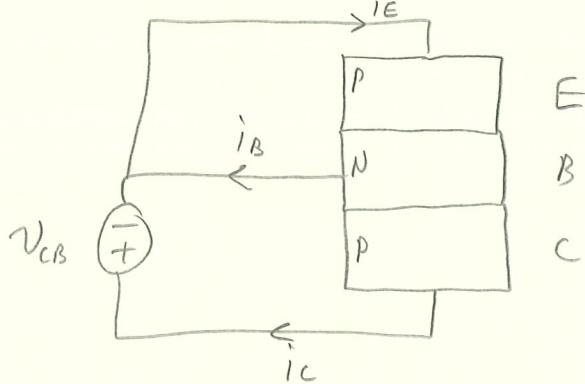


### b. Reverse characteristics - PNP BJT

$\rightarrow V_{EB} = 0$  and  $V_{CB} > 0$



Observe:  $i_B > 0A$ , but  $i_C < 0A$  and  $i_E < 0A$

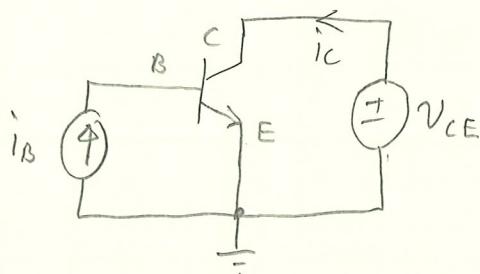
$$\therefore i_R = I_s [e^{V_{CB}/V_T} - 1] = -i_E$$

$$i_B = \frac{i_R}{B_R} = -\frac{i_E}{B_R}$$

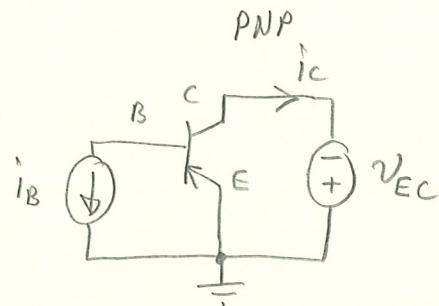
$$|i_E| = |i_C| + i_B$$

### 1. BJT output characteristics

NPN



or



plot  $i_C$  vs  $i_B + V_{CE}$

plot  $i_C$  vs  $i_B + V_{EC}$

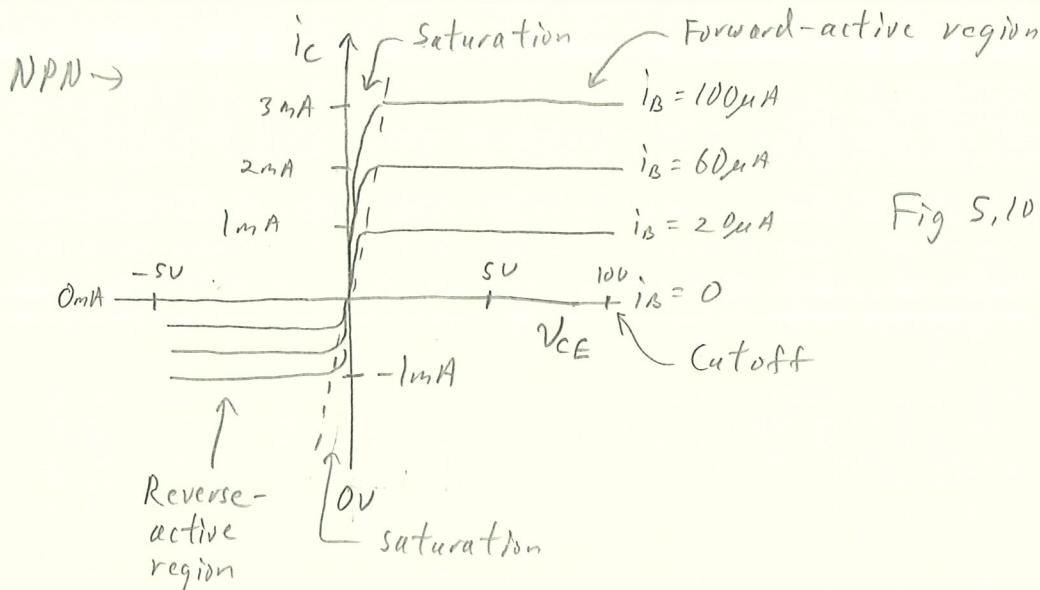


Fig 5.10, p. 226

For PNP: same plot except  $V_{EC}$  instead of  $V_{CE}$

$\rightarrow$  4 Regions of Operation (NPN)

