shurm@rpi.edu

BJT-TO92

Bipolar Junction Transistors

The first transistors were Bipolar
Why is that RAMs nowadays unipolar?

From http://nina.ecse.rpi.edu/shur/Alphab.htm

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History of Semiconductors

Seebeck

von Siemens

- •1821: Thomas Seebeck discovered semiconductor properties of PbS
- •1833: Michael Faraday reported on conductivity temperature dependence of semiconductors
- •1875: Werner von Siemens invented a selenium photometer
- •1878: Alexander Graham Bell used this
- •device for a wireless communication system
- •1907 Round demonstrated the first LED (using SiC)
- •1947: Bardeen, Brattain, and Shockley discovered a Bipolar Junction transistor

Introduction

- First transistor in practical use (invented in 1947, used in 1950 - 1960's)
- Largely replaced by CMOS but still a very important device (especially in high-speed and high power applications)
- Heterojunction bipolar transistor - high performance devices (including Si-Ge HBTs)

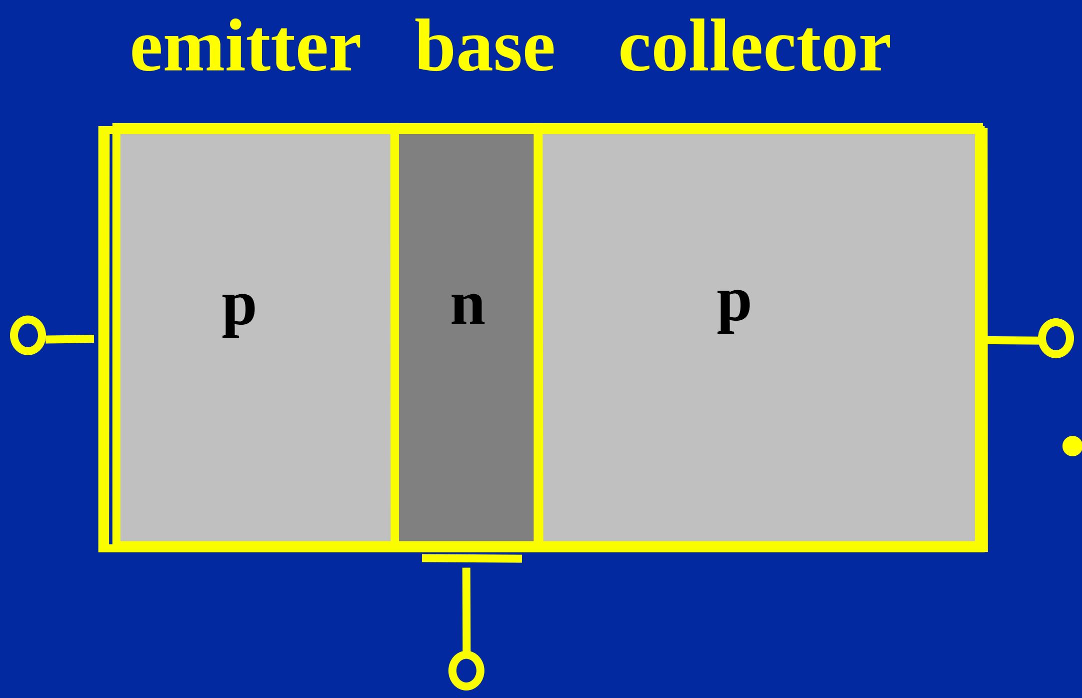
Bipolar Advantages

- Vertical Current flow - high speed for large areas
- High current drive capability because of the large area
- High transconductance (exponential dependence of current on voltage)
- High breakdown voltage possible
- Fixed threshold voltage
- Low 1/f noise

Outline

- BJT Basics
  - – Principle of operation
  - – Operation regimes
  - – Circuit configurations
  - – *I*–*V* characteristics

