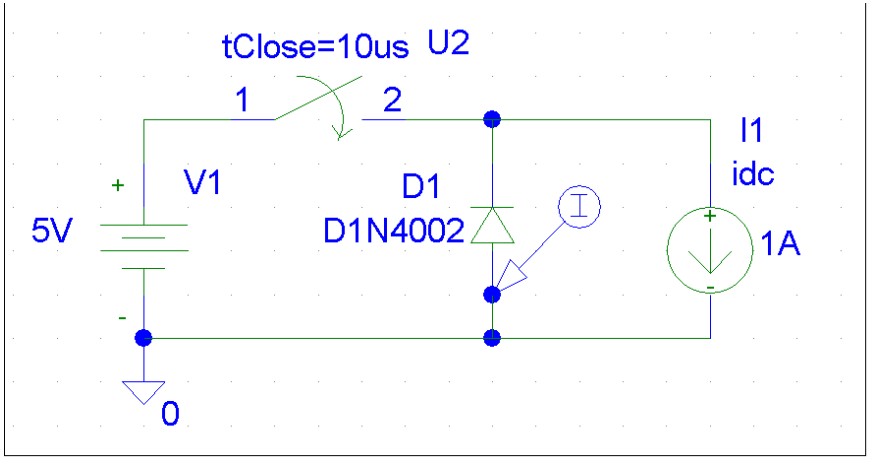
- A majority carrier device
- Essentially no recovered charge
- Model with equilibrium I-V characteristic, in parallel with depletion region capacitance
- Restricted to low voltage (few devices can block 110V or more)

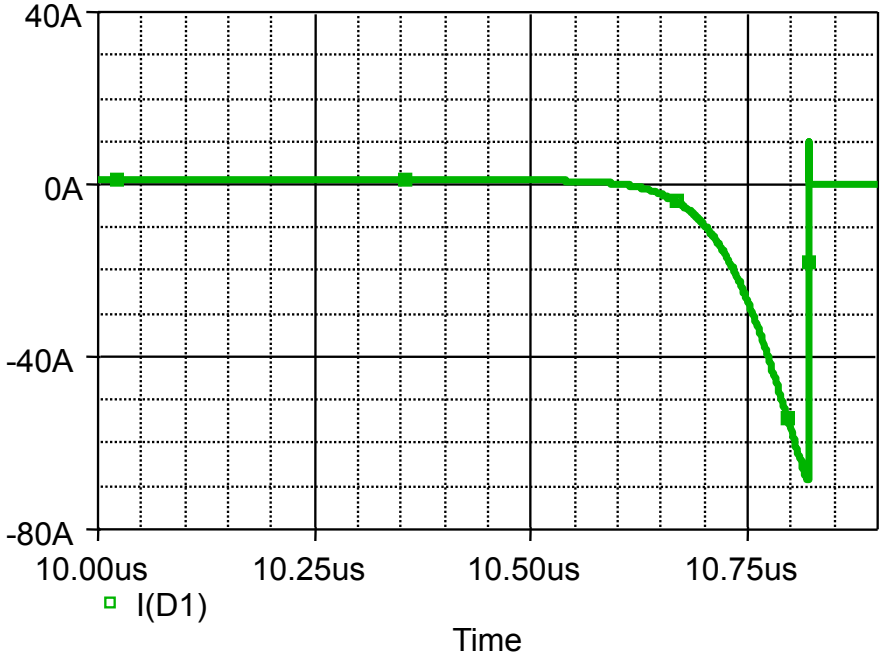
Diode Switching Characteristics Simulation-Dbreak

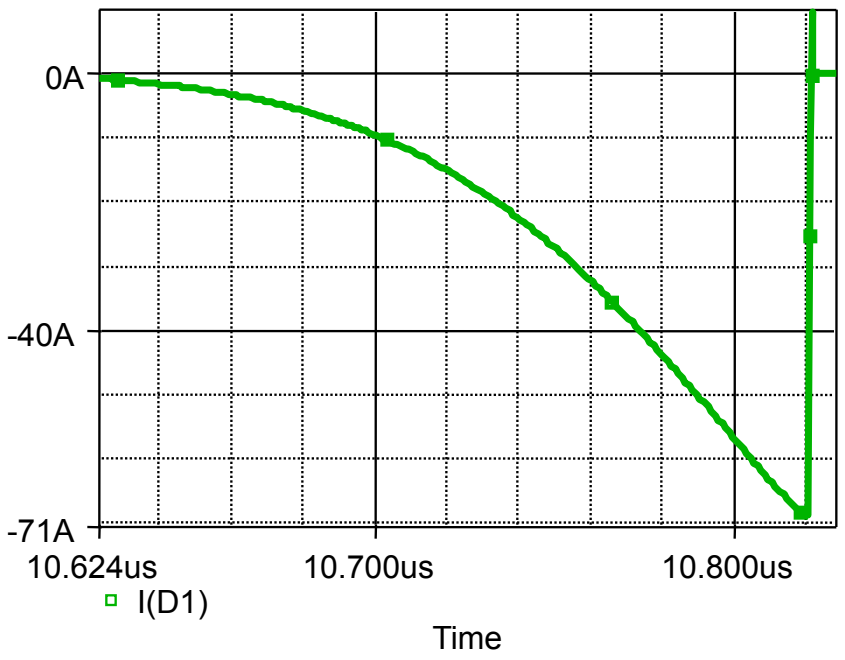




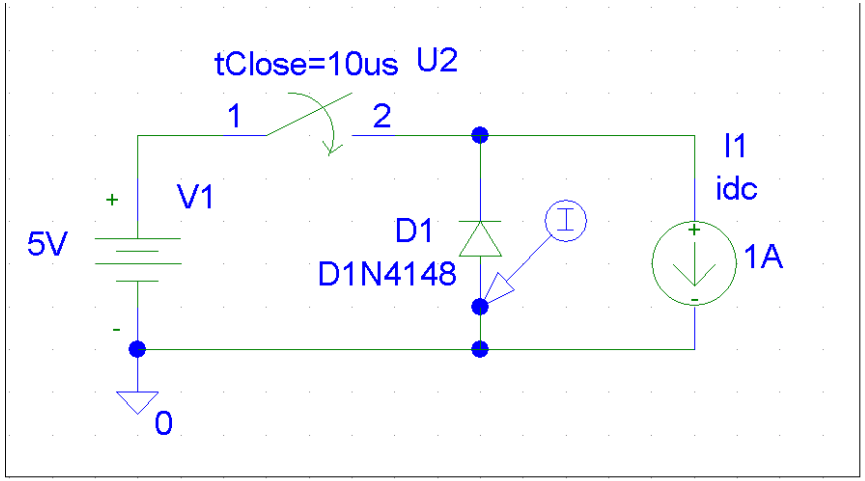
Diode Switching Characteristics Simulation-1N4002 General Purpose

