Review of high-current effects and their modeling in bipolar transistors

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OUTLINE

- Introduction
- High voltage operation
- Low-voltage operation
- Misconceptions about base widening
- Conclusions

Introduction

- Highest speed in BJT/HBT *circuits* is typically obtained by maximizing the current drive into the load, possibly by increasing the collector current density even beyond peak f_T operating point (optimization problem)

  => need modeling of high-current region and associated effects

- Even if operation only up to peak f_T is desirable, the f_T drop at high current densities needs to be described sufficiently accurate.

- High-current effects have been widely discussed in literature since 1950s
  - 1962 paper of Kirk coined the name "*Kirk*" effect
  - Later papers showing carrier densities at high current densities led to designations "*base widening*" and "*base push-out*"

- Some literature also state that operation beyond $J_{lim} = qN_{Ci}v_s$ leads to high-current effects and, hence, should be avoided => incorrect notion!

=> there seems to be confusion as to what these designations physically mean and how mobile charge and transit/storage time relate to each other

=> clarify physics of high-current effects and their modeling

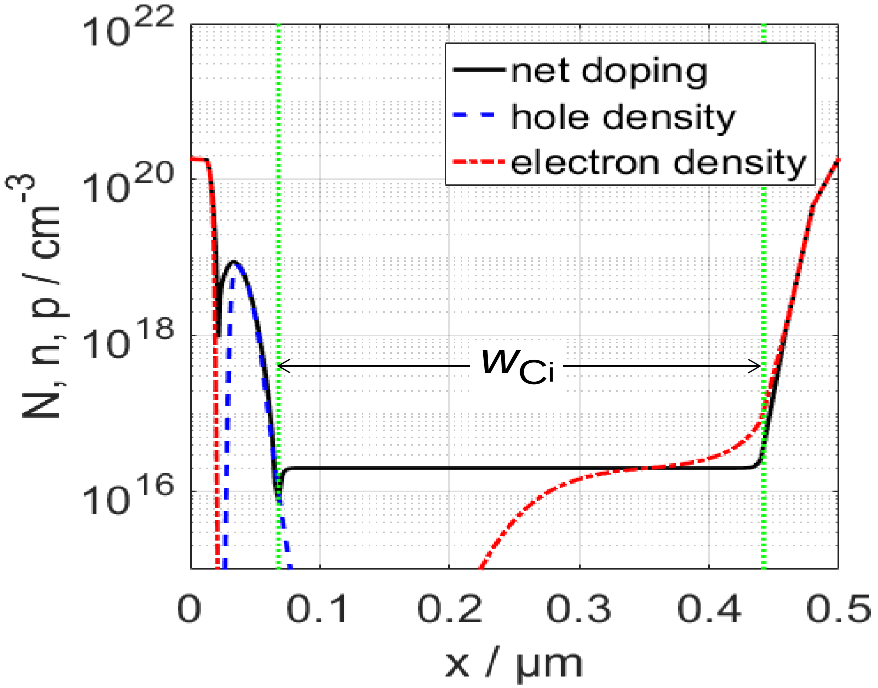
Analysis approach

- 1D transistor structure is sufficient

- lightly doped epi-collector:
  width w_{Ci} = 0.375 µm
  doping concentr. $N_{Ci} = 2\ 10^{16}$ cm^{-3}

=> $J_{lim} = qN_{Ci}v_{sn}$ = 0.34 mA/µm^2

  - $v_{sn} = 1.07\ 10^7$ cm/s (electron drift saturation velocity)
  - q (elementary charge)
  - μ_{nCi0} = 1066 cm^2/Vs (low-field electron mobility in collector region)



- transit frequency f_T used for quantitatively evaluating the various notions
  - f_T determined from extrapolating single-pole frequency dependence of small-signal current gain in common emitter configuration

