EEE6206 Power Semiconductor Devices:

Section 2d: Bipolar Junction Power Transistors

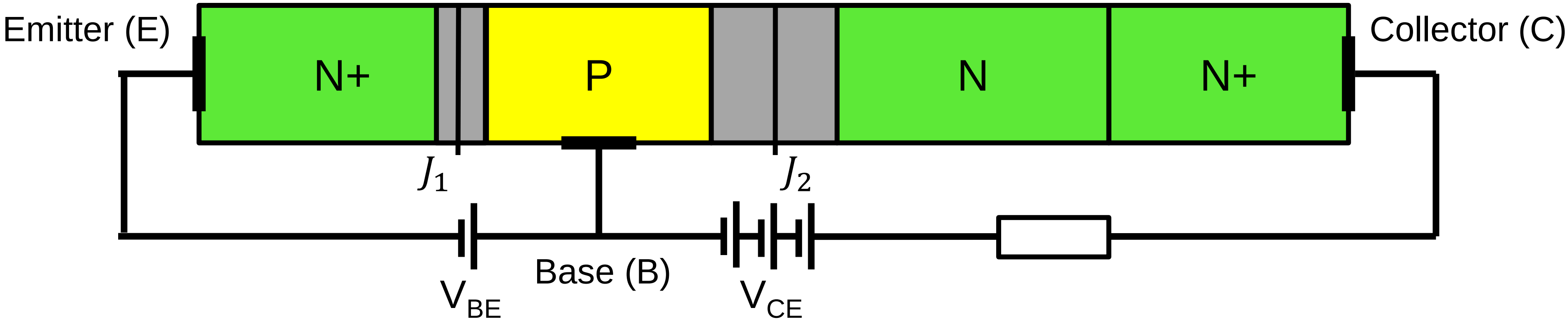
Bipolar Junction Power Transistors

- The invention of the bipolar transistor and the development of the technology necessary for its mass production initiated a revolution in electronics
- The transistor has become a key element in this revolution and the bipolar junction transistor structure form the basis of several families of monolithic integrated circuits
- The Power BJT has also been important as a switching device at frequencies greater than 1kHz
  - Although in Silicon this has been replaced by the Insulated Gate Bipolar Transistor (IGBT) for high voltage application and power MOSFETs for low voltage application
- However, today we are starting to see power BJT’s in wide band gap technologies (SiC)
- This analysis considers NPN transistors, most common form of high voltage BJT devices
  - The same considerations is applicable to PNP transistor
    - Commonly found in MOS Bipolar devices (IGBT)

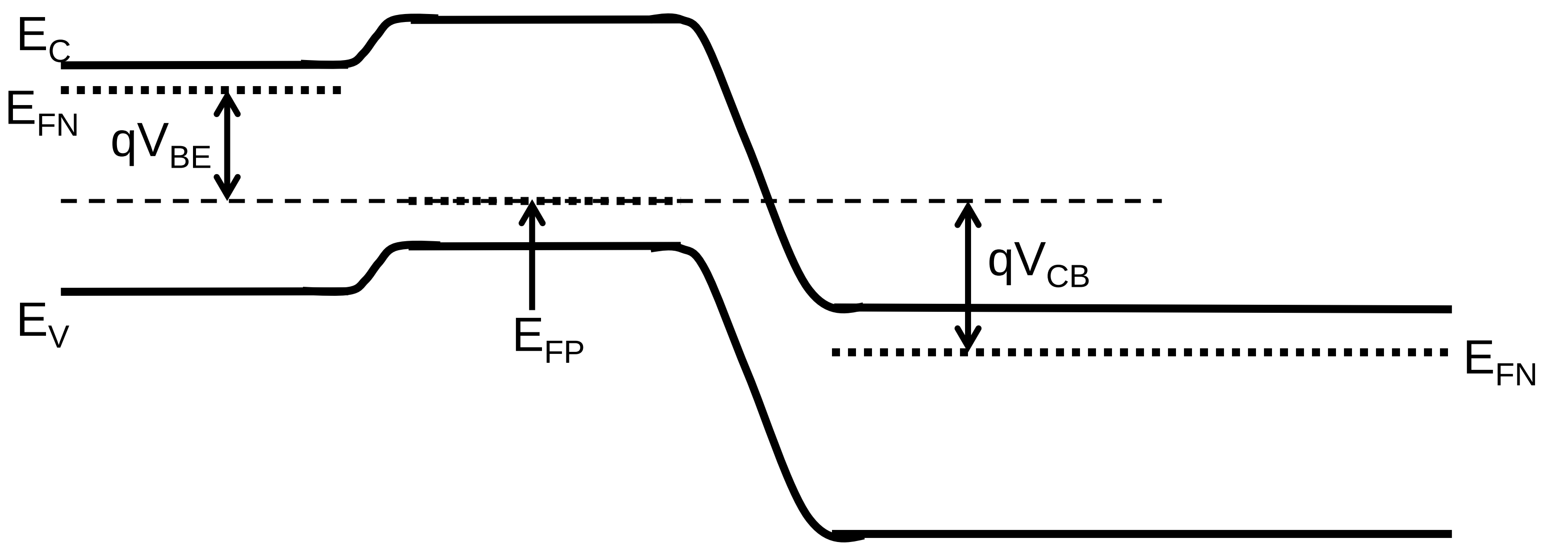
Characteristics of the Bipolar Junction Transistor Structure

NPN transistor in a common base configuration

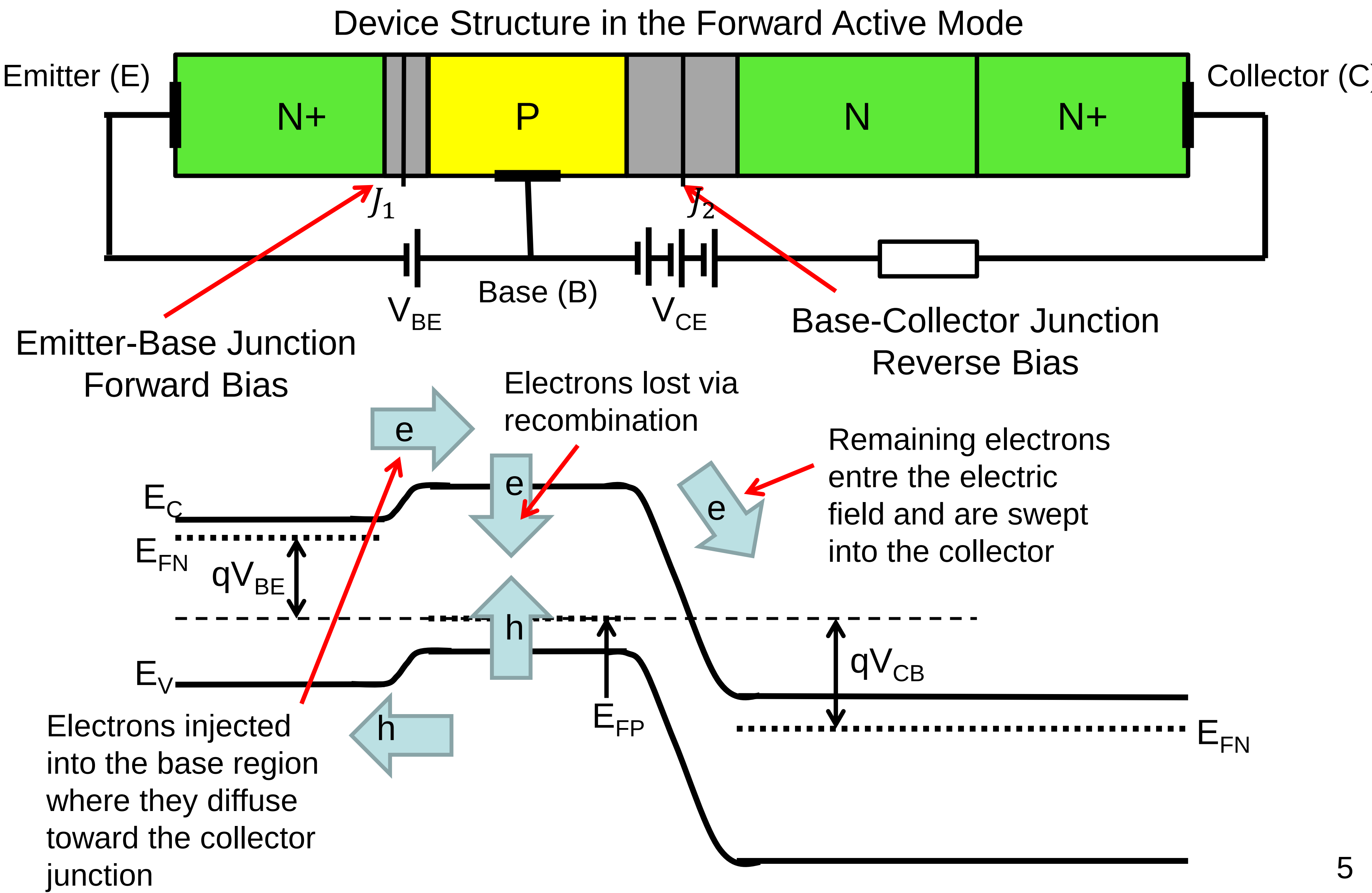
Device Structure in the Forward Active Mode