① Cutoff  $\rightarrow i_B = 0A : i_C = 0A$

② Forward-active region

$$\rightarrow V_{CE} \geq V_{BE}$$

$$\rightarrow i_C \neq f(V_{CE}) \text{ and } i_C \approx \beta_F i_B$$

③ Saturation region

$$0 \leq V_{CE} \leq V_{BE} \text{ and for } V_{BE} \leq V_{CE} \leq 0$$

$\rightarrow$  very small  $V_{CE}$

\* not same as saturation in a MOSFET

④ Reverse-active region

$$V_{CE} \leq V_{BE} \leq 0$$

$$i_C \neq f(V_{CE}) \text{ and } i_C \approx -(\beta_R + 1)i_B$$

2. BJT  $\rightarrow$  4 Regions of Operation

BE Junction

BC Junction

	Reverse Bias	Forward Bias
Forward Bias	Forward-Active Region	Saturation Region
Reverse Bias	Cutoff Region	Reverse-Active Region

Table 5.2, p. 228 ↗

BJT Q-point:  $(I_C, V_{CE})$

a. Uses

① Cutoff

both pn junctions reverse biased

$$I_C = 0$$

$\rightarrow$  T as an open switch

② Saturation (both junctions forward biased)

$$V_{BE} \geq V_{CE} \geq 0 \rightarrow \therefore \text{small } V_{CE}$$

$\rightarrow$  T as a closed switch

NOTE: BJT Saturation  $\neq$  MOSFET Saturation

③ Forward-Active Region

also called "Active Region"

BE junction FB, BC junction RB

$\rightarrow$  high gain possible

#### ④ Reverse - Active Region

BE junction RB, BC junction is FB

→ low current gain

#### b. Applications

① Switching and binary logic states

→ Cutoff → off

→ Saturation → on

② ECL based BJT logic circuits

→ Cutoff → off

→ Forward Active → on

③ Amplification

→ Forward Active Region → high gain

④ TTL logic circuits

→ make use of all 4 regions

#### 3. BJT Transport Model Equations

Forward Characteristics:  $i_C = I_S [e^{\frac{V_{BE}}{V_T}} - 1]$

$$i_C = \beta_F i_B = \alpha_F i_E$$

$$\alpha_F = \frac{\beta_F}{1 + \beta_F}, \quad \beta_F = \frac{\alpha_F}{1 - \alpha_F}$$

$$i_E = (\beta_F + 1) i_B = i_C + i_B$$

→ can derive similar  $I_S [e^{\frac{V_{BE}}{V_T}} - 1]$  equations for  $i_B$  and  $i_E$   
using  $\beta_F$  and  $\alpha_F$

Reverse Characteristics:  $-i_E = I_s [e^{V_{BE}/V_T} - 1]$

$$i_E = \alpha_R i_C = -\beta_R i_B$$

$$i_C = -\frac{I_s}{\alpha_R} [e^{V_{BC}/V_T} - 1]$$

and similar equation for  $i_B$

a. Complete Transistor Model Equations

→ combine equations for forward and reverse characteristics

$$\therefore i_C = I_s [e^{V_{BE}/V_T} - 1] - \frac{I_s}{\alpha_R} [e^{V_{BC}/V_T} - 1]$$

$$\text{but: } \alpha = \frac{\beta}{\beta+1} \rightarrow \frac{1}{\alpha} = 1 + \frac{1}{\beta}$$

$$\therefore i_C = I_s [e^{V_{BE}/V_T} - e^{V_{BC}/V_T}] - \frac{I_s}{\beta_R} [e^{V_{BC}/V_T} - 1]$$

similar equations for  $i_B$  and  $i_E$ :

$$i_E = I_s [e^{V_{BE}/V_T} - e^{V_{BC}/V_T}] + \frac{I_s}{\beta_F} [e^{V_{BC}/V_T} - 1]$$

$$i_B = \frac{I_s}{\beta_F} [e^{V_{BE}/V_T} - 1] + \frac{I_s}{\beta_R} [e^{V_{BC}/V_T} - 1]$$

Gummel-Poon model

↳ used to  
model BJTs  
in SPICE

Note: 1<sup>st</sup> term in  $i_E$  and  $i_C$  equations

$I_s [e^{V_{BE}/V_T} - e^{V_{BC}/V_T}] = i_T \equiv \text{current being transported completely}$

across the base region

### Simplifications

4/14/08 → 11

① Cutoff Region

$$e^{V_{BE}/V_T} \rightarrow 0, e^{V_{BC}/V_T} \rightarrow 0$$

$$\therefore i_C = \frac{I_s}{\beta_R}$$

$$i_E = -\frac{I_s}{\beta_F}$$

$$i_B = -\frac{I_s}{\beta_F} - \frac{I_s}{\beta_R}$$

Very small currents

→ usually assumed to be zero

## ② Forward Active Region

NPN BJT:  $V_{BE} \geq 0$  and  $V_{BC} \leq 0$

in most cases:  $V_{BE} > 4 \frac{kT}{q} = 0.1V$

and  $V_{BC} < -4 \frac{kT}{q} = -0.1V$

$\therefore$  simplification:  $e^{-V_{BC}/V_T} \ll 1$

$$\therefore i_C = I_S e^{V_{BE}/V_T} + \frac{I_S}{\beta_R}$$

$$i_E = \frac{I_S}{\alpha_F} e^{V_{BE}/V_T} + \frac{I_S}{\beta_F}$$

$$i_B = \frac{I_S}{\beta_F} e^{V_{BE}/V_T} - \frac{I_S}{\beta_F} - \frac{I_S}{\beta_R}$$

