FUNDAMENTALS OF POWER ELECTRONICS

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Contents

Power Electronics: Goals and Methods

- Efficient Conversion, Conditioning and Control of Electrical Energy using Power Semiconductor Devices and Passive elements.
  - Use of Semiconductor Devices as 'Switches'
  - Switching Vs Linear Power Electronics
  - Say 'NO' to R, 'YES' to L and C!!
  - Circuits: AC-DC, DC-DC, DC-AC and AC-AC
  - Reactive Elements: L, C —> energy storage, filters and snubbers
  - Control methods to 'shape' voltages and currents
  - Digital/Analog Control: Algorithms and methods

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Ideal Switches

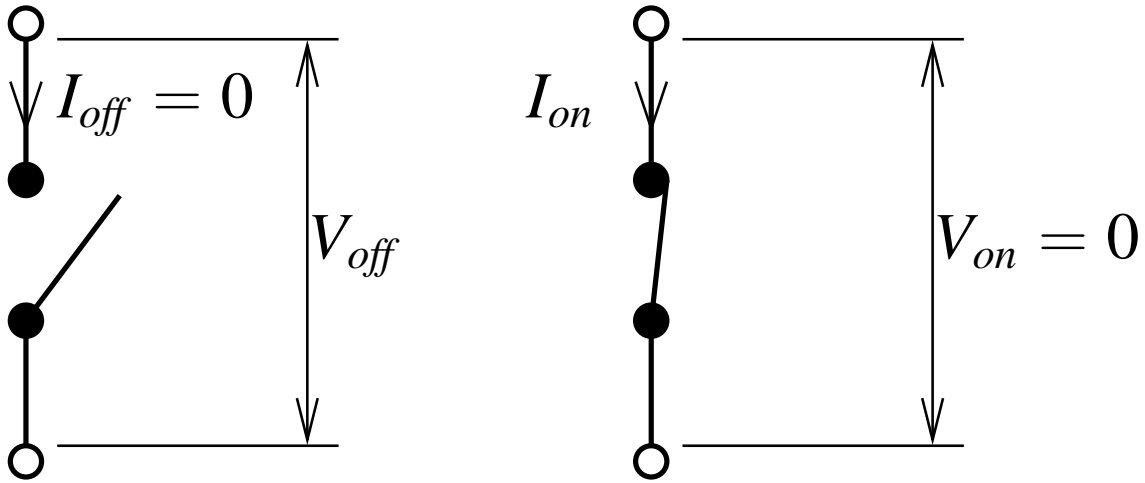

FIGURE: Ideal Switch

- Infinite I_{on} and V_{off}
- Zero I_{off} and V_{on}
- Zero t_{on} and t_{off}
- Zero Temperature rise
- Zero energy to turn ON/OFF and maintain states
- Infinite “Power-to-Weight" or “Power-to-Volume” ratio
- Zero Cost!!!