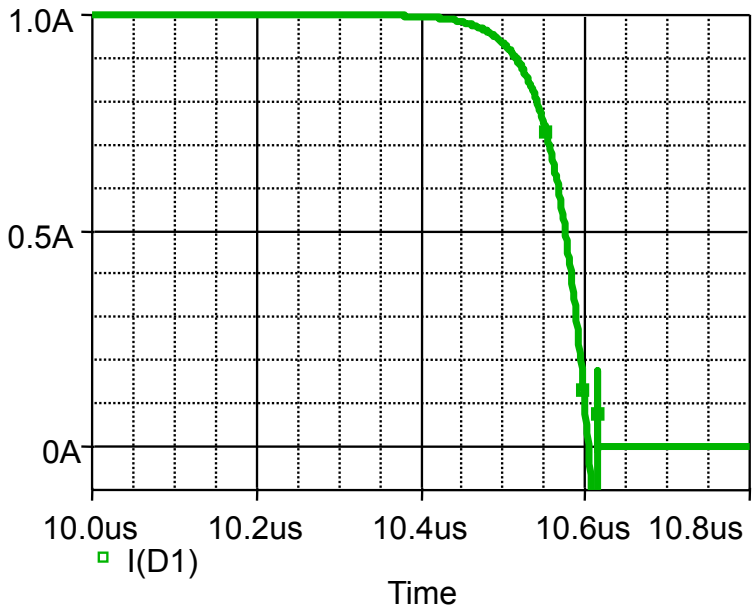


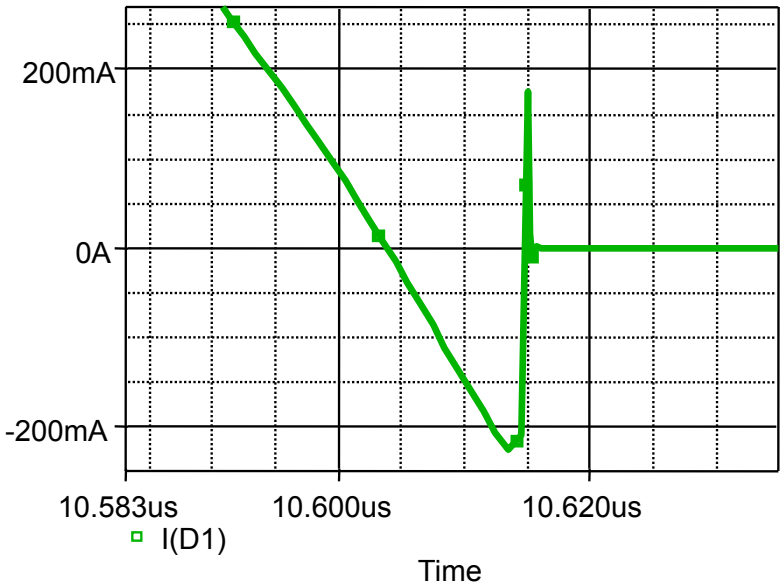




Diode Switching Characteristics Simulation-D1N4148-Fast Recovery









Survey of Commercial Power Diodes

Part Number	Rated Max. Voltage	Rated Avg. Current	V_F(typical)	t_y(max)
Fast Recovery Rectifiers				
IN3913	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	

General Comments on Power Diodes

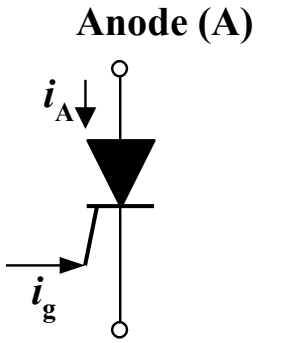
- Inverse Relationship between Blocking voltage/Forward current and reverse recovery time/forward voltage drop
- Generally, Diode turn on fast enough to be considered ideal
- Device turn off generally considered ideal but can effect circuit operation
  - Diode turn off means negative current needed to remove stored charge
    - This charge removal is required for device turn off
    - In some instances, this negative current and delay can have an effect on circuit operation
    - Can result in inductive ringing (particularly when fast recovery used in an inductive enviornment)
- When required, series diodes add to blocking capability

Thyristors - Overview

- **Thyristors**
  - **"Controlled diode"**
  - **In off state, can block positive forward polarity voltage and thus not conduct**
  - **Can be trigger into the on state by providing a short pulse of gate current provided that device is in forward blocking state**
  - **Once device begins to conduct, it is LATCHED on and gate current can be removed**

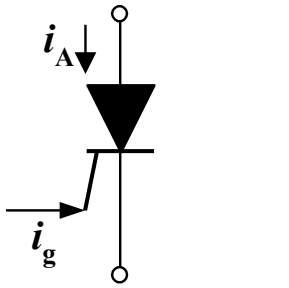
Thyristors -SCR

- **Silicon Controlled Rectifier**
  - **Once device begins to conduct, it is LATCHED on and gate current can be removed**
  - **Cannot be turned off by active control (activity at gate)**
  - **When current reduces and tries to go to negative, device turns off**
  - **External circuit must reverse bias the SCR to achieve turn off**
  - **After turn off, gate regains control allowing active turn on once the device is in forward blocking state**