However, the  $e^x$  terms  $\gg$  other terms  
usually

$\therefore$  use  $i_C = I_S e^{V_{BE}/V_T} \rightarrow i_C$  is a voltage controlled current source

$$i_E = \frac{I_S}{\alpha_F} e^{V_{BE}/V_T}$$

$$i_B = \frac{I_S}{\beta_F} e^{V_{BE}/V_T}$$

$$\therefore i_C = \alpha_F i_E = \beta_F i_B$$

$$i_C = (\beta_F + 1) i_B = i_C + i_B$$

$\therefore$  For forward active region for DC analysis,

where  $V_{CE} \geq V_{BE} \geq 0$

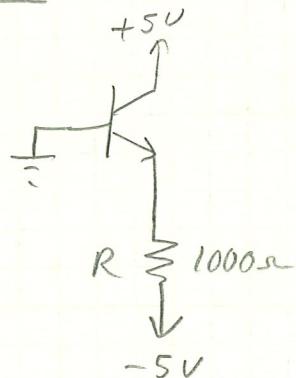
show example  
on next page

$\rightarrow$  use (1)  $V_{BE} = 0.7V$

(2)  $I_C = \beta_F I_B = \alpha_F I_E$

(3)  $I_E = (\beta_F + 1) I_B = I_C + I_B$

4/14/08

ExampleFind  $V_{BE}$ 

$$\beta_F = 100, I_S = 1 \times 10^{-16} A, \text{ room temp}$$

3-0235 — 50 SHEETS — 5 SQUARES  
 3-0236 — 100 SHEETS — 5 SQUARES  
 3-0237 — 200 SHEETS — 5 SQUARES  
 3-0137 — 200 SHEETS — FILLER

COMET

$$\text{room temp: } V_T = 0.025V$$

$$\alpha_F = \frac{\beta_F}{1 + \beta_F} = \frac{100}{101}$$

$$V_E = -5 + I_E R$$

$$\text{or } I_E = \frac{V_E + 5}{R} \quad (1)$$

$$I_E = \frac{I_S}{\alpha_F} e^{\frac{V_{BE}}{V_T}}$$

$$V_B = 0V$$

$$\therefore I_E = \frac{I_S}{\alpha_F} e^{-\frac{V_E}{V_T}} \quad (2)$$

$$(1) \rightarrow (2) \quad \therefore \frac{V_E + 5}{R} = \frac{I_S}{\alpha_F} e^{-\frac{V_E}{V_T}}$$

$$\text{rearrange: } \frac{\alpha_F(V_E + 5)}{R I_S} = e^{-\frac{V_E}{V_T}}$$

$$V_E = -V_T \ln \left( \frac{\alpha_F(V_E + 5)}{R I_S} \right)$$

How do we solve this for  $V_E$

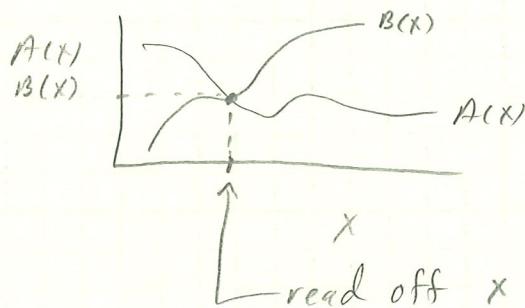
- Closed form solution? Maybe - I'm too lazy to find it

Easy way:  $\rightarrow$  Solve Graphically

$$\text{note: } A(x) = B(x)$$

plot  $A(x)$  vs  $x$  and  $B(x)$  vs  $x$

the point where the 2 curves cross is the solution



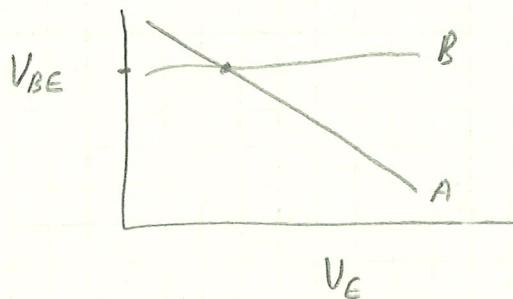
read off  $x$  for the answer

$$\therefore V_E = -V_T \ln\left(\frac{\alpha_F(V_E + 5)}{R I_S}\right)$$

We desire to find  $V_{BE} = V_B - V_E = -V_E$  since  $V_B = 0V$

$$\therefore A = -V_E, B = V_T \ln\left(\frac{\alpha_F(V_E + 5)}{R I_S}\right)$$

Plot  $A$  vs  $V_E$ ,  $B$  vs  $V_E$



Plot for  $R = 10\Omega$ ,  $100\Omega$ ,  $1k\Omega$ ,  $10k\Omega$ ,  $100k\Omega$