Ideal Switches

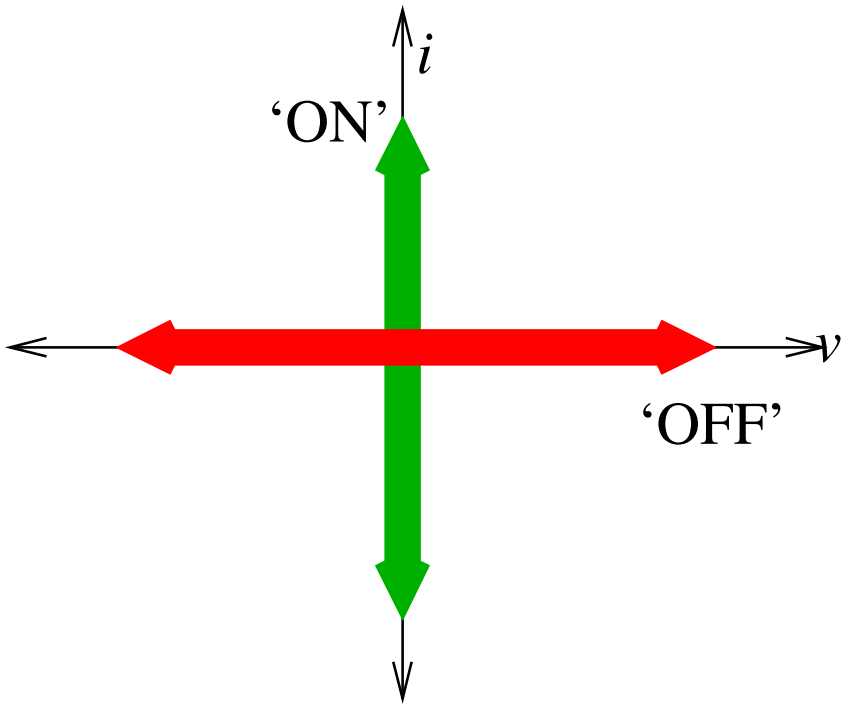

FIGURE: Ideal Switch Characteristics

Ideal Switches : SPDT and SPTT

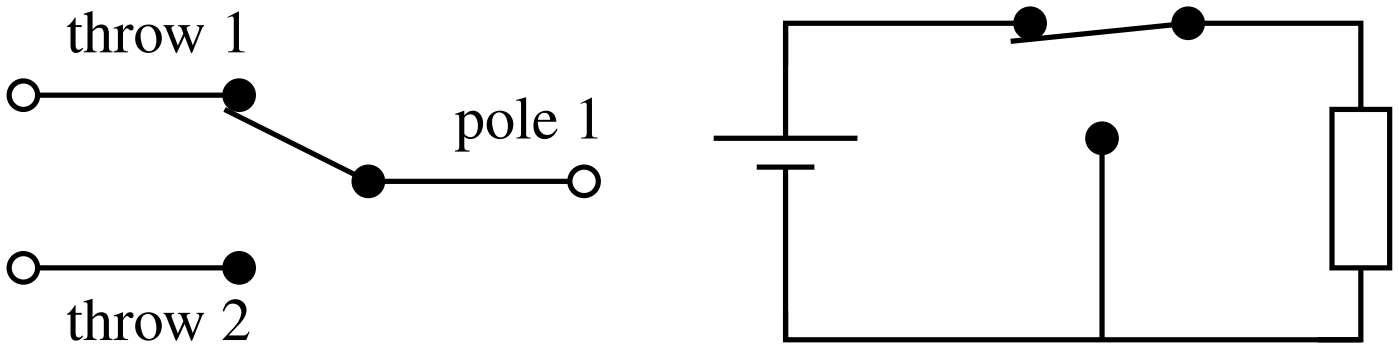

FIGURE: Ideal SPDT Switch and its use in Buck converter

- Two states

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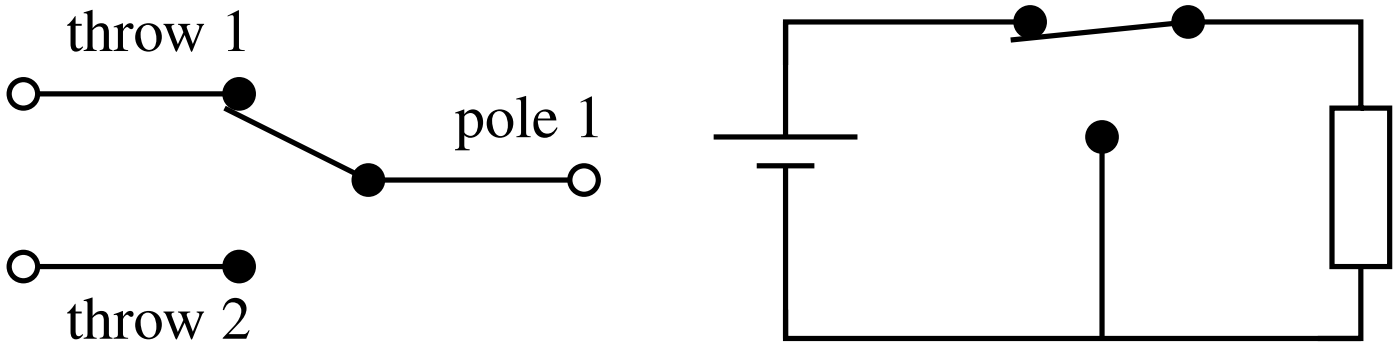

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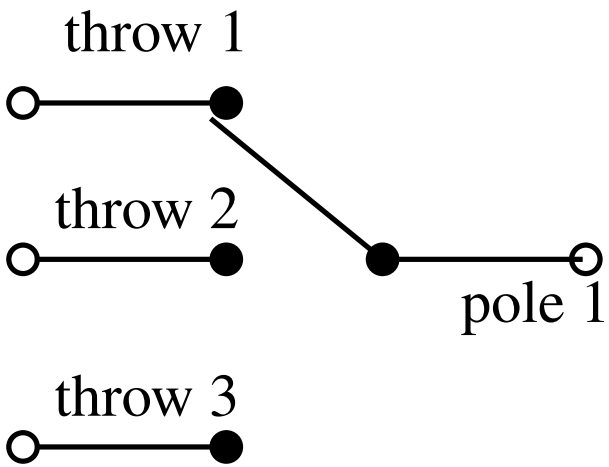

FIGURE: Ideal Single Pole Triple Throw Switch

The Realities: Switches Do not 'Know' KVL and KCL!

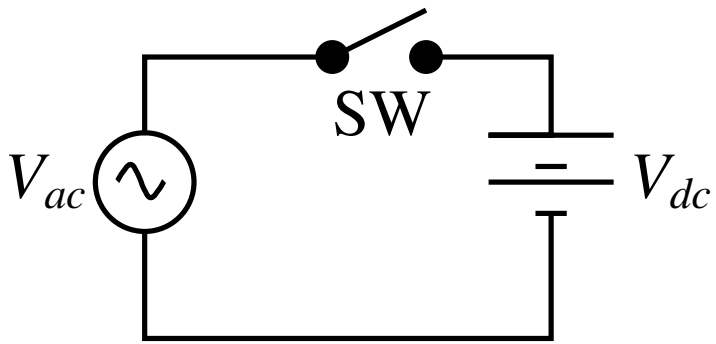

FIGURE: KVL: Switch SW must always be 'OFF'

- Dangerous to switch between two"Voltage-stiff" circuits!!
- KVL causes large currents to flow
- FIRE! in practical cases

The Realities: Switches Do not 'Know' KVL and KCL!

- Dangerous to switch between two"Current-stiff" circuits!!
- KCL causes large voltages to be induced
- Damages due to high-voltages in practical cases

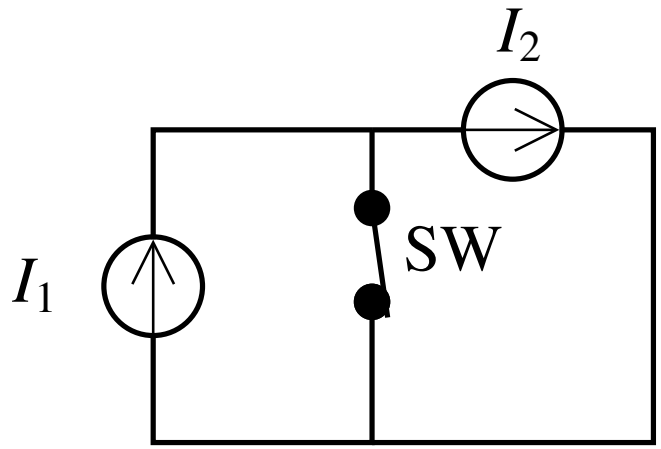

FIGURE: KCL: Switch SW must always be 'ON'

The Realities: Switches Do not 'Know' KVL and KCL!

- Switchings can be done ONLY between a Voltage-stiff circuit and a Current-stiff circuit
- Long-term KVL problem : Voltage switched in to an Inductor
- Long-term KCL problem : Current switched in to a Capacitor

Practical/Real Switches

- The Non-idealities
  - V_{off} and I_{on} are finite, limited values : Limited blocking voltage, limited current capacity
  - V_{on} and I_{off} are non-zero values : ON-state and OFF-state losses
  - t_{on}, t_{off} are non-zero values : Non-zero switching losses
  - Non-zero drive energy : Losses in drive circuits
  - Power and thermal limits : Power and Temperature limits
  - Safe Operating Area

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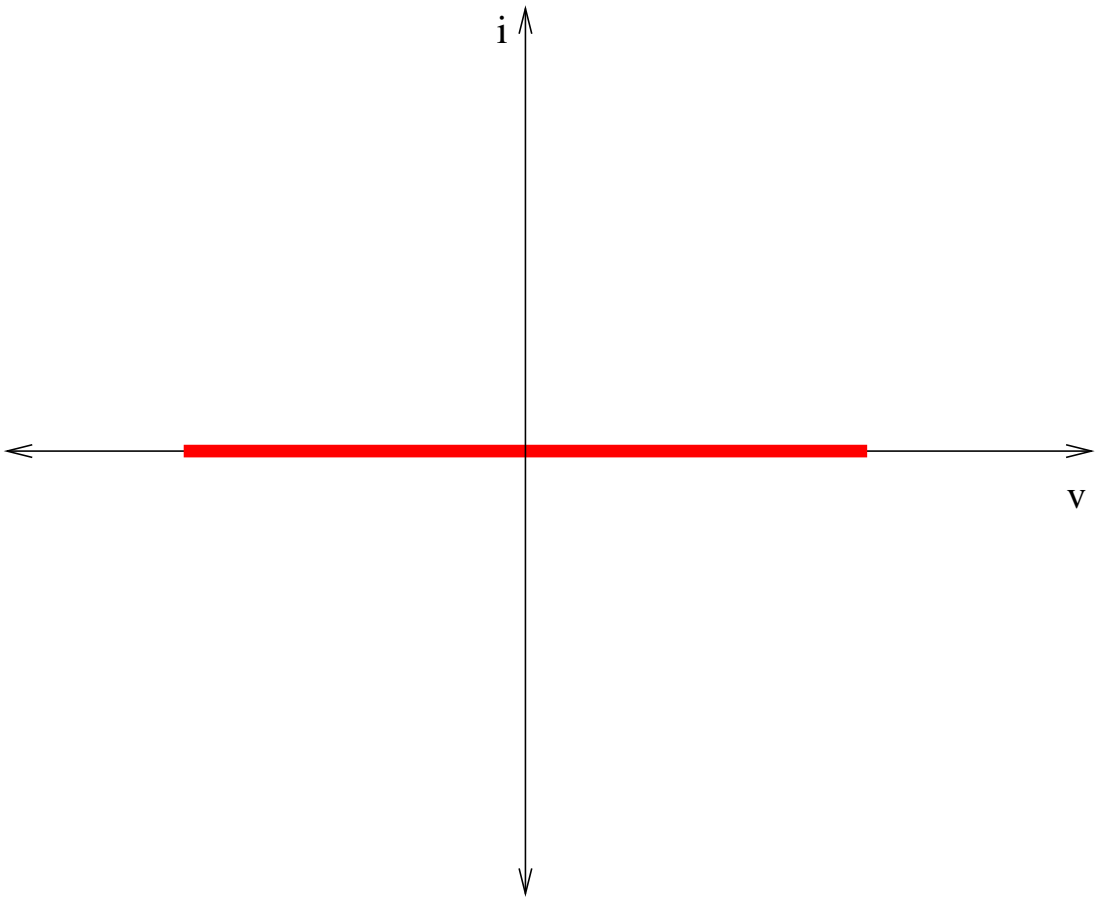

