Modeling the collector related charge in SiGe-HBTs

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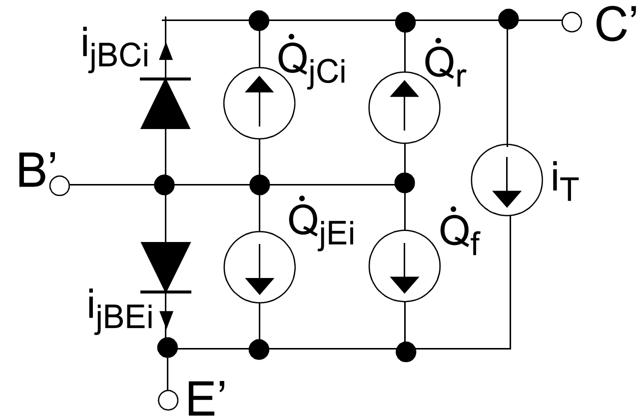
12th HICUM Workshop, Newport Beach, CA (USA), 2012

Outline

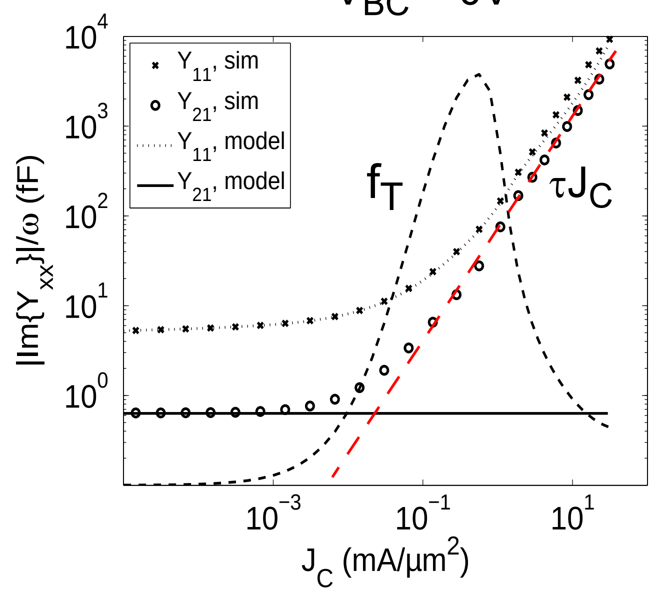
- Introduction
- Analysis
- Charge partitioning
- Modeling the collector field
- Conclusions

Introduction

- present version of HICUM
  - partitions total mobile charge Q_m into $Q_f(I_{Tf})$ and $Q_r(I_{Tr})$
  - assigns mobile charge $Q_f(I_{Tf})$ entirely to (internal) B'E' branch, although charge is distributed (1D)
- mobile charge partitioning from quasi-static considerations is arbitrary
  => to be based on dynamic terminal currents
  (i.e. their phase shift)
- III-V HBT models often try to separate mobile charge into component for B'E' and B'C' branch
- observations:
  - 1D device simulation: at low forward bias, $|\mathrm{Im}\{y_{21}\}|/\omega \sim J_C$ although Q_{jCi} depends only on $V_{B'C'}$
  - measurements: slightly larger phase shift in y_{21}



V_{BC} = 0V



=> cause of increase?

=> investigate necessity of charge "partitioning" and possible modeling options

Analysis

- Taking the derivatives of Q_f and Q_r yields the capacitances:

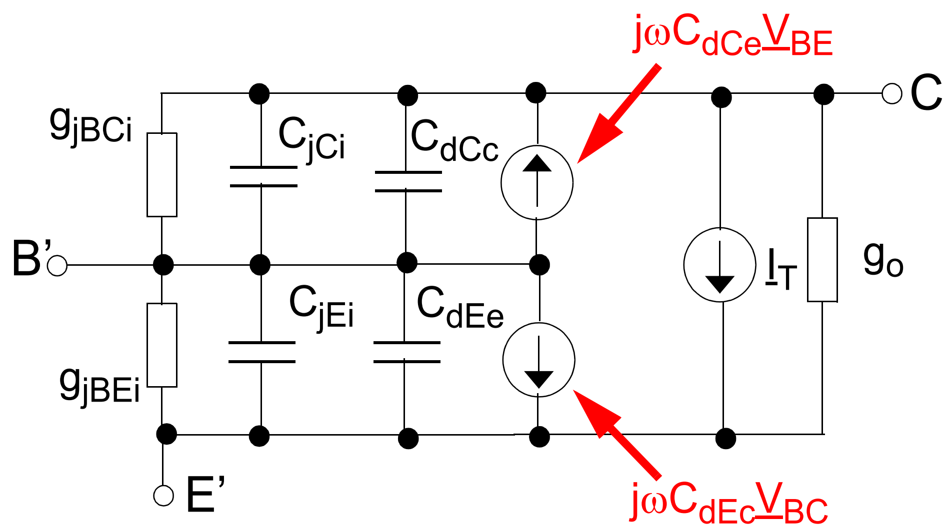
$$C_{dEe} = \left.\frac{dQ_f}{dV_{BE}}\right|_{V_{BC}} , \quad C_{dEc} = \left.\frac{dQ_f}{dV_{BC}}\right|_{V_{BE}} , \quad C_{dCe} = \left.\frac{dQ_r}{dV_{BE}}\right|_{V_{BC}} , \quad C_{dCc} = \left.\frac{dQ_r}{dV_{BC}}\right|_{V_{BE}}$$

