Safe Operating Limits of SiGe-THz Devices

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SiGe-THz devices: Physics and reliability
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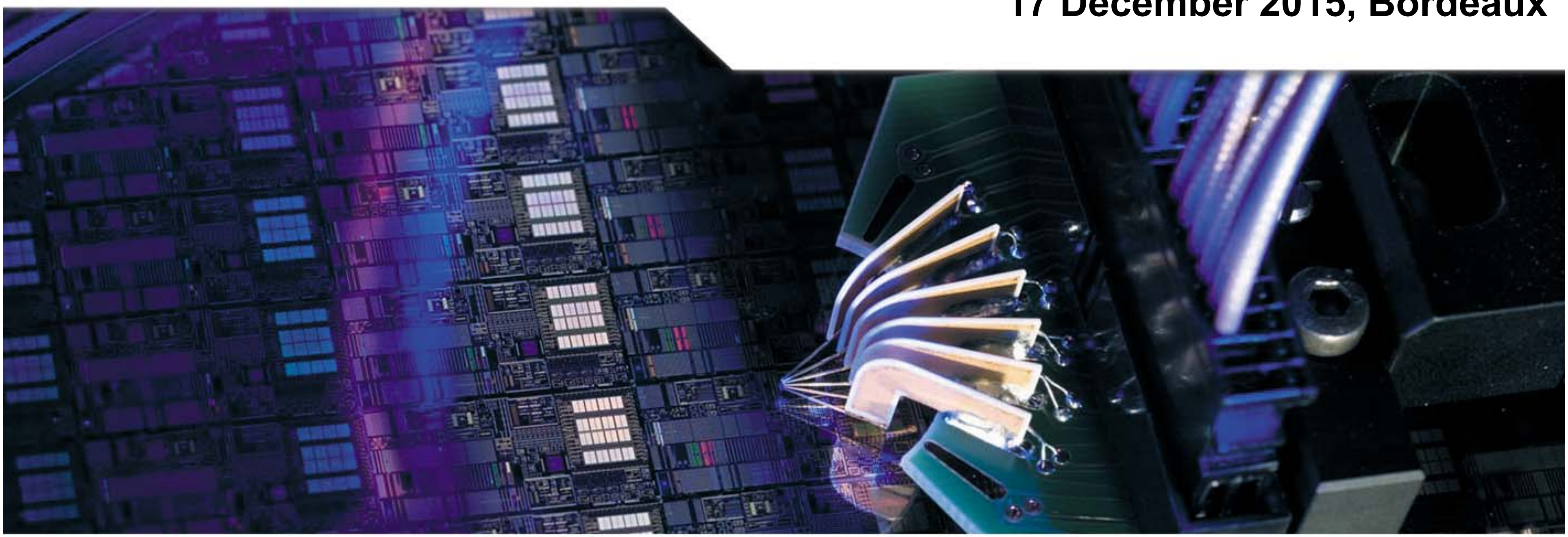
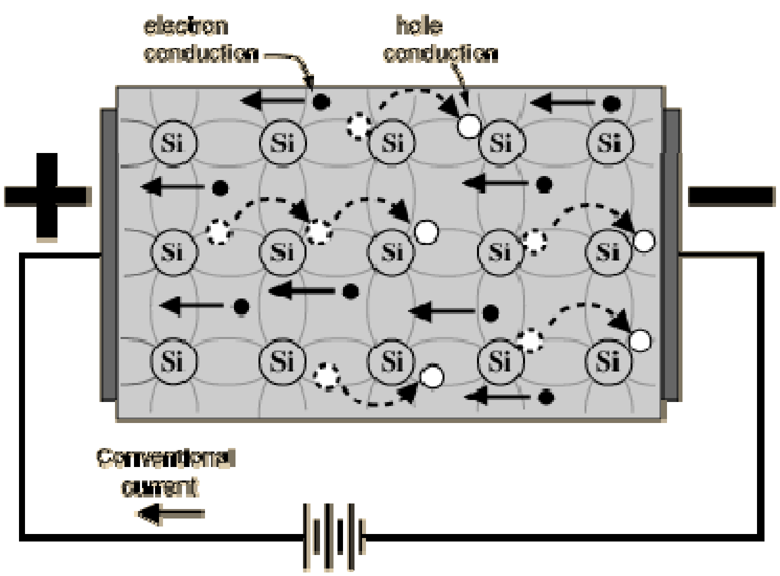


A European Project supported within the Seventh Framework Programme for Research and Technological Development

Outline

- Introduction
- Motivation
- Electro-Thermal (ET) Effects
- Impact Ionization (II) Effects
- Simultaneous ET and II Effects
- Device Design for Power Amplifier
- Multi-Finger Transistors
- Summary

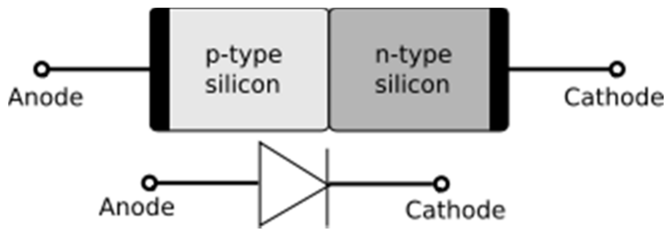
Introduction

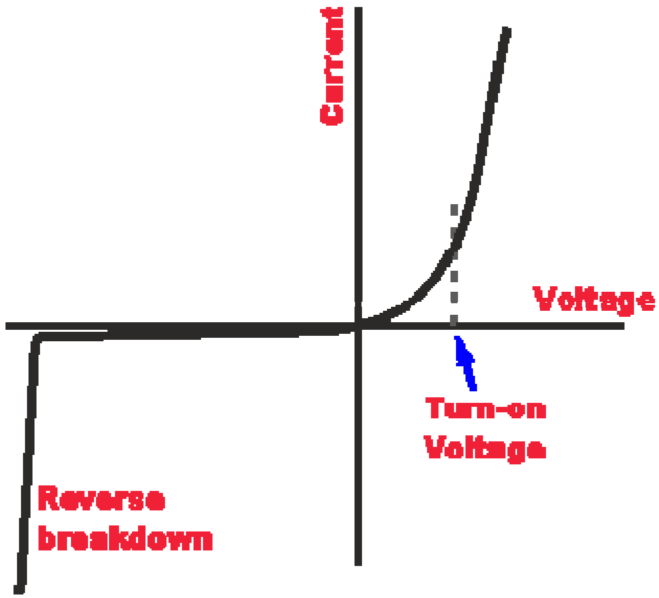


- Electrons and holes carry currents in a semiconductor material (Si, Ge, etc.)
- Doping increases either electron density (n-type) or hole density (p-type)
- A huge conductivity range (~10^{-8} to 10^{3} S/cm) appears interesting for application devices

Introduction (contd.)

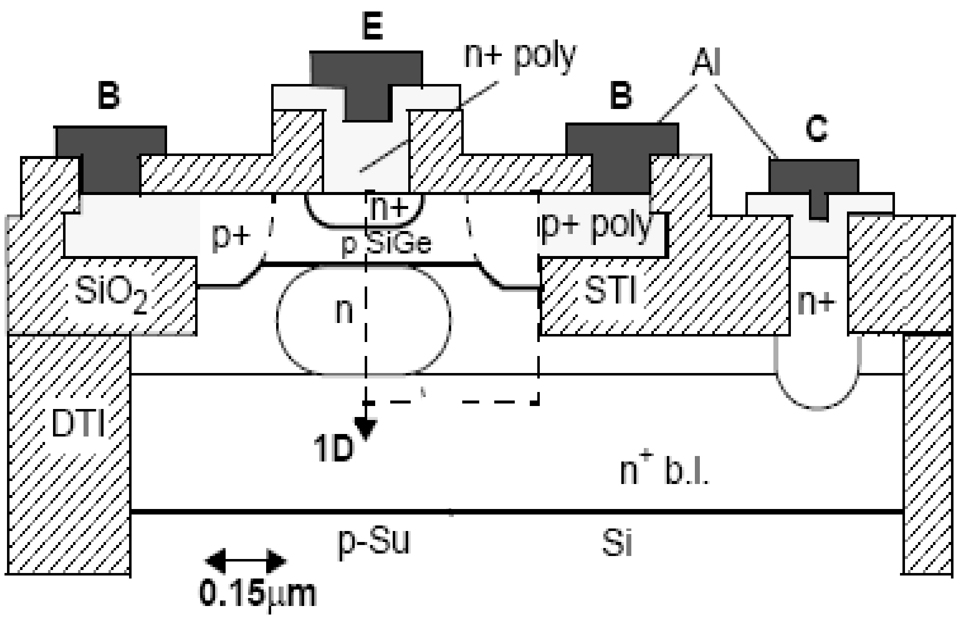
p-n diode

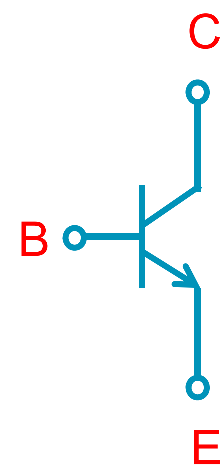




Introduction (contd.)

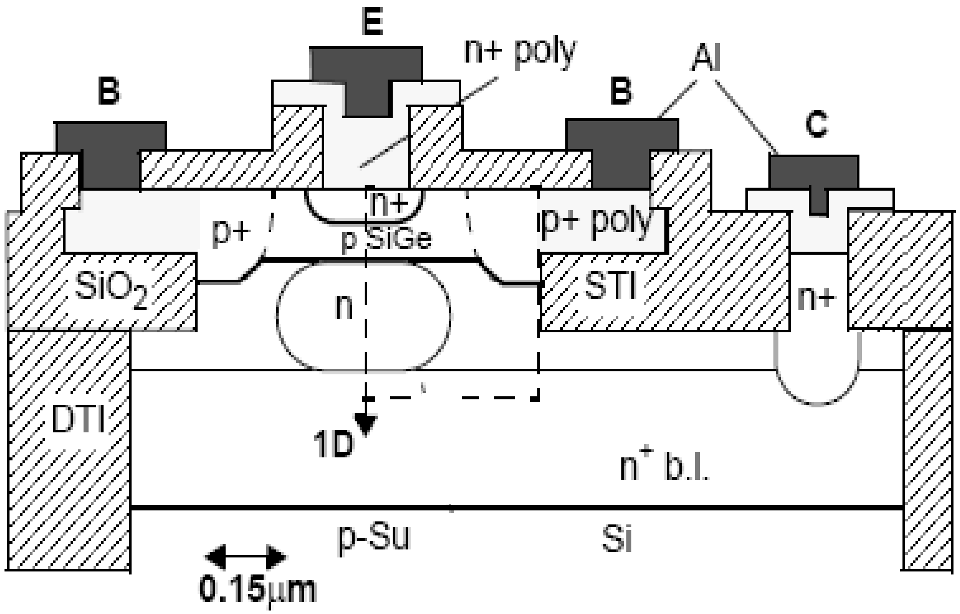
bipolar transistor

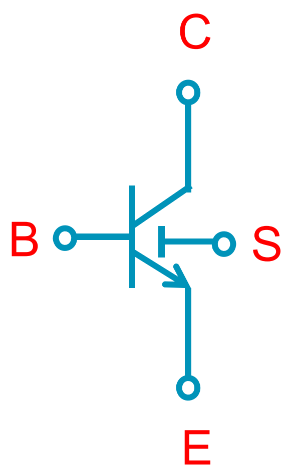




Introduction (contd.)

bipolar transistor





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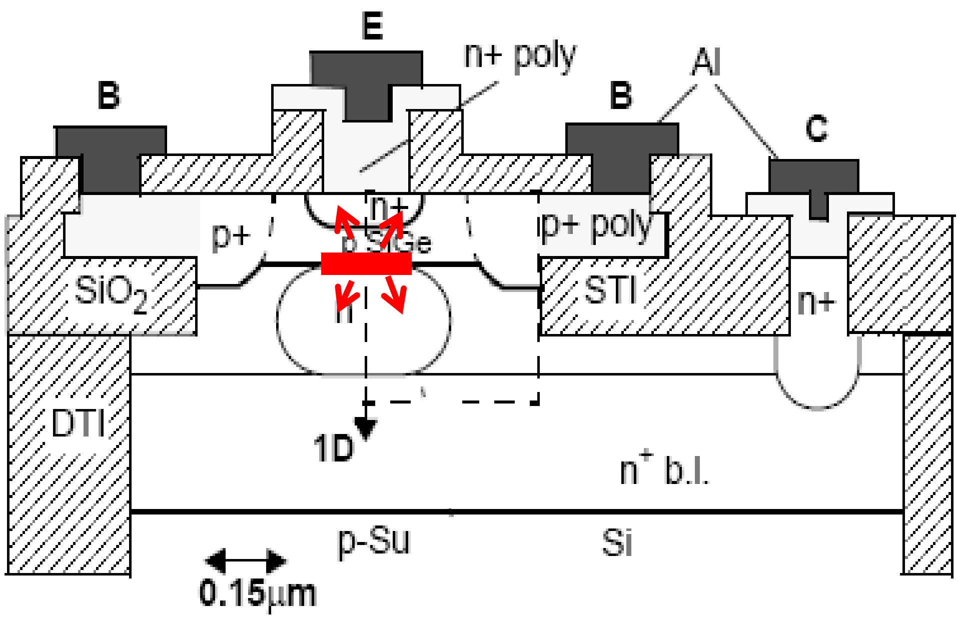
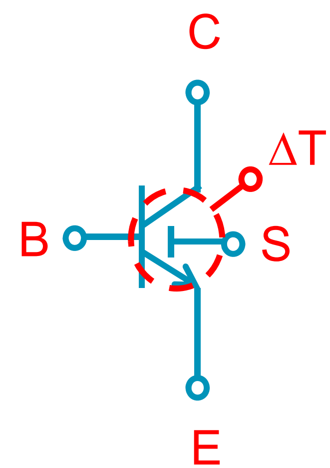
bipolar transistor

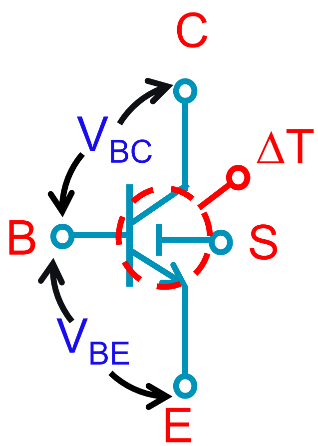




J x ***E*** = ***I*** x ***V*** / ***cm³*** = *volume power density*

Introduction (contd.)

Safe operating limit of bipolar transistor



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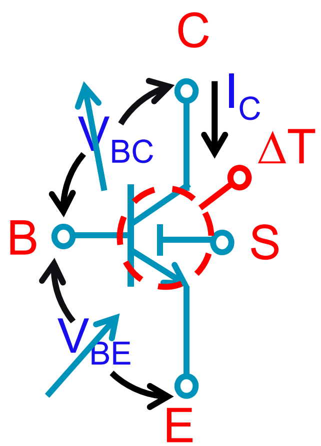

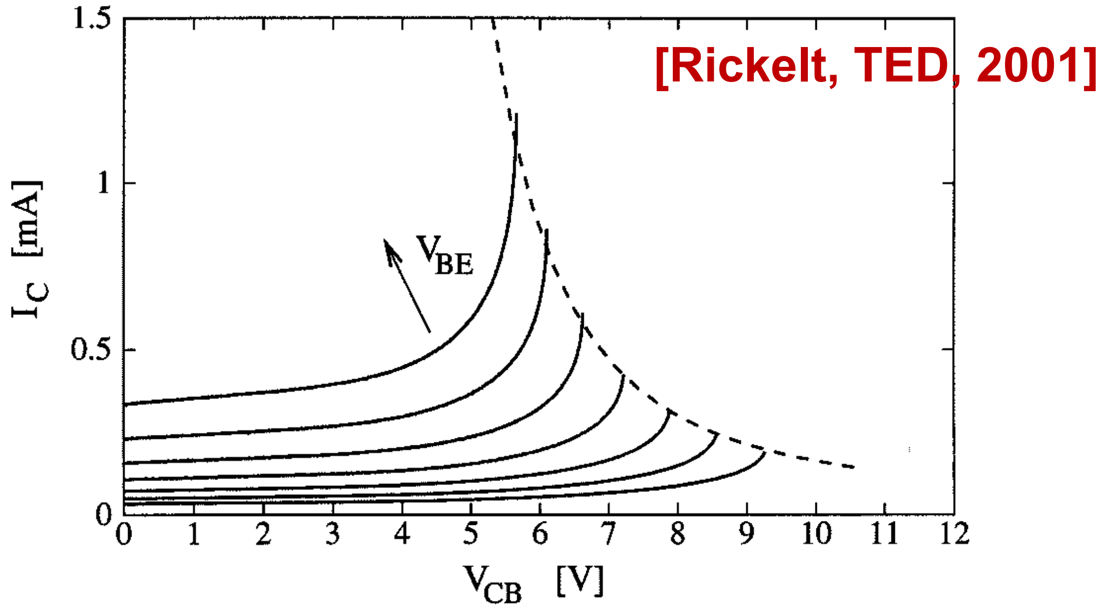

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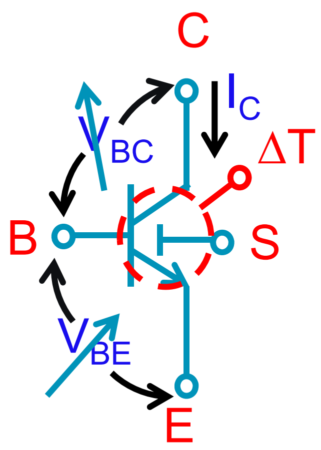
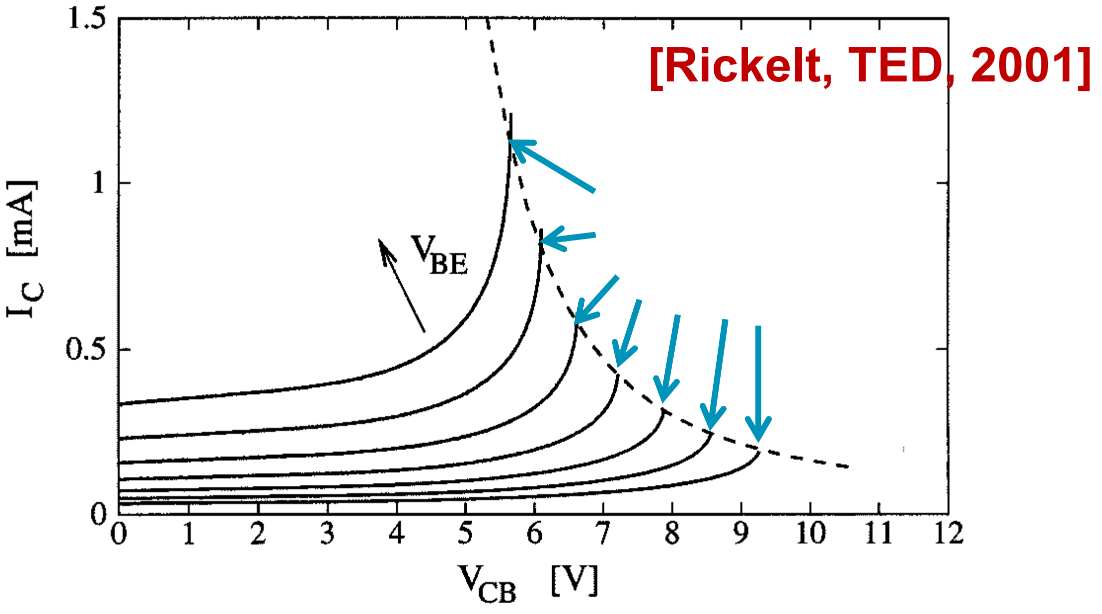
Safe operating limit of bipolar transistor





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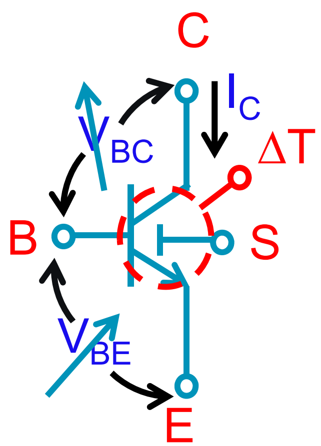
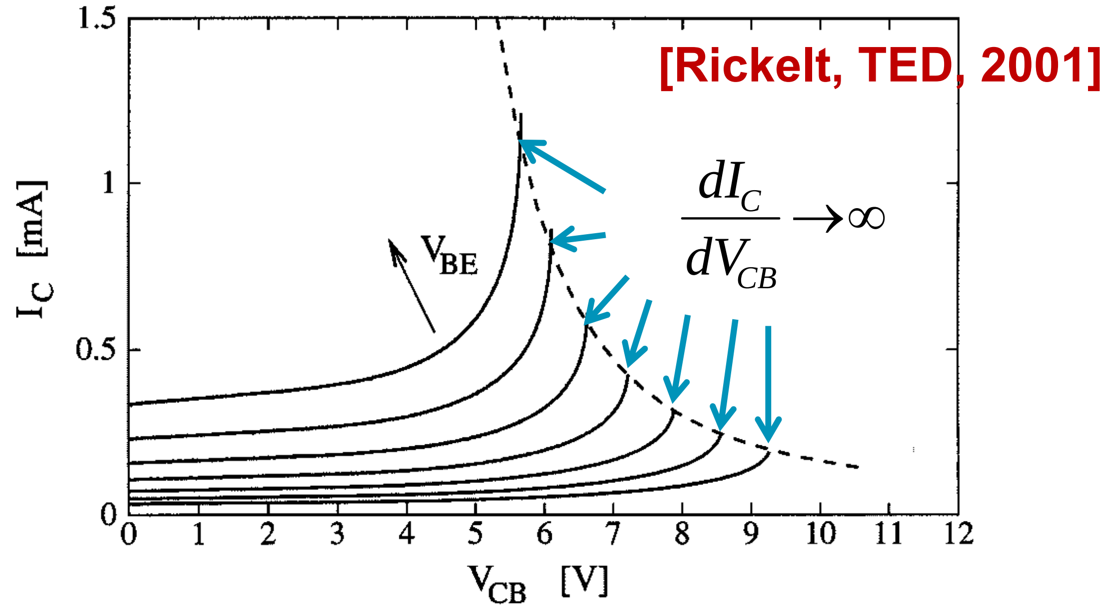
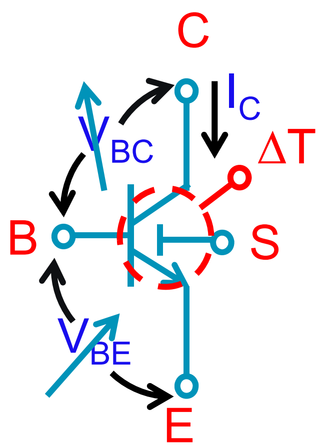
Safe operating limit of bipolar transistor

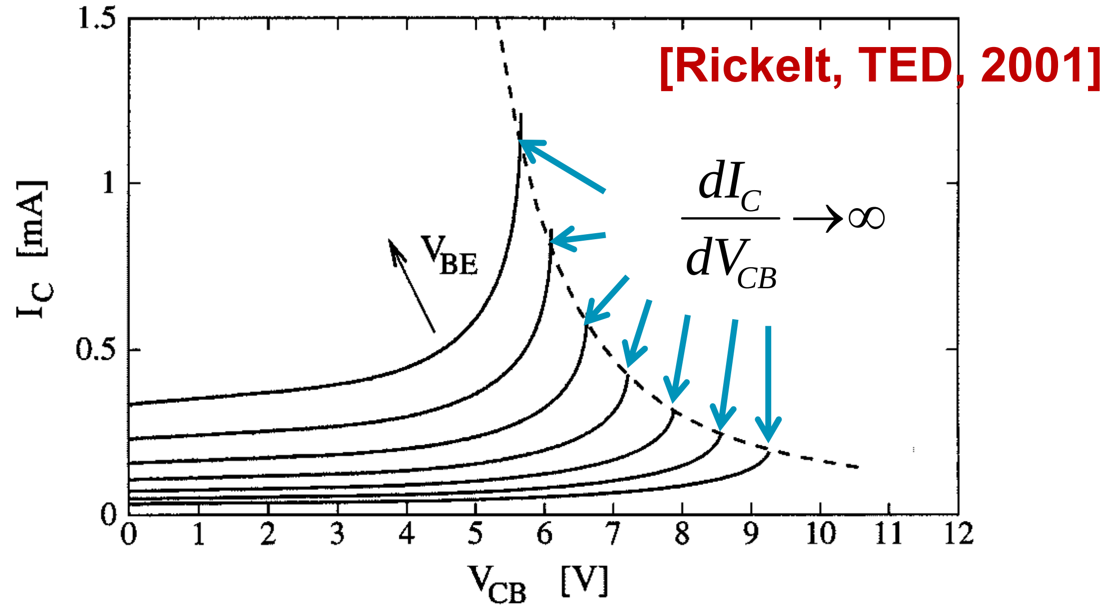




Introduction (contd.)

