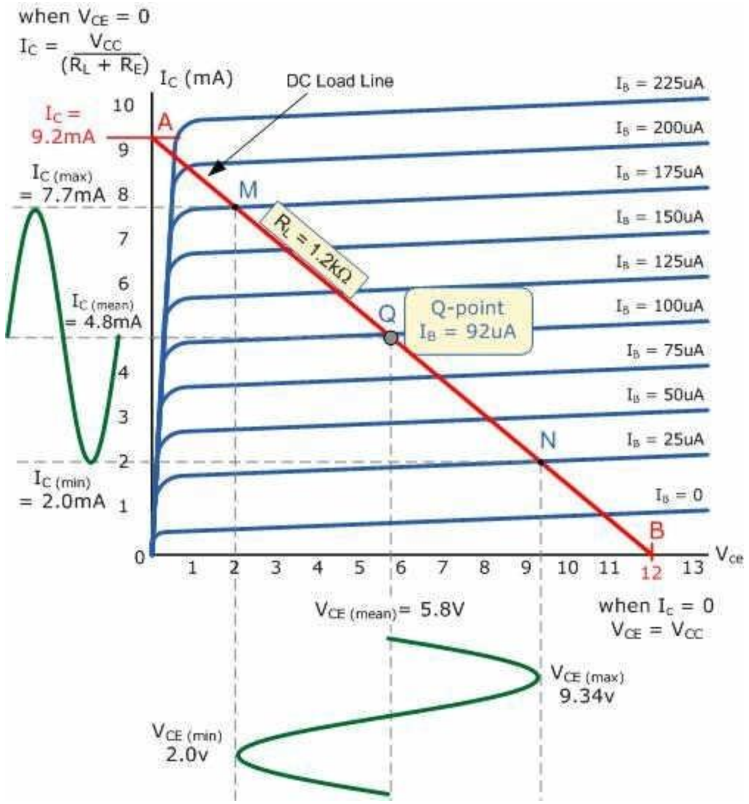
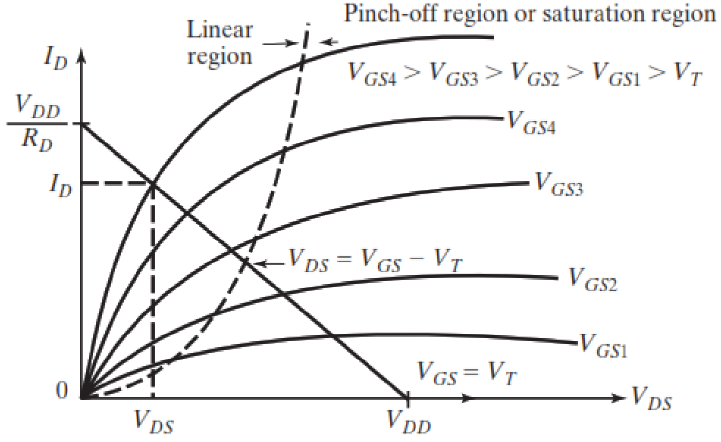
IGBT

IGBT Insulated-Gate Bipolar Transistor.

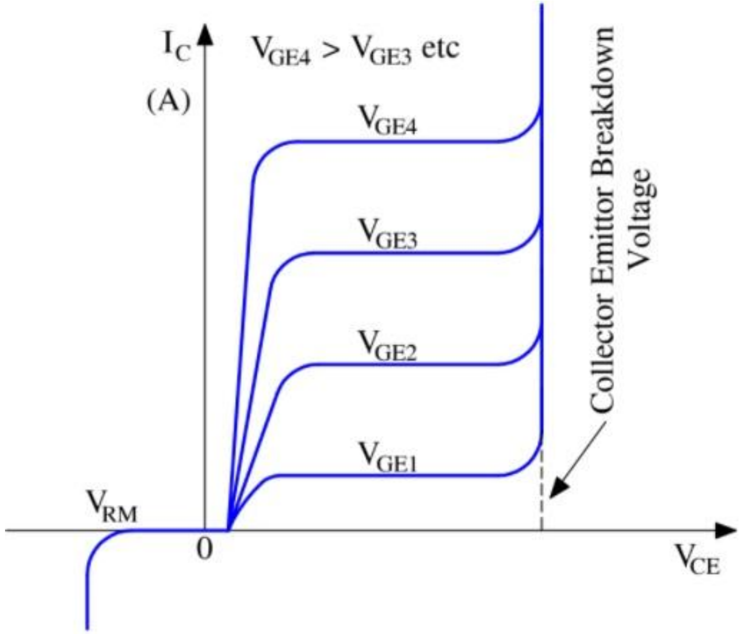
- **IGBT** is a relatively new device in power electronics and before the advent of IGBT, Power MOSFETs and Power BJT were common in use in power electronic applications.
- Both of these devices possessed some advantages and simultaneously some disadvantages.
- On one hand, we had bad switching performance, low input impedance, secondary breakdown and current controlled Power BJT and on the other we had excellent conduction characteristics of it.
- Similarly, we had excellent switching characteristics, high input impedance, voltage controlled PMOSFETs, which also had bad conduction characteristics and problematic parasitic diode at higher ratings.
- Though the unipolar nature of PMOSFETs leads to low switching times, it also leads to high ON-state resistance as the voltage rating increases



when $V_{CE} = 0$
$I_C = \frac{V_{CC}}{(R_L + R_E)}$
I_C (mA)
DC Load Line
I_C = 9.2mA
$I_{C\,(max)}$ = 7.7mA
$I_{C\,(mean)}$ = 4.8mA
$I_{C\,(min)}$ = 2.0mA
A
M
Q
N
B
$R_L = 1.2k\Omega$
Q-point
I_B = 92uA
I_B = 225uA
I_B = 200uA
I_B = 175uA
I_B = 150uA
I_B = 125uA
I_B = 100uA
I_B = 75uA
I_B = 50uA
I_B = 25uA
I_B = 0
V_{ce}
$V_{CE\,(mean)}$ = 5.8V
when $I_C = 0$
$V_{CE} = V_{CC}$
$V_{CE\,(max)}$ 9.34v
$V_{CE\,(min)}$ 2.0v



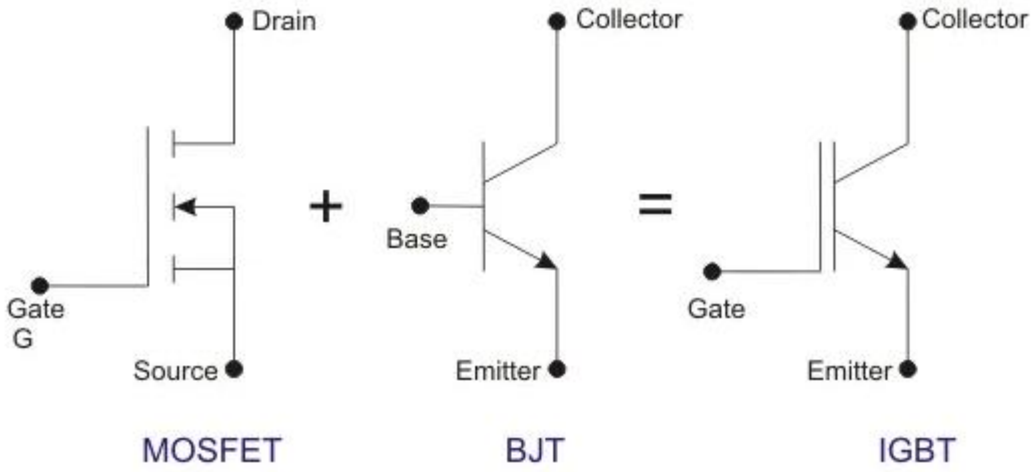
Linear region
Pinch-off region or saturation region
$V_{GS4} > V_{GS3} > V_{GS2} > V_{GS1} > V_T$
I_D
$\frac{V_{DD}}{R_D}$
V_{GS4}
V_{GS3}
V_{GS2}
V_{GS1}
$V_{DS} = V_{GS} - V_T$
$V_{GS} = V_T$
V_{DS}
V_{DD}
0



I_C (A)
$V_{GE4} > V_{GE3}$ etc
V_{GE4}
V_{GE3}
V_{GE2}
V_{GE1}
Collector Emitter Breakdown Voltage
V_{RM}
0
V_{CE}

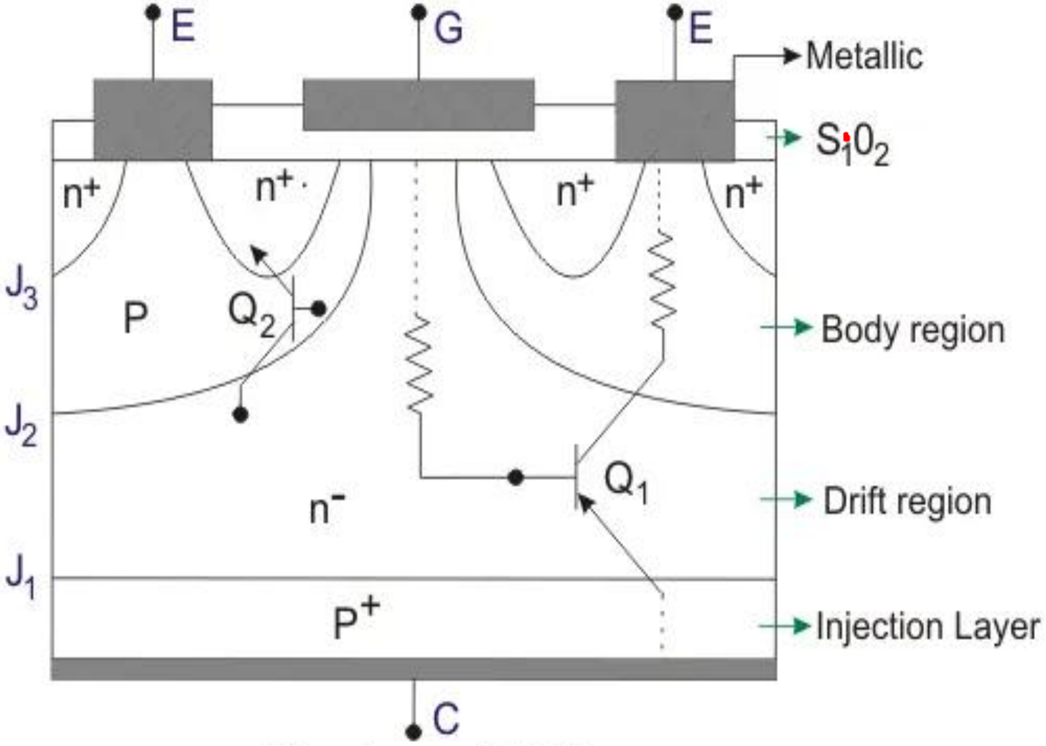
IGBT

- Thus the need was for such a device which had the goodness of both PMOSFETs and Power BJT and this was when IGBT was introduced in around the early 1980s and became very popular among power electronic engineers because of its superior characteristics.
- IGBT has PMOSFET like input characteristics and Power BJT like output characteristics and hence its symbol is also an amalgamation of the symbols of the two parent devices.
- The three terminals of IGBT are Gate, Collector and Emitter.
- The figure below shows the symbol of IGBT.

