Lecture 10a

EE-215 Electronic Devices and Circuits

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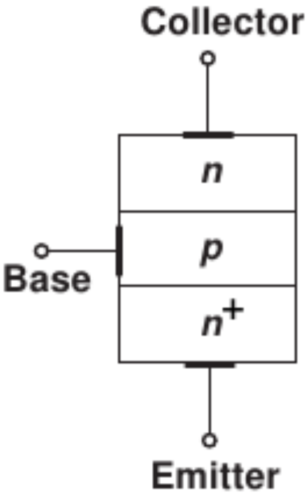
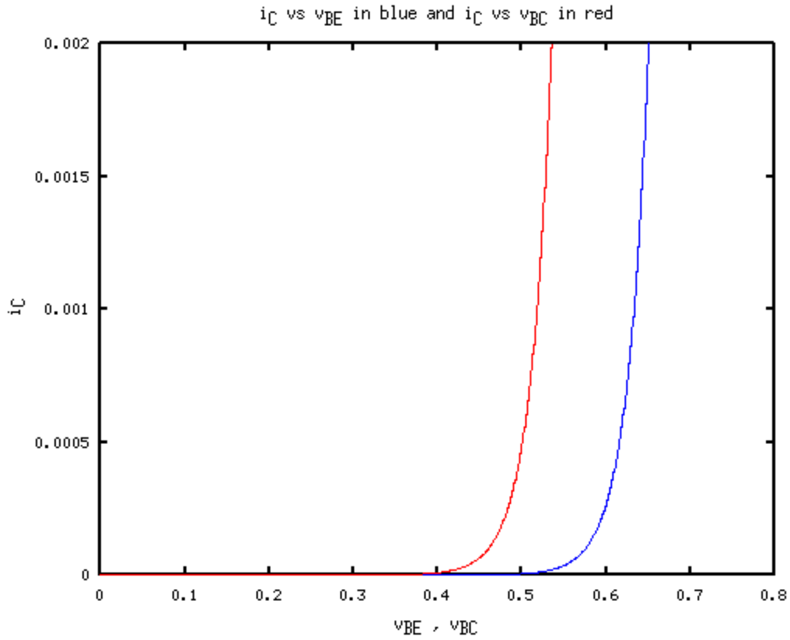
BJT: Device Structure and Physical Operation

Operation in the Saturation Mode

- for an npn BJT to operate in the active mode,
    - the EBJ is forward biased and
        - the CBJ is reverse biased i.e $v_{CB} \geq 0$
        - but as a pn junction doesnot effectively becomes forward biased
            - until the forward voltage across it, exceeds the cut-in voltage of approximately 0.5V
        - 

    - the cut-in voltage of the EBJ is typically 0.5V,
        - but as the CBJ area is 10 to 100 times the EBJ area
        - the cut-in voltage of the CBJ will be lesser around typically 0.4V
- figure shows plot of $i = I_S e^{v_{BE}/V_T}$ in blue and $i = \left(100 \times I_S\right) e^{v_{BC}/V_T}$ in red