Safe operating limit of bipolar transistor



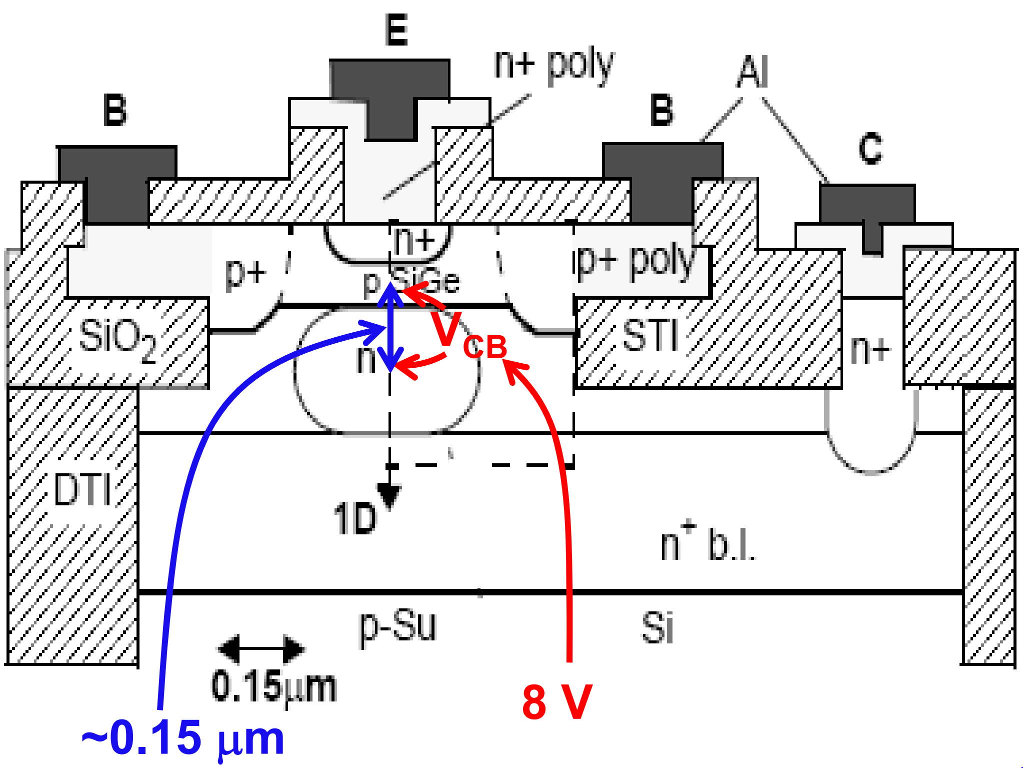


Two major factors

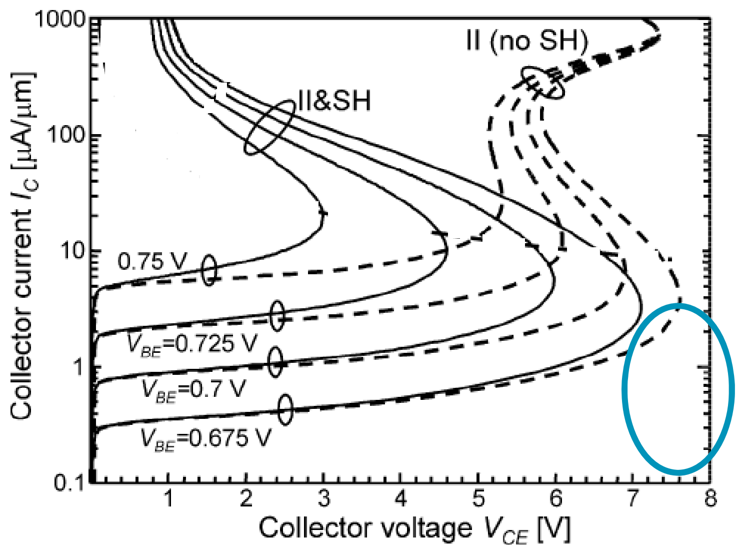
- **Impact ionization (or avalanche breakdown)**
- **Electro-thermal heating (or self-heating)**

Introduction (contd.)

Safe operating limit of bipolar transistor



[Rinaldi, TED, 2005]

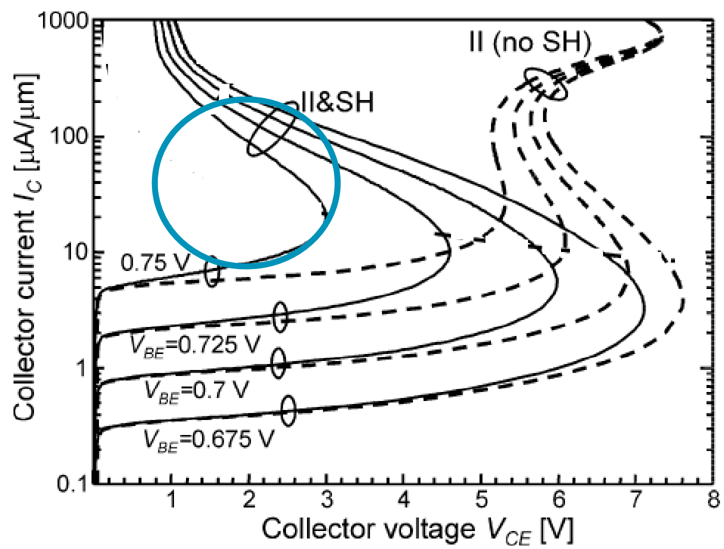


Electric field E~10^6 V/cm → avalanche breakdown

Introduction (contd.)

Safe operating limit of bipolar transistor

[Rinaldi, TED, 2005]



high current density → high self-heating

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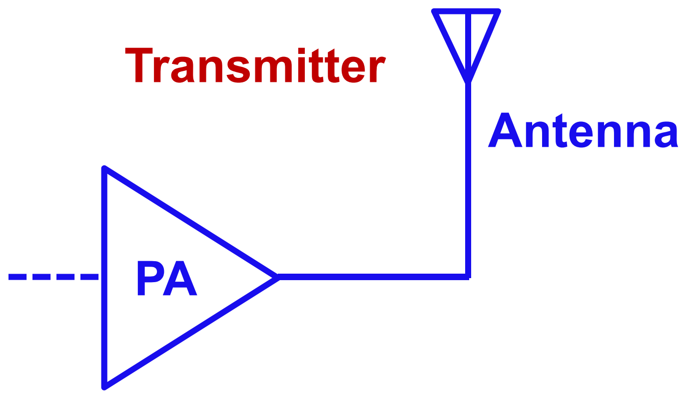
Motivation

1. Circuits that handle higher power, such as power amplifier (PA), usually forces the transistors to operate at their safe operating limits

2. While designing the PA, one should have clear idea on the safe operating limits of the given transistors

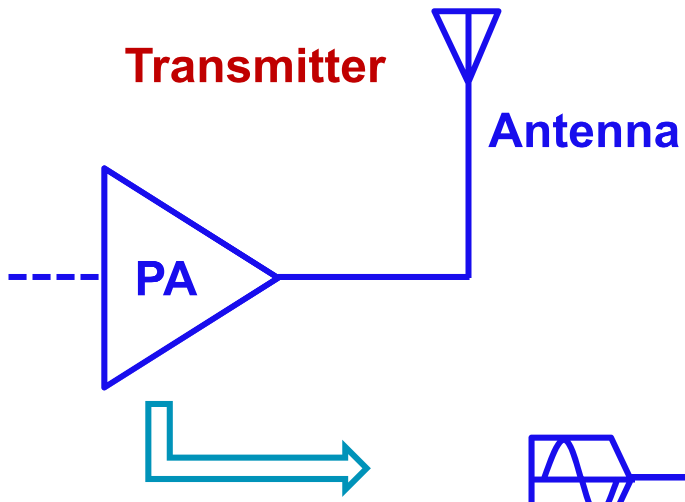
3. Transistors with higher safe operating limits are useful for PA design

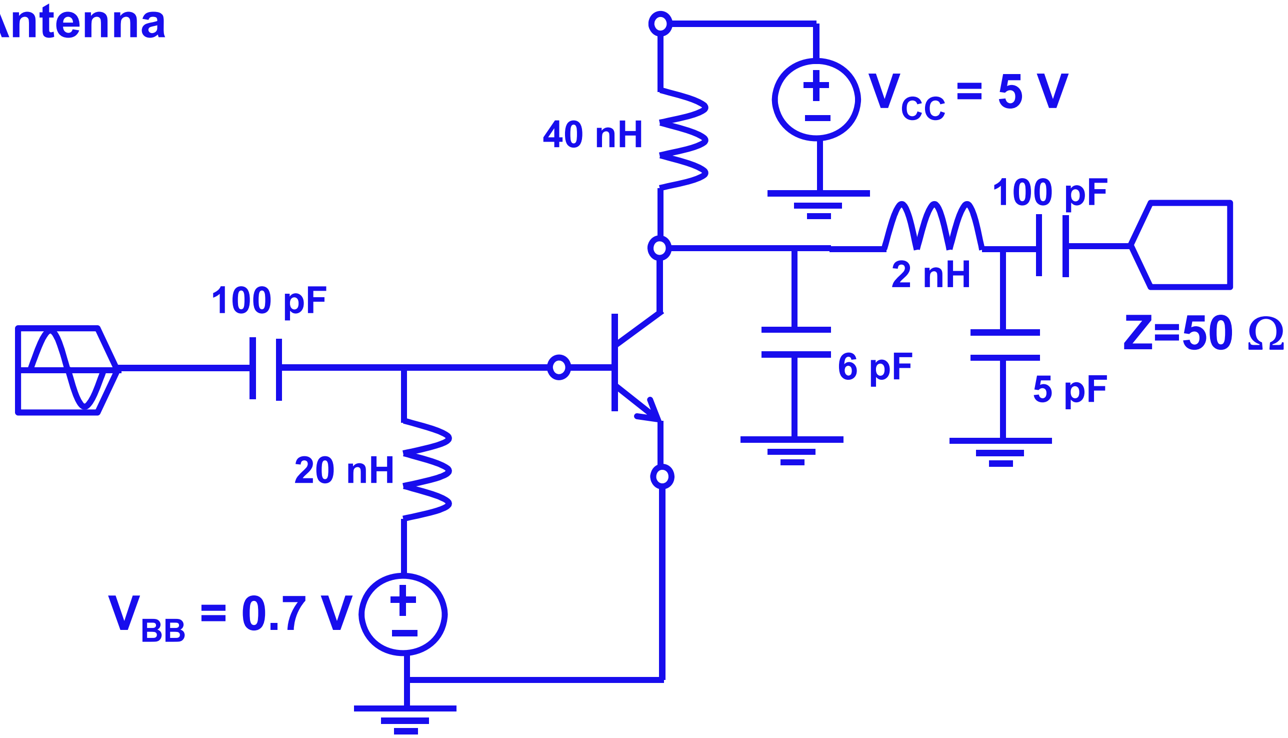
Motivation (contd.)



Motivation (contd.)

[Cripps, RF Power Amplifiers for Wireless Communications, Artech House, 2nd Edn., Ch. 5, 2006]





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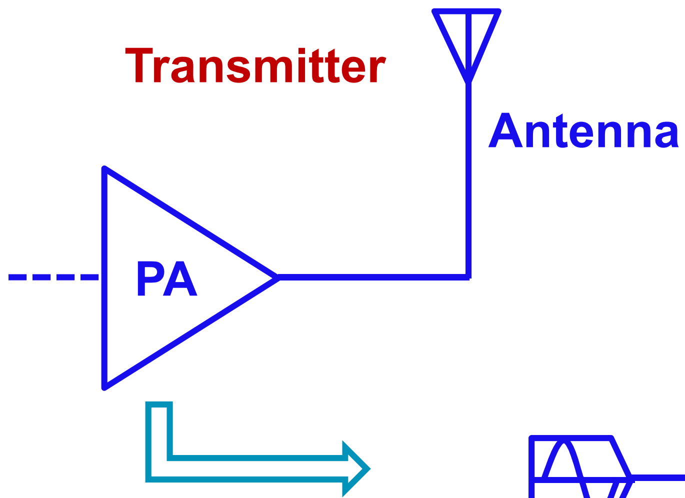

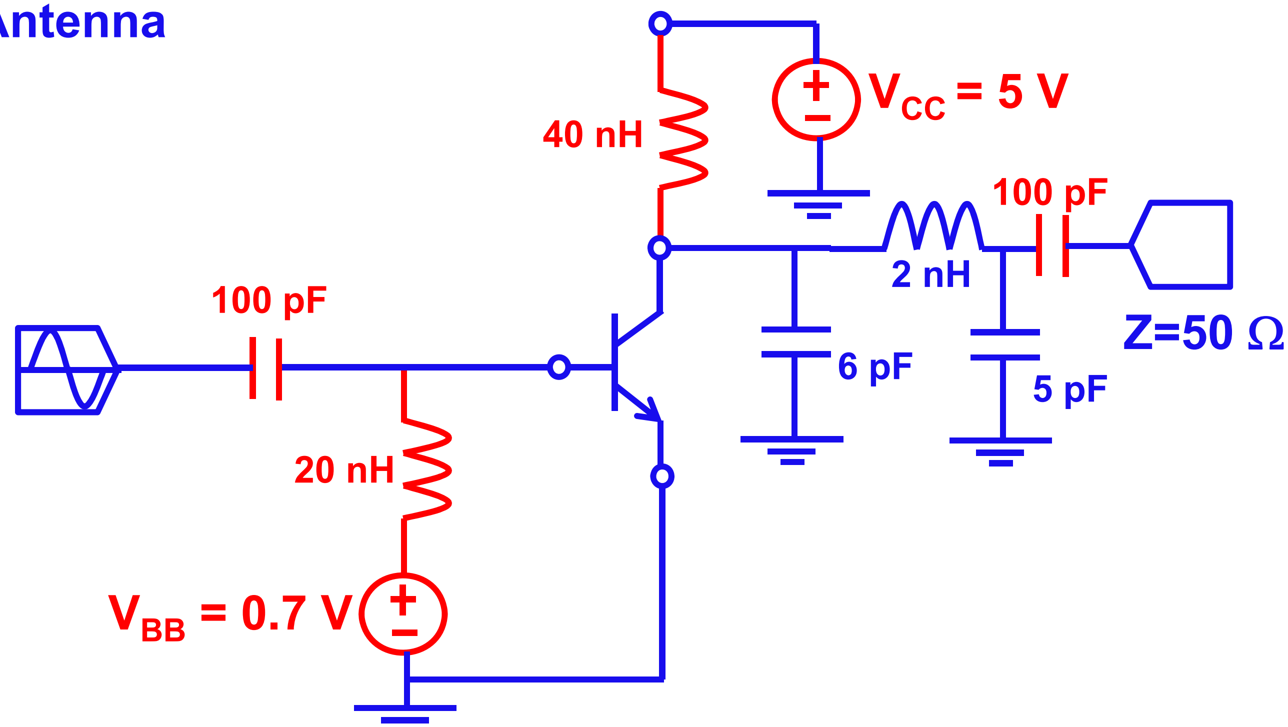

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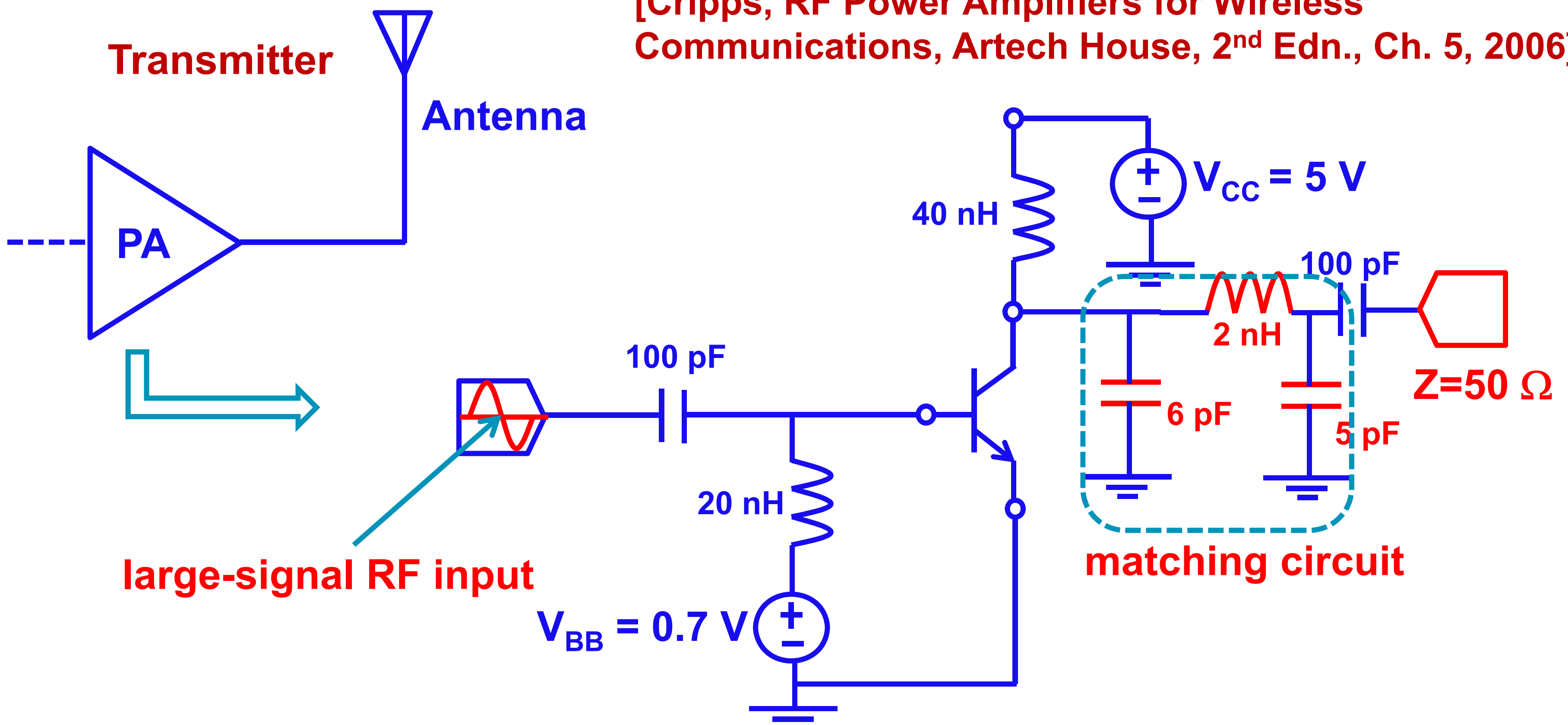