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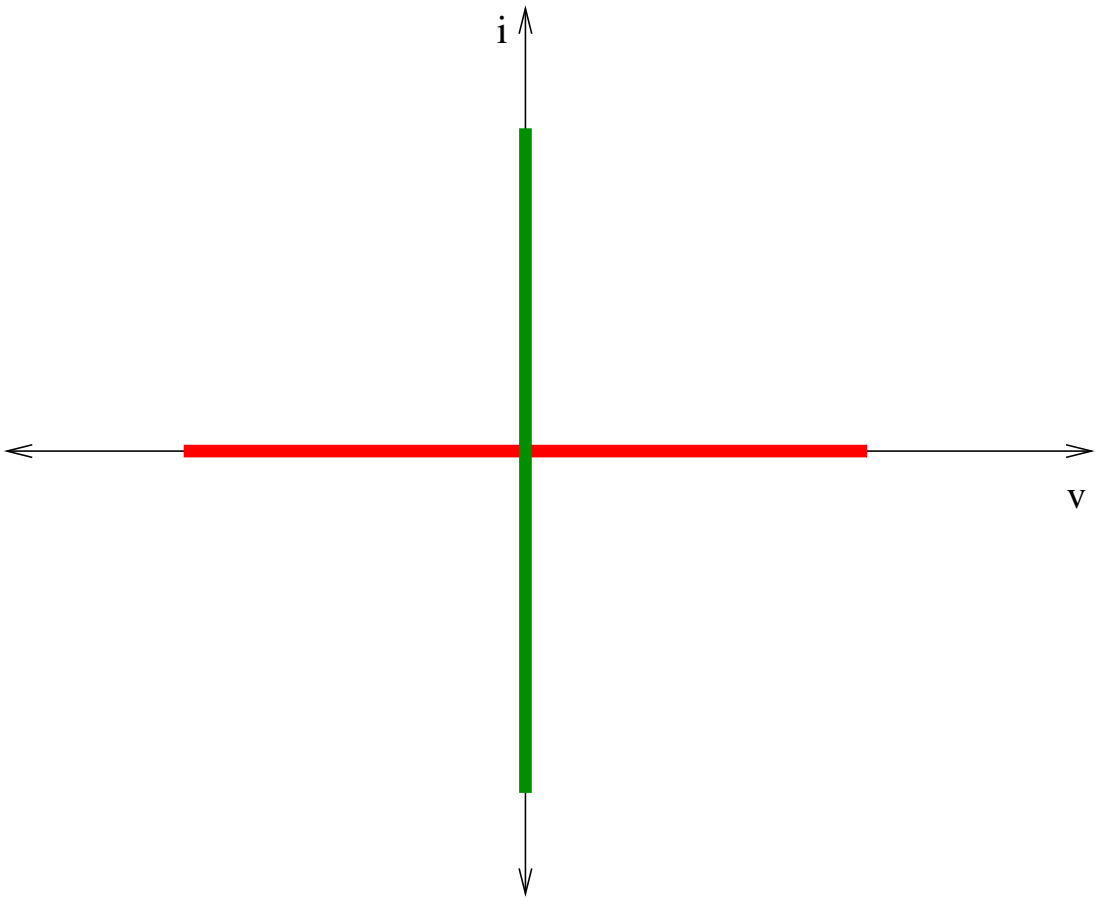

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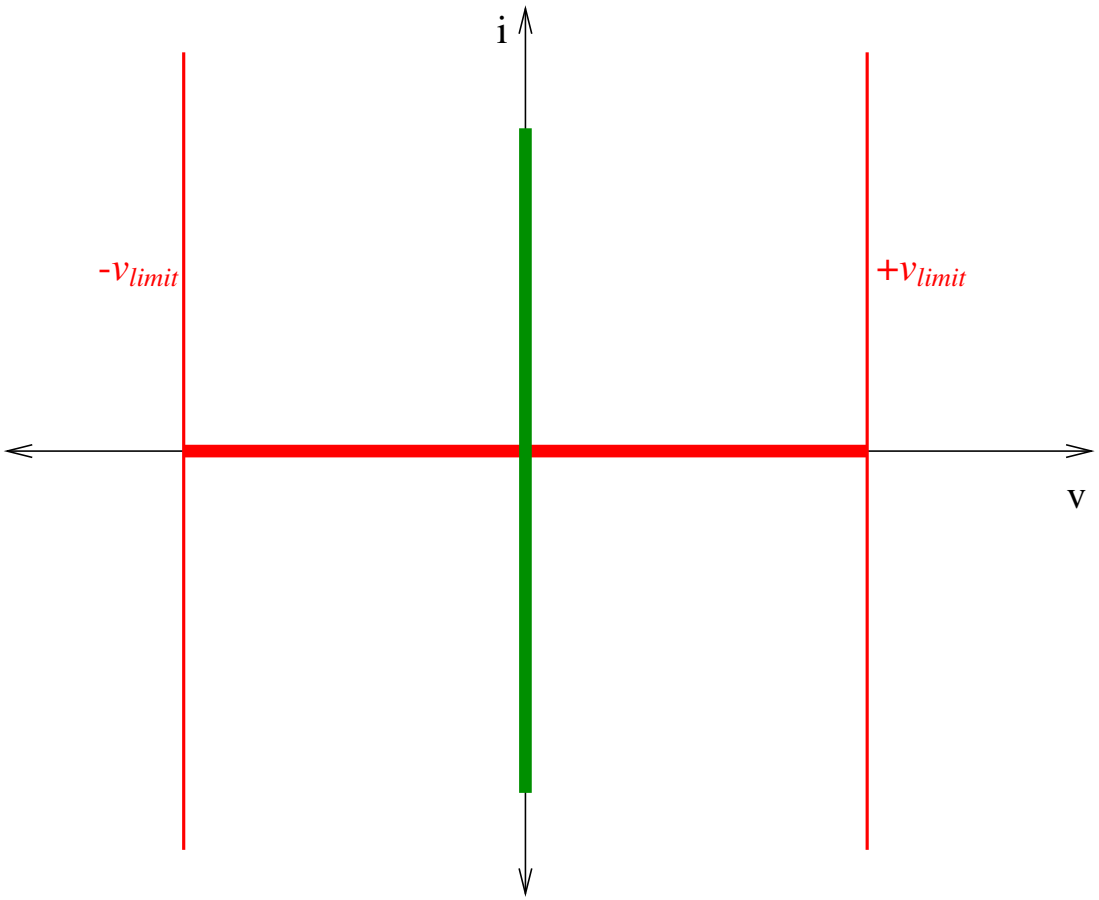