  -
  - from the figure cut-in voltage for CBJ is $\approx 0.4V$
- thus for the BJT to operate in the active mode,
  - the EBJ is forward biased and
    - the CBJ must be reverse biased i.e $v_{CB} \geq 0$
  - but as a pn junction doesnot effectively becomes forward biased
    - until the forward voltage across it, exceeds the cut-in voltage of approximately 0.4V (CBJ)
  - $= \Rightarrow$the active mode operation of an npn transistor still continues
    - for negative v_{CB} down to approximately $-0.4V$
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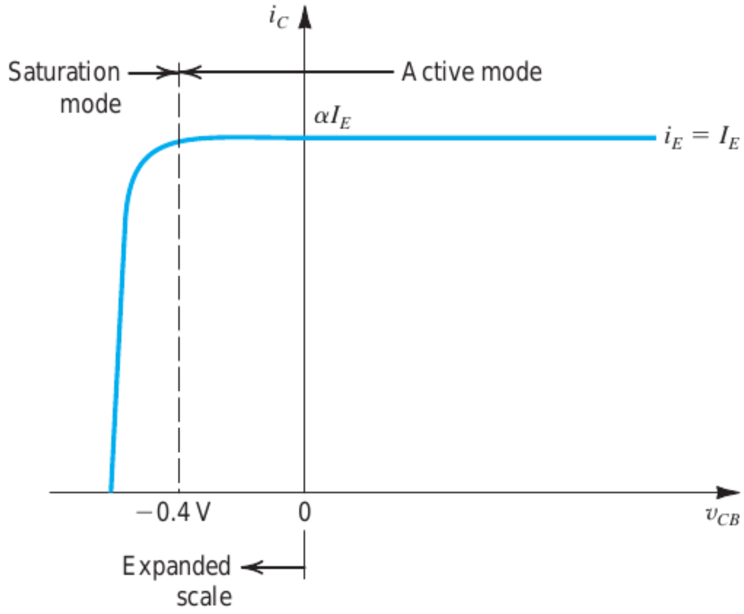
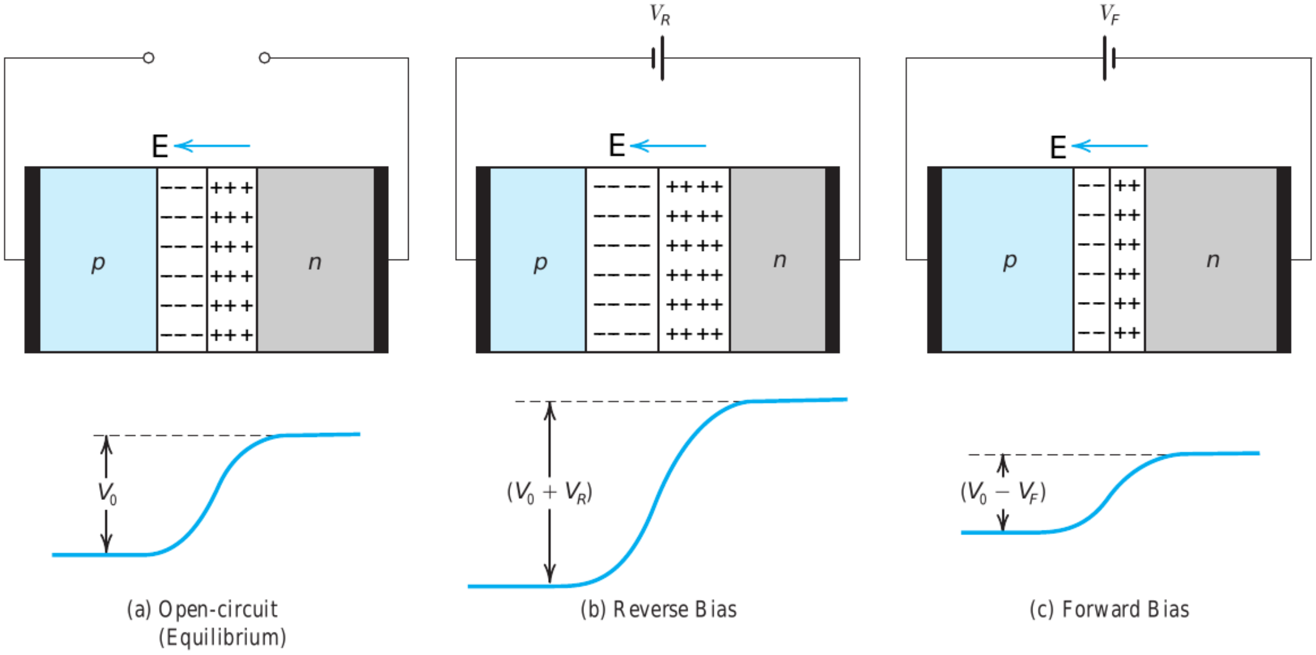


- **Figure 6.8** The i_C–v_{CB} characteristic of an *npn* transistor fed with a constant emitter current I_E. The transistor enters the saturation mode of operation for $v_{CB} < -0.4$ V, and the collector current diminishes.

