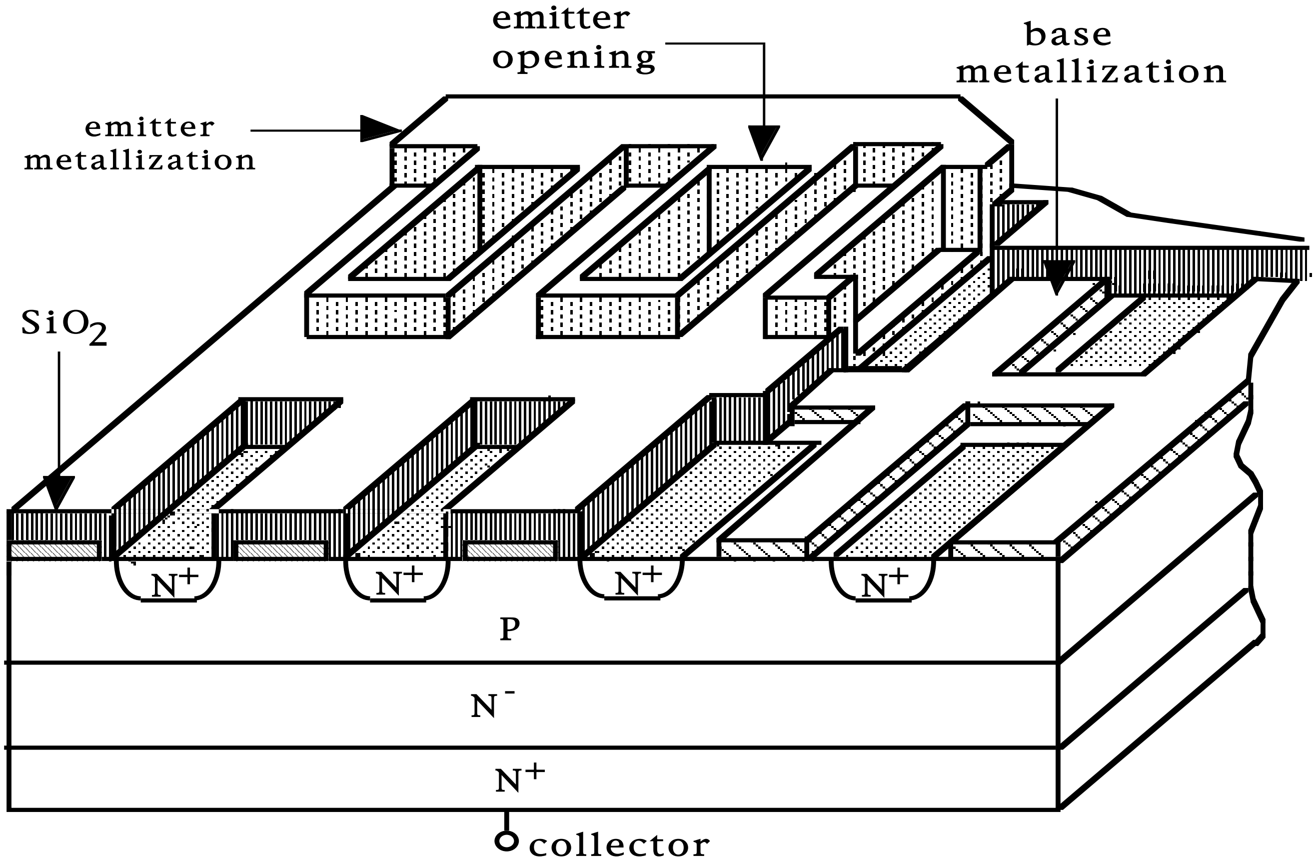
Lecture Notes

Bipolar Junction Transistors (BJTs)

Outline

- BJT structure and I-V characteristics
- Physical operation of power BJTs
- Switching characteristics
- Breakdown voltage
- Second breakdown
- On-state voltage
- Safe operating areas

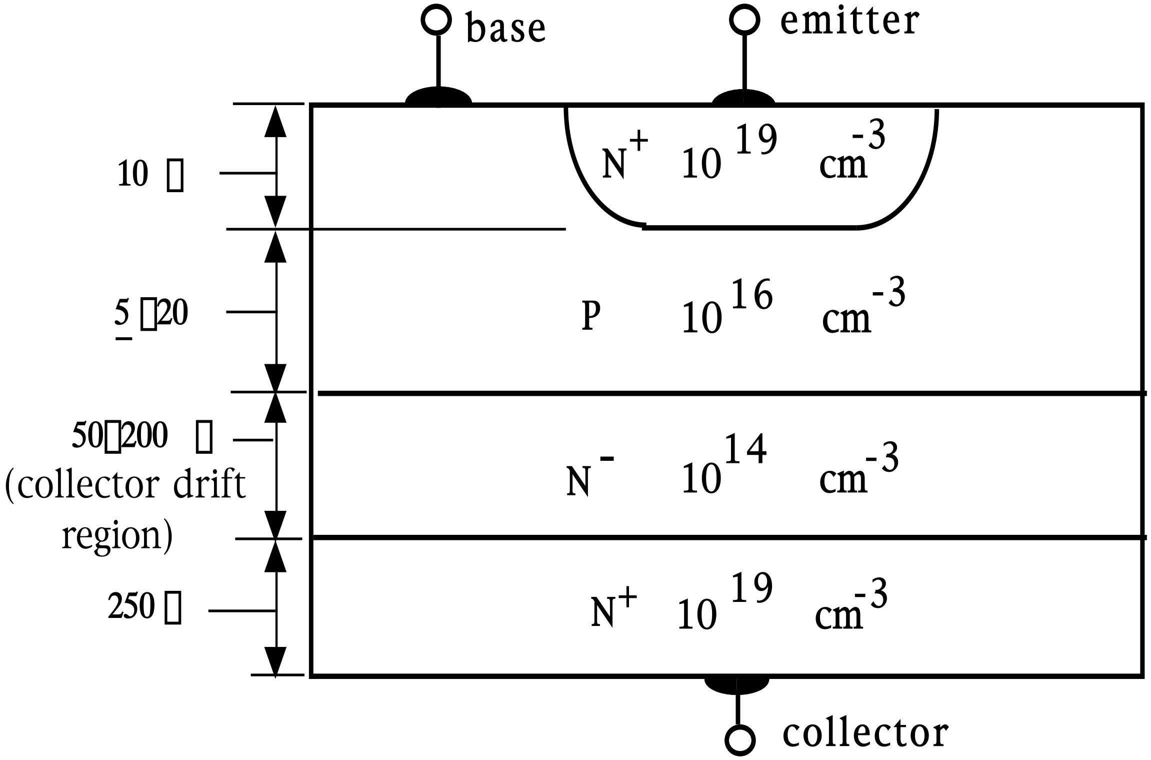
Basic Geometry of Power BJTs

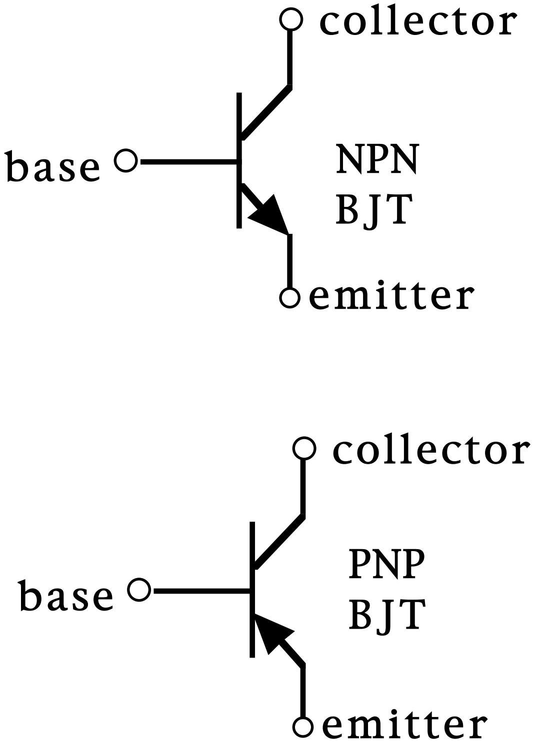


Features to Note

- Multiple narrow emitters - minimize emitter current crowding.
- Multiple parallel base conductors - minimize parasitic resistance in series with the base.