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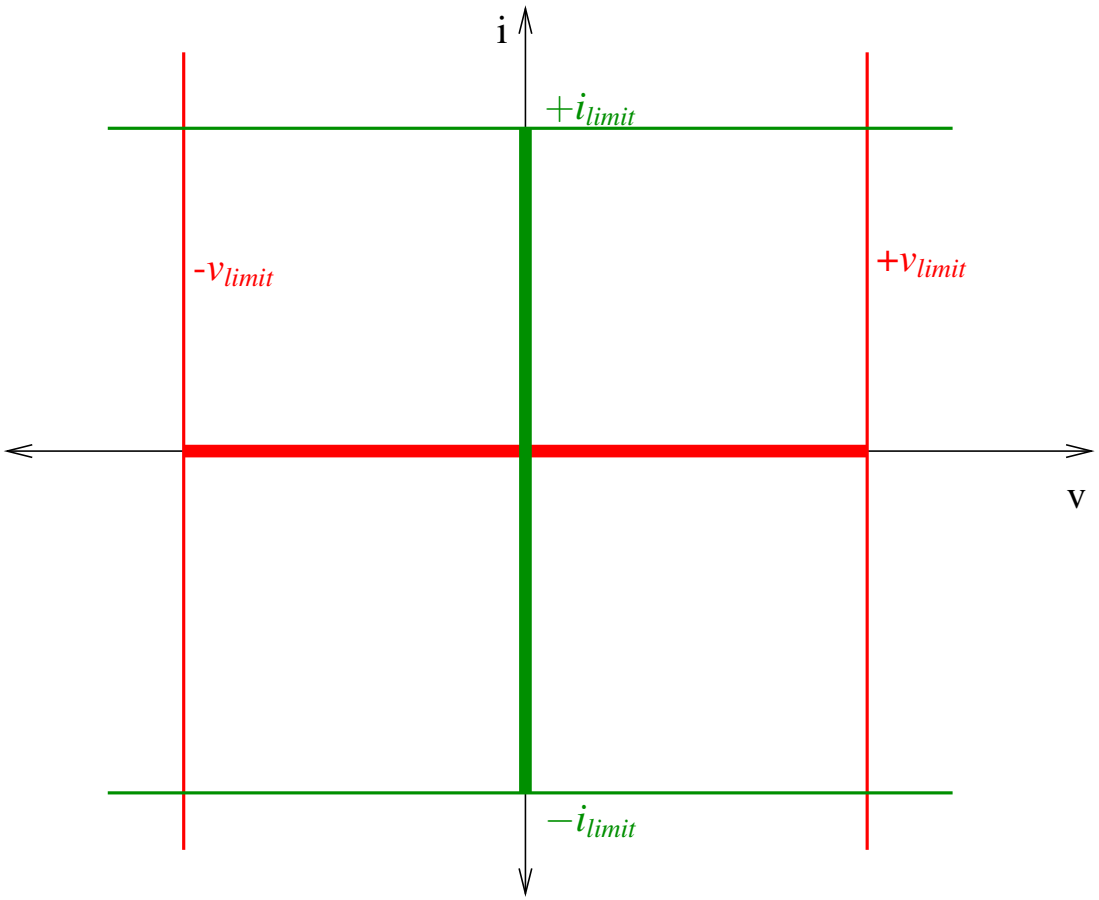

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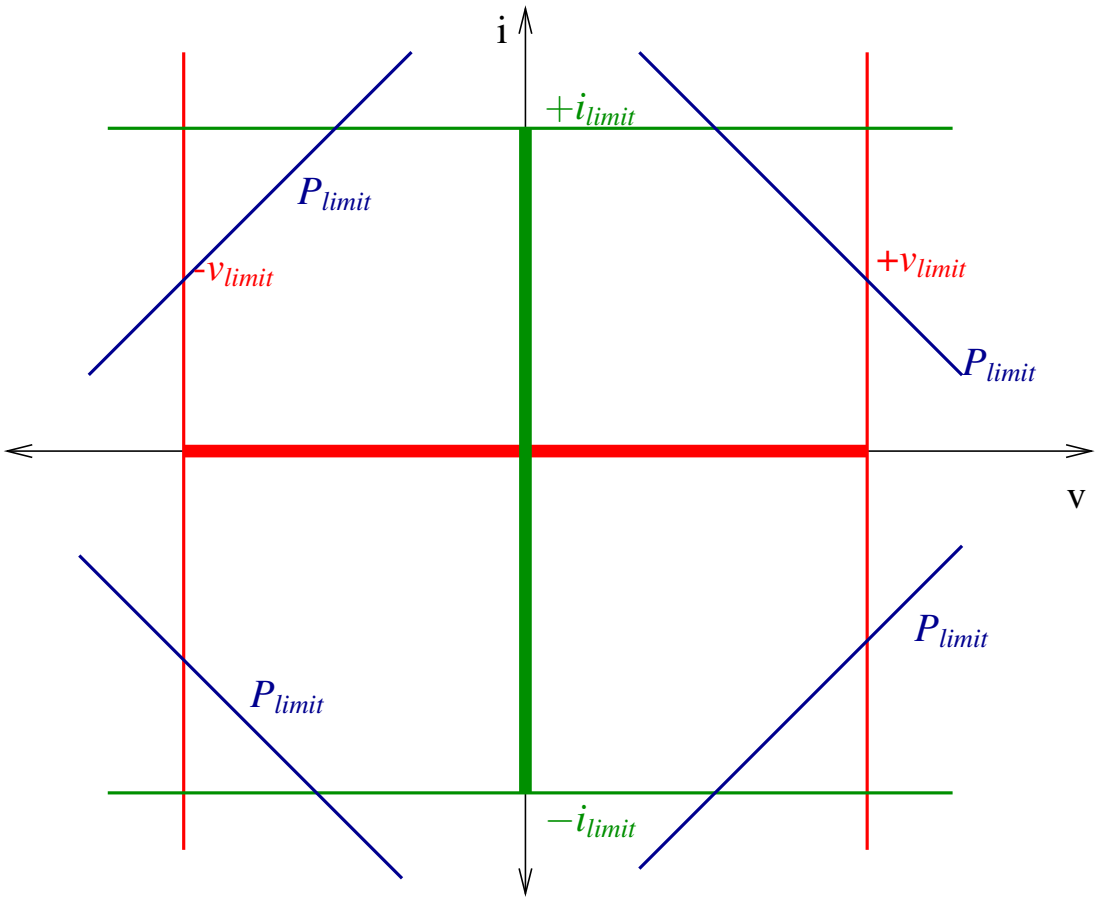

