Power Converters

Power Transistors

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Power BJT

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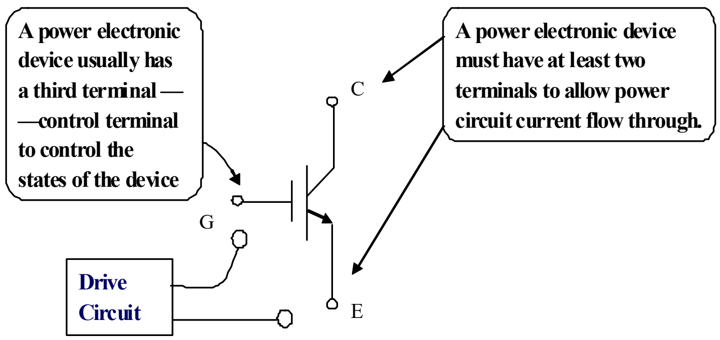
Power Transistor

- Power Transistor is a controlled Device



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Power Transistor

- Two types of transistor are extensively used in power switching circuits: bipolar junction transistor (BJT) and Metal Oxide Semiconductor Field Effect Transistor (MOSFET).
- The BJT consists of a ***pnp*** or ***npn*** single-crystal silicon structure.
- It operates by the injection and collection of minority carriers, both electrons and holes, and is therefore termed a '*Bipolar Transistor'.*

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Power Transistor

- The MOSFET depends on the voltage control of a depletion width, it is therefore a *Uni-polar Transistor.*
- Unlike the BJT, the MOSFET is a majority carrier device and therefore does not exhibit minority carrier storage delays, so switching times of the MOSFETs are ultra fast.

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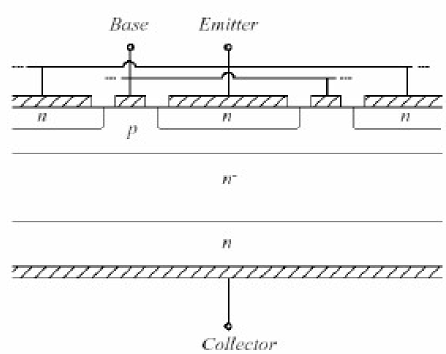
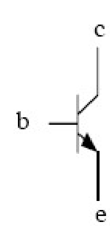
Power BJT Structure

- Power BJT can handle high voltage and large current.

Basic structure



Symbol



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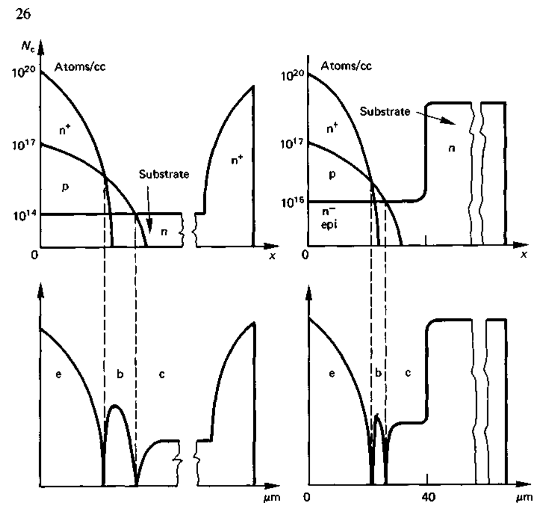
Power BJT doping

A typical high-voltage triple-diffused transistor doping profile is shown below

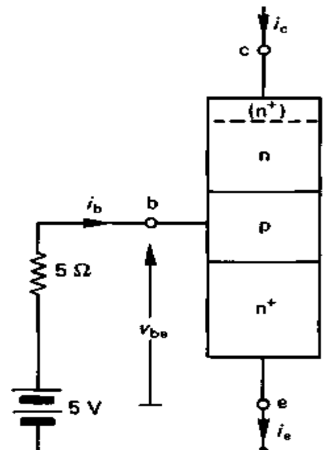


Power BJT

- The n-collector region is the initial high-resistivity silicon material and the collector n^+ diffusion is performed first, usually into both sides.
- One n^+ diffusion is lapped off and the p-base and n^+ emitter diffusions are sequentially performed.