=> possible 1D small-signal (HICUM) equivalent circuit

- "cross-coupled" capacitances represent charge controlled by other branch voltage
- Note: mobile charge in BC SCR affects both Q_{jCi} and Q_f

  => physics-based approach:

  - $Q_r \rightarrow Q_r + \tau_{BC} I_{Tf}$ includes mobile charge in BC SCR at low and medium bias
  - current dependence of C_{jCi} at medium and high current densities



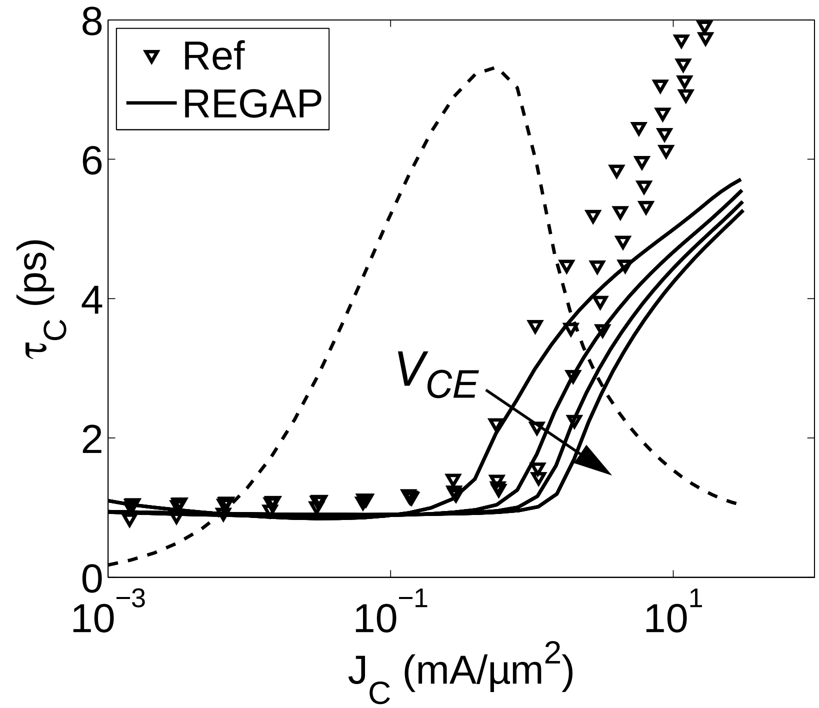
=> is modification of these elements sufficient?

Corresponding transit time

- Calculation of transit time corresponding to increase of Im{y_{21}}.

$$\tau_C = \left(\frac{\Im m(y_{21})}{\omega} - C_{jCi}(V_{BC})\right)/g_m \quad \text{with} \quad C_{jCi} = \lim_{I_T \to 0} \frac{\Im m(y_{21})}{\omega}.$$

- Comparison of 1D quasi-static transit times $\tau_C = \tau_{BC} + \tau_{pC}$ with $\tau = dQ_p/dI_C\big|_{V_{CE}}$



