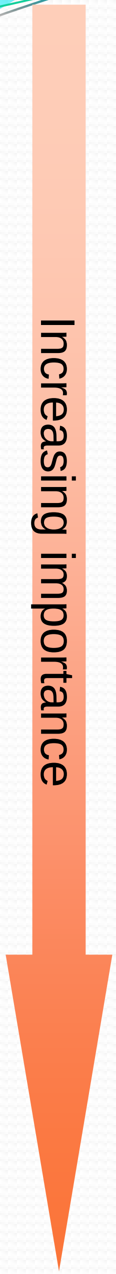
Transistors: FET & BJT Basic Concepts

Summary of Key Points

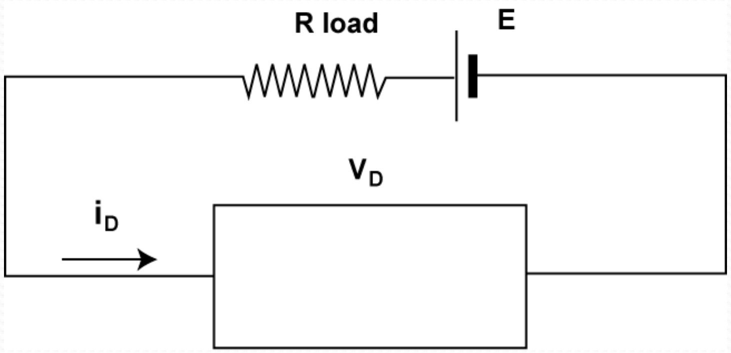


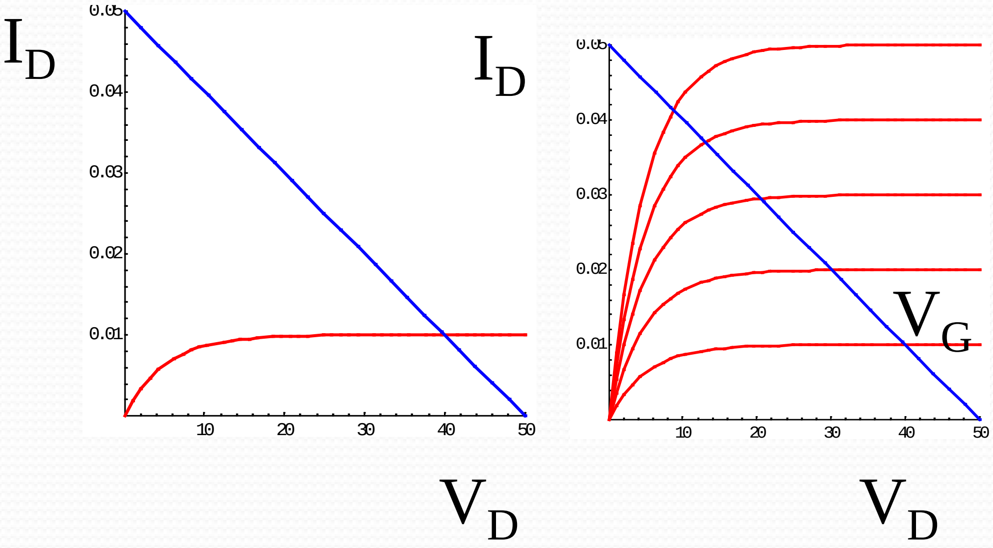
- The basic device physical structures (S-G-D for FET and E-B-C for BJT)
- The basic steps in fabrication these transistors:
  - elements of lithography: photoresist, mask, projection, baking, developing…
  - altering the semiconductors by doping (ion implantation, diffusion…)
  - oxidation, deposition of insulator layer for FET channel
  - metalization (metal deposition), Ohmic contact
- The basic concepts of the device operation of these transistors
  - for FET: how gate voltage can control the current between the source and drain (Gate bias voltage threshold, channel conductivity above and below threshold, pinch-off, source-drain current and current saturation)
  - for BJT: how base current can control the emitter majority carrier current, and the transport (base transport factor) to collector
- The physical principles in the operation of these transistors:
  - for FET: carrier behavior in the channel as a function of gate voltage: weak-field screening, depletion, inversion; mobile charge, non-mobile charge; related C-V characteristics, role of oxide (or insulator) capacitance;
  - for BJT: effects of base current (both majority and minority carriers).
  - for both: carrier mobility, temperature effects, doping effects
- Fundamental engineering principles of these transistors:
  - for FET: doping type, level, profile, oxide or insulator capacitance (dielectric constant, thickness) and efficiency in gate voltage
  - for BJT: doping type, level, profile; base length, carrier mobilities in base, diffusion lengths; minority carrier behaviors in emitter, emitter length, and emitter efficiency