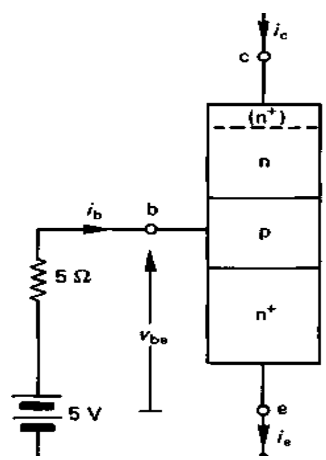
Power BJT Operation

- A simple and qualitative view of the bipolar power switching transistor.
- *npn* bipolar transistor connected in the common *emitter* configuration.



Power BJT Operation

- In this configuration, injection of electrons from the lower n^+p junction into the centre p-region supplies minority carrier electrons to participate in the reverse current through the upper np junction.



Power BJT Operation

- The n^+ region which serves as the source of injected electrons is called the *emitter* and forms the emitter junction with the *p^-base,* while the n-region into which electrons are swept by the reverse bias np junction is called the *collector* and, with the p-base, forms the collector junction

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Power BJT Operation

- To have a 'good' npn transistor almost all the electrons injected by the emitter into the base should be collected.
- Thus the p-base region should be narrow and the electron minority carrier lifetime should be long to ensure that the average electron injected at the emitter will diffuse to the collector ***scl*** without recombining in the base.
- The average lifetime of electrons in the p-base increases as the p-base concentration decreases, that is as the hole concentration decreases.

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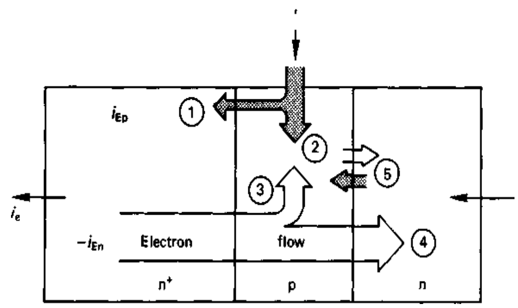
Power BJT Operation

- The fraction of electrons which make it across to the collector is called the *base transport factor, b_t.*
- If we neglect the saturation current at the collector, component 5 in figure below, and such effects as space charge layer recombination, then $i_c = b_t i_{En}$ where i_{En} is the electron component of the total emitter current i_e.



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Power BJT Operation

- Electrons lost to recombination in the p-base must be re-supplied through the base contact.
- It is also required that the emitter junction carrier flow should be composed almost entirely of electrons injected into the base, rather than holes crossing from the base region to the emitter.
- Any such holes must be provided by the base current, which is minimised by doping the base region lightly compared with the emitter such that an n^+p emitter results.

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Power BJT Operation

- Such a junction is said to have a high *injection efficiency.*
- Holes swept into the base at the reverse-biased collector junction because of thermal generation in the collector must also be accounted for by the base current.
- This base current component is generally very small in high-voltage transistors when in the on-state since the collector scl electric field is small.

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Power BJT Operation

- In the common emitter configuration, the ratio between the base current I_b and the collector current I_c is of practical importance.
- Since the base current is the difference between the emitter and the collector current.
- The factor β, relating the collector current to the base current, is defined as the base-to-collector *current amplification factor.*
- If α is near unity, β is very large, implying the base current is very small compared with the collector current.

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Power BJT Operation

- In power switching applications a transistor is controlled in two states: the *off-state and the on-state.*
- Ideally the transistor should appear as a short circuit when on and an open circuit when in the off-state.
- Furthermore the transition time between these two states is ideally zero. In reality, transistors only approximate these requirements.

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Power BJT Operation

- The two operational states for the power switching transistor are defined as follows.
- ***Cut-off region:*** In this region the emitter junction is not injecting; hence only leakage current flows.
- ***The saturation:*** In traversing from the off-state to the saturated state the transistor passes through the linear operating region, where the collector junction voltage changes from a large reverse bias to a forward bias state.