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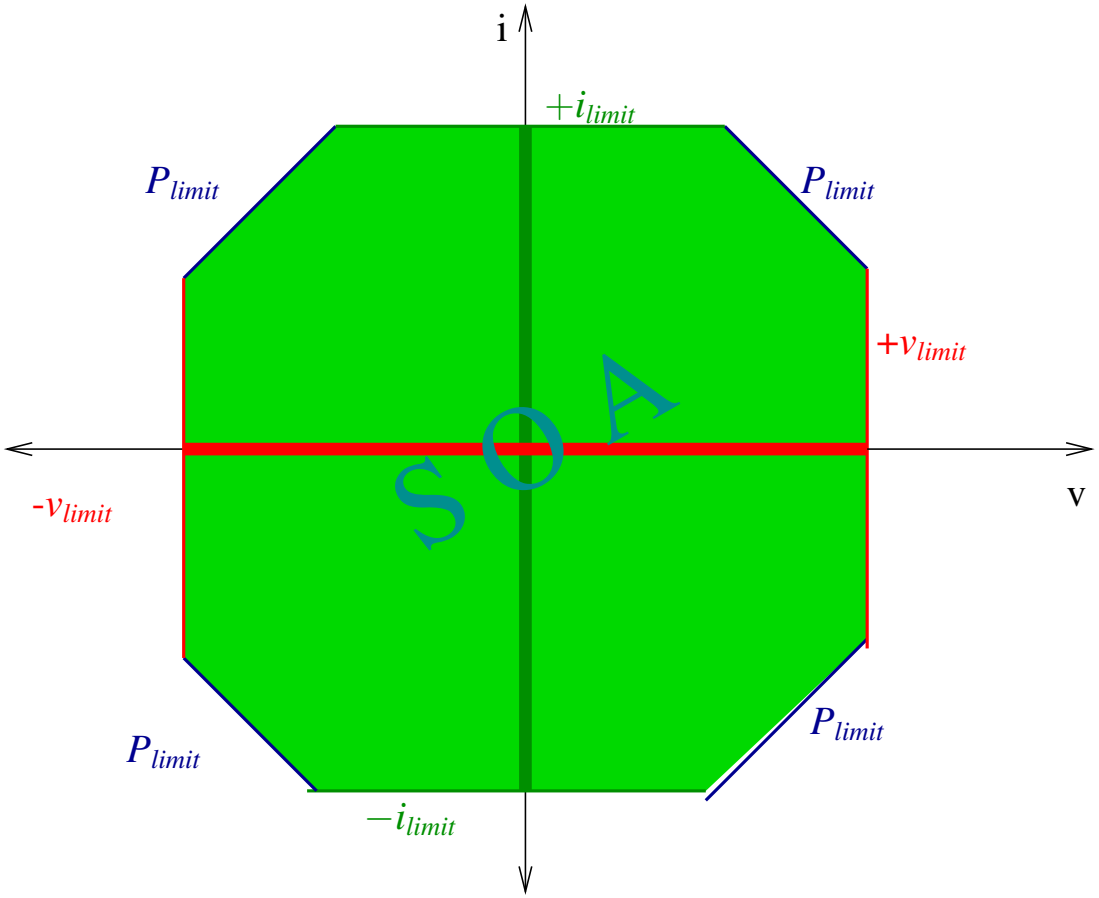


Practical/Real Switches

- Three States
  - Static States: ON and OFF
  - Dynamic State: Commutation or Transition
  - Energy losses in ALL THREE states

Practical/Real Switches

- Current Ratings in ON state
  - Continuous current :Worst case design
  - Average Current :ON-state loss
  - RMS current :ON-state Losses
  - Peak current :Local heating and metal contacts
  - Current-time values : Peak current for short duration: Duty Cycle

Practical Uncontrolled Switch : Diodes

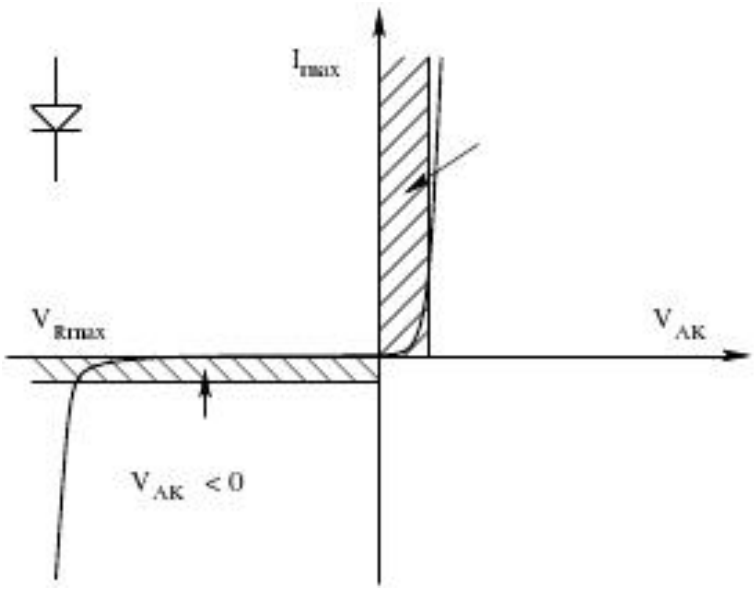


FIGURE: Diode Characteristics

- PN, PiN, Schottky
- 1A to 5000A+
- 10V to 10kV+
- 20 ns to 100μs
- Data sheet

Practical Uncontrolled Switch : Diodes

- Operating Quadrants: Forward Conduction, Reverse Blocking
- Non-idealities: r_d, V_f, I_{off}, V_{PIV}
- Static and Dynamic performance
  - Reverse Recovery: *Snap* and *Soft* :(Diffusion Capacitance)
- Important Specs:
  - I_F, V_{PIV}, V_F, I_{off}, Z_{th}, t_{rr}, I^2T
- Static Equivalent Circuit

Practical Semi-Controlled Switches: SCR and Triac

- Charge/Current Controlled
- Operating Quadrants: Forward Conducting, Forward and Reverse Blocking
- External Turn-off control not possible
- 1A-5000A
- 200V-6000V
- $1\mu s$ - $200\mu s$
- Two-Transistor equivalent circuit:
- Important Specs: I_F, V_{RRM}, V_F, I_{off}, $\frac{di}{dt}$, $\frac{dv}{dt}$, Z_{th}, t_q, I^2t
- Static and Dynamic Characteristics
- Turn ON and Turn OFF conditions
- Data Sheet
- Triac : 2A-50A, 200V-800V