- thus for active mode operation for an npn BJT
  - EBJ is forward-biased and CBJ is reverse-biased $= \Rightarrow v_{CB} \geq -0.4V$
  - beyong $v_{CB} = -0.4V$ i.e. for $v_{BC} > 0.4V$, the CBJ begins to
    - conduct sufficiently and thus the transistor leaves the active mode,
    - and enters the saturation mode of operation, where i_C decreases.
  - to understand why i_C decreases in saturation, first we need to take a look at the forward and reverse biased pn juntions



(a) Open-circuit (Equilibrium)

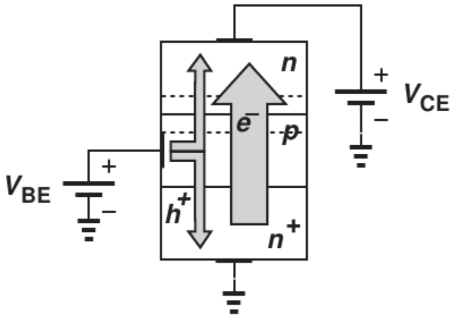
(b) Reverse Bias

(c) Forward Bias

Figure 3.11 The *pn* junction in: **(a)** equilibrium; **(b)** reverse bias; **(c)** forward bias.

- in case of active mode

  - EBJ is forward biased, electrons flow from the emitter to the base
    - and holes from the base to the emitter
    - these electrons will diffuse across the thin base region and reach the depletion region,
    - experiences the electric field across the space charge region and move into the collector
  - in case of reverse active mode
    - CBJ is forward biased, electrons flow from the collector to the base
    - and holes from the base to the collector
    - the electrons will diffuse across the thin base region and reach the
    - depletion region of EBJ, these electrons experience the electric field and are swept into the emitter region.
- in case of saturation mode
  - both EBJ and CBJ are forward biased
    - for EBJ
      - electrons flow from the Emitter to the base and
      - holes from the base to the emitter
    - for CBJ
      - electrons flow from the collector to the base and
      - holes from the base to the collector



  - As the Emitter is strongly doped relative to the collector, the minority carrier (electons) distribution in the base can be given as
- As CBJ is now forward-biased, the electron concentration at
  - the collector edge is no longer zero rather it is a value proportional to e^{v_{BC}/V_T}
    - $= \Rightarrow i_C = I_S e^{v_{BE}/V_T} - I_{SC} e^{v_{BC}/V_T}$
    - where I_{SC} is the scale current for CBJ

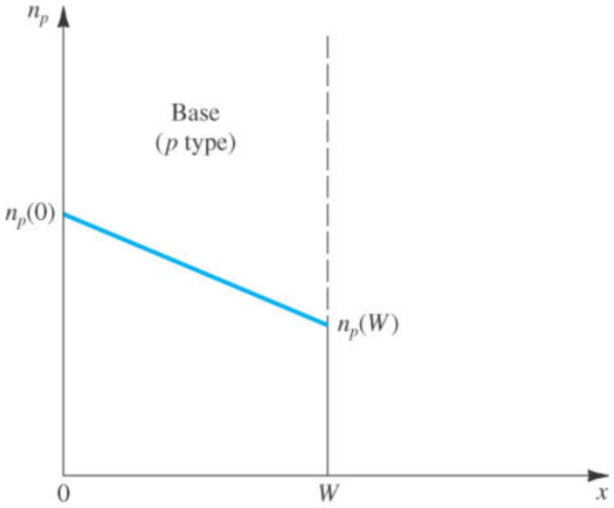


Figure 5.10 Concentration profile of the minority carriers (electrons) in the base of an *npn* transistor operating in the saturation mode.

- $i_C = I_S e^{v_{BE}/V_T} - I_{SC} e^{v_{BC}/V_T}$
  - thus we can construct a model for the saturated npn transistor as