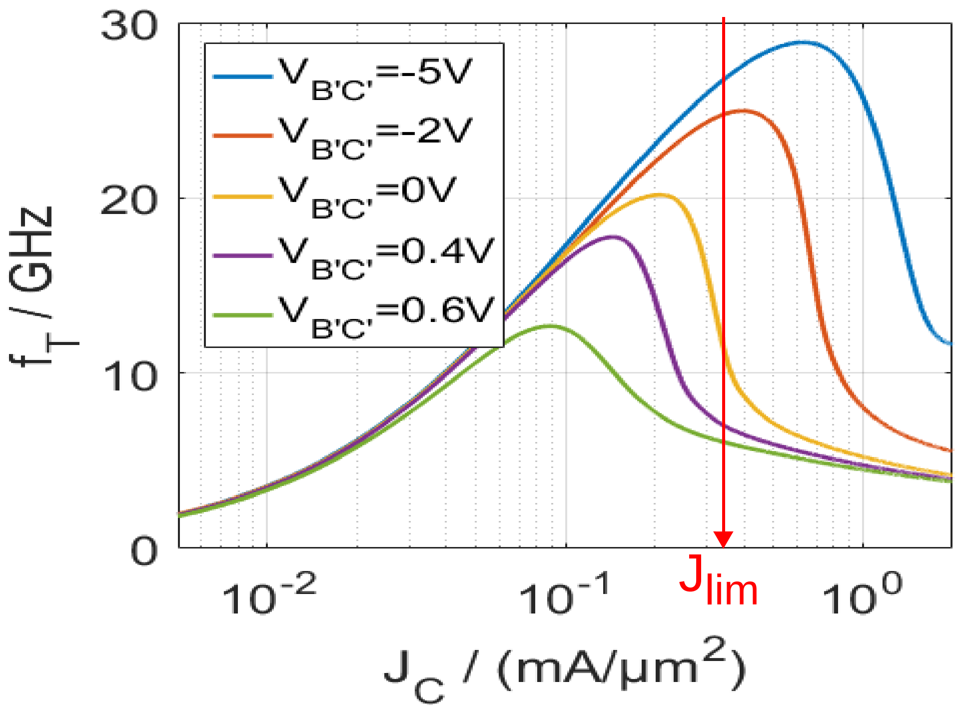
- 2D/3D effects will only change absolute collector current at which f_T starts deteriorating for a given device size

Transit frequency

... from 1D device simulation

- wide range of $V_{C'B'}$ (or $V_{C'E'}$)
- high-current effects => f_T drop
- current density at peak f_T depends on $V_{C'B'}$
- for higher voltages, J_C at peak f_T exceeds J_{lim}