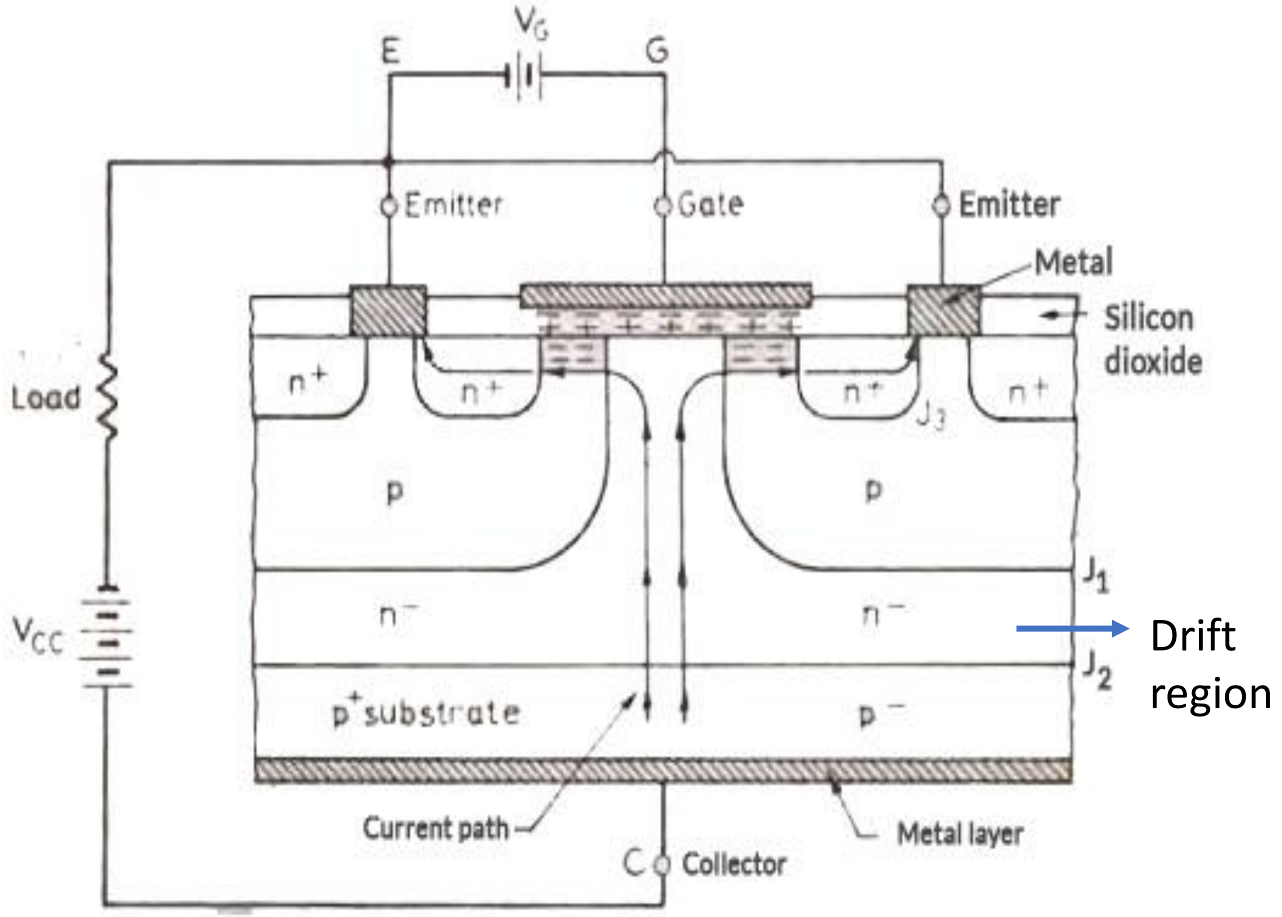


structure of IGBT

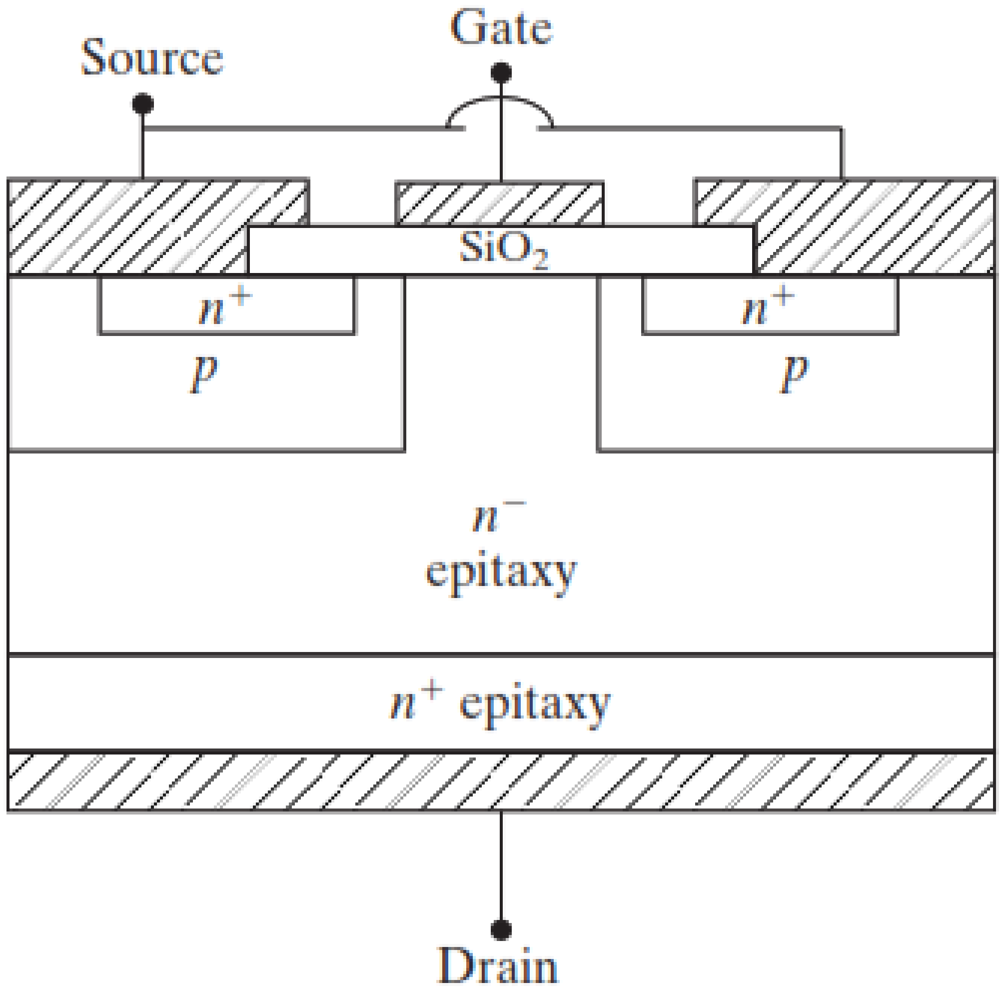
- The **structure of IGBT** is very much similar to that of PMOSFET, except one layer known as injection layer which is p^+ unlike n^+ substrate in PMOSFET.
- This injection layer is the key to the superior characteristics of IGBT.
- Other layers are called the drift and the body region.
- The two junctions are labeled J_1 and J_2.
- Figure below show the structure of n-channel IGBT.



Structure of IGBT



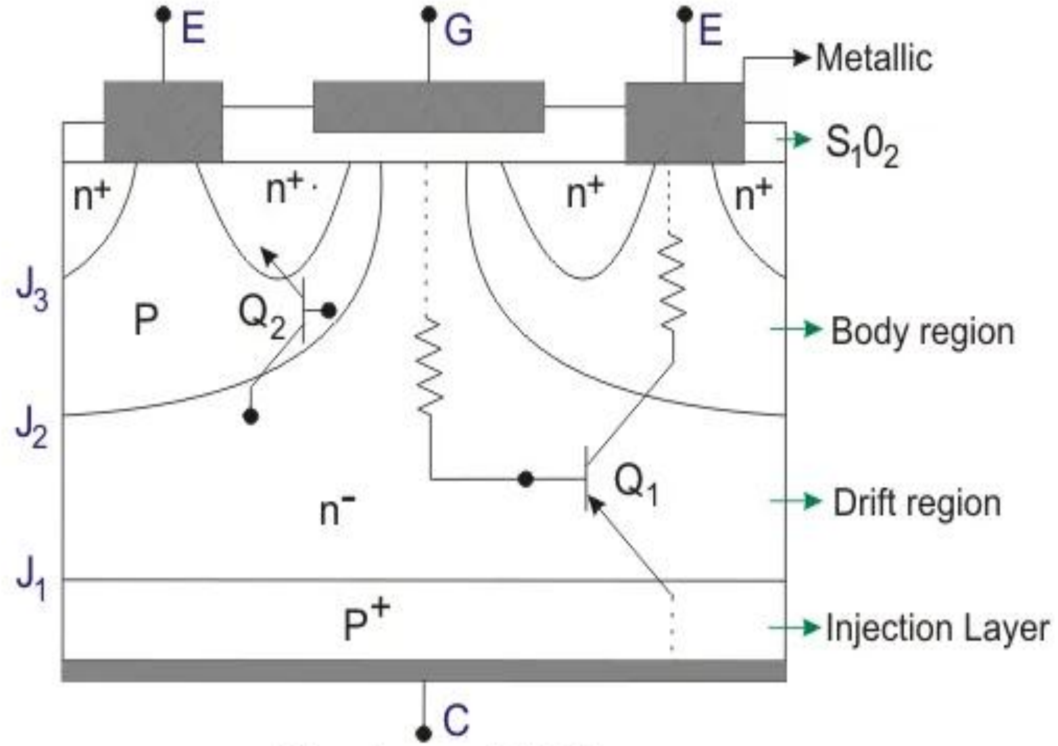
Basic Strcuture of an insulated gate bipolat transistor (IGBT)



(a) Cross section of V-MOSFET

Structure of an IGBT

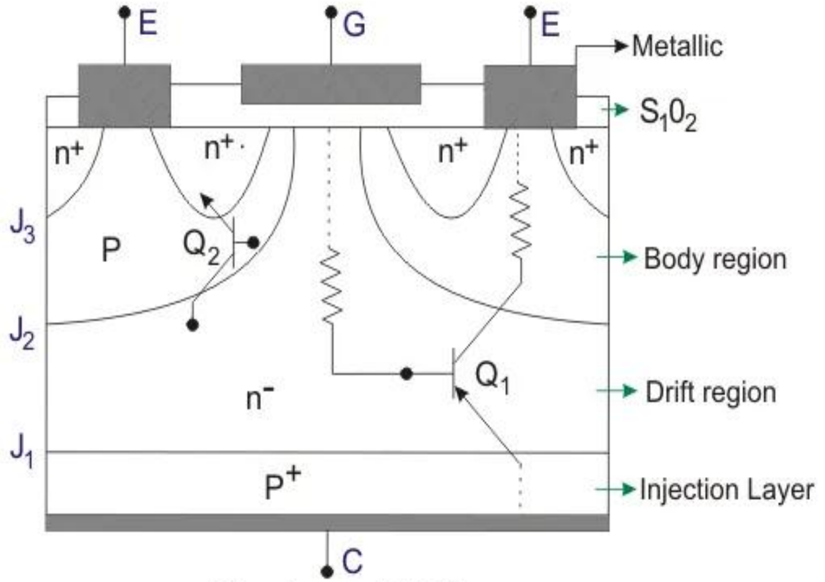
- An IGBT consists of **four layers (p+, n- p, and n+)** and **three terminals**:
  - **Gate (G)**
  - **Collector (C)**
  - **Emitter (E)**
- The key regions are:
  - **n+ Emitter:** Provides majority carriers (electrons).
  - **p-body:** (MOSFET region).
  - **n- Drift Region:** Lightly doped for high voltage blocking but highly resistive.
  - **p+ Collector (Injection Layer):** Injects **holes** into the drift region for conduction