BJT Construction Parameters

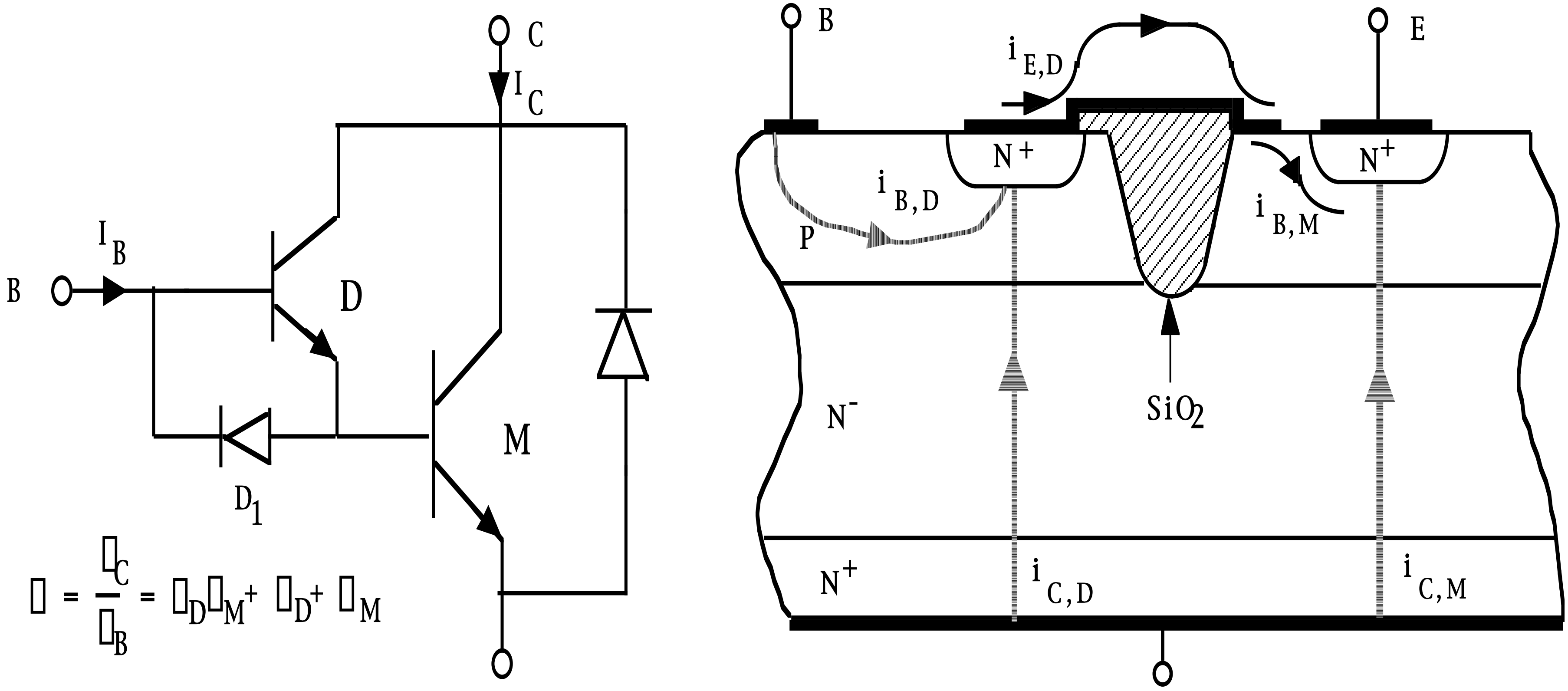




Features to Note

- Wide base width - low (<10) beta.
- Lightly doped collector drift region - large breakdown voltage.

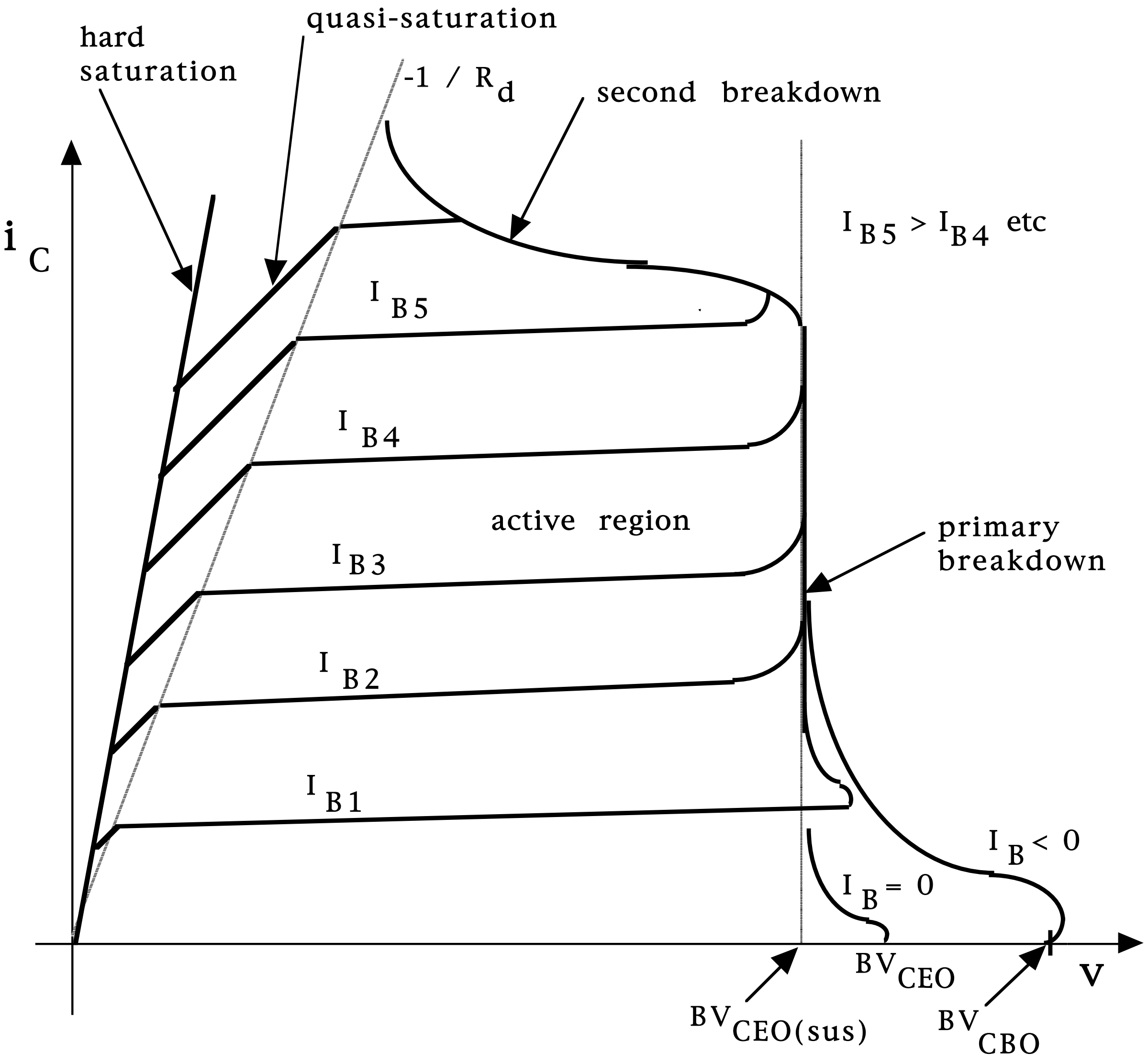
Darlington-connected BJTs



$$\beta = \frac{I_C}{I_B} = \beta_D\beta_M + \beta_D + \beta_M$$

- Composite device has respectable beta.

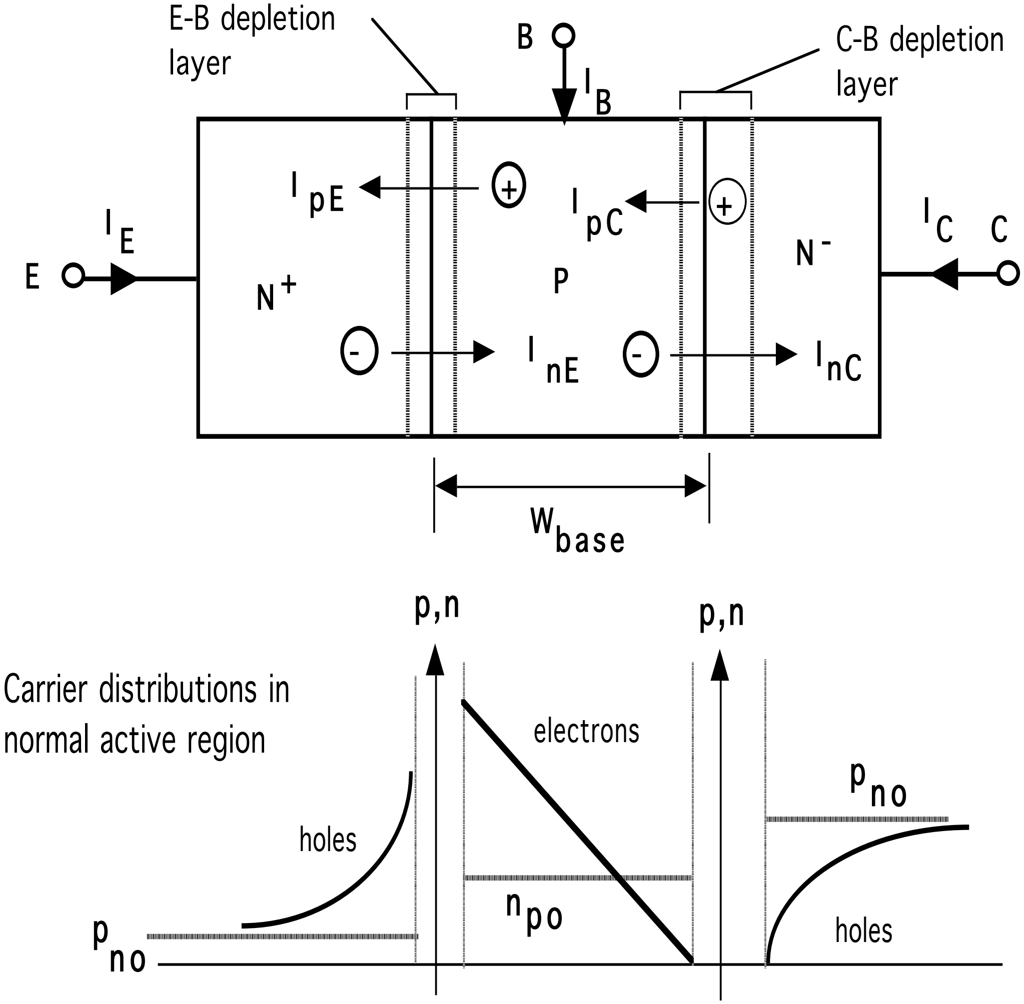
Power BJT I-V Characteristic



Features to Note

- 2nd breakdown - must be avoided.
- Quasi-saturation - unique to power BJTs
- $BV_{CBO} > BV_{CEO}$ - extended blocking voltage range.