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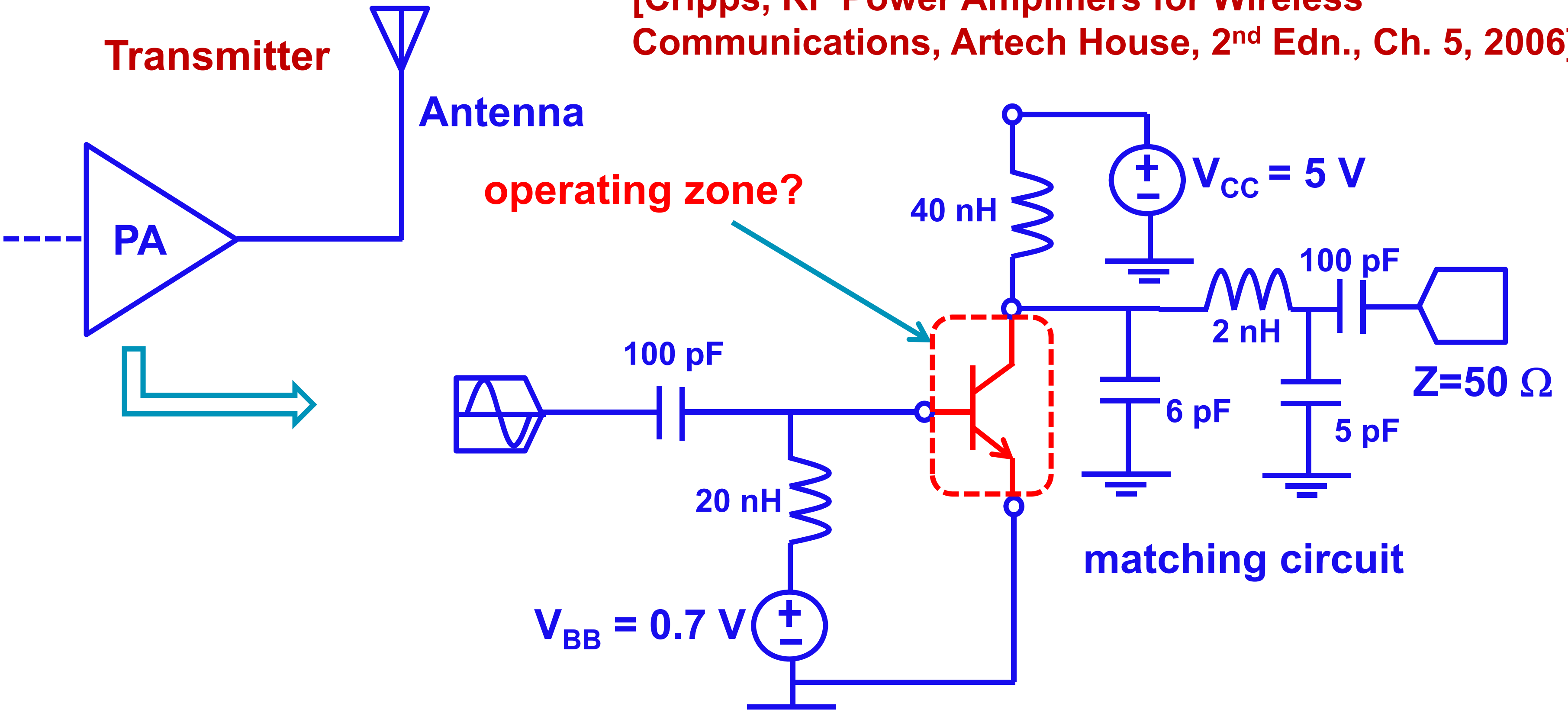
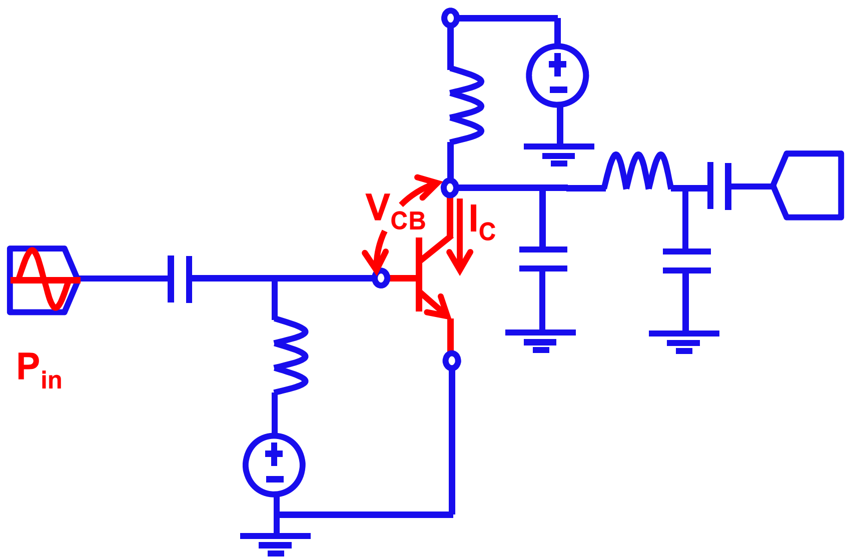
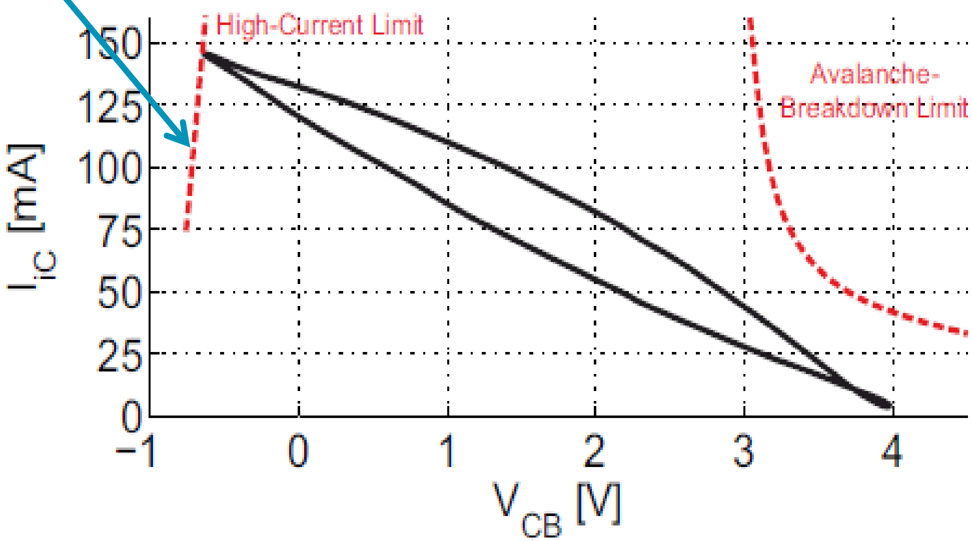


Motivation (contd.)

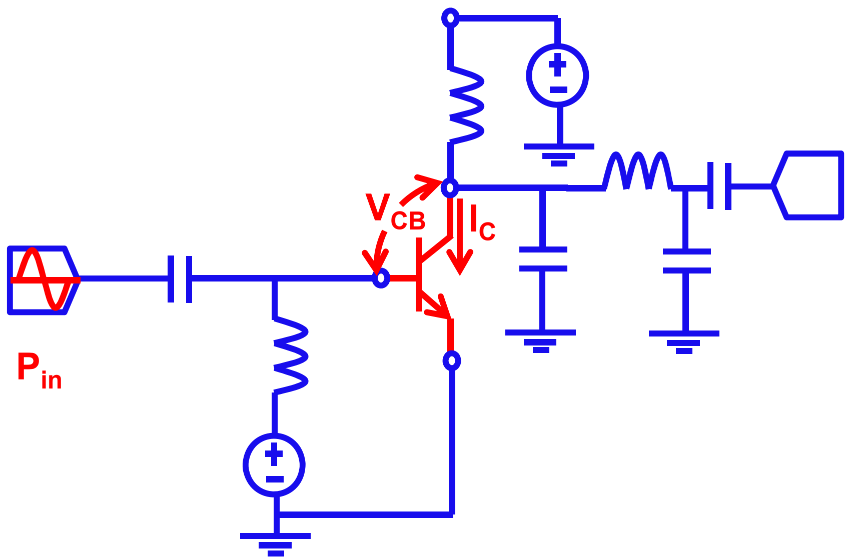
[Welp, BCTM, 2015]

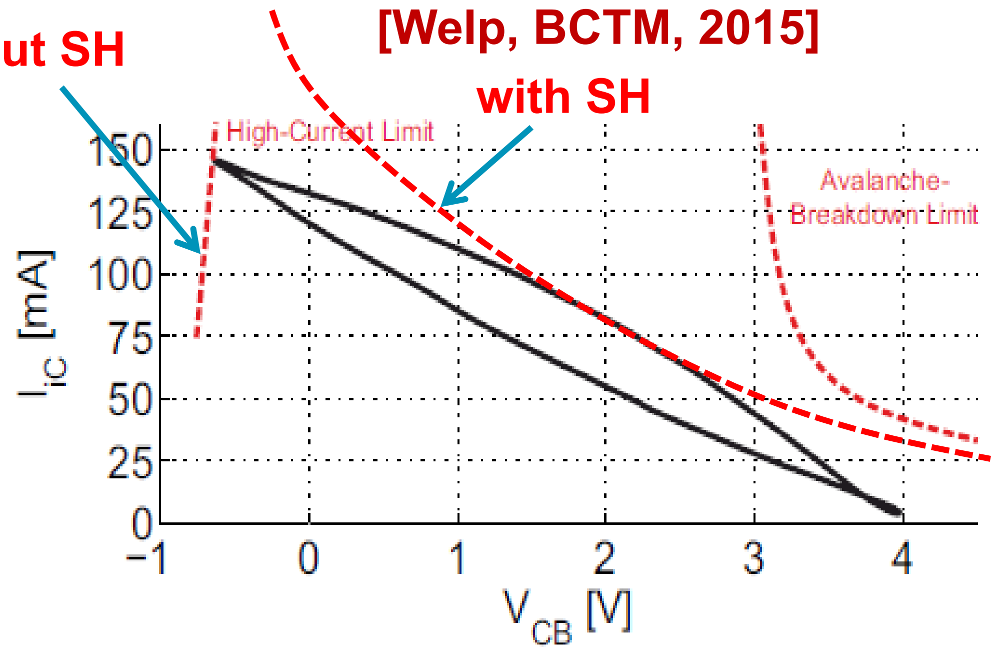
without SH





Motivation (contd.)





1. Circuits that handle higher power, such as power amplifier (PA), usually forces the transistors to operate at their safe operating limits

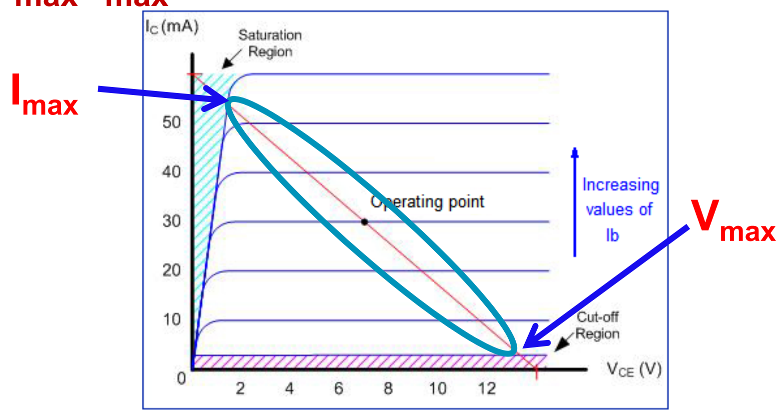
Motivation (contd.)

2. While designing the PA, one should have clear idea on the safe operating limits of the given transistors

PA design considerations

(from transistor's perspective)

- **To maximize the output power of the transistor, the optimal load value is equal to $R_{opt} \approx V_{max}/I_{max}$ which has to match with 50 Ω off-chip antenna**



- **Usually I_{max} is high for bipolar transistors and the V_{max} is limited by the breakdown voltage that depends on bias configuration**

Motivation (contd.)

3. Transistors with higher safe operating limits are useful for PA design

MOSFETs vs. Bipolar Transistors

- **continued scaling aggressively reduces the BV for MOSFETs (more than BJTs)**
- **also I_{ON} for MOSFETs is saturated to ~1mA/μm in the newer technology nodes**
- **larger bias current needed to obtain a comparable output power → requires larger MOSFETs**
- **$R_{opt}=BV/I_{max}=BV/2.I_{dc}$ appears smaller → complicated output matching**
- **relatively larger BV of BJTs permits lower bias current → smaller devices**
- **simplified output matching!!**
- **design better bipolar transistors for high end PAs**

Motivation (contd.)

Understanding the theory behind the safe operating limits of modern bipolar transistors is important!!

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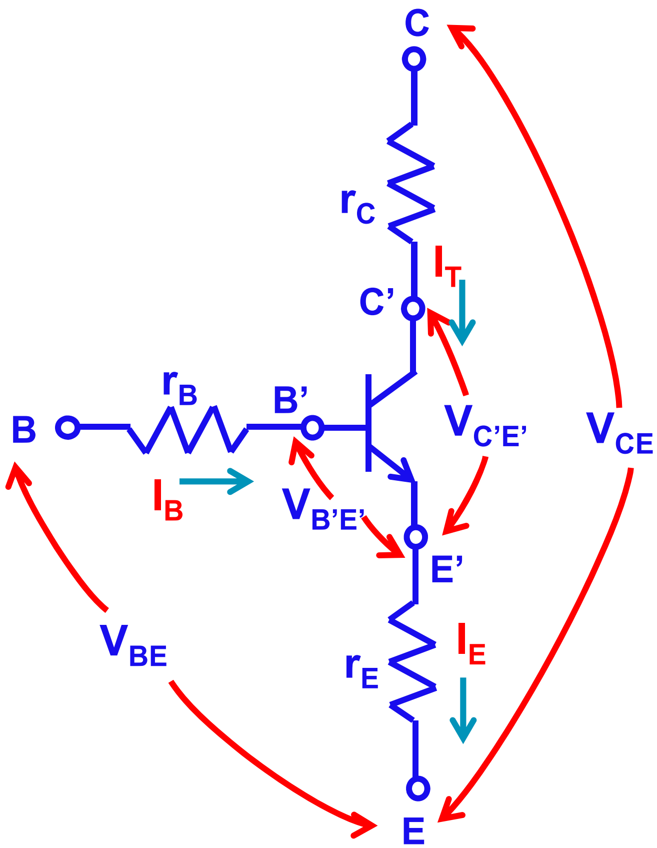
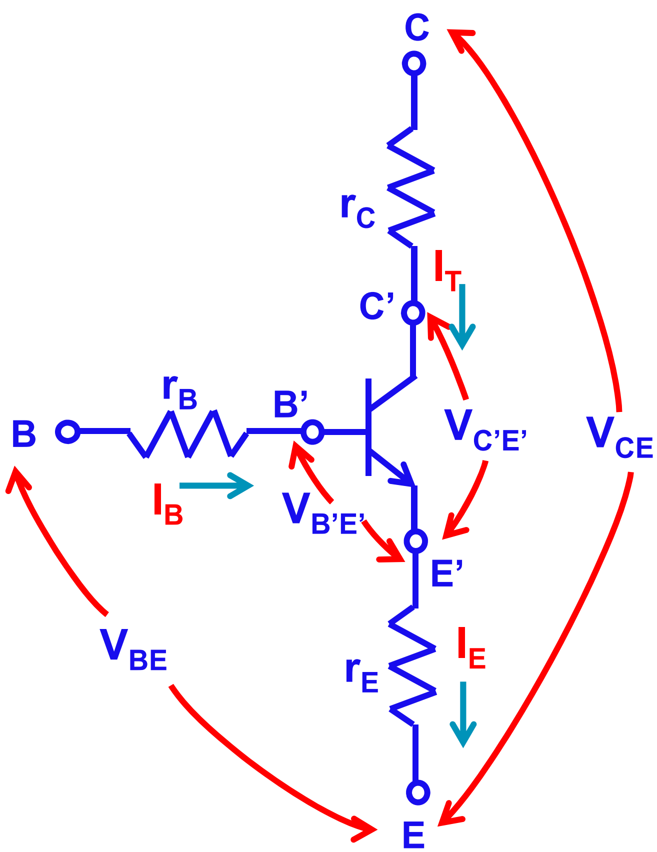
Electro-Thermal Effects



Electrical current dissipates power within the device increasing the junction temperature, which in turn increases the electrical current further, and so on and so forth…..a positive feedback…causing an instability or unsafe operation.

Electro-Thermal Effects



$$I_C = I_T = \frac{I_S}{1 - \frac{V_{CE}}{V_A}} \exp\left(\frac{V_{B'E'} + \phi \Delta T}{\eta V_{T0}}\right)$$

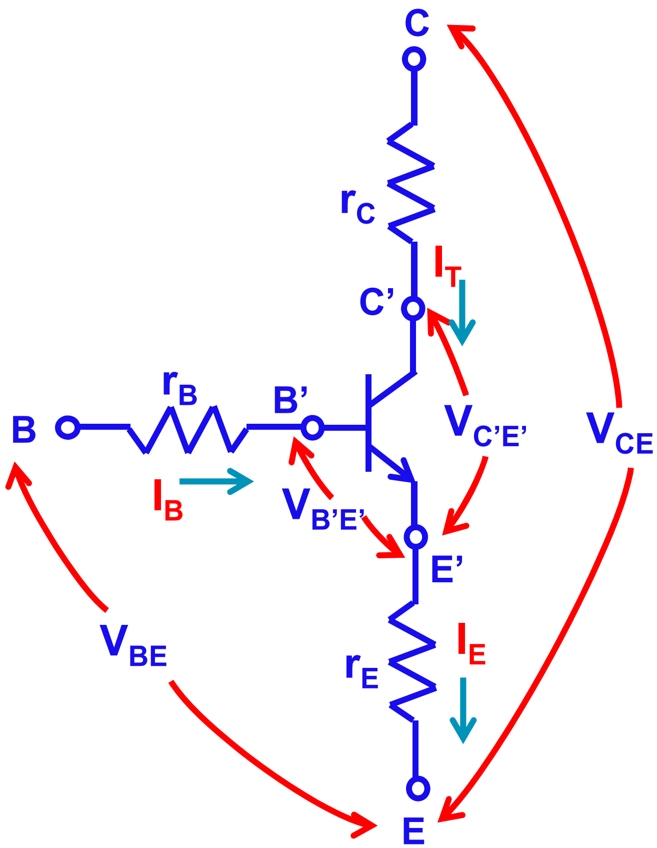
$$V_{B'E'} = V_{BE} - I_B r_B - I_E r_E = V_{BE} - I_C R_{EB}$$

$$\Delta T = R_{TH} P_{diss} = R_{TH}\left(I_B V_{BE} + I_C V_{CE}\right) = R_{TH} I_C V_{eq}$$

$$V_{eq} = V_{CE} + V_{BE}\left(\frac{1}{\alpha_F} - 1\right)$$

$$R_{EB} = \frac{R_E}{\alpha_F} + \frac{R_B}{\beta_F} \qquad \phi = -\left.\frac{\partial V_{BE}}{\partial T}\right|_{I_C}$$

Electro-Thermal Effects



$$I_C = I_T = \frac{I_S}{1 - \frac{V_{CE}}{V_A}} \exp\left(\frac{V_{B'E'} + \phi \Delta T}{\eta V_{T0}}\right)$$

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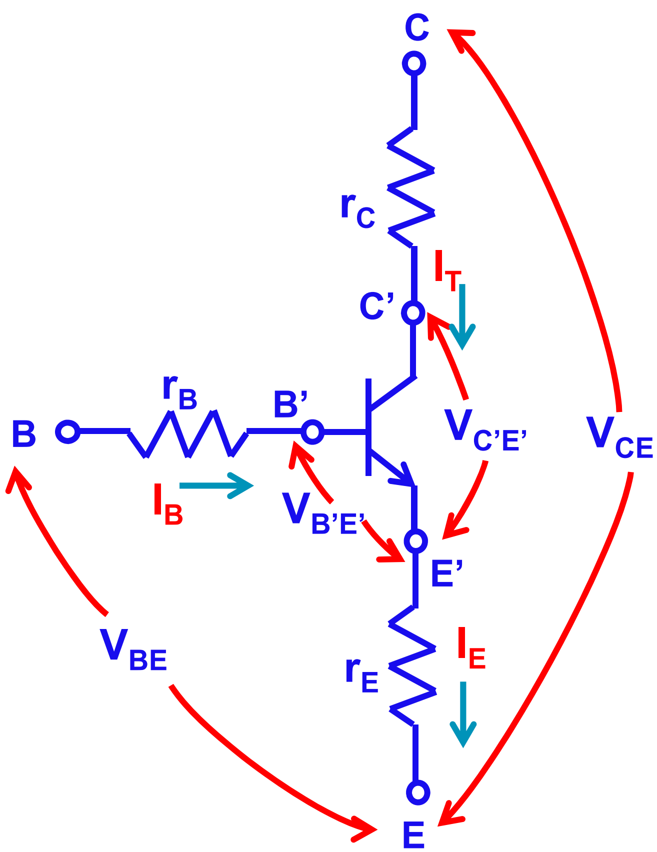
Electro-Thermal Effects



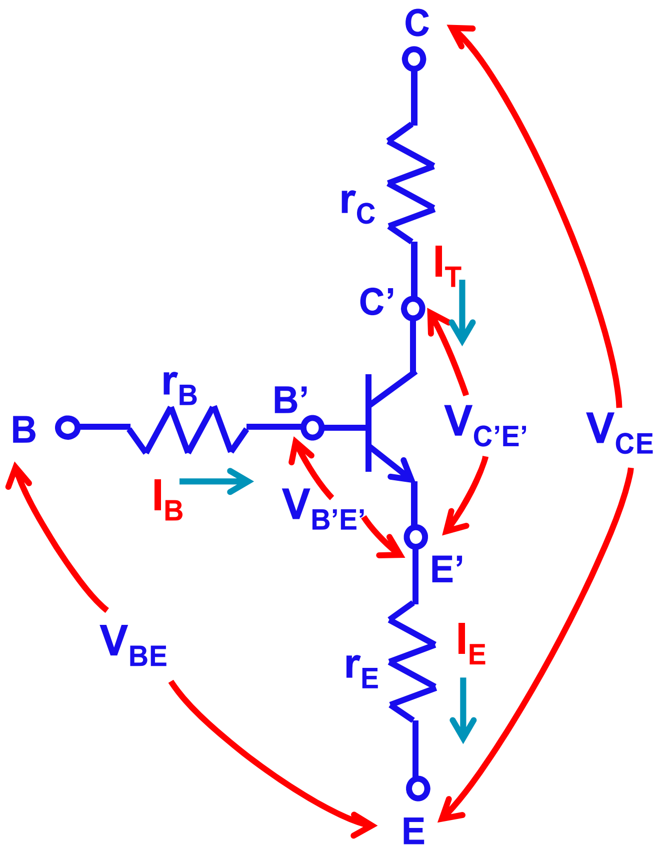
$$I_C = I_T = \frac{I_S}{1 - \frac{V_{CE}}{V_A}} \exp\left(\frac{V_{BE} + I_C \left[\phi R_{TH} V_{eq} - R_{EB} \right]}{\eta V_{T0}} \right)$$

$$V_{eq} = V_{CE} + V_{BE}\left(\frac{1}{\alpha_F} - 1 \right)$$

$$R_{EB} = \frac{R_E}{\alpha_F} + \frac{R_B}{\beta_F}$$

$$\phi = -\left. \frac{\partial V_{BE}}{\partial T} \right|_{I_C}$$

Electro-Thermal Effects



$$I_C = I_T = \frac{I_S}{1 - \frac{V_{CE}}{V_A}} \exp\left(\frac{V_{BE} + I_C\left[\phi R_{TH} V_{eq} - R_{EB}\right]}{\eta V_{T0}} \right)$$

$$V_{eq} = V_{CE} + V_{BE}\left(\frac{1}{\alpha_F} - 1 \right) \approx V_{CE}$$

$$R_{EB} = \frac{R_E}{\alpha_F} + \frac{R_B}{\beta_F}$$

$$\phi = -\left.\frac{\partial V_{BE}}{\partial T}\right|_{I_C}$$

Electro-Thermal Effects

Constant ϕ model

$$I_C = \frac{I_S}{1 - \frac{V_{CE}}{V_A}} \exp\left(\frac{V_{BE} + I_C \left[\phi R_{TH} V_{CE} - R_{EB} \right]}{\eta V_{T0}} \right)$$