Structure of IGBT

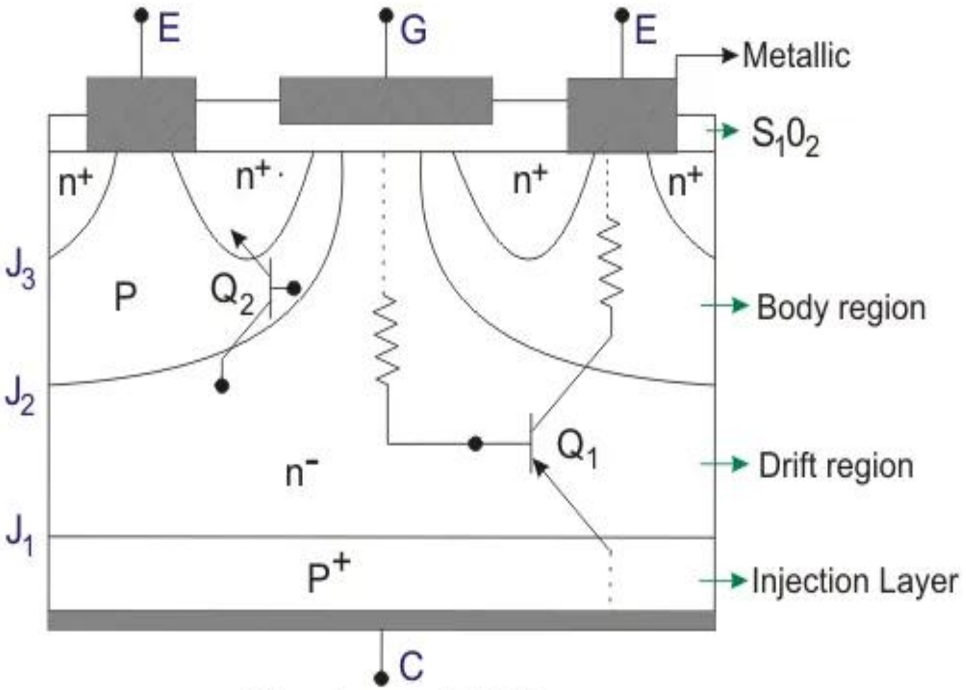
2. Operation of IGBT

- **Step 1: OFF State (No Conduction)**
- **Condition**: VGE=0V (or below threshold voltage Vth)
- **What Happens?**
  - The gate does not create an electric field, so the p-body remains a barrier.
  - The p-body prevents electrons from moving from the n+ emitter to the drift region.
  - The p+ collector is forward biased, but holes do not significantly inject because there is no electron flow from the emitter.
  - The IGBT is in the blocking state, with only a very small leakage current flowing.
- Before applying VGE, there is no conduction because the **p-body blocks current flow**.



Structure of IGBT

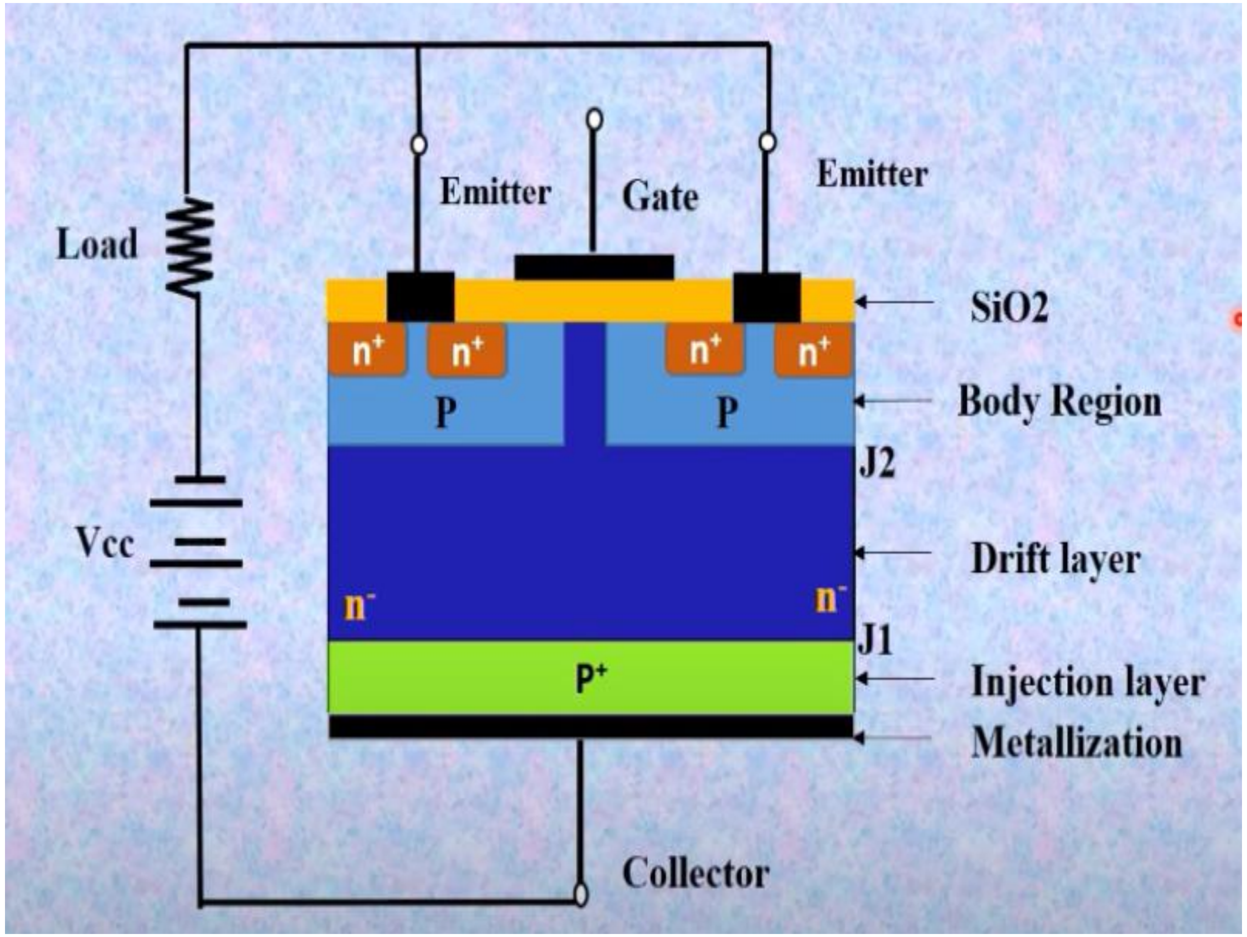
- **Step 2: ON State (Conduction Begins)**
- **Condition**: VGE>Vth(Threshold Voltage)
- **What Happens?**
  - **Gate Action (MOSFET-like behavior)**
    - A **positive gate-emitter voltage (V_{GE})** creates an **electric field** in the **p-body region**.
    - This field **repels holes from the p-body**, reducing its resistance.
    - Now, **electrons from the n+ emitter can move into the n-drift region**.
  - **Bipolar Conduction Begins (BJT-like behavior)**
    - As **electrons flow from the n+ emitter into the drift region**, the **p+ collector starts injecting holes**.
    - These **holes neutralize the high resistance of the drift region**, a process called **conductivity modulation**.
    - This leads to a **high current flow with low conduction loss**.
    - **Electrons move from emitter → drift region → collector (like a MOSFET)**.
    - **Holes move from collector → drift region → p-body (like a BJT)**.
    - This **bipolar conduction** reduces the voltage drop (VCE) across the device.
- **Conclusion:** Once VGE is applied, electrons from the **n+ emitter enter the drift region**, allowing hole injection from the **p+ collector**. This **enables conduction with lower resistance**.