BJT Internal Current Components

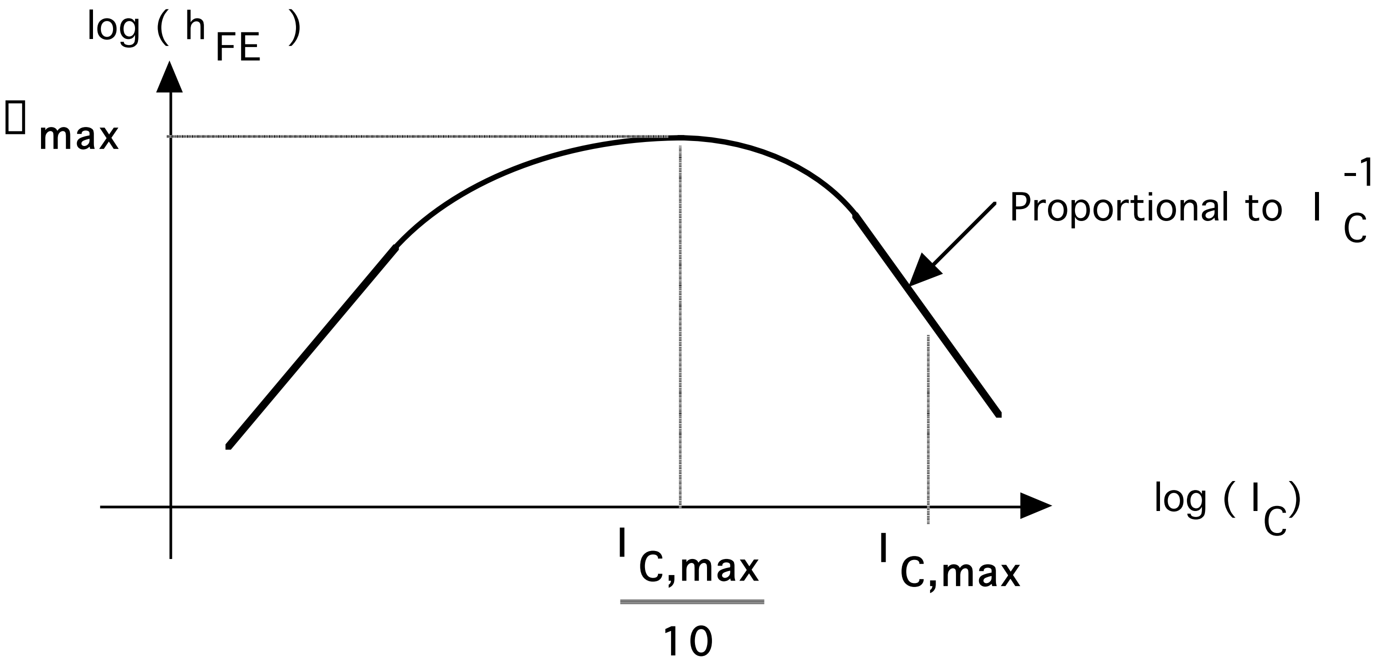


- I_{ne} and I_{pe} flow via diffusion. I_{nc} and I_{pc} flow via drift.
- $I_{ne} >> I_{pe}$ because of heavy emitter doping.
- $I_{ne} \approx I_{nc}$ because $L_{nb} = \{D_{nb}\,\tau_{nb}\}^{1/2} << W_{base}$ and collector area much larger than emitter area.
- I_{pc} << other current components because very few holes in b-c space charge region.

Power BJT Current Gain □

- $I_C \approx I_{nc}$ since I_{pc} very small : $I_B = - I_C - I_B = - I_{nc} + I_{ne} + I_{pe}$
- $I_B / I_C = 1/\square = (I_{ne} - I_{nc})/I_{nc} + I_{pe}/I_{nc}$
- $(I_{ne} - I_{nc})/I_{nc}$ represents fraction of electrons injected into base that recombine in the base. Minimize by having large values of $\square_{nb}$ (for long diffusion lengths) and short base widths W_{base}
- I_{pe} proportional to $p_{no} = (n_i)^2/N_{de}$; Minimize via large N_{de}
- Short base width conflicts with need for larger base width needed in HV BJTs to accomodate CB depletion region.
- Long base lifetime conflicts with need for short lifetime for faster switching speeds
- Trade-offs (compromises) in these factors limit betas in power BJTs to range of 5 to 20

Beta versus Collect Current

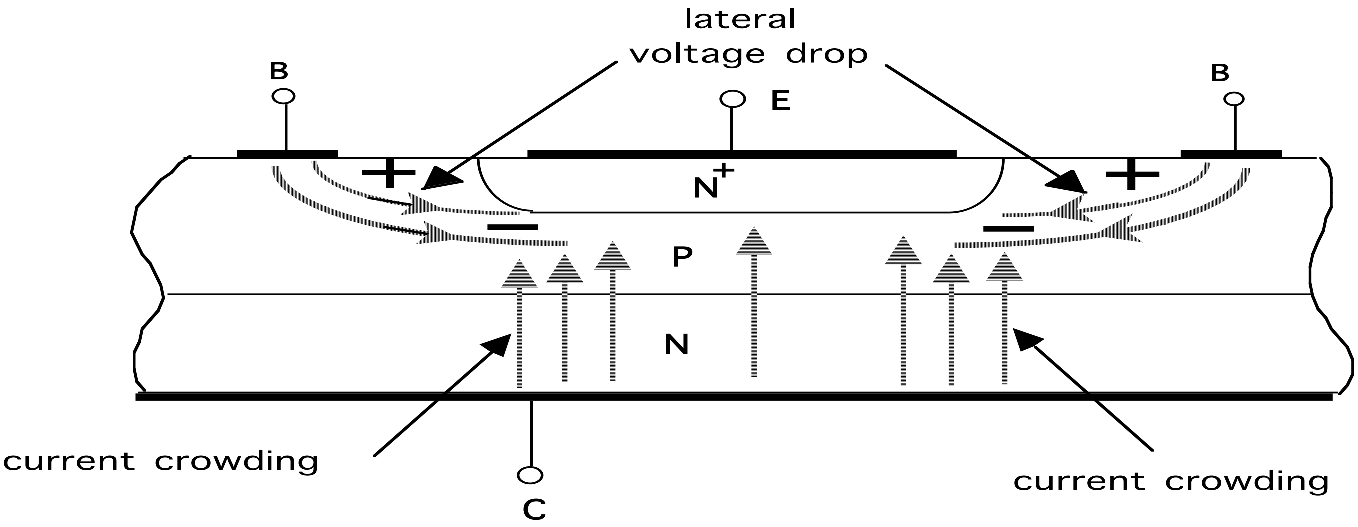


- Beta decrease at large collector current due to high level injection effects (conductivity modulation where $\Delta n = \Delta p$) in base.

- When $\Delta n = \Delta p$, base current must increase faster than collector current to provide extra holes. This constitutes a reduction in beta.

- High level injection conditions aided by emitter current crowding.

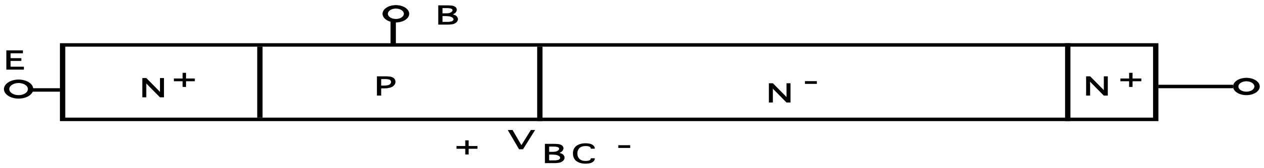
Emitter Current Crowding



- I_B proportional to $\exp\{qV_{BE}/(kT)\}$
- Later voltage drops make V_{BE} larger at edge of emitters.
- Base/emitter current and thus carrier densities larger at edge of emitters. So-called emitter current crowding.
- This emitter current crowding leads to high level injection at relatively modest values of current.
- Reduce effect of current crowding by breaking emitters into many narrow regions connected electrically in parallel.

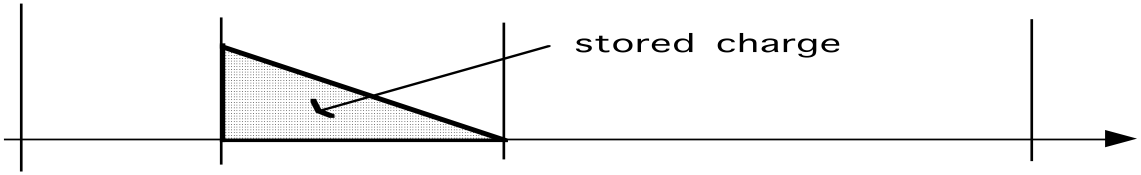
Quasi-saturation in Power BJTs

Power BJT



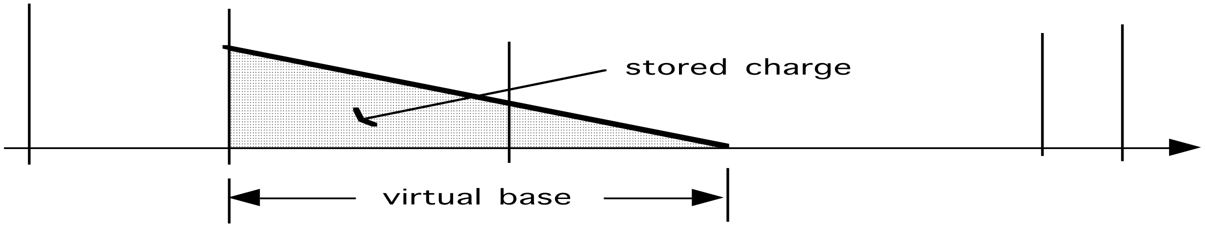
Active region

$V_{BC} < 0$



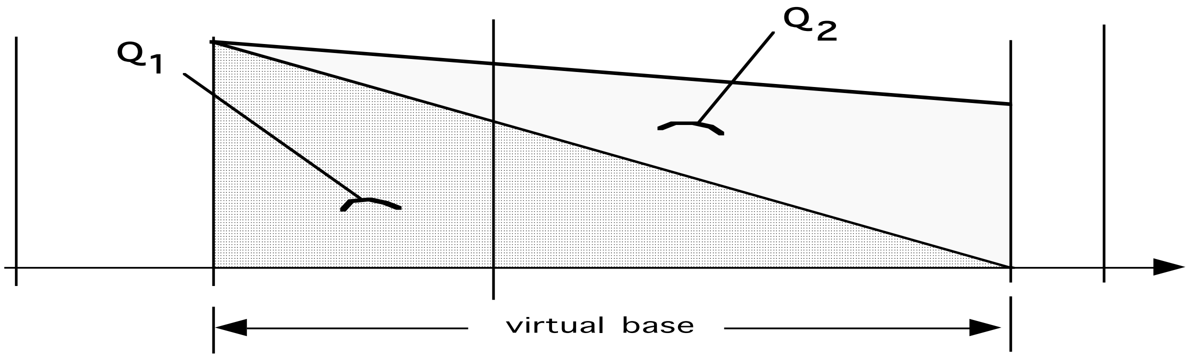
Quasi-saturation

$V_{BC} > 0$ but drift region not completely filled with excess carriers.