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Power BJT Operation

- Both junctions are forward-biased, termed *saturated,* and the collector-to-emitter voltage is almost zero, high current is able to flow.
- This saturated situation represents the switched-on hard mode, and over-saturation exists.
- The gain ***β*** is a minimum in the saturated mode since the neutral base width between the two forward-biased ***scl's*** is at a maximum.

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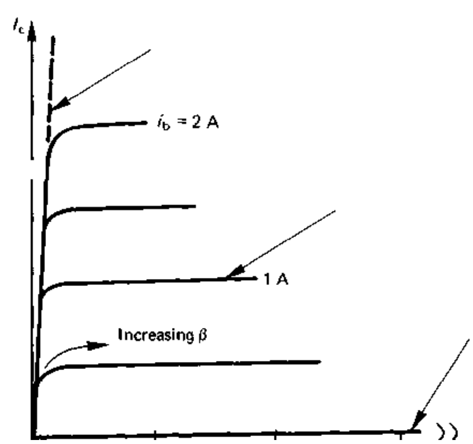
Power BJT Characteristics

The typical BJT collector output characteristics are shown below which illustrates the various BJT operating regions.



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Power BJT
Current Gain

- A number of electrical phenomena are of particular importance to the high-voltage, power switching ***BJT***.
- The characteristics to be considered are as a result of the device structure and geometry.
- The gain of a power transistor falls off at both very low and very high current levels.
- At low currents the gain decreases as a result of generation recombination.

Conductivity Modulation

- At high currents, as the concentration of excess electrons in the base becomes large, the matching excess hole concentration can become greater than the base doped level.
- A balance of holes and electrons must occur in order to maintain a neutral base region.
- Thus holes in the base are injected into the emitter, countering the conversely injected electrons, and thus effectively decreasing the emitter injection efficiency.
- This effect is called *conductivity modulation.*

First Breakdown

- The collector junction supports the off-state voltage and in so doing develops a wide ***scl***.
- This ***scl*** increases in width with increased reverse bias, penetrating into the base.
- It is unusual that a correctly designed high-voltage power switching ***BJT*** would break down as a result of punch-through of the collector ***scl*** through the base to the emitter ***scl***.

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First Breakdown

- Because of the profile of the diffused base, collector junction voltage breakdown is usually due to the avalanche multiplication mechanism, created by the high electric field at the collector junction.
- In the common emitter configuration, the transistor usually breaks down gradually, but before the collector junction avalanches.
- This occurs because the avalanche-generated holes in the collector ***scl*** are swept by the high-field into the base.

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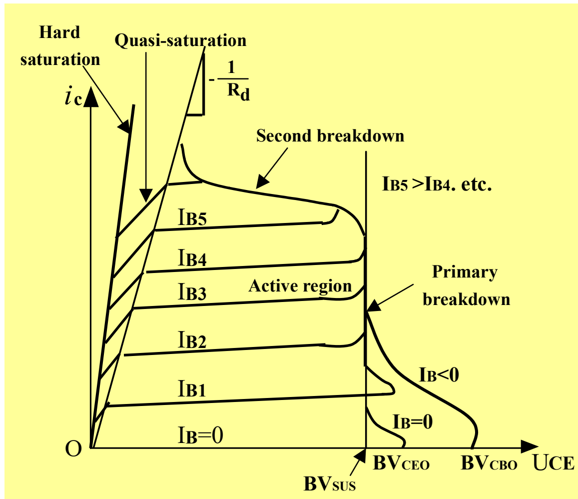
First Breakdown

- The emitter injects electrons in order to maintain base neutrality.
- This emitter junction in turn causes more collector current, creating more avalanche pairs and causing a regenerative action.
- Thus the gain mechanisms of the transistor cause collector emitter breakdown- *first breakdown*