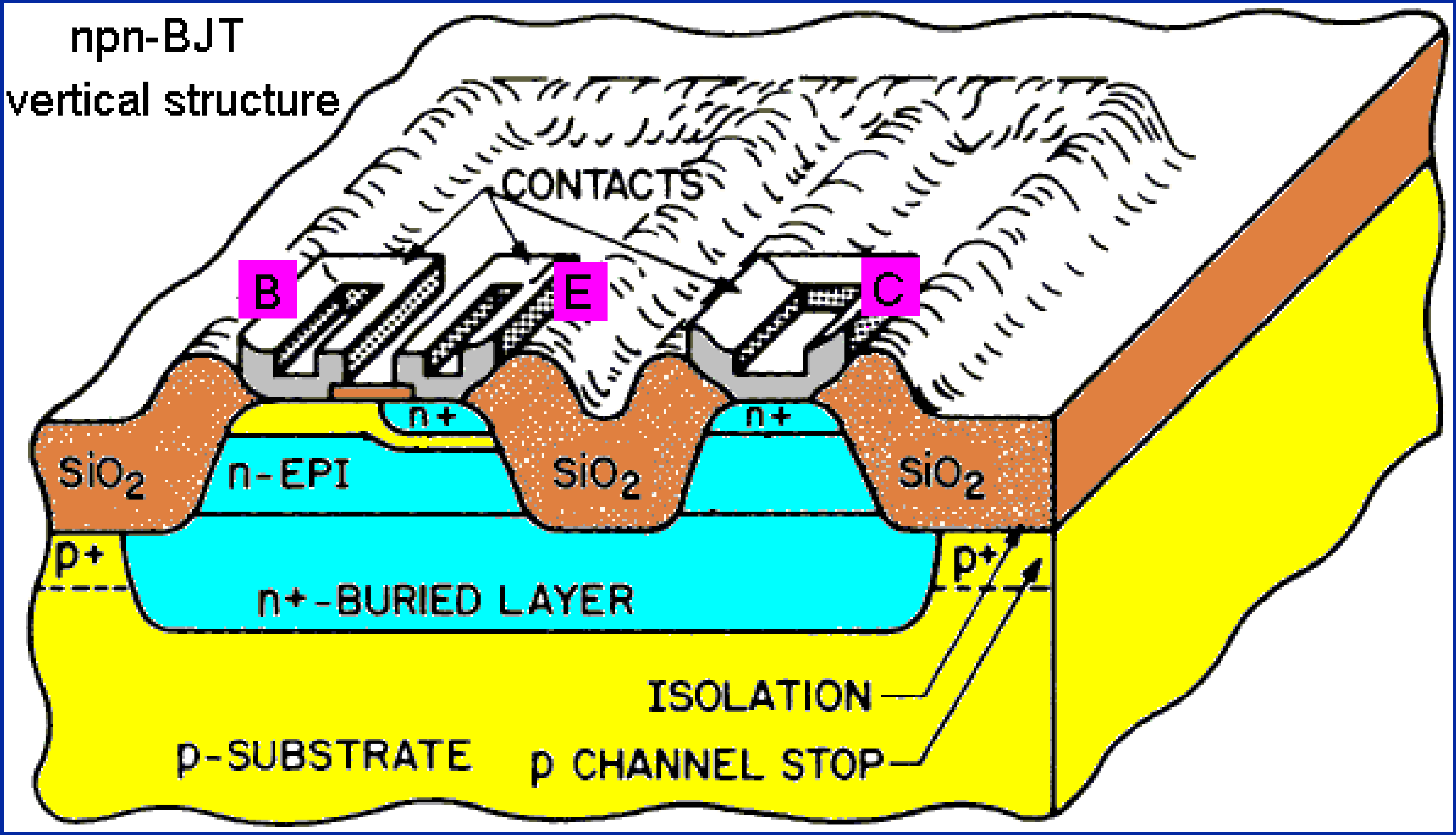
BJT Basics



p-n-p

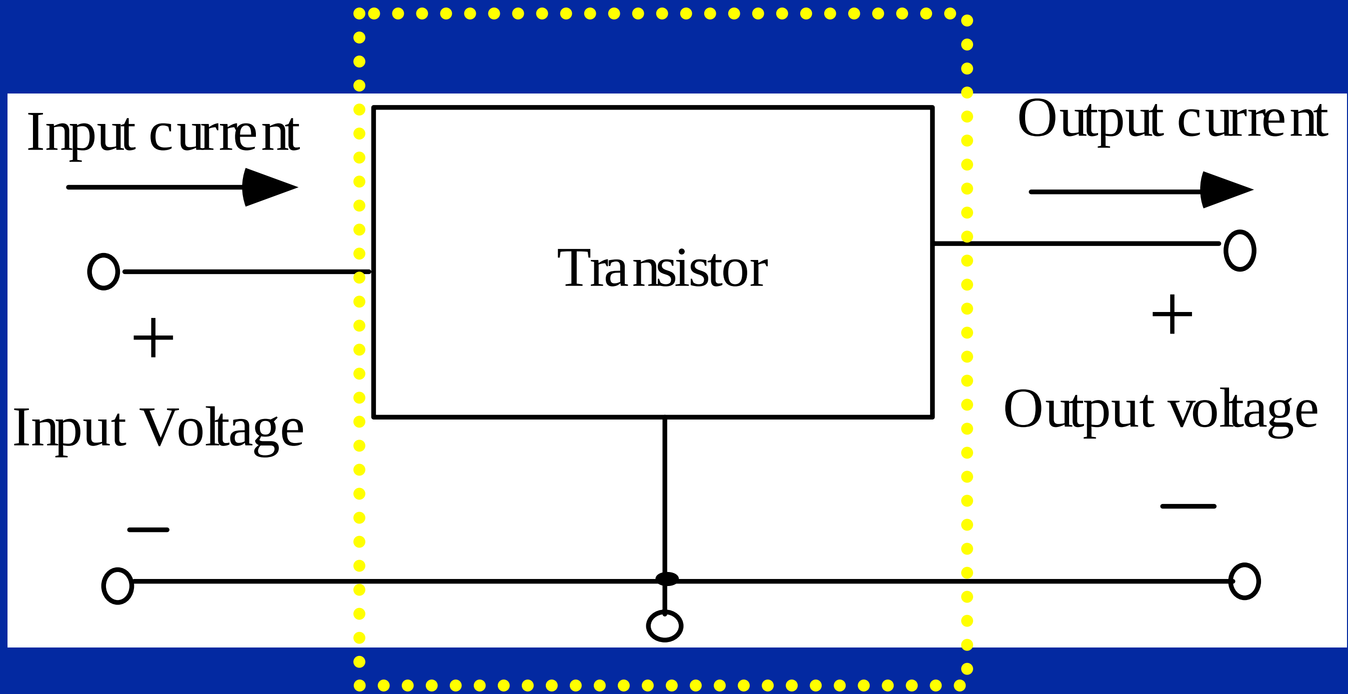
- Two back-to-back *p-n* junctions sharing a common base region