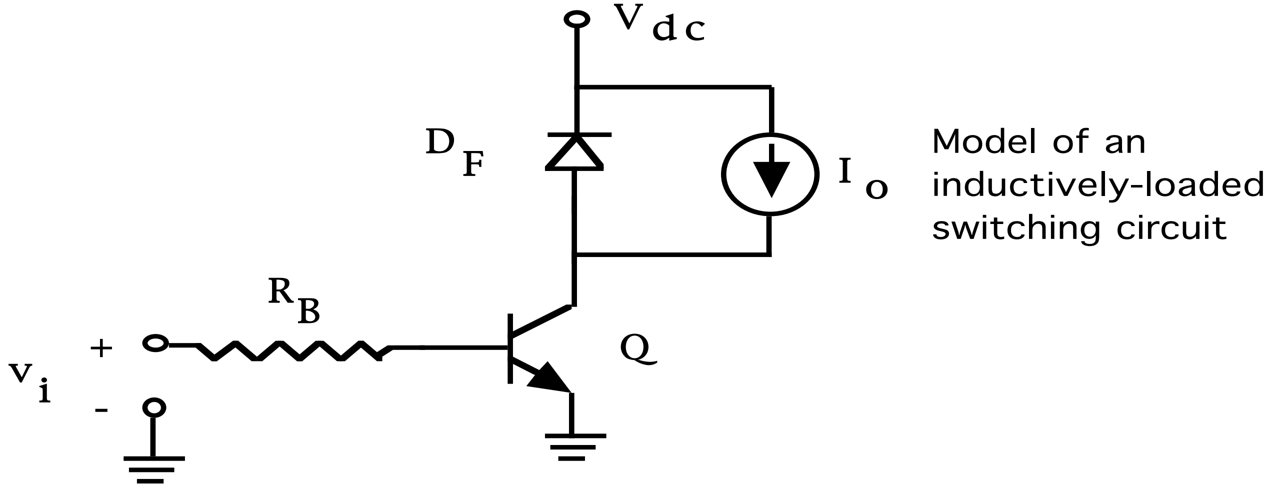
Hard saturation

$V_{BC} > 0$ and drift region filled with excess carriers.



- Beta decreases in quasi-saturation because effective base width (virtual base) width has increased.

Generic BJT Application - Clamped Inductive Load



Model of an inductively-loaded switching circuit

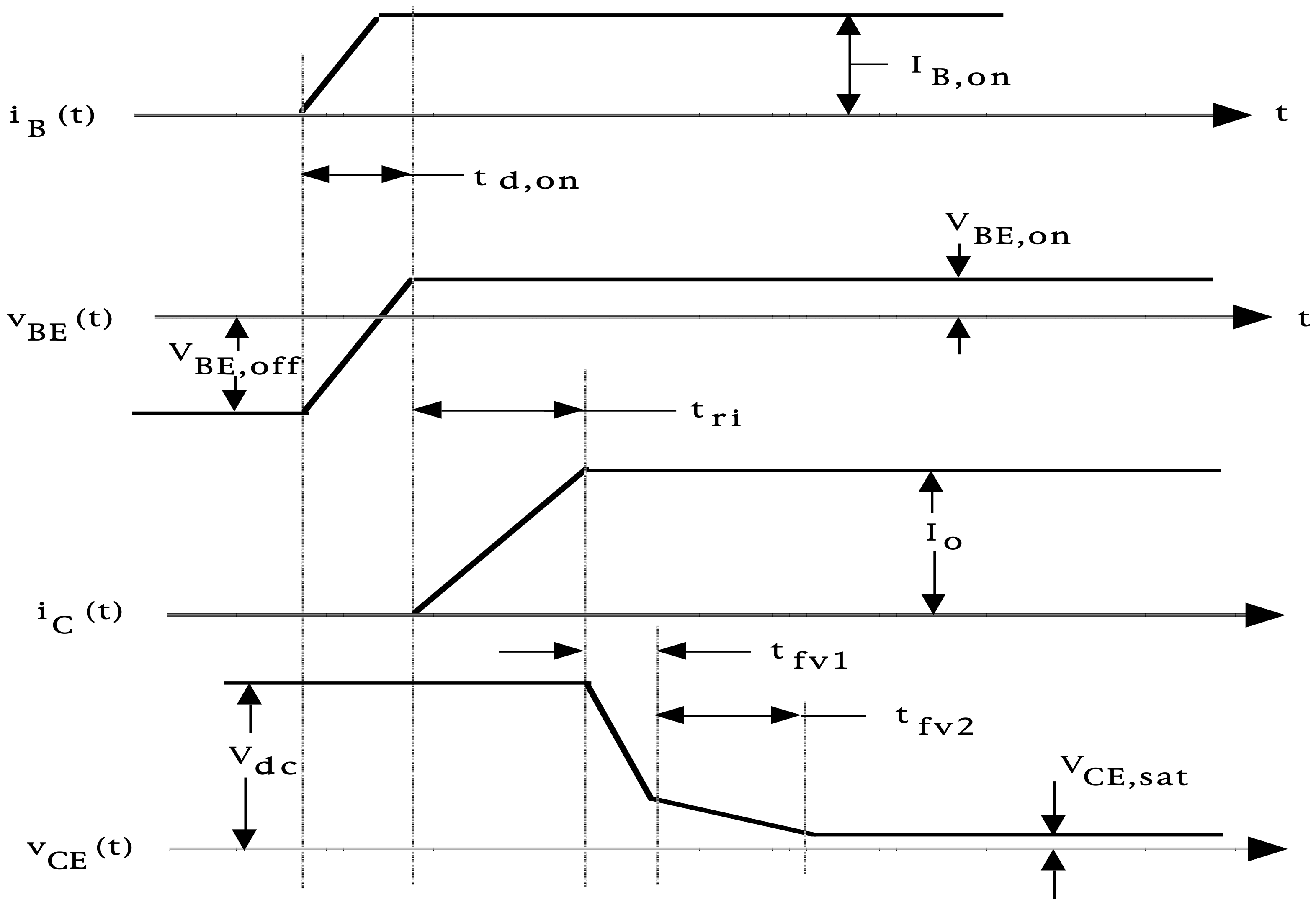
- Current source I_o models an inductive load with an L/R time constant >> than switching period.

- Positive base current turns BJT on (hard saturation). So-called forward bias operation.

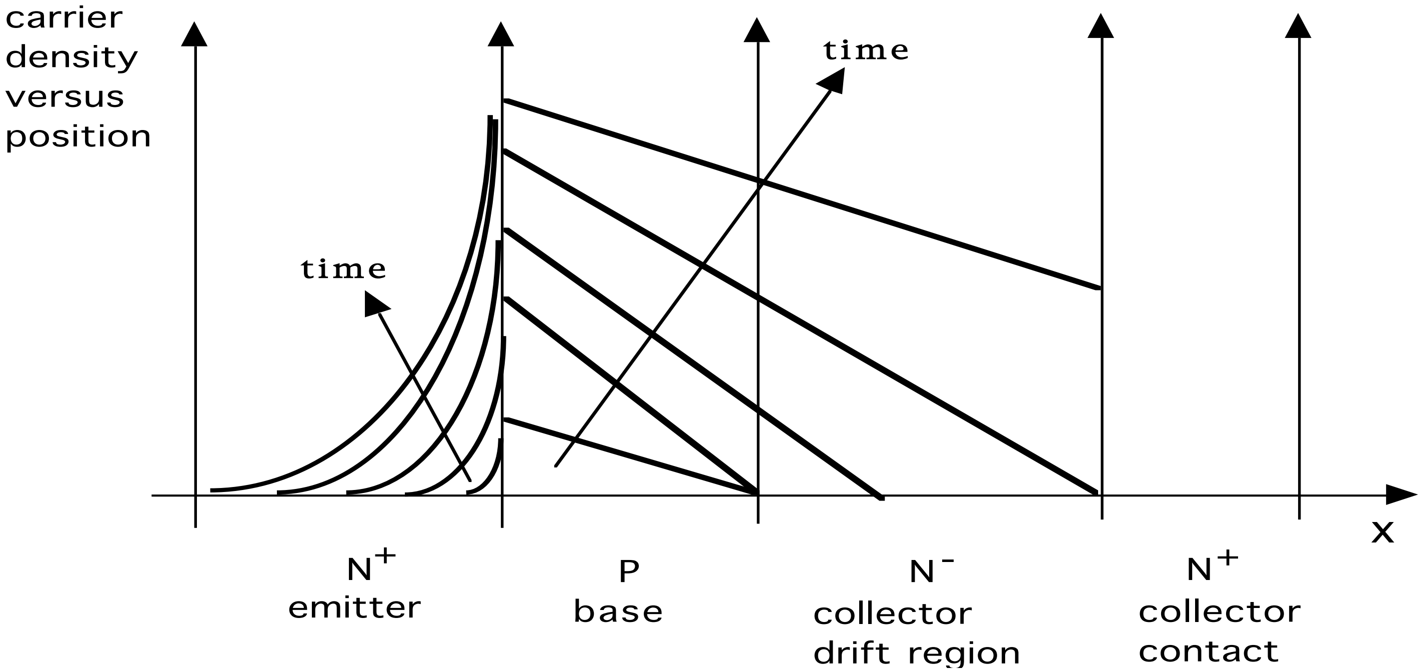
- Negative base current/base-emitter voltage turns BJT off. So-called reverse bais operation.