Energy Band Diagram in the Forward Active Mode



NPN transistor in a common base configuration



Excess electron concentration in the base region

- The relationship between the emitter current I_E and the collector current I_C and the parameters of the p base can be found by solving the continuity equation
- In a one-dimensional approximation under steady-state, low injection conditions
  - The electron concentration (n_p) in the neutral region of the base is given by:

$$\frac{d^2 n_p}{dx^2} - \frac{n_p}{D_n \tau_n} = 0$$

Carrier profile within the base region

- Taking the origin of the x-coordinate as the edge of the depletion region within the base so the boundary conditions with the base-emitter junction forward biased and with the base-collector junction is at a short circuit (V_{BC})=0

$$n_p(x=0) = n_{po} exp\left(\frac{qV_{BE}}{kT}\right)$$

$$n_p(x=w) = n_{po}$$

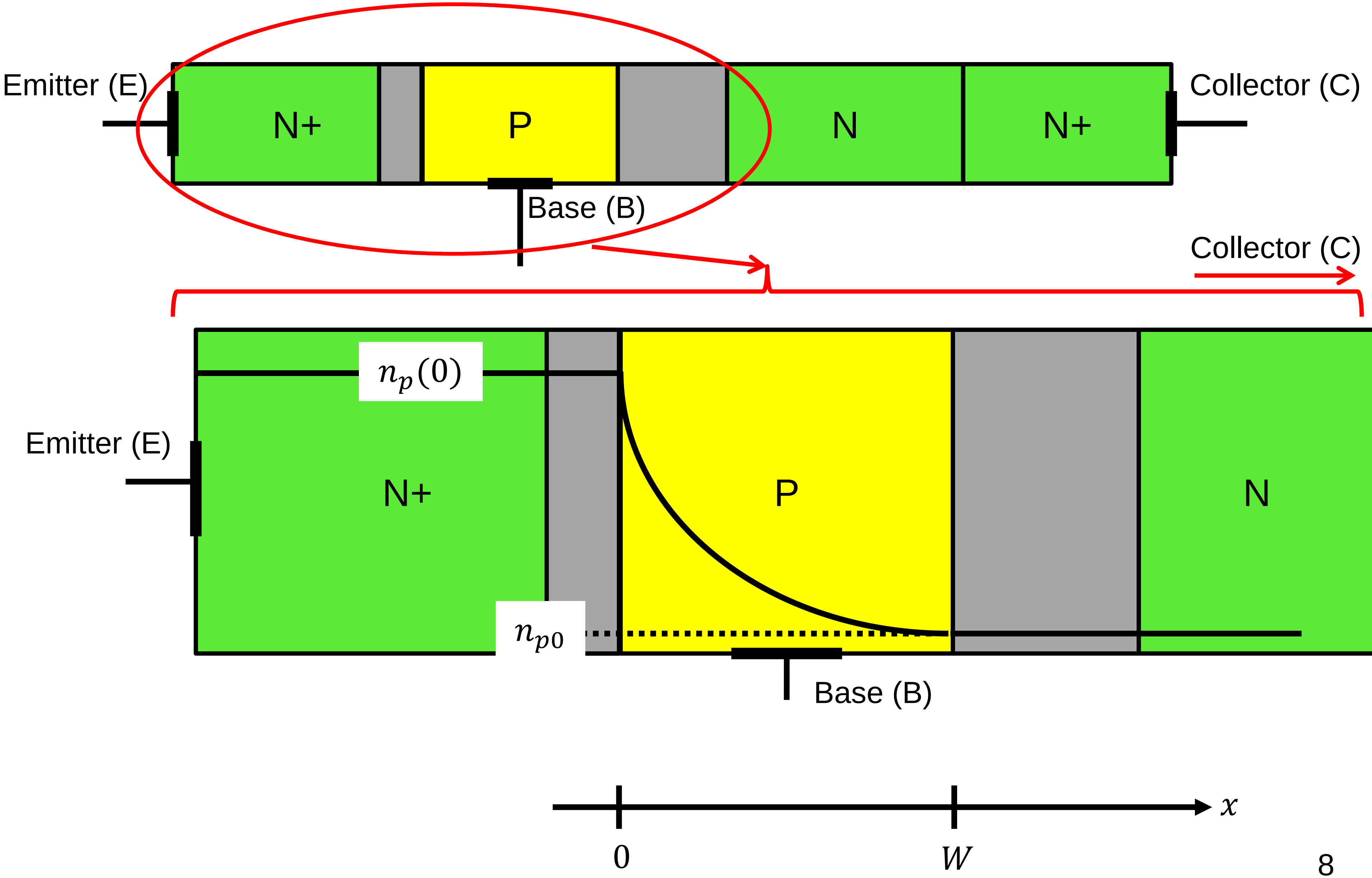
- The solution of this takes the form:

$$n_p(x) - n_{p0} = \left\{n_p(0) - n_{p0}\right\} \frac{sinh\left\{{w-x}/{L_n}\right\}}{sinh\left\{{w}/{L_n}\right\}}$$

Where $L_n = \sqrt{D_n \tau_n}$ is the electron diffusion length

***NOTE $sinh$ = hyperbolic sine function $sinh(x) = \frac{e^x - e^{-x}}{2}$

Distribution of excess electrons across the transistor base



Electron current density at the emitter/base and base/collector junctions

- Assuming electron current is only due to diffusion, the electron current at the emitter junction ($x = 0$) can be expressed as:

$$J_n(0) = qD_n\left(\frac{dn_p}{dx}\right)_{x=0} = \frac{qD_n}{L_n}\{n_p(0) - n_{p0}\}\frac{cosh\left\{{}^{w}/_{L_n}\right\}}{sinh\left\{{}^{w}/_{L_n}\right\}}$$

- Likewise, on the over side of the base at the edge of the space charge region ($x = w$)

$$J_n(w) = qD_n\left(\frac{dn_p}{dx}\right)_{x=w} = \frac{qD_n}{L_n}\{n_p(0) - n_{p0}\}\frac{1}{sinh\left\{{}^{w}/_{L_n}\right\}}$$

Common base current gain

- The injection efficiency of a junction is defined at the fraction of the total current density transported by one carrier type:

  Electron injection efficiency: $\gamma_n = \frac{J_n}{J_n + J_p}$ Hole injection efficiency: $\gamma_p = \frac{J_p}{J_n + J_p}$

- This gives the total emitter current density of:

$$J_E = \frac{J_n(0)}{\gamma_n}$$

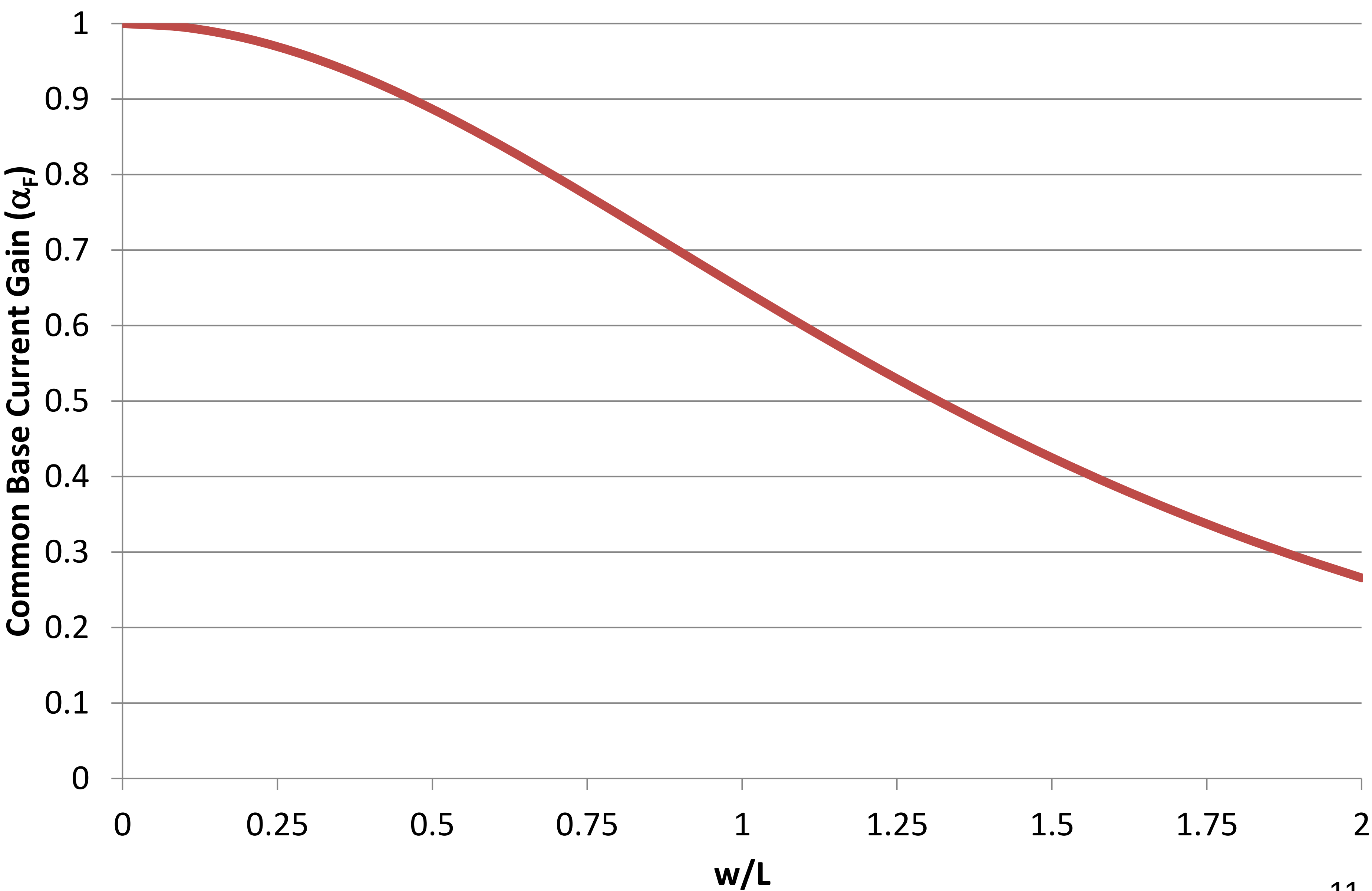
- As the collector current is made up entirely by the flow of electrons:

$$J_C = J_n(w)$$

- It is possible to define the common base current gain as:

$$\alpha_F = h_{21B} = \frac{J_C}{J_E} = \frac{\gamma_n J_n(w)}{J_n(0)} = \frac{\gamma_n}{\sinh(w/L_n)}$$