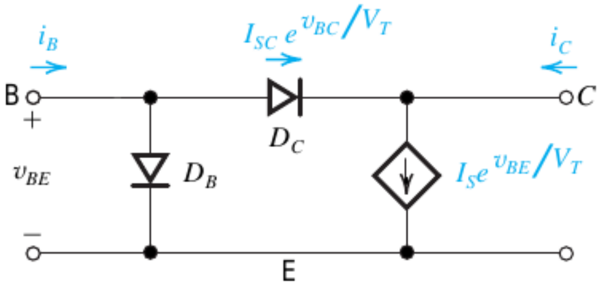
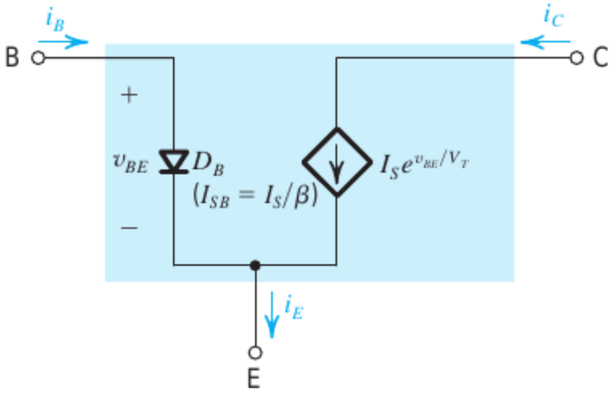
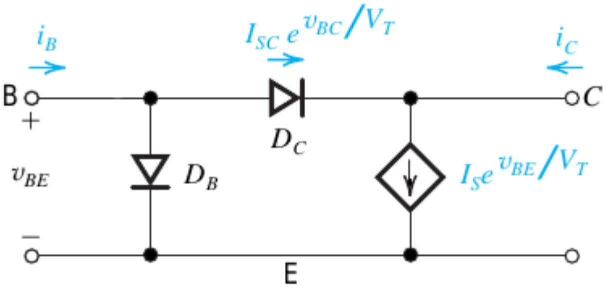


Figure 6.9 Modeling the operation of an *npn* transistor in saturation by augmenting the model of Fig. 6.5(c) with a forward conducting diode D_C. Note that the current through D_C increases i_B and reduces i_C.

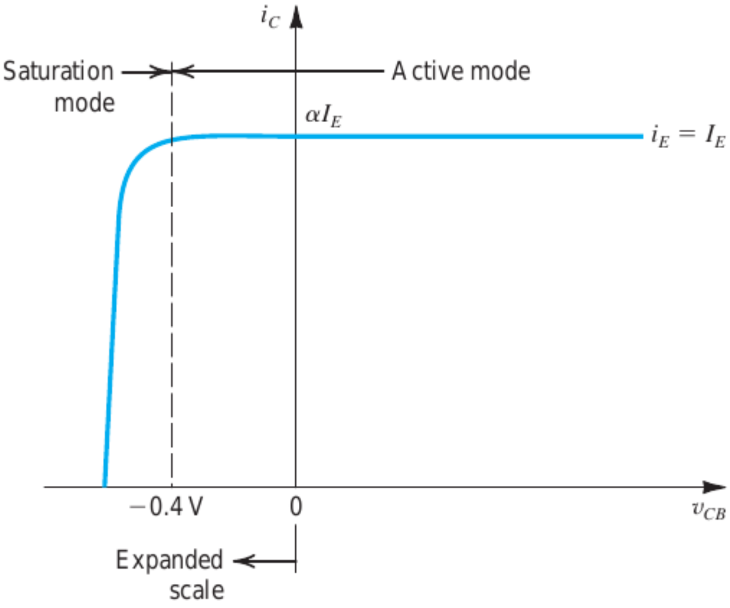
- Note that here we augment the $\pi - model$ for active region, with the forward-conducting CBJ diode D_C

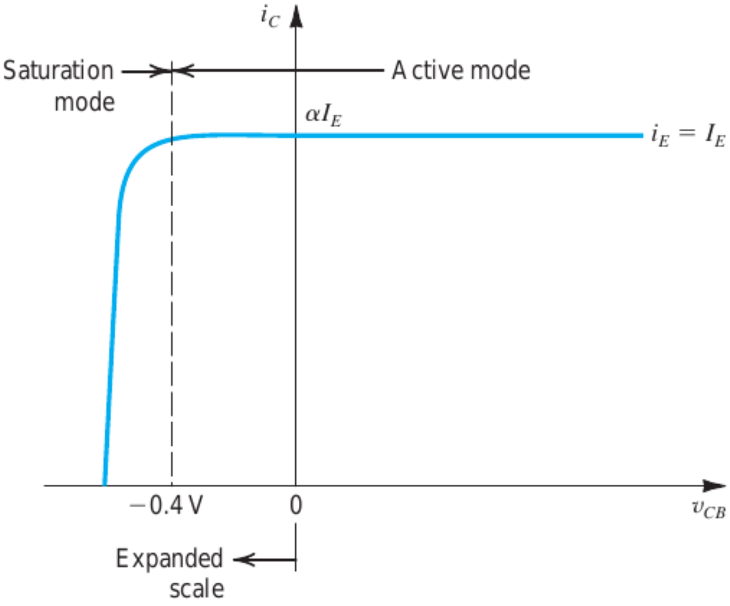


(c)