Second Breakdown

- First breakdown need not be catastrophic provided junction temperature limits are not exceeded.
- If local hot spots occur because of non-uniform current density distribution as a result of crystal faults, doping fluctuation etc., *second breakdown* occurs.
- Silicon crystal melting and irrepairable damage results, the collector voltage falls and the current increases rapidly as shown in figure below

Second Breakdown



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Power MOS

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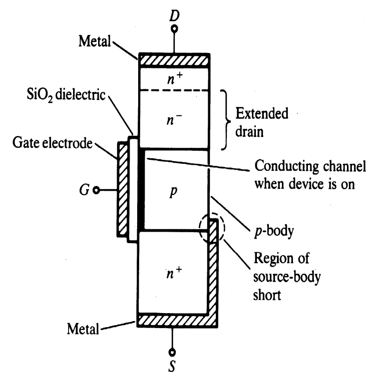
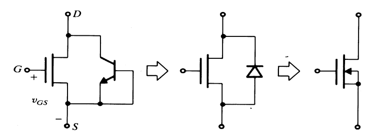
Power MOS

- When positive V_{GS} is applied, a conducting n-channel is formed beneath the gate in the p-region (body).
- MOSFET turns 'on' when V_{GS} exceeds V_T.
- The gate acts like a capacitor.
- The gate power is zero.
- The gate-drive circuit is very simple as compared to BJT.





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Power MOS

- If the MOSFET has to operate at high frequencies, the gate capacitance must be charged and discharged quickly, therefore, the gate drive circuit should have low source impedance.
- When MOSFET is 'on' it acts like a resistor of Value '$R_{DS(on)}$'.
- $R_{DS(on)}$ consists of two parts:
  a) Conducting channel resistance
  b) Resistance of the extended drain region. Which is unique to Power MOS due to its vertical structure.

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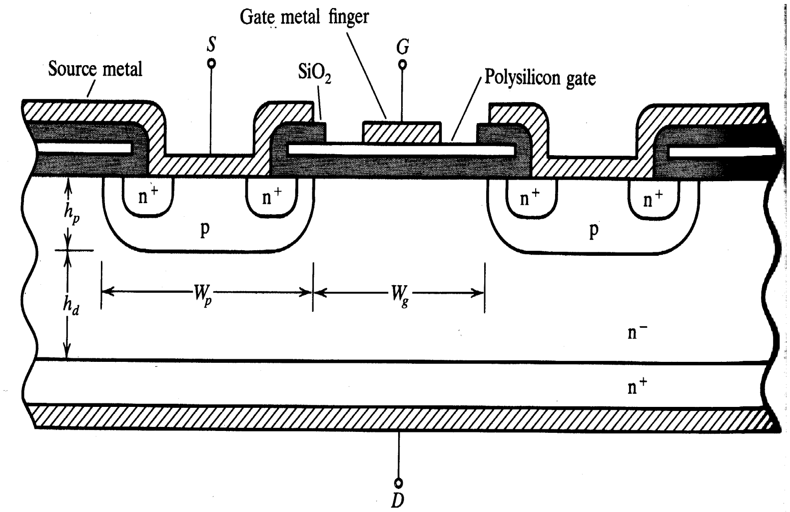
Power MOS Physical Structure



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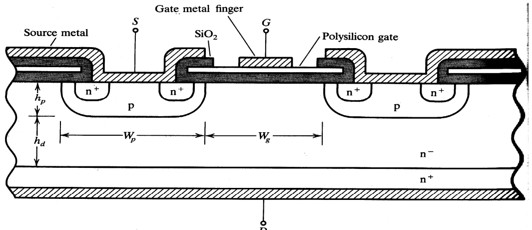
Power MOS Structure

- The drain contact is on the bottom of the die, rather than on the top as in signal MOSFET.
- This vertical structure gives maximum area to both drain and source contacts.