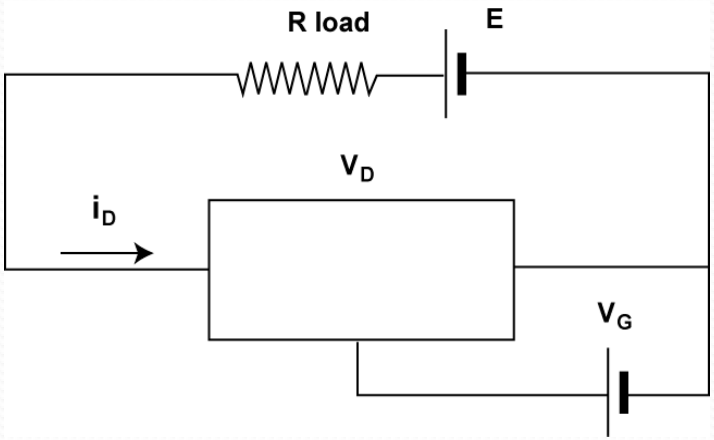
Bipolar Junction Transistor

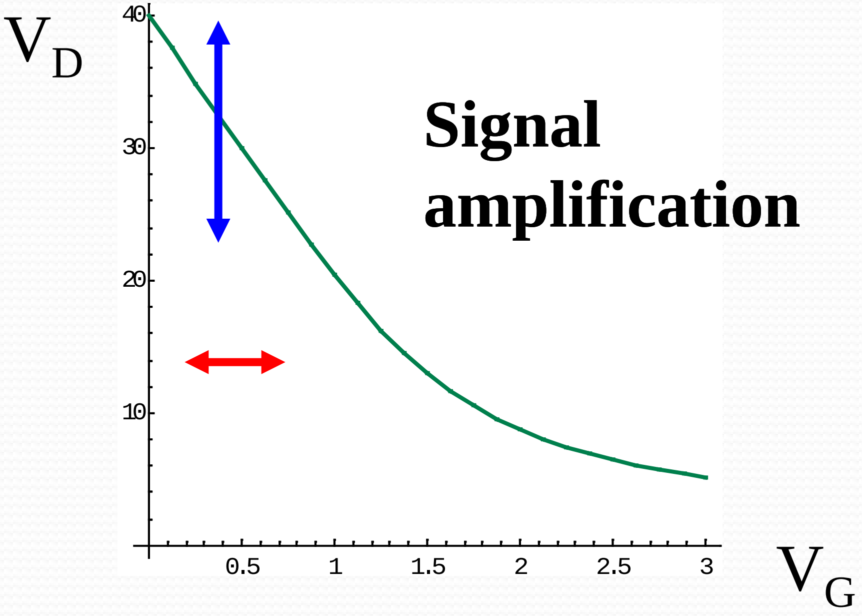
An overview

Transistor: a 3-terminal device



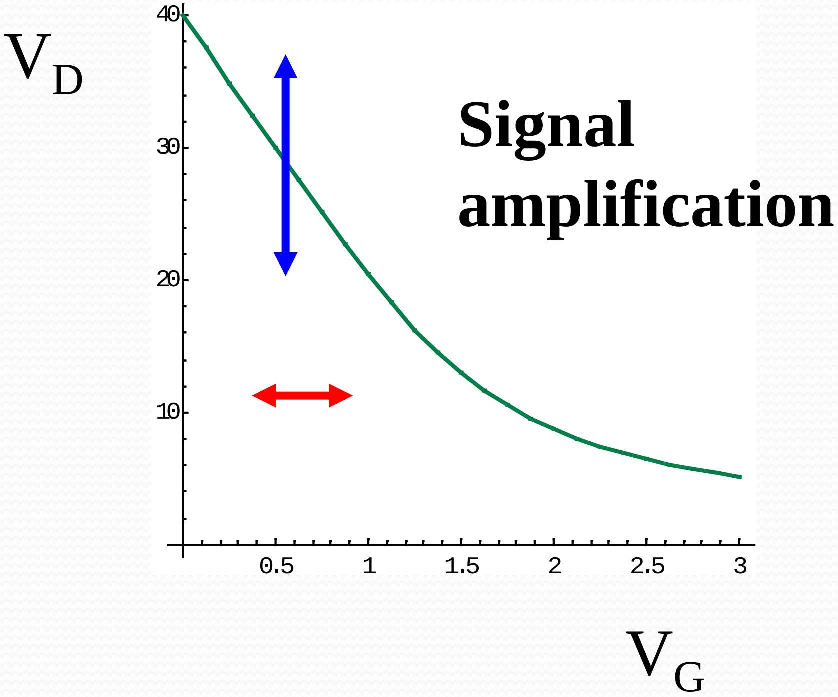




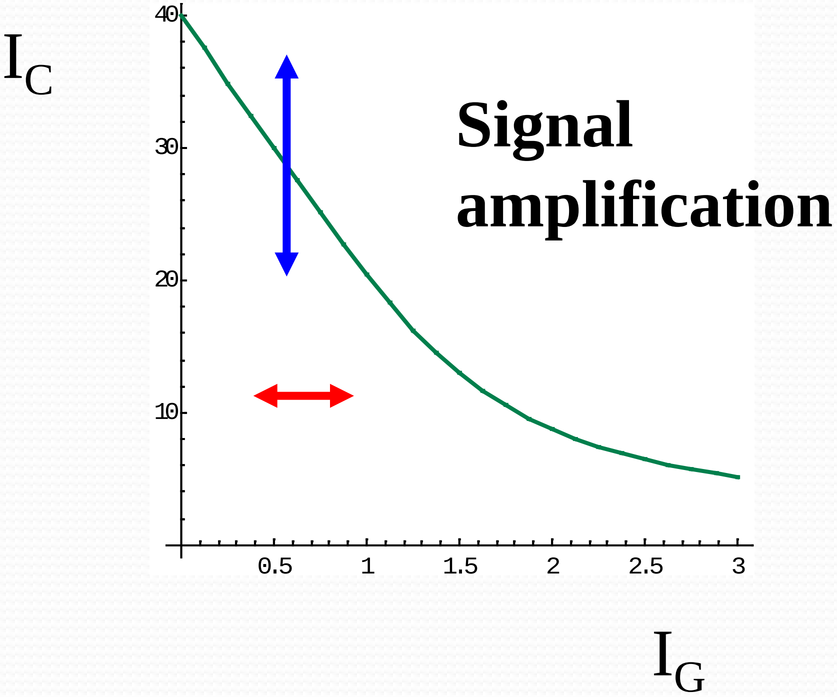


Signal amplification

Signal control in voltage mode or current mode



Signal amplification



Signal amplification

Voltage control

Electric field is the “lever”

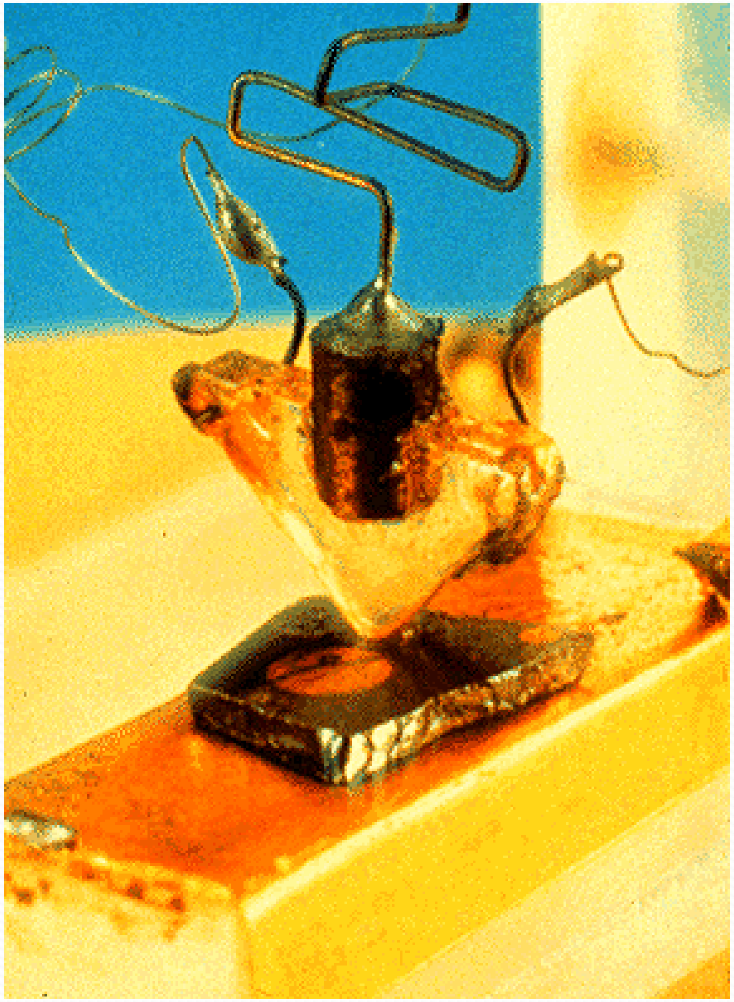
→ Field-effect transistor

Current control

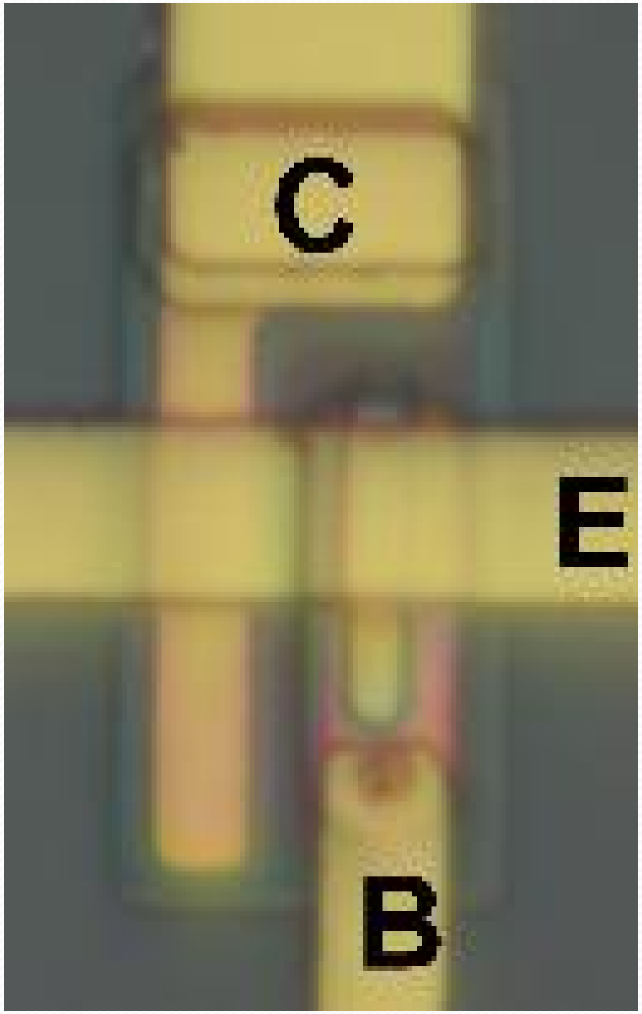
Injected (gate) current is the “lever”

→ Bipolar junction transistor

Bipolar Junction Transistor Summary



From the first transistor…



To today state-of-the-art …

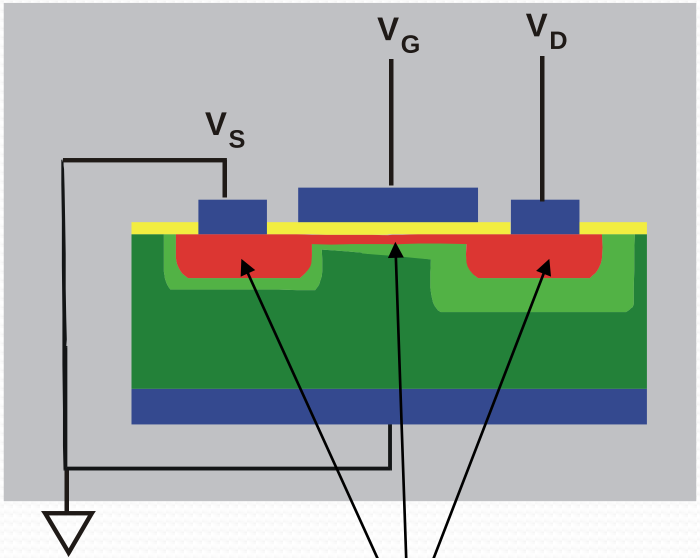
Bipolar device: a device that involves carriers of both polarities