=> no single onset current density for high-current effects

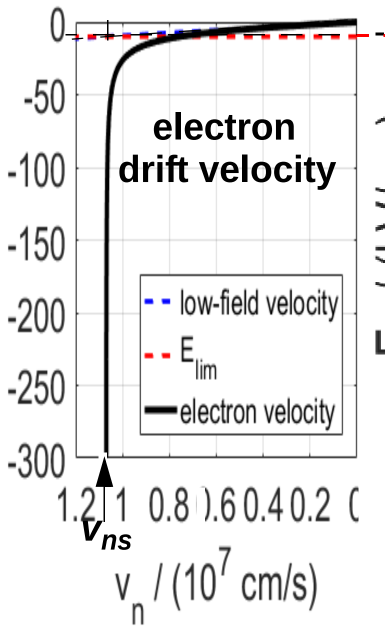


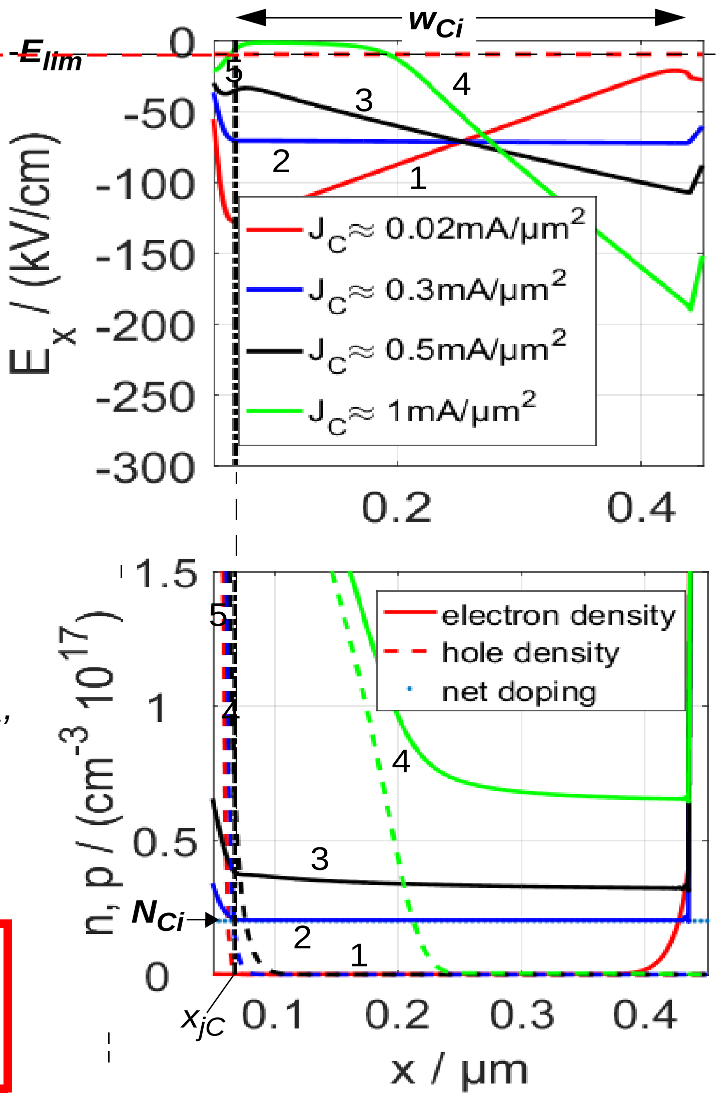
- for analysis, instead of $V_{C'B'}$ (or $V_{C'E'}$) => use internal collector voltage:

$$V_{ci} = -\int_0^{w_{Ci}} E dx \approx V_{DCi} - V_{B'C'}$$ = voltage drop across epi-collector

High voltage operation

Electric field, carrier density and drift velocity





$V_{ci} = V_{DCi} - V_{B'C'}$

$= -2.9$ V

($V_{B'C'} = -2$ V)

"high" voltage:

$V_{ci} > V_{lim}$

- electron density in BC SCR at high fields

$$n = n_c = J_T / (q v_{ns})$$

- Poisson eq. in BC SCR:

$$\frac{dE_x}{dx} = \frac{qN_{Ci}}{\varepsilon}\left(1 - \frac{J_T}{J_{lim}}\right)$$

with $J_{lim} = qN_{Ci} v_{ns}$

- neutral collector at x_{jC} once

$$E(x_{jC}) \le E_{lim} = v_{ns} / \mu_{nCi0}$$

μ_{nCi0}: low-field mobility in C

- $V_{lim} = E_{lim} w_{Ci}$

⇒ high injection starts when electric field at x_{jC} drops below E_{lim}

High-voltage case

... conclusions from device simulation analysis

- horizontal field is reached at $J_C = J_{lim}$, but electrons have saturation velocity

  => transistor still functions "as usual"

- once $E(x_{jC})$ reaches E_{lim} => drift velocity drops strongly
  => current can only be supported by additional (diffusion) current

  => carrier gradient and $n > N_{Ci}$ at x_{jC} => excess charge storage

- electric field in collector: $E(x') = -E_{lim} + \frac{dE_x}{dx'}x'$ with $\frac{dE_x}{dx'} = \frac{qN_{Ci}}{\varepsilon}\left(1 - \frac{J_{Ckh}}{J_{lim}}\right)$