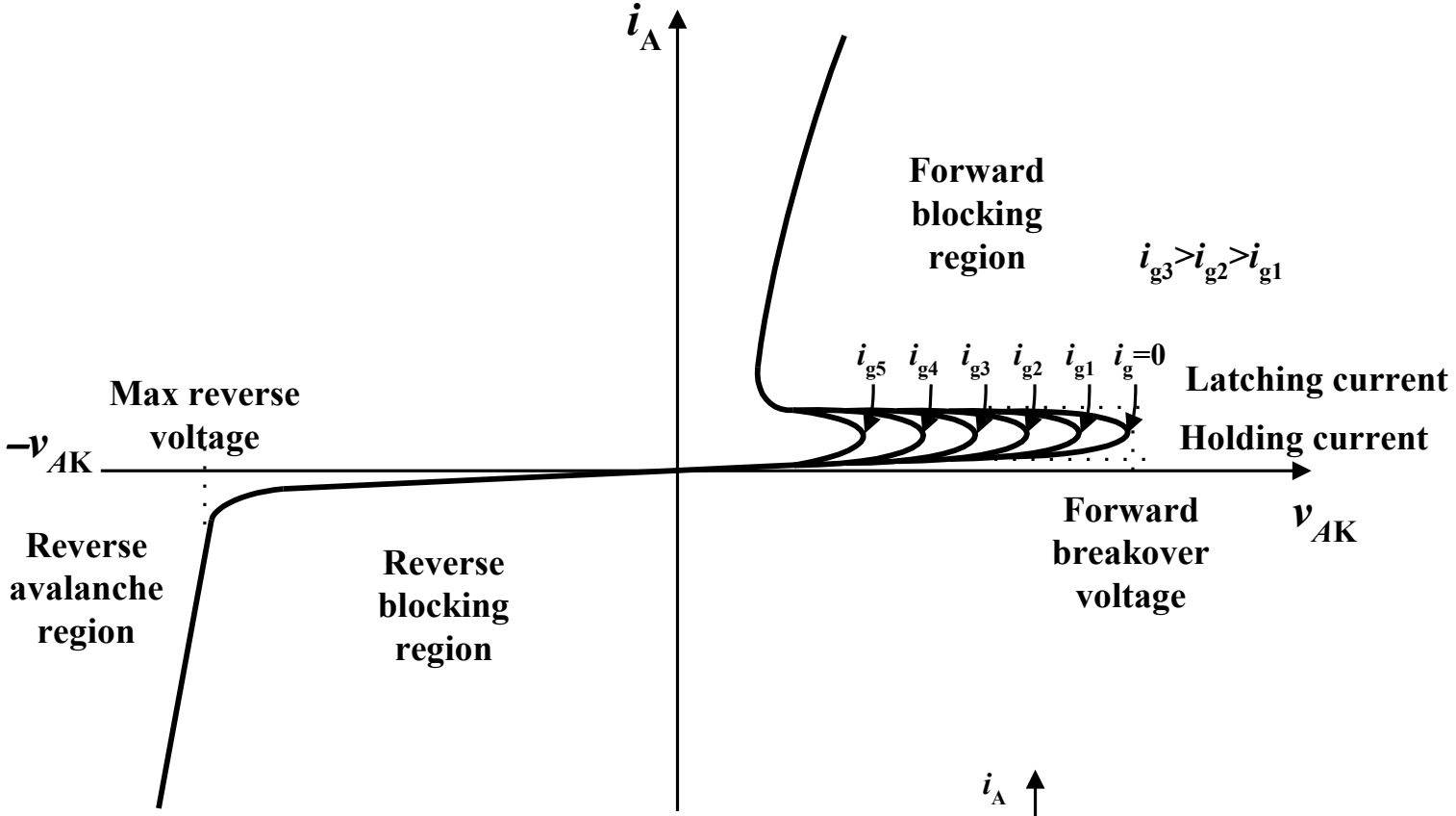


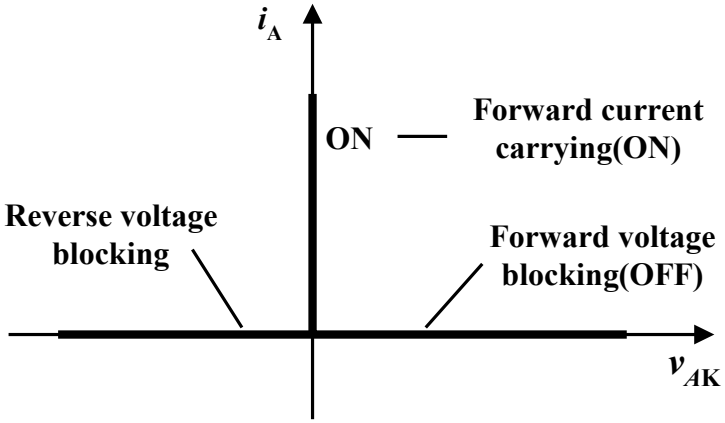
(a) Circuit symbol

Thyristors -SCR Symbol and Terminal Characteristics

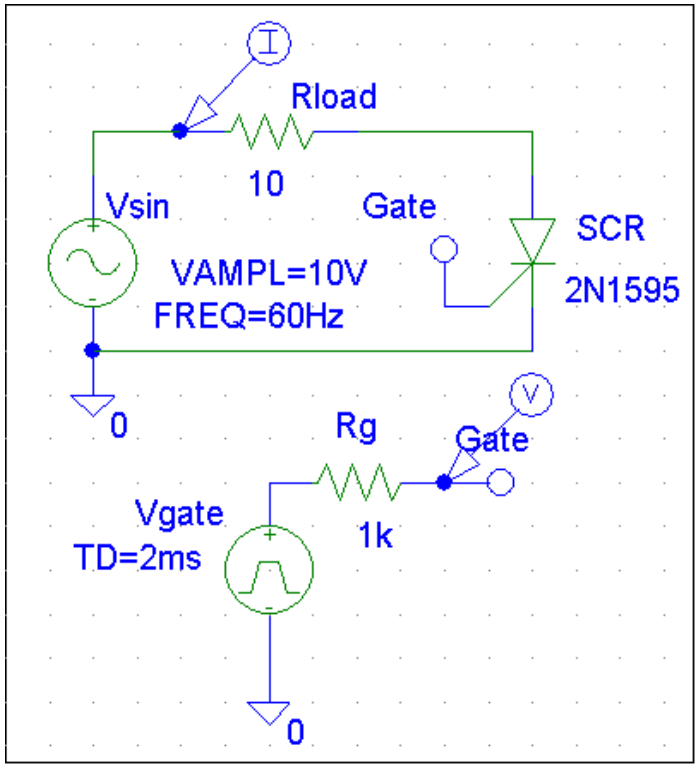


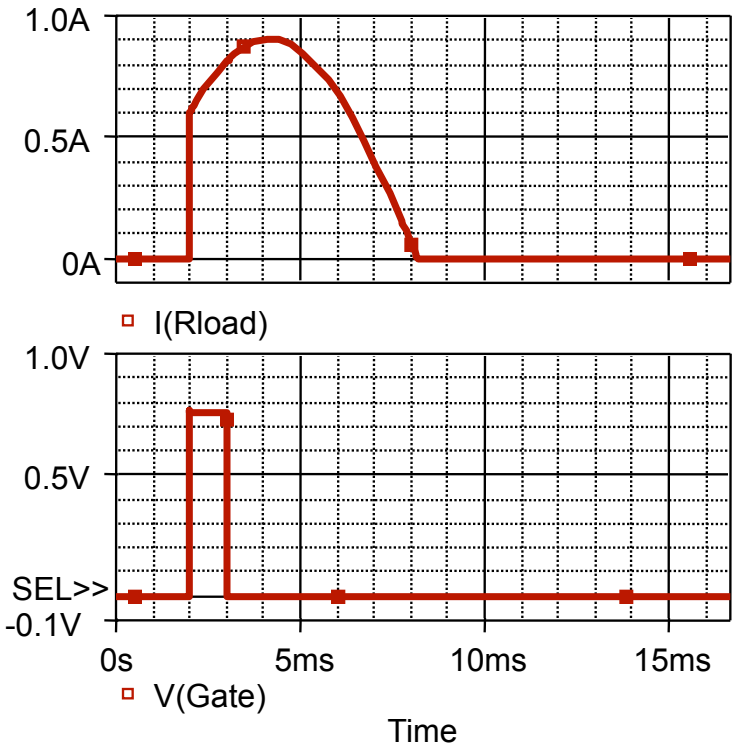
(a) Circuit symbol





Thyristors -SCR Simulation





Commercial SCR Survey

International IOR Rectifier

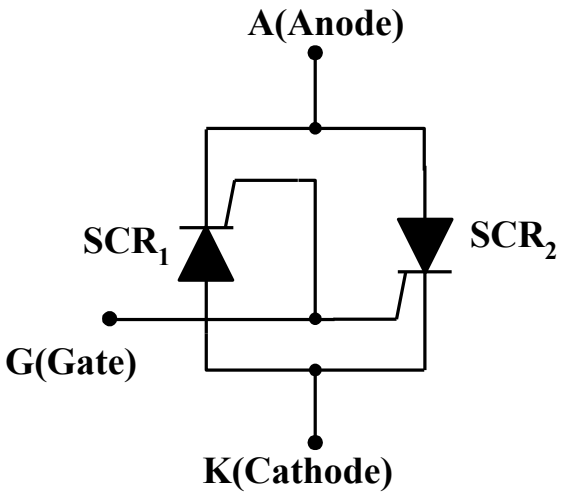
Product	Package	Circuit	VDRM	IT(RMS)
ST180C04C0	TO-200AA (A-Puk)	DISCRETE	400	660
ST230C04C0	TO-200AA (A-Puk)	DISCRETE	400	780
ST280C04C0	TO-200AA (A-Puk)	DISCRETE	400	960
ST280C06C0	TO-200AA (A-Puk)	DISCRETE	600	960
ST280CH06C0	TO-200AA (A-Puk)	DISCRETE	600	1130
ST230C08C0	TO-200AA (A-Puk)	DISCRETE	800	780
ST180C08C0	TO-200AA (A-Puk)	DISCRETE	800	660
ST180C12C0	TO-200AA (A-Puk)	DISCRETE	1200	660
ST230C12C0	TO-200AA (A-Puk)	DISCRETE	1200	780
ST230C14C0	TO-200AA (A-Puk)	DISCRETE	1400	780
ST230C16C0	TO-200AA (A-Puk)	DISCRETE	1600	780
ST180C16C0	TO-200AA (A-Puk)	DISCRETE	1600	660