- Free wheeling diode DF prevents large inductive overvoltage from developing across BJT collector-emitter terminals.

Power BJT Turn-on Waveforms

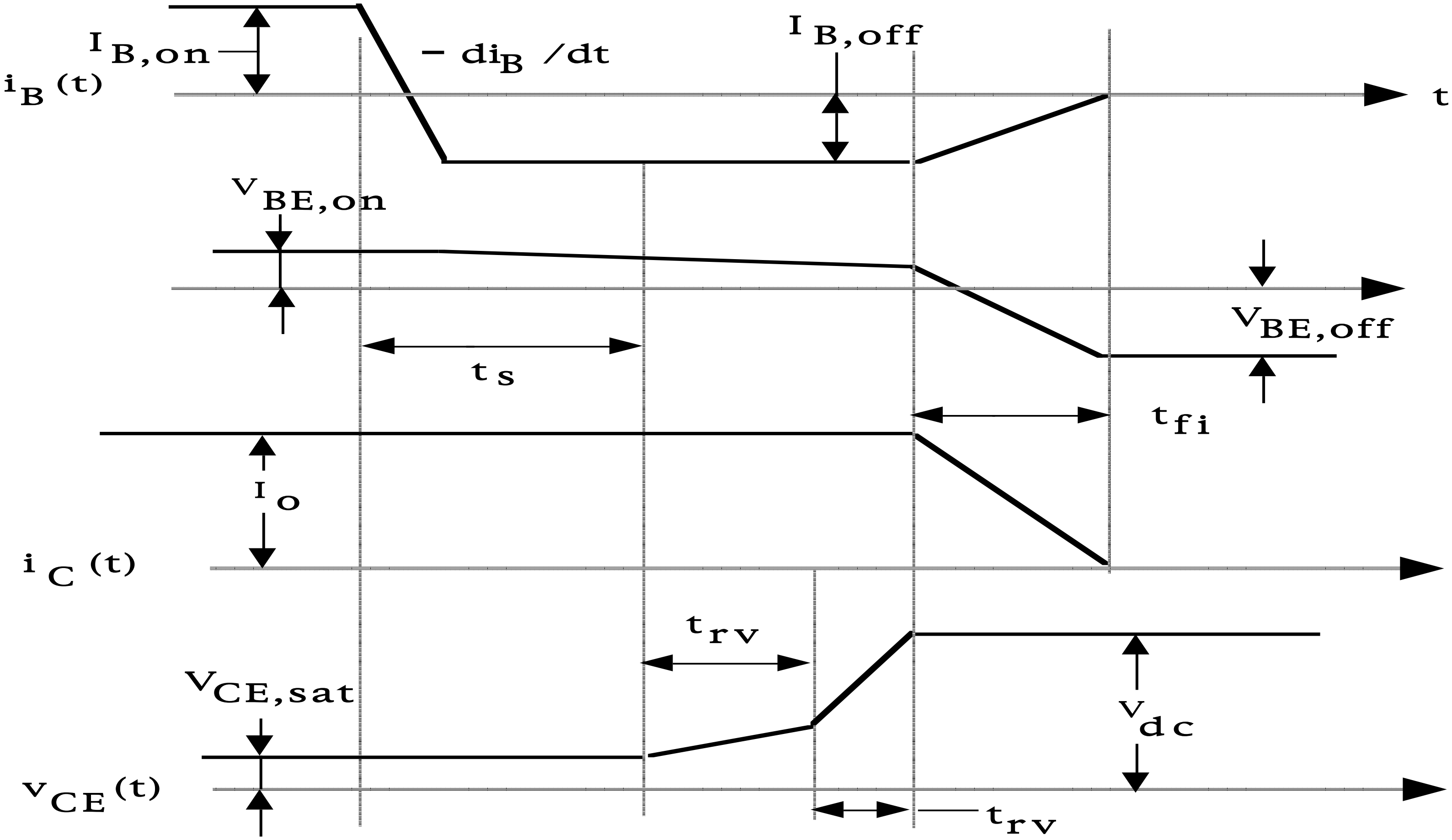


Excess Carrier Growth During BJT Turn-on



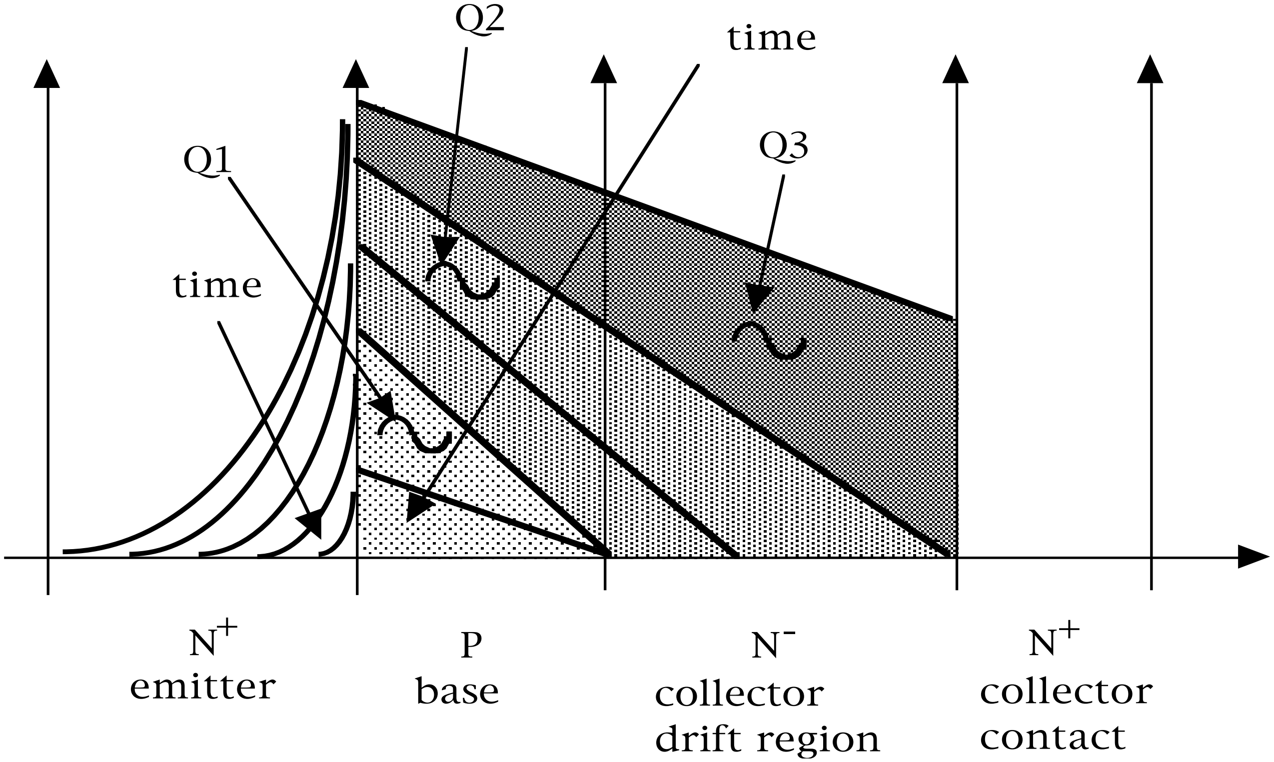
- Growth of excess carrier distributions begins after $t_{d(on)}$ when B-E junction becomes forward biased.
- Entrance into quasi-saturation discernable from voltage or current waveform at start of time t_{vf2}.
- Collector current “tailing” due to reduced beta in quasi-saturation as BJT turns off.
- Hard saturation entered as excess carrier distribution has swept across dirft region.