BJT structure

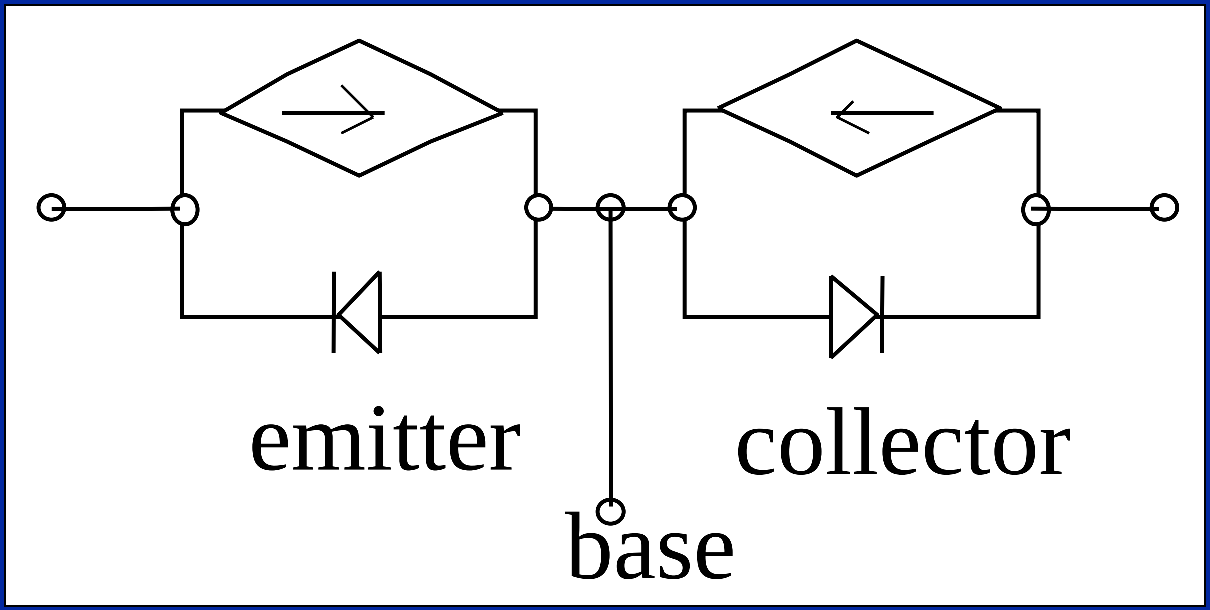


From http://www.hl.pc.uec.ac.jp/~hays/electronics/lecture/chapter5.htm

Input and Output Loops

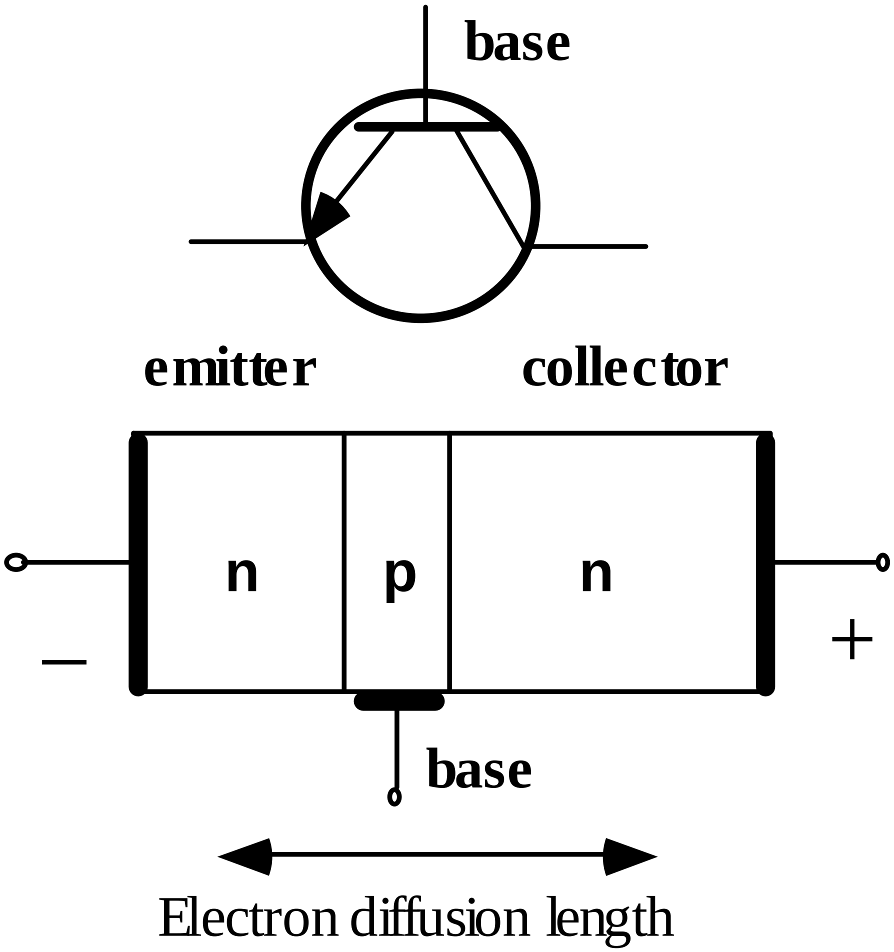


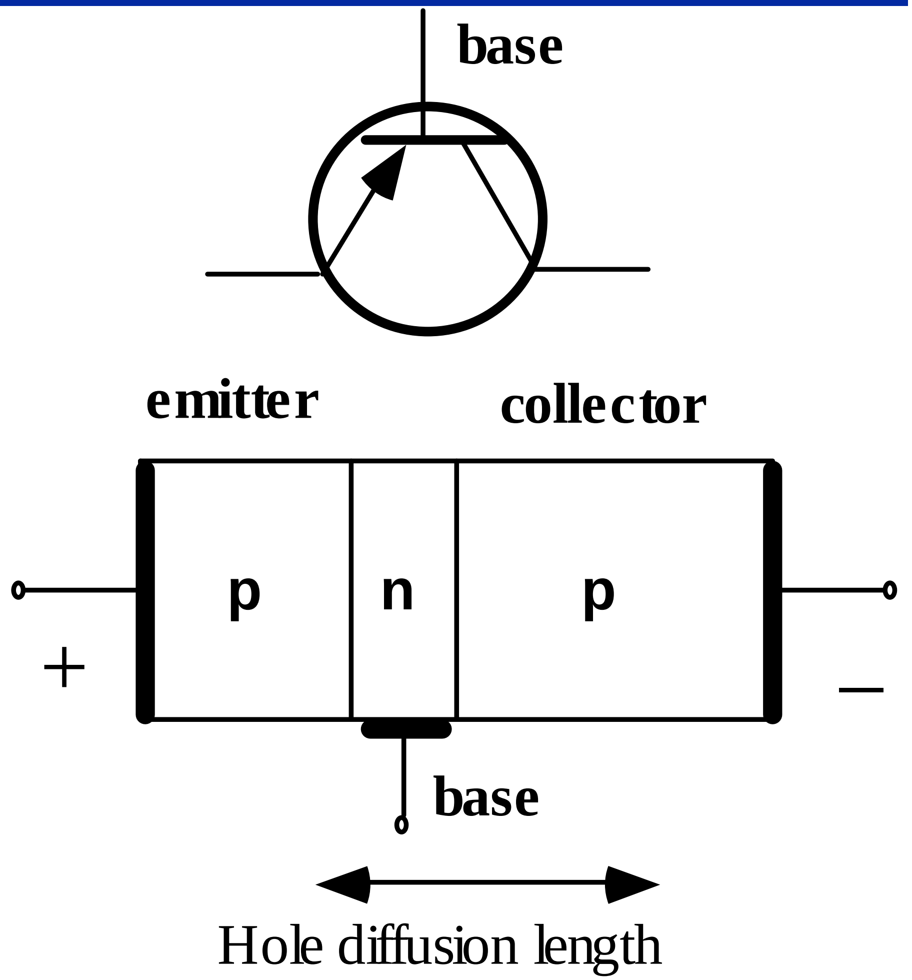
Equivalent circuit



Equivalent circuit of ideal n-p-n BJT

Transistor design and diffusion length





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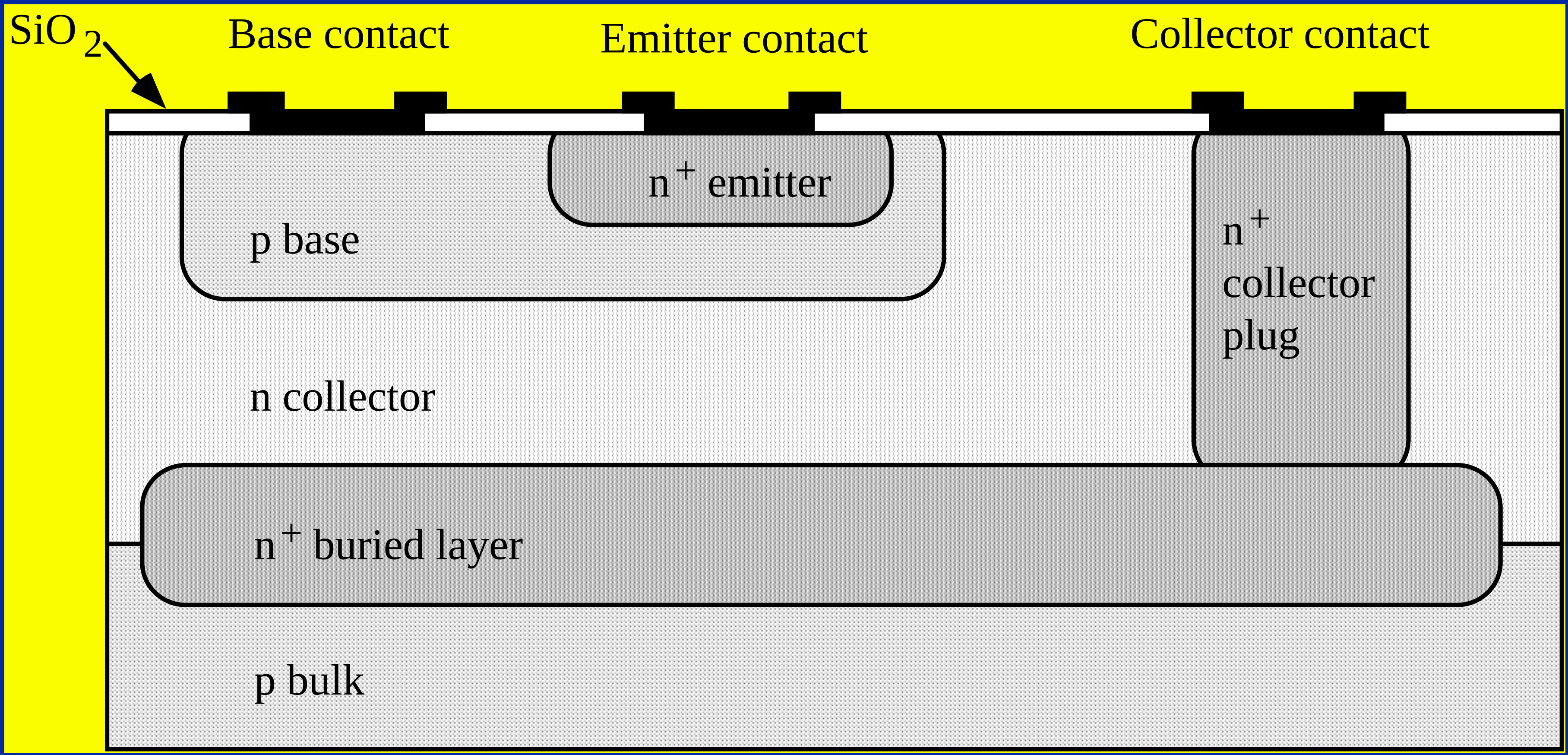
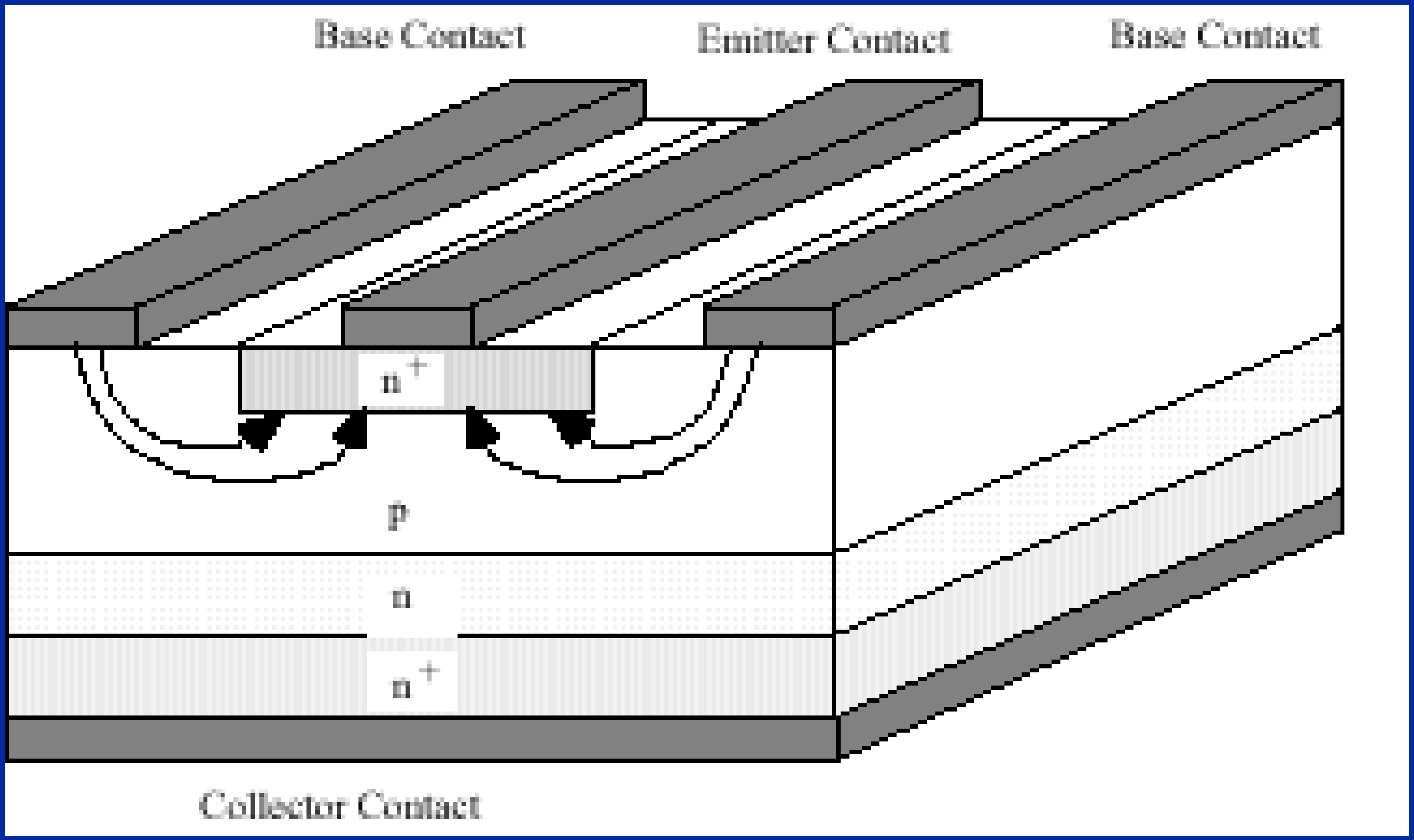
Schematic BJT Layout for IC



From T. A. Fjeldly, T. Ytterdal, M. S. Shur, *Introduction to Device Modeling and Circuit Simulation*, Wiley, New York , 1998