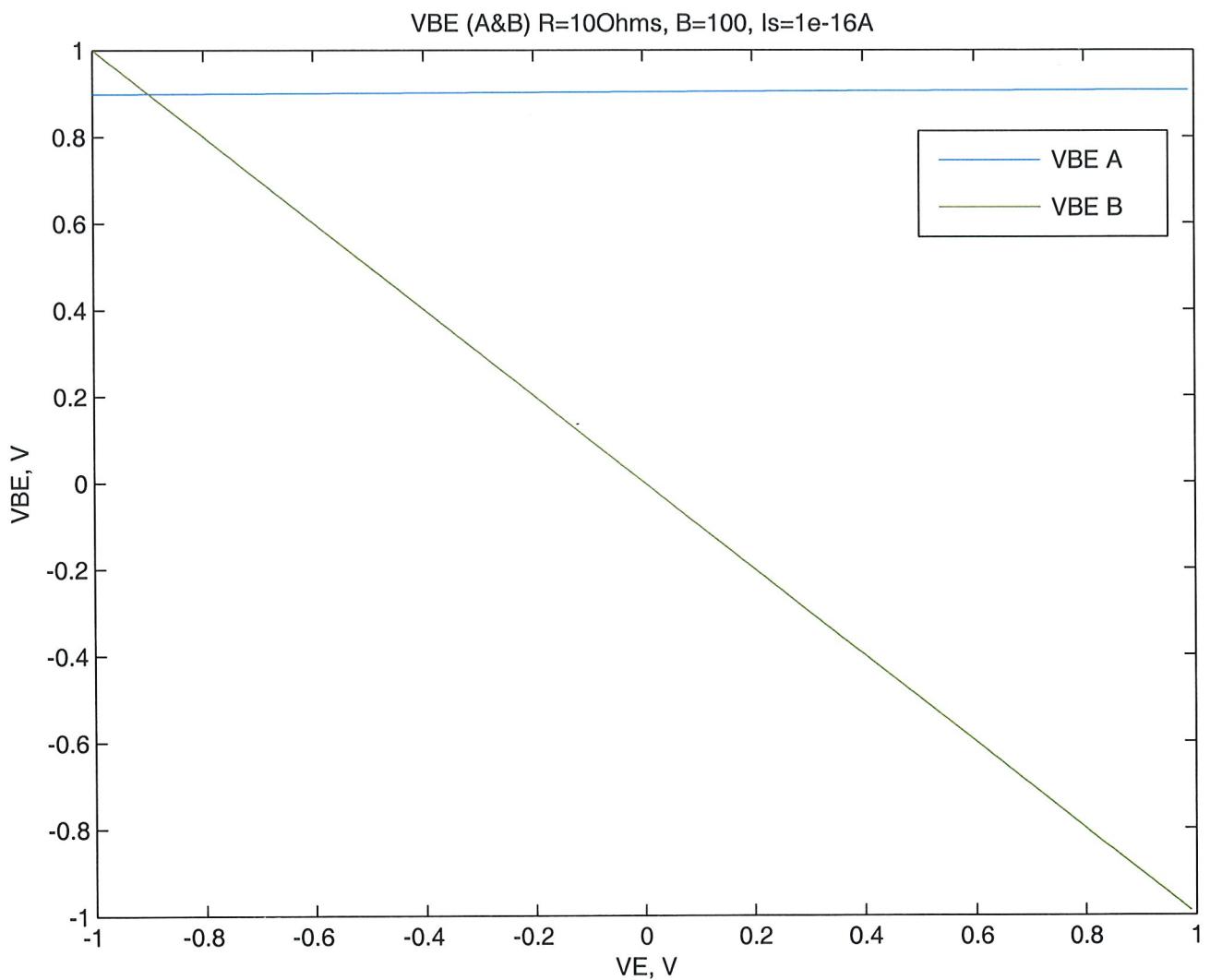
Plot using Matlab

```
%BJT Analysis 4/12/08
clear all;
format compact;
format long;
R=100000
Is=1e-16
B=100

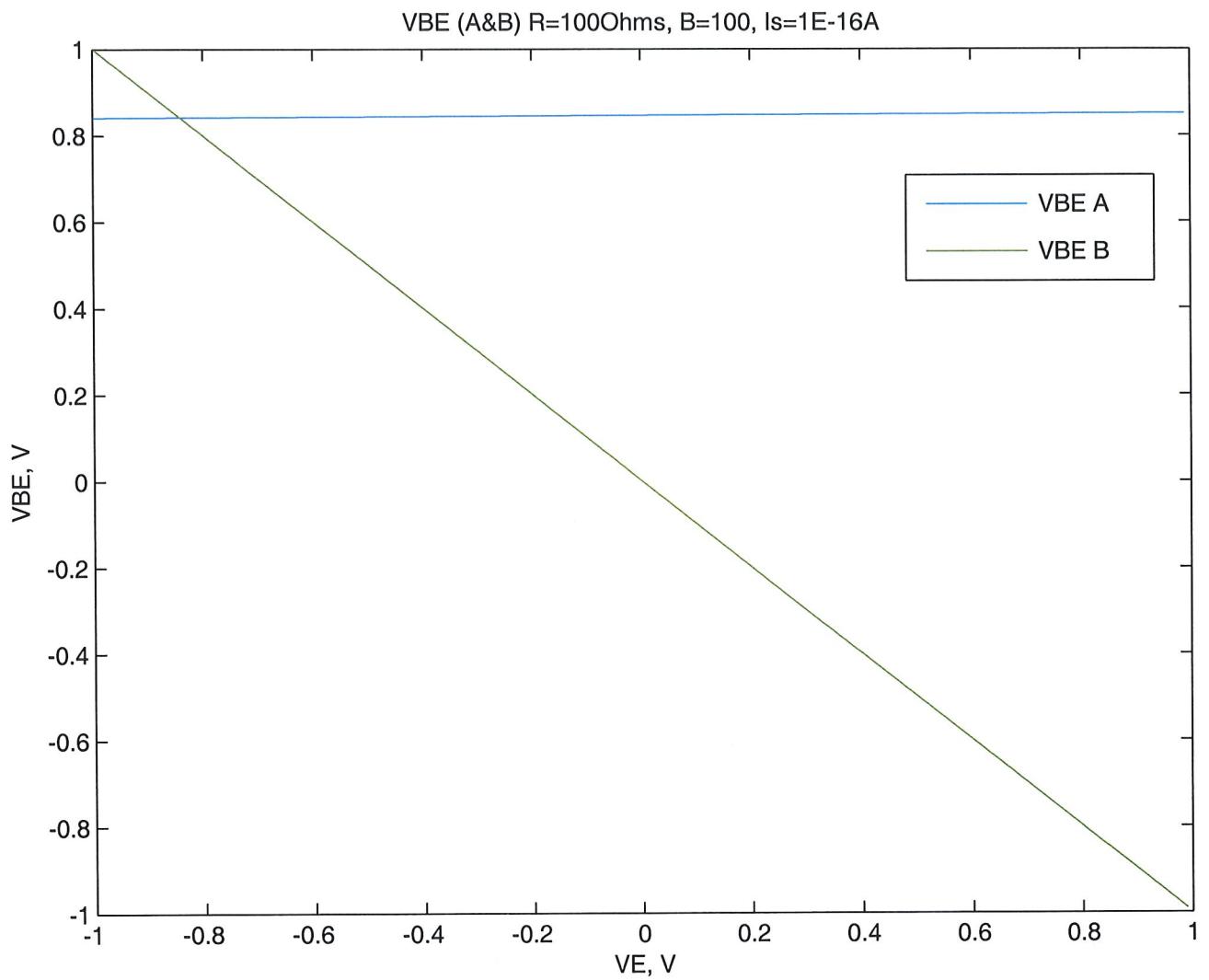
alpha=B/(B+1)
for i=1:200;           → sets  $V_E$  range from  $-1V \leq V_E \leq 1V$ 
    p(i)=(100-i)/100;
    a(i)= -1*(-0.025)*log(alpha*(p(i)+5)/(Is*R));
    b(i)=-1*p(i);
end

plot(p,a,p,b)
```