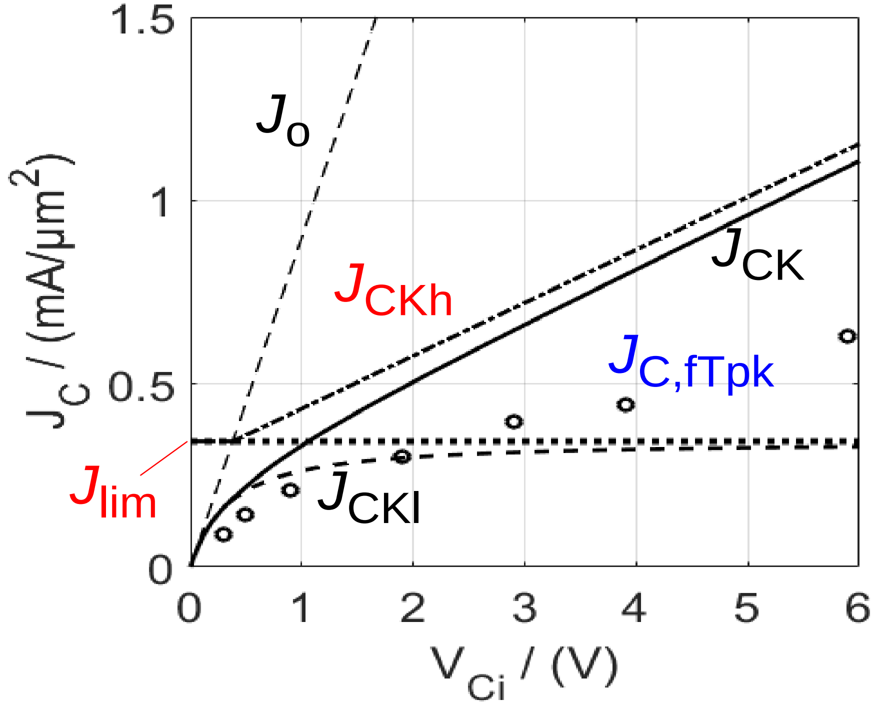
- critical current density from $V_{ci} = -\int_0^{w_{Ci}} E\,dx'$

$$\Rightarrow \boxed{J_{CKh} = J_{lim}\left[1 + \frac{V_{ci} - V_{lim}}{V_{PT}}\right]}$$

- punch-through voltage $V_{PT} = \frac{qN_{Ci}}{2\varepsilon}w_{Ci}^2$

Critical current density at high voltages

$$J_{CKh} = J_{lim}\left[1 + \frac{V_{ci} - V_{lim}}{V_{PT}}\right]$$ => can exceed J_{lim}



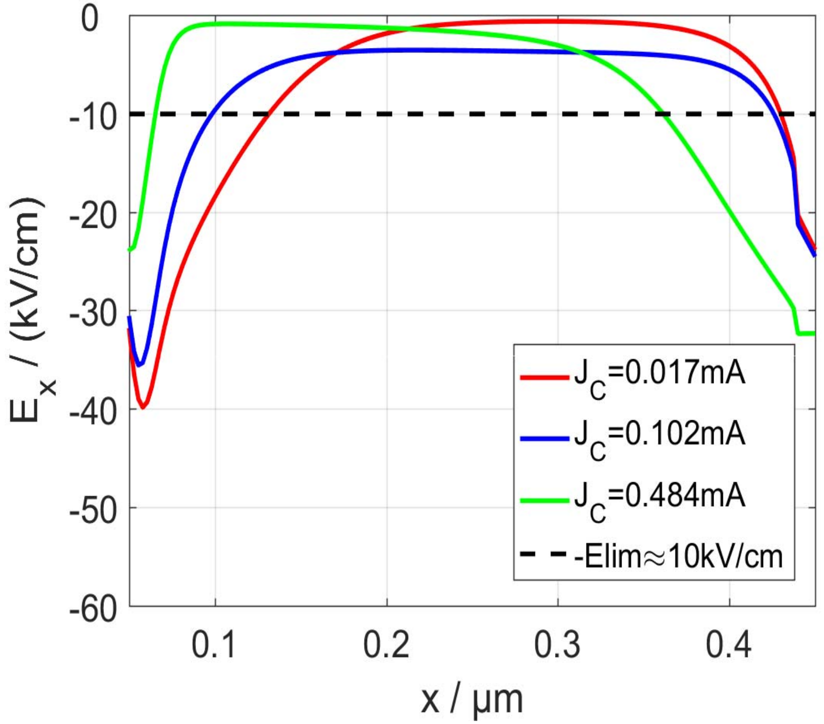
- Note1: ignoring V_{lim} leads to significantly overprediction of $J_C(f_T$ drop)
- Note2: future advanced HBTs operate in collector punch-through

Theory of high voltages was ***not*** treated by Kirk!