- *opposite:* unipolar

Find an example of unipolar transistors

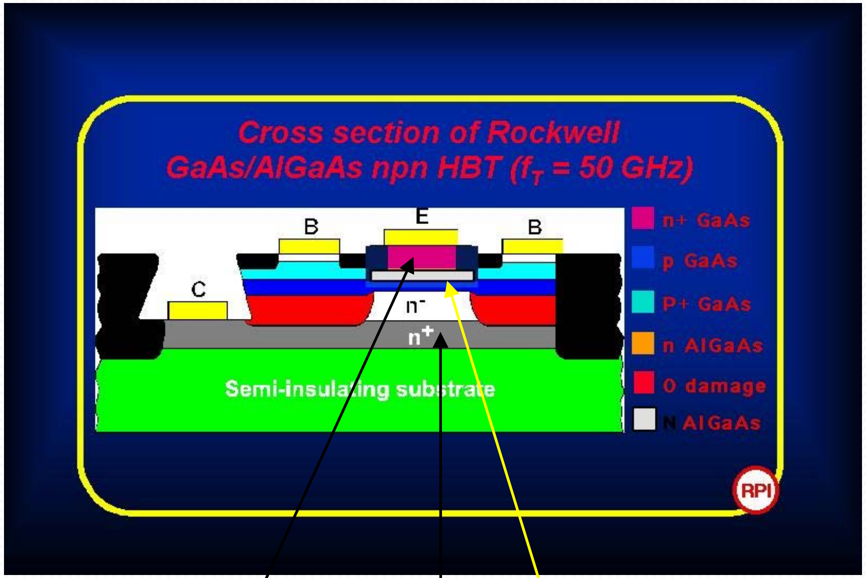
The key difference between FET and BJT

FET



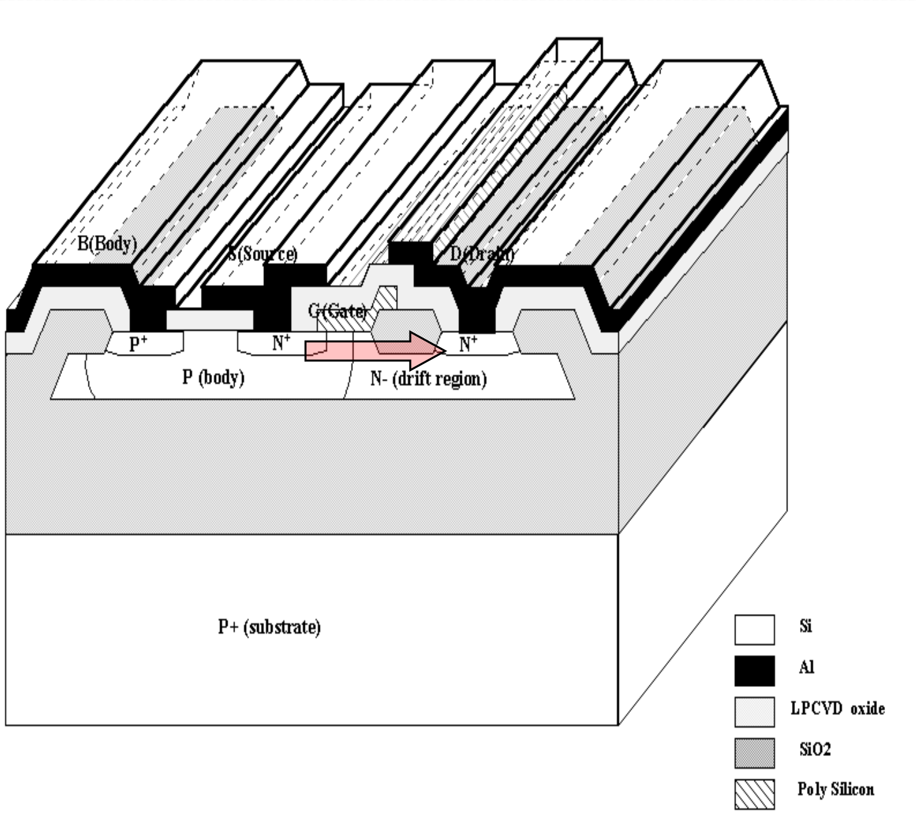
Same type of carriers in source, drain, channel

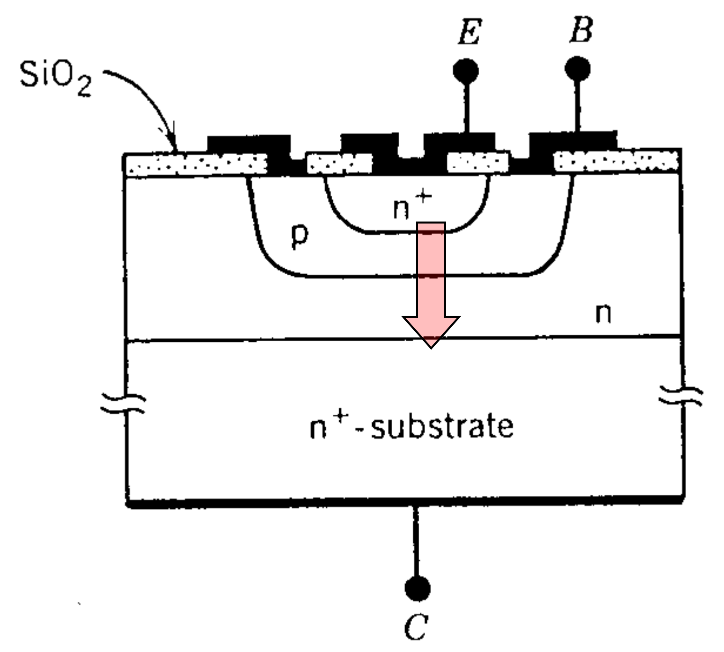
BJT



Same type of carriers for emitter and collector, opposite type for base

FET vs BJT
lateral vs planar (usually)