Influence of w/L ratio to common base gain



Factors determining current gain

- When the collector terminal is under reverse bias
  - Not shorted to the base in these calculations
- A leakage current I_{CB0} needs to be included to the overall collector current

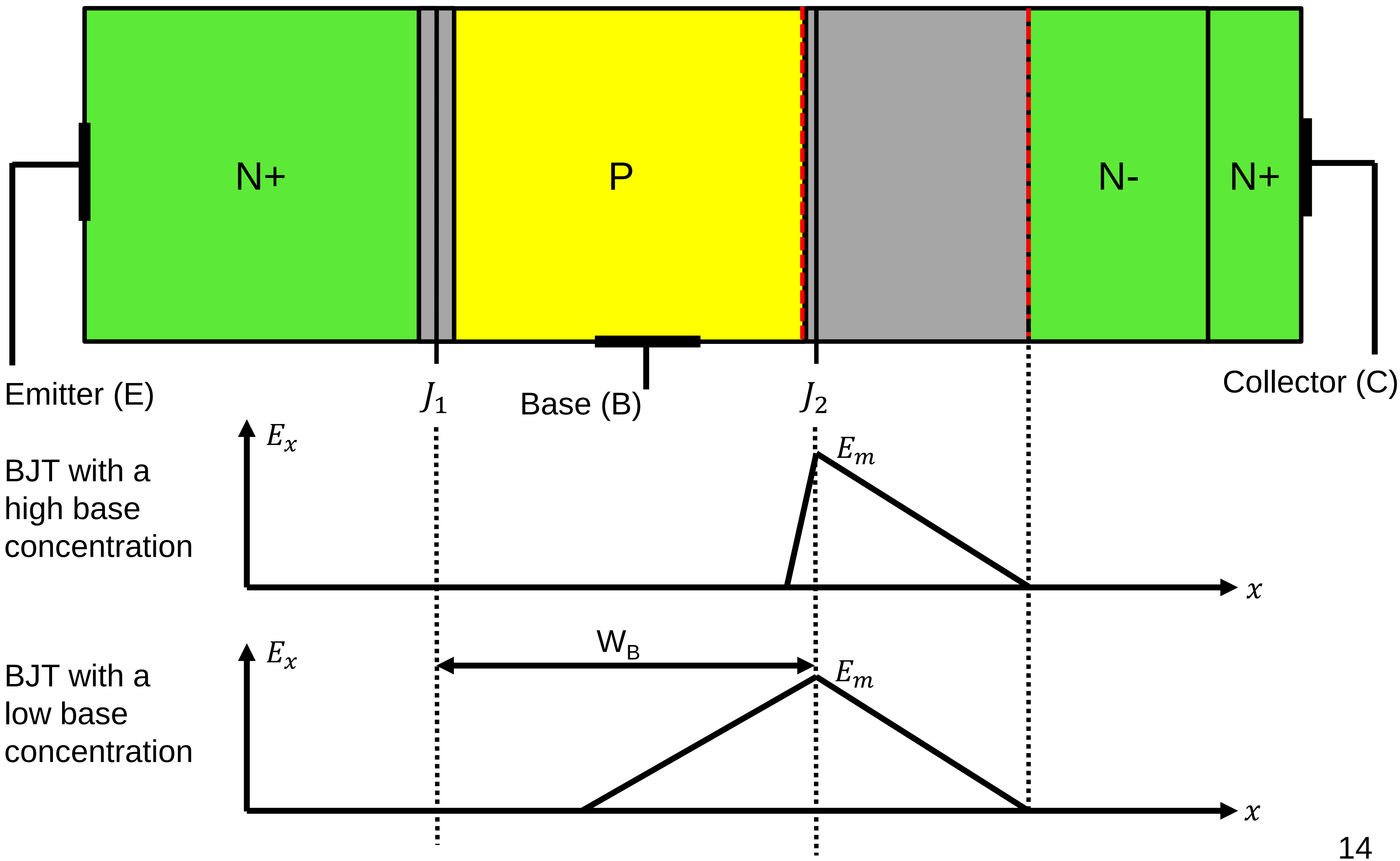
$$I_C = h_{21B} I_E + I_{CB0}$$

- Therefore the common base gain is the incremental ratio of the collector and emitter currents dI_C/dI_E
- These show that to achieve the highest possible gain we need to maximise the emitter efficiency (γ_n) and to minimise the value of $\cosh(w/L_n)$
  - To obtain a high injection efficiency the majority carrier concentration in the emitter should be at least two orders of magnitude greater than the base
  - To maximise $\cosh(w/L_n)$ the base region should be designed as small as possible or the excess carrier lifetime needs to be very long

Base-Collector Consideration

- When designing the transistor it is important that the depletion region at the base/collector junction does not spread far into the base region as the collector voltage increases
  - This avoids the current gain becoming voltage-dependent and minimises the risk of *punch-through*
- For power applications the breakdown voltage at the collector junction has to be high
- To satisfy these two requirements the concentration of active impurities of the collector region should be low and the base should be considerably higher

Electric field profile within a NPN transistor



Common base configuration: Base Current

- Electron mobility is ~3x higher than that of holes
  - Therefore it follows that a NPN transistor should a higher gain than that of a PNP transistor with the same base width
  - Therefore the majority of high power transistors are NPN in design
- The carriers that recombine in the base region is considered at the base current in the structure

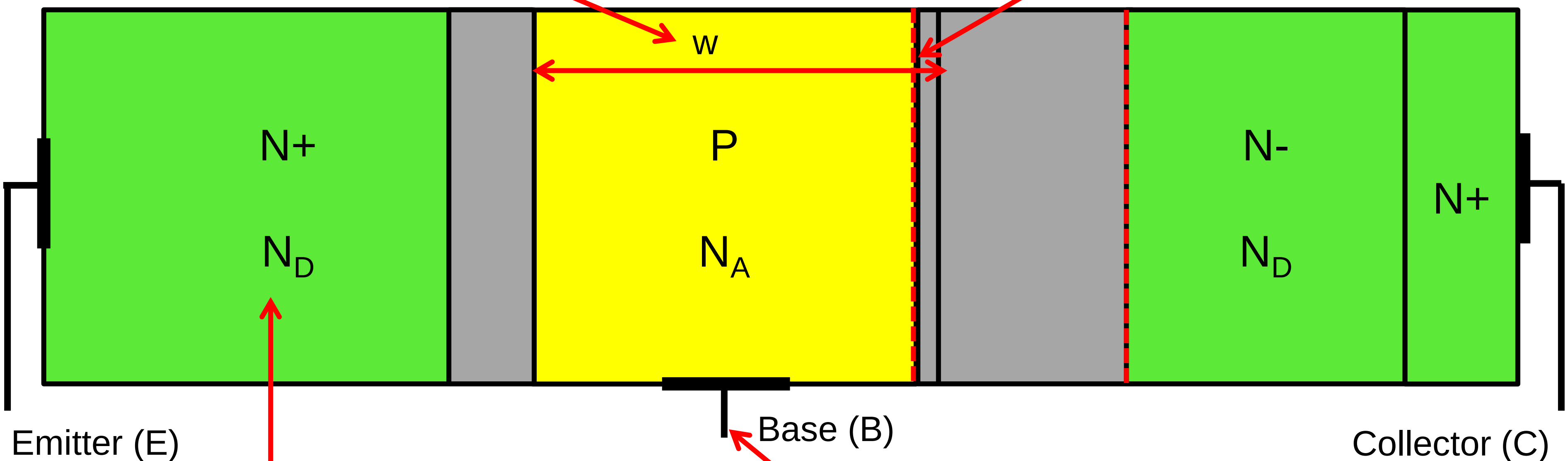
$$I_B = I_E - I_C = I_E(1 - h_{21B})$$

- This can be considered to be the current arising from the carriers injected from the emitter that recombine during their transport through the base region
  - Less any leakage current across the collector-base junction

Basic device design

Base thickness (w) need to be as thin as possible
Minority carrier lifetime needs to be maximised (minimising (w/L) ratio)

Gain is dependent upon w, as collector voltage rises gain will increase as a direct result of the depletion region moving into the base. If this reaches the emitter-base junction the device breaks down due to punch through
To prevent this the doping in the collector region is reduced

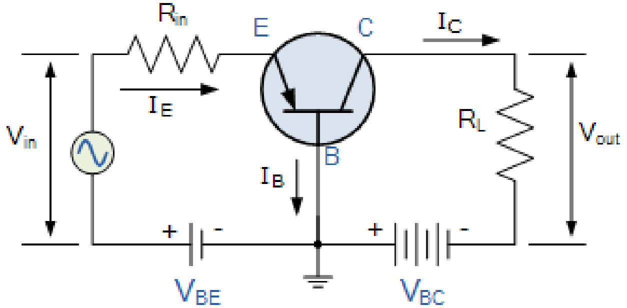


High emitter injection efficiencies are required γ~1. Donor doping (N_D) concentration in the emitter region is set two orders of magnitude greater than the acceptor doping of the base