Schematic diagram of a BJT and Base Spreading Resistance



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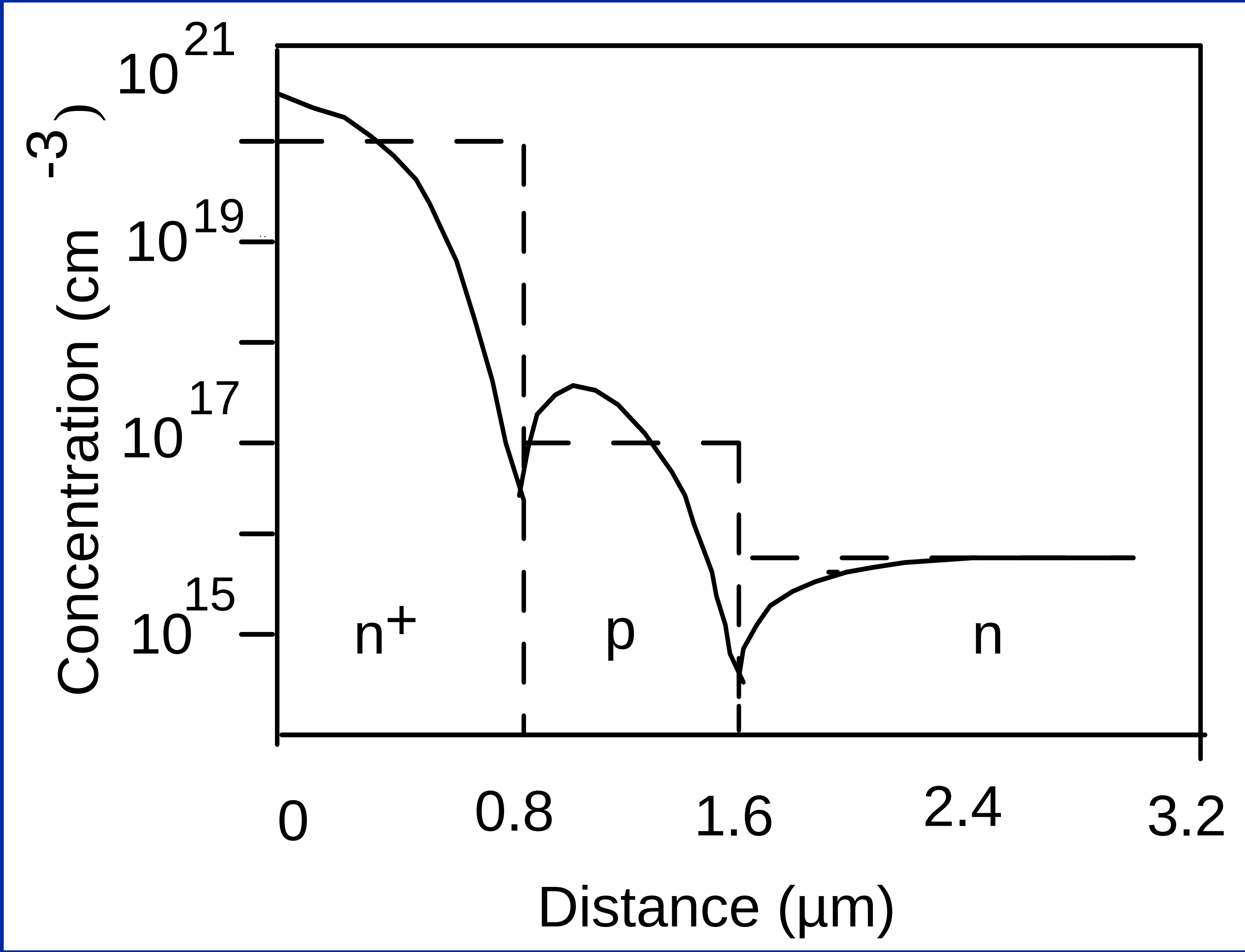
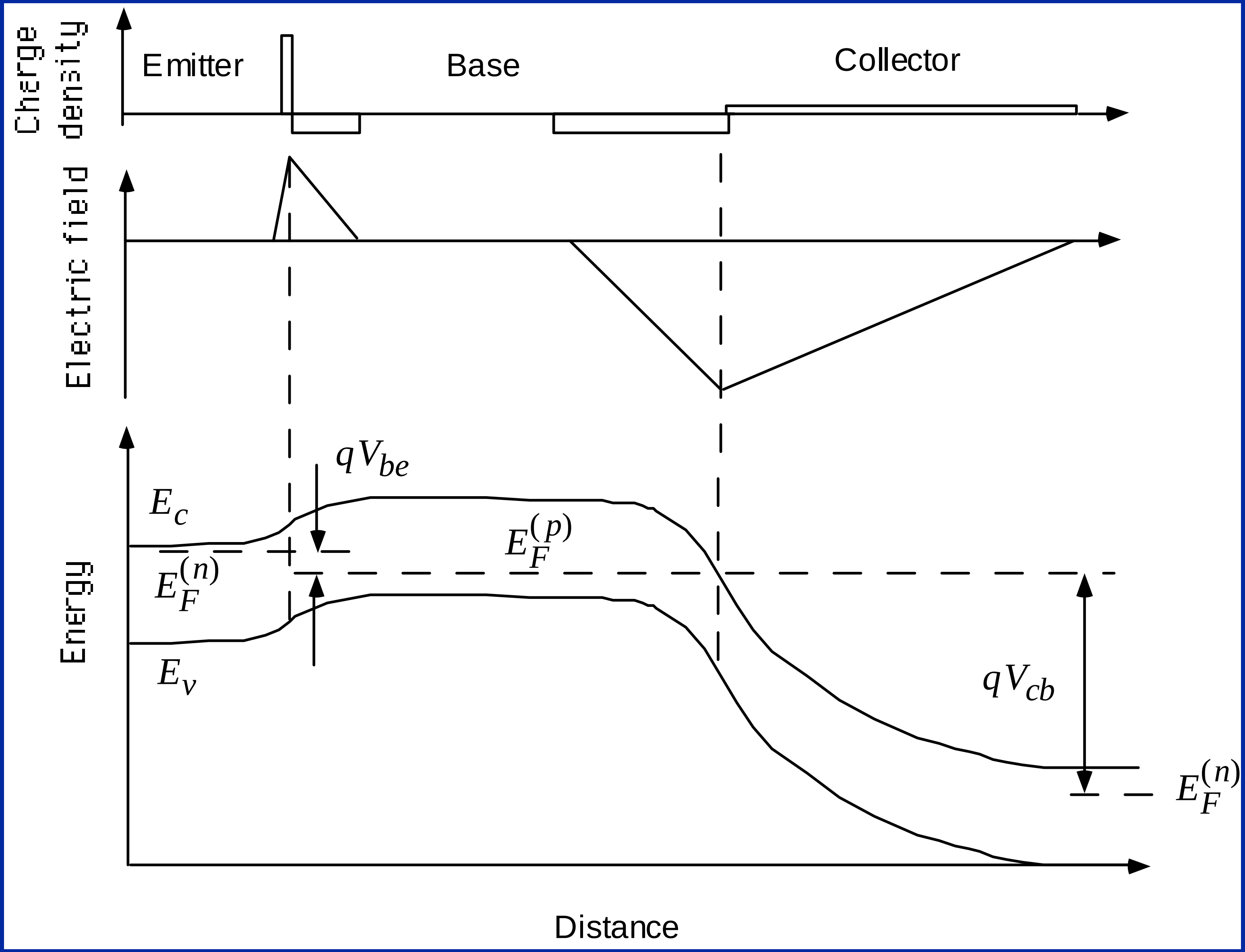
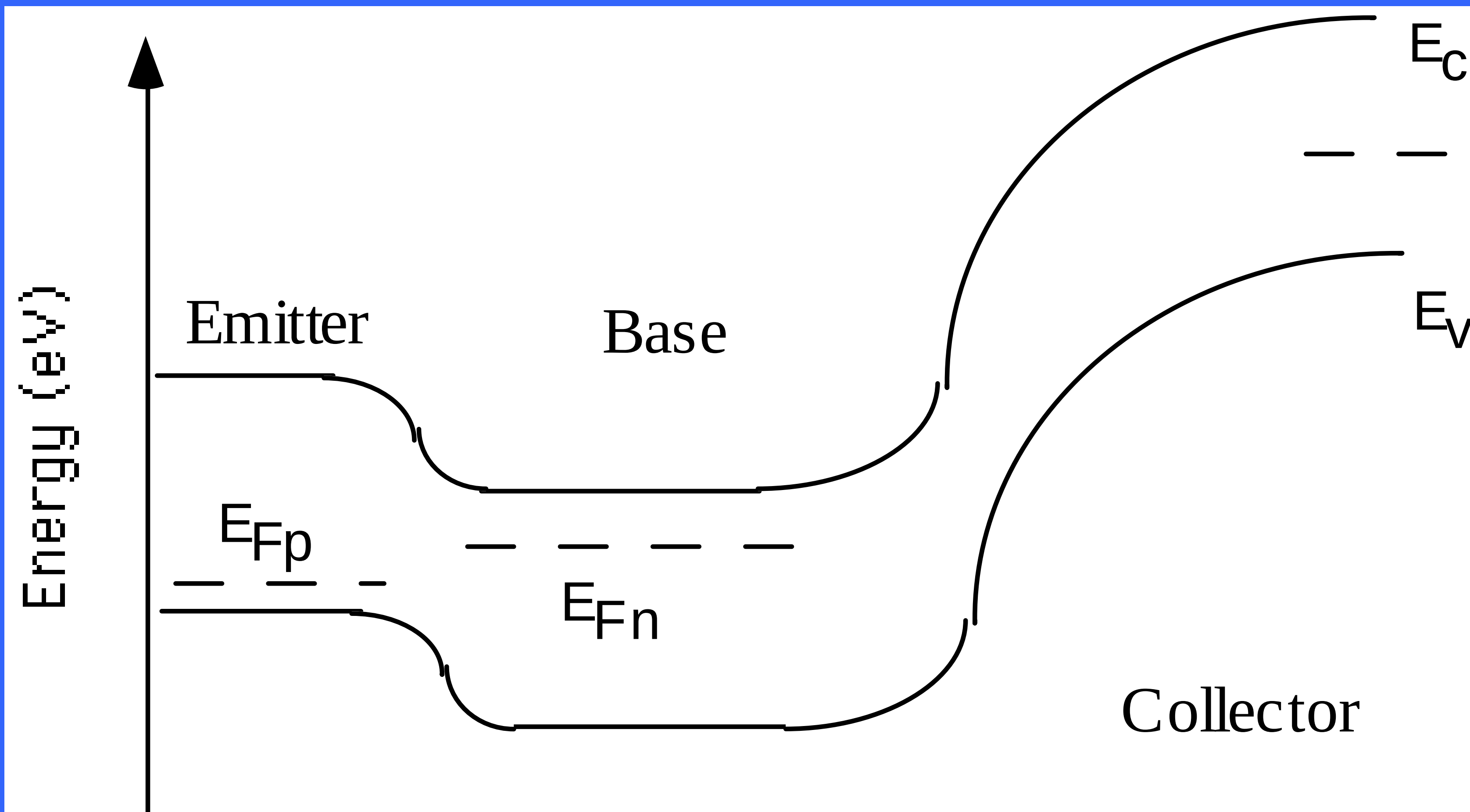
Typical Doping Profile