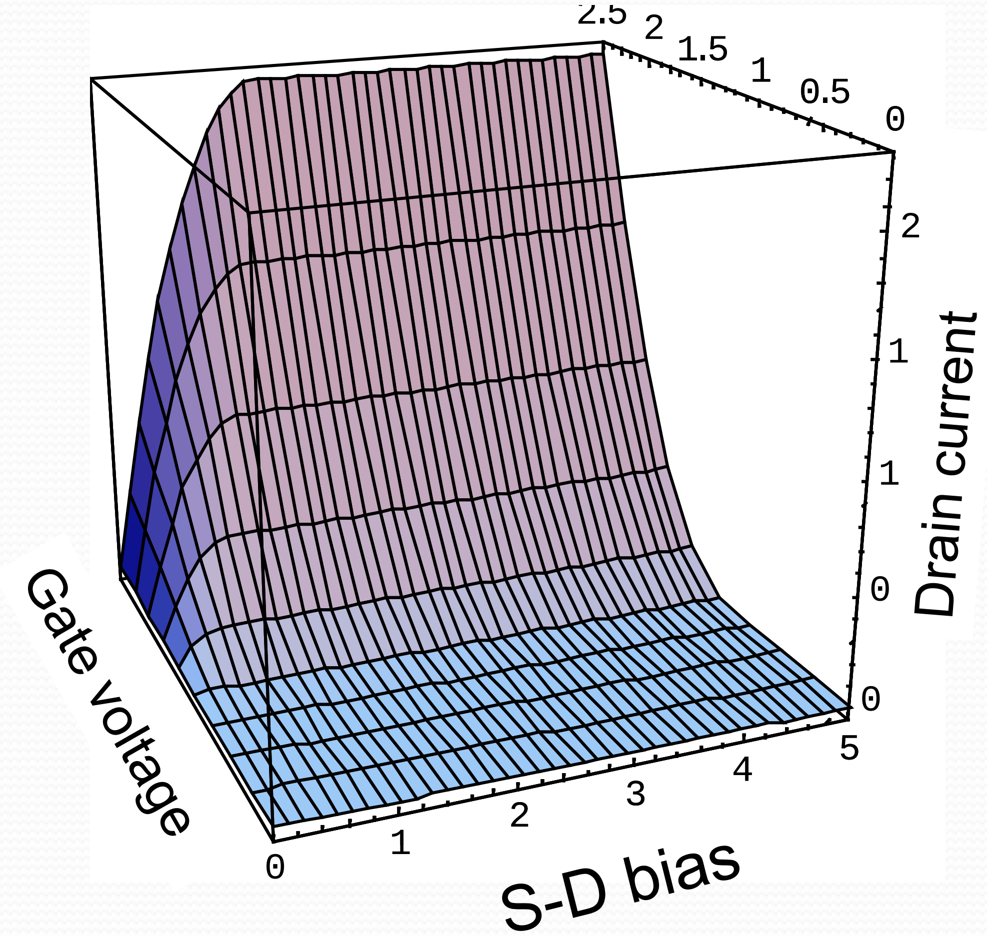


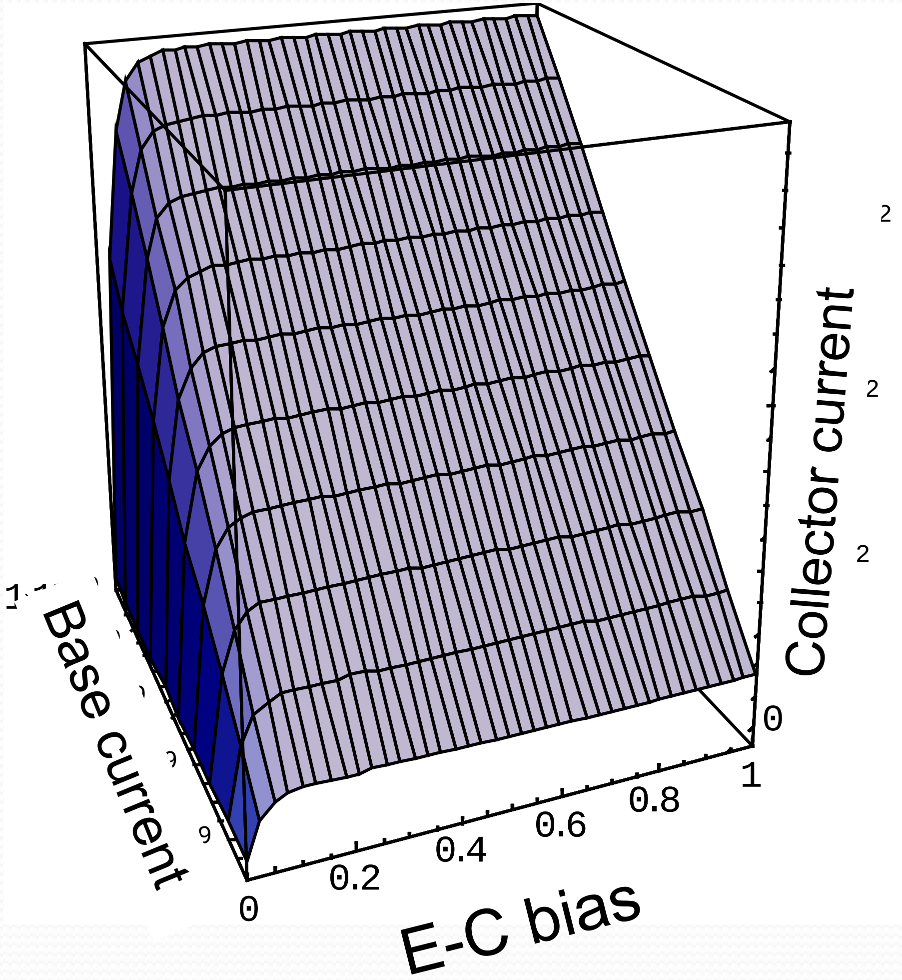


FET vs. BJT: main features

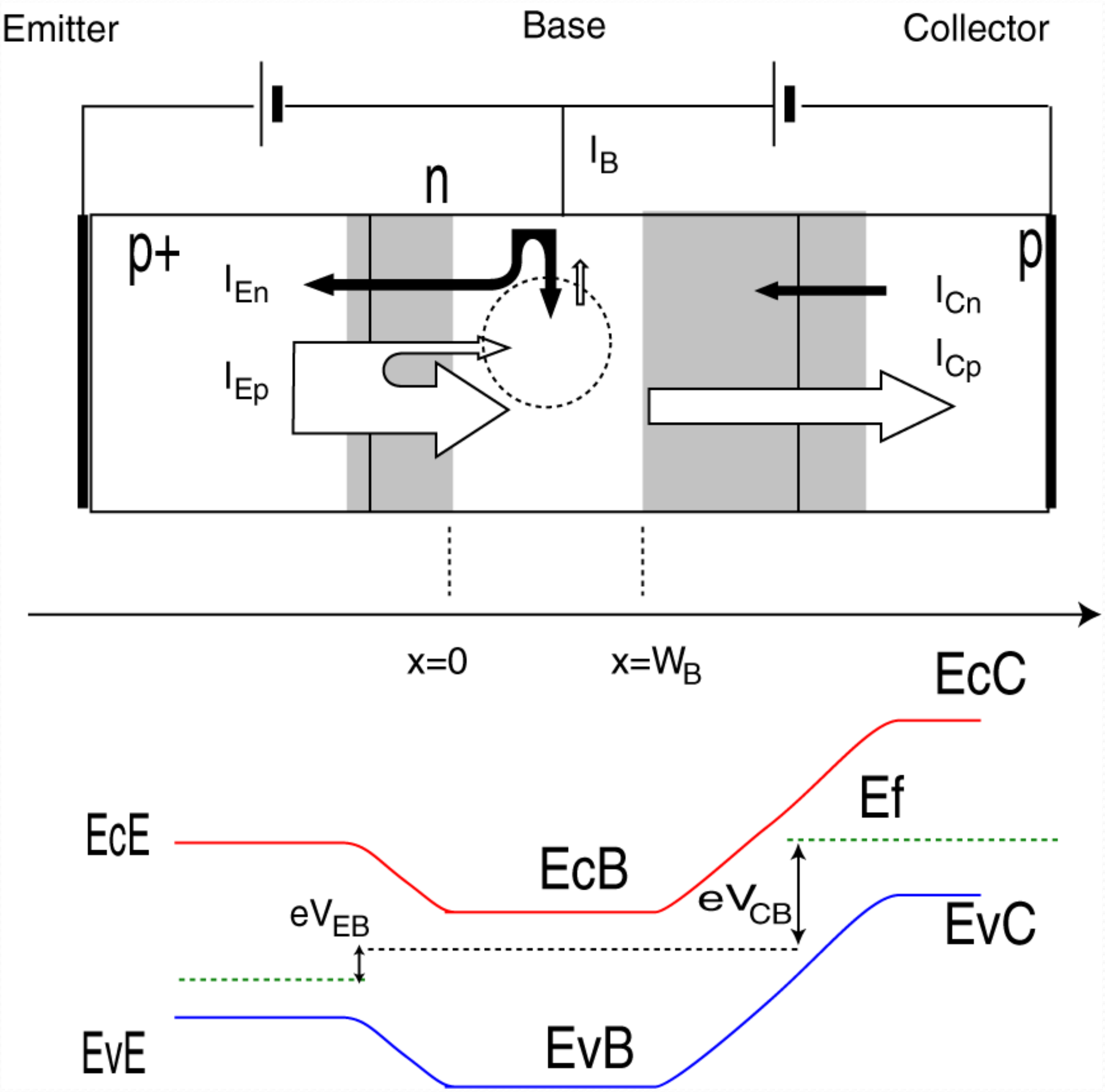
Source (S), gate (G), drain (D)	Emitter (E), base (B), collector (C)
IT'S ALL IN THE GATE CHANNEL!	IT'S ALL IN THE BASE!
Channel (underneath the gate) provides carriers for S-D	Base does NOT contribute (much) carriers nor current to the E-C current
Channel serves as a transport medium (D current comes from current provided from S)	Base serves as a transport medium (C current comes from E carriers)
But G does NOT provide (much) current to S-D current	**There is a B current, usually small but crucial** to the control of currents between E and C
There is a "critical" G voltage (threshold bias VT) for the transistor to be ON	There is no need for any "threshold" B voltage or current for the transistor to be ON
A "relatively" abrupt change from non-conductive to conductive state at VT	B current controls E-C current like a "lever" (small force lifts big force) – gradual
Above threshold, channel charge accumulation is linear vs. gate voltage	E current is exponential vs. B voltage. Linear control is by B current
Device design and engineering: gate oxide (or insulator) and channel	Device design and engineering: B length, carrier diffusion, E doping, length, carrier diffusion