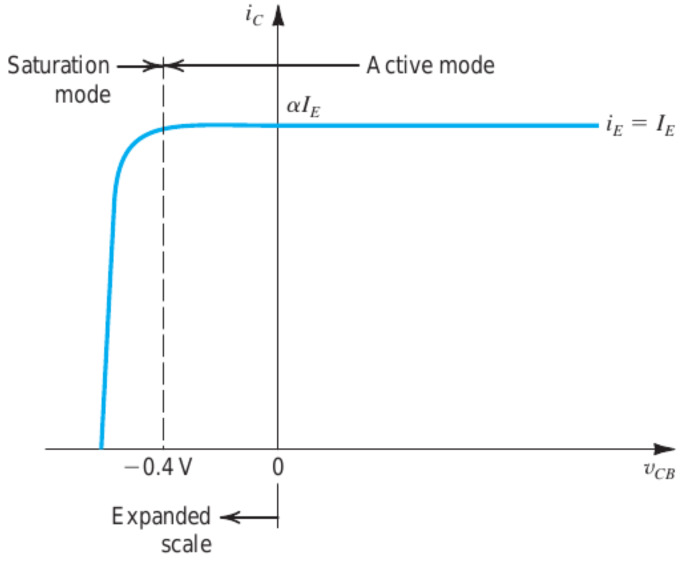


- Apply KCL at collector terminal
  - $= \Rightarrow I_{SC}e^{v_{BC}/V_T} + i_C = I_S e^{v_{BE}/V_T}$
    - or $i_C = I_S e^{v_{BE}/V_T} - I_{SC}e^{v_{BC}/V_T}$
  - applying KCL at base terminal
    - $i_B = \frac{I_S}{\beta} e^{v_{BE}/V_T} + I_{SC}e^{v_{BC}/V_T}$
    - now we have an additional hole current term because of the forward biased CBJ i.e. $I_{SC}e^{v_{BC}/V_T}$
- $i_C = I_S e^{v_{BE}/V_T} - I_{SC}e^{v_{BC}/V_T}$ and $i_B = \frac{I_S}{\beta} e^{v_{BE}/V_T} + I_{SC}e^{v_{BC}/V_T}$
  - divide 1st eq by 2nd $= \Rightarrow \frac{i_C}{i_B} = \frac{I_S e^{v_{BE}/V_T} - I_{SC}e^{v_{BC}/V_T}}{\frac{I_S}{\beta} e^{v_{BE}/V_T} + I_{SC}e^{v_{BC}/V_T}}$
  - this ratio, $\frac{i_C}{i_B}$ is called $forced\ \beta$ and is denoted as β_{forced}
    - (because $\frac{i_C}{i_B}$ can be set to any desired value lower than β by adjusting v_{BC})
  - thus $\beta_{forced} < \beta$ and β_{forced} can be reduced by increasing v_{BC} i.e. by driving the transistor deeper into saturation
  - the collector-to-emitter voltage of a saturated transistor can be given as
    - $v_{CEsat} = v_C - v_E = v_{CB} - v_{EB}$
    - $v_{CEsat} = -v_{BC} + v_{BE} \because v_{CB} = -v_{BC}$ and $v_{EB} = -v_{BE}$
    - $v_{CEsat} = v_{BE} - v_{BC}$
- $v_{CEsat} = v_{BE} - v_{BC}$
  - as $v_{BE} \approx 0.7V$ in active region and $v_{BC} \approx 0.4V$ at the start of saturation region
  - $= \Rightarrow v_{CEsat} = 0.7 - 0.4 = 0.3V$ at the start of saturation region