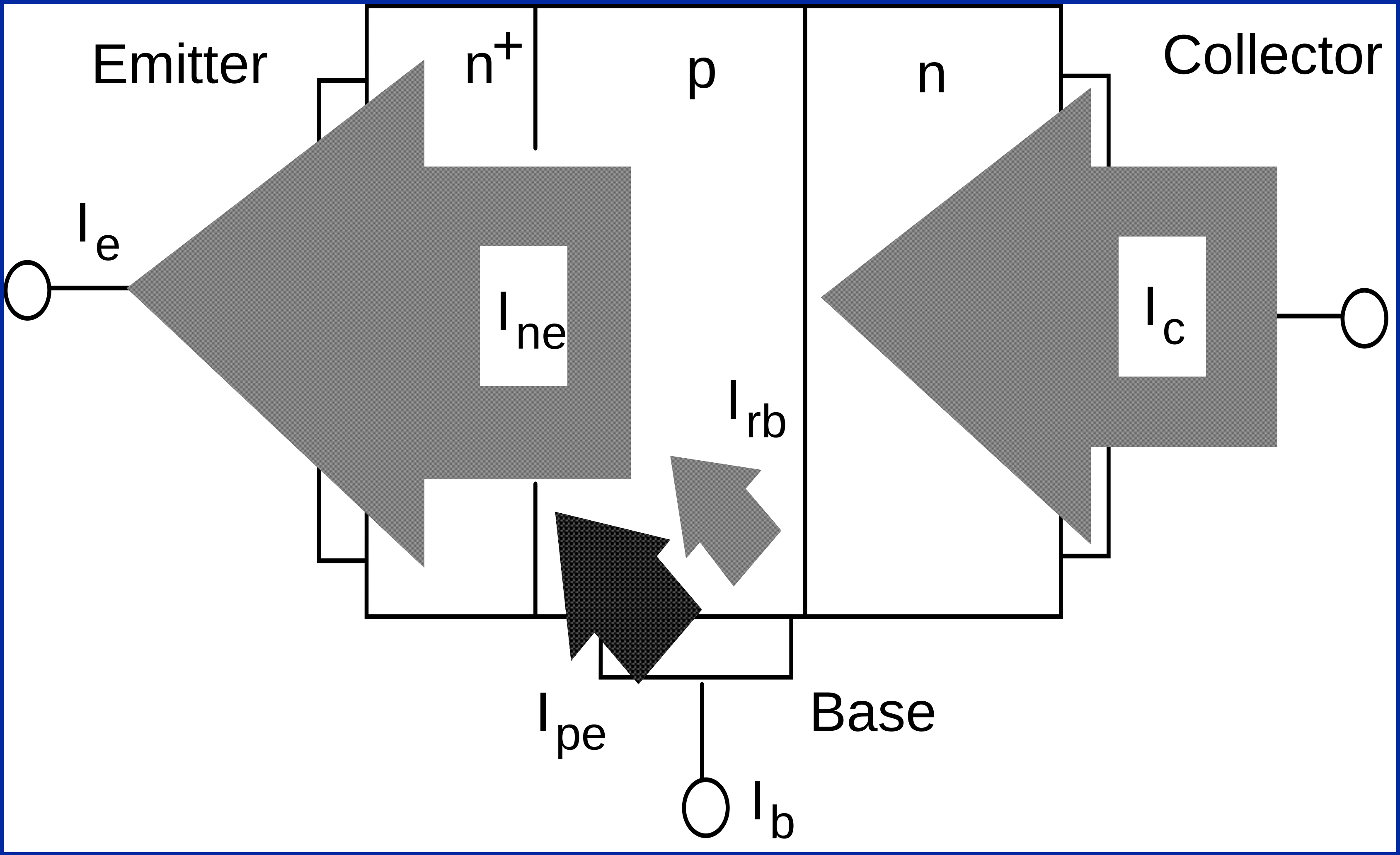
Band diagram and field profile



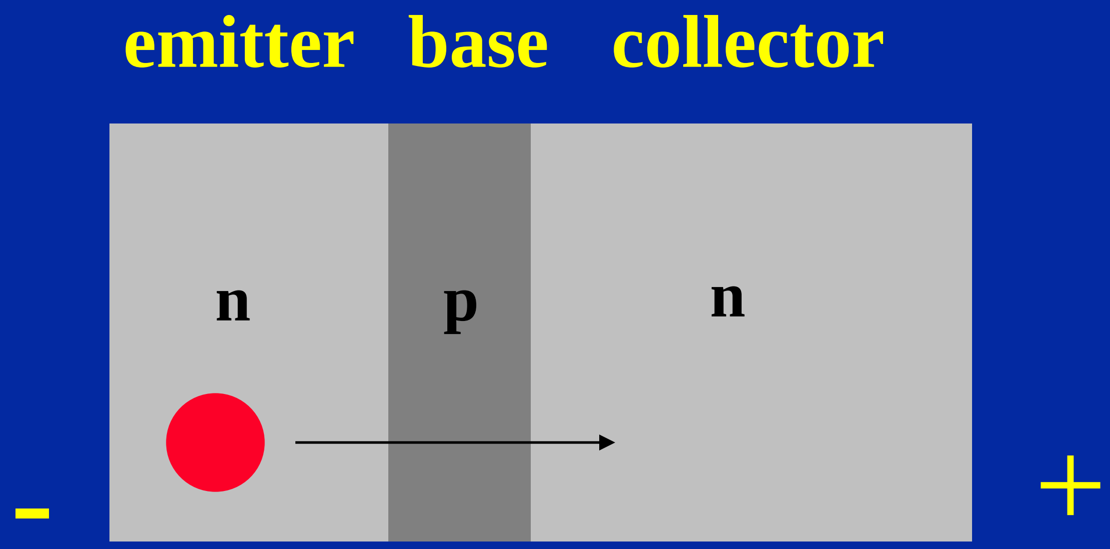
Band diagram of p-n-p transistor



Principle of Operation



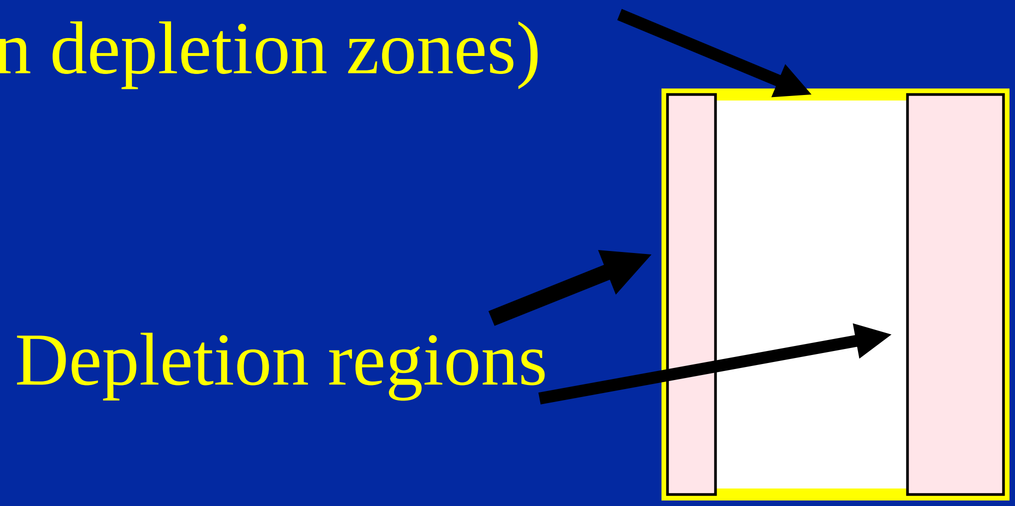
Minority carrier injection



- Carriers are injected into the base from the emitter by forward biasing the E-B junction (normal operation)

Minority carrier injection into the base

- The base is much shorter than the carrier diffusion length ⇒ the carriers traverse the base to reach the collector
- The base remains neutral (except for the junction depletion zones)



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Minority Carrier Injection Equations

Electron concentration in the base at the boundary of the forward biased emitter-base depletion region is given by

$$n_{be} = n_{bo} \exp\left(V_{be} / V_{th}\right) >> n_{bo}$$

where $n_{bo} = n_{ib}^2/N_{ab}$, n_{ib} is the intrinsic carrier concentration in the base region, N_{ab} is the acceptor doping density in the base region, $V_{th} = k_B T/q$ is the thermal voltage, and V_{be} is the emitter-base voltage ($V_{be} >> V_{th}$). Hence, inority carriers are supplied (we say "**injected** ") into the base region from the emitter region.