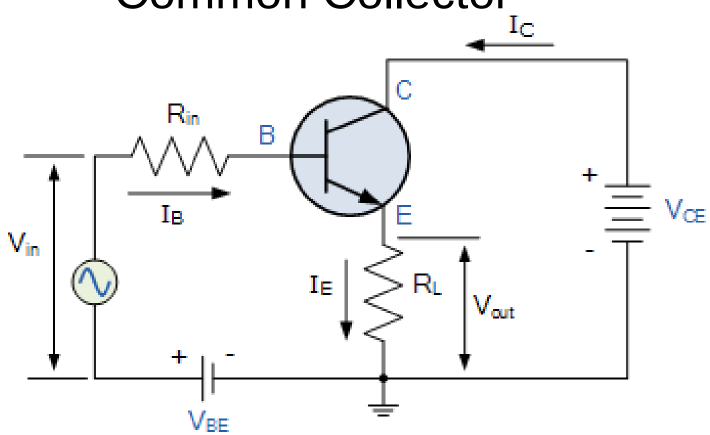
In common base mode the current caused by injected carrier recombination causes a base current to flow

Transistor configurations

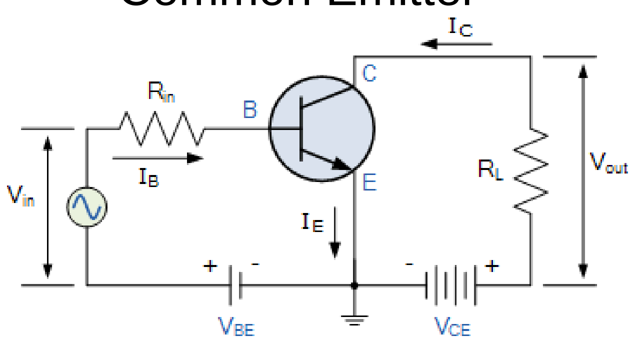
Common Base



Common Collector



Common Emitter

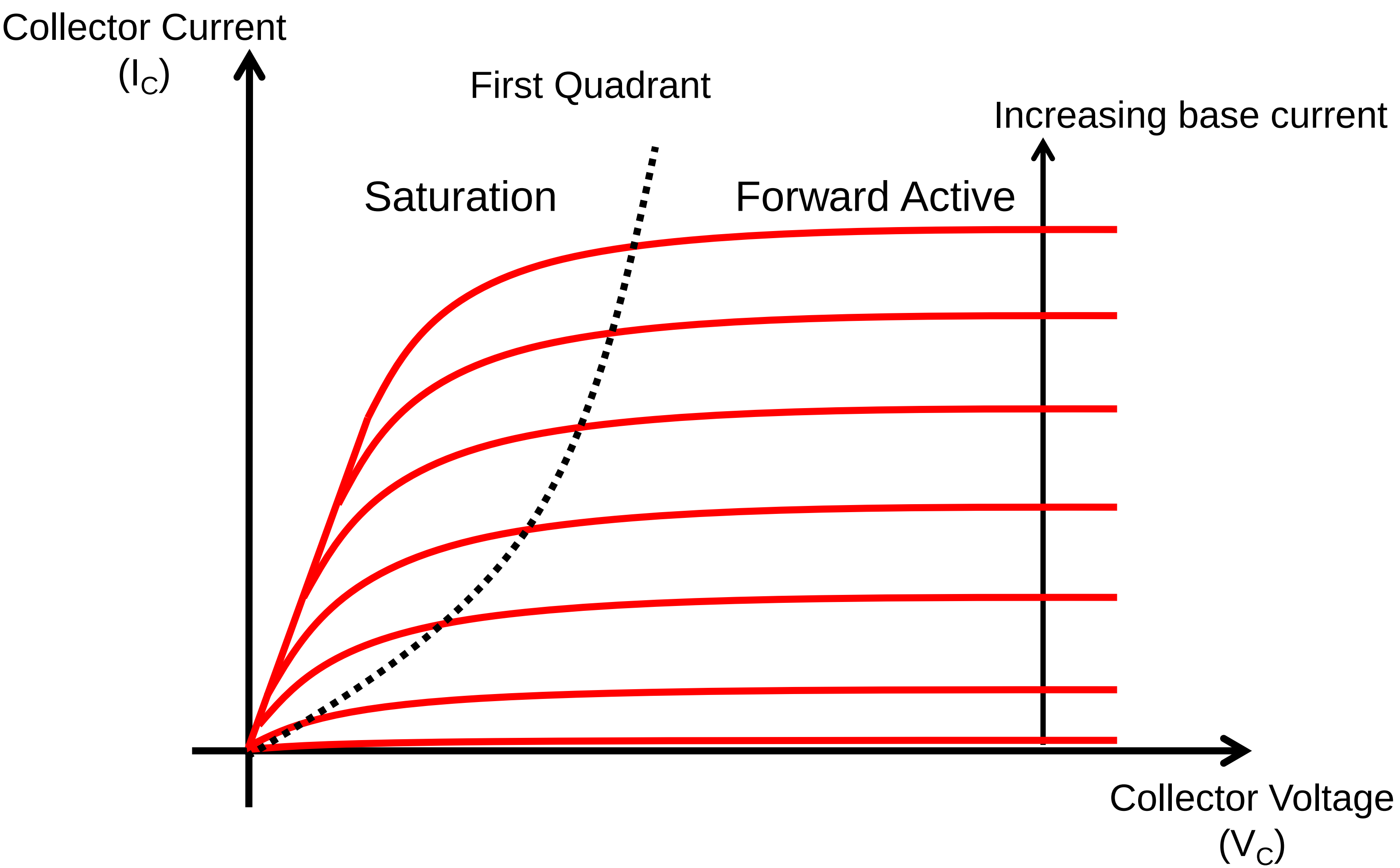


- BJT's can be operated in three circuit configurations: Common base/collector and emitter
- Common Base or Common Collector configurations are not normally suitable for power electronic applications
- The Common Emitter configuration is generally used since it provides good current and power amplification
- The Common Emitter current gain:

$$h_{21E} = \frac{dI_c}{dI_B} = \frac{h_{21B}}{1 - h_{21B}}$$

- This is related to the common base gain therefore any modification to improve h_{21B} would result in an increase in common emitter current gain h_{21E}

Common emitter bipolar transistor characteristic



- Transition from saturation to active governed when collector base junction becomes reverse bias
- I.e. base current is positive therefore base-collector and base-emitter junctions are forward biased in saturation mode

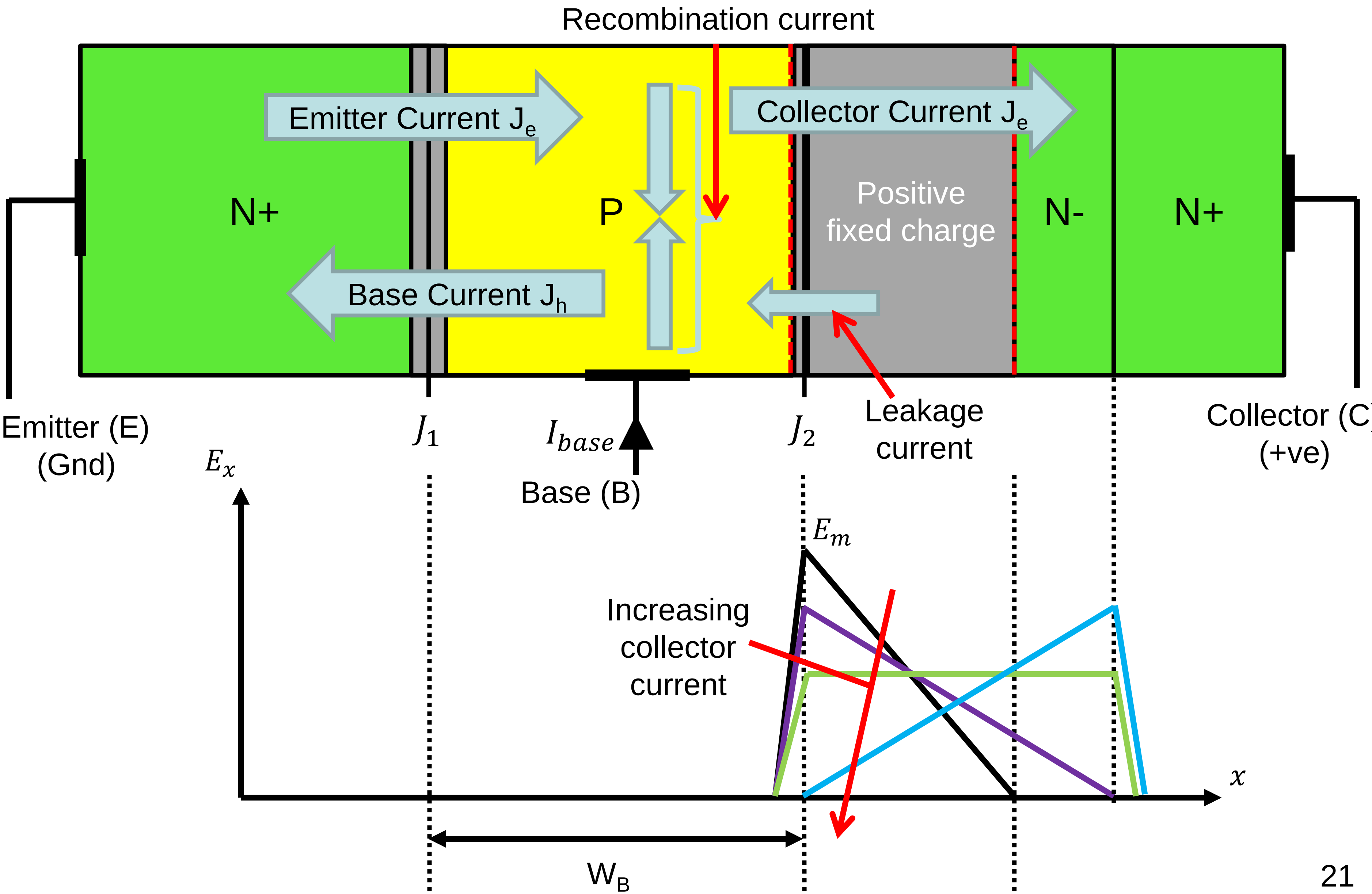
Affect of emitter current density on gain