Turn-off Waveforms with Controlled Base Current



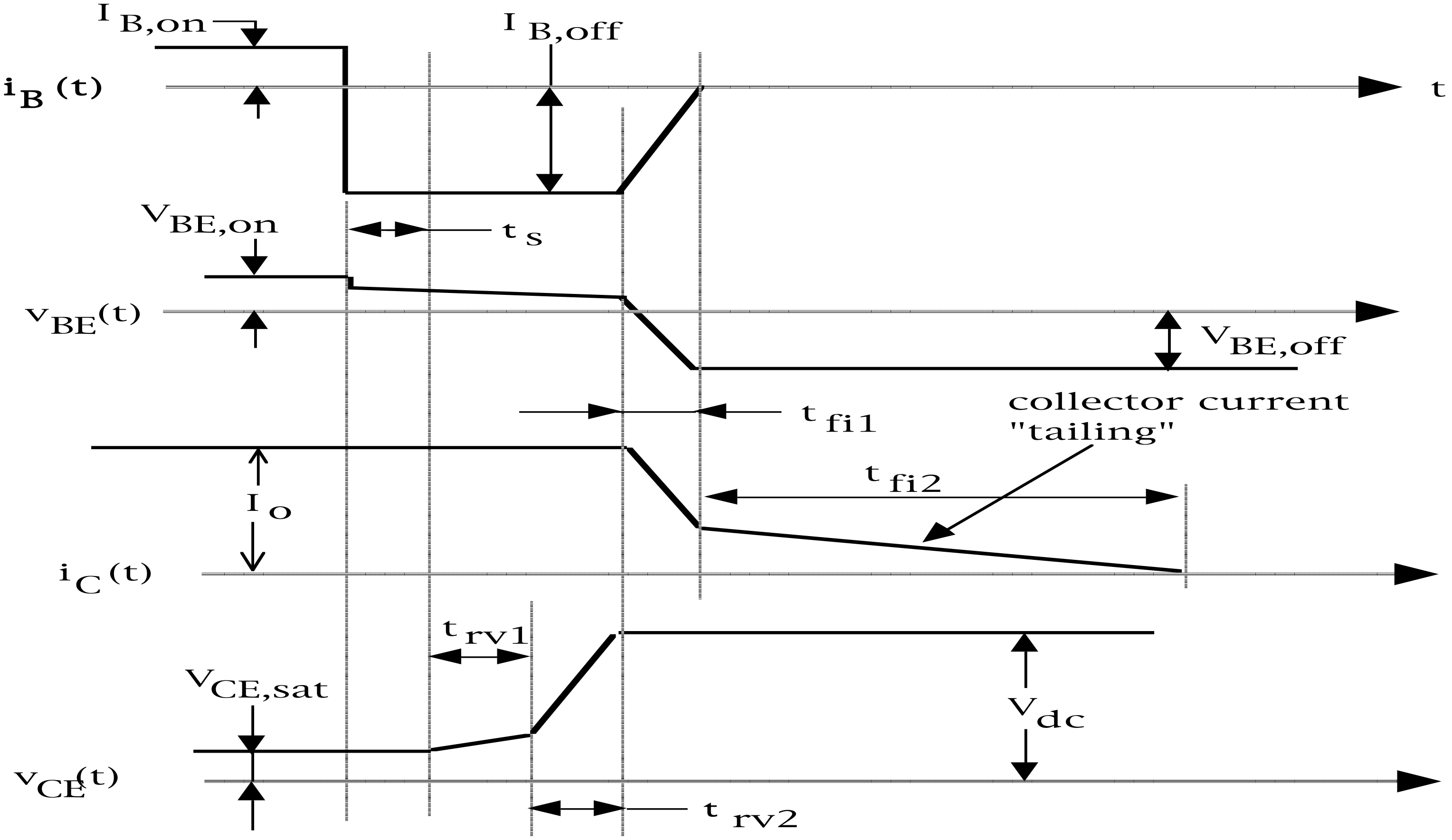
- Base current must make a controlled transition (controlled value of $-di_B/dt$) from positive to negative values in order to minimize turn-off times and switching losses.

Controlled Turn-off Excess Carrier Removal



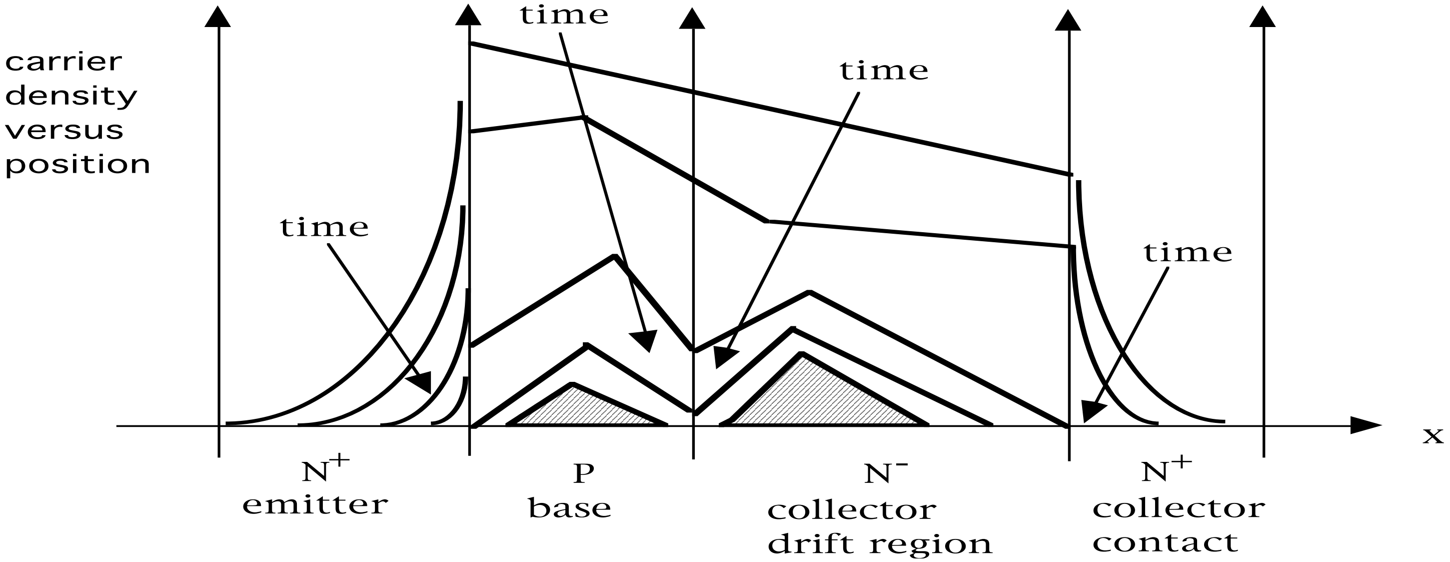
- t_s = storage time = time required to remove excess charge Q3.
- t_{rv1} = time to remove charge Q2 holding transistor in quasi-saturation.
- t_{rv2} = time required for VCE to complete its growth to Vdc with BJT in active region.
- t_{fi} = time required to remove remaining stored charge Q1 in base and each edge of cut-off.

Turn-off Waveforms with Uncontrolled Base Current



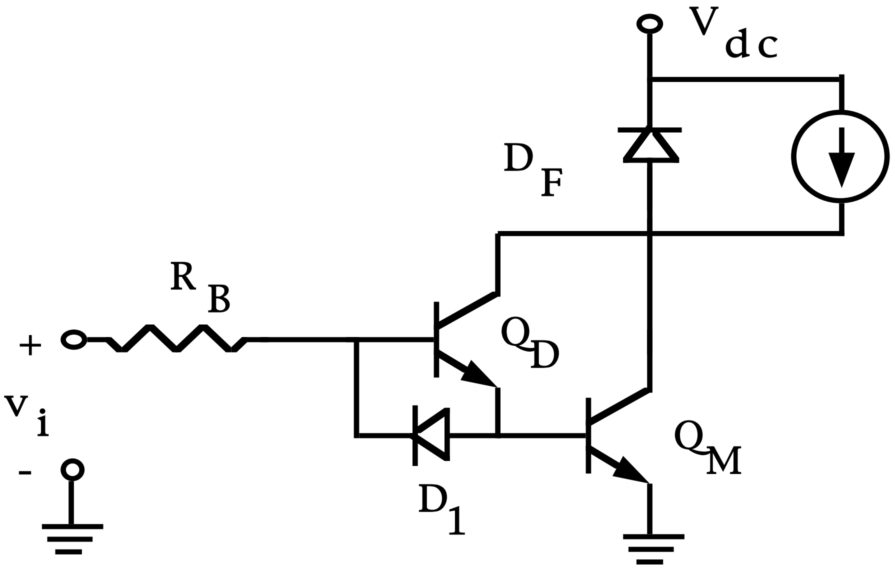
- Excessive switching losses with collector current tailing.

Uncontrolled Turn-off Excess Carrier Removal



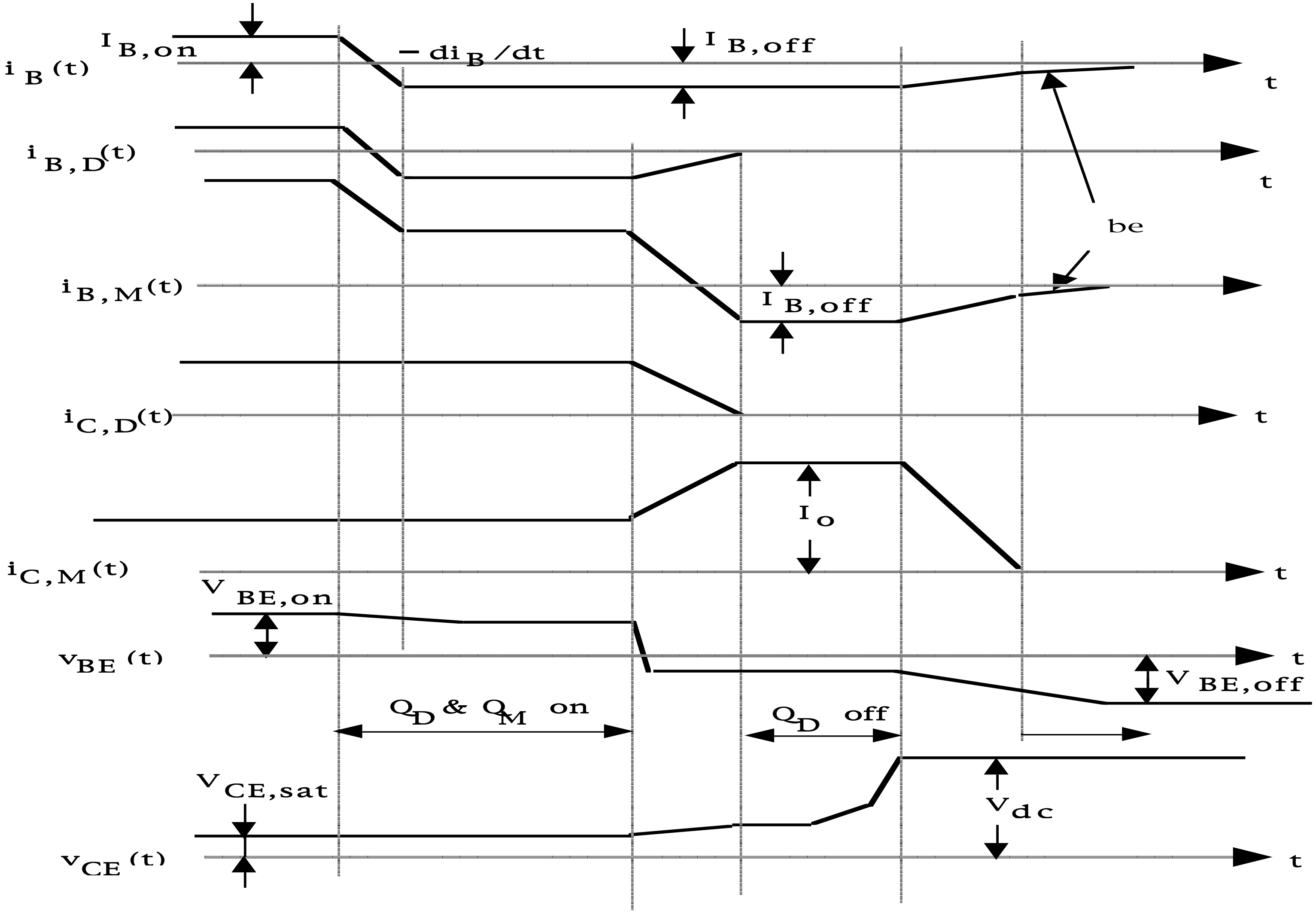
- Uncontrolled base current removes stored charge in base faster than in collector drift region.
- Base-emitter junction reverse biased before collector-base junction.
- Stored charge remaining in drift region now can be only removed by the negative base current rather than the much larger collector current which was flowing before the B-E junction was reverse biased.
- Takes longer time to finish removal of drift region stored charge thus leading to collector current “tailing” and excessive switching losses.