Holes are injected into the emitter region, just like electrons are injected into the base. The minority carrier (hole) concentration in the emitter at the boundary of the emitter-base depletion region is given by

$$p_{eb} = p_{eo} \exp\left(V_{be} / V_{th}\right) >> p_{eo}$$

where $p_{eo} = n_{ie}^2/N_{de}$, $n_{ie} = n_{ib}$ is the intrinsic carrier concentration , N_{de} is the donor doping density in the emitter region. However, since $N_{de} >> N_{ab}$ the number of holes injected into the emitter region is much smaller than the number of electrons injected into the base: $p_{eb} << n_{be}$.

Law of the Junction

$$n_{be} = n_{bo} \exp\left(V_{be} / V_{th}\right) >> n_{bo}$$

Injection

$$n_{be} = n_{bo} \exp\left(V_{be} / V_{th}\right) >> n_{bo}$$

$$p_{eb} = p_{eo} \exp\left(V_{be} / V_{th}\right) >> p_{eo}$$

However, since $N_{de} >> N_{ab}$ the number of holes injected into the emitter region is much smaller than the number of electrons injected into the base:

Regimes of operation

Emitter-base bias	Collector-base bias	Mode
Forward	Reverse	Forward active mode
Reverse	Forward	Reverse active mode
Forward	Forward	Saturation mode
Reverse	Reverse	Cutoff mode

Diffusion equation for minority carriers in the base

$$D_n \frac{d^2 n_b}{dx^2} - \frac{n_b - n_{bo}}{\tau_{nl}} = 0$$

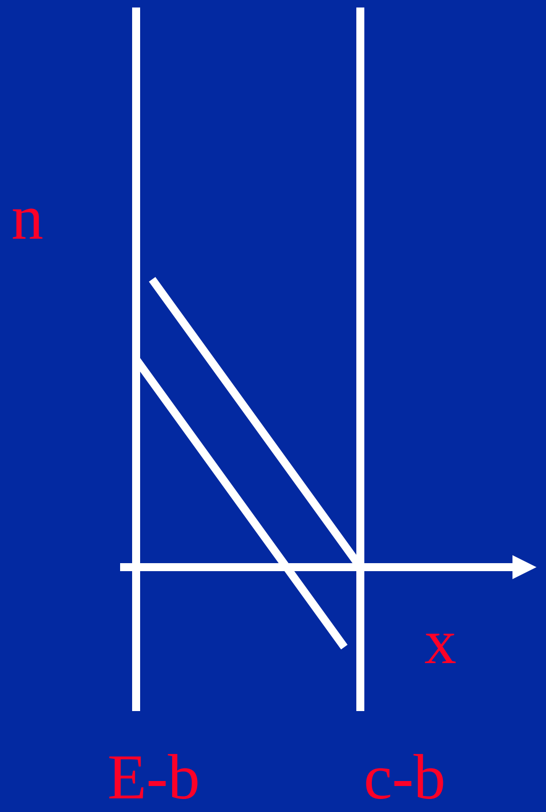
$$\Delta n = A \exp\left(\frac{x}{L_{nb}}\right) + B \exp\left(-\frac{x}{L_{nb}}\right)$$

For $W << L_{nb}$

$$\Delta n = A + B + (A - B)\frac{x}{L_{nb}}$$

Lecture 8

Boundary conditions



$$\Delta n(0) = n_{be} - n_{bo}$$

$$\Delta n(W) \approx -n_{bo}$$

$$A + B = n_{be} - n_{bo}$$

$$A + B + (A - B)\frac{W}{L_{nb}} = -n_{bo}$$

Hence

$$\Delta n = n_{be}\left(1 - \frac{x}{W}\right) - n_{bo}$$

Forward Active Mode Emitter and Base Currents

Excess minority carrier charge in the base:

$$n_{be} = n_{bo}\exp\left(V_{be}/V_{th}\right) >> n_{bo} \qquad n_{bc} = n_{bo}\exp\left(V_{bc}/V_{th}\right) << n_{bo}$$

$$\Rightarrow n_b \approx n_{be}\left(1 - x/W\right) \qquad \Delta Q_b \approx qS\int_0^W \left[n_b(x) - n_{bo}\right]dx \approx \frac{qSWn_{bo}}{2}\exp\left(\frac{V_{be}}{V_{th}}\right)$$

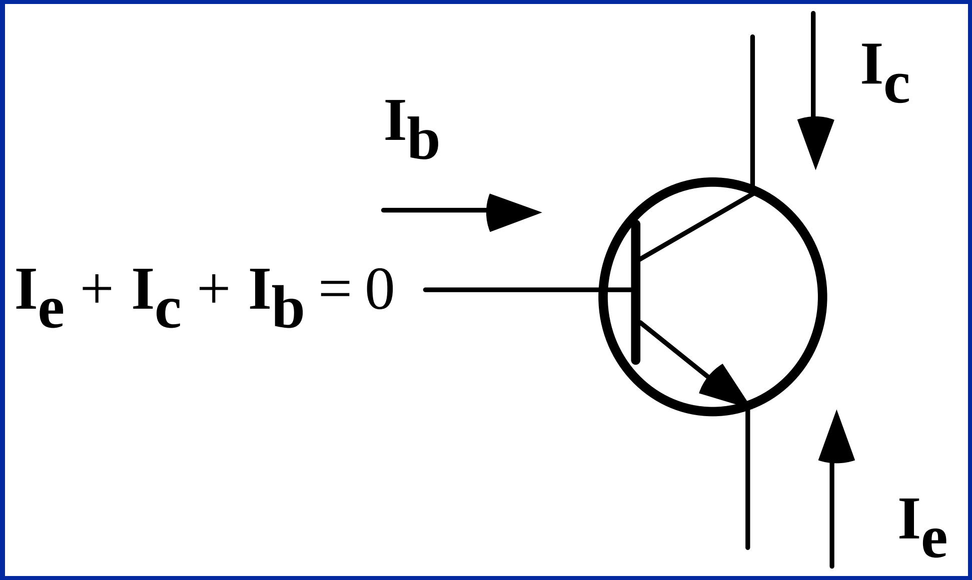
Emitter current ($I_e >> I_b$):

$$I_e \approx I_c \approx SqD_n \left.\frac{\partial n_b}{\partial x}\right|_{x=0} \approx \frac{SqD_n n_{bo}}{W}\exp\left(\frac{V_{be}}{V_{th}}\right)$$

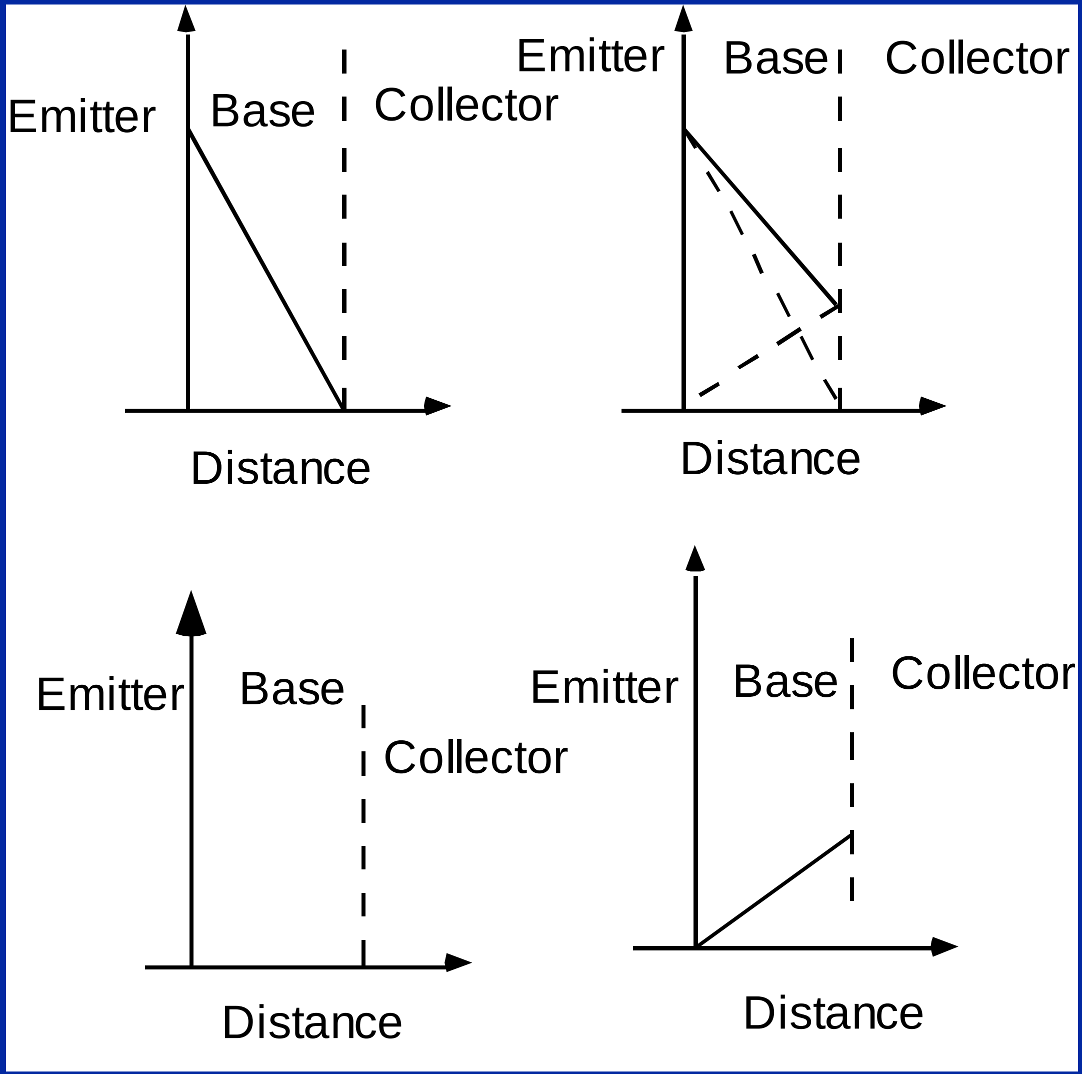
Base current (from injection into emitter – short *n*+ emitter):