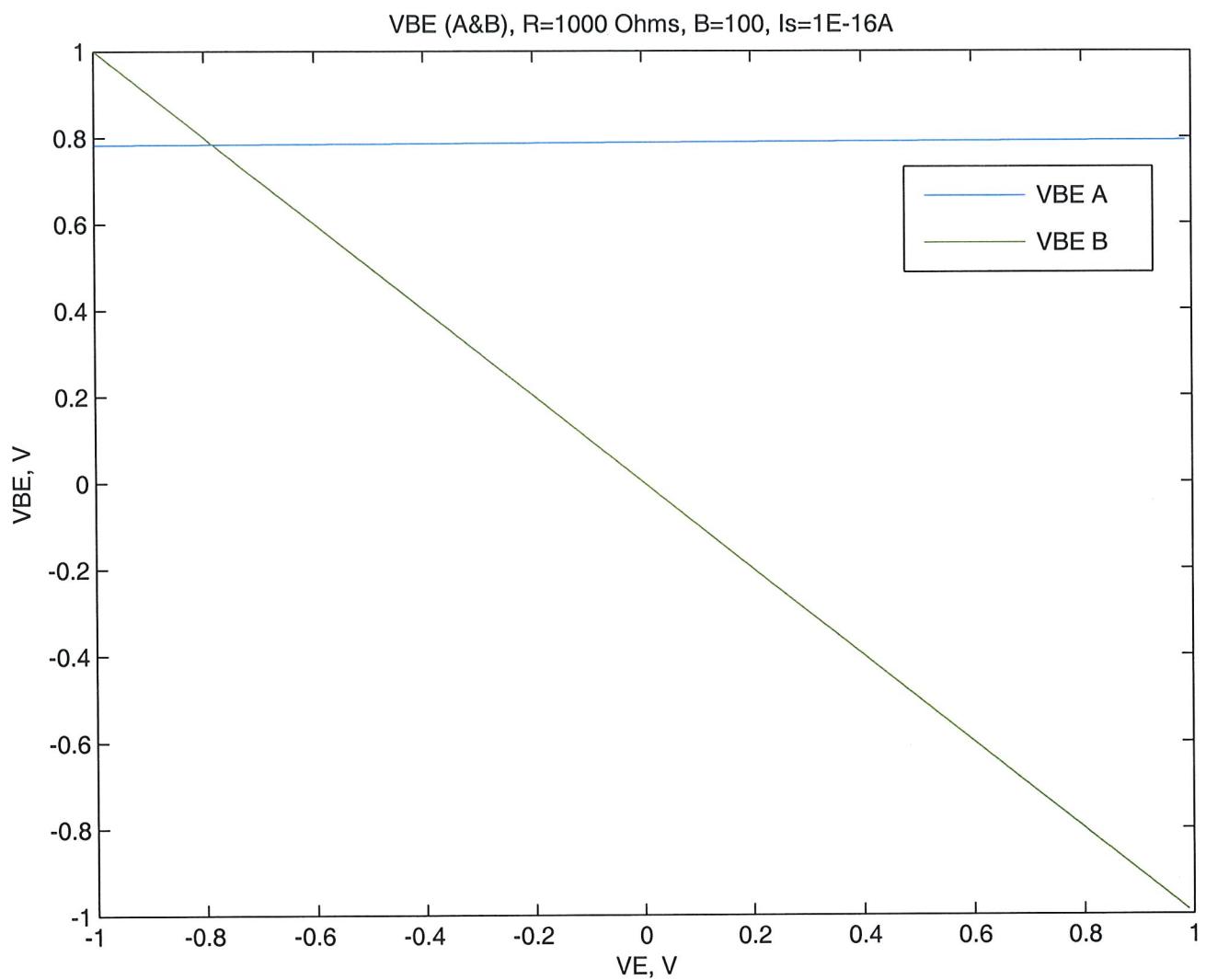
Matlab m-File



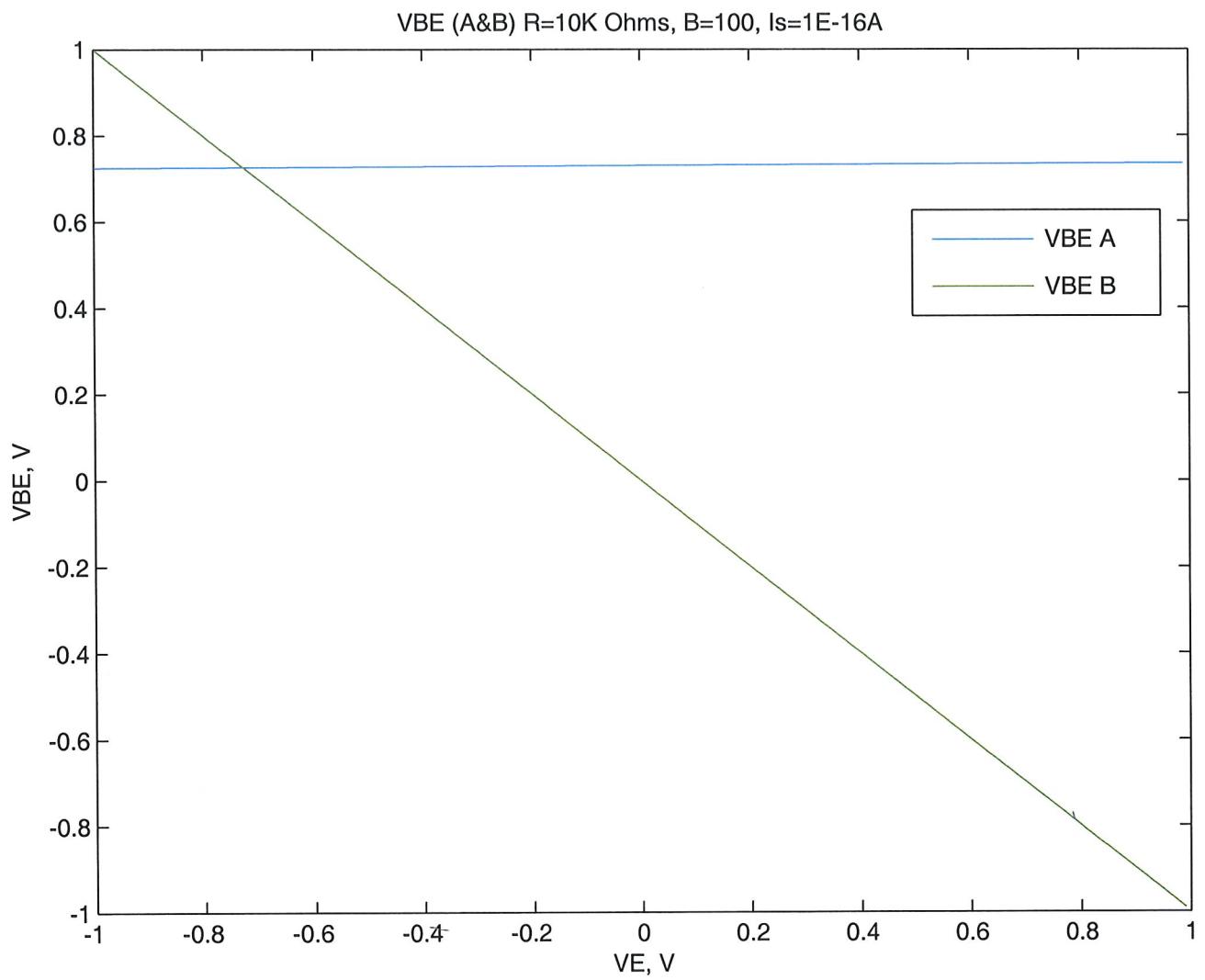
$$V_{BE} \approx 0.9V$$



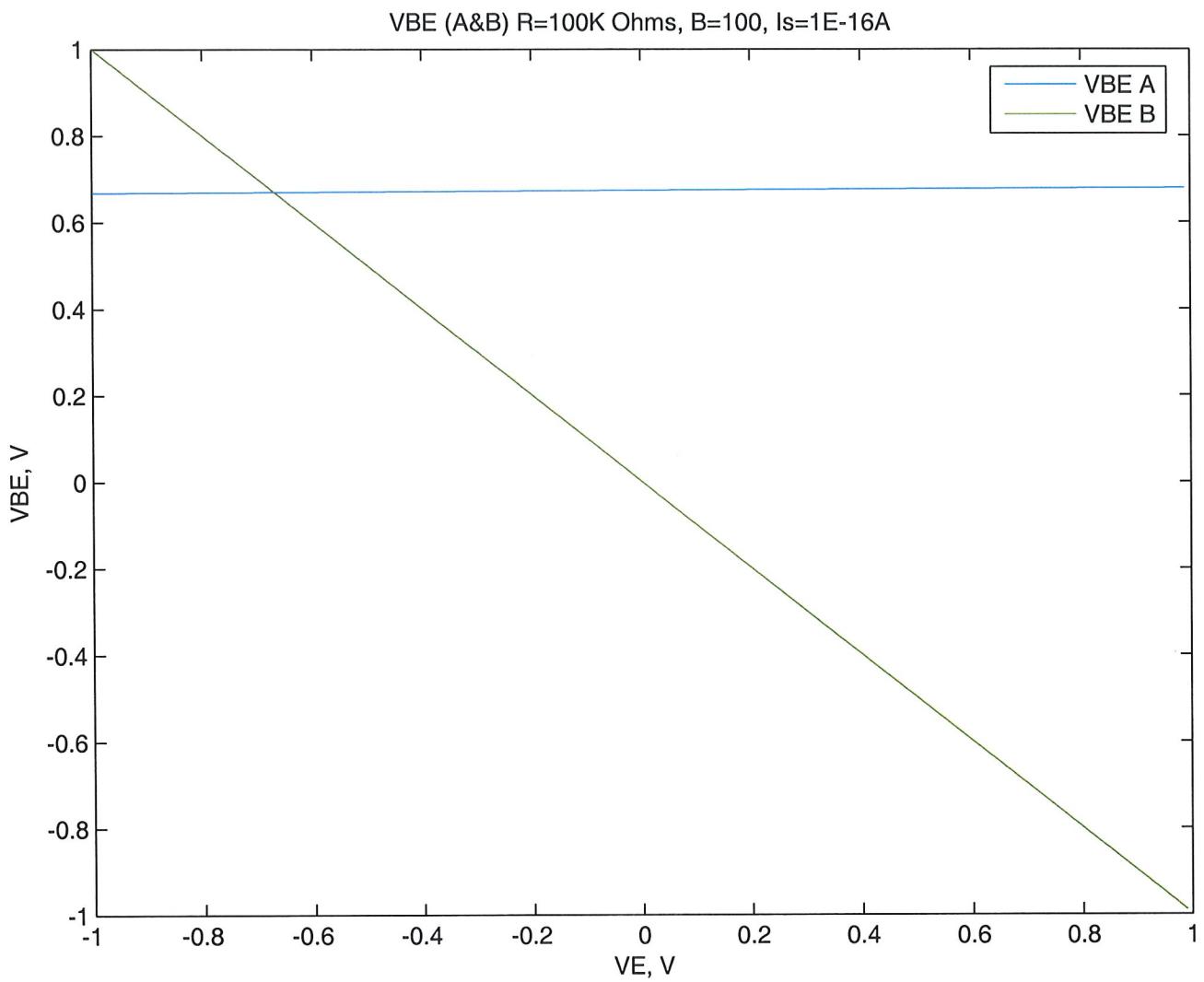
$$V_B \approx 0.84 \text{ V}$$



$$V_{BE} \approx 0.78V$$



$$V_{BE} \approx 0.72 V$$



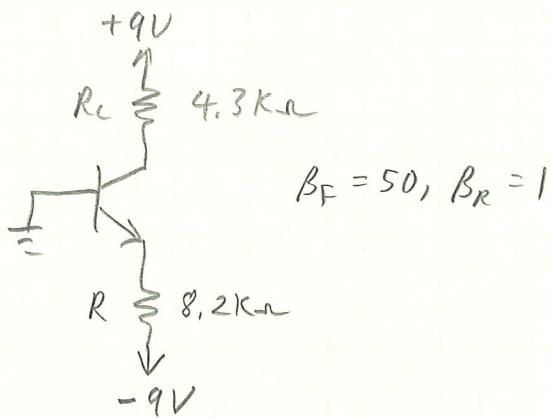
$$V_{BE} \approx 0.68V$$

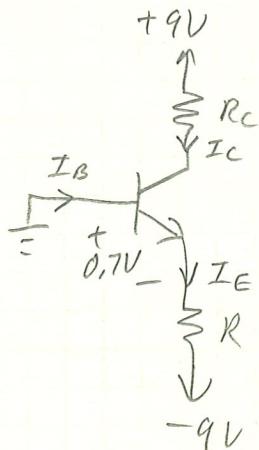
results :

$R$	$V_{BE}$
$10\text{k}\Omega$	$0.9V$
$100\text{k}\Omega$	$0.84V$
$1\text{K}\Omega$	$0.78V$
$10\text{k}\Omega$	$0.72V$