Low-voltage operation

Kirk's contribution

$V_{ci} < V_{lim}$



- assumptions for deriving BC SCR width and injection width:
  - spatially constant N_{Ci} and complete ionization
  - negligible SCR extension into the base region;
  - negligible hole carrier and current density;
  - negligible recombination;
  - spatially constant carrier velocity $v_n = v_{ns}$;
  - **zero voltage drop in the undepleted portion of the collector, i.e. $E(w_{BC}) = 0$ => revoked during derivation**
  - **SCR width $w_{BC} << w_{Ci}$:**

$$\Rightarrow \quad w_{BC} = w_{BC0}\sqrt{\frac{1 - J_C/J_o}{1 - J_C/J_{lim}}}$$

=> Kirk arrives at correct result by revoking an unnecessary assumption

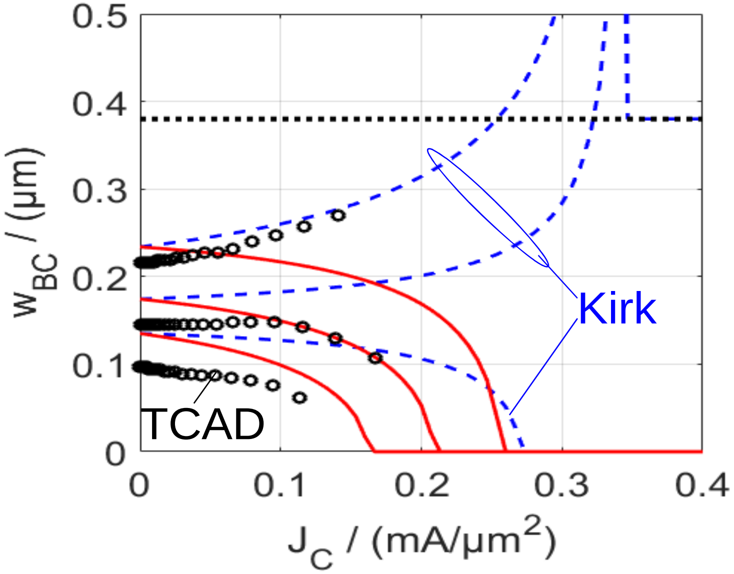
- NOTE: theory is valid only for wide epi collector layers (for which the BC SCR region collapses at high current densities)

Kirk's result ...

$$J_o = \frac{q\mu_{nCi0}N_{Ci}}{w_{Ci}}V_{ci} = \frac{V_{ci}}{r_{Ci0}}$$

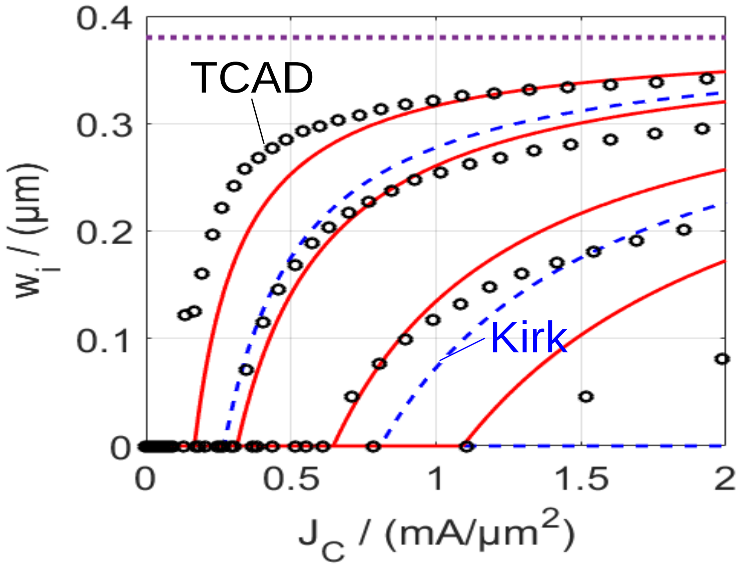
BC SCR width

$$w_{BC} = w_{BC0}\sqrt{\frac{1-J_C/J_o}{1-J_C/J_{lim}}}$$



injection width

$$w_i = w_{Ci}(1-J_o/J_C)$$



... versus device simulation & improved theories

$$w_{BC} = w_{BC0}\sqrt{\frac{1-J_C/J_{CKl}}{1-J_C/J_{lim}}}$$

$$w_i = w_{Ci}(1-J_{CKl}/J_C)$$

$$J_{CKl} = q\mu_{nCi}(E_{CKl})N_{Ci}E_{CKl} = \frac{J_o}{\left[1+\left(\frac{V_{ci}}{V_{lim}}\right)^{\gamma}\right]^{1/\gamma}}$$