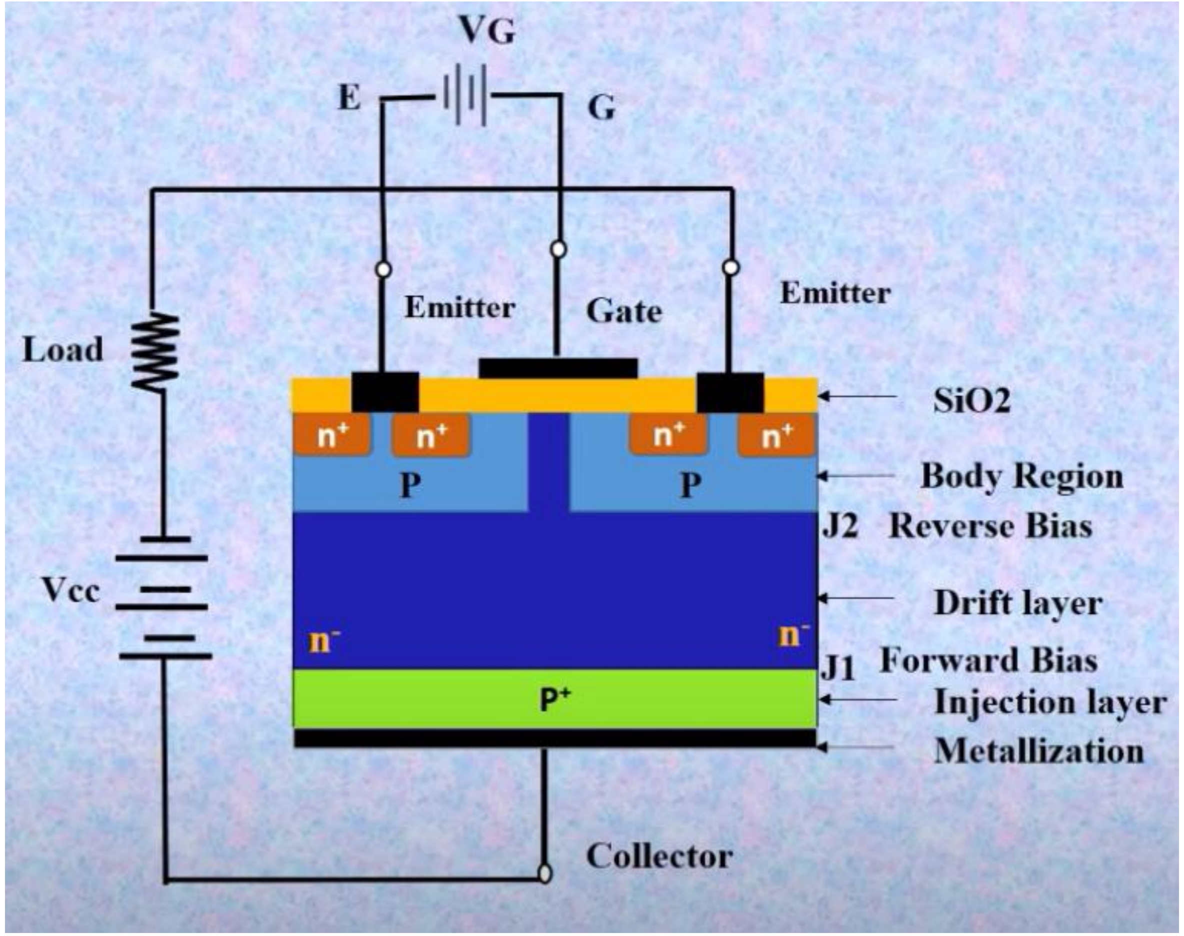
Structure of IGBT

(C) Turn-OFF Process and Tail Current Effect

- **Step 3: Turn-Off Process (Tail Current Effect)**
- **Condition**: VGE=0V (Gate voltage removed)
- **What Happens?**
  - **Gate No Longer Controls Conduction**
    - Removing VGE **stops electron flow from the n+ emitter**.
    - However, the drift region **still contains stored holes** from the previous conduction.
  - **Tail Current Effect**
    - The stored holes **take time to recombine**, leading to a **gradual decrease in current**.
    - This is called the **"tail current"**, which slows down the turn-off time.
- **Conclusion:** Unlike MOSFETs, IGBTs have a **delayed turn-off** due to the **tail current effect**, which must be managed in high-frequency applications.

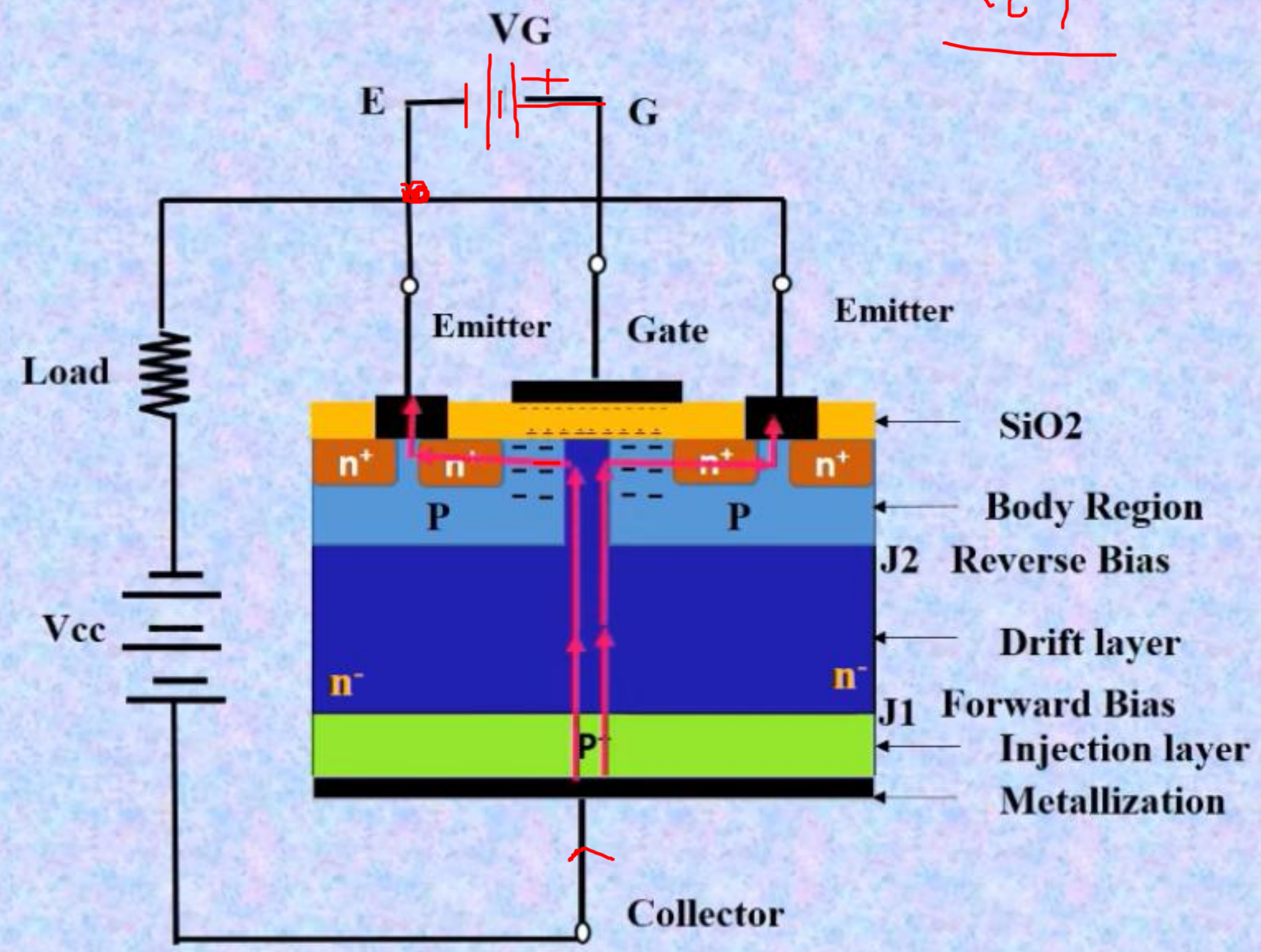


Load
Emitter
Gate
Emitter
SiO2
n+
P
Body Region
J2
Vcc
Drift layer
n-
J1
P+
Injection layer
Metallization
Collector

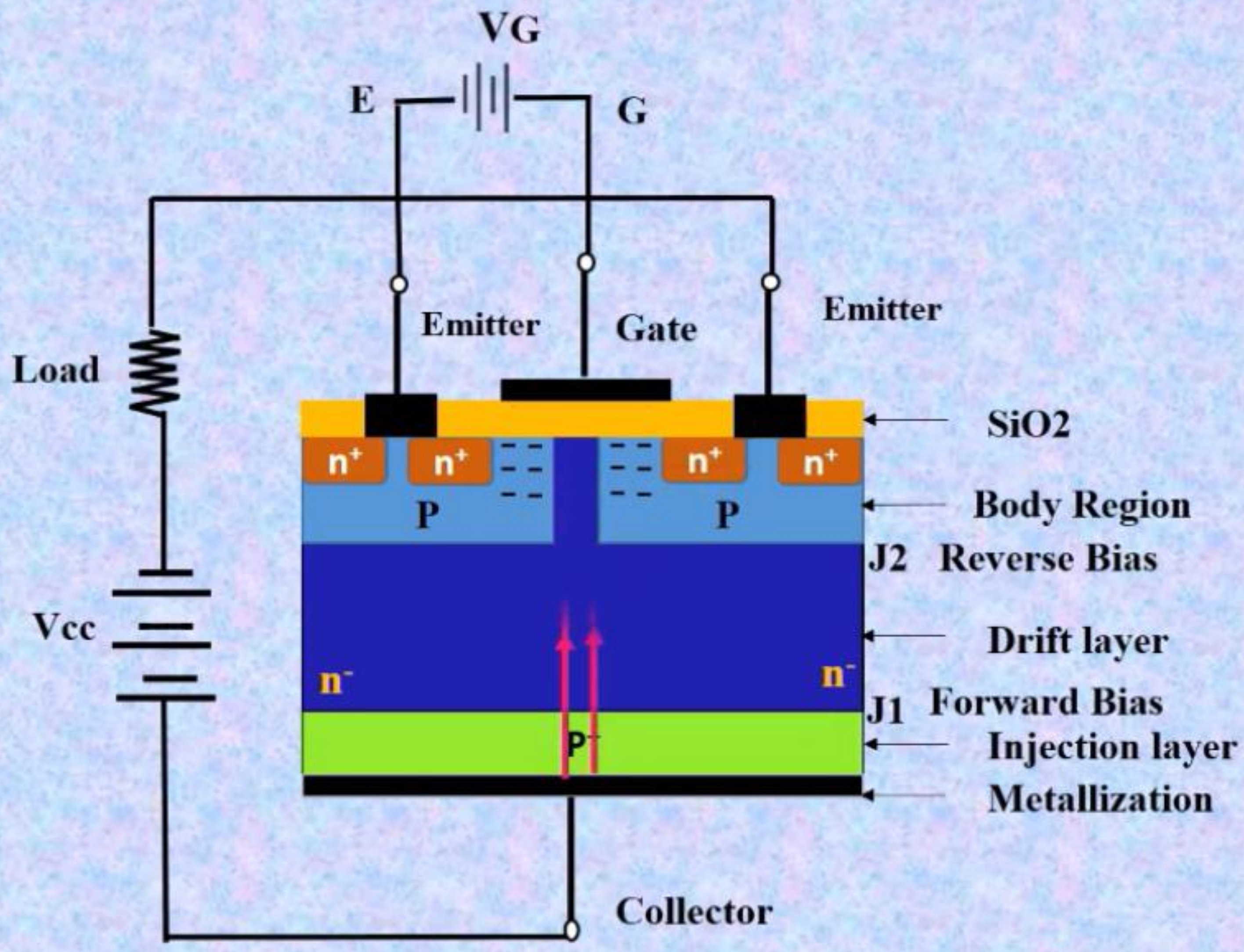


VG
E
G
Load
Emitter
Gate
Emitter
SiO2
n+
P
Body Region
J2 Reverse Bias
Vcc
Drift layer
n-
J1 Forward Bias
P+
Injection layer
Metallization
Collector