Electro-Thermal Effects

$$I_C = \frac{I_S}{1 - \frac{V_{CE}}{V_A}} \exp\left(\frac{V_{BE} + I_C\left[\phi R_{TH} V_{CE} - R_{EB}\right]}{\eta V_{T0}} \right)$$

$$V_{CE} \rightarrow 0$$

$$I_C = I_{C0} = I_S \exp\left(\frac{V_{BE} - R_{EB} I_C}{\eta V_{T0}} \right)$$

Electro-Thermal Effects

$$I_C = \frac{I_S}{1-\frac{V_{CE}}{V_A}} \exp\left(\frac{V_{BE} + I_C\left[\phi R_{TH} V_{CE} - R_{EB}\right]}{\eta V_{T0}}\right)$$

$$V_{CE} \rightarrow 0$$

$$I_{C0} = I_S \exp\left(\frac{V_{BE} - R_{EB} I_C}{\eta V_{T0}}\right)$$

$$i = \frac{I_C}{I_{C0}} \qquad v = \frac{\phi R_{TH} V_{CE} I_{C0}}{V_{T0}}$$

$$r_{EB} = \frac{R_{EB} I_{C0}}{V_{T0}} \qquad v_A = \frac{\phi R_{TH} V_A I_{C0}}{V_{T0}}$$

Electro-Thermal Effects

$$i = \frac{\exp\left(\left(v - r_{EB}\right)i + r_{EB}\right)}{1 - \dfrac{v}{v_A}}$$

$$i = \frac{I_C}{I_{C0}}$$

$$v = \frac{\phi R_{TH} V_{CE} I_{C0}}{V_{T0}}$$

$$r_{EB} = \frac{R_{EB} I_{C0}}{V_{T0}}$$

$$v_A = \frac{\phi R_{TH} V_A I_{C0}}{V_{T0}}$$

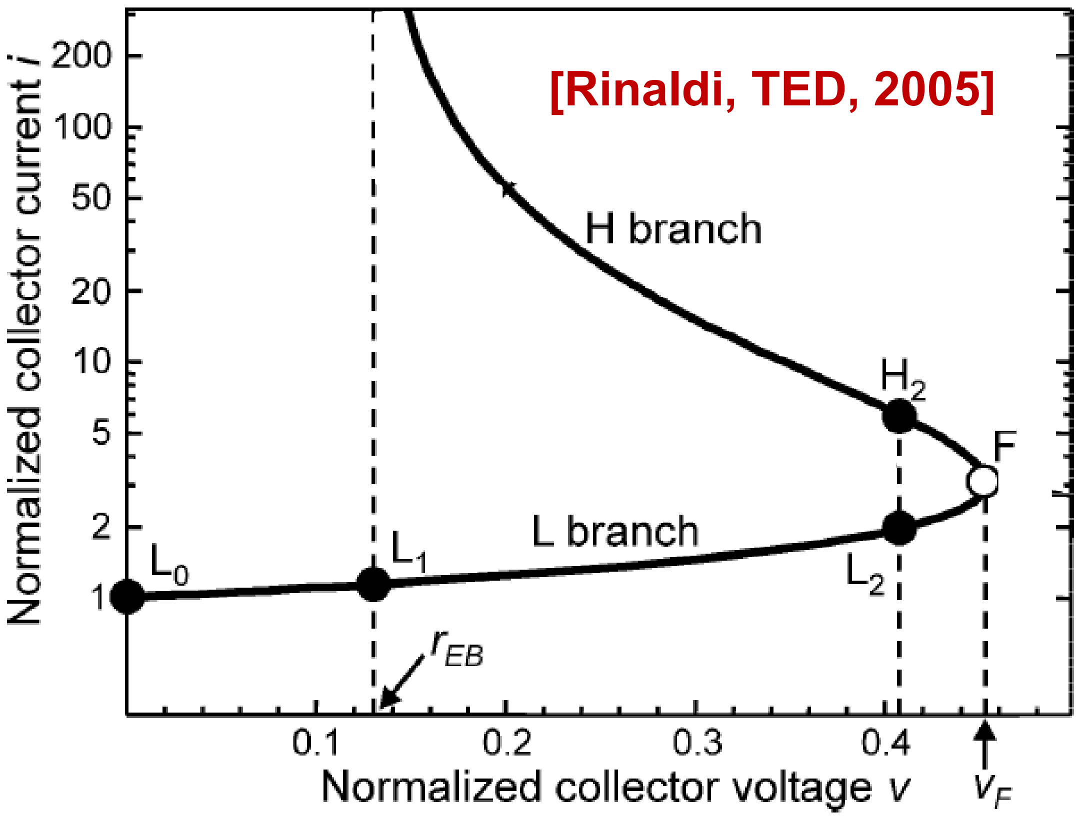
Electro-Thermal Effects

Iterative solution

$$i = \frac{\exp\left(\left(v - r_{EB}\right)i + r_{EB}\right)}{1 - \dfrac{v}{v_A}}$$

$$r_{EB} = 0.13$$

$$v_A \rightarrow \infty$$



Electro-Thermal Effects

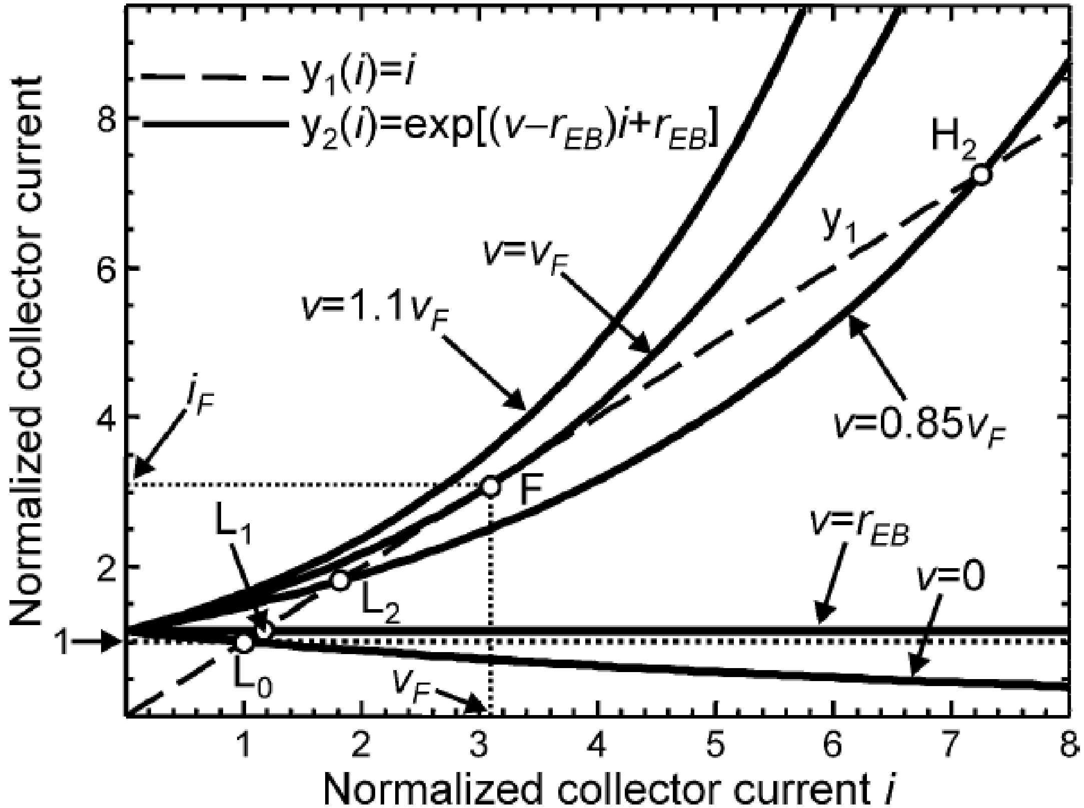
Geometric solution

$$i = \frac{\exp\left(\left(v - r_{EB}\right)i + r_{EB}\right)}{1 - \frac{v}{v_A}}$$

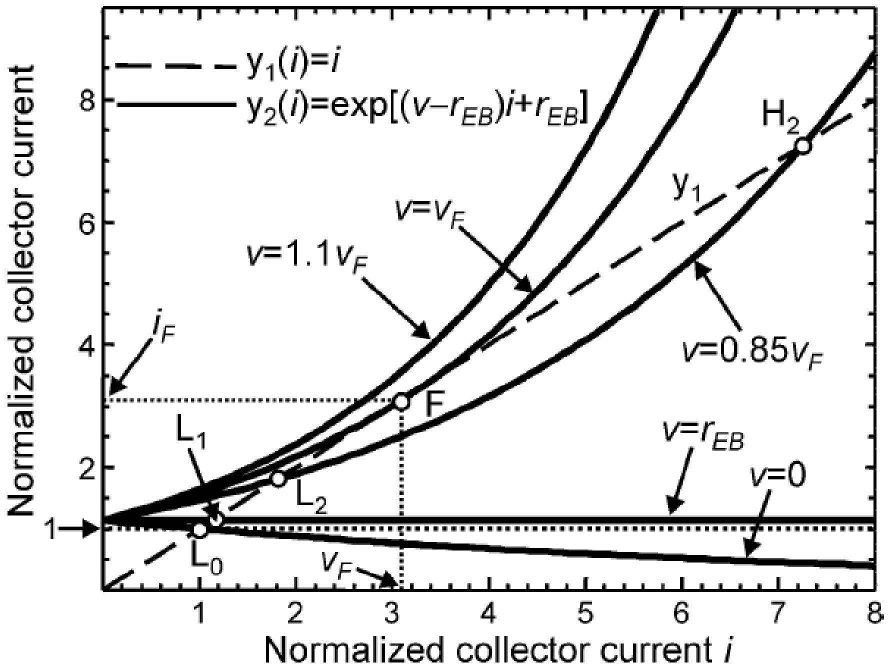
$$r_{EB} = 0.13$$

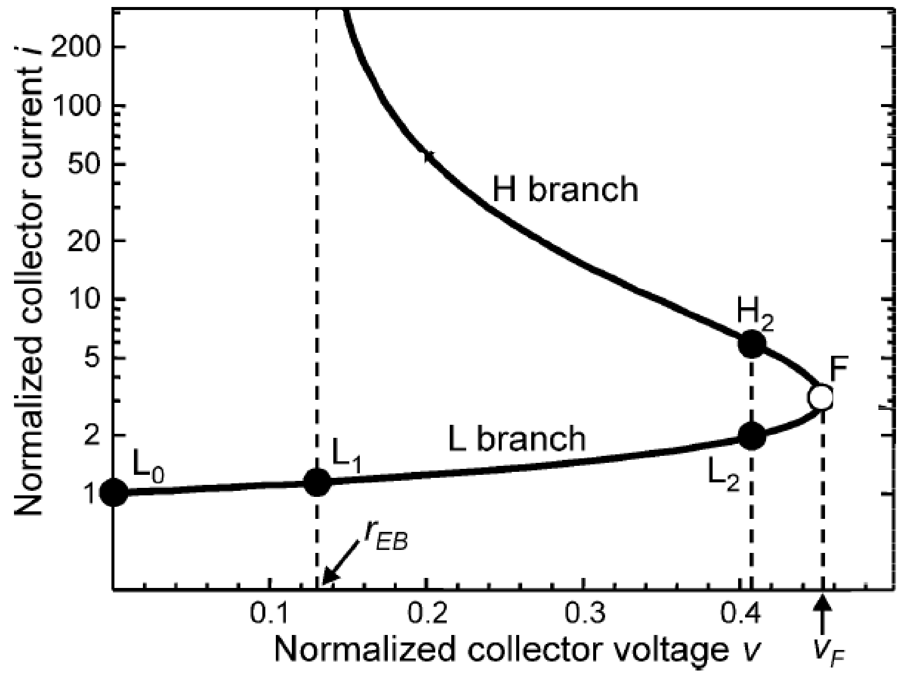
$$v_A \to \infty$$

[Rinaldi, TED, 2005]



Electro-Thermal Effects





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Electro-Thermal Effects

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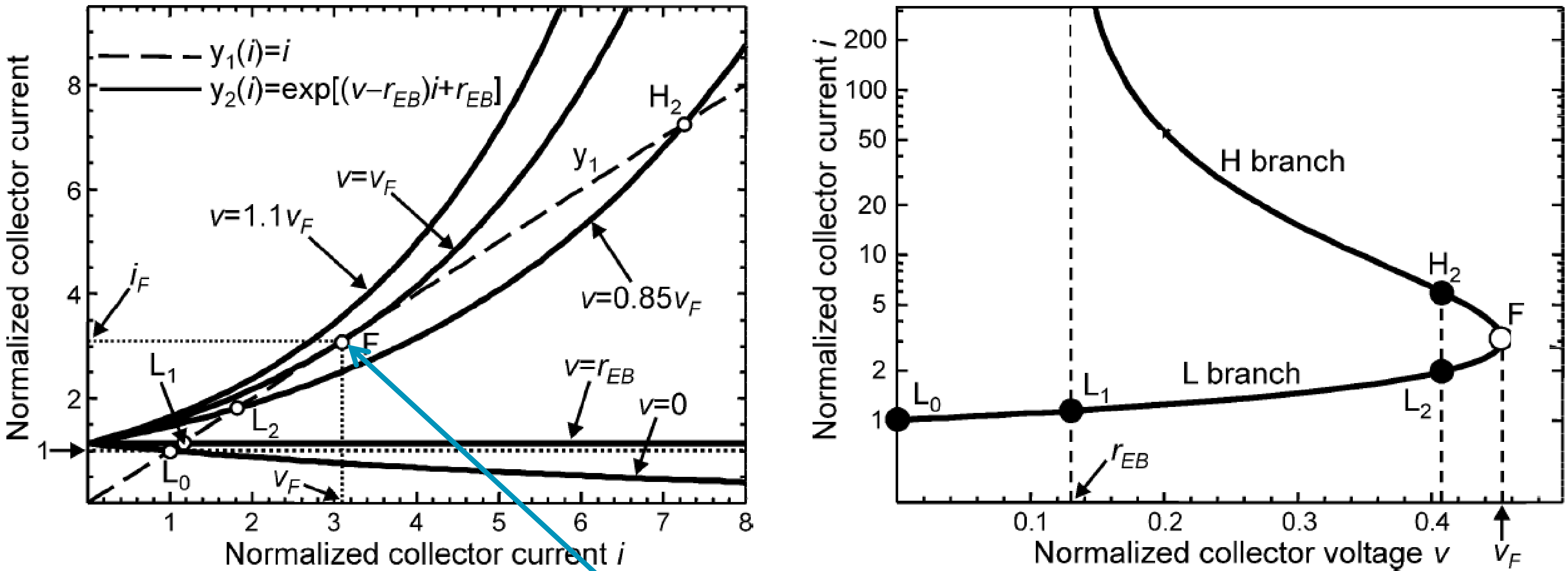


y_1(i) and y_2(i) are tangent at this flyback point

Electro-Thermal Effects

Therefore, the flyback locus can be obtained by differentiating

$$i = \frac{\exp\left(\left(v - r_{EB}\right)i + r_{EB}\right)}{1 - \dfrac{v}{v_A}}$$

that gives

$$i = \frac{1}{v - r_{EB}}$$

Electro-Thermal Effects

Therefore, the flyback locus can be obtained by differentiating

$$i = \frac{\exp\left(\left(v - r_{EB}\right)i + r_{EB}\right)}{1 - \dfrac{v}{v_A}}$$

that gives $$i = \frac{1}{v - r_{EB}}$$

Solving above two equations, we get flyback current and voltage

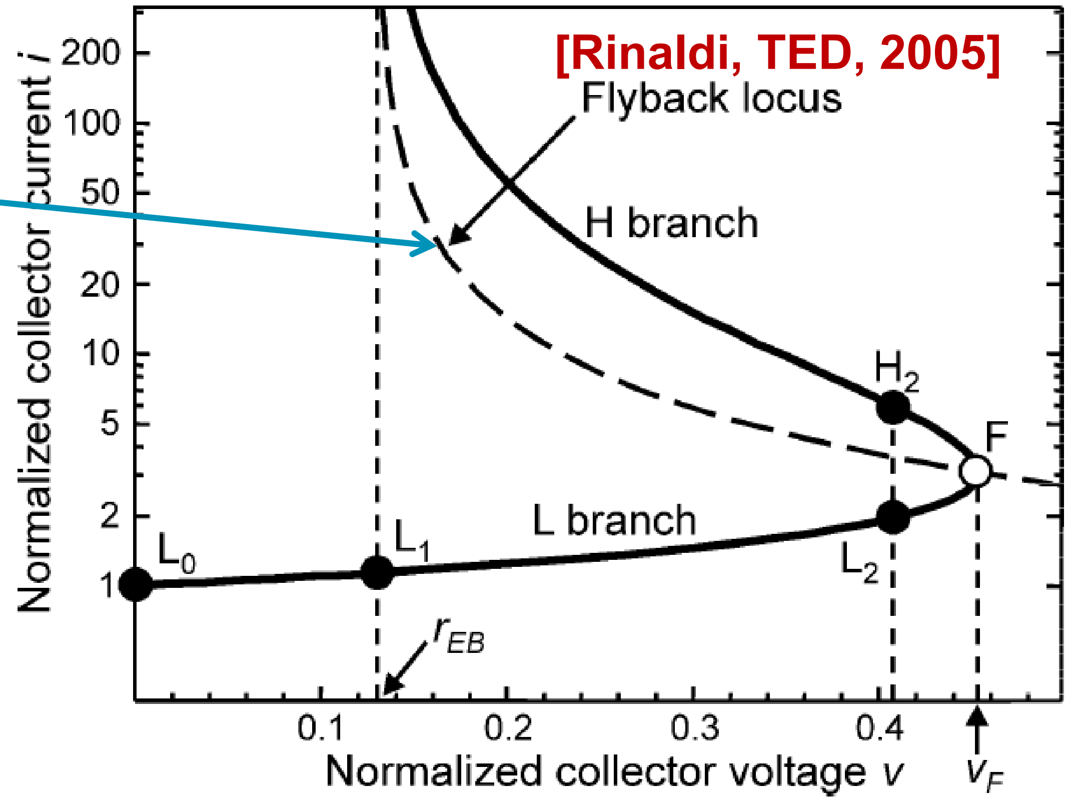
$$i_F = \frac{\exp\left(1 + r_{EB}\right) + \dfrac{1}{v_A}}{1 - \dfrac{r_{EB}}{v_A}}$$

$$v_F = \frac{\dfrac{1}{\exp\left(1 + r_{EB}\right)} + r_{EB}}{1 + \dfrac{1}{v_A \exp\left(1 + r_{EB}\right)}}$$

Electro-Thermal Effects

$$i = \frac{1}{v - r_{EB}}$$

$$I_C = \frac{\eta V_{T0}}{\phi R_{TH} V_{CE} - R_{EB}}$$

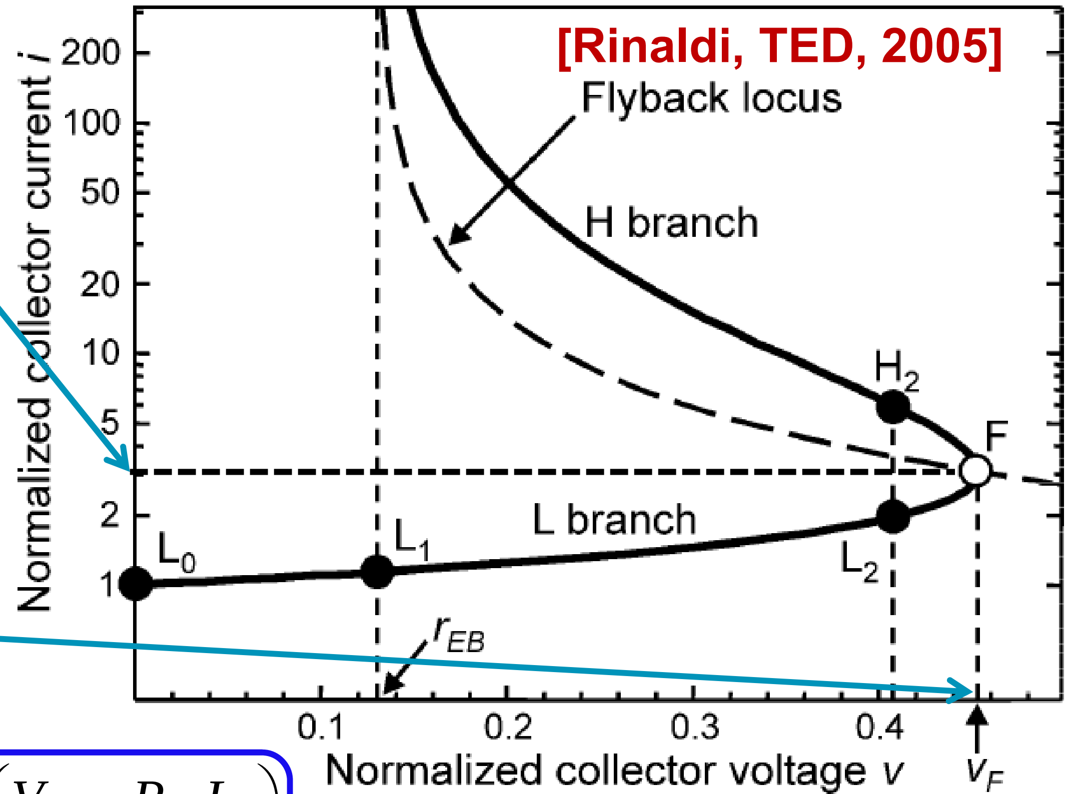


This flyback locus determines the safe operating limits of the transistor

Electro-Thermal Effects

$$i_F = \frac{\exp(1 + r_{EB}) + \dfrac{1}{v_A}}{1 - \dfrac{r_{EB}}{v_A}}$$

$$v_F = \frac{\dfrac{1}{\exp(1 + r_{EB})} + r_{EB}}{1 + \dfrac{1}{v_A \exp(1 + r_{EB})}}$$