Summary of critical currents

- Kirk:

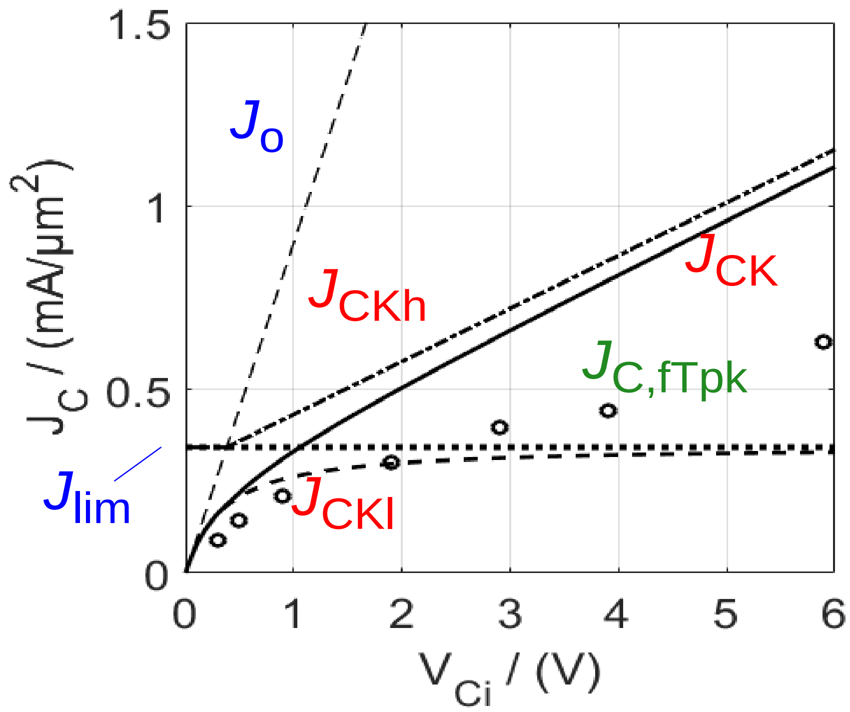
$$J_o = \frac{q\mu_{nCi0}N_{Ci}}{w_{Ci}}V_{ci} = \frac{V_{ci}}{r_{Ci0}}$$

- improved low-voltage theory:

$$J_{CKl} = \frac{J_o}{\left[1+\left(\frac{V_{ci}}{V_{lim}}\right)^{\gamma}\right]^{1/\gamma}}$$

- high-voltage theory

$$J_{CKh} = J_{lim}\left[1+\frac{V_{ci}-V_{lim}}{V_{PT}}\right]$$



- J_{CK}: smooth combination of J_{CKl} and J_{CKh}

  => theory yields consistently higher J_{CK} than $J_C(f_{T,peak})$

  - caused by V_{ci} from terminal voltages being larger than voltage drop across epi collector