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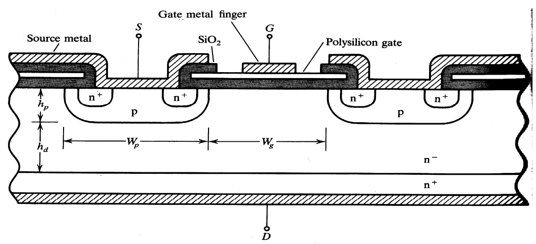
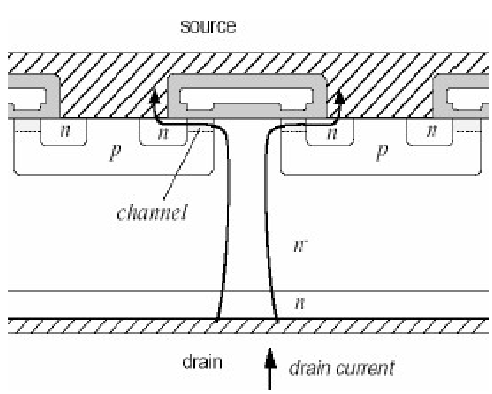
Power MOS Structure

- There are P-wells between drain and source. These wells are the body regions of the device.
- The channel is formed on the surface of the p-wells just beneath the gate-oxide.
- The p-type wells are shorted to the source electrode.



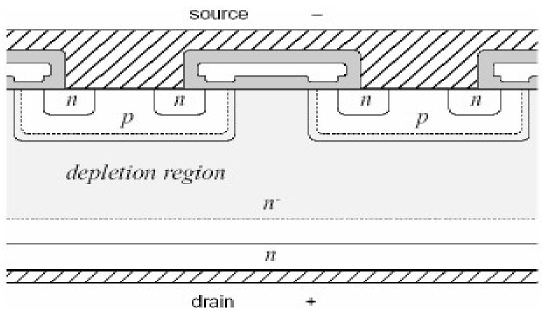
Power MOS

Creation of channel beneath the gate in the p-regions.



Power MOS

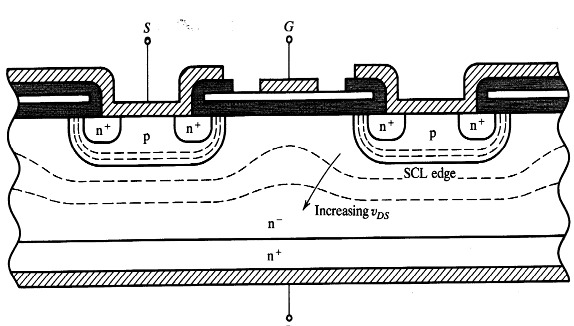
- The lightly doped n-type drain region is unique to Power MOS.
- It will allow the growth of long SCL to block high voltage when the device is 'off'.



Power MOS

Under Reverse Biased

Following figure illustrate how the SCL grows with increasing V_{DS} , pinching off the n- region between the p-wells.



Power MOS

- The lightly doped drain region is also referred as extended drain region.
- When the device is off, SCL grows and pinches off the region between P-wells.
- The gate electrode acts as a field plate to promote the depletion of the region between p-wells.
- The voltage just beneath the gate oxide is only 5-10 volts w.r.t. gate even though the drain voltage is 200-400V, as a result the gate oxide can be made relatively thin keeping V_T low.

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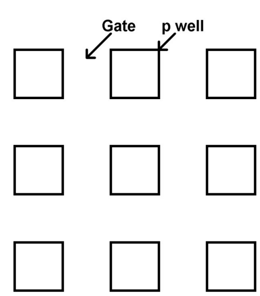
Power MOS

- If viewed from the top, the gate and source contacts look like interleaved pattern of cells as shown in the figure.
- These cells can be arranged in a square pattern.
- For a large power device, the cells can be increased over a large area of the die.
- This is similar to connecting the Power MOS transistors in parallel on a single die to increase the conduction region and power.