$$I_b \approx SqD_p \left.\frac{\partial p_e}{\partial x}\right|_{x=0} \approx \frac{SqD_p p_{eo}}{X_e}\exp\left(\frac{V_{be}}{V_{th}}\right)$$

Generalized KCL law for BJT

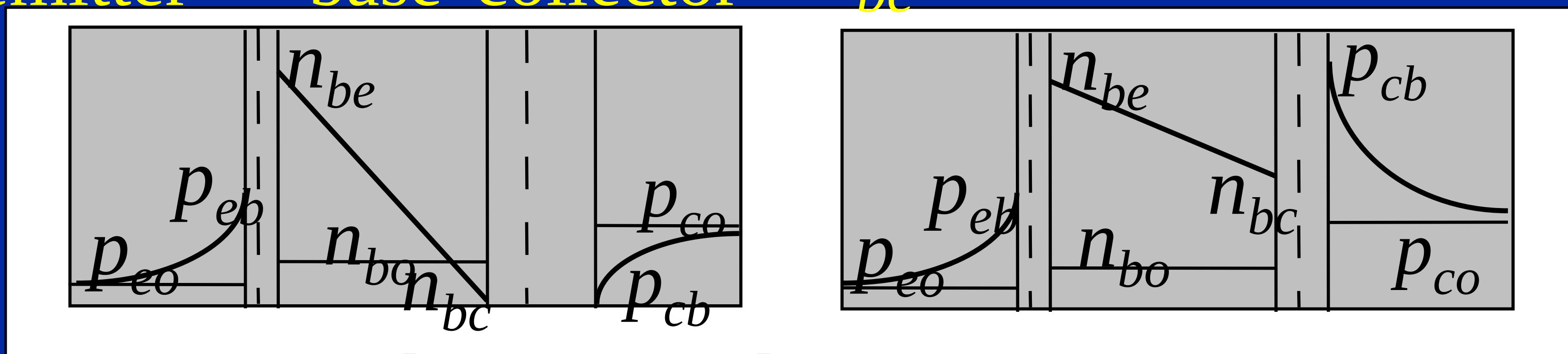


Hole distributions in the base of *p-n-p* BJT for active forward mode, saturation, cutoff, and reverse active mode



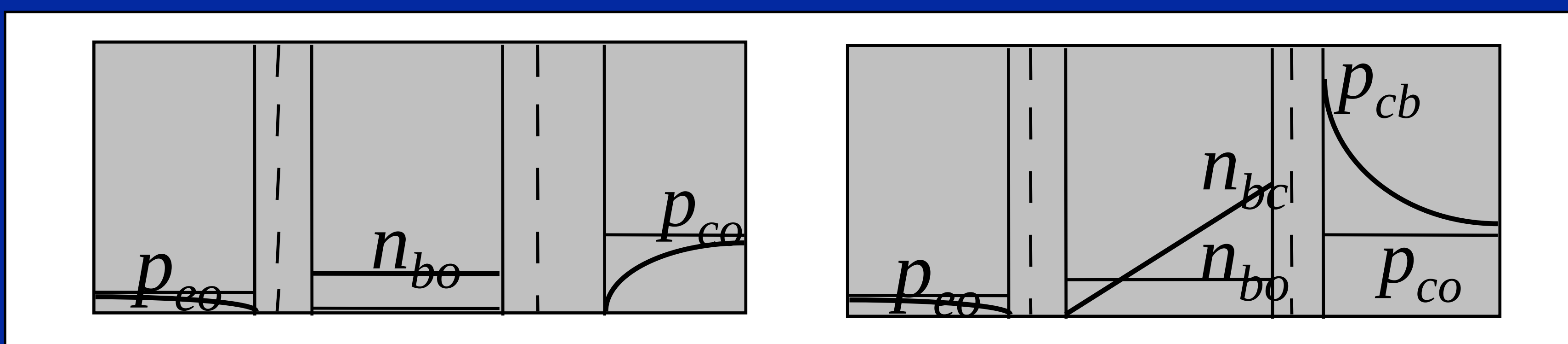
More details

emitter base collector V_{be}(+)



Forward active mode

Saturation mode V_{bc}(+)



Cutoff mode

Inverse active mode

Emitter and collector currents

$$I_e \approx I_c \approx |I_n| \approx |I_{ne}| = \frac{SqD_n n_{bo}}{W} \exp\left(\frac{V_{be}}{V_{th}}\right)$$

Example

Relate the emitter current to the total concentration of acceptors, n_G, in the base (called the **Gummel number**).

Solution

Substituting

$$n_{bo} = \frac{n_i^2}{N_{ab}}$$

into

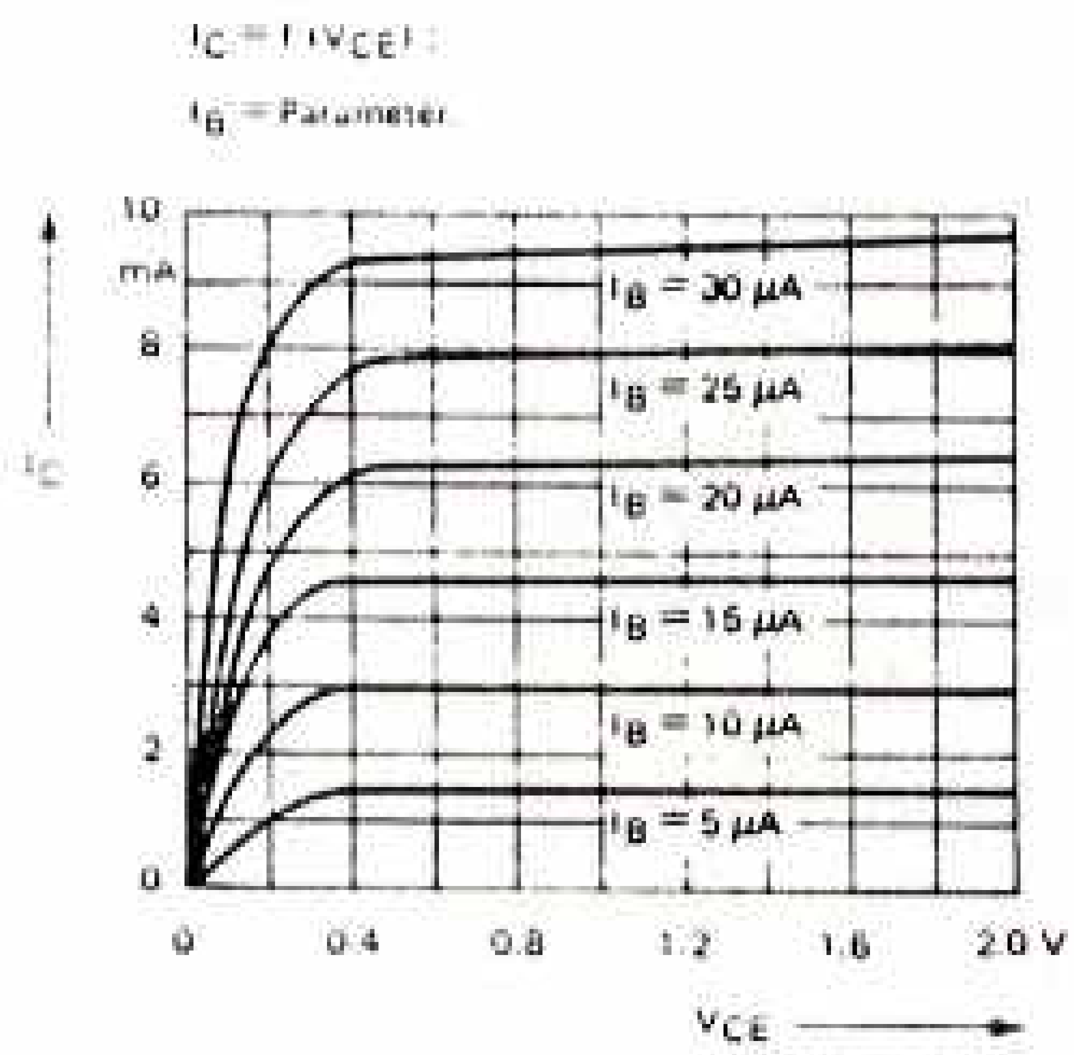
$$I_e \approx I_c \approx |I_n| \approx |I_{ne}| = \frac{SqD_n n_{bo}}{W} \exp\left(\frac{V_{be}}{V_{th}}\right)$$

we obtain

$$I_e \approx \frac{SqD_n n_i^2}{n_G} \exp\left(\frac{V_{be}}{V_{th}}\right)$$

since $n_G = N_{ab}W$.