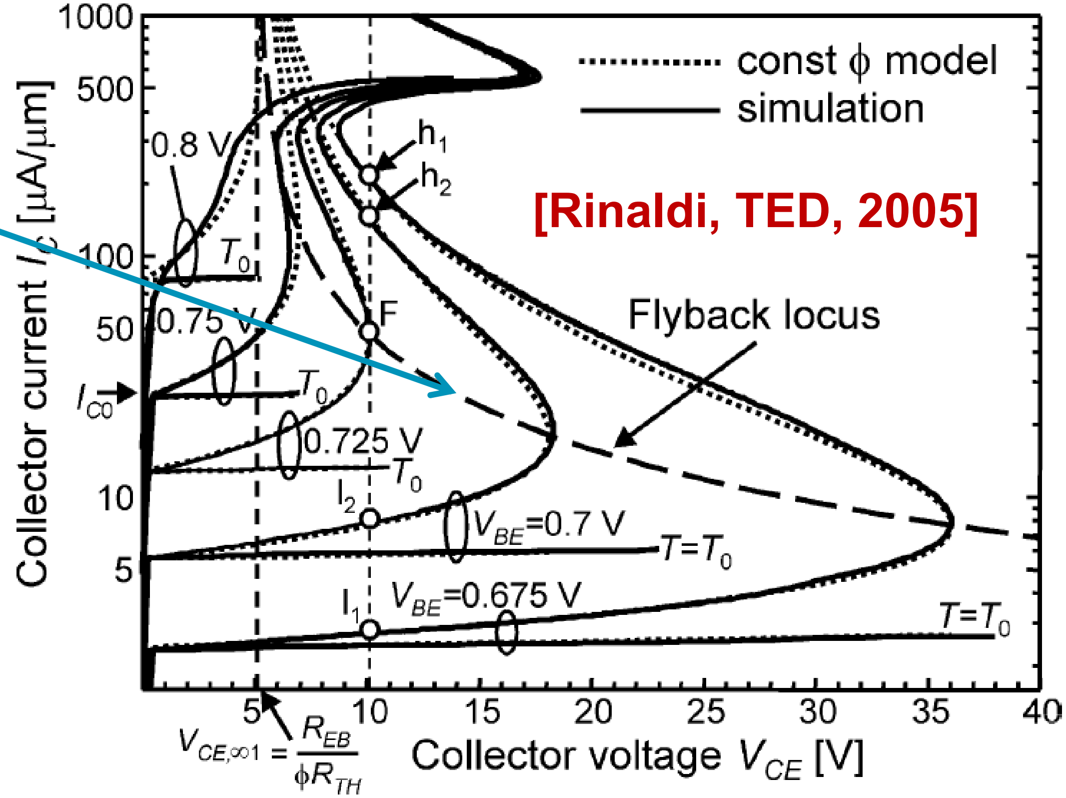


Normalizing current

$$I_{C0} = I_S \exp\left(\frac{V_{BE} - R_{EB} I_C}{\eta V_{T0}}\right)$$

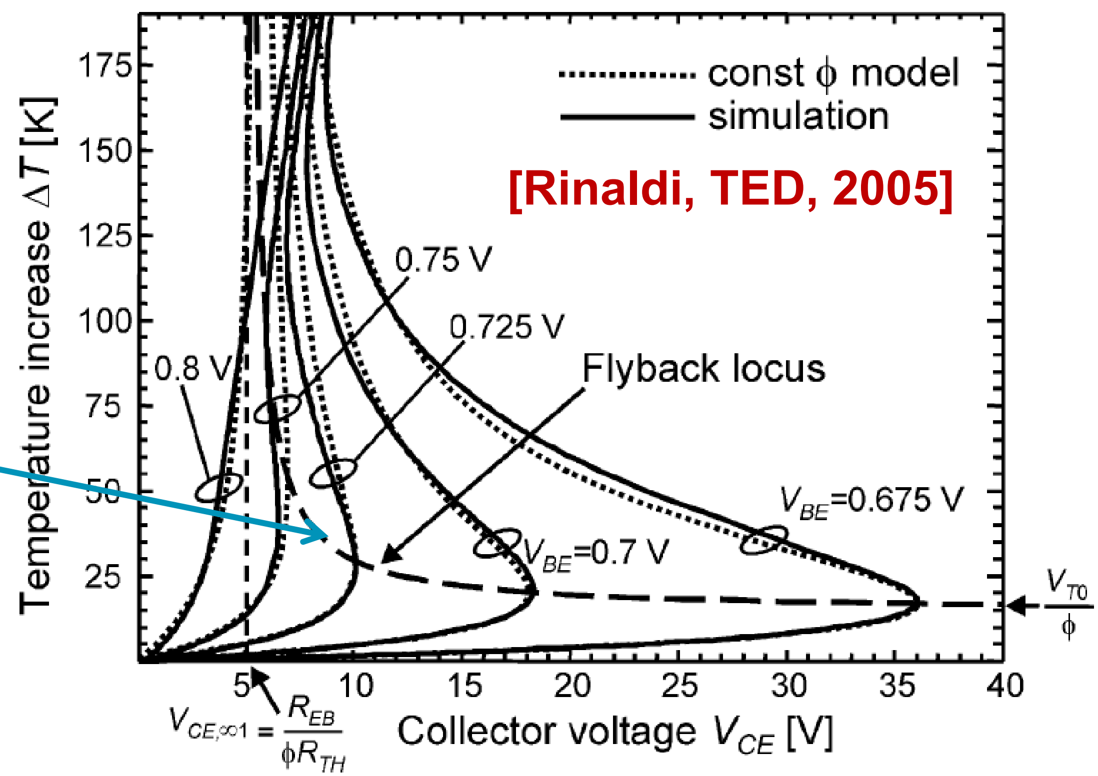
Electro-Thermal Effects

$$I_C = \frac{\eta V_{T0}}{\phi R_{TH} V_{CE} - R_{EB}}$$



Electro-Thermal Effects

$$\Delta T = R_{TH} V_{CE} I_C = \frac{R_{TH} V_{CE} \eta V_{T0}}{\phi R_{TH} V_{CE} - R_{EB}}$$



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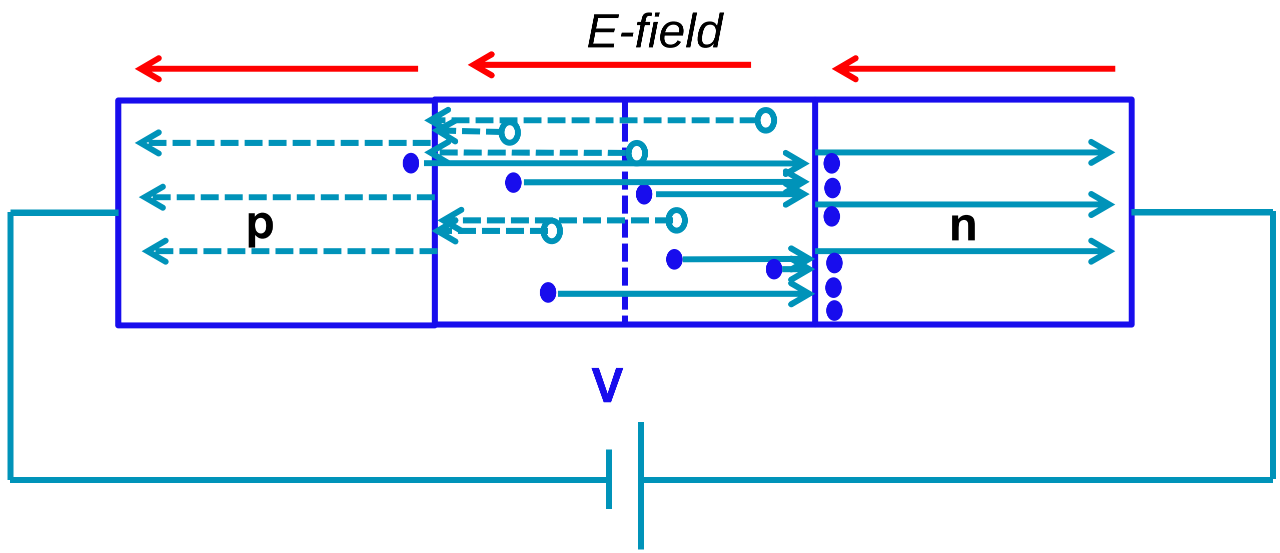
Impact Ionization Effects



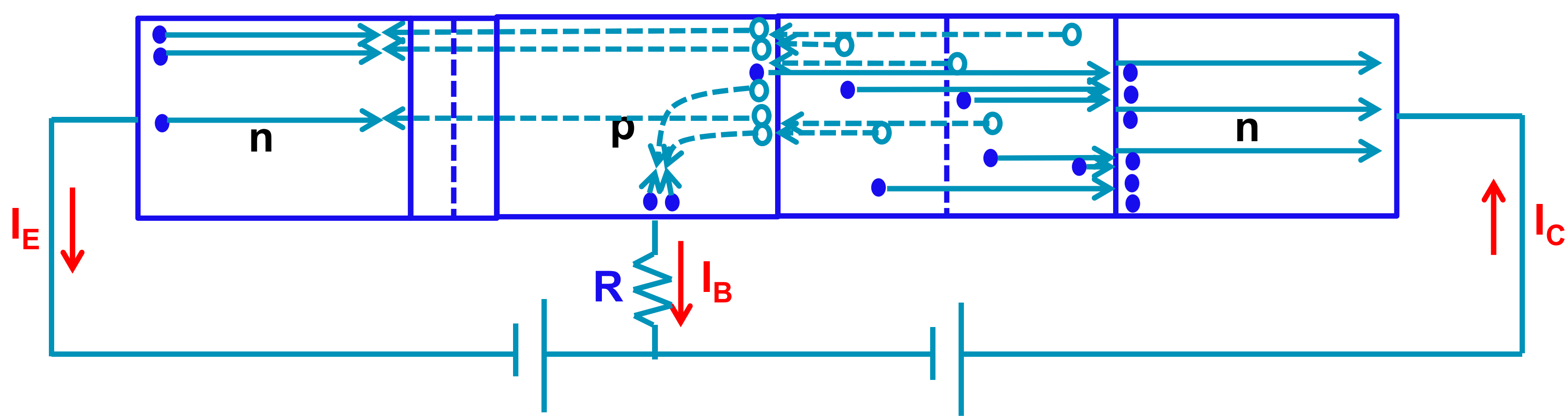
- Avalanche of carrier generation
- Holes move toward p-side
- Electrons move toward n-side

$$M = \frac{I_{out}}{I_{in}} = \frac{1}{1-\left(\frac{V}{BV}\right)^m}$$

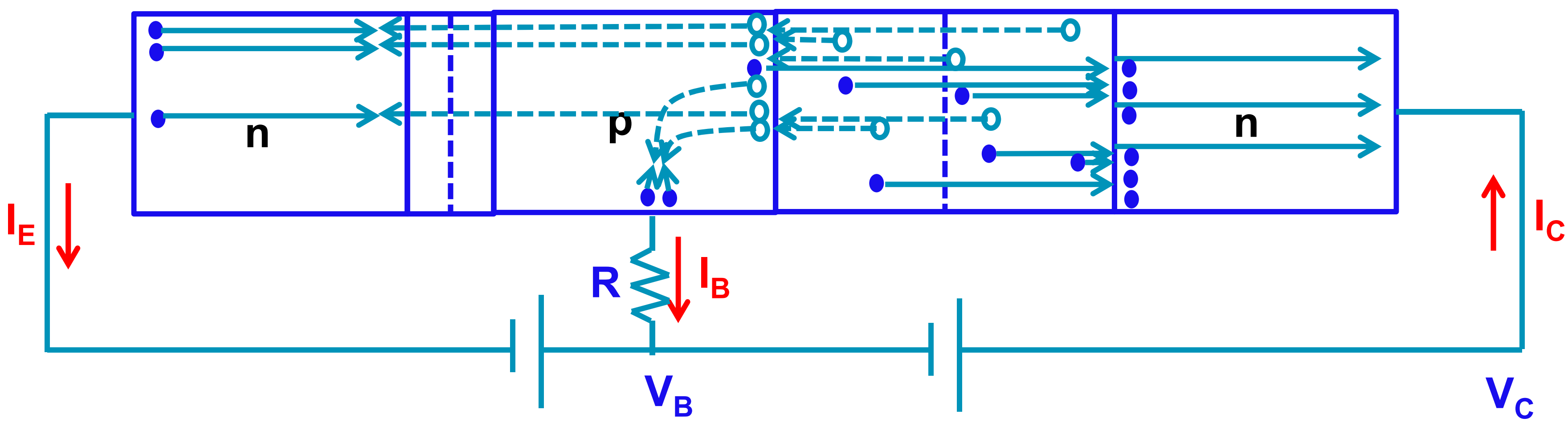
Multiplication factor → M

Breakdown voltage → BV

Impact Ionization Effects



Impact Ionization Effects



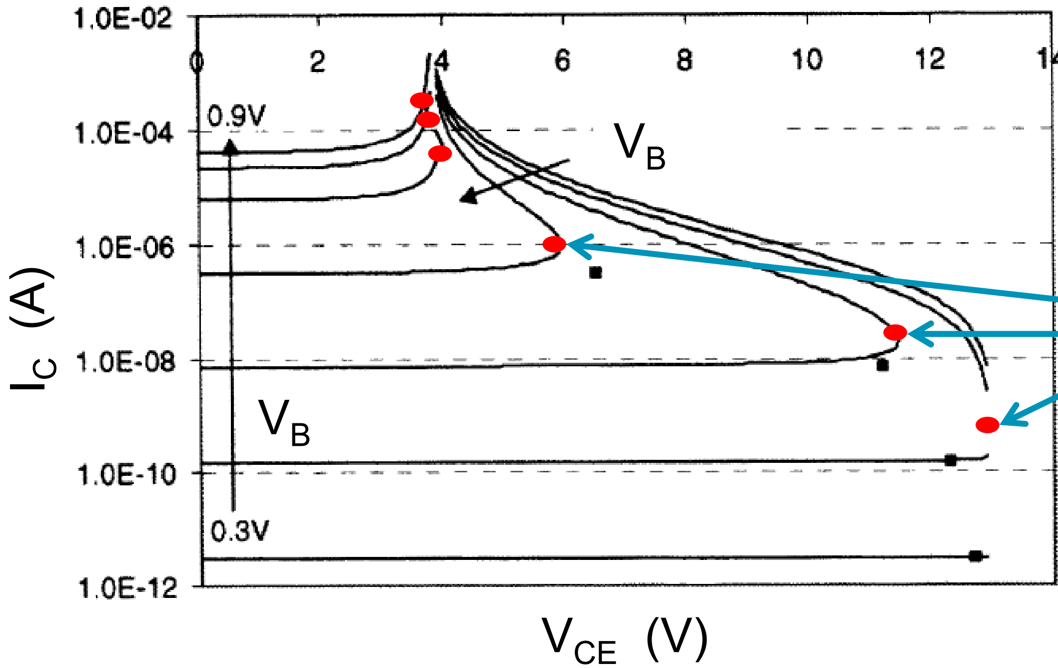
$$I_C = MI_S \exp\left(\frac{V_B + RI_C(M-1)/M - 1/\beta_F}{V_{T0}}\right)$$

$$M = \frac{1}{1 - \left(\frac{V_{CB}}{BV_{CB0}}\right)^m}$$

Impact Ionization Effects

$$I_C = MI_S \exp\left(\frac{V_B + RI_C(M-1)/M - 1/\beta_F}{V_{T0}}\right)$$

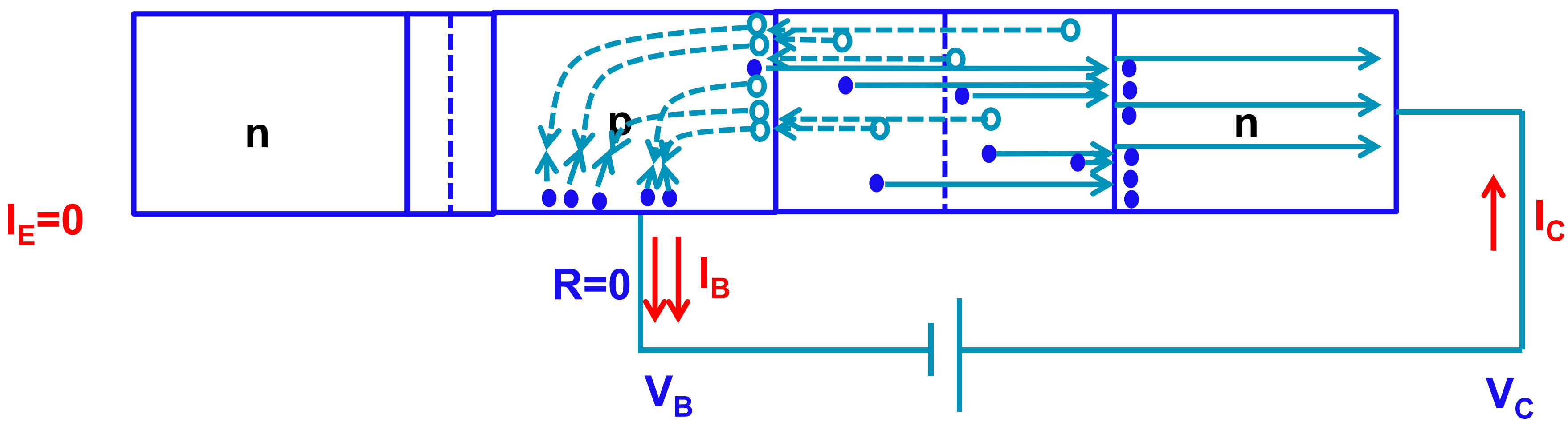
$$M = \frac{1}{1-\left(\frac{V_{CB}}{BV_{CB0}}\right)^m}$$



[Kraft, BCTM, 2005]

$$V_{CE,crit} = BV_{CER}$$

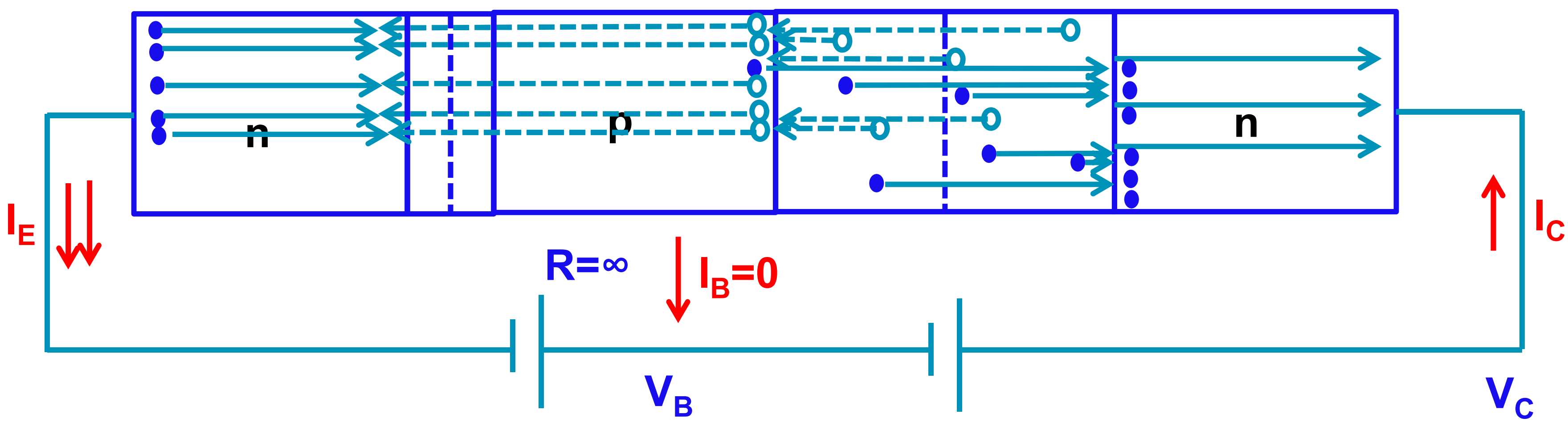
Impact Ionization Effects



$$M = \frac{1}{1-\left(\frac{V_{CB}}{BV_{CB0}}\right)^m}$$

$$R = 0$$
$$M \rightarrow \infty$$
$$V_{CB} = BV_{CB0}$$

Impact Ionization Effects

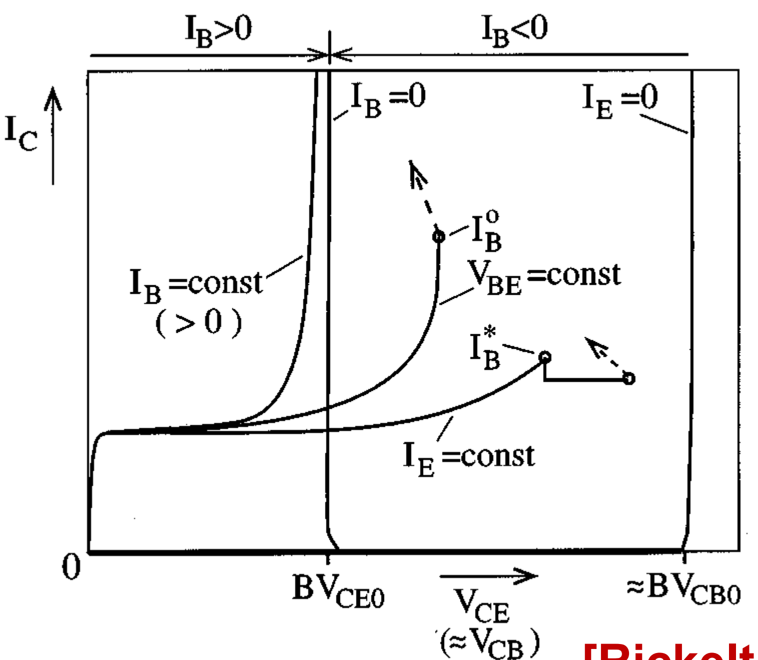


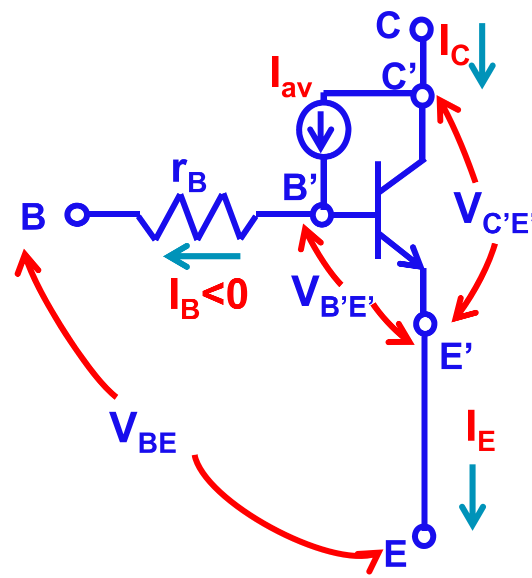
$$R = \infty$$
$$I_B = 0$$
$$V_{CE} = BV_{CE0}$$