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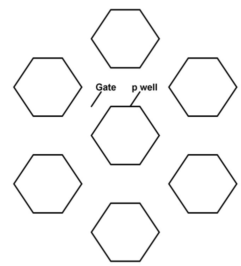
Power MOS

- The p-type wells can also be arranged in hexagonal cell pattern to increase the gate perimeter for a given die area as shown in the diagram.
- This hexagonal structure is a patent of ‘International Rectifiers (IR)’ for its trademark “HEXFET”



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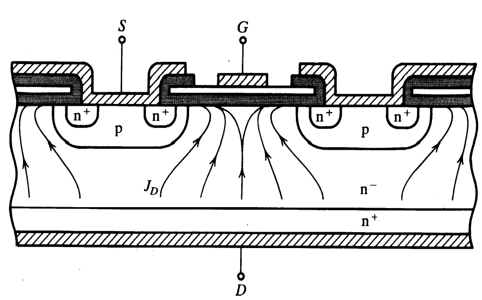
On state Resistance

- The drain current distribution when the device is ‘on’, is shown below.
- The current flows from drain to source when ‘on’.
- The current focuses in the area between the p-wells called the neck region.



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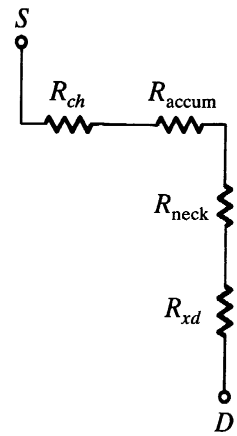
On state Resistance

- The current further focuses in the thin entrance to the p-well channels on either sides of the neck regions.
- The n-region just beneath gate is accumulated which makes it much more conductive than rest of the n-region.



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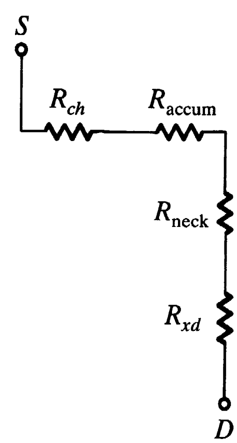
On state Resistance

- The total R_{DS}(on) can be divided into four components as shown in the diagram.
- For high voltage device, R_{xd} and R_{neck} are much larger than R_{accum} and R_{ch}.
- For low voltage devices, R_{ch} is ⅓ to ½ of total R_{DS}(on).



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Temperature Effect

- For high voltage device, $R_{DS(ON)}$ is dominated by extended drain resistance.
- This on resistance is temperature dependent.
- $R_{DS(ON)}$ increases with temperature.
- A 100 degree rise produces an increase of approximately 90%.

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Body Diode

- The connection of the p-wells to the source metal gives the MOSFET an anti-parallel body diode.
- This body diode is a PIN diode as discussed earlier.
- It displays the static and dynamic characteristics of a PIN diode.

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Body Diode

- The cross sectional area of
- MOSFET is approximately same as the body diode.
- The body diode displays a reverse recovery phenomenon in the order of 100nS but this is not as short as possible in separate diode.

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Switching Characteristics

Turn- on transient

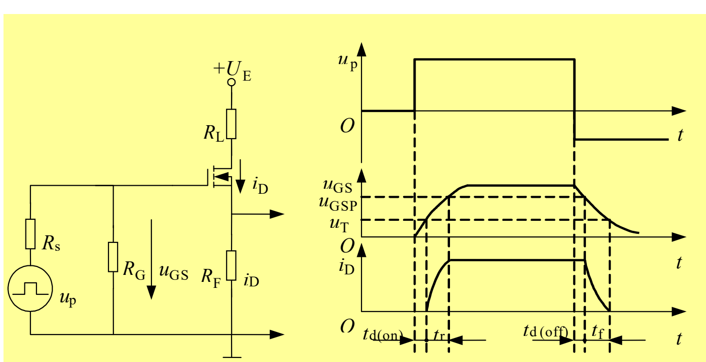
– Turn- on delay time $t_{d(on)}$

– Rise time t_r

Turn- off transient

– Turn- off delay time $t_{d(off)}$

– Falling time t_f



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Switching Performance

- The speed at which a Power MOS turns on or off is determined by the rate at which its parasitic capacitance can be charged or discharged.
- The more current the gate drive circuit can deliver or sink, the faster the device switch.