I-V characteristics of FET vs. BJT



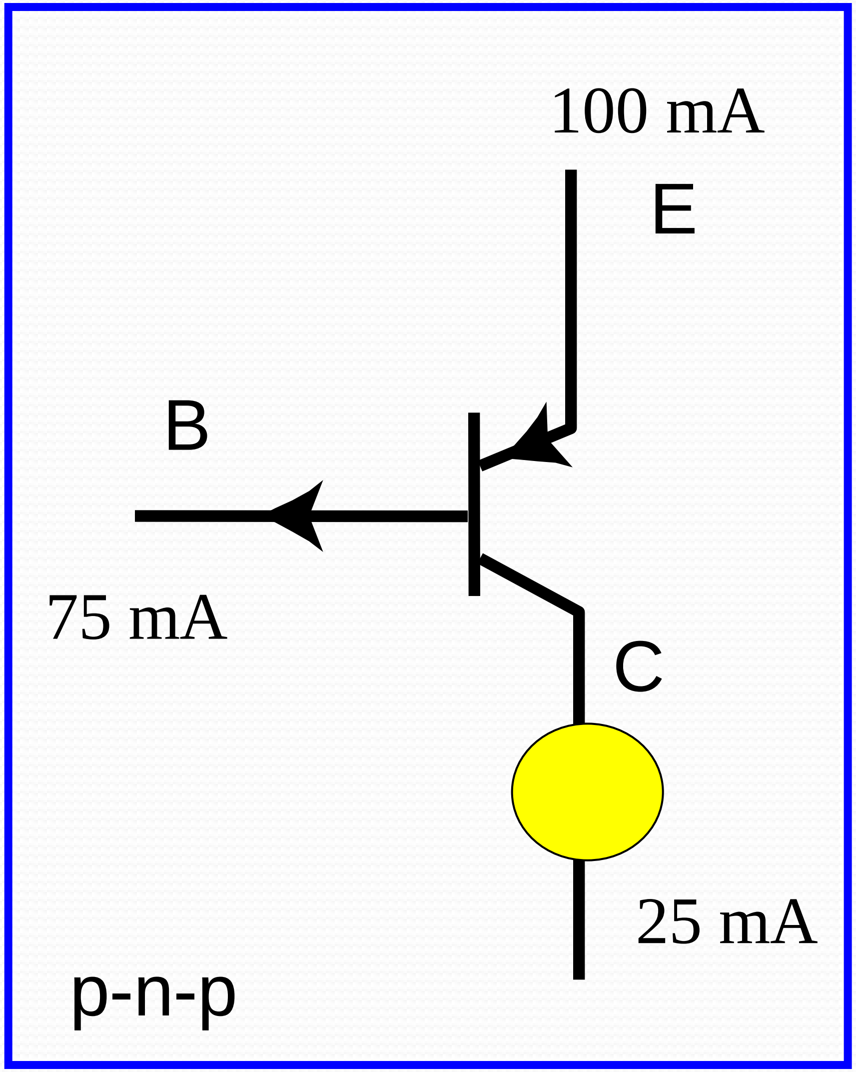


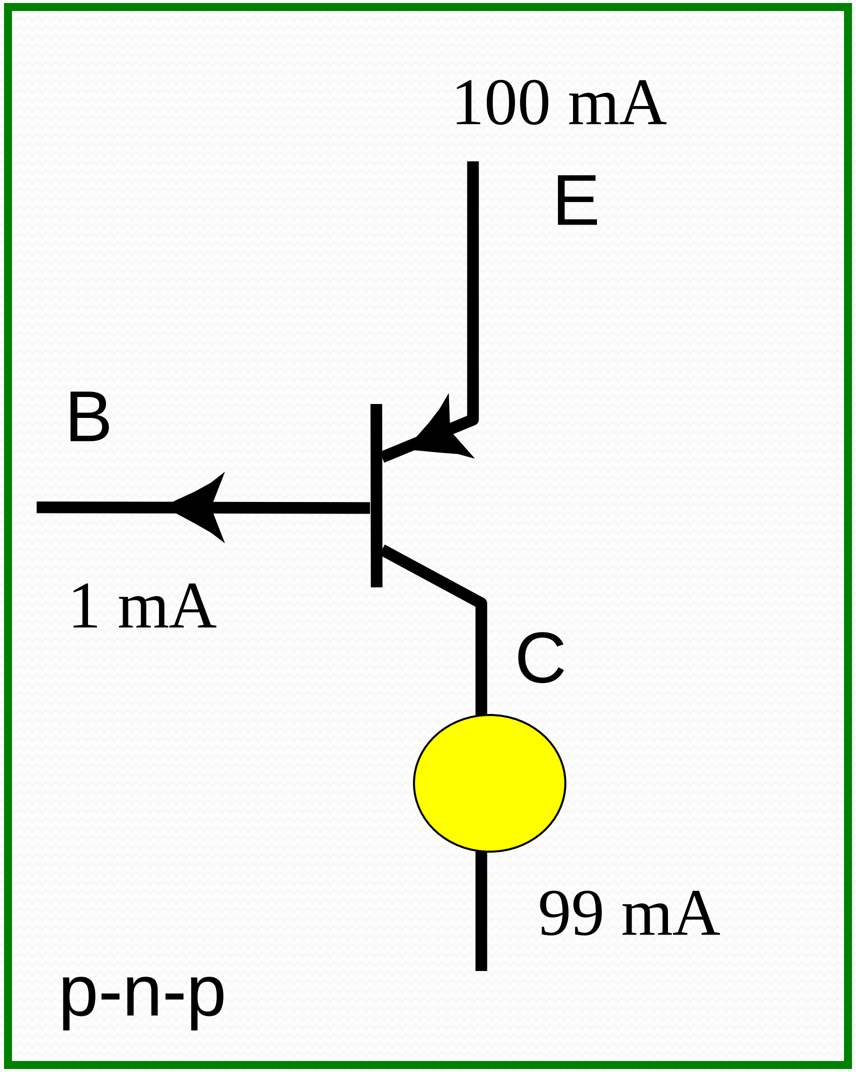
BJT basic principle



- Base-emitter current is used to draw a large population of majority carrier from emitter to the base
- The base is engineered such that these carriers do not disappear in the base, but transferred to the collector as many as possible
- To do that, we need:
  - short base/large diffusion length
  - low density of opposite carriers (minority) in the base
  - low minority current in the emitter as well

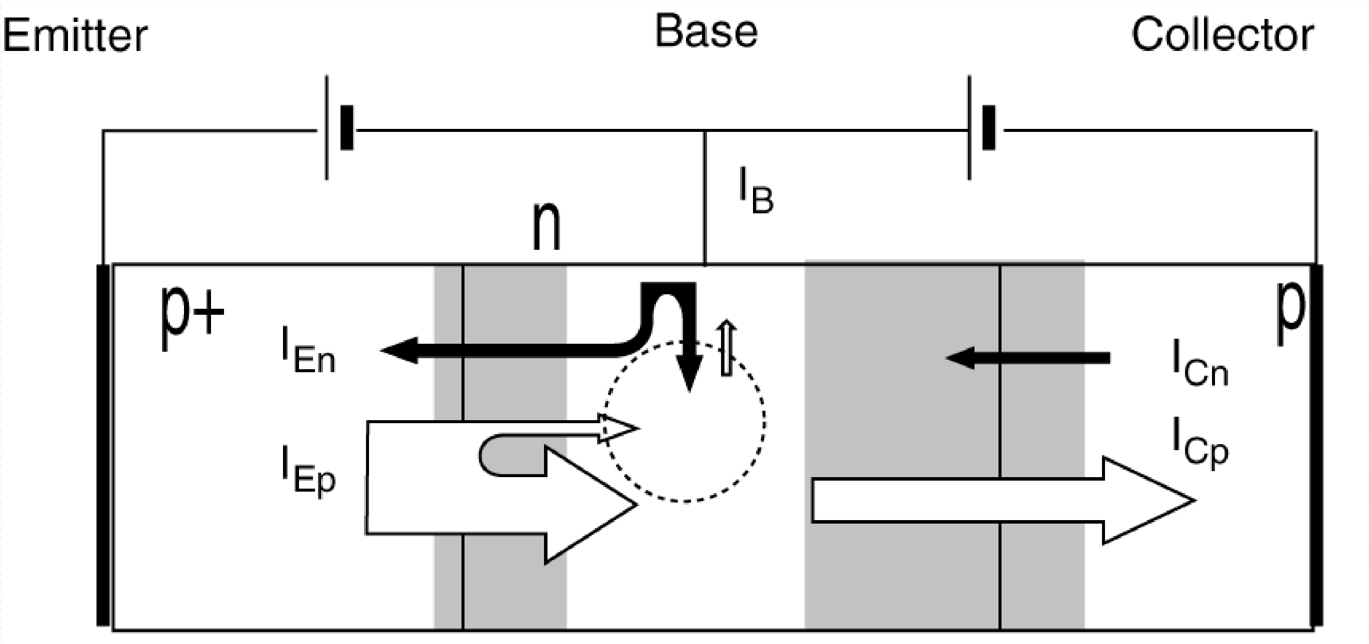
What are the performance parameters?