V_{GET}



Basic Structure of IGBT

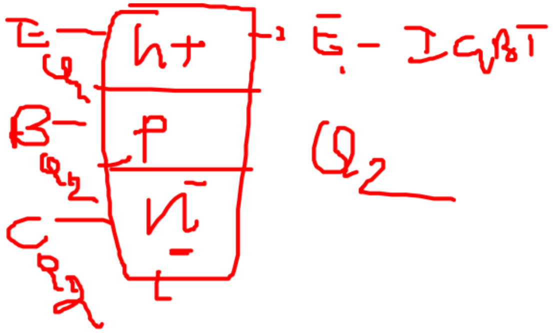


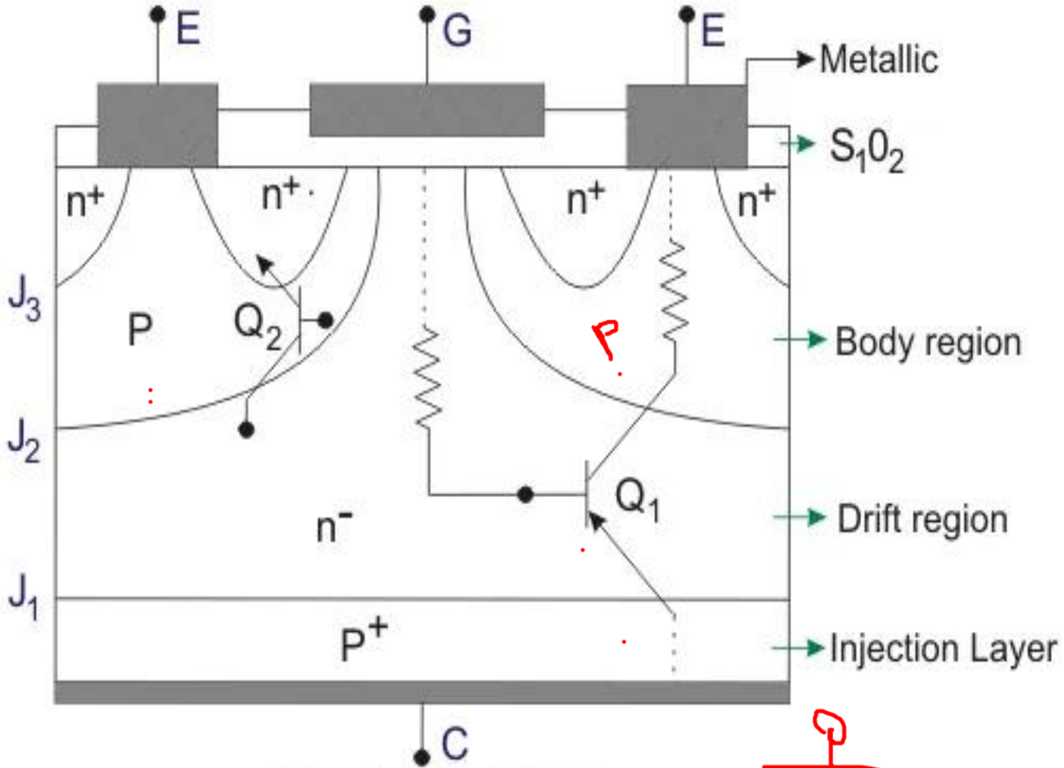
Basic Structure of IGBT

- ✓ When VG>VGthreshold, an n channel is formed in the p region similar to that as in MOSFET
- ✓ This n channel short circuits the n^- region with n^+ emitter regions
- ✓ An electron movement in the n-channel in turn causes substantial hole injection from P^+ substrate layer into the epitaxial n^- layer

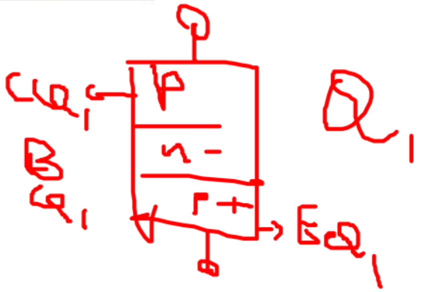
structure of IGBT

- Upon careful observation of the structure, we'll find that there exists an n-channel MOSFET and two BJTs- Q_1 and Q_2 as shown in the figure.
- Q_1 is p^+n^-p BJT and Q_2 is n^-pn^+ BJT. R_d is the resistance offered by the drift region and R_b is the resistance offered by p body region.
- We can observe that the collector of Q_1 is same as base of Q_2 and collector of Q_2 is same as base of Q_1.
- Hence we can arrive at an equivalent circuit model of IGBT as shown in the figure below.



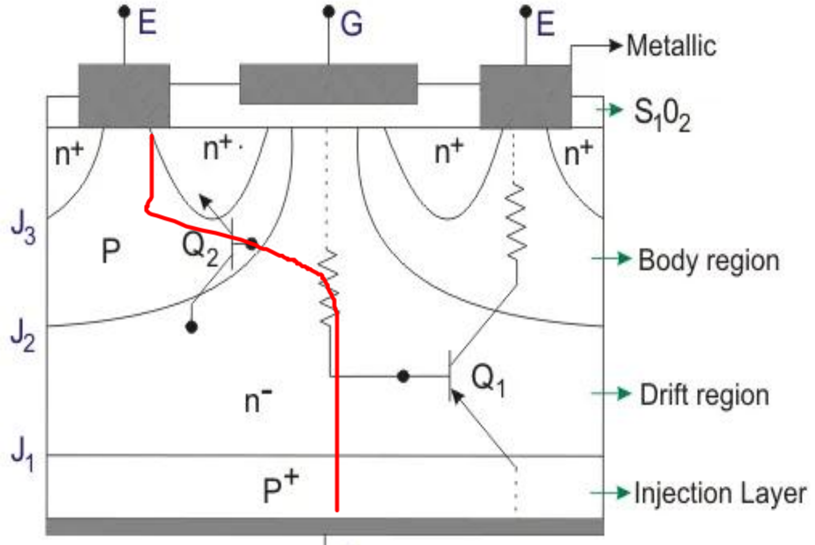


Structure of IGBT

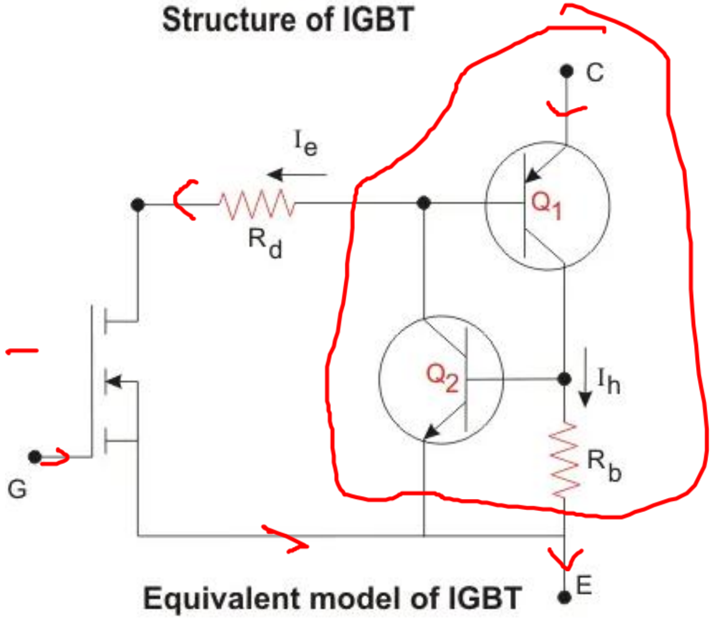


structure of IGBT

- The two transistor back to back connection forms a parasitic thyristor as shown in the above figure.
- N-channel IGBT turns ON when the collector is at a positive potential with respect to emitter and gate also at sufficient positive potential (>V_{GET}) with respect to emitter.
- This condition leads to the formation of an inversion layer just below the gate, leading to a channel formation and a current begins to flow from collector to emitter.
- The collector current I_c in IGBT constitutes of two components- I_e and I_h.
- I_e is the current due to injected electrons flowing from collector to emitter through injection layer, drift layer and finally the channel formed.
- I_h is the hole current flowing from collector to emitter through Q_1 and body resistance R_b.