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Switching Performance

- The gate-drive circuit determines the rise and fall times of the drain current and voltage.
- For instant, if the gate drive is capable to source 1A, and the gate charge is 40nC then;

$$t_f = \frac{40nC}{1A} = 40nS$$

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IGBT

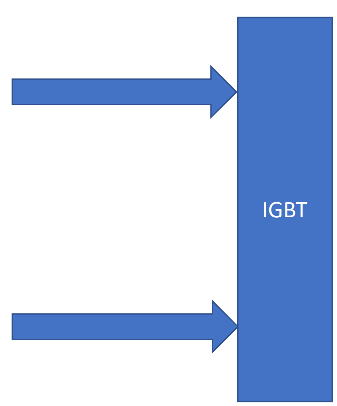
Insulated Gate Bipolar Transistor

IGBT

Combination of MOSFET and Power BJT

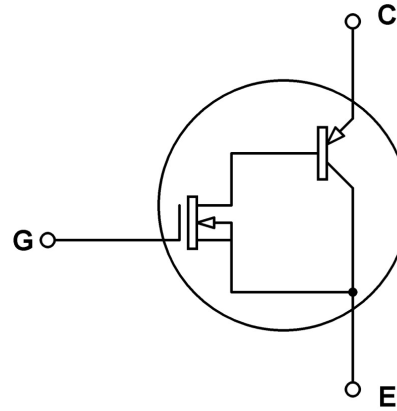
BJT:
Low conduction losses
(especially at larger blocking voltages)
Longer switching times
Current driven

MOSFET
Faster switching speed
Easy to drive(voltage driven)
Large conduction losses
(especially for higher blocking Voltage)



IGBT

IGBT is an integrated Darlington like connection of MOSFET and BJT.



IGBT

- The driving is simple like Power MOS.
- Low forward drop per unit area of BJT.
- Much smaller area results compared to same power MOSFET.

IGBT

- The two transistors are of opposite polarity (n-channel and PNP).
- The gate is driven with respect to collector of BJT.
- Therefore, the collector of BJT is designated as Emitter of IGBT and Emitter of BJT as collector of IGBT.

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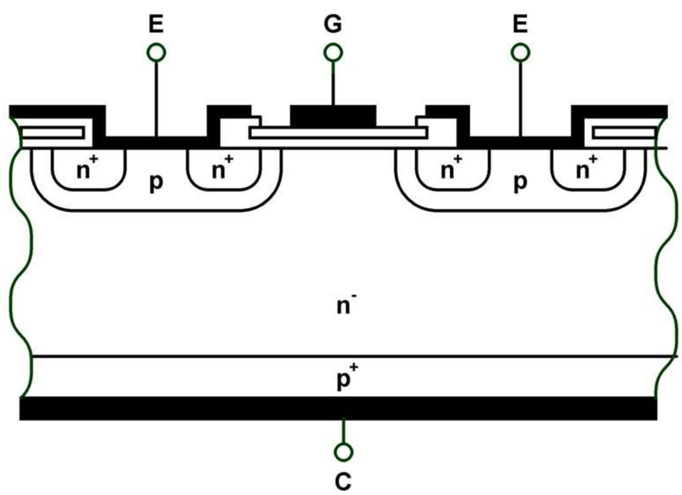
IGBT Physical Structure



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Structure of IGBT

- The structure of IGBT is very much like vertical MOSFET, except that the substrate is heavily doped p-type rather than n-type.
- Integration of two devices rather than discrete connection has an advantage: when the IGBT is on, the BJT is also on conductivity modulating the drift region and greatly reducing the drain resistance of MOSFET.

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Structure of IGBT

- If the two devices are connected discretely, the FET un-modulated resistive drop would result in a higher collector-base drop resulting higher V_{CE} for the Bipolar Transistor.
- One disadvantage of integration is that the structure forces the BJT with wide base.