- 

- thus $v_{CEsat} = 0.7 - 0.4 = 0.3V$ at the start of saturation region
  - ultimately the current i_C is reduced to zero
  - $= \Rightarrow i_C = I_S e^{v_{BE}/V_T} - I_{SC} e^{v_{BC}/V_T} = 0 = \Rightarrow I_S e^{v_{BE}/V_T} = I_{SC} e^{v_{BC}/V_T}$
  - 

- $I_S e^{v_{BE}/V_T} = I_{SC} e^{v_{BC}/V_T}$
  - $= \Rightarrow \frac{e^{v_{BE}/V_T}}{e^{v_{BC}/V_T}} = \frac{I_{SC}}{I_S} = \Rightarrow e^{(v_{BE} - v_{BC})/V_T} = \frac{I_{SC}}{I_S}$
  - $\left(v_{BE} - v_{BC}\right)/V_T = \ln \frac{I_{SC}}{I_S}$
  - $v_{BE} - v_{BC} = V_T \ln \frac{I_{SC}}{I_S}$
  - $\left(v_B - v_E\right) - \left(v_B - v_C\right) = V_T \ln \frac{I_{SC}}{I_S}$
  - $-v_E + v_C = V_T \ln \frac{I_{SC}}{I_S} = \Rightarrow v_{CE} = V_T \ln \frac{I_{SC}}{I_S}$
  - if CBJ area is 100 times the EBJ area $= \Rightarrow \frac{I_{SC}}{I_S} = 100$
  - for $\frac{I_{SC}}{I_S} = 100 = \Rightarrow v_{CE} = V_T \ln 100 = 0.115V$

  - for $\frac{I_{SC}}{I_S} = 50 = \Rightarrow v_{CE} = V_T \ln 50 = 0.098V$
  - $= \Rightarrow v_{CE} \approx 0.1V$ at the end of saturation mode of operation
- $v_{CEsat} = v_{BE} - v_{BC}$
  - $v_{CEsat} = 0.7 - 0.4 = 0.3V$ at the start of saturation region (end of active region)
  - and $v_{CEsat} \approx 0.1V$ at the end of saturation mode of operation (when $i_C = 0$)
  - $= \Rightarrow v_{CEsat} \approx 0.1 \text{ to } 0.3V$
  - 

- $v_{CEsat} \approx 0.1 \text{ to } 0.3V$
  - thus at the edge of the saturation
    - $v_{CEsat} = 0.3V$
  - while for a BJT deep into saturation has
    - $v_{CEsat} = 0.2V$

Exercise 6.8

- Use Eq. (6.14) i.e. $i_C = I_S e^{v_{BE}/V_T} - I_{SC} e^{v_{BC}/V_T}$ to show that i_C reaches zero at $V_{CE} = V_T \ln(I_{SC}/I_S)$.
  - Calculate V_{CE} for a transistor whose CBJ has 100 times the area of EBJ.

Solution

- $i_C = I_S e^{v_{BE}/V_T} - I_{SC} e^{v_{BC}/V_T} = 0$
  - $= \Rightarrow I_S e^{v_{BE}/V_T} = I_{SC} e^{v_{BC}/V_T}$
  - $= \Rightarrow \frac{e^{v_{BE}/V_T}}{e^{v_{BC}/V_T}} = \frac{I_{SC}}{I_S} = \Rightarrow e^{(v_{BE} - v_{BC})/V_T} = \frac{I_{SC}}{I_S}$
  - $\left(v_{BE} - v_{BC}\right)/V_T = \ln \frac{I_{SC}}{I_S}$
  - $v_{BE} - v_{BC} = V_T \ln \frac{I_{SC}}{I_S}$
  - $\left(v_B - v_E\right) - \left(v_B - v_C\right) = V_T \ln \frac{I_{SC}}{I_S}$
- $\left(v_B - v_E\right) - \left(v_B - v_C\right) = V_T \ln \frac{I_{SC}}{I_S}$
  - $v_B - v_E - v_B + v_C = V_T \ln \frac{I_{SC}}{I_S}$
  - $-v_E + v_C = V_T \ln \frac{I_{SC}}{I_S}$
  - $= \Rightarrow v_{CE} = V_T \ln \frac{I_{SC}}{I_S}$
  - As CBJ area is 100 times the EBJ area $= \Rightarrow I_{SC} = 100 \times I_S$