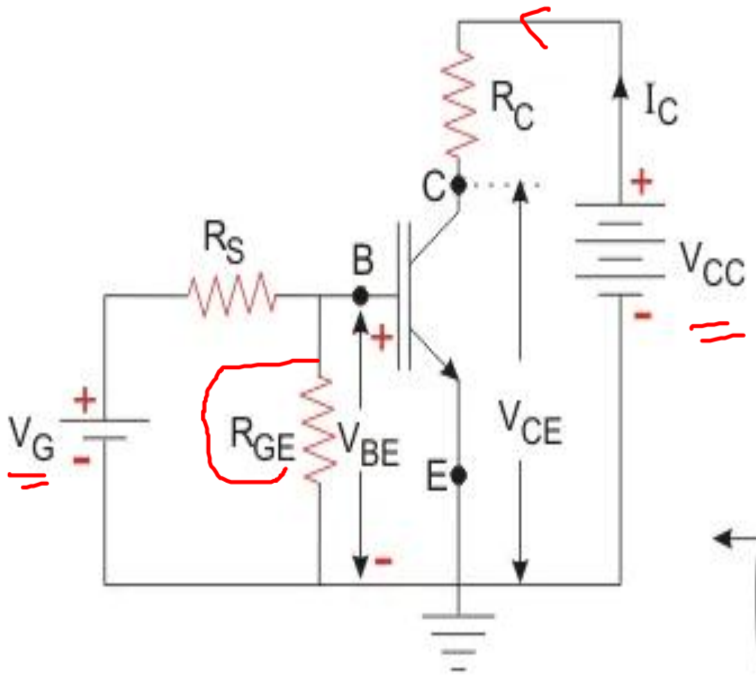
Structure of IGBT



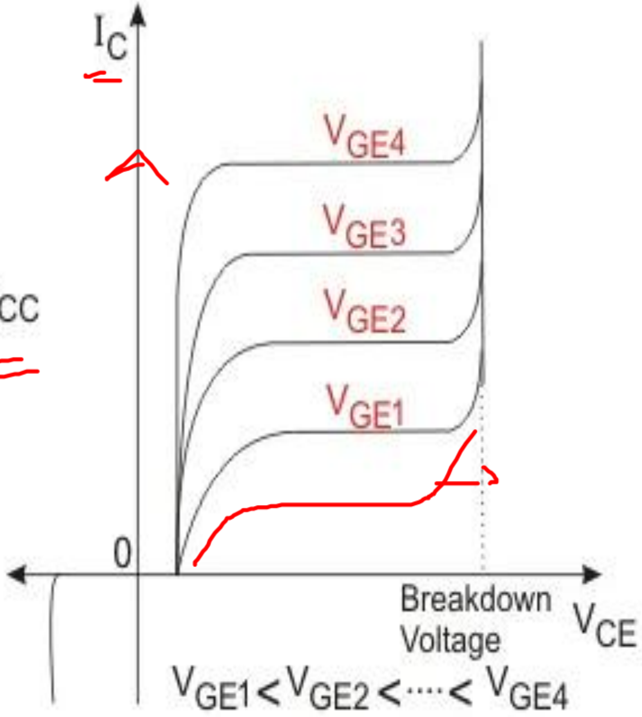
Equivalent model of IGBT

Static Characteristics

Output → BJT

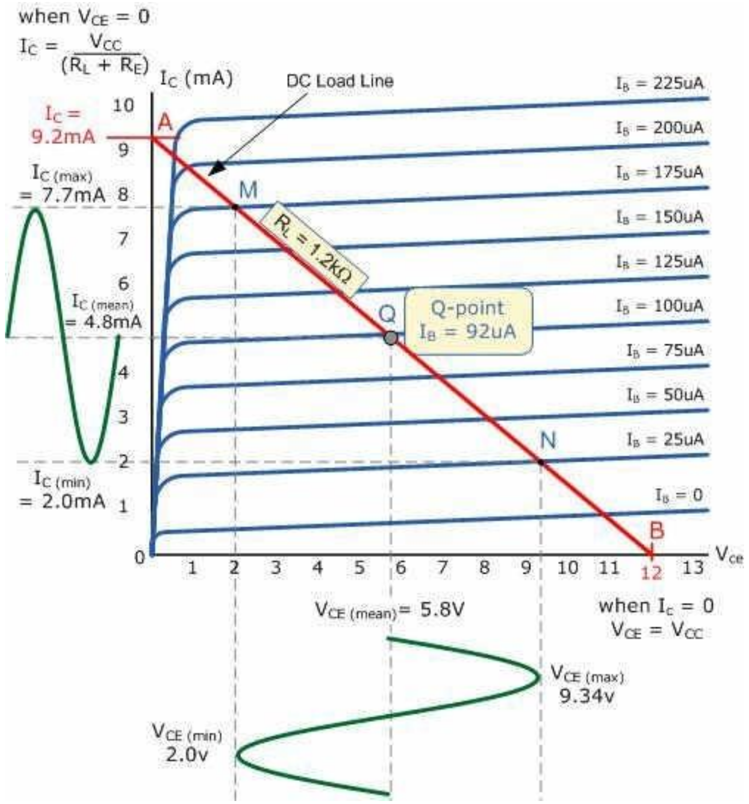


Circuit Diagram

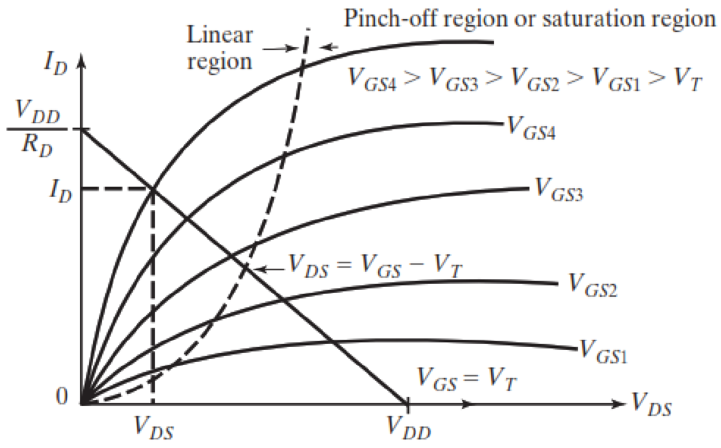


Static I - V Characteristics

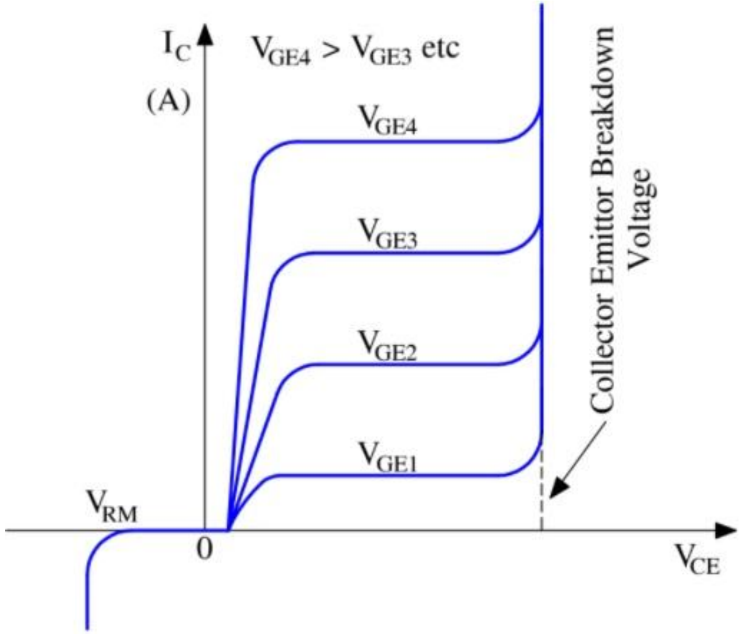
- The graph is similar to that of a BJT except that the parameter which is kept constant for a plot is VGE because IGBT is a voltage controlled device unlike BJT which is a current controlled device.
- When the device is in OFF mode (VCE is positive and VGE < VGET) the reverse voltage is blocked by J2 and when it is reverse biased,
  - i.e. VCE is negative, J1 blocks the voltage.



when $V_{CE} = 0$
$I_C = \frac{V_{CC}}{(R_L + R_E)}$
I_C (mA)
DC Load Line
I_C = 9.2mA
A
$I_{C\,(max)}$ = 7.7mA
M
$R_L = 1.2k\Omega$
$I_{C\,(mean)}$ = 4.8mA
Q
Q-point
I_B = 92uA
N
$I_{C\,(min)}$ = 2.0mA
B
I_B = 225uA
I_B = 200uA
I_B = 175uA
I_B = 150uA
I_B = 125uA
I_B = 100uA
I_B = 75uA
I_B = 50uA
I_B = 25uA
I_B = 0
V_{ce}
$V_{CE\,(mean)}$ = 5.8V
when $I_c = 0$
$V_{CE} = V_{CC}$
$V_{CE\,(max)}$ 9.34v
$V_{CE\,(min)}$ 2.0v



Linear region
Pinch-off region or saturation region
I_D
$\frac{V_{DD}}{R_D}$
$V_{GS4} > V_{GS3} > V_{GS2} > V_{GS1} > V_T$
V_{GS4}
V_{GS3}
$V_{DS} = V_{GS} - V_T$
V_{GS2}
V_{GS1}
$V_{GS} = V_T$
0
V_{DS}
V_{DD}



I_C
(A)
$V_{GE4} > V_{GE3}$ etc
V_{GE4}
V_{GE3}
V_{GE2}
V_{GE1}
Collector Emitter Breakdown Voltage
V_{RM}
0
V_{CE}

Transfer Characteristics of IGBT

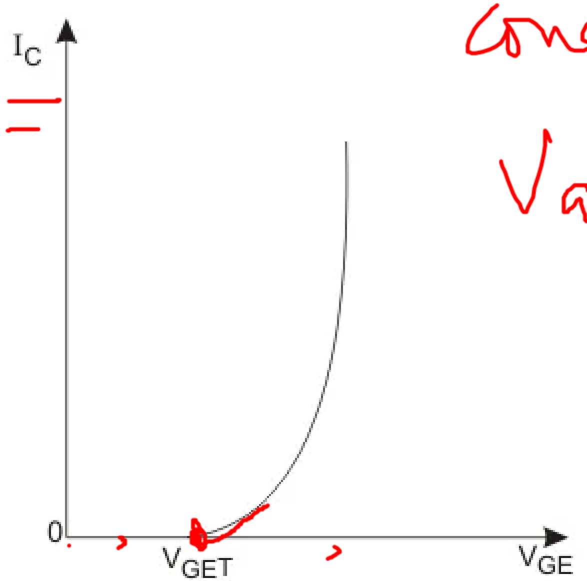
Input

MOSFET

- Figure below shows the transfer characteristic of IGBT, which is exactly same as PMOSFET.
- The IGBT is in ON-state only after V_{GE} is greater than a threshold value V_{GET}.

conduction

V_G

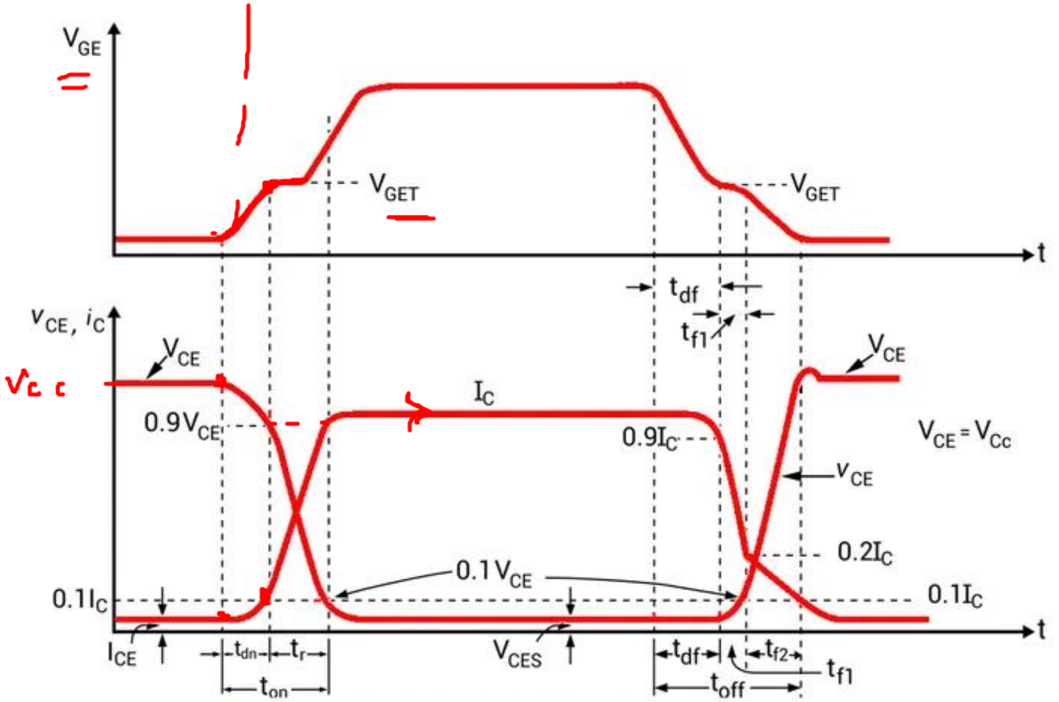


Transfer Characteristics

Dynamic

Switching Characteristics of IGBT

- Turn on time t_{on} is composed of two components as usual, delay time (t_{dn}) and rise time (t_r)
- Delay time is defined as the time in which collector current rises from leakage current I_{CE} to 0.1 I_C (final collector current) and collector emitter voltage falls from V_{CE} to $0.9V_{CE}$.
- Rise time is defined as the time in which collector current rises from 0.1 I_C to I_C and collector emitter voltage falls from $0.9V_{CE}$ to 0.1 V_{CE}.