- Both common base and common emitter gain coefficients (h_{21B} h_{21E}) are functions of the emitter current density
  - At low current densities the current crossing the p-n junction is mostly generation-recombination current and the injection efficiency is low
  - At higher current densities the fraction of the current that consists of injected minority carriers increase to a level very close to unity and the current gain coefficients are as given previously
  - At still higher current densities the concentration of carriers injected into the base region affects the majority doping concentration. Conductivity modulation of the base and n-collector occurs reducing emitter efficiency.
  - At high levels of current density the base widening effect occurs : Termed the **kirk effect**

Base width widening (Kirk Effect)

- When the collector current density is large another phenomenon that reduces the transistor gain is an increase in effective base width
  - Referred as the Kirk Effect
- Occurs when the device is biased in its forward active region with a large collector bias voltage which is supported via the base-collector junction
- As the device is in forward conduction as the injected carrier increase with current the electron density in the drift region becomes comparable in magnitude to the charge of donor atoms in the drift region
- The compensation of the positive charge within the depletion region by the negative charge due to current flow modifies the electric field profile
- When the net charge do to current flow equals the donor doping density the resulting electric field would be flat
- Further increase in current, and hence negative charge would cause the electric field profile to reverse

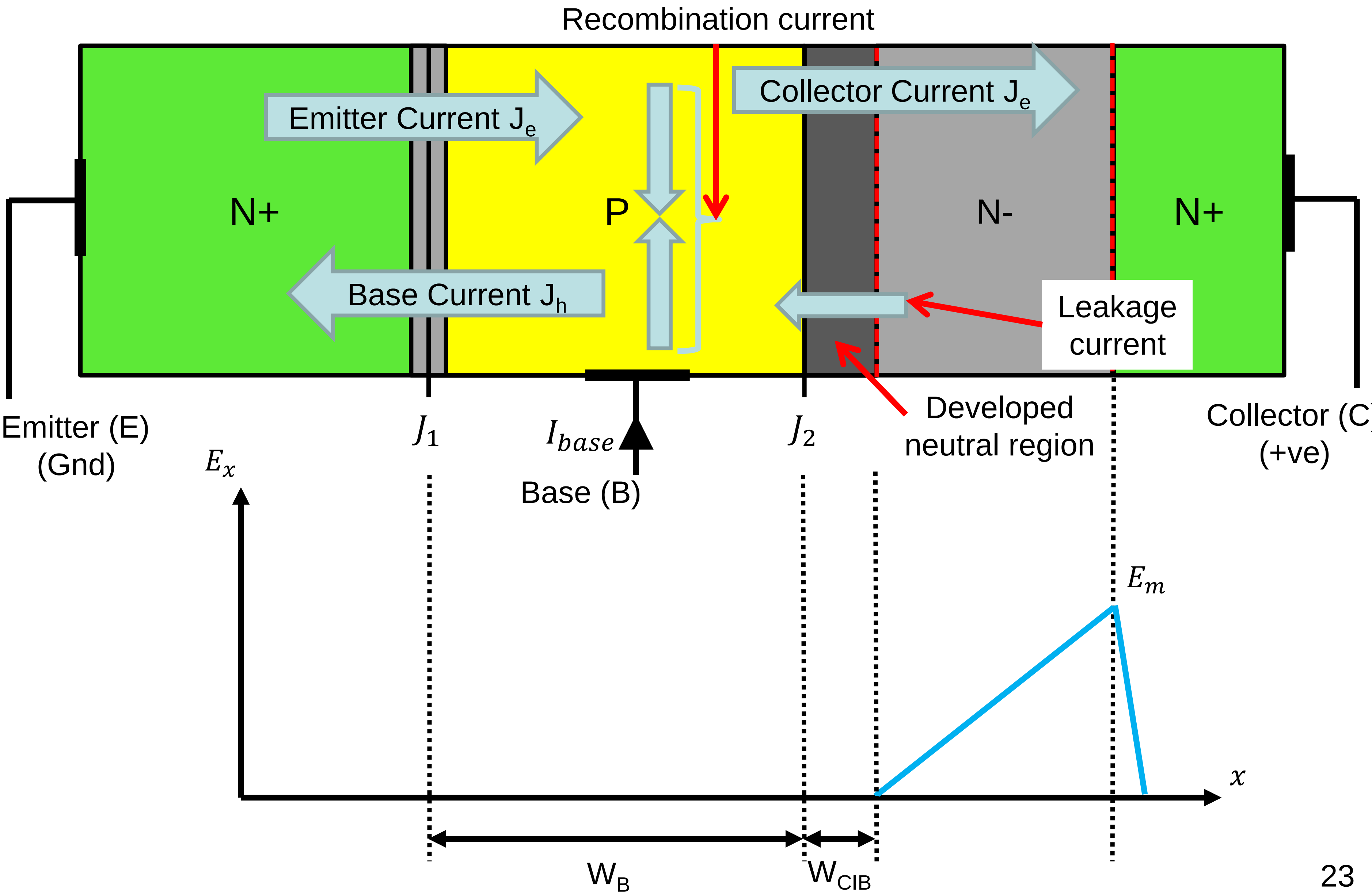
Collector base electric field profile with respect to collector current density



Kirk Effect: continued…

- The current density at which the electric field at the base-collector junction becomes zero is termed the Kirk current density
- Further increase in current density results in a current induced base region developed within the collector drift region
- A neutral region develops in the drift region adjacent to the base-collector junction
- Electrons injected into the p base region now needs to diffuse not only through the physical width of the base (W_B) but also the current induced base width (W_{CIB})
- This reduces the base transport factor and the current gain of the bipolar transistor

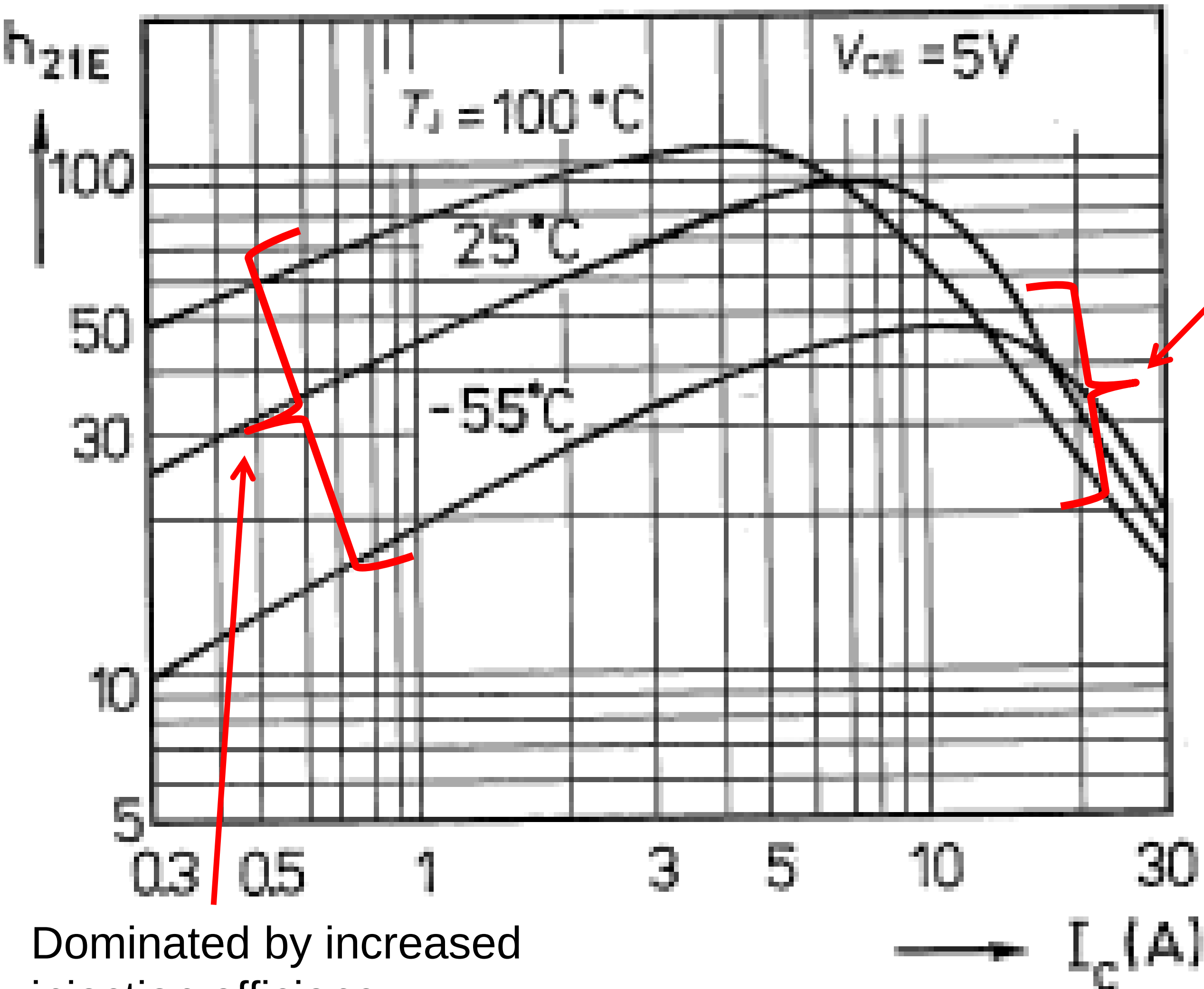
Collector base electric field profile with respect to collector current density