I-V Characteristics (transistor NPN BCW82)



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First SiC BJT Inverter

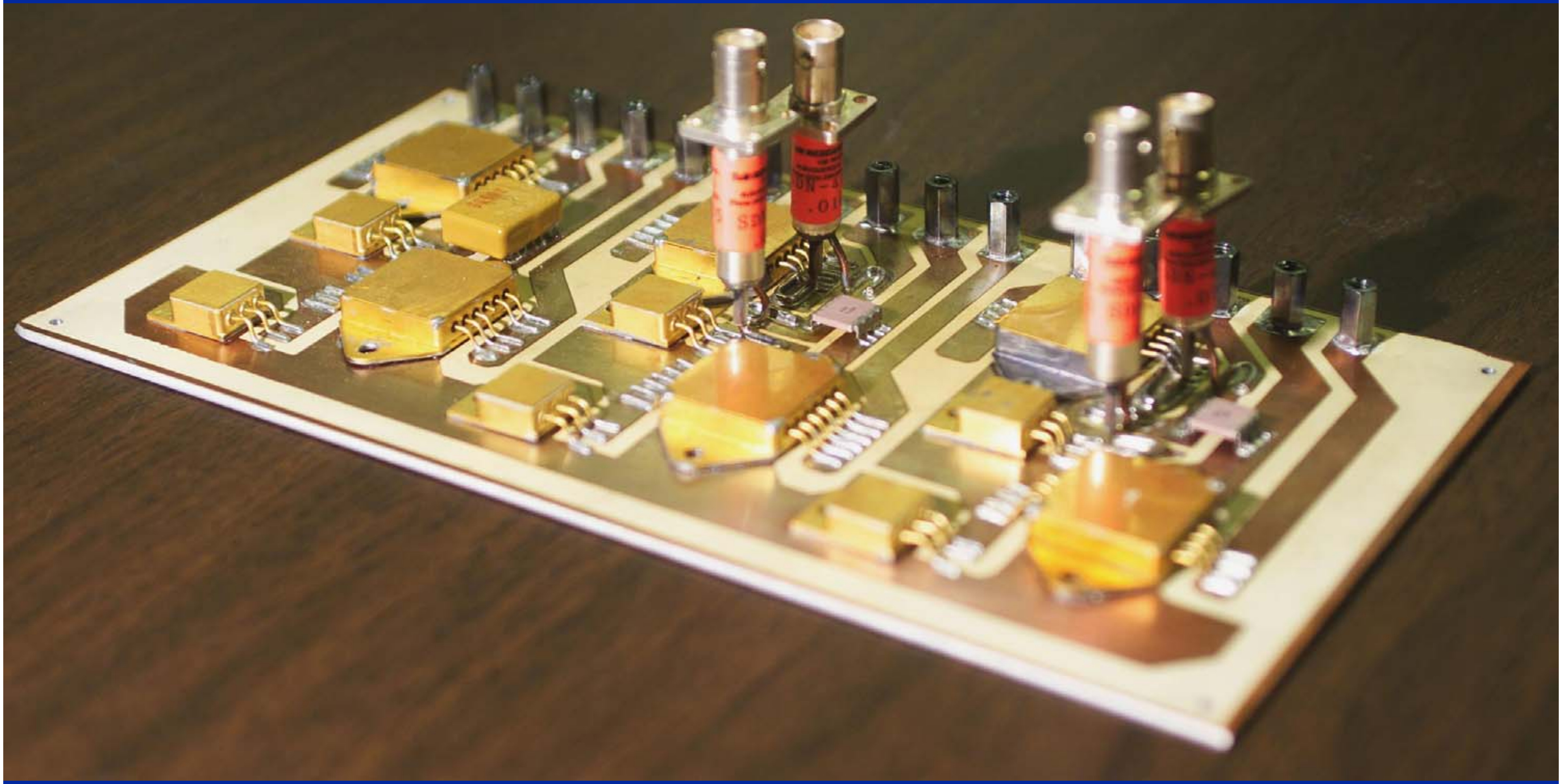
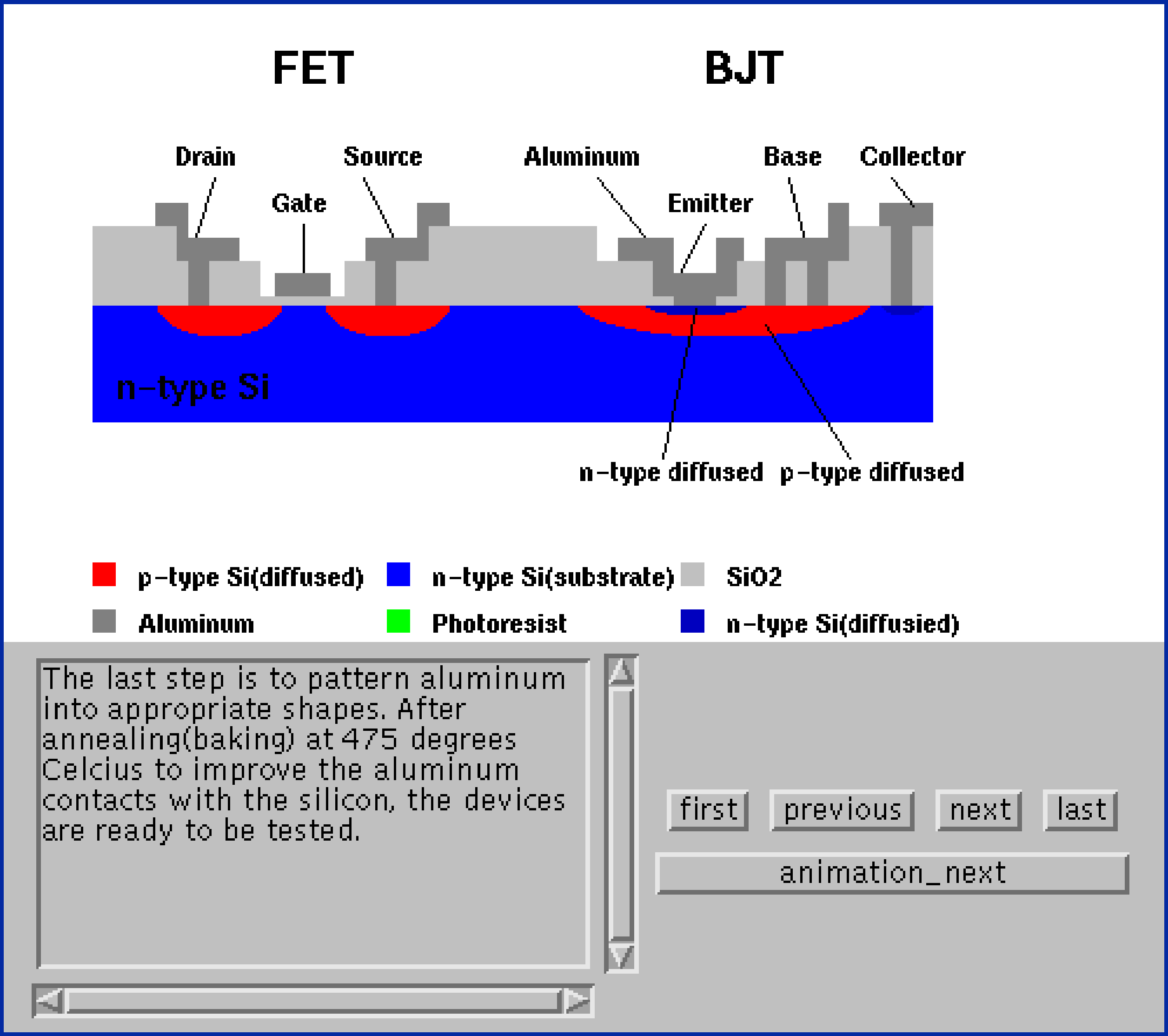


Photo courtesy of Rick Griffiths

MOSFET/BJT Fabrication



From: http://jas.eng.buffalo.edu/education/fab/BjtFet/index.html