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Structure of IGBT

- Another disadvantage is that the BJT has PNP configuration rather than superior NPN transistor.
- A further problem of integration of the two devices eliminates access to the base terminal of the BJT, preventing the use of negative base current to improve turn-off.

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Structure of IGBT

- Turn-off can be improved by reducing the transistor gain but at the expense of on-state drop.
- The integration of two devices produces a parasitic SCR as a regenerative connection of PNP and NPN transistors.

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Structure of IGBT

- Although the base of NPN transistor is shorted to emitter which should keep this transistor off, however, there is some resistance in this connection.

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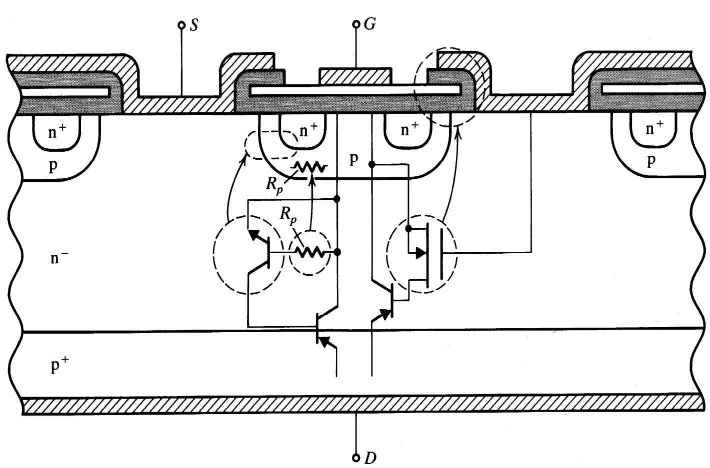
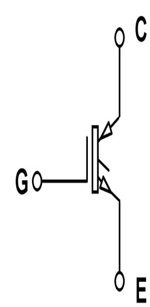
Structure and Symbol of IGBT





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Structure of IGBT

- If during operation, the current through this region becomes high, the NPN transistor might be turned on, and SCR may latch.
- Once latched, nothing can be done to turn off the device.

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Structure of IGBT

- If the rate of rise of voltage at turn off is high enough, the capacitive charging current could trigger the SCR.
- Even with these problems IGBT has much to offer.
- This device is well suited to high voltage with moderate frequencies

  (1200 V, up to 50KHz.)

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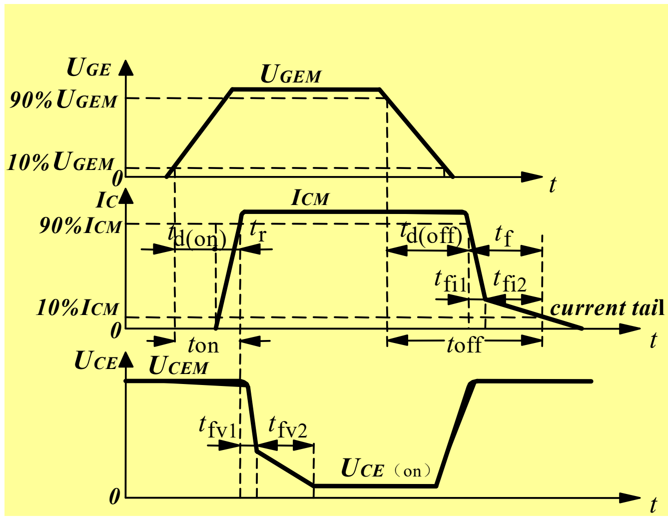
IGBT-Switching characteristics



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Commercial IGBTs

part number	Rated max voltage	Rated avg current	V_F(typical	t_f(typical)
Single-chip devices				
HGTG32N60E2	600V	32A	2.4V	0.62 μs
HGTG30N120D2	1200V	30A	3.2V	0.58 μs
multiple-chip power modules_				
CM400HA-12E	600V	400A	2.7V	0.3 μs
CM300HA-24E	1200V	300A	2.7V	0.3 μs

Thank you

For your attention

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