Impact Ionization Effects

$$BV_{CB0} > BV_{CER} > BV_{CE0}$$

One can bias accordingly to obtain high possible breakdown voltage

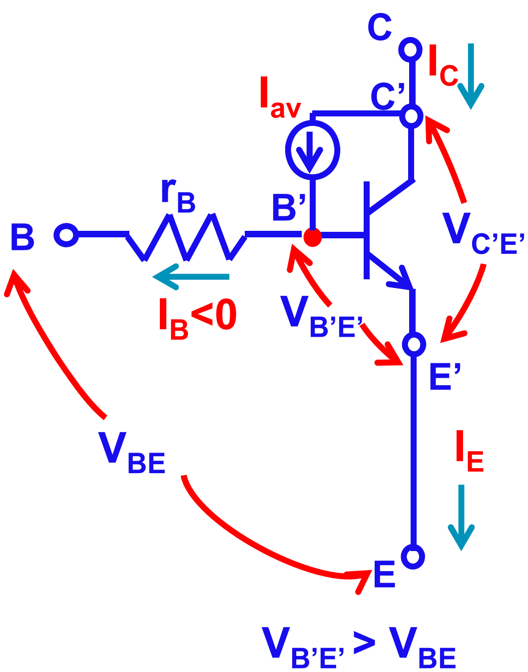


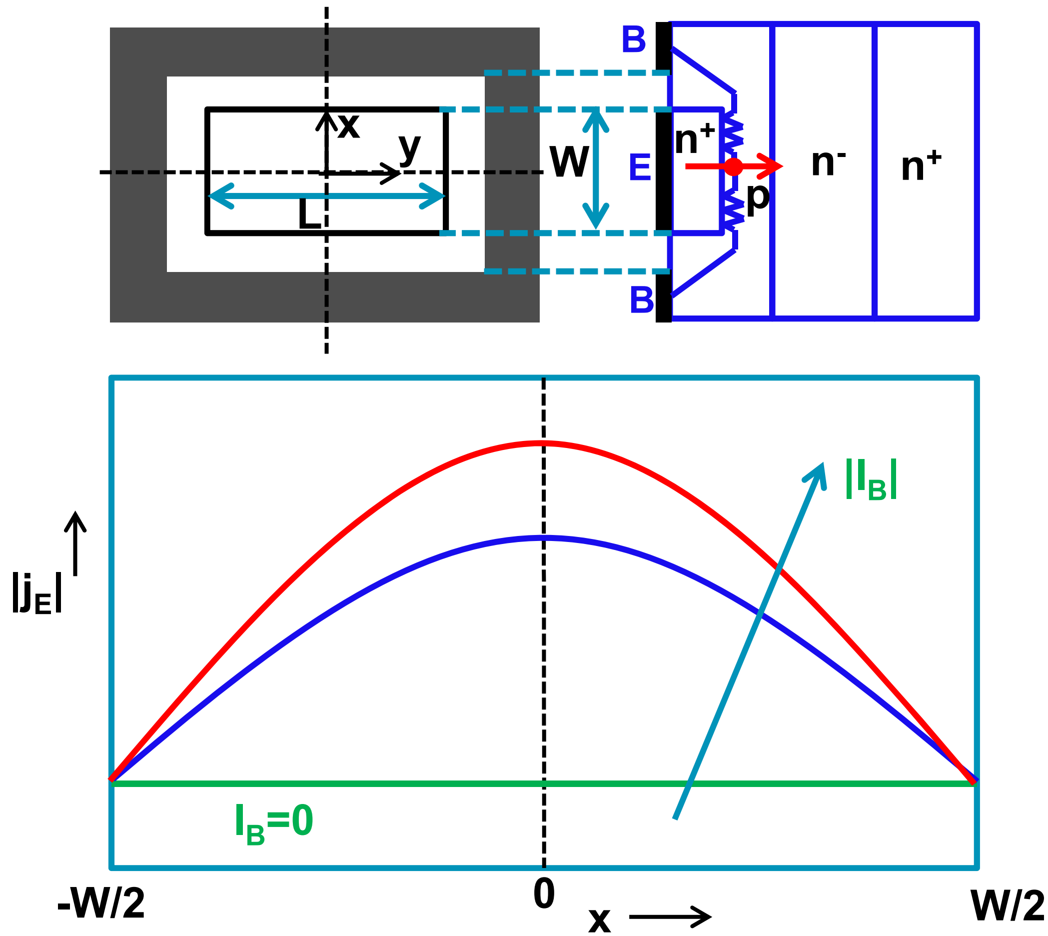


$V_{B'E'} > V_{BE}$

[Rickelt, TED, 2001]

Impact Ionization Effects





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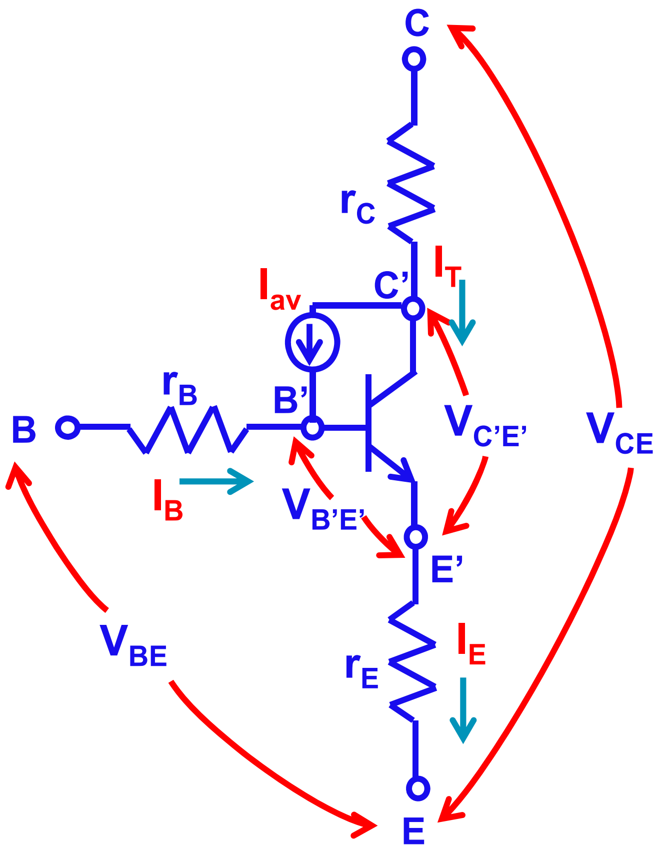
Electro-Thermal and Impact Ionization Effects



$$I_C = MI_T = \frac{MI_S}{1-\frac{V_{CE}}{V_A}}\exp\left(\frac{V_{B'E'}+\phi\Delta T}{\eta V_{T0}}\right)$$

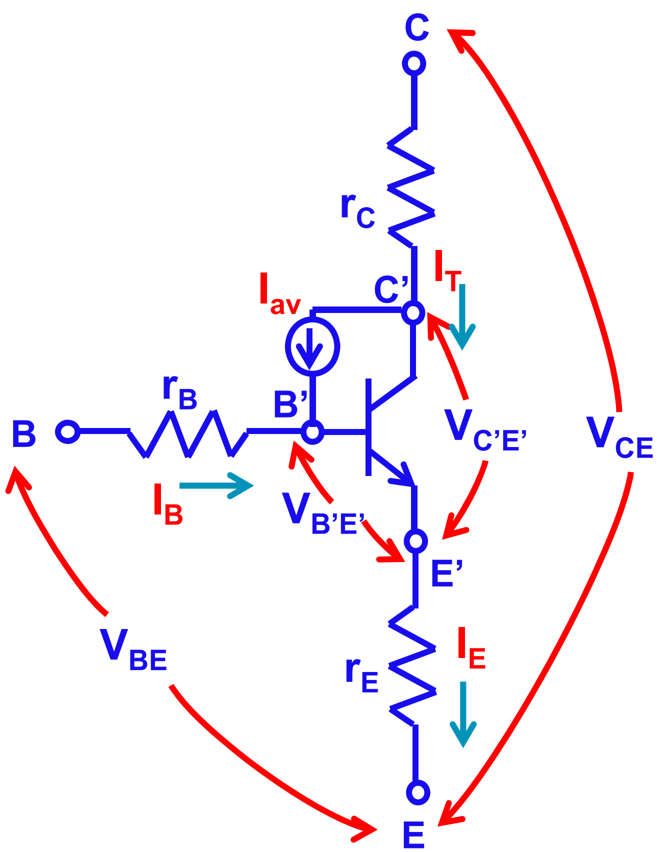
$$V_{B'E'} = V_{BE} - I_B r_B - I_E r_E = V_{BE} - I_C R_{eq}$$

$$\Delta T = R_{TH} P_{diss} = R_{TH}\left(I_B V_{BE} + I_C V_{CE}\right) = R_{TH} I_C V_{eq}$$

$$V_{eq} = V_{CE} + V_{BE}\left(\frac{1}{\alpha_F} - 1\right) \qquad \phi = -\left.\frac{\partial V_{BE}}{\partial T}\right|_{I_C}$$

$$R_{eq} = \frac{R_E}{\alpha_F} + \frac{R_B}{\beta_F} - \frac{R_B + R_E}{\alpha_F}\left(1 - \frac{1}{M}\right) = \frac{R_B + R_E}{M\alpha_F} - R_B$$

Electro-Thermal and Impact Ionization Effects



$$I_C = M I_T = \frac{M I_S}{1 - \dfrac{V_{CE}}{V_A}} \exp\left(\frac{V_{B'E'} + \phi \Delta T}{\eta V_{T0}}\right)$$

$$V_{B'E'} = V_{BE} - I_B r_B - I_E r_E = V_{BE} - I_C R_{eq}$$

$$\Delta T = R_{TH} P_{diss} = R_{TH}\left(I_B V_{BE} + I_C V_{CE}\right) = R_{TH} I_C V_{eq}$$

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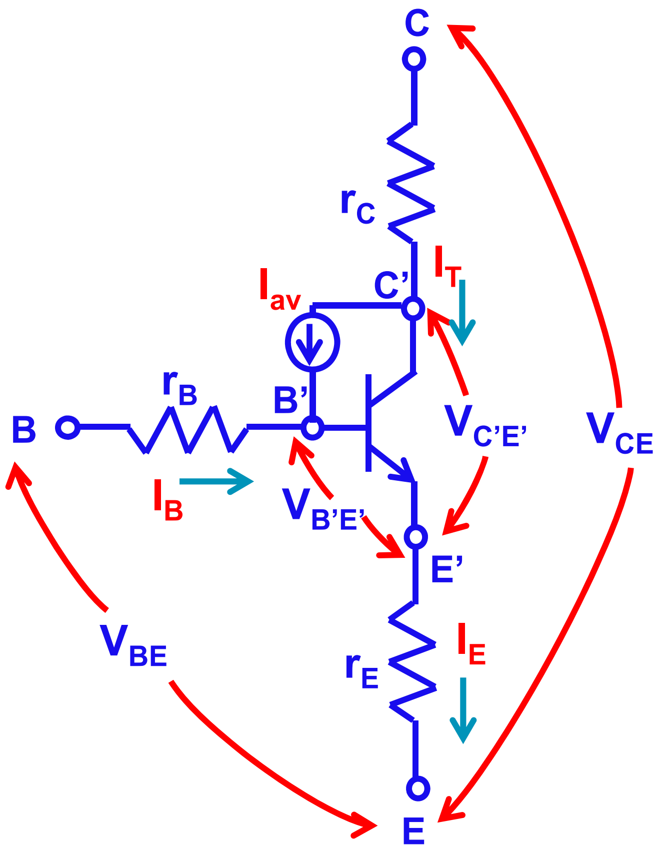
$$R_{eq} = \frac{R_E}{\alpha_F} + \frac{R_B}{\beta_F} - \frac{R_B + R_E}{\alpha_F}\left(1 - \frac{1}{M}\right) = \frac{R_B + R_E}{M \alpha_F} - R_B$$

Electro-Thermal and Impact Ionization Effects



$$I_C = \frac{MI_S}{1-\dfrac{V_{CE}}{V_A}} \exp\left(\frac{V_{BE} + I_C\left[\phi R_{TH} V_{eq} - R_{eq}\right]}{\eta V_{T0}} \right)$$

$$V_{eq} = V_{CE} + V_{BE}\left(\frac{1}{\alpha_F} - 1\right) \qquad \phi = -\left.\frac{\partial V_{BE}}{\partial T}\right|_{I_C}$$

$$R_{eq} = \frac{R_E}{\alpha_F} + \frac{R_B}{\beta_F} - \frac{R_B + R_E}{\alpha_F}\left(1 - \frac{1}{M}\right) = \frac{R_B + R_E}{M\alpha_F} - R_B$$

Electro-Thermal and Impact Ionization Effects

The flyback locus can be obtained by differentiating

$$I_C = \frac{MI_S}{1-\dfrac{V_{CE}}{V_A}} \exp\left(\frac{V_{BE} + I_C\left[\phi R_{TH} V_{eq} - R_{eq}\right]}{\eta V_{T0}} \right)$$

w.r.t. V_{CE}

and putting

$$\frac{dI_C}{dV_{CE}} \rightarrow \infty$$

that gives

$$I_{CF} = \frac{\eta V_{T0}}{\phi R_{TH} V_{eq} - R_{eq}}$$

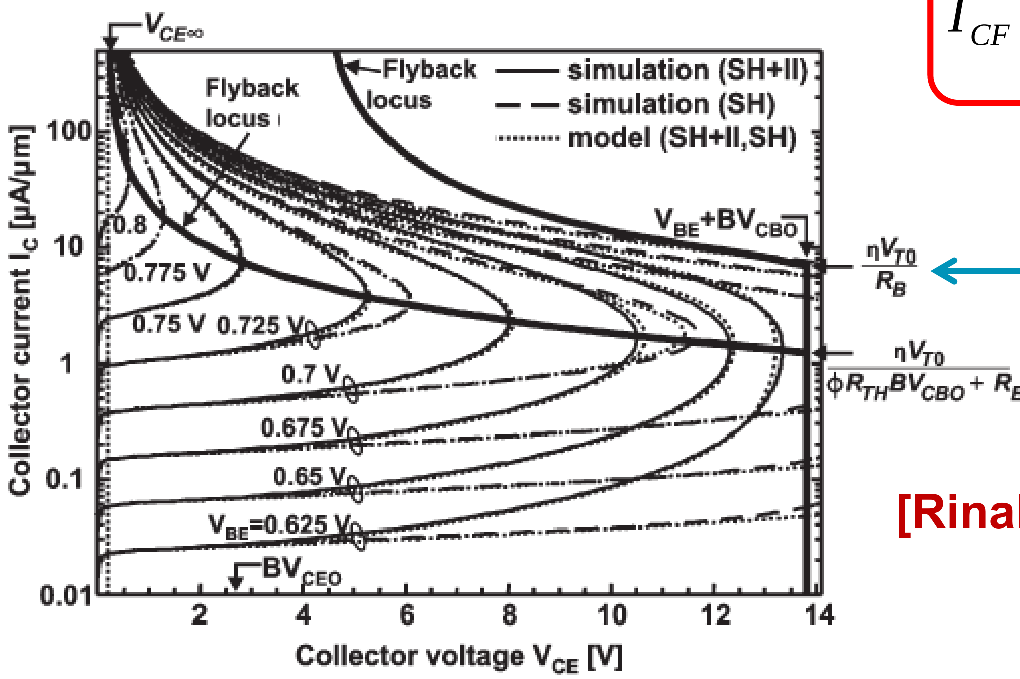
Electro-Thermal and Impact Ionization Effects

$$I_C = \frac{MI_S}{1-\frac{V_{CE}}{V_A}} \exp\left(\frac{V_{BE} + I_C\left[\phi R_{TH} V_{eq} - R_{eq}\right]}{\eta V_{T0}}\right)$$

$$I_{CF} = \frac{\eta V_{T0}}{\phi R_{TH} V_{eq} - R_{eq}}$$

$$R_{TH} = 0$$

$$M \rightarrow \infty$$



[Rinaldi, TED, 2006]

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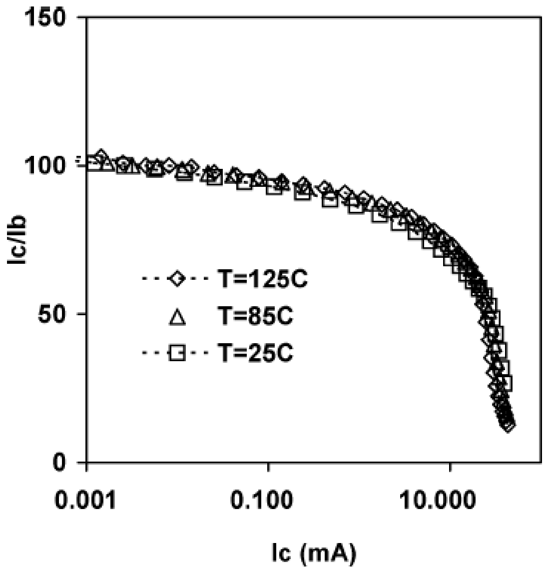
Device Design for Power Amplifier

Why SiGe HBT? Why not GaAs HBT?

- ✓ Reduced chip area and increased chip robustness due to heat-conductive Si substrate
- ✓ Temperature insensitive current gain reduces the circuit design issues arising from thermal runaway
- ✓ Reliabilities at high current densities enables further reduction in device size

[Johnson, JSSC, 2004]



Device Design for Power Amplifier

Johnson limit

$$BV_{CE0} \times f_T = const.$$

- ✓ BV_{CB0} and BV_{CER} are more important than BV_{CE0} since device is not operated at I_B=0 in PA applications
- ✓ f_{max} is a more useful figure-of-merit than f_T and SiGe HBT does not demand a rigid trade-off between BV_{CB0} and f_{max}

Unity current gain (cutoff) frequency

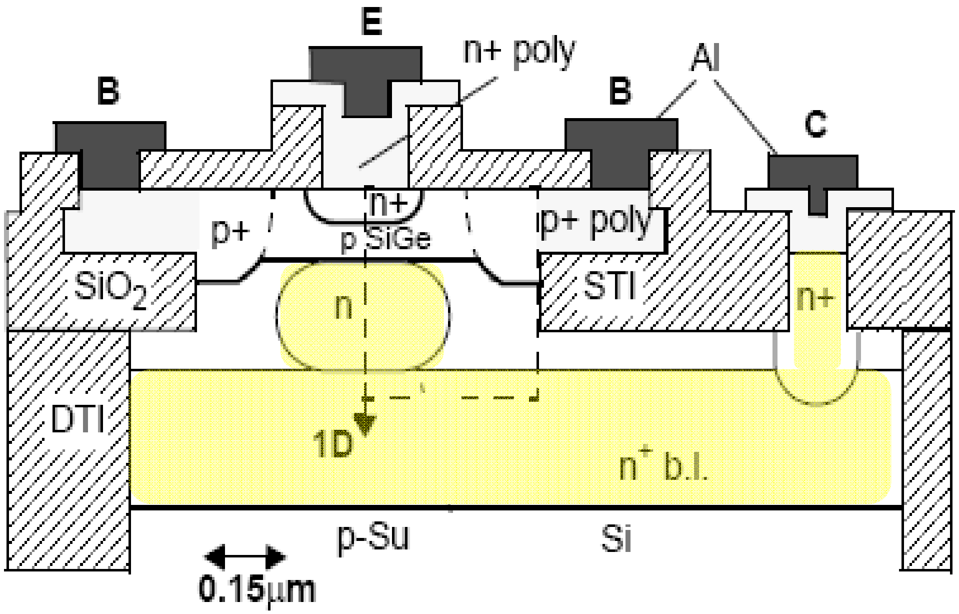
$$f_T = \frac{1}{2\pi\tau_f} = \frac{g_m}{2\pi C_{in}}$$

Unity power gain (maximum oscillation) frequency

$$f_{\max} = \sqrt{\frac{f_T}{2\pi C_{bc} r_b}}$$

Device Design for Power Amplifier

collector engineering

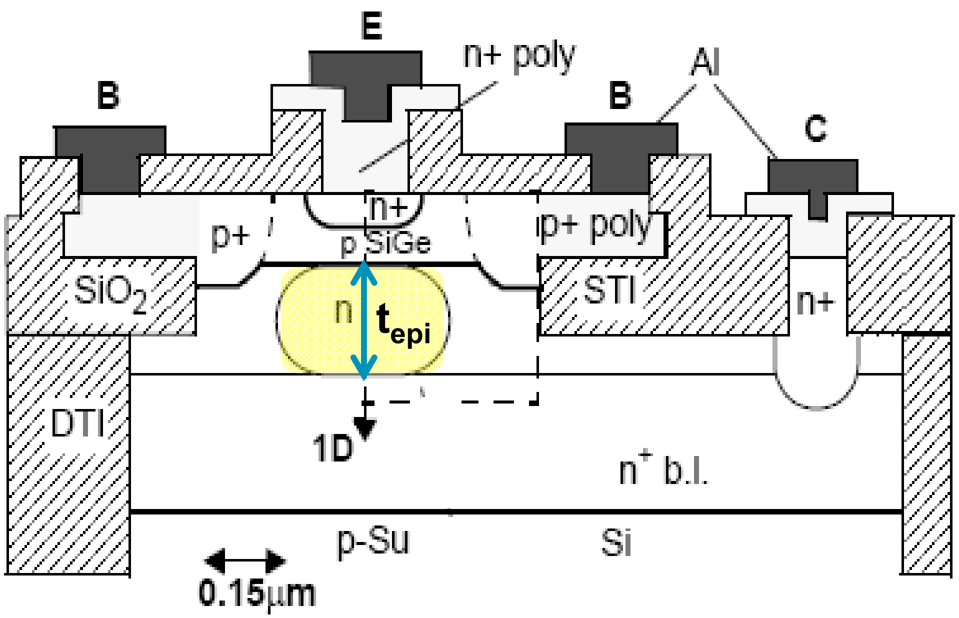


Bipolar Transistor	Collector doping	Collector thickness
Higher	faster, lower BV_{CB0}	slower, higher BV_{CB0}
Lower	slower, higher BV_{CB0}	faster, lower BV_{CB0}