Which one is the better transistor?

Performance Parameter Concepts



How many % of emitter current is "useful" current?

$$\gamma = \frac{I_{Ep}}{I_{Ep} + I_{En}} = \frac{1}{1 + I_{En} / I_{Ep}}$$

Emitter efficiency

How many % of emitter majority carrier get to collector?

$$\alpha_T = \frac{I_{Cp}}{I_{Ep}}$$

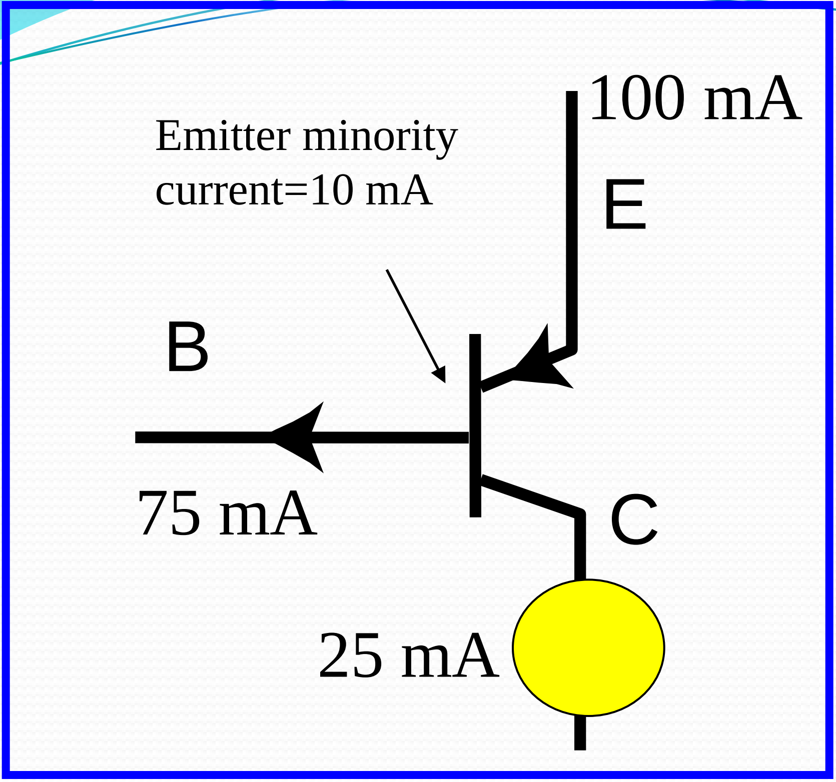
Base transport factor

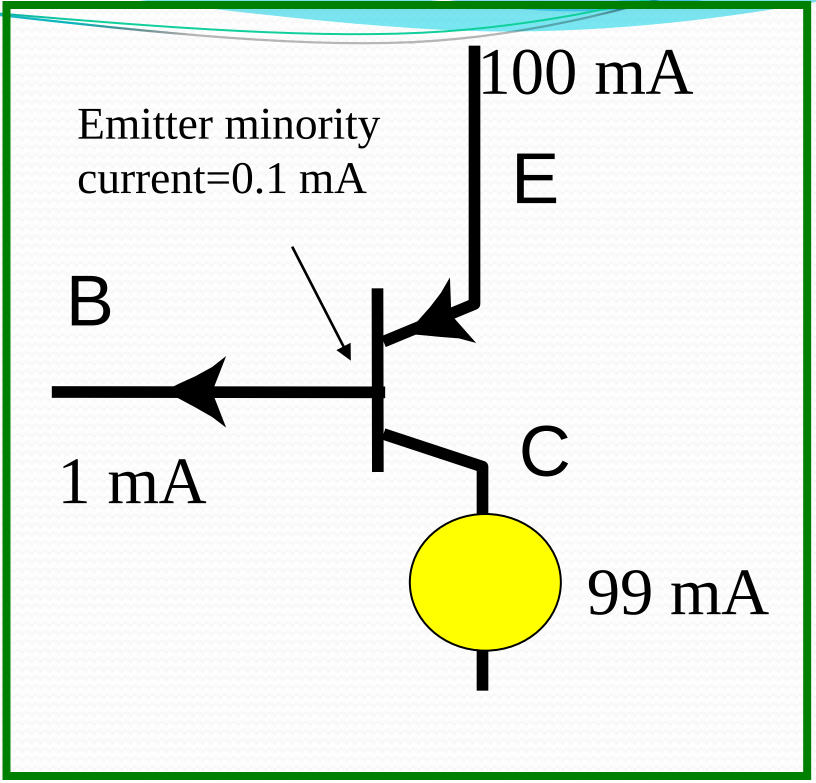
How many % of emitter total get to collector?

$$\alpha = \gamma \alpha_T = \frac{I_{Cp}}{I_{Ep} + I_{En}}$$

Common-base current gain

Example





Common-base current gain: (assume mostly holes in collector)

$$\alpha \approx \frac{25}{100} = 0.25$$

$$\alpha \approx \frac{99}{100} = 0.99$$

Approx. base transport factor

$$\alpha_T \approx \frac{25}{100-10} = 0.28$$

$$\alpha_T \approx \frac{99}{100-0.1} = 0.991$$

Emitter efficiency:

$$\gamma = \frac{100-10}{100} = 0.9$$

$$\gamma = \frac{100-0.1}{100} = 0.999$$

Amplification

$$\beta \approx \frac{\alpha}{1-\alpha} = \frac{0.25}{1-0.25} = 0.33$$

$$\beta \approx \frac{\alpha}{1-\alpha} = \frac{0.99}{1-0.99} = 99\ (\approx 100)$$

Amplification factor

- Most emitter are efficient: $\gamma \sim 1$
- Base transport factor:

$$\alpha_T = \left|\frac{I_{Cp}}{I_{Ep}}\right| \cong \left|\frac{\left(-qAv_T p_1 \frac{1}{\sinh\left[W_B / L_{Bp}\right]} + qAv_T p_2 \coth\left(W_B / L_{Bp}\right)\right)}{\left(qAv_T p_1 \coth\left(W_B / L_{Bp}\right) - qAv_T p_2 \frac{1}{\sinh\left[W_B / L_{Bp}\right]}\right)}\right| \approx \frac{qAv_T p_1 \frac{1}{\sinh\left[W_B / L_{Bp}\right]}}{qAv_T p_1 \coth\left(W_B / L_{Bp}\right)}$$