Effect of increasing temperature on gain coefficients

- Increased temperature has two opposing effect on current gain coefficients
  - At low current densities the reduced bandgap give an increase in the emitter injection efficiency
  - As temperature increases carrier mobility reduces due to increased scattering and Auger recombination increases
    - Reducing the diffusion coefficients and diffusion length which reduced gain coefficients

Effect of temperature and current density upon gain



Dominated by high levels of injected charge. Base widening (kirk effect), reduced mobility and increased Auger recombination

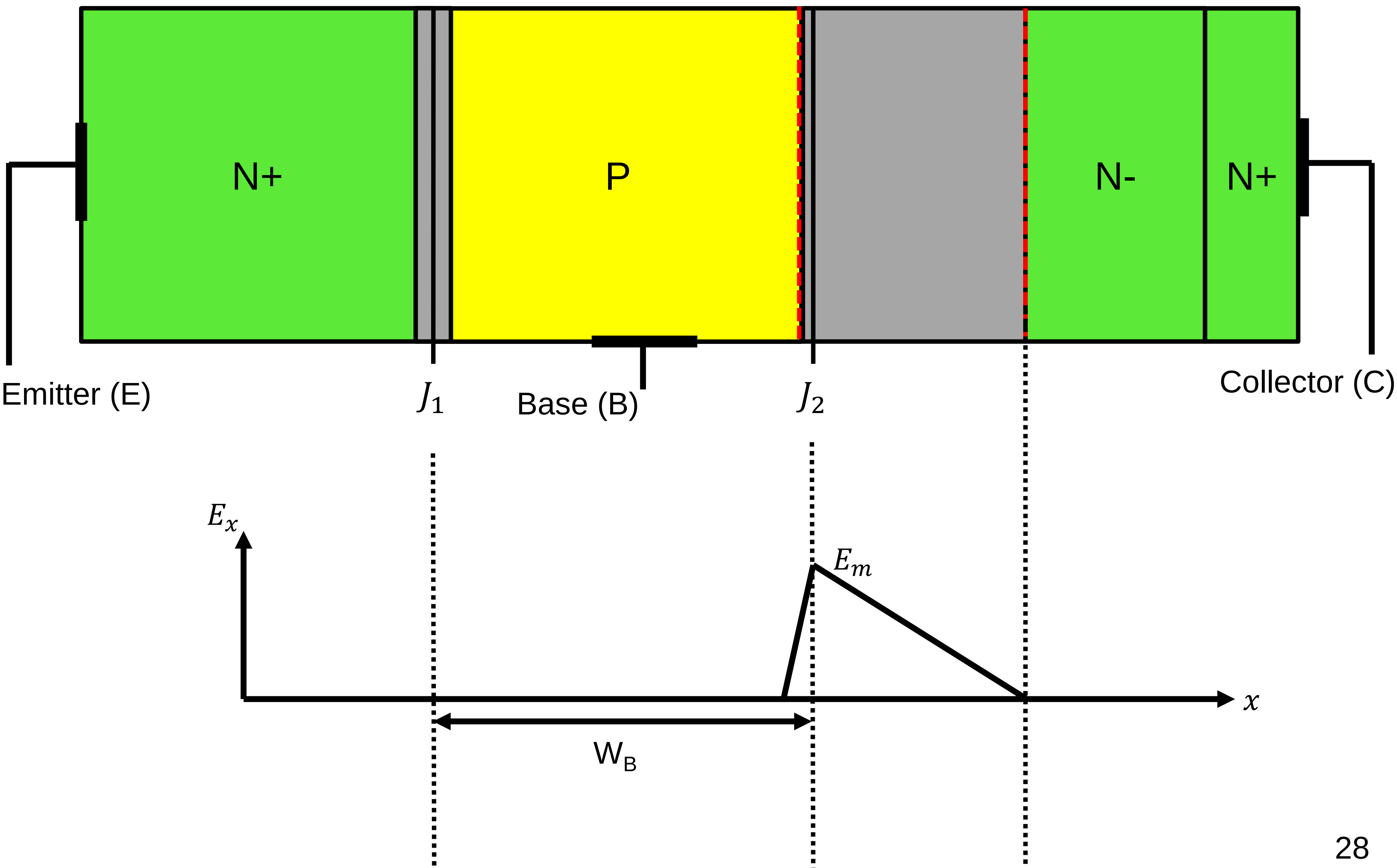
Dominated by increased injection efficiency
Either by increased current density or by temperature

High Voltage Consideration

Static blocking characteristics

- In principle the bipolar transistor is capable of supporting voltage in the first and third quadrants
  - In the first quadrant with a positive bias applied to the base-collector junction (J1) becomes reverse biased
- For high voltage operating the simple transistor structure is modified to include a n- region
  - When the device is operated in its third quadrant (negative bias applied to the collector terminal) the breakdown voltage of the emitter base junction is limited to approximately 50V
    - Since this junction is formed via two moderately doped regions
  - For this reason the power bipolar transistor is usually used as a power switch in a DC circuit with a positive collector power source

Electric field profile within a NPN transistor



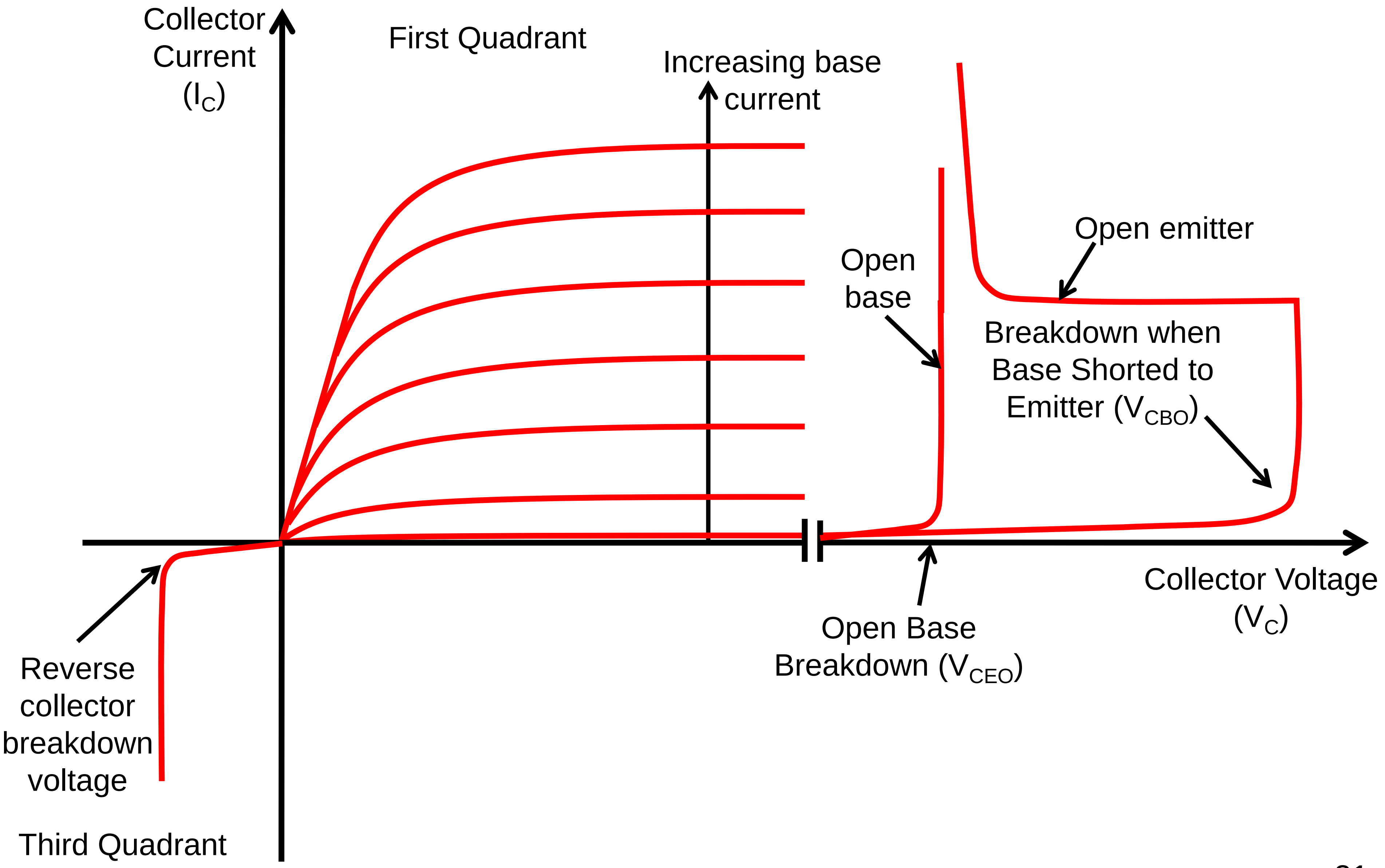
Shorted base-emitter breakdown

- Voltage supported depend upon the biasing conditions of the base and emitter terminals
- With the base connected to the emitter the configuration is similar to that if the emitter junction was open
- Under this condition the device operates like a diode between the base and collector terminals
  - Maximum voltage rating of the structure is determined by the breakdown voltage of the base-collector junction (J_1)