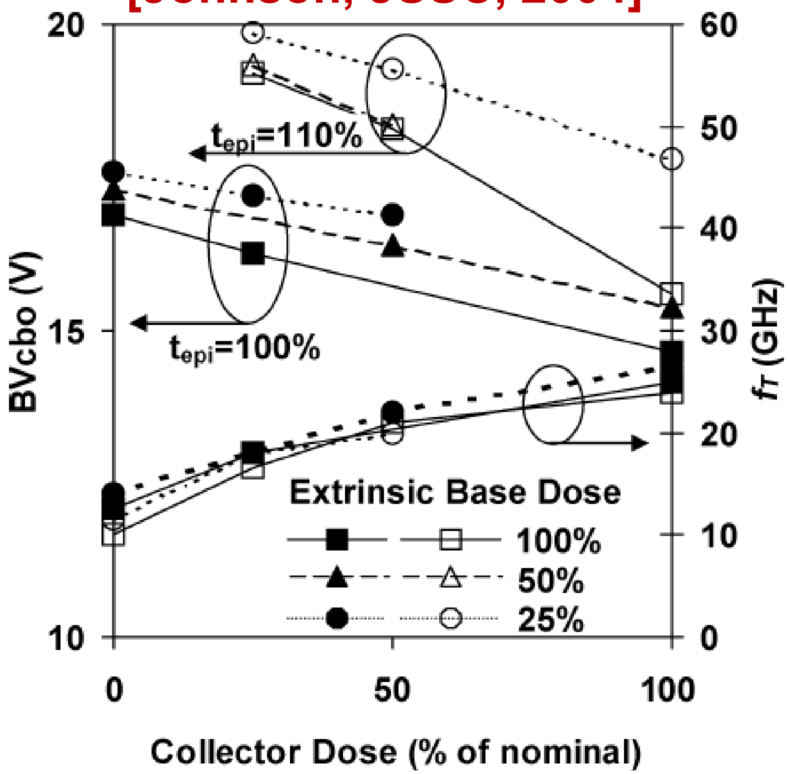
- very slow transistor is not useful in PA design

Device Design for Power Amplifier

collector engineering



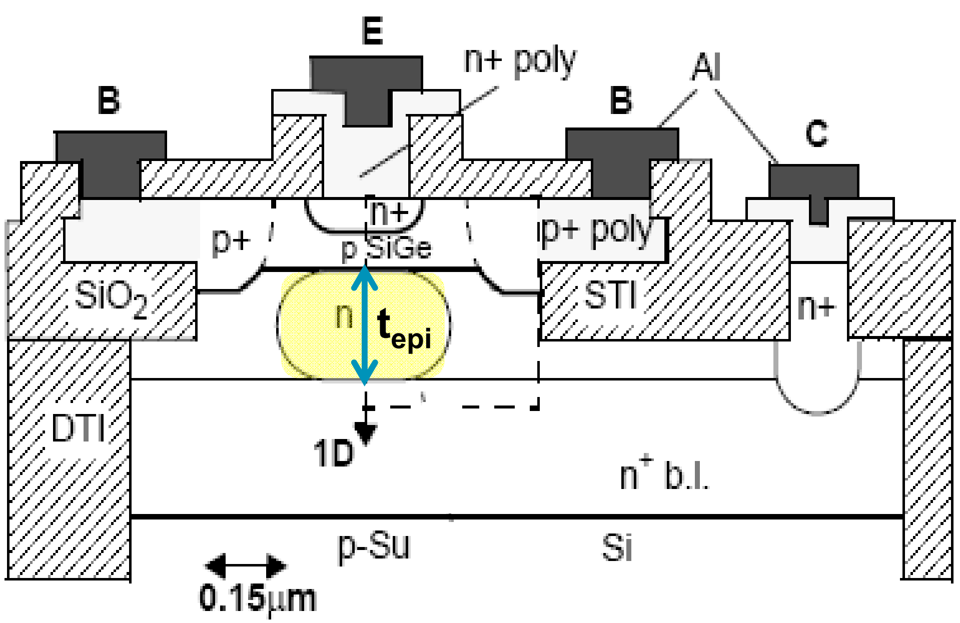
[Johnson, JSSC, 2004]



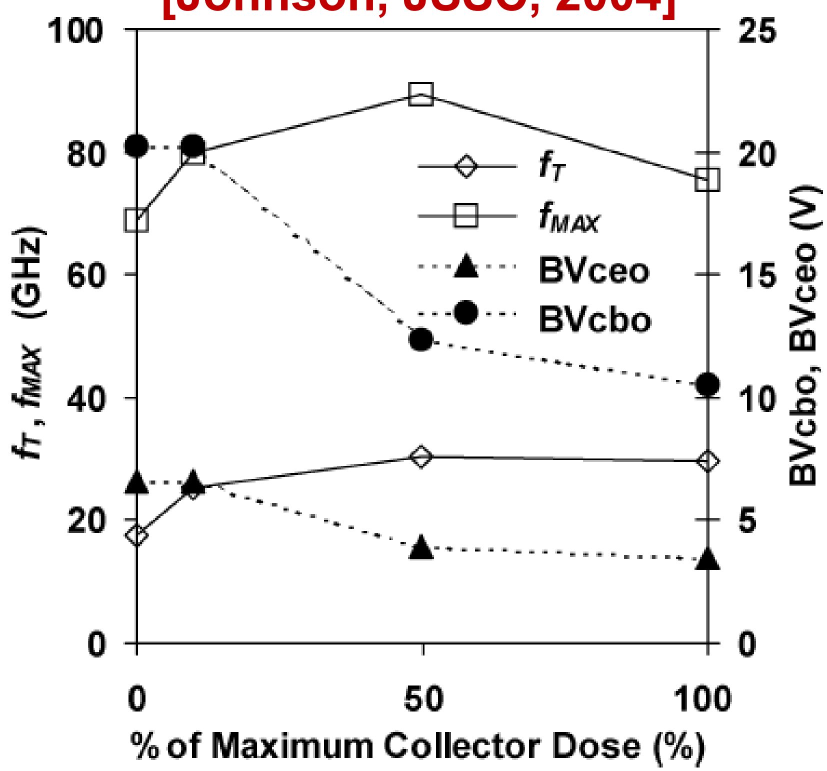
✓ significant opportunity to engineer SiGe HBT performance

Device Design for Power Amplifier

collector engineering



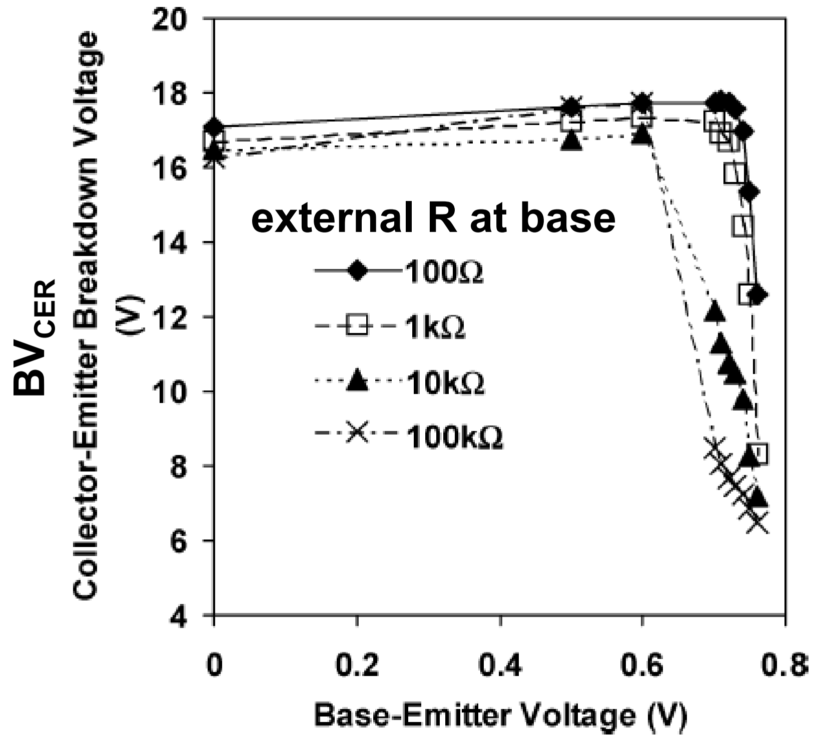
[Johnson, JSSC, 2004]



✓ **significant opportunity to engineer SiGe HBT performance**

Device Design for Power Amplifier

safe operating voltage



[Johnson, JSSC, 2004]

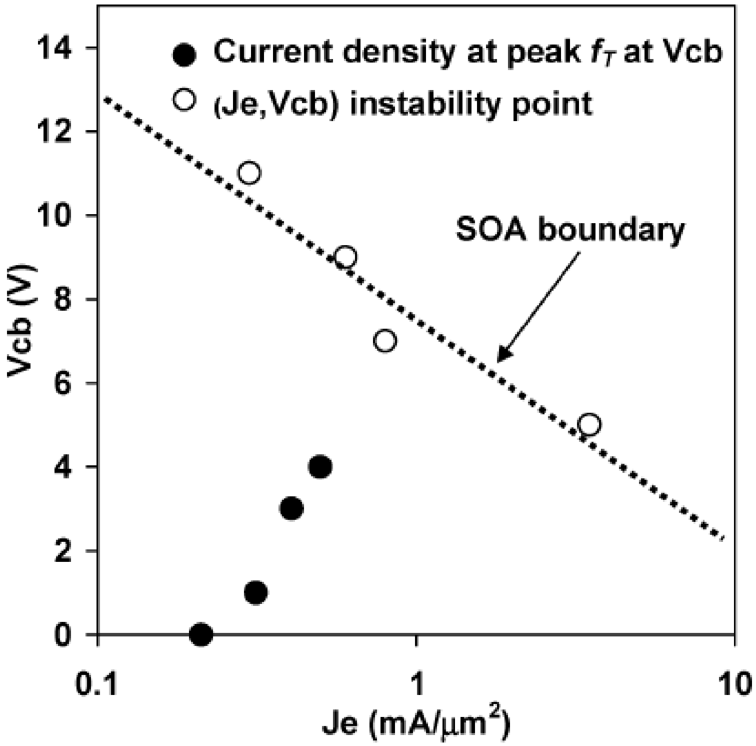
BV_{CE0}=6V

BV_{CB0}=18V

✓ **R at base improves the breakdown voltage enormously**

Device Design for Power Amplifier

safe operating limit

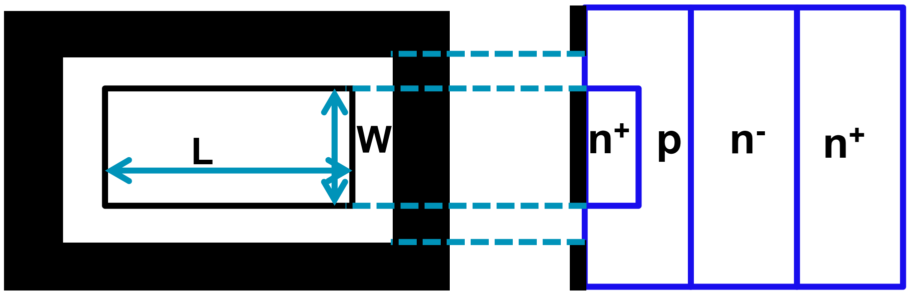


[Johnson, JSSC, 2004]

✓ **expected operating areas are well within the safe operating limits**

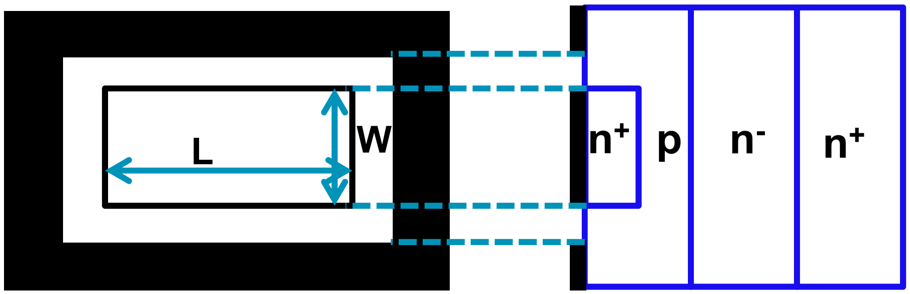
Device Design for Power Amplifier

scaling effects



Device Design for Power Amplifier

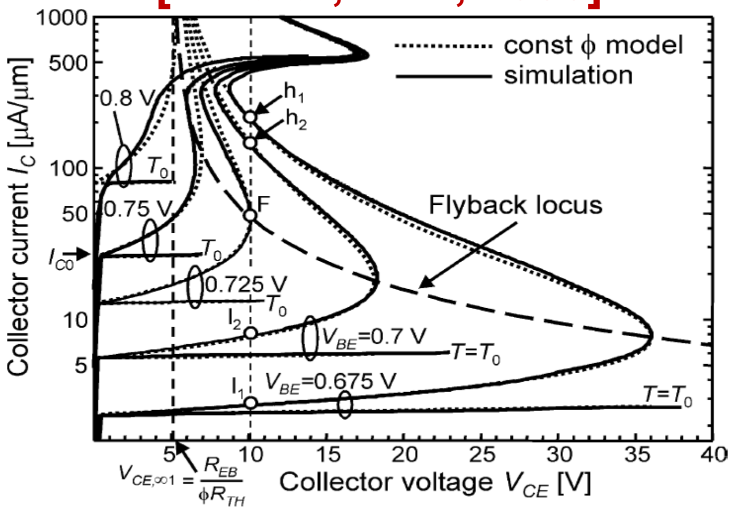
scaling effects



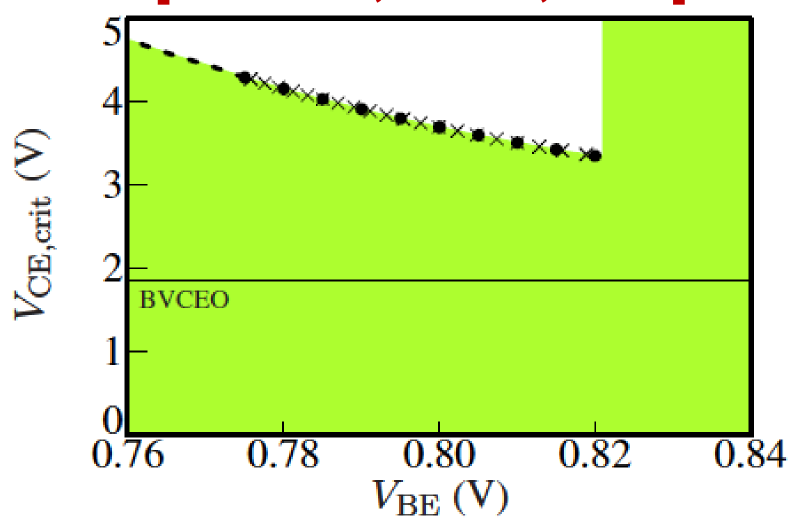
$$I_{CF} = \frac{\eta V_{T0}}{\phi R_{TH} V_{eq} - R_{eq}}$$

$$V_{BE} \downarrow I_{CF} \downarrow V_{CF} \uparrow$$

[Rinaldi, TED, 2005]

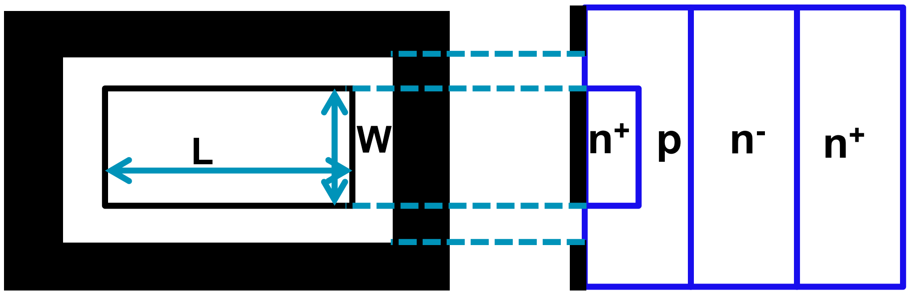


[Scholten, BCTM, 2012]



Device Design for Power Amplifier

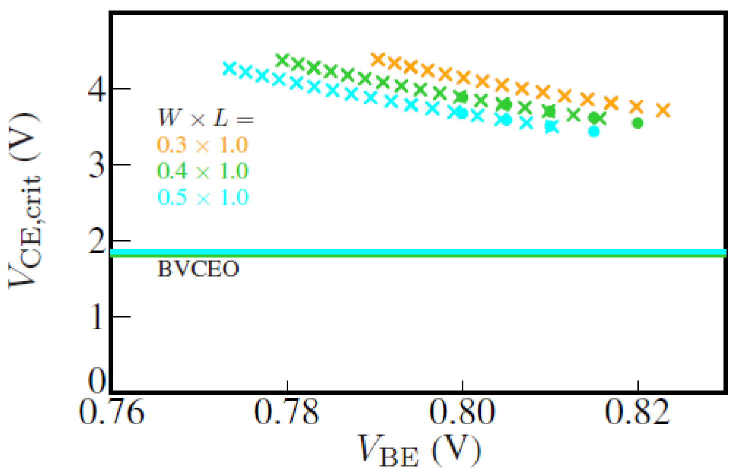
scaling effects



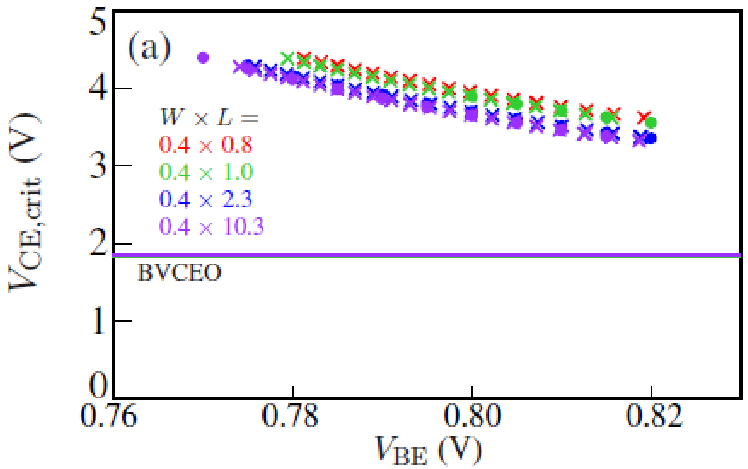
$$I_{CF} = \frac{\eta V_{T0}}{\phi R_{TH} V_{eq} - R_{eq}}$$

$$R_{TH} \propto \frac{1}{WL}, R_B \propto \frac{1}{L}$$

[Scholten, BCTM, 2012]

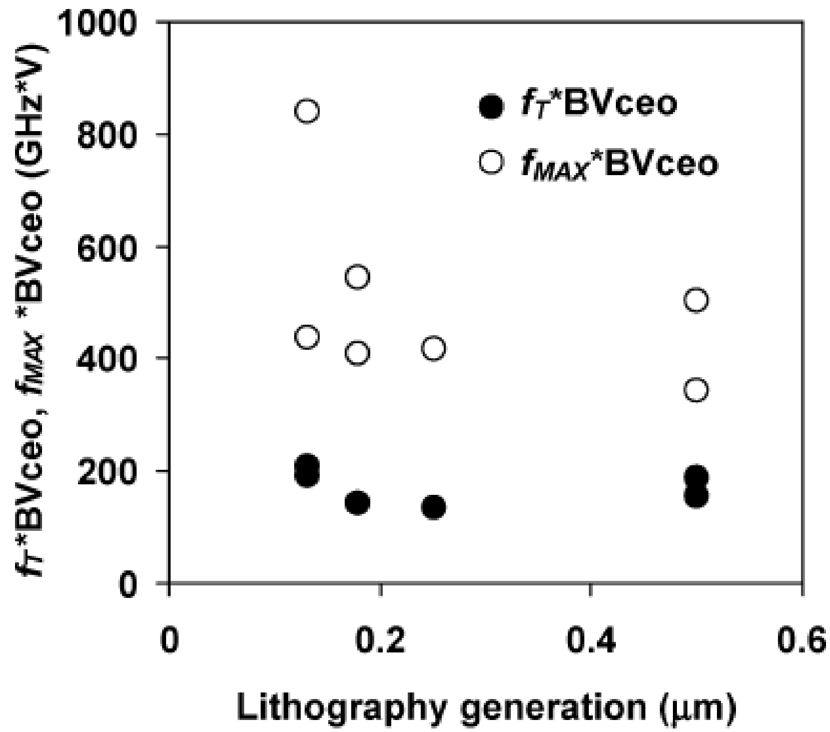


[Scholten, BCTM, 2012]



Device Design for Power Amplifier

technology scaling effects



[Johnson, JSSC, 2004]

✓ f_{max}*BV_{CE0} is significantly improved with technology scaling

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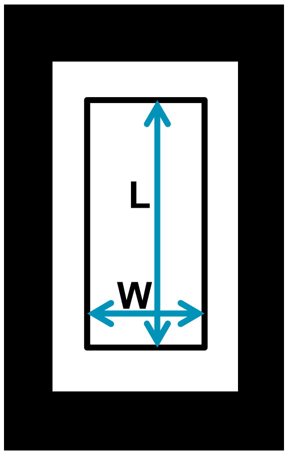
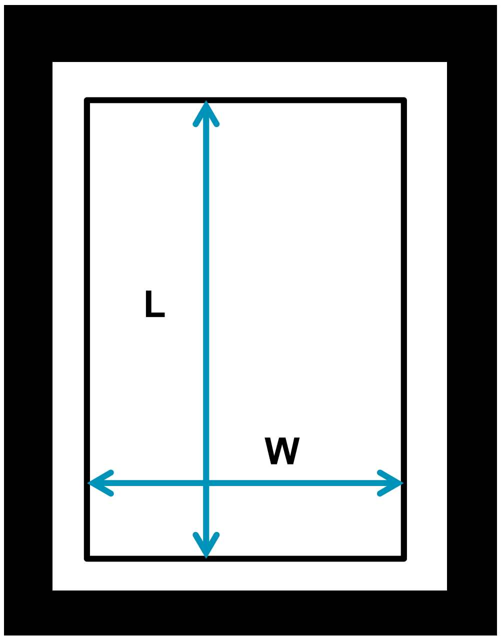
Multi-Finger Transistors