Majority current at collector

p2 small

Majority current at emitter

$$\alpha_T \approx \frac{1}{\cosh\left(W_B / L_{Bp}\right)}$$

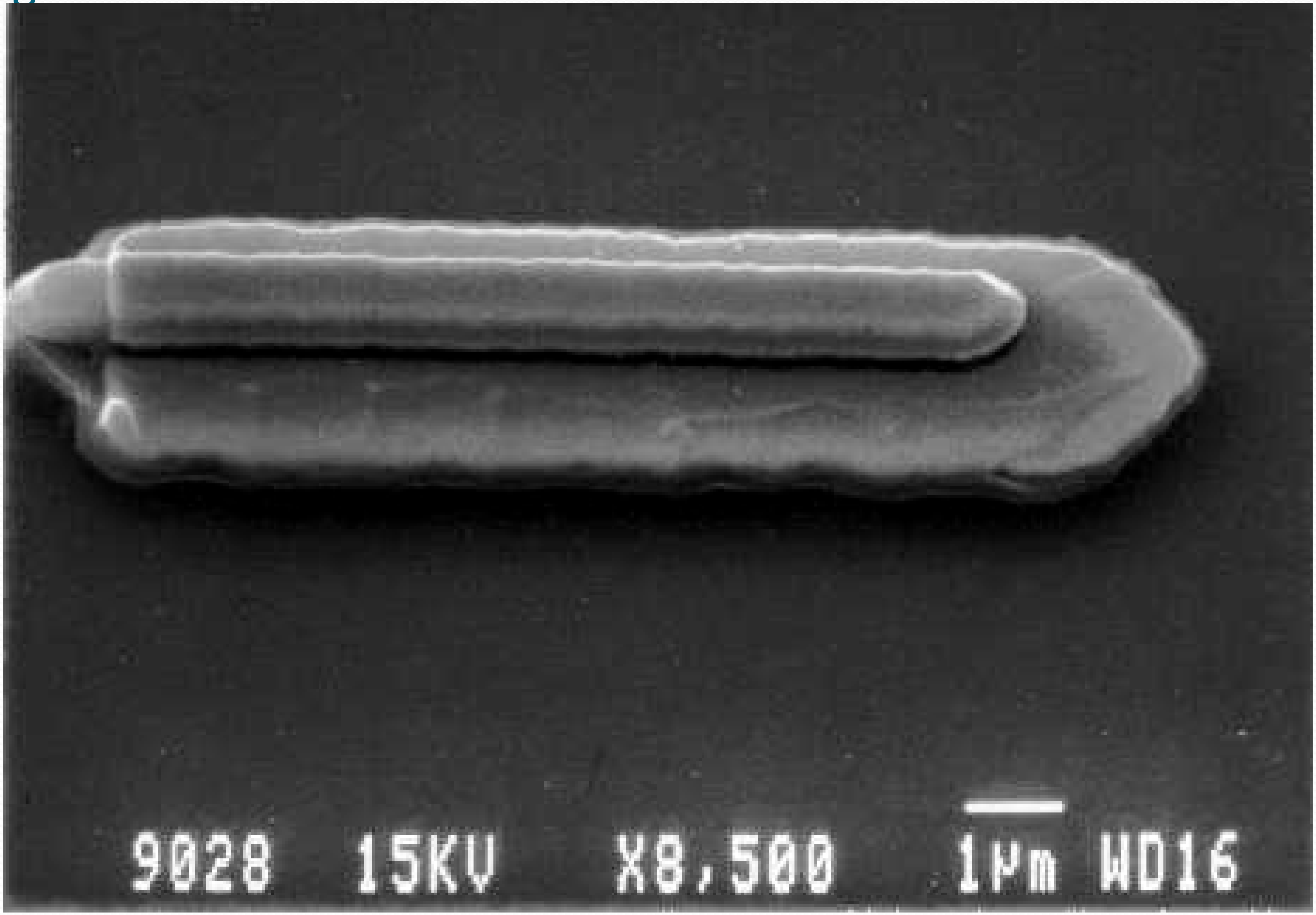
$$\beta \text{ (or } h_{FE}) = \frac{\alpha}{1-\alpha} = \frac{1}{1/\gamma\alpha_T - 1} \approx \frac{1}{\cosh\left(W_B / L_{Bp}\right) - 1} \approx \frac{1}{1 + W_B^2 / 2L_{Bp}^2 - 1} = \frac{2L_{Bp}^2}{W_B^2}$$

Example: base width = 2 um, diffusion length = 20 um

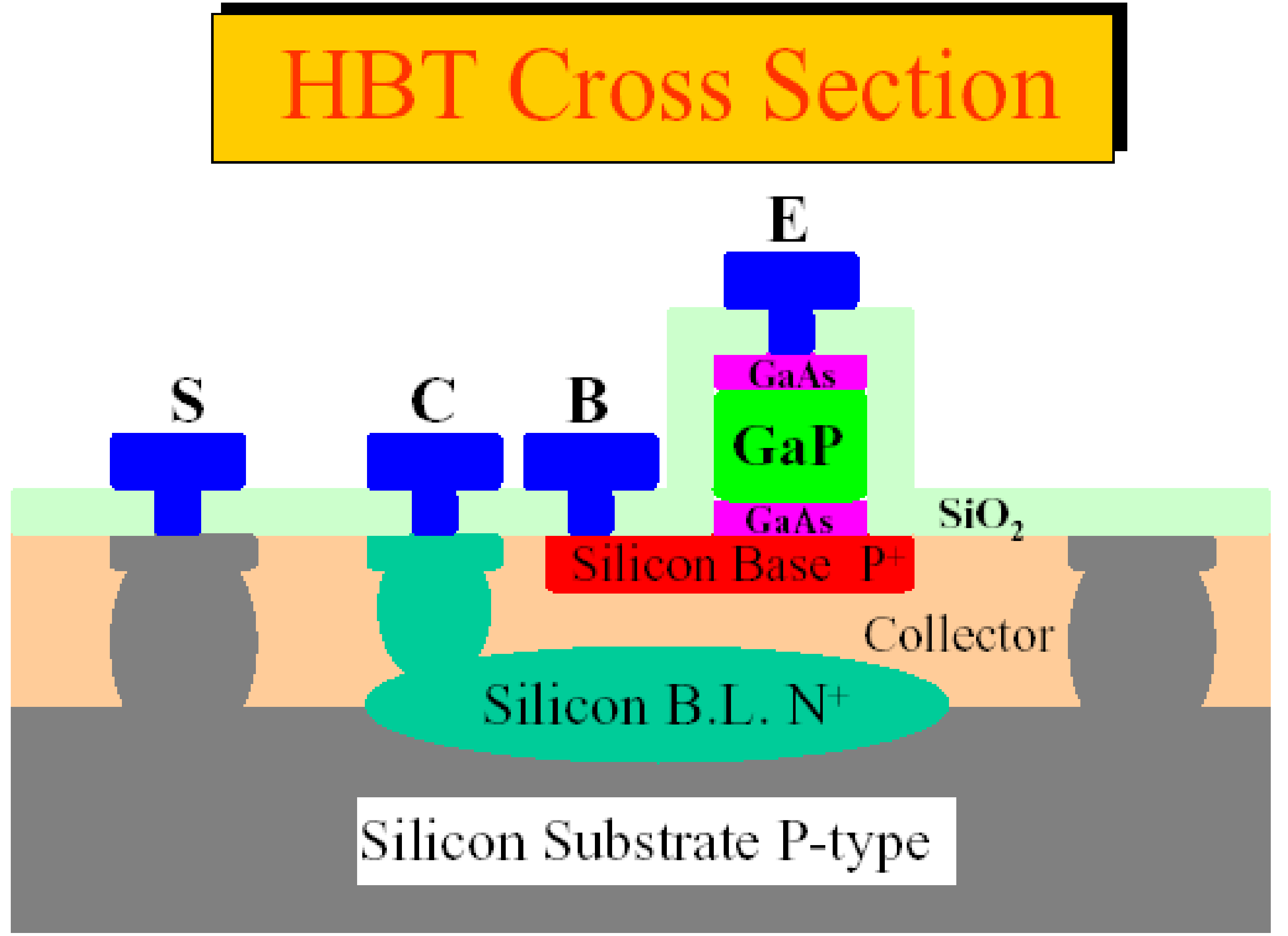
$$\beta \approx \frac{2\,L_{LBp}^2}{W_B^2} = \frac{2 \times 400}{4} = 200$$

How small can it get?