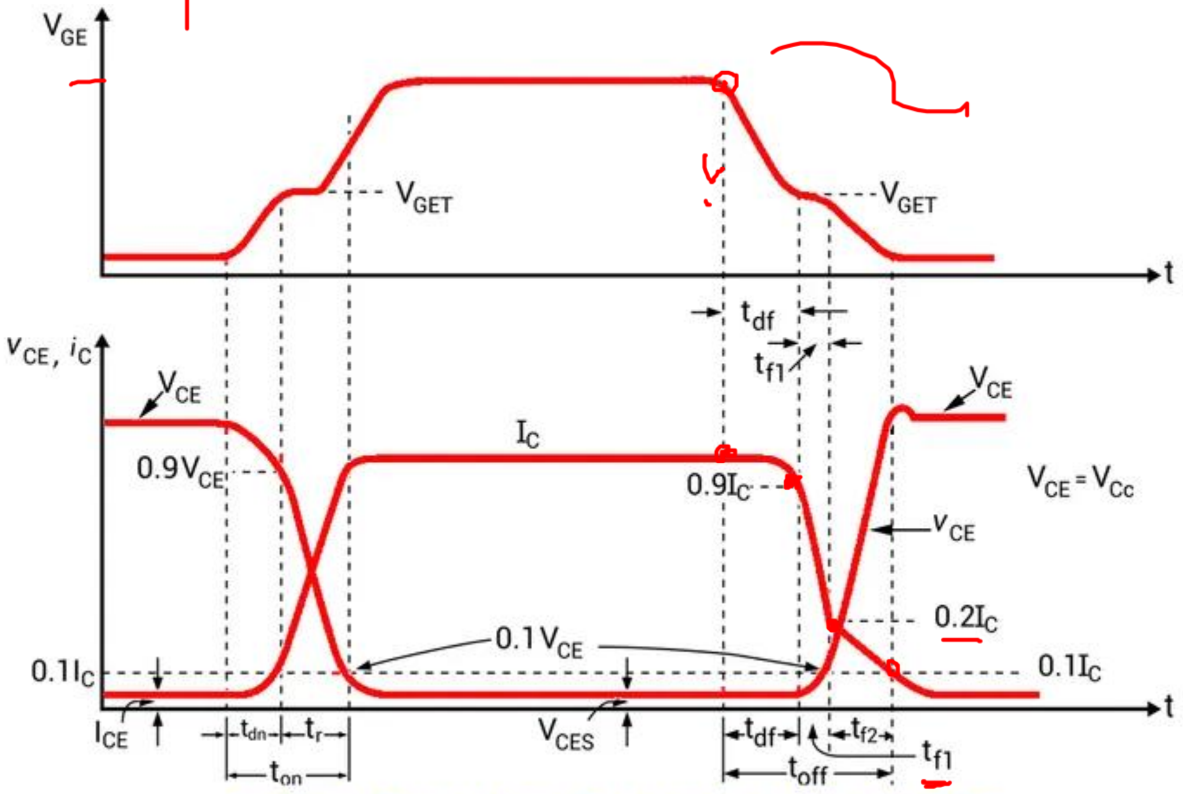
Typical Switching Characteristic of IGBT

$$t_{on} = t_{dn} + t_r$$

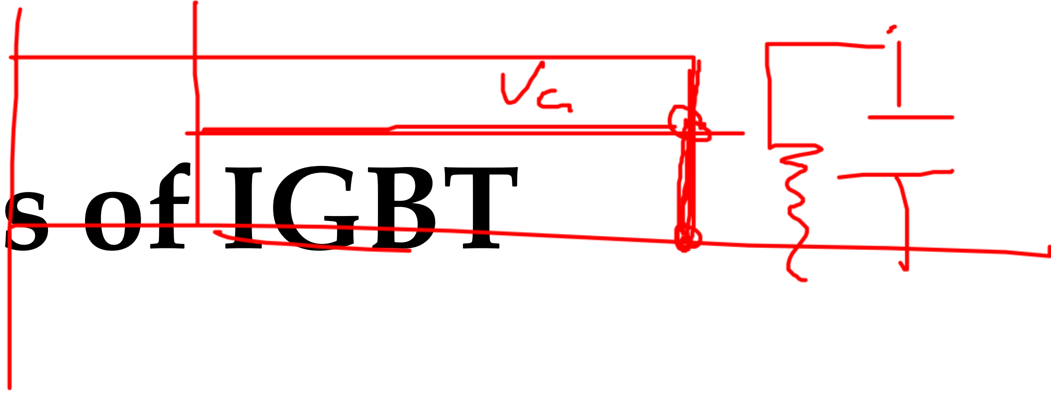
Switching Characteristics of IGBT

- The turn off time t_{off} consists of three components, delay time (t_{df}), initial fall time (t_{f1}) and final fall time (t_{f2}).
- Delay time is defined as time when collector current falls from I_C to $0.9\ I_C$ and V_{CE} begins to rise.
- Initial fall time is the time during which collector current falls from $0.9\ I_C$ to $0.2\ I_C$ and collector emitter voltage rises to $0.1\ V_{CE}$.
- The final fall time is defined as time during which collector current falls from $0.2\ I_C$ to $0.1\ I_C$ and $0.1V_{CE}$ rises to final value V_{CE}.

$$t_{off} = t_{df} + t_{f1} + t_{f2}$$



Typical Switching Characteristic of IGBT



Advantages of IGBT

Advantages of IGBT are

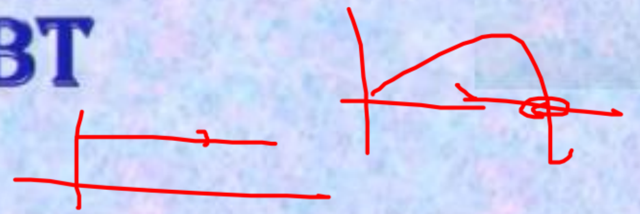
- Lower gate drive requirements
- Low switching losses → O/P → BJT
- Small snubber circuitry requirements
- High input impedance
- Voltage controlled device
- Temperature coefficient of ON state resistance is positive and less than PMOSFET, hence less On-state [voltage drop] and power loss.
- Enhanced conduction due to bipolar nature
- Better Safe Operating Area

Disadvantages:

- Cost
- Latching-up problem
- High turn off time compared to PMOSFET

DC-DC
DC-AC

LATCHING UP OF IGBT



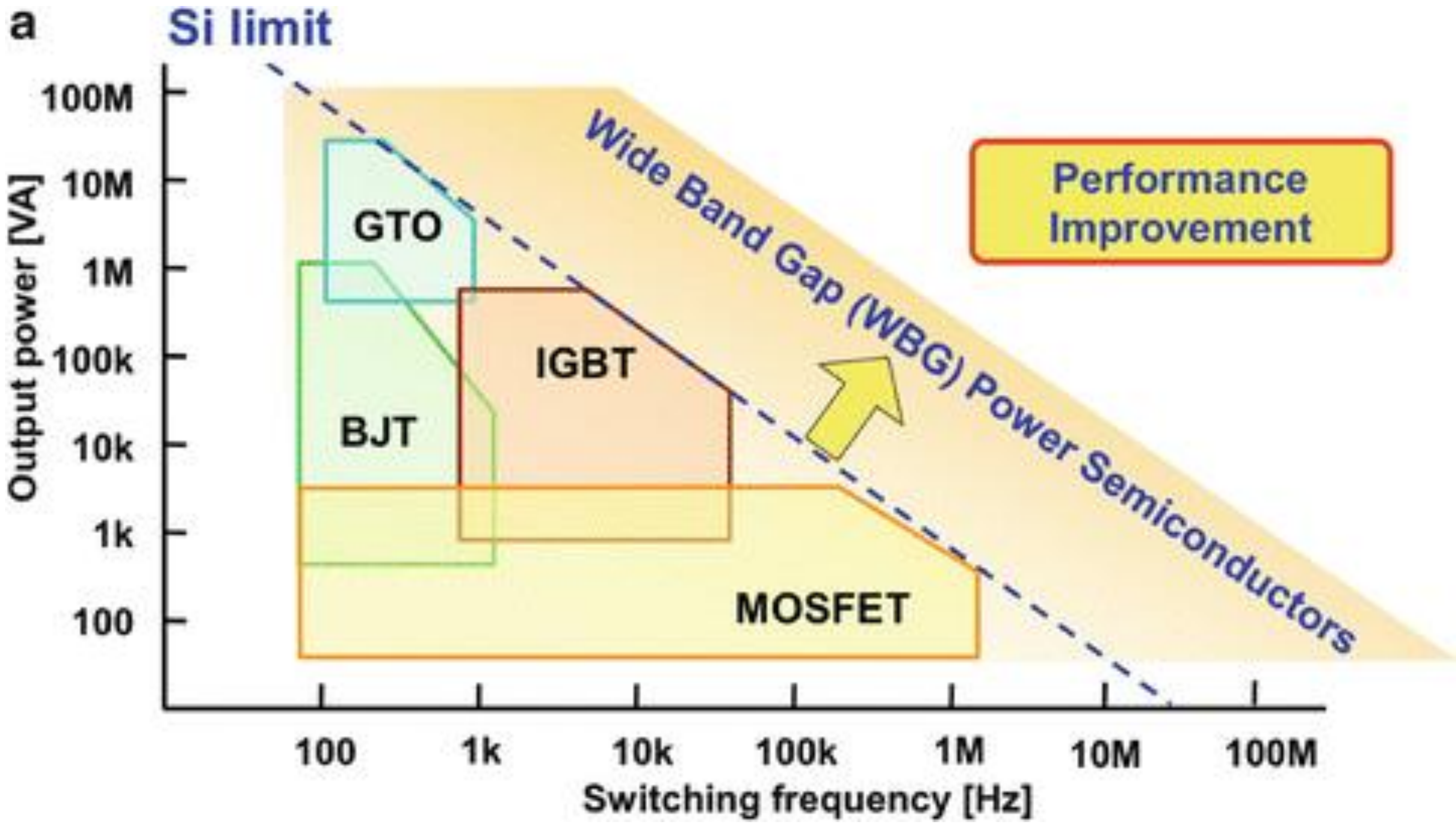
- ✓ Due to the presence of a parasitic thyristor, a unique phenomenon is observed in IGBT known as Latching up of IGBT by regenerative action
- ✓ This occurs when **collector current exceeds a certain threshold value (I_{CE})** $I_{CE} > I_{CE}$
- ✓ In this the parasitic thyristor gets **latched up** and the **gate terminal loses control over collector current**
- ✓ IGBT fails to turn off even when gate potential is reduced below V_{GET}
- ✓ For turning OFF of IGBT now, we need typical commutation circuitry as in the case of forced commutation of thyristors.

Applications and Ratings

The current rating of a single IGBT can be up to 6500 V, 2400 A and the switching frequency can be up to 20 kHz. IGBTs are finding increasing applications in medium-power applications such as dc and ac motor drives, power supplies, solid-state relays, and contractors.

As the upper limits of commercially available IGBT ratings are increasing (e.g., as high as 6500 V and 2400 A), IGBTs are finding and replacing applications where BJTs and conventional MOSFETs were predominantly used as switches.