- **Mainly evolved for PA applications**
- **High power application → large A_E reqd.**

$$A_E = WL$$

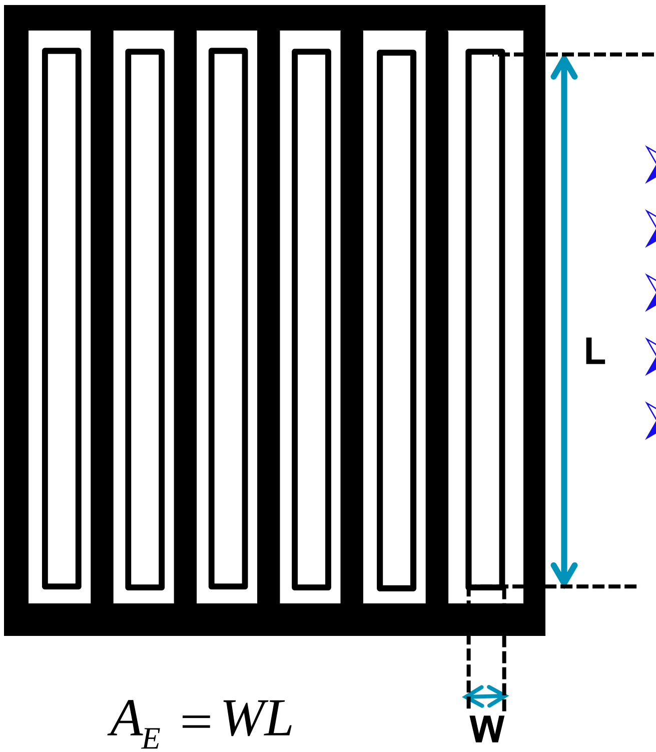
Multi-Finger Transistors



$$A_E = WL$$

- Mainly evolved for PA applications
- High power application → large A_E reqd.
- Large W → degraded performance

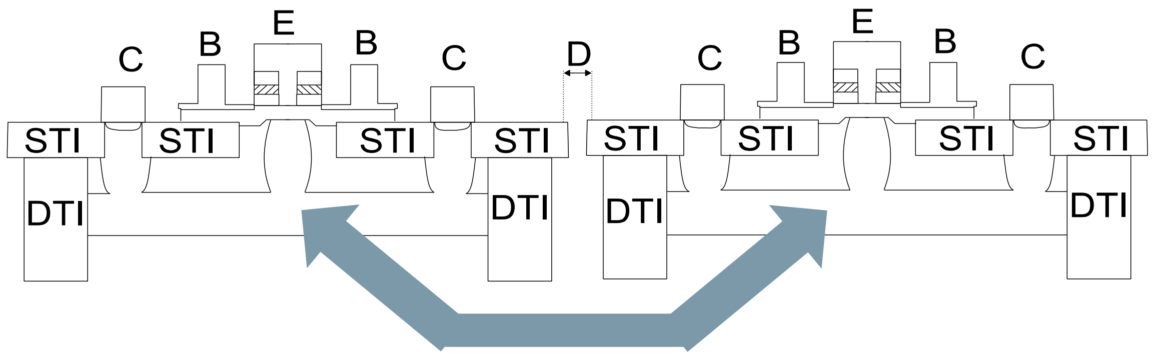
Multi-Finger Transistors



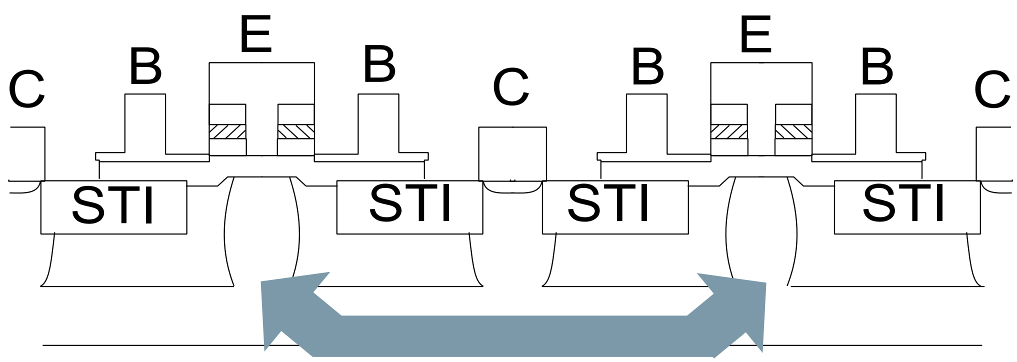
$$A_E = WL$$

- **Mainly evolved for PA applications**
- **High power application → large A_E reqd.**
- **Large W → degraded performance**
- **Solution → reduced W, large L**
- **Segmented emitters with small W→ multi-finger**

Multi-Finger Transistors

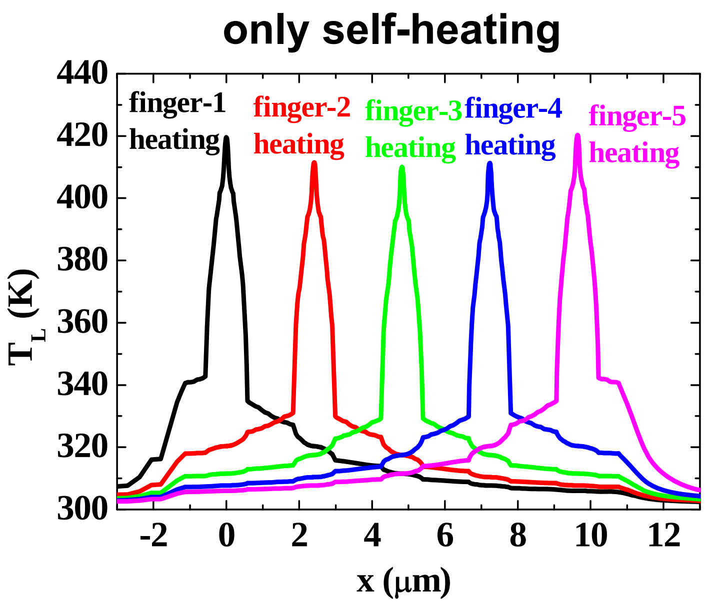


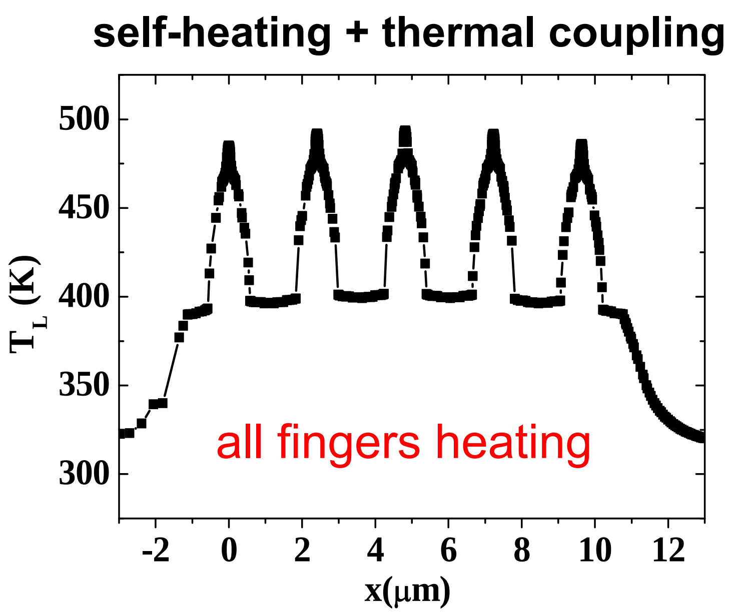
low inter-device thermal coupling



significant intra-device thermal coupling

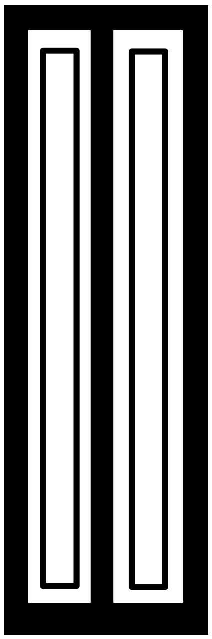
Multi-Finger Transistors



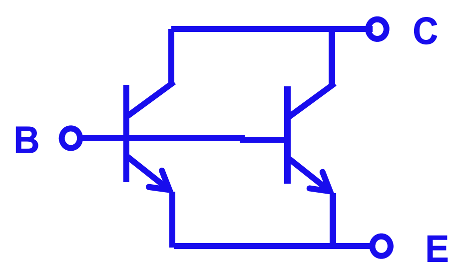


- **finger-3 → least self-heating but highest thermal coupling**
- **finger-1,5 → highest self-heating, but least thermal coupling**

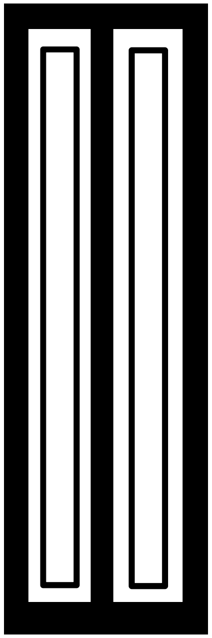
Multi-Finger Transistors



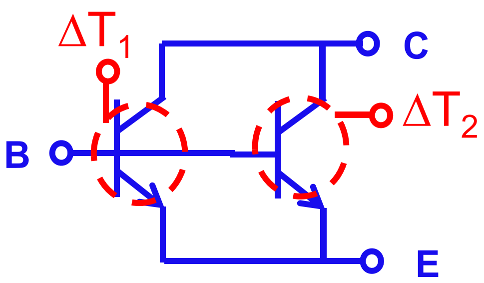
two finger device



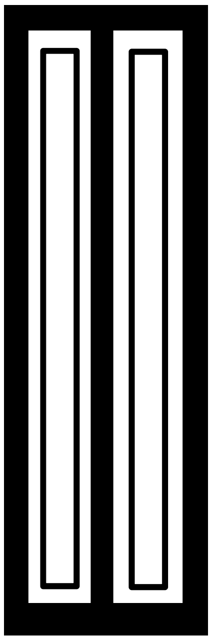
Multi-Finger Transistors



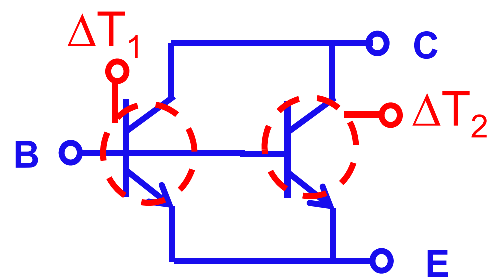
two finger device



Multi-Finger Transistors



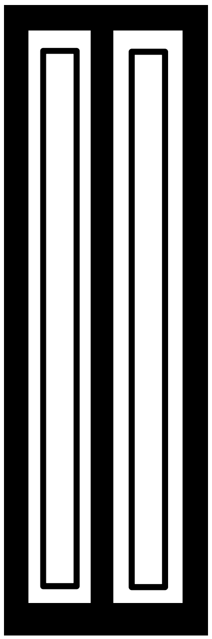
two finger device



$$\Delta T_1 = R_{TH,11}P_{diss,1} + R_{TH,12}P_{diss,2}$$
$$= R_{TH,11}V_{eq}I_{C1} + R_{TH,12}V_{eq}I_{C2}$$

$$\Delta T_2 = R_{TH,21}P_{diss,1} + R_{TH,22}P_{diss,2}$$
$$= R_{TH,21}V_{eq}I_{C1} + R_{TH,21}V_{eq}I_{C2}$$

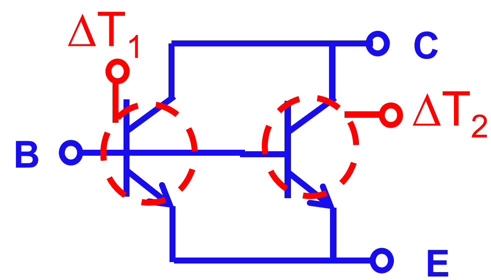
Multi-Finger Transistors



two finger device

identical fingers

$$R_{TH,11} = R_{TH,22} = R_{TH}$$
$$R_{TH,12} = R_{TH,21} = R_M$$



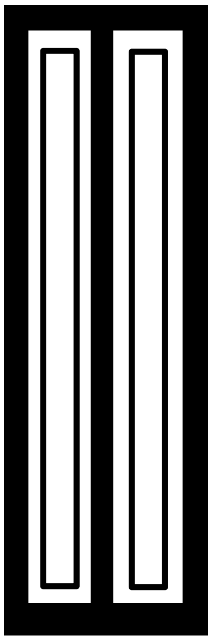
normal operation

$$I_{C1} = I_{C2} = I_C$$
$$P_{diss,1} = P_{diss,2} = P_{diss}$$

$$\Delta T_1 = R_{TH,11} P_{diss,1} + R_{TH,12} P_{diss,2}$$
$$= R_{TH,11} V_{eq} I_{C1} + R_{TH,12} V_{eq} I_{C2}$$

$$\Delta T_2 = R_{TH,21} P_{diss,1} + R_{TH,22} P_{diss,2}$$
$$= R_{TH,21} V_{eq} I_{C1} + R_{TH,21} V_{eq} I_{C2}$$

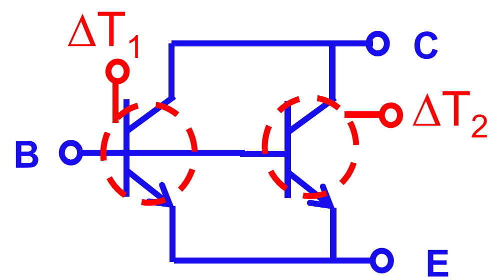
Multi-Finger Transistors



two finger device

identical fingers

$$R_{TH,11} = R_{TH,22} = R_{TH}$$
$$R_{TH,12} = R_{TH,21} = R_M$$



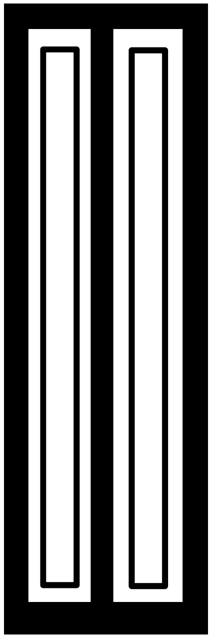
normal operation

$$I_{C1} = I_{C2} = I_C$$
$$P_{diss,1} = P_{diss,2} = P_{diss}$$

$$\Delta T_1 = \Delta T_2 = \left(R_{TH} + R_M\right)P_{diss}$$

✓ **electro-thermal behavior of each finger is identical to a single-finger device with a modified self-heating resistance!**

Multi-Finger Transistors



two finger device

flyback locus

$$I_{CF} = \frac{\eta V_{T0}}{\phi\left(R_{TH} + R_M\right)V_{eq} - R_{eq}}$$

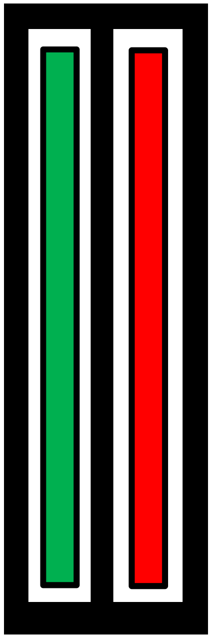
✓ **flyback behavior of each finger is identical to a single-finger device!**

❑ **after a critical amount of current drive, it is likely that one of the fingers will carry most of the current causing a current bifurcation!**

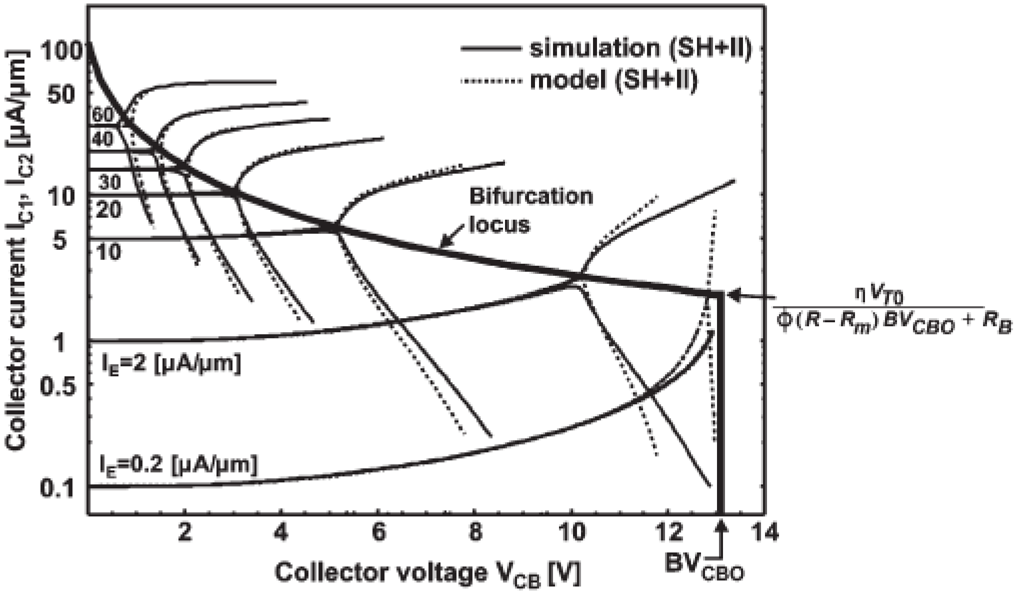
$$R_{TH,11} = R_{TH,22} = R_{TH}$$

$$R_{TH,12} = R_{TH,21} = R_M$$

Multi-Finger Transistors

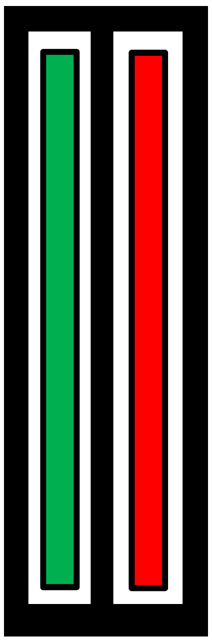


two finger device



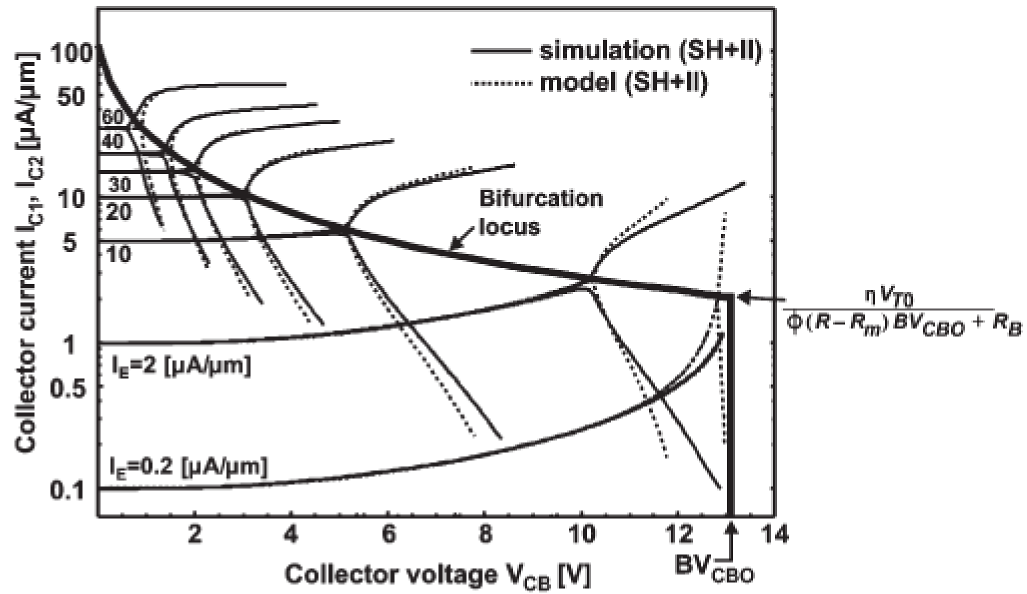
[Rinaldi, TED, 2006]

Multi-Finger Transistors



two finger device

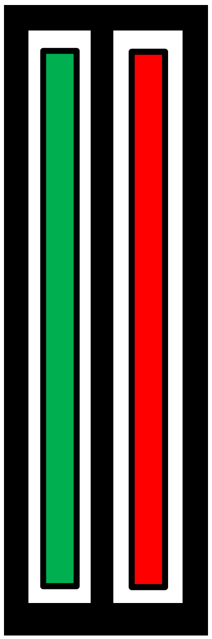
[Rinaldi, TED, 2006]



bifurcation locus

$$I_{CB} = \frac{\eta V_{T0}}{\phi(R_{TH} - R_M)V_{eq} - R_{eq}}$$

Multi-Finger Transistors



two finger device

bifurcation locus

$$I_{CB} = \frac{\eta V_{T0}}{\phi\left(R_{TH} - R_M\right)V_{eq} - R_{eq}}$$

flyback locus

$$I_{CF} = \frac{\eta V_{T0}}{\phi\left(R_{TH} + R_M\right)V_{eq} - R_{eq}}$$

- ✓ **safe operating limit is determined by the flyback locus with V_{BE} excitation**
- ✓ **with I_B and I_E excitation, no flyback occurs and the safe operating limit is determined by the bifurcation locus**
- ✓ **in case the limit is determined by the current bifurcation, thermal coupling improves the thermal stability!**

Outline

- Introduction
- Motivation
- Electro-Thermal (ET) Effects
- Impact Ionization (II) Effects
- Simultaneous ET and II Effects
- Device Design for Power Amplifier
- Multi-Finger Transistors
- Summary

Summary

- ✓ Understanding safe operating limits is important for circuit design, especially the high power circuits
- ✓ Modeling of the locus for the safe operating limits primarily depends on electro-thermal and impact ionization effects
- ✓ At lower current drive, impact ionization is the limiting factor whereas the electro-thermal heating is the main concern in high current operation
- ✓ Formulation details and underlying physics are discussed with individual and concurrent presence of both the effects
- ✓ Device design aspects in view of power amplifier applications are discussed showing the opportunities of the advanced SiGe process
- ✓ Multi-finger transistors are presented as promising device for high power applications
- ✓ Safe operating limits of multi-finger devices are determined by flyback or bifurcation locus depending on the excitation condition

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THANK YOU