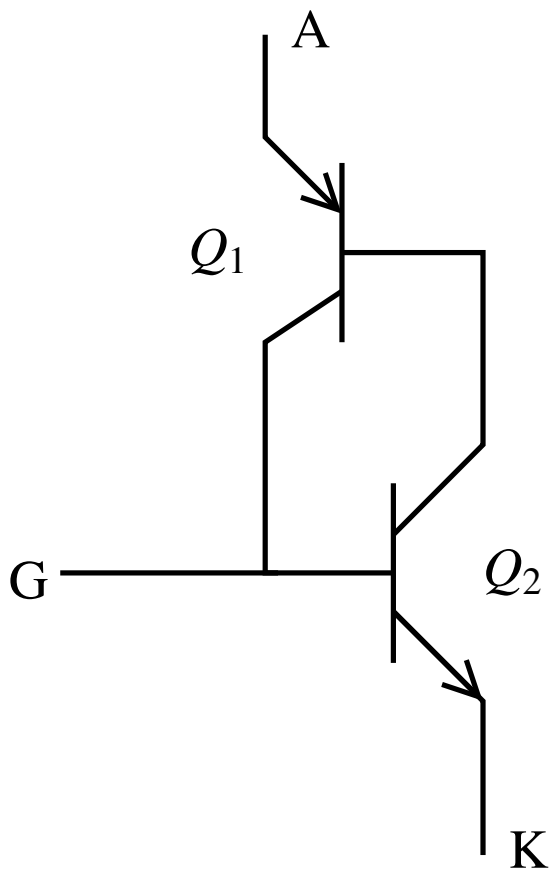


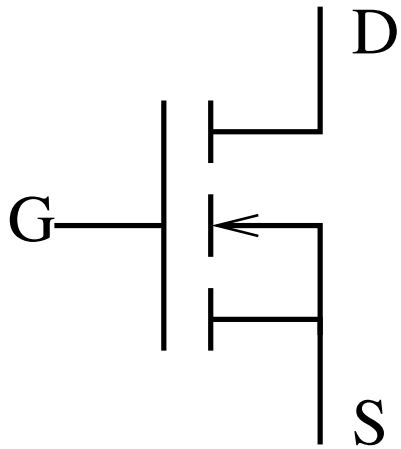
FIGURE: Two-Transistor model:
$I_A = \frac{\alpha_2 I_g + I_{cbo1} + I_{cbo2}}{1-(\alpha_1+\alpha_2)}$

Practical Controlled Switches: BJTs

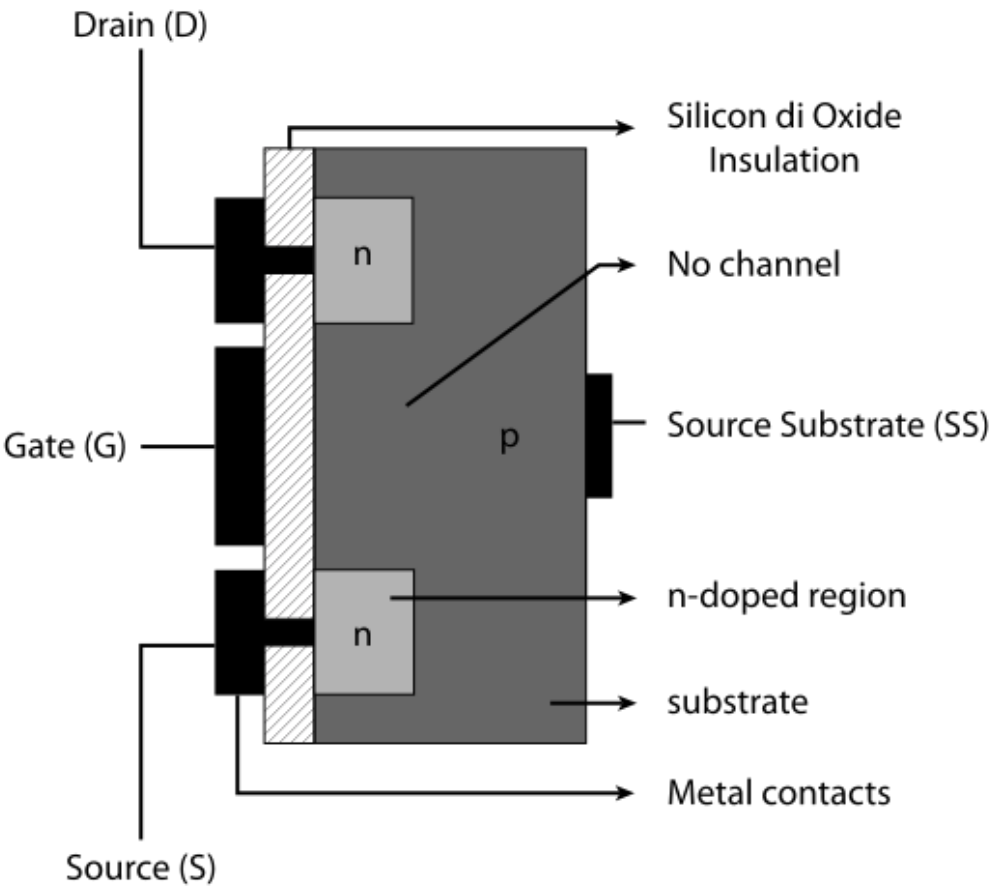
- Base region is wider than small-signal BJT
- Current Controlled
- Low Current Gain: Increased drive power requirement, losses, slow switching
- 0.5A-500A+
- 30V-1200V
- $0.5\mu s$ - $100\mu s$
- Operating Quadrants: Forward Conducting, Forward Blocking
- Data Sheet

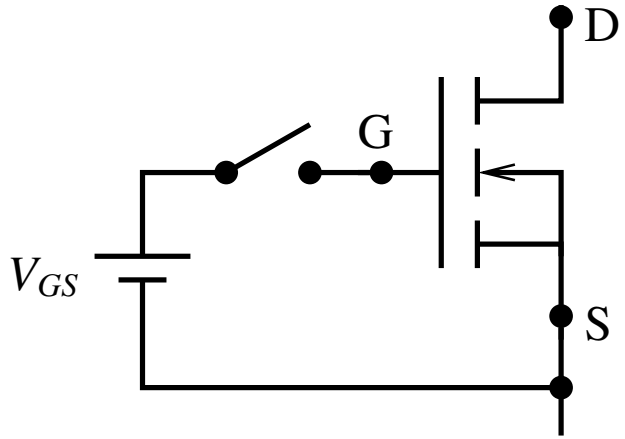
Practical Controlled Switches: MOSFETs

- Voltage controlled: Low drive power requirements, fast switching
- Operating Quadrants: Forward/Reverse Conducting, Forward Blocking (Body Diode)
- 1A-100A+
- 30V-1000V
- 50 ns - 200 ns
- Important Specs: I_D, I_M, BV_{DSS}, $r_{ds(on)}$, Z_{th}, t_{on}, t_{off}, V_{gs}, R_{gs}, $V_{gs(th)}$, I_{SD}, t_{rr}, C_{iss}
- Data Sheet