$100\text{k}\Omega$	$0.68V$

most likely  $R$  valuesResultFor forward Active Region ( $V_{BE} \geq 0V, V_{BC} \leq 0V$ )→ use  $V_{BE} = 0.7V$ 

$$I_C = \beta_F I_B = \alpha_F I_E$$

→ find Q-point:  $(I_C, V_{CE})$ Ex: find Q-point (p. 235)it appears that  $V_C > V_B > V_E$  ; assume Forward-Active Region

solution

$$KVL: -9 + I_E R + 0.7 = 0$$

$$\therefore I_E = \frac{9 - 0.7}{R} = \frac{9 - 0.7}{8.2k} = 1.012 \text{ mA}$$

$$I_C = \alpha_F I_E = \frac{50}{51} (1.012 \text{ mA}) = 0.922 \text{ mA}$$

$$I_B = \frac{I_C}{\beta_F} = \frac{0.922 \text{ mA}}{50} = 19.85 \mu\text{A}$$

$$V_C = 9 - I_C R_C = 9 - (0.922 \text{ mA})(4.3 \text{ k}\Omega) = 4.732 \text{ V}$$

$$V_E = -0.7 \text{ V}$$

$$\therefore V_{CE} = 4.732 - -0.7 = 5.43 \text{ V}$$

check: F.A.R. :  $V_C \geq V_B \geq V_E$

$$4.73 \text{ V} > 0 \text{ V} > -0.7 \text{ V} \quad \checkmark$$

$$Q\text{-point: } (I_C, V_{CE}) = (0.922 \text{ mA}, 5.43 \text{ V})$$

Note : Q-point in textbook is wrong