Darlington Switching Behavior



- Turn-on waveforms for Darlington very similar to single BJT circuit.
- Turn-on times somewhat shorter in Darlington circuit because of large base drive for main BJT.
- Turn-off waveforms significantly different for Darlington.
- Diode D_1 essential for fast turn-off of Darlington. With it, Q_M would be isolated without any negative base current once Q_D was off.
- Open base turn-off of a BJT relies on internal recombination to remove excess carriers and takes much longe than if carriers are removed by carrier sweepout via a large collector current.

Darlington Turn-off Waveforms



Power BJT Breakdown Voltage

- Blocking voltage capability of BJT limited by breakdown of CB junction.
  - BV_{CBO} = CB junction breakdown with emitter open.
  - BV_{CEO} = CB junction breakdown with base open.
  - $BV_{CEO} = BV_{CBO}/(\square)^{1/n}$; n = 4 for npn BJTs and n = 6 for PNP BJTs

- BE junction forward biased even when base current = 0 by reverse current from CB junction.

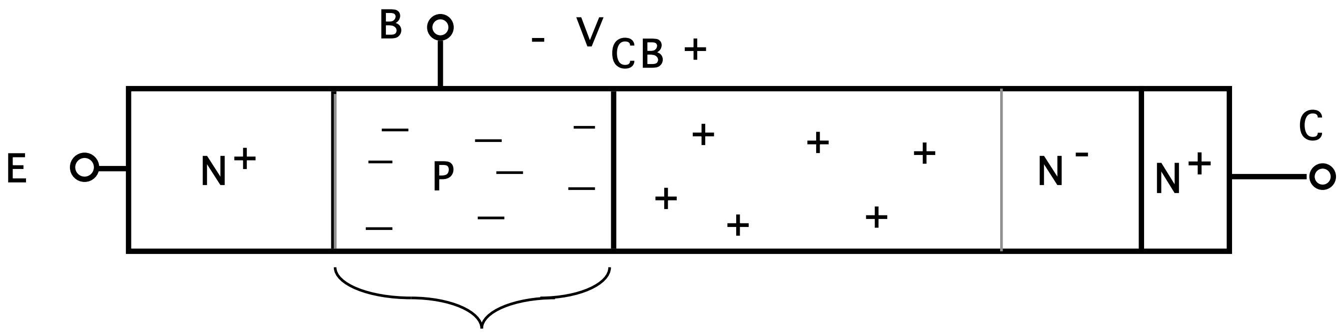
- Excess carriers injected into base from emitter and increase saturation current of CB junction.

- Extra carriers at CB junction increase likelyhood of impact ionization at lower voltages , thus decreasing breakdown voltage.

- Wide base width to lower beta and increase BV_{CEO} .

- Typical base widths in high voltage (1000V) BJTs = 5 to 10 and $BV_{CEO} = 0.5 \quad BV_{CBO}$.

Avoidance of Reach-thru

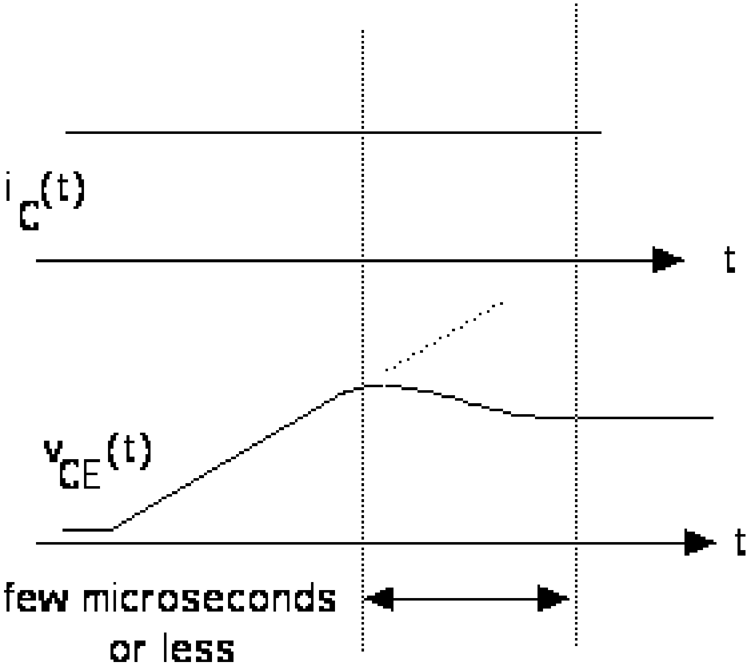


Reach-thru of CB depletion across base to emitter

- Large electric field of depletion region will accelerate electrons from emitter across base and into collector. Resulting large current flow will create excessive power dissipation.

- Avoidance of reach-thru
  - Wide base width so depletion layer width less than base width at CB junction breakdown.
  - Heavier doping in base than in collector so that most of CB depletion layer is in drift region and not in the base.

Second Breakdown



- 2nd breakdown during BJT turn-off in step-down converter circuit.

- Precipitious drop in C-E voltage and perhaps rise in collector current.

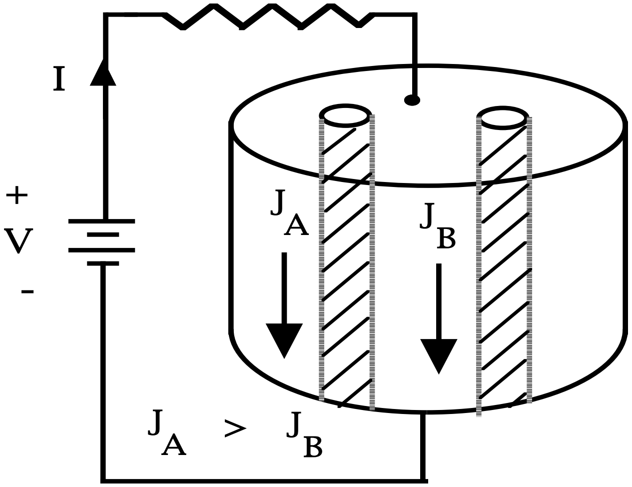
- Simultaneous rise in highly localized regions of power dissipation and increases in temperature of same regions.

  1. Direct observations via infrared cameras.
  2. Evidence of crystalline cracking and even localized melting.

- Permanent damage to BJT or even device failure if 2nd breakdown not terminated within a few μsec.

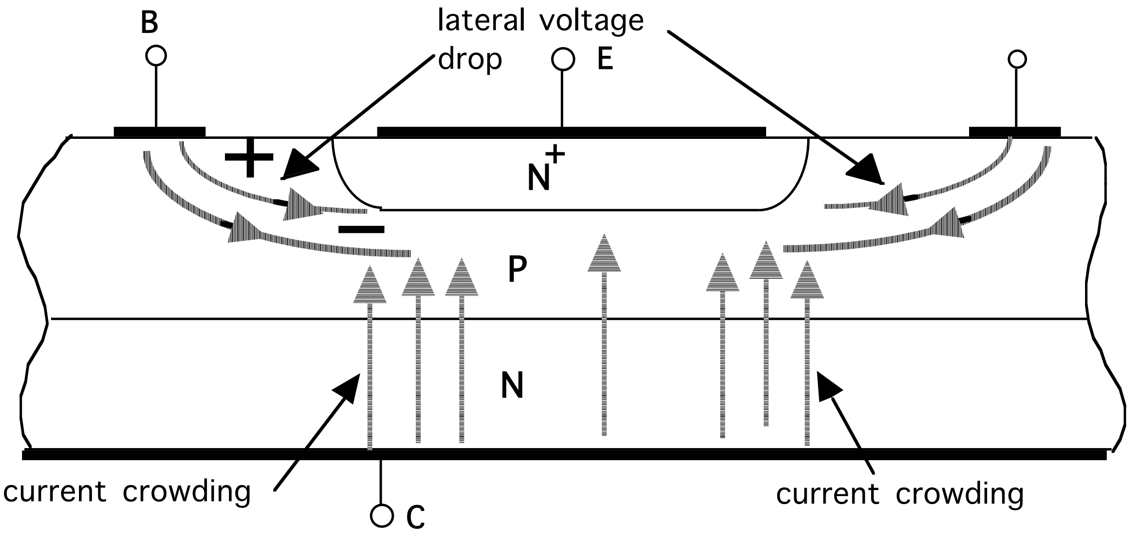
2nd Breakdown and Current Density Nonuniformities