Open Emitter breakdown

- Open base breakdown is much smaller than the voltage blocking capability when the base terminal is shorted to the emitter by the base drive circuit (open emitter)
  - Ultimately open-base breakdown limits voltage blocking capability
- The voltage blocking capability of the transistor is a fraction of the open emitter voltage
  - Reduced drift region doping densities, increased drift region thicknesses are required to increase the voltage rating: at the expense of forward voltage drop and current gain
- However during open emitter configuration as collector current increases voltage blocking capability reduces to the open base condition
  - This also occurs when a base current is applied to the transistor

Typical BJT electrical characteristics



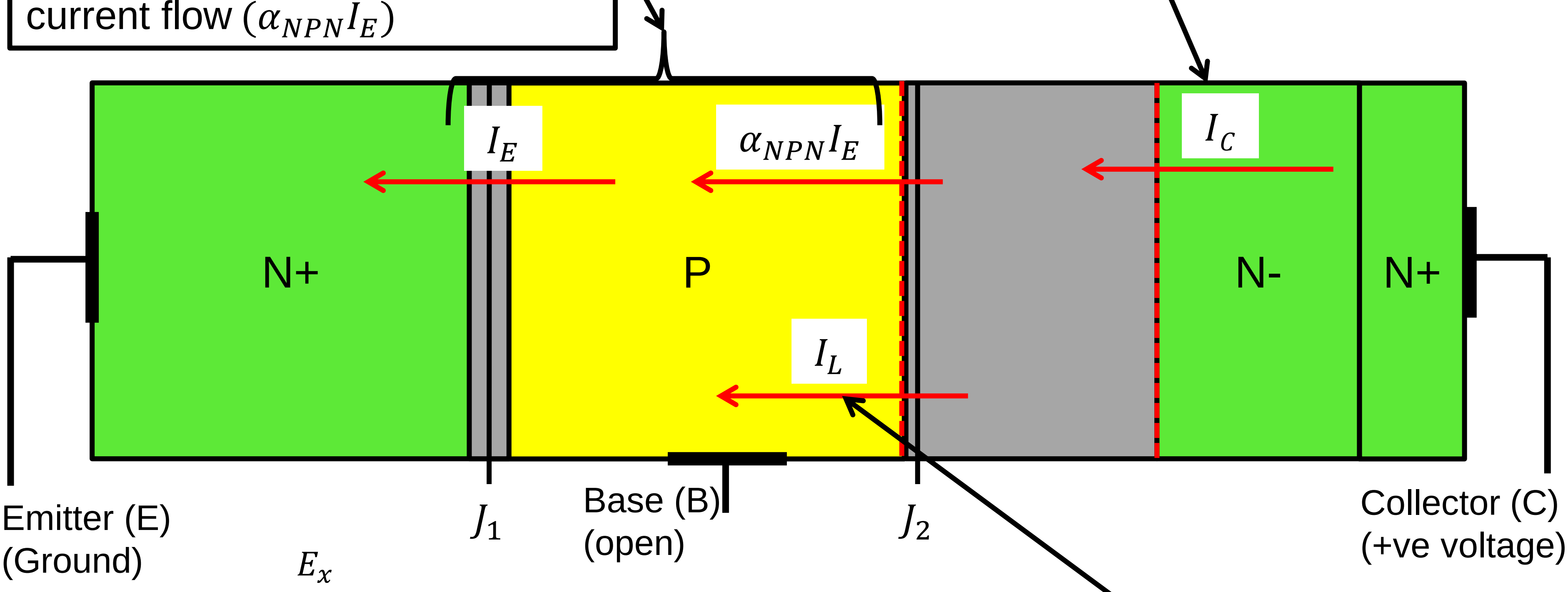
Open base breakdown voltage

- When the base terminal is as a open circuit and a positive bias is applied to the collector electron the base-emitter junction becomes forward biased and the base-collector becomes reverse bias
  - The majority of the applied voltage is supported across the base-collector junction
- However the leakage current flowing through this junction must also flow through the base-emitter junction
- As a result this leakage current is amplified by the gain of the transistor
  - Reducing the maximum voltage capability

Current transport through an open base transistor

Injection of minority carriers across the forward biased base-emitter junction (I_E) produces a current flow ($\alpha_{NPN} I_E$)

Currents are interrelated i.e.
$I_C = \alpha_{npn} I_E + I_L = I_E$



Since base terminal is a open circuit small leakage current I_L flows through the emitter-base junction

Transistor breakdown voltage

$$I_C = \alpha_{NPN} I_E + I_L = I_E$$

- Consequently:

$$I_E = \alpha_{NPN} I_E + I_L = \frac{I_L}{1-\alpha_{NPN}}$$

- From this expression we can see that collector and emitter currents will become very large as the transistor gain (α_{NPN}) approaches unity
- The criteria from breakdown for an open base transistor can be defined by:

$$\alpha_{NPN} = \gamma_E \alpha_T M$$

Emitter injection efficiency

Base transport factor

Multiplication coefficient

Multiplication coefficient (M)

- Multiplication coefficient (M) allows calculation of the number of electron-hole pairs during impact ionisation created as a result of generation of a single pair
  - The definition of avalanche breakdown occurs when the total number of electron-hole pairs generated within the depletion region approaches infinity
  - For P+/N junction diodes this is given by:

$$M = \frac{1}{1 - \left(\frac{V}{BV_{pp}}\right)^6}$$

  - Whereas for a N+/P junction:

$$M = \frac{1}{1 - \left(\frac{V}{BV_{pp}}\right)^4}$$

  - Where V is the applied voltage and BV_{PP} is the maximum plane parallel breakdown voltage for the material

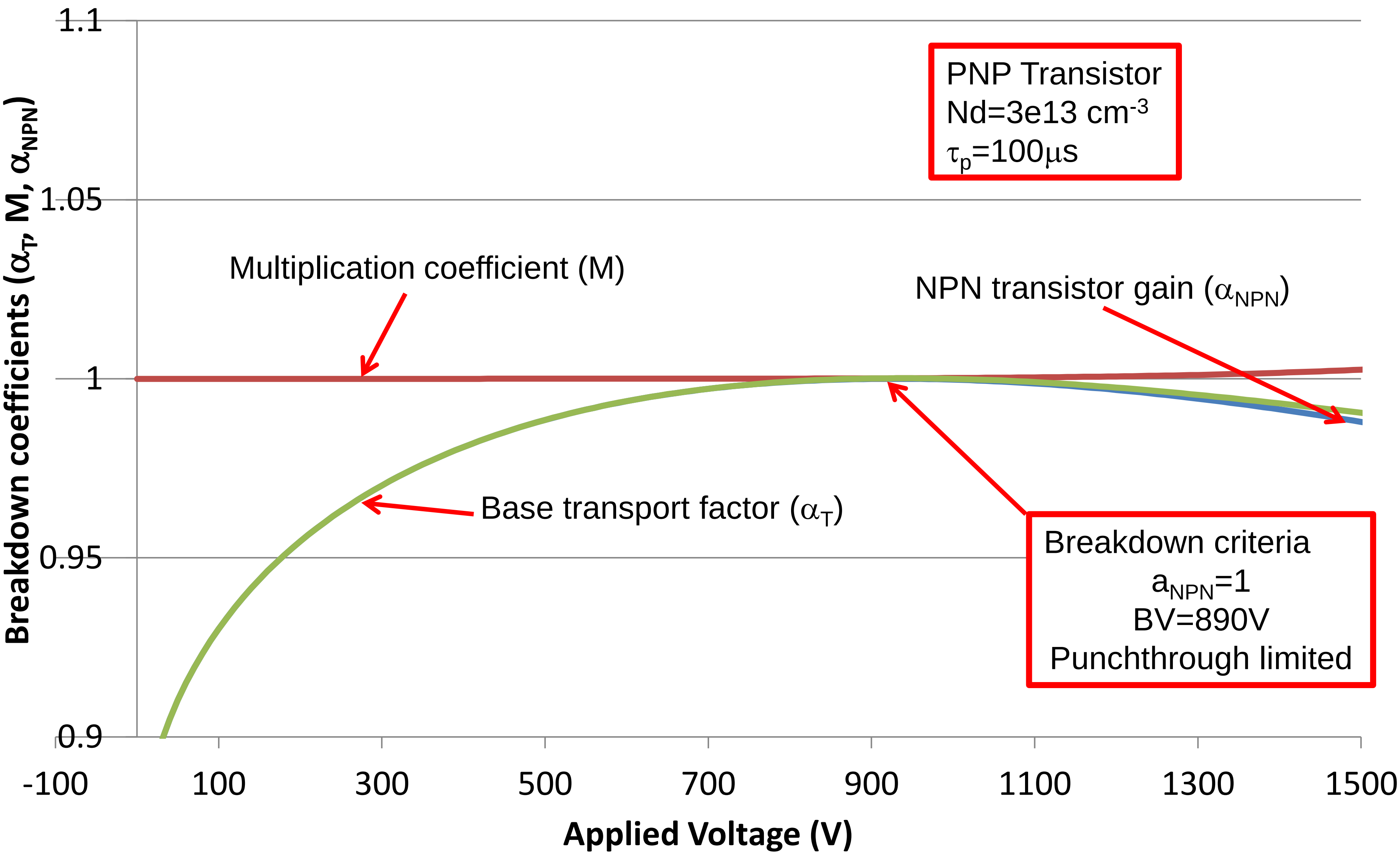
Base transport factor (α_T)

- Base transport factor is a measure of the ability for the minority carrier injected from the emitter-base junction to reach the base-emitter junction
- For a NPN transistor it is expressed in terms of the ratio of the electron current at the base-emitter junction to the electron current at the base-collector junction
- When the minority carrier diffusion length ((L_n) for NPN transistors) is much greater than the base width (w) the base transport factor is equal to unity
- However a unity base transport factor would result in breakdown of the transistor
  - Main trade off in transistor design is breakdown voltage and current gain
- The base transport factor can be obtained from:

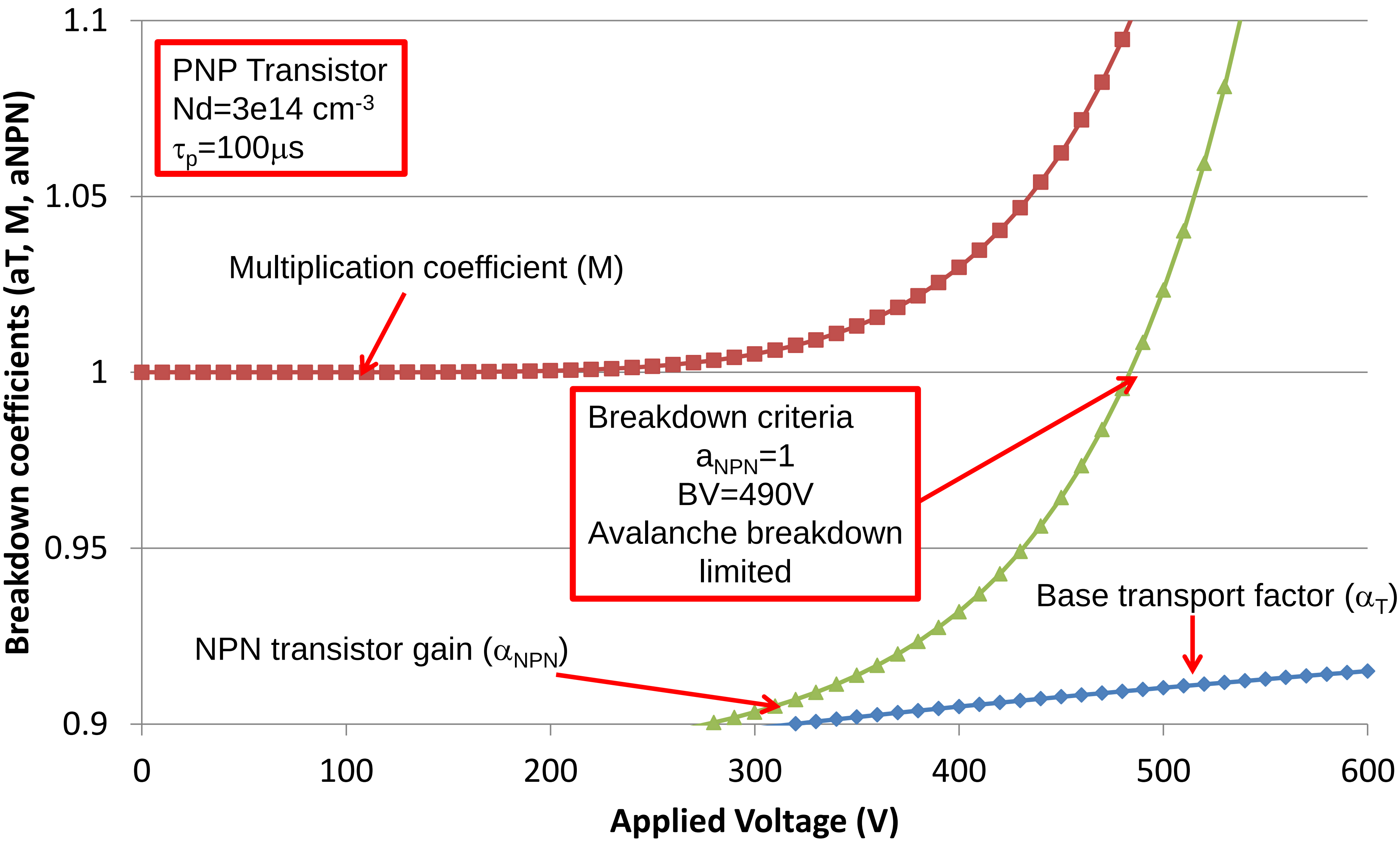
$$\alpha_T = \frac{J_{nC}}{J_{nE}} = \frac{1}{cosh\left(\frac{W_N - W_D}{L_n}\right)}$$

- Where W_N is the width of the drift region W_D is the depletion layer thickness and L_n the minority carrier diffusion length

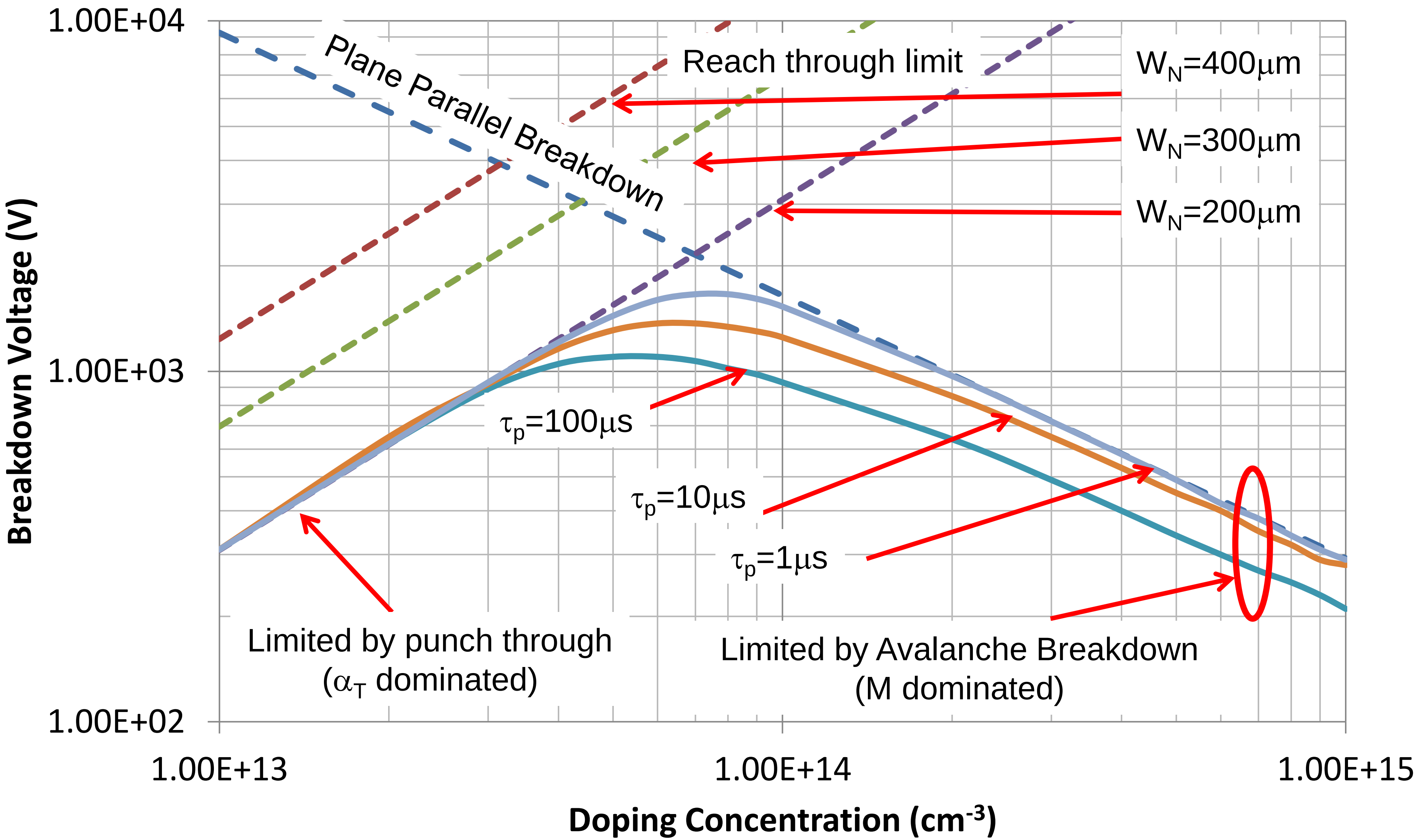
Breakdown voltage limited by base transport factor: Punchthrough (sometimes termed reach through)



Breakdown limited by multiplication coefficient (M): Avalanche breakdown



Open base transistor breakdown voltage of a PNP transistor



Summary

- Current gain and breakdown performance of the transistor structure is limited by the base transport factor (α_T), Base width (w) and the emitter junction efficiency (γ)
- This trade off between current gain and breakdown performance limits the voltage capability of the design
  - Larger base regions required to withstand higher voltages reduces base transport factor and current gain
  - Silicon BJTs are limited in terms of breakdown voltage (~1000V)
- Electrical characteristics are dominated by carrier diffusion
  - This results in a on-state forward voltage which reduce with temperature causing current hogging and making it difficult to parallel BJT dies to achieve high current modules
- Minority carrier injection occurs in the base and n- drift region
  - Tail currents during switching events increasing transient losses

Summary continued

- Device is current controlled
  - i.e. to maintain the device in the on-state a base current **MUST** be continuously supplied
    - Significant base drive losses
- With these technological drawbacks and the development of high voltage MOSFETs and IGBT technologies
  - High voltage BJTs are only found in niche applications, mainly focused on price and not performance
- Recently Silicon carbide BJTs have now been developed are now available in the market
  - With the improved material performance with respect to power device requirements these device show significant increase in gain, especially at high temperatures
    - 1000V NPN Silicon Transistor: h_{FE}=30@150^{o}C
    - 1200V NPN Silicon Carbide Transistor: h_{FE}=50@175^{o}C