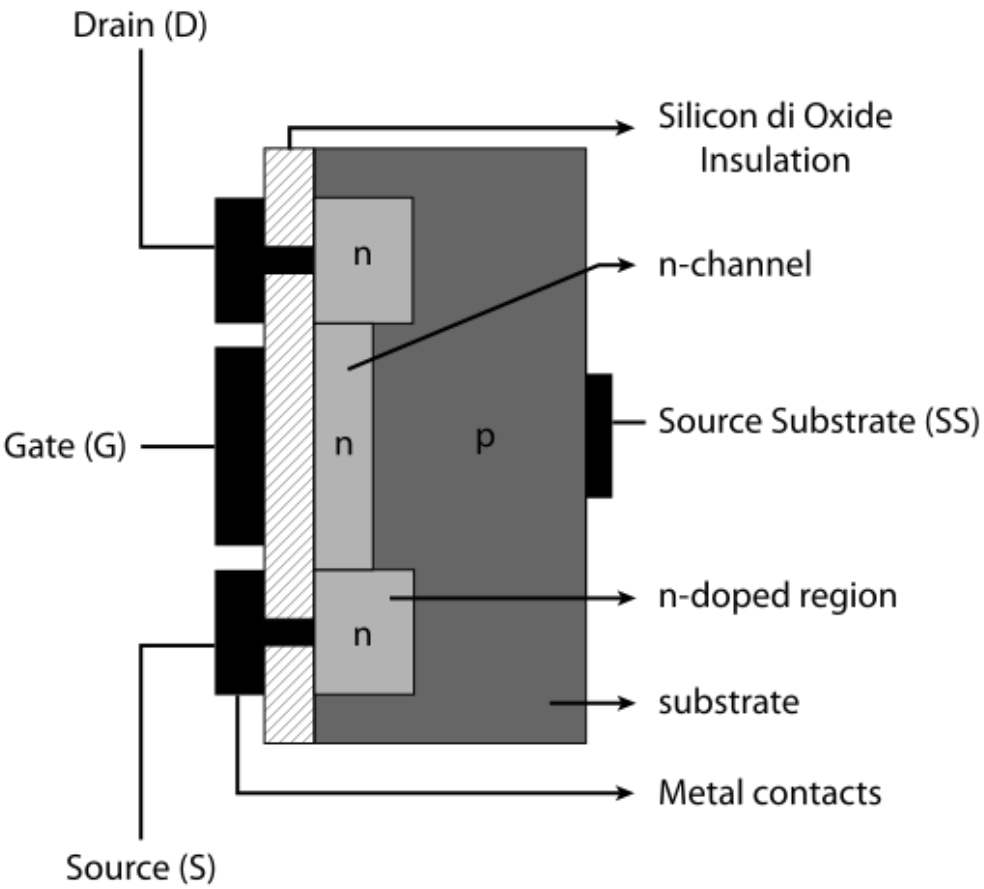
Practical Controlled Switches: MOSFETs

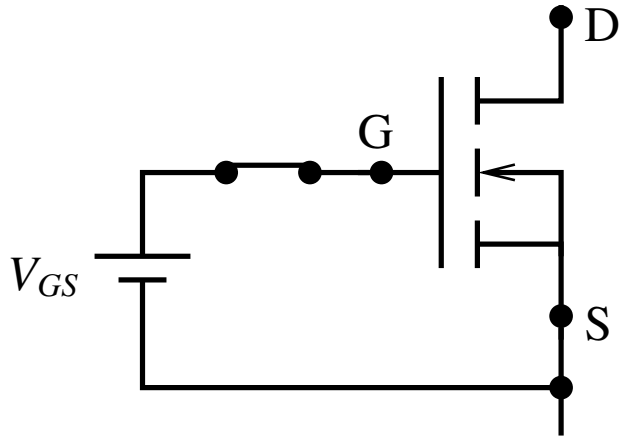




$$V_{GS} > V_{GS(th)}$$

Practical Controlled Switches: MOSFETs

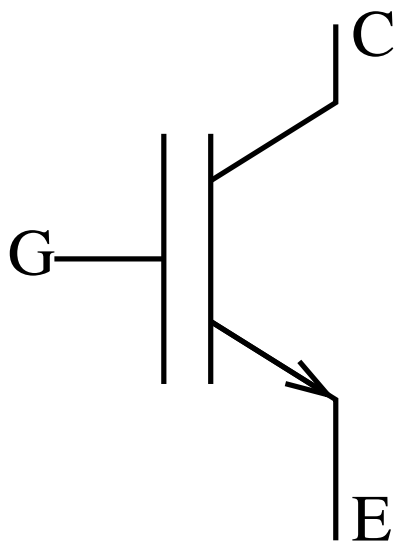




$$V_{GS} > V_{GS(th)}$$

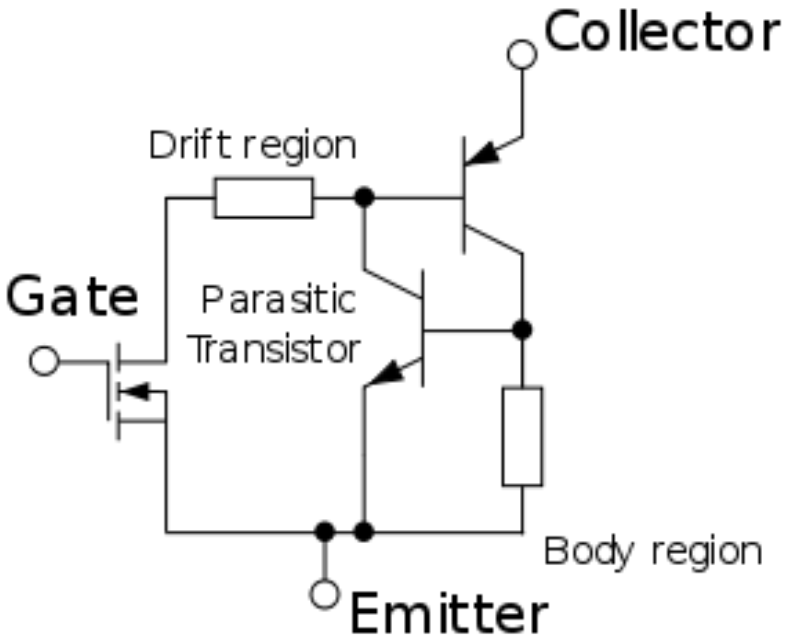
Practical Controlled Switches: IGBTs

- Voltage Controlled: Like MOSFET
- Faster than BJTs, slower than MOSFETs
- Operating Quadrants: Forward Conducting, Forward Blocking
- 10A-1200A+
- 600V-3300V
- 500 ns -
- Important Specs: I_D, I_M, BV_{DSS}, $r_{ds(on)}$, Z_{th}, t_{on}, t_{off}, V_{gs}, R_{gs}, $V_{gs(th)}$, I_{SD}, t_{rr}, C_{iss}
- Data Sheet