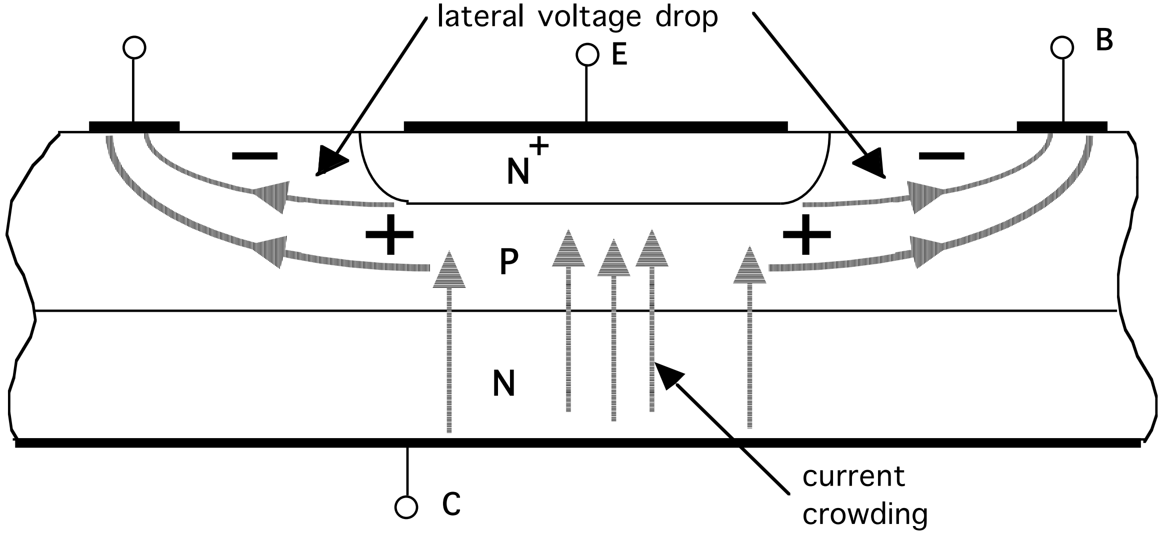
- Minority carrier devices prone to thermal runaway.
  - Minority carrier density proportional to $n_i(T)$ which increases exponentially with temperature.
  - If constant voltage maintained across a minority carrier device, power dissipation causes increases in temp. which in turn increases current because of carrier increases and thus better conduction characteristic.
  - Increase in current at constant voltage increases power dissipation which further increases temperature.
  - Positive feedback situation and potentially unstable. If temp. continues to increase, situation termed thermal runaway.



- Current densities nonuniformities in devices an accenuate problems.
- Assume $J_A > J_B$ and $T_A > T_B$
- As time proceeds, differences in J and T between regions A and B become greater.
- If temp. on region A gets large enough so that $n_i >$ majority carrier doping density, thermal runaway will occur and device will be in 2nd breakdown.

Current Crowding Enhancement of 2nd Breakdown Susceptibility

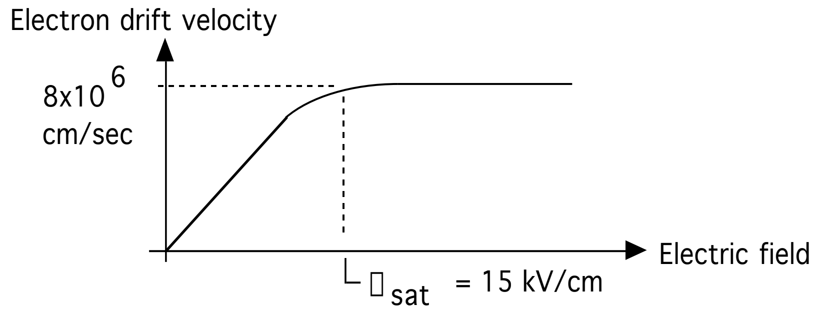


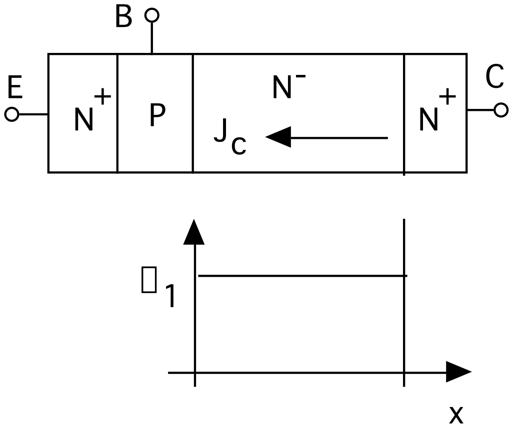


- Emitter current crowding during either turn-on or turn-off accenuates propensity of BJTs to 2nd breakdown.

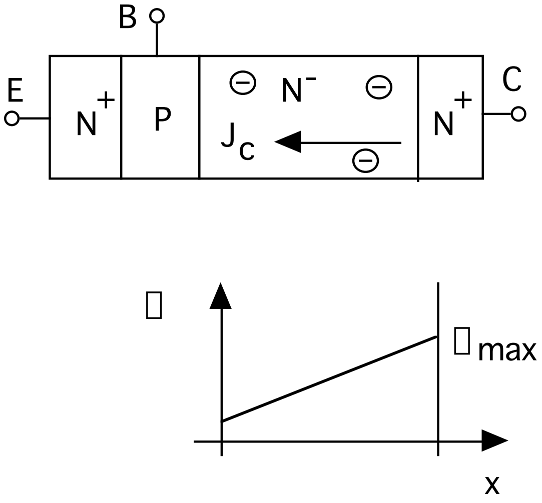
- Minimize by dividing emitter into many narrow areas connected electrically in parallel.

Velocity Saturation and Second Breakdown



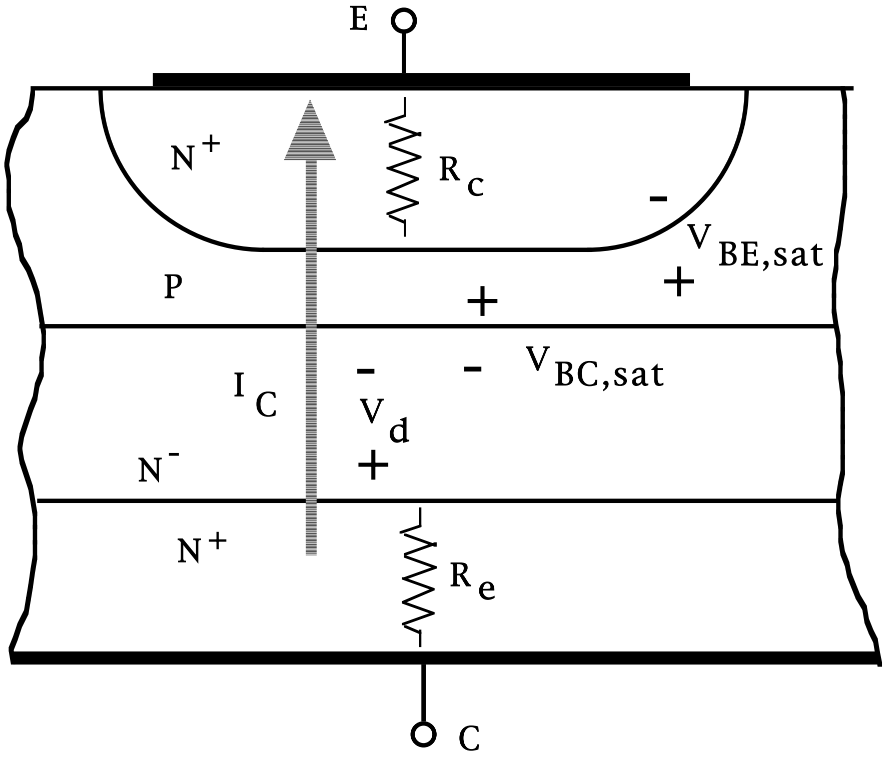


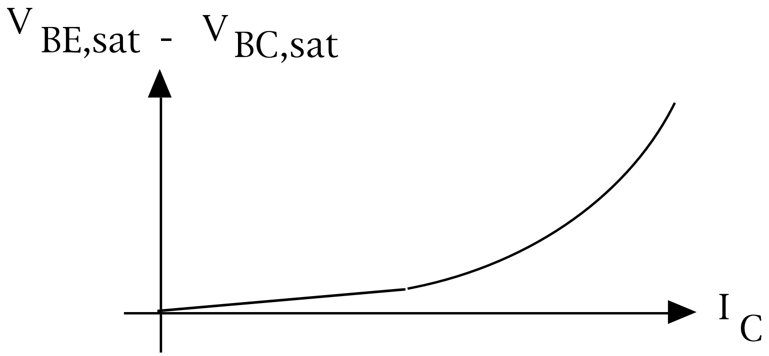
- Moderate current in drift region - BJT active
- Electric field $E_1 = J_c/(q\mu_n N_d) < E_{sat}$



- Large current density in drift region - BJT active.
- $J_c > q\mu_n N_d E_{sat}$. Extra electrons needed to carry extra current.
- Negative space density gives rise to nonuniform electric field.
- E_{max} may exceed impact ionization threshold while total voltage < BV_{CEO}.

Contributions to BJT On-State Losses





- $V_{BE,sat} - V_{BC,sat}$ typically 0.1-0.2 V at moderate values of collector current.

- $P_{on} = I_C V_{CE,sat}$

- Rise in $V_{BE,sat} - V_{BC,sat}$ at larger currents due to emitter current crowding and conductivity modulation in base.

- $V_{CE,sat} = V_{BE,sat} - V_{BC,sat} + V_d + I_C(R_c + R_e)$

BJT Safe Operating Areas

Forward bias safe operating area

Reverse bias safe operating area