  - $= \Rightarrow \frac{I_{SC}}{I_S} = 100 = \Rightarrow v_{CE} = V_T \ln 100 = 0.11513V = 115.13mV$

Exercise 6.9

- Use Eqs. (6.14), (6.15), and (6.16) to show that a BJT operating in saturation with $V_{CE} = V_{CEsat}$ has a forced β given by

$$\beta_{forced} = \beta \frac{e^{V_{CEsat}/V_T} - \frac{I_{SC}}{I_S}}{e^{V_{CEsat}/V_T} + \frac{\beta I_{SC}}{I_S}}$$

  - Fing β_{forced} for $\beta = 100$, $I_{SC}/I_S = 100$, and $V_{CEsat} = 0.2V$

Solution

- eq6.14 $= \Rightarrow i_C = I_S e^{v_{BE}/V_T} - I_{SC} e^{v_{BC}/V_T}$
  - eq6.15 $= \Rightarrow i_B = \frac{I_S}{\beta} e^{v_{BE}/V_T} + I_{SC} e^{v_{BC}/V_T}$
  - Eq6.16 $= \Rightarrow \beta_{forced} = . \left. \frac{i_C}{i_B} \right|_{saturation}$
  - $\beta_{forced} = . \left. \frac{i_C}{i_B} \right|_{saturation} = \frac{I_S e^{v_{BE}/V_T} - I_{SC} e^{v_{BC}/V_T}}{\frac{I_S}{\beta} e^{v_{BE}/V_T} + I_{SC} e^{v_{BC}/V_T}}$
- $\beta_{forced} = \frac{I_S e^{v_{BE}/V_T} - I_{SC} e^{v_{BC}/V_T}}{\frac{I_S}{\beta} e^{v_{BE}/V_T} + I_{SC} e^{v_{BC}/V_T}}$
  - $\beta_{forced} = \beta \left(\frac{I_S e^{v_{BE}/V_T} - I_{SC} e^{v_{BC}/V_T}}{I_S e^{v_{BE}/V_T} + \beta I_{SC} e^{v_{BC}/V_T}} \right)$
  - divide numerator and denominator by e^{v_{BC}/V_T}
  - $\beta_{forced} = \beta \left(\frac{I_S \frac{e^{v_{BE}/V_T}}{e^{v_{BC}/V_T}} - I_{SC}}{I_S \frac{e^{v_{BE}/V_T}}{e^{v_{BC}/V_T}} + \beta I_{SC}} \right)$
  - $\beta_{forced} = \beta \left(\frac{I_S e^{\frac{v_{BE} - v_{BC}}{V_T}} - I_{SC}}{I_S e^{\frac{v_{BE} - v_{BC}}{V_T}} + \beta I_{SC}} \right)$
  - As $v_{BE} - v_{BC} = (v_B - v_E) - (v_B - v_C) = v_B - v_E - v_B + v_C = -v_E + v_C = v_C - v_E = v_{CE}$
  - $= \Rightarrow \beta_{forced} = \beta \left(\frac{I_S e^{\frac{v_{CE}}{V_T}} - I_{SC}}{I_S e^{\frac{v_{CE}}{V_T}} + \beta I_{SC}} \right)$
- $\beta_{forced} = \beta \left(\frac{I_S e^{\frac{v_{CE}}{V_T}} - I_{SC}}{I_S e^{\frac{v_{CE}}{V_T}} + \beta I_{SC}} \right)$
  - divide numerator and denominator by I_S
  - $= \Rightarrow \beta_{forced} = \beta \left(\frac{e^{\frac{v_{CE}}{V_T}} - \frac{I_{SC}}{I_S}}{e^{\frac{v_{CE}}{V_T}} + \frac{\beta I_{SC}}{I_S}} \right)$
  - when $\beta = 100$, $I_{SC}/I_S = 100$, and $V_{CEsat} = 0.2V$
  - $\beta_{forced} = 100 \left(\frac{e^{0.2/25e-3} - 100}{e^{0.2/25e-3} + (100)(100)} \right) = 22.194$