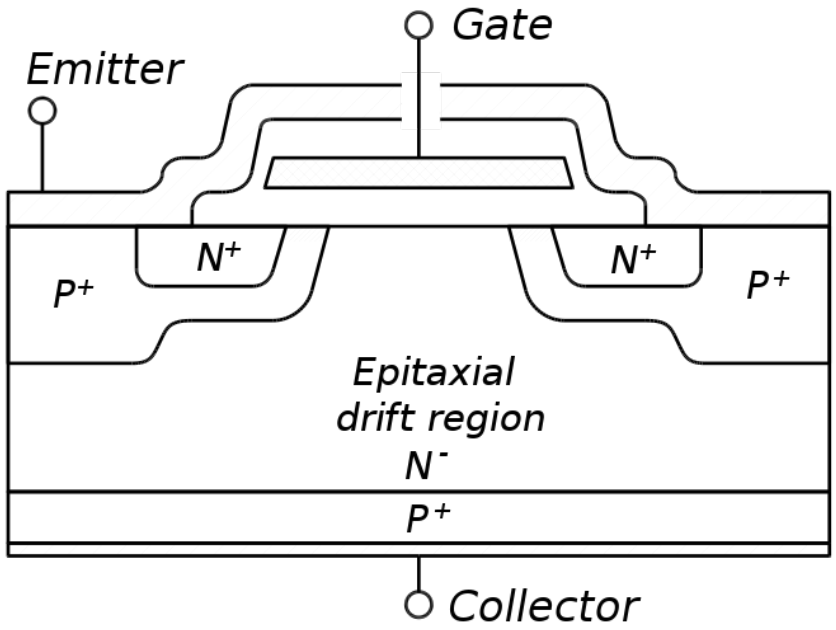


Practical Controlled Switches: IGBTs

Equivalent Circuit



Structure of IGBT



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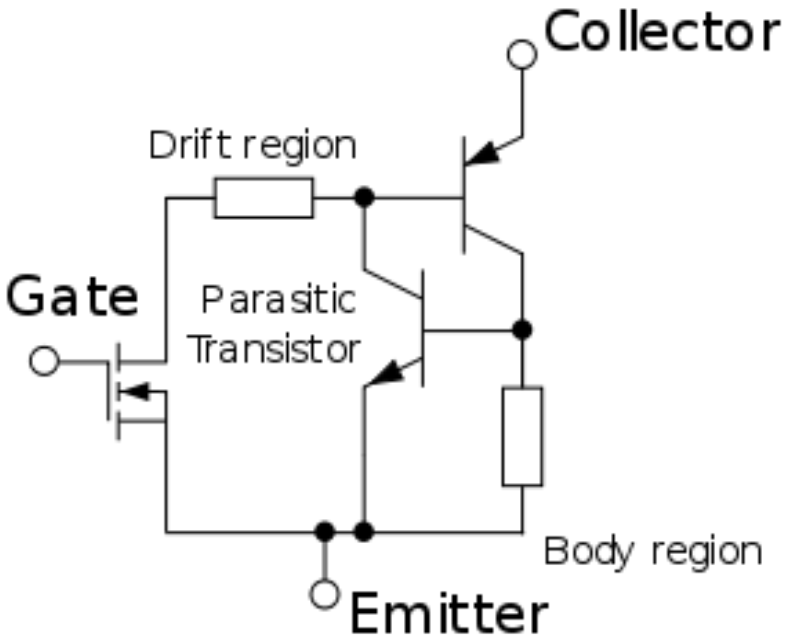

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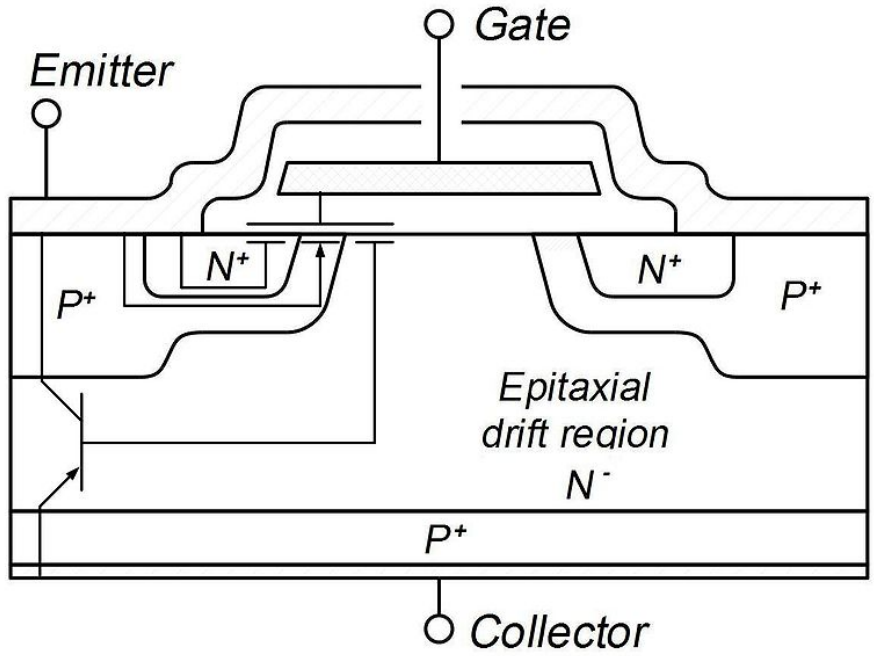

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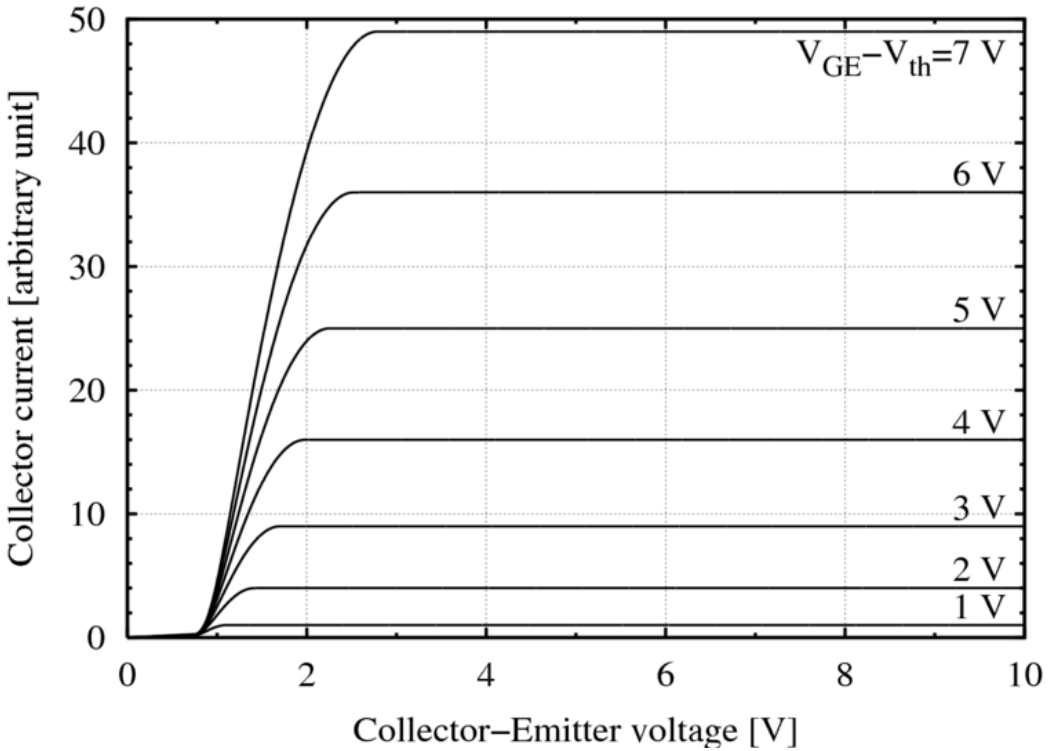

Gate Drive Circuits