ST180C18C0	TO-200AA (A-Puk)	DISCRETE	1800	660
ST180C20C0	TO-200AA (A-Puk)	DISCRETE	2000	660



General Comments on SCRs

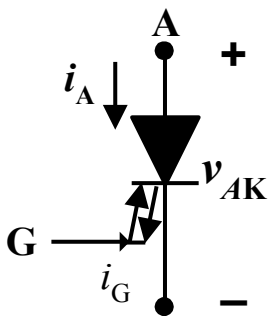
- Used to be device of choice for high power applications
- SCR based Phase Controlled Rectifiers still common in three-phase industrial environment
- A minority carrier device
- SCR has highest blocking voltage and current carrying capabilities of all the semiconductor switches
- Large reverse recovery current
- Long carrier lifetimes allow low on state resistance but mean long turn off times
  - Switching very slow
- Newer designs rarely use SCRs unless very high power required
  - Most newer designs use MOSFETs or IGBTs

Thyristors -Triac



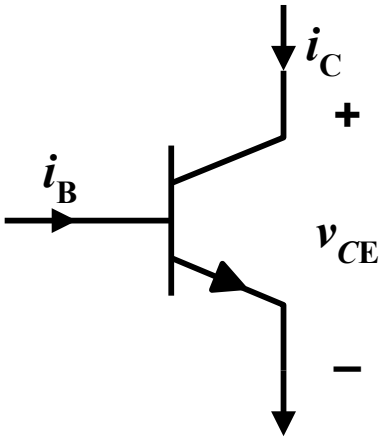
- Triac
  - "Back to back" SCR
  - Bidirectional current flow, bidirectional voltage blocking
  - Often used:
    - AC waveform chopping: dimmers, soldering stations, controlled heating elements