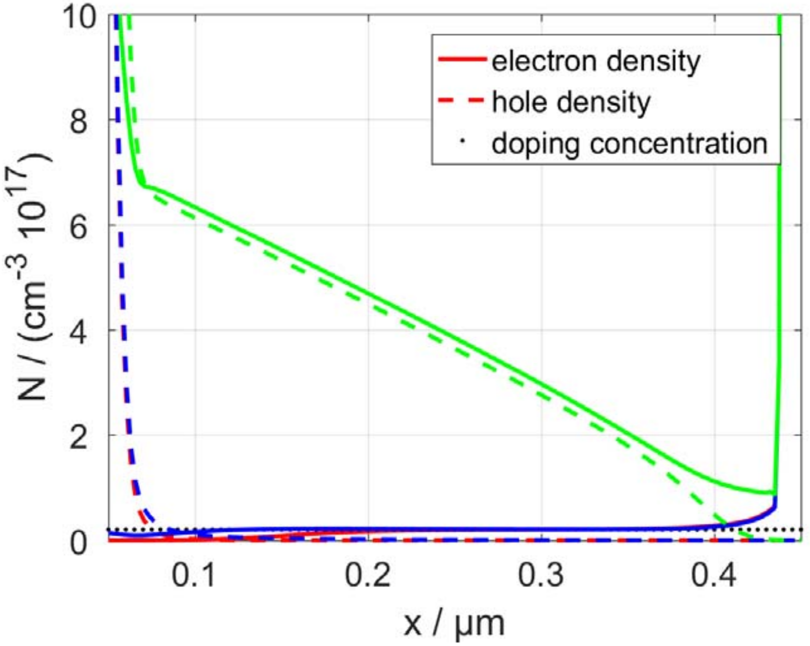
Misconceptions about base widening

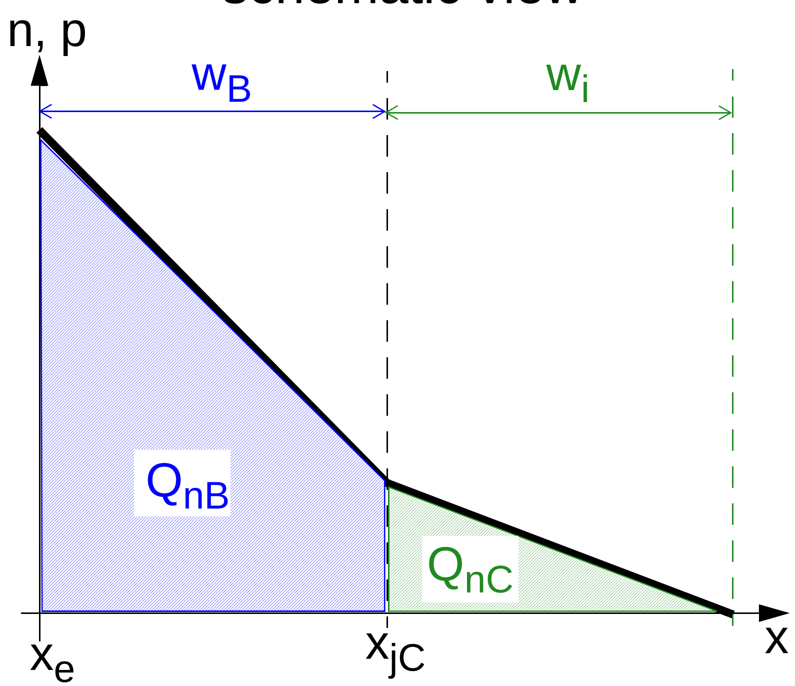
(a.k.a. current-induced base region)

Collector injection zone

- notion: minority carrier density gradient from neutral base region extends into collector injection zone

device simulation => schematic view





1. the gradient of the electron density in base and collector is different (due to different drift fields, doping concentrations => different mobility & velocity)

2. minority charge in the collector consists of holes, not electrons => holes have very different base exit velocity

Charge storage at high current densities

- notion of extended base leads to simple extension of transit time

$$\tau = \frac{(w_{Bm} + w_i)^2}{F_\zeta \overline{\mu_n} V_T} + \frac{w_{Bm} + w_i}{\overline{v_n}} \quad \text{with} \quad w_{B,ext} = w_{Bm} + w_i$$

  - $\overline{v}_n$: base exit velocity; F_ζ: field factor; $\overline{\mu}_n$: average mobility in total base region;

=> incorrect approach since "DC" ratio $\tau = Q_{nB}/I_C$ is assumed

- measured transit time results from small-signal operation:

$$\tau = \frac{d(\bar{Q}_{nB} + \bar{Q}_{pC})}{dJ_C} = \frac{d\bar{Q}_{nB}(J_C)}{dJ_C} + \frac{d\bar{Q}_{pC}(J_C)}{dJ_C}$$