- Good agreement for not too high current densities
- In HICUM:

$$\tau_{pC} = f_{\tau hC}\tau_{fh}$$

and

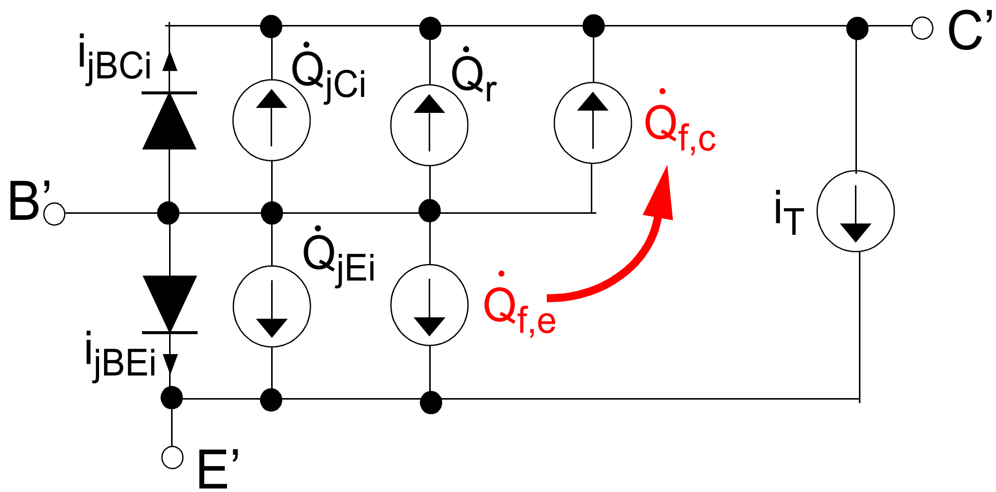
$$\tau_{BC} = f_{\tau BC}\tau_{f0}$$

with unknown partitioning factor $f_{\tau BC}$
=> difficult to extract

Charge partitioning

- difficulty to determine separate components in transit time and distinguish phase shift contributions from C_{BC}, $R_B C_{BE}$, NQS effect in y_{21} experimental data
- requirement for distributing charge to BE and BC branch:
  Total charge at B' node has to remain the same (=> accurate y_{11} modeling)

=> general and flexible approach: partitioning factor for Q_f



$Q_{f,c} = f_{\tau hC} * Q_f$

$Q_{f,e} = (1 - f_{\tau hC}) * Q_f$

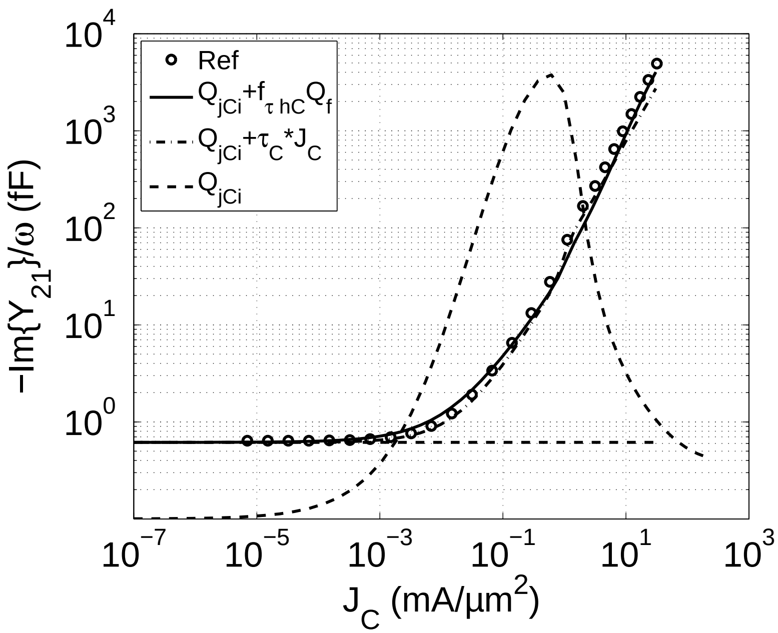
=> $Q_{f,c}$ leads to additional phase shift and bias dependence of y_{21}

- Note: NQS effect now needs to be applied to $Q_{f,e}$ only

Results

- simple physics-based approach, $Q_{f,c} = \tau_{BC} I_{Tf}$, vs. general approach, $Q_{f,c} = f_{\tau hc} Q_f$