Thyristors -GTO



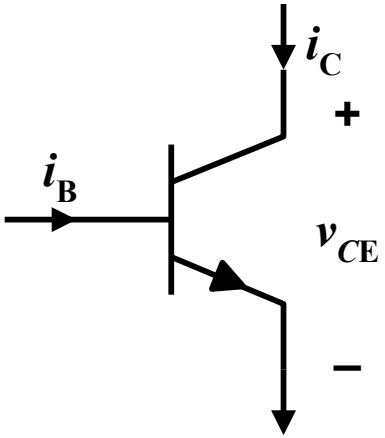
- **Gate Turn Off Thyristor**
  - **Like SCR, once device begins to conduct, it is LATCHED on and gate current can be removed**
  - **Unlike SCR, GTO can be turned off with a negative gate-cathode voltage (i.e. active turn off control)**
  - **This negative gate current pulse can be short duration but must be large magnitude (~ .33 i_A)**
  - **A controlled switch like BJT/MOSFET but not suitable for inductive turn off**
  - **Slow switching time (fs max ~10 kHz)**

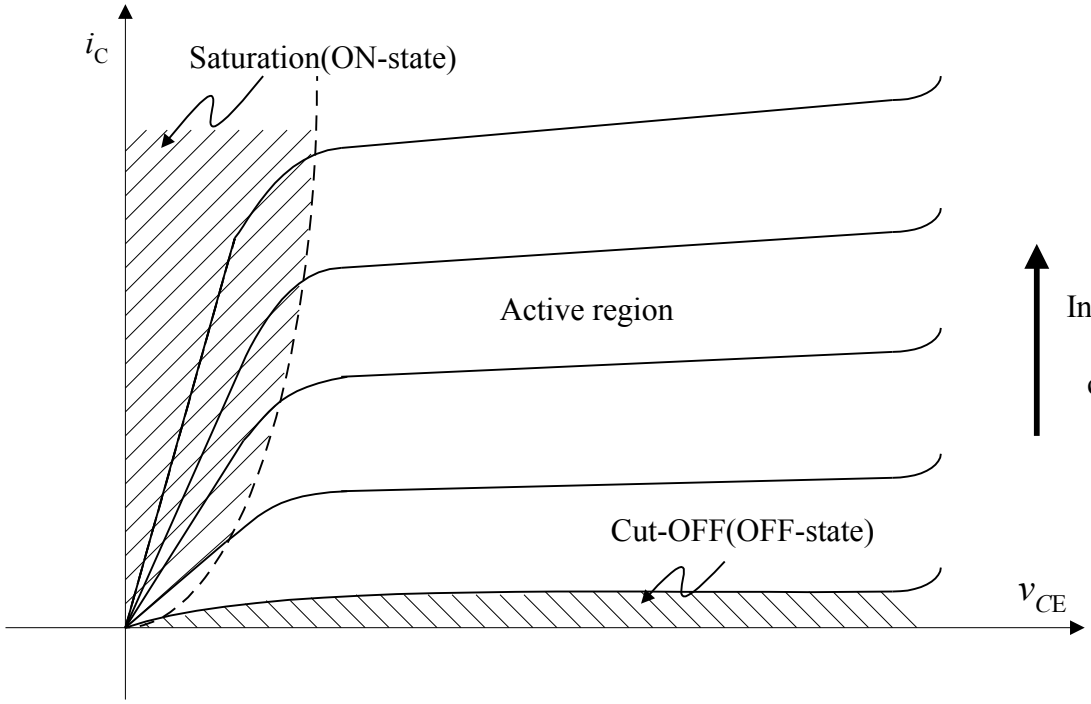
BJT - Overview

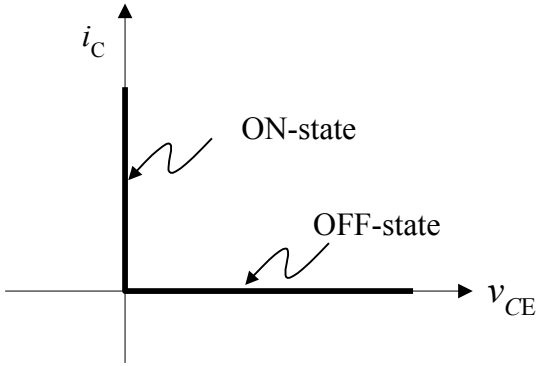


- **Bipolar Junction Transistor**
  - **A minority carrier device**
  - **Current controlled**
    - **Requires a continuous base current to remain in on (conducting) state**
  - **Significant delays during turn off transition**
  - **On-state resistance has negative temperature characteristic so device paralleling not always straightforward**