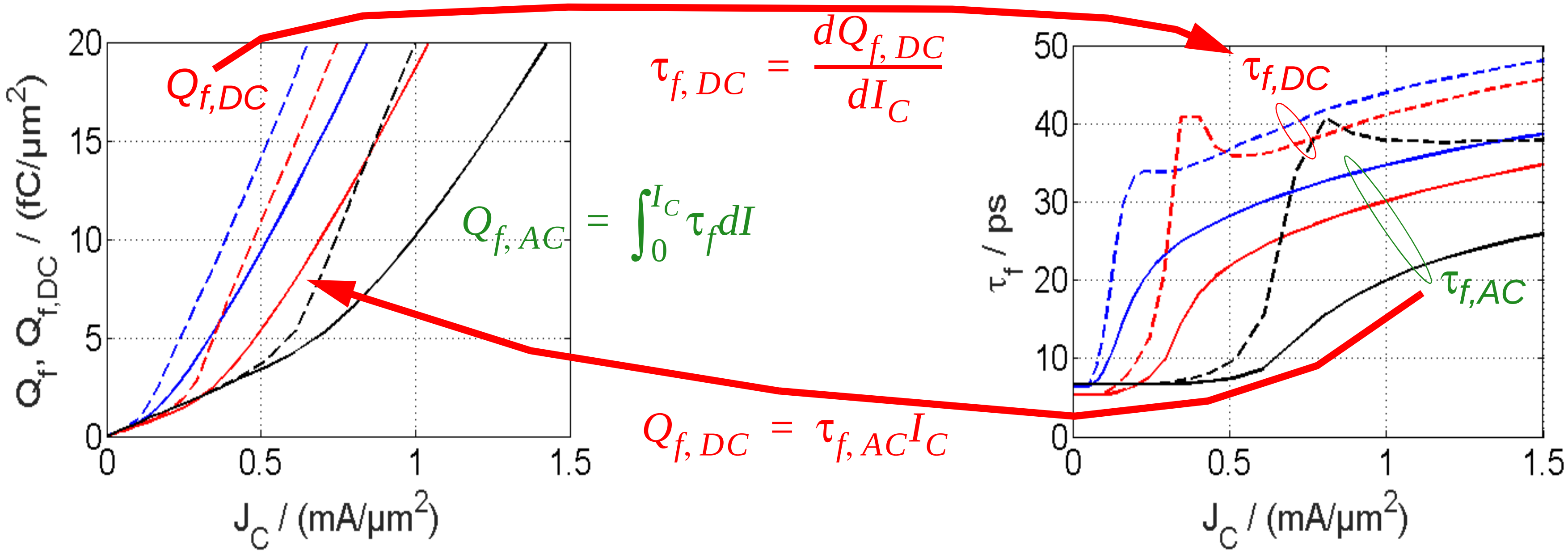
$$\text{with} \quad \bar{Q}_{nB}(J_C) \cong \left(\frac{w_{Bm}^2}{F_\zeta \overline{\mu_{nB}} V_T} + \frac{w_{Bm} w_{Ci}}{2\mu_{nCi0} V_T}\right) J_C \quad \text{and} \quad \bar{Q}_{pC}(J_C) \cong \frac{w_i^2(J_C)}{4\mu_{nCi0} V_T} J_C$$

$$\Rightarrow \quad \tau \approx \frac{w_{Bm}^2}{F_\zeta \overline{\mu_{nB}} V_T} + \frac{w_{Bm} w_{Ci}}{2\mu_{nCi0} V_T} + \frac{w_i^2(J_C)}{4\mu_{nCi0} V_T}\left[2\frac{w_{Ci}}{w_i} - 1\right]$$

=> all formulations based on "extended" base notion are incorrect!

"DC" versus "AC" transit/storage time

- Example SPICE Gummel-Poon model:
  stored minority charge is calculated as $Q_{f,DC} = \tau_f I_C$ where $\tau_f(I_C, V_{BC})$ is supposed to be the bias dependent small-signal forward transit time
  => inserting τ_f from small-signal measurement grossly overestimates charge



- AC simulation with DC charge gives far too large transit time (& too low f_T)

  => all formulations based on a DC transit time are incorrect or at least inconsistent with measurements!

Conclusions

- Reviewed physics and modeling of high-current operation of BJTs and HBTs (incl. classical literature and text books)

1. Original theory of Kirk covers low-voltage case only, which corresponds to operation at $V_{C'E'} < 0.5$ V in today's BJTs/HBTs

2. Notion of base widening was shown (i) to be physically incorrect and (ii) to lead to incorrect description of charge and small-signal transit time for base and collector

3. Notion of single current density level (J_{lim}) as onset for high injection into epi-collector is invalid

- Correct formulations have been provided for
  (a) calculating minority charge in base and collector and
  (b) the onset of high injection into collector at "high" voltages

=> suggestion: use designation ***high-current effects*** to avoid misconceptions or misleading information

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