Comparison of Power Electronic switches


a
Si limit
Wide Band Gap (WBG) Power Semiconductors
Performance Improvement
GTO
BJT
IGBT
MOSFET
Output power [VA]
100M
10M
1M
100k
10k
1k
100
Switching frequency [Hz]
100
1k
10k
100k
1M
10M
100M

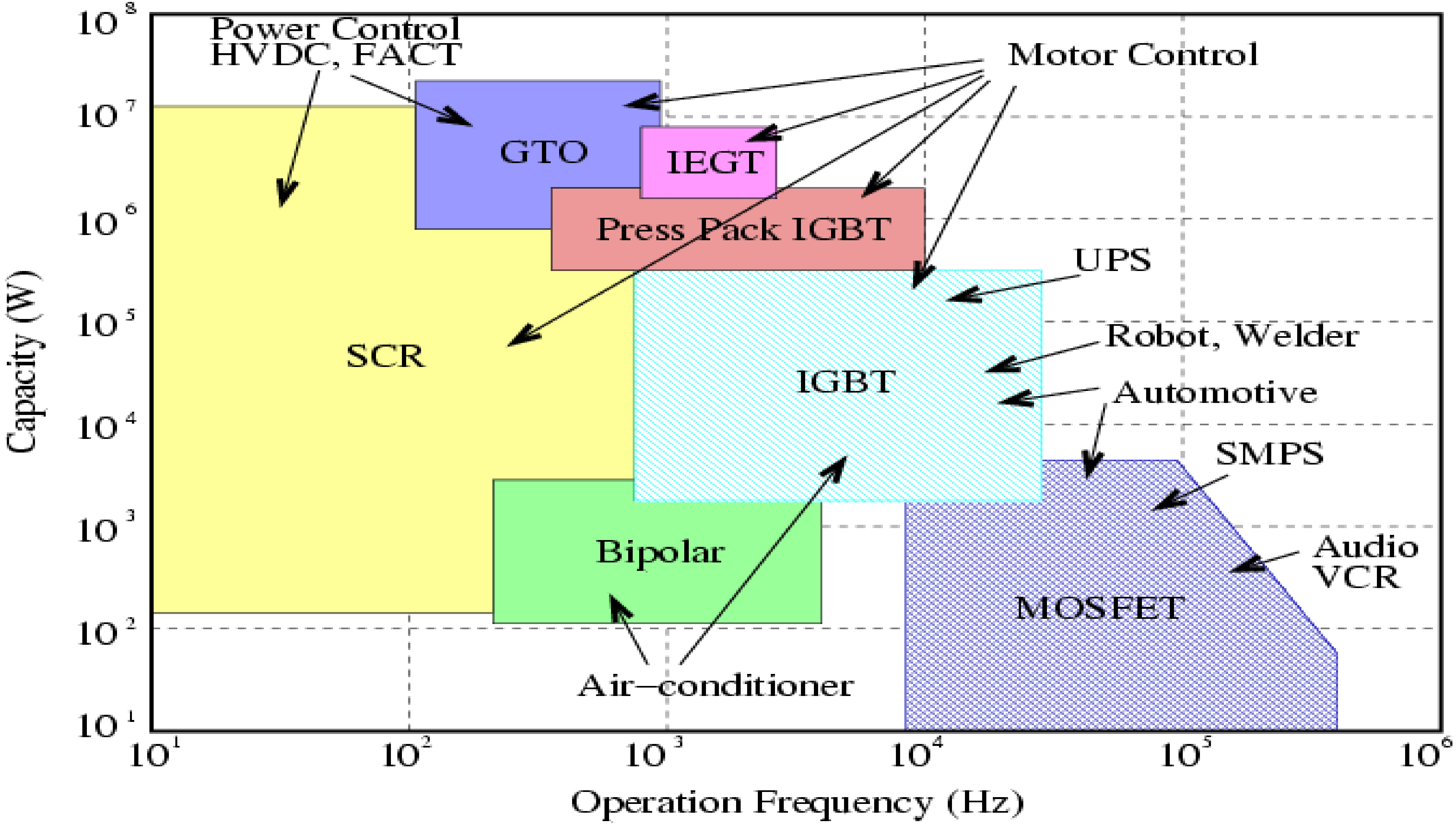


Figure 2.2: Application of discrete power semiconductors.

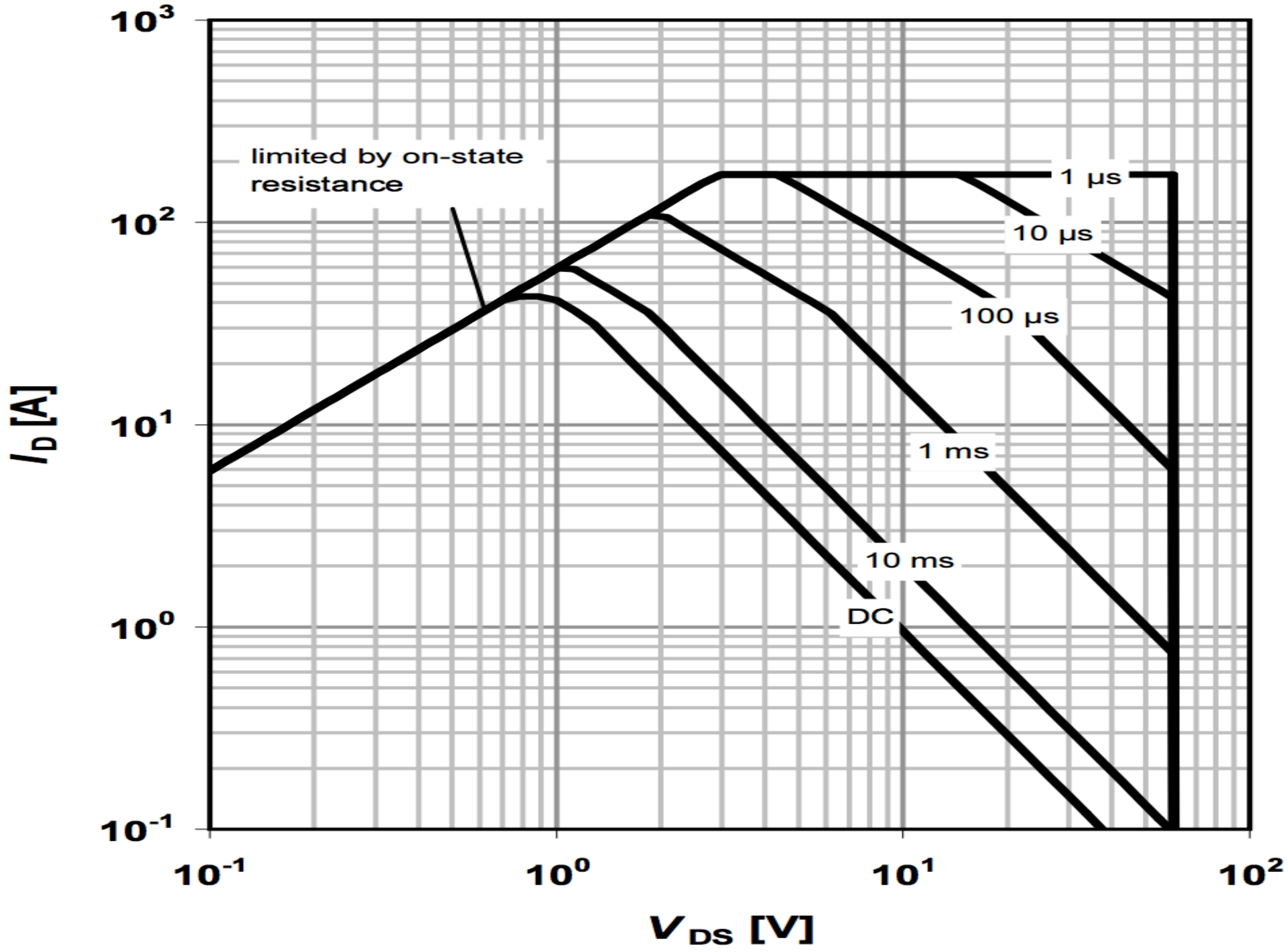
Safe Operating Area (SOA)

- The Safe Operating Area (SOA) for a power electronics switch is essentially a defined region in the voltage–current (V–I) space within which the device can operate safely without risking damage or failure.
- In power electronics, this concept is vital for ensuring that switches like MOSFETs, IGBTs, or bipolar transistors do not exceed their inherent electrical and thermal limits.

3 Safe operating area

$I_D = f(V_{DS})$; $T_C = 25$ °C; $D = 0$

parameter: t_p



What Is the SOA?

- **Graphical Representation:**
  Manufacturers provide an SOA graph in the device datasheet where the horizontal axis typically represents the voltage across the switch and the vertical axis shows the current through it. The area bounded by the curve represents the combinations of voltage and current that the switch can handle safely.
- **Time Dependency:**
  The SOA isn't just a static boundary—it can change depending on the duration of the applied stress. Devices often handle higher current pulses for very short durations compared to continuous operation. This means the SOA curve will typically have different segments for continuous, repetitive, and pulse conditions.
- **Thermal Limits:**
  Apart from electrical limits, thermal constraints are a key part of the SOA. Even if a given combination of voltage and current is within the SOA, the device must also be able to dissipate the generated heat. Exceeding the maximum junction temperature due to inadequate heat dissipation can lead to failure.

Why is SOA Important?

- **Reliability:**
  Ensuring that the device operates within its SOA prevents excessive stress that could lead to phenomena like thermal runaway, avalanche breakdown, or permanent degradation. Staying within these limits maximizes the longevity and reliability of the switch.
- **Design Safety Margin:**
  Engineers use the SOA to design circuits with sufficient safety margins. By factoring in worst-case operating conditions and transient events, designers can prevent scenarios where the device is pushed into unsafe territory.
- **Performance Optimization:**
  Knowledge of the SOA allows designers to optimize both the performance and efficiency of power electronic systems. It helps in selecting the right device for an application and in designing protection circuits that can shut down or limit operation if conditions approach unsafe levels.
- **Prevention of Catastrophic Failure:**
  Operating outside the SOA can result in immediate or cumulative damage, which may lead to catastrophic failure of the switch and potentially the entire system. This is especially critical in high-power applications where the consequences of failure are severe.

Practical Applications in Power Electronics

- **Circuit Design:**
  In applications like DC–DC converters, inverters, and motor drives, the SOA is a key design parameter. Engineers use it to ensure that transient surges, load variations, and other disturbances remain within the safe boundaries.
- **Testing and Validation:**
  During prototyping and testing, devices are often stressed near their SOA limits to validate that the actual performance aligns with the datasheet specifications. This helps in refining the design for both robustness and efficiency.
- **Protection Mechanisms:**
  Many modern circuits incorporate protection features that monitor operating conditions. If a device nears its SOA boundary, these systems can limit the current, reduce the voltage, or even shut down the operation to prevent damage.

- https://www.youtube.com/watch?v=aVQacT79nkc
- https://www.youtube.com/watch?v=86S-CEXImzU
- https://www.youtube.com/watch?v=noVu5bgYTTA

Comparison

Parameter	SCR	MOSFET	IGBT	WBG Devices (SiC/GaN)
Switching Speed	Slow (Turn-off limitations)	Very Fast (Voltage-controlled gate)	Moderate (Slower than MOSFET)	Fastest (Superior material properties)
Efficiency	Moderate (High conduction losses)	High (Low conduction losses)	Good (Better than SCR, lower than MOSFET)	Highest (Low switching & conduction losses)
Voltage Rating	Very High (Up to several kV)	Low to Moderate (Up to 900V)	High (Up to 3-4 kV)	Excellent (Up to 10 kV for SiC)
Current Rating	Very High	Limited (Higher on-resistance)	High (Better than MOSFET)	Moderate to High
Cost	Low (Mature technology)	Moderate	Higher (Hybrid structure)	Most Expensive
Applications	High-power AC/DC converters, industrial motor drives, HVDC applications	Low-power switching applications, SMPS, motor control	Medium-to-high power applications, EV inverters, industrial motor drives, renewable energy inverters	High-frequency, high-efficiency applications (EV chargers, data centers, advanced power electronics)
Thermal Performance	Requires significant cooling (High conduction losses)	Generates less heat, easier thermal management	Produces moderate heat, requires efficient cooling	Excellent thermal performance, operates at high temperatures
Voltage/Current Controlled	Current-Controlled	Voltage-Controlled	Voltage-Controlled	Voltage-Controlled