BJT Symbol and i-v Characteristics





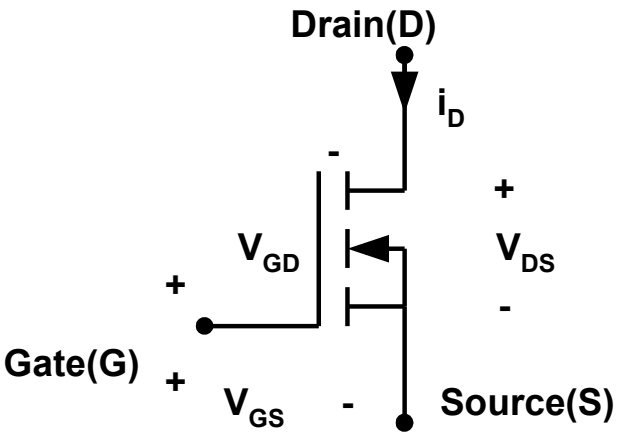


Ideal switch characteristics

General Comments on BJT

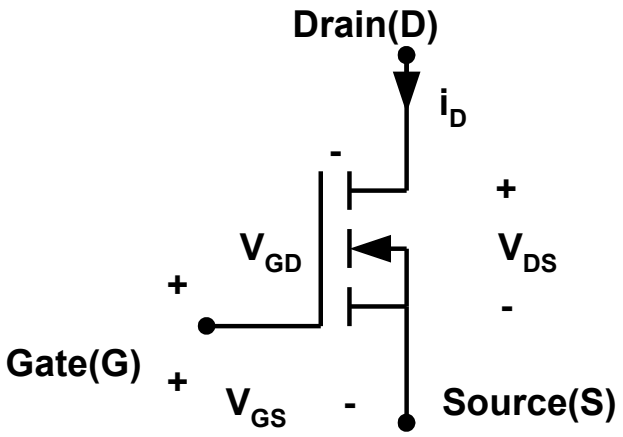
- **BJT has been replaced by MOSFET in low-voltage (<500V) applications**
- **BJT is being replaced by IGBT in applications at voltages above 500V**
- **Design trade off between on-state losses and switching times**
- **A minority-carrier device: compared with MOSFET, the BJT exhibits slower switching,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

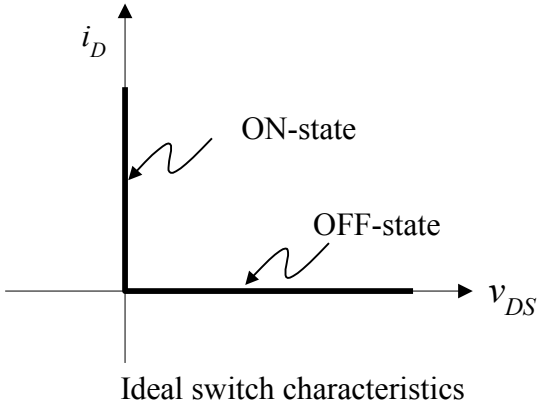
MOSFET Overview



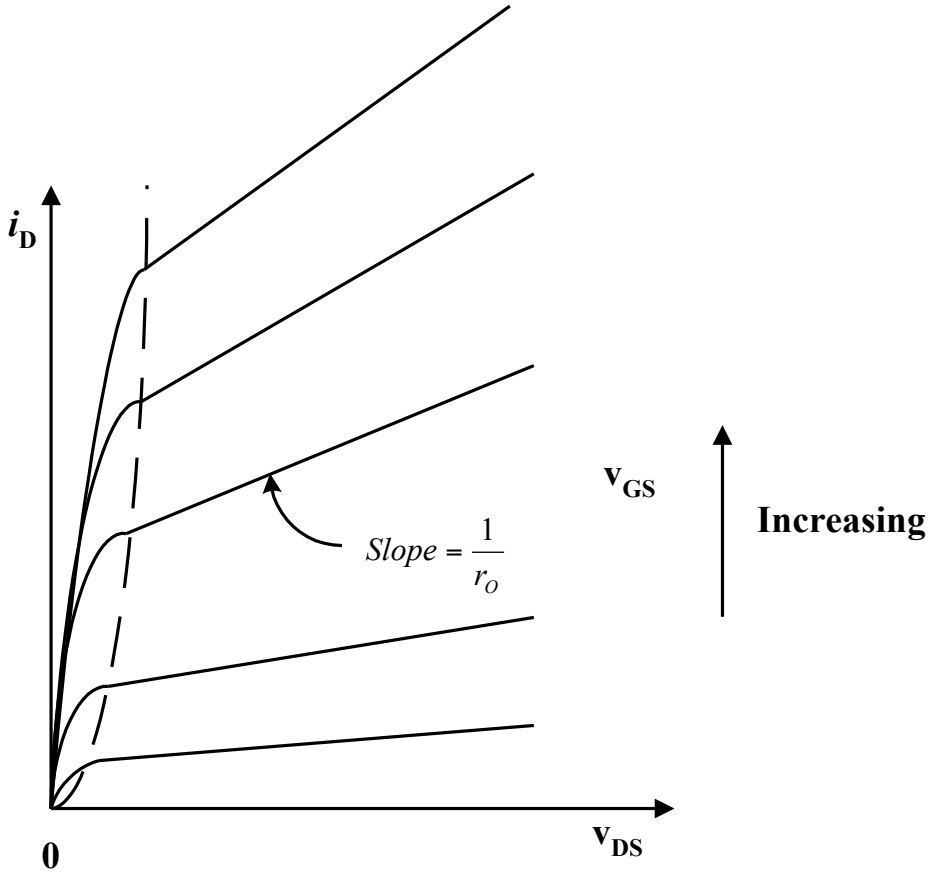
- **Metal-Oxide-Semiconductor Field Effect Transistor**
  - **A majority carrier device**
  - **Voltage controlled**
    - **Require continuous application of Gate to Source voltage to maintain on-state (conduction)**
  - **No gate current flows except during transitions to charge and discharge gate capacitance**
  - **Very short switching times**
  - **On-state resistance has positive temperature coefficient so device paralleling simple**

MOSFET Symbol and i-v Characteristics





Ideal switch characteristics



Survey of Commercially Available MOSFETs

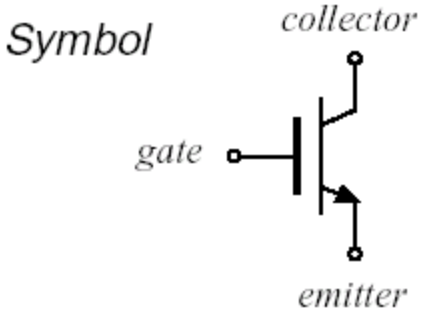
Part Number	Rated Max. Voltage	Rated Avg. Current	Ron	Qg(typical)
IRFZ48	60V	50A	0.018Ω	110nC
IRF510	100V	5.6A	0.54Ω	8.3nC
IRF540	100V	28A	0.077Ω	72nC
APT10M25BNR	100V	75A	0.025Ω	171nC
IRF740	400V	10A	0.55Ω	63nC
MTM15N40E	400V	15A	0.3Ω	110nC
APT5025BN	500V	23A	0.25Ω	83nC
APT1001RBNR	1000V	11A	1.0Ω	150nC