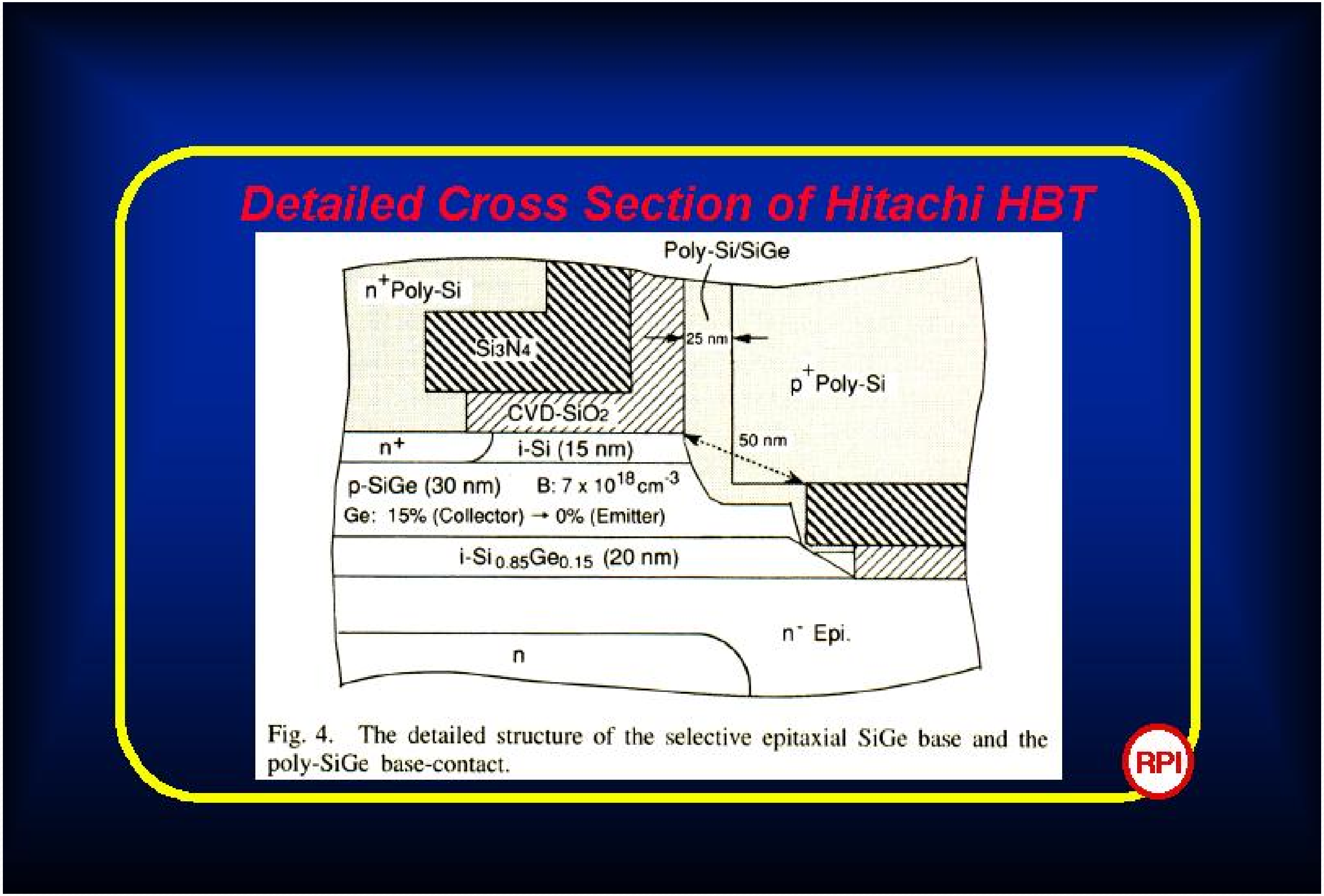
Image of sub-micron HBT



How many different semiconductors can be put in?



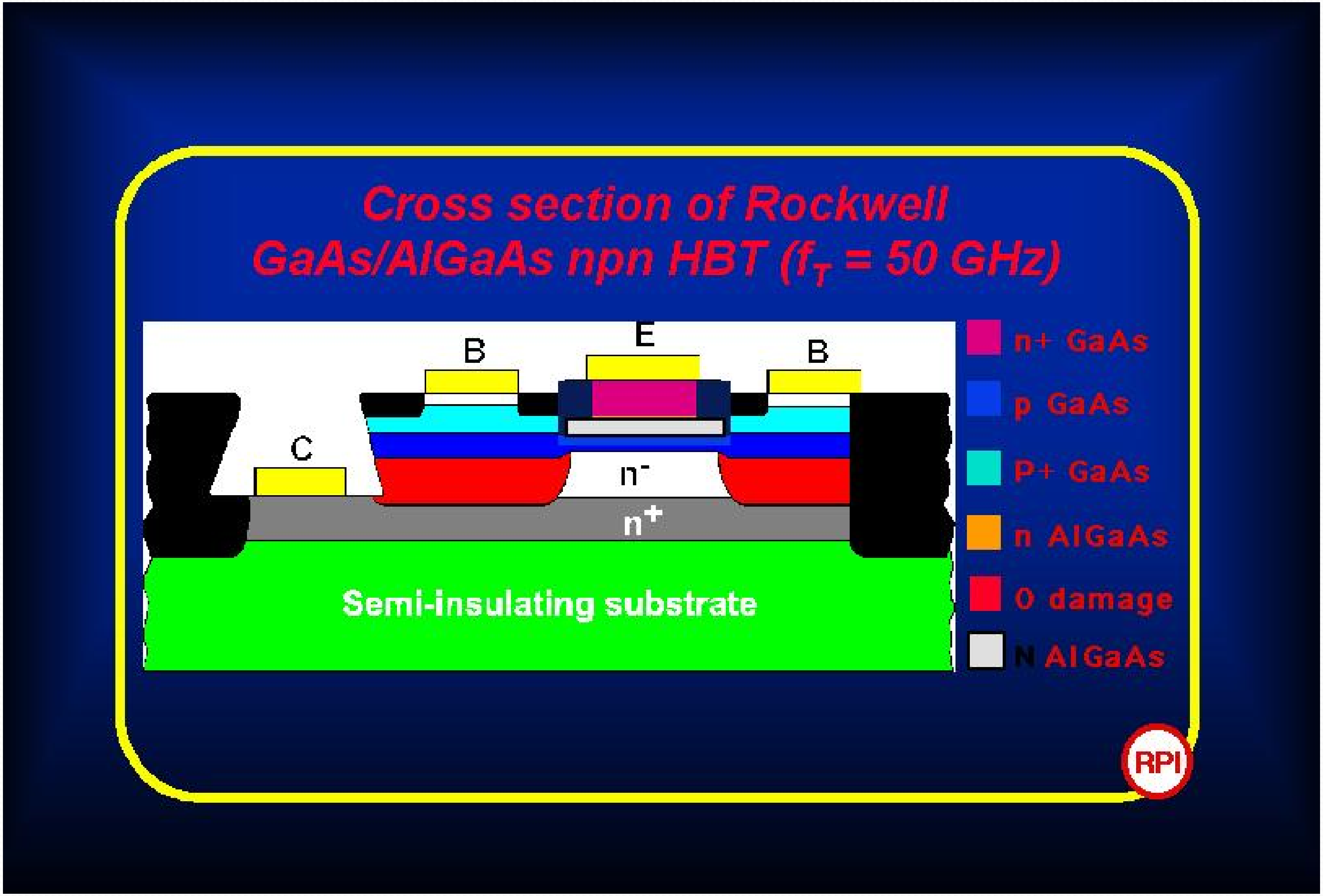
HBT: how complex can the base be?



Detailed Cross Section of Hitachi HBT

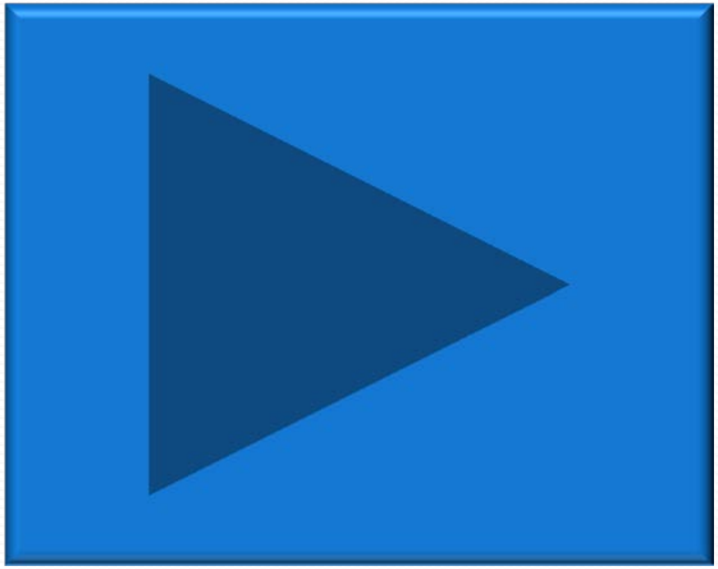
Fig. 4. The detailed structure of the selective epitaxial SiGe base and the poly-SiGe base-contact.

How complex can the fabrication be?



Cross section of Rockwell GaAs/AlGaAs npn HBT (f_T = 50 GHz)

Example: an extreme design



Example: power BJT and the physics of breakdown effects

Example: high speed low noise BJT

Summary

- A crude beginning (1947) to “undreamed of” performance
- Progress from all fronts:
  - materials
  - fabrication technology
  - advanced in design and modeling
  - advanced scientific understanding
- ... yet, the fundamental principle remains the same: control of majority carriers in the base