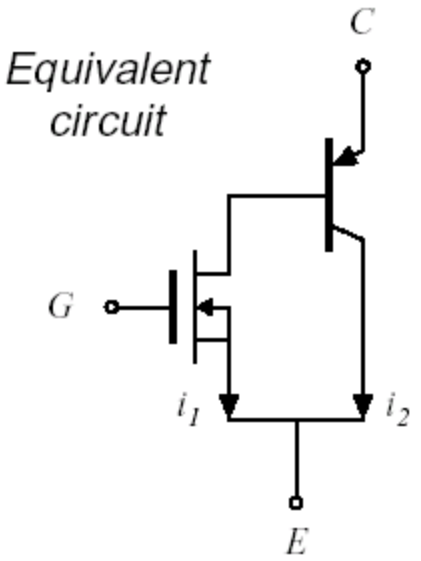


General Comments on MOSFET

- **Majority carrier device: fast switching times**
- **Typical switching frequencies: tens and hundreds of kHz**
- **On state losses rise more rapidly with blocking voltage than in a comparable BJT**
- **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)**
- **Generally, on state resistance most significant factor when selecting device**

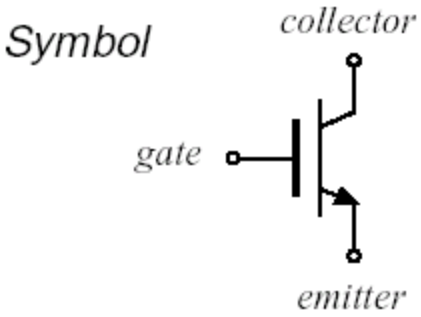
IGBT Overview

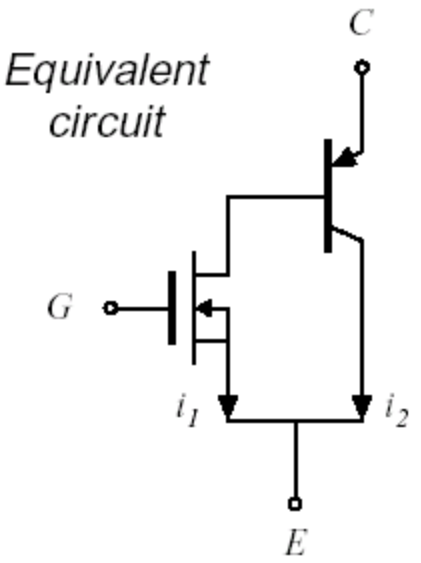


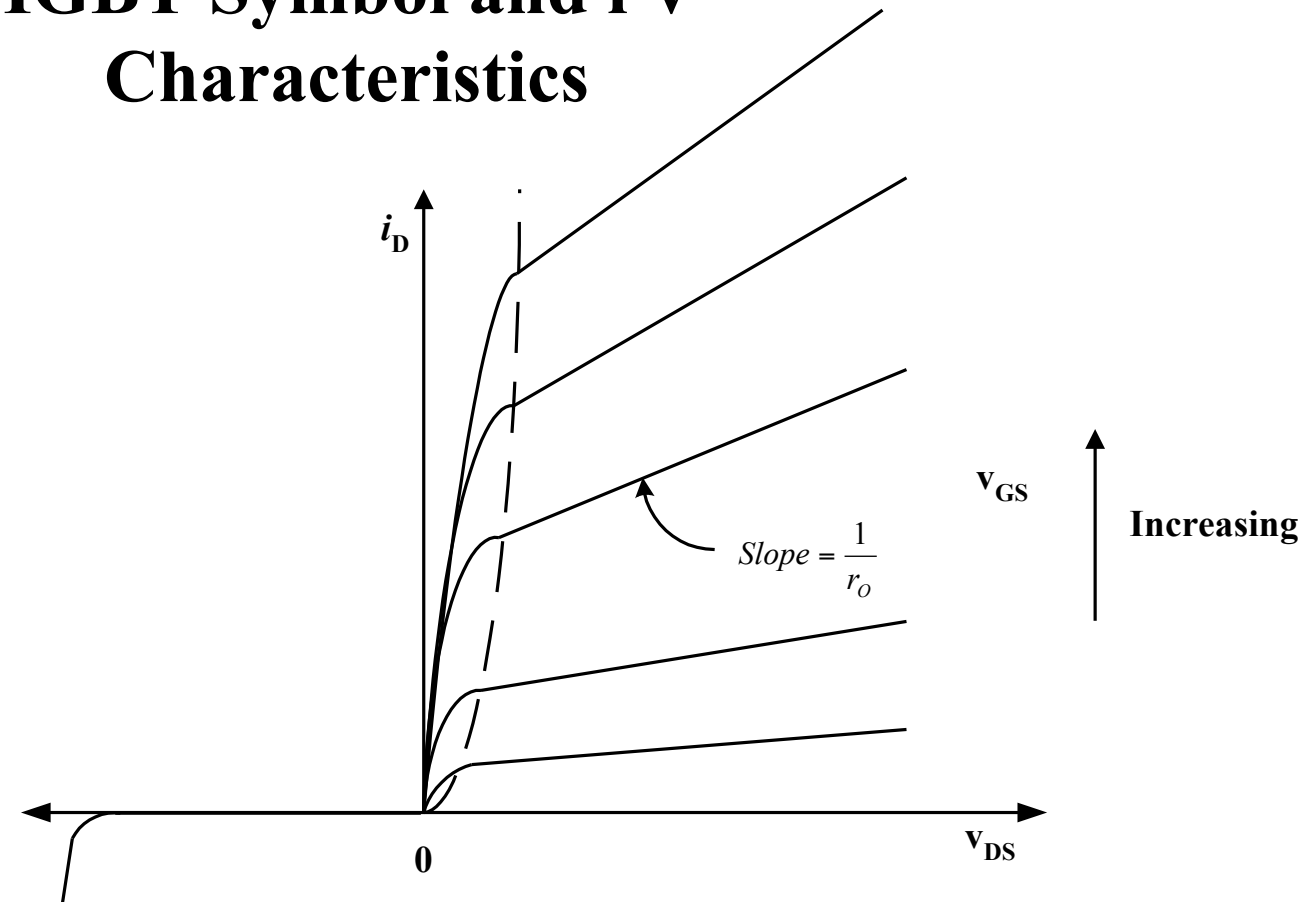


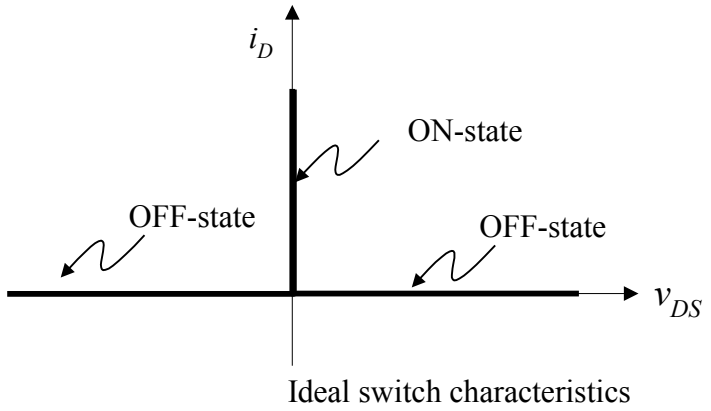
- **Insulated Gate Bipolar Transistor**
  - **Combination of BJT and MOSFET**
    - **Like MOSFET, has high impedance gate which requires small charge to turn on**
    - **Like BJT, small on state resistance even for devices with large blocking voltage ratings**
  - **Can be designed to block negative voltages like thysistors**

IGBT Symbol and i-v Characteristics









Ideal switch characteristics

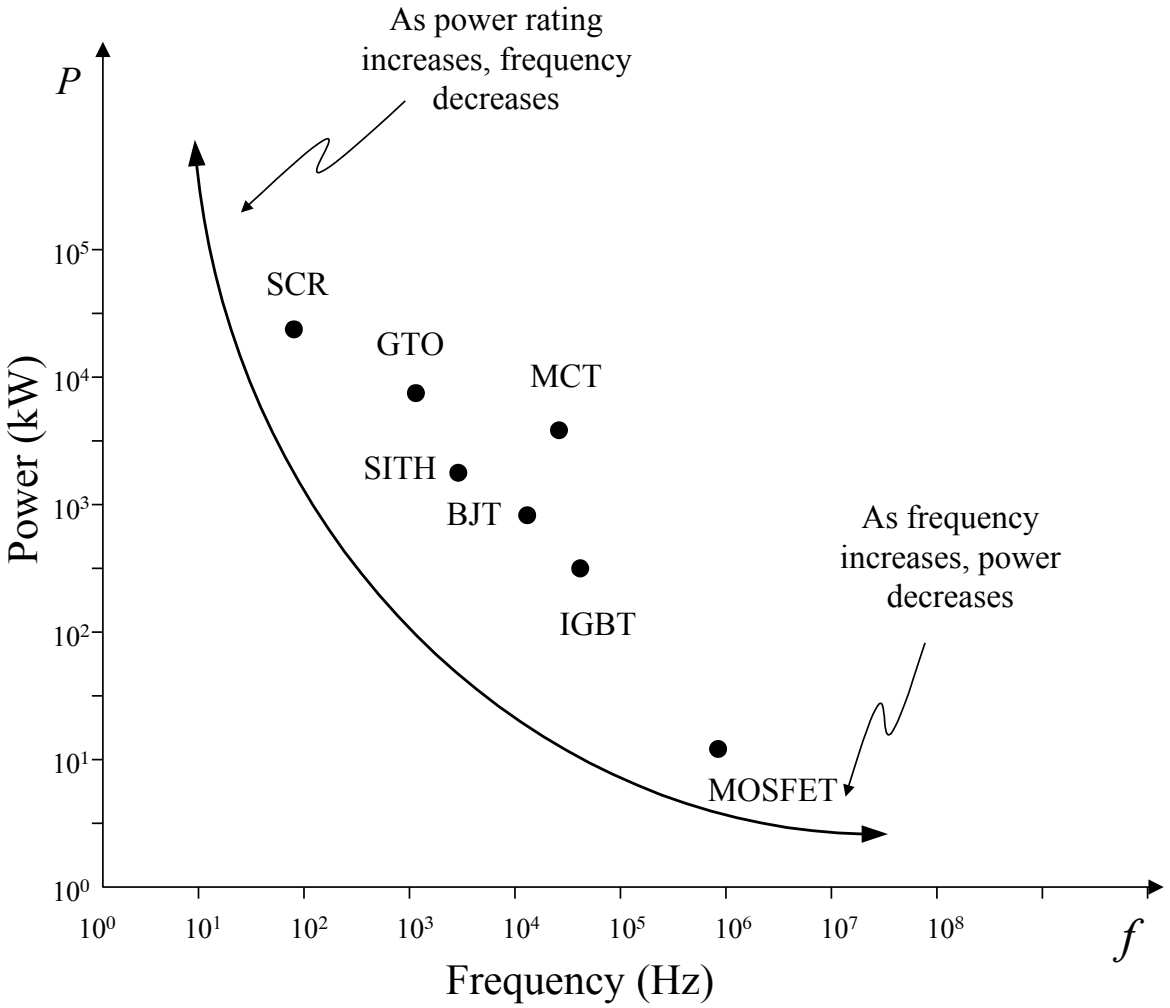
Survey of Commercially Available IGBTs

Part Number	Rated Max. Voltage	Rated Avg. Current	V_F (typical)	t_r(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

General Comments on IGBT

- **Faster than comparable BJT, Slower than a comparable MOSFET**
- **On state losses smaller than MOSFET and are comparable to BJT**
- **Turn on time can be effected by rate of change of v_{gs}**
- **Most new designs in the industrial power electronics market use IGBTs for medium power applications**

Device Comparison
f_s vs. Power



Future Trends in Device Progress

Power Devices:

Technological Improvement:

- Speed of switching
- Power Rating