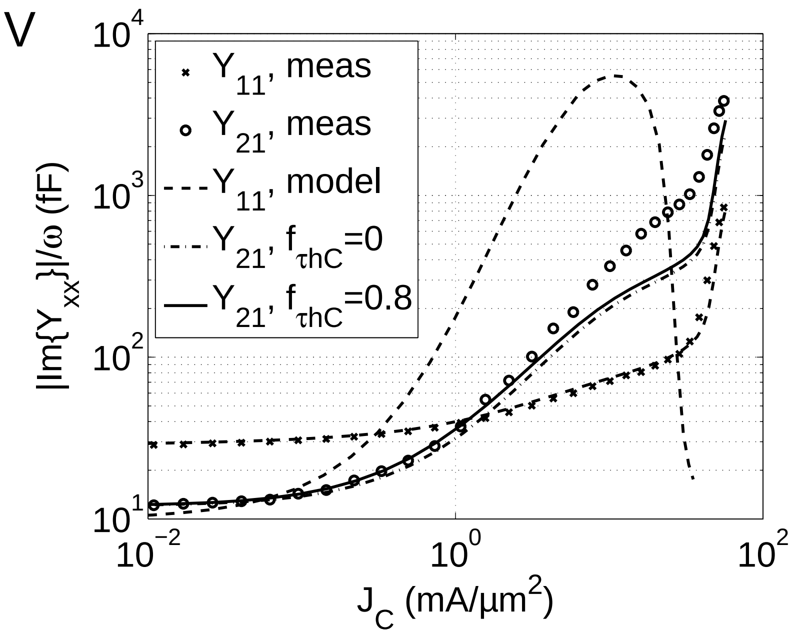
1D device simulation



=> significant improvement

V_{BC} = 0 V

experimental results



=> some improvement

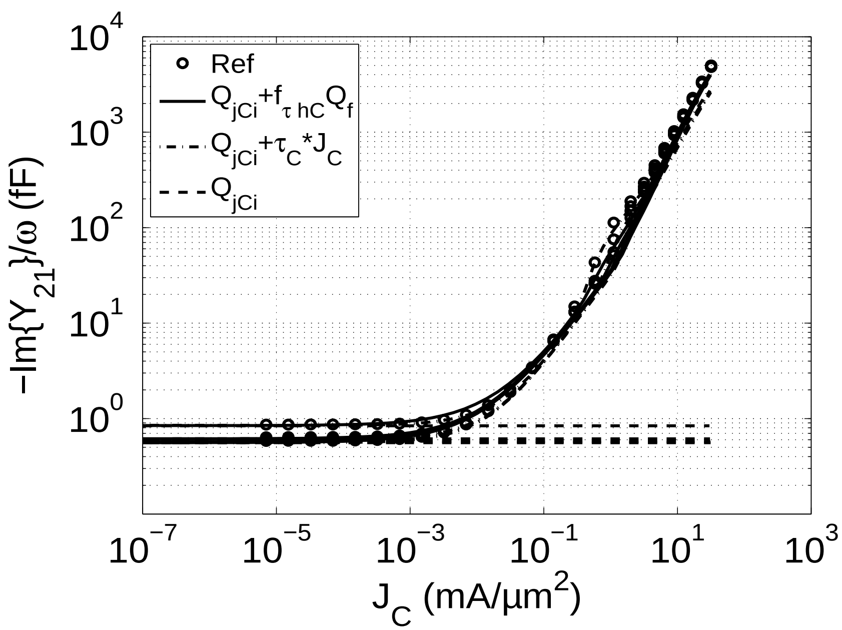
- effect masked in experimental data by influence of $R_B C_{BE}$, C_{BC}, NQS effect

  => time constant difficult to extract from measured data

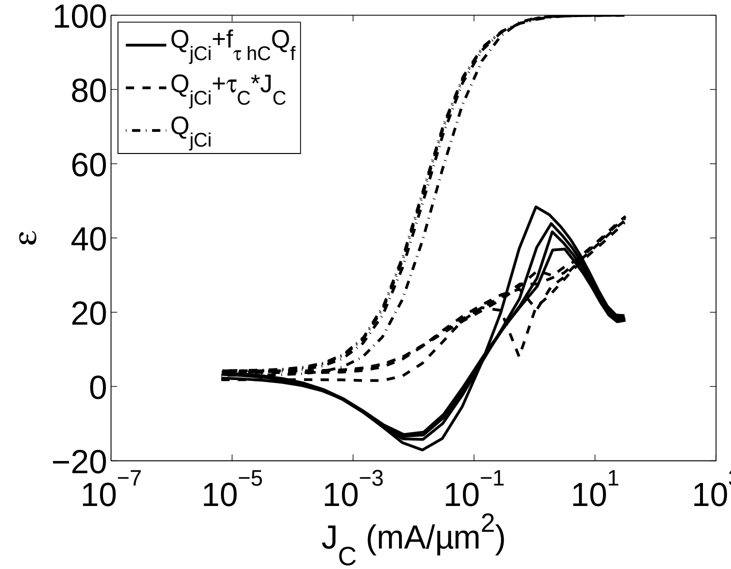
VBC dependence

Comparison for different V_{BC} (1D device simulation)

V_{BC}=(0.5, 0, -0.5, -1.0) V



relative error



- Both approaches reduce error significantly
- General approach more easy to extract
- Using τ_{BC} is more physics-based but requires also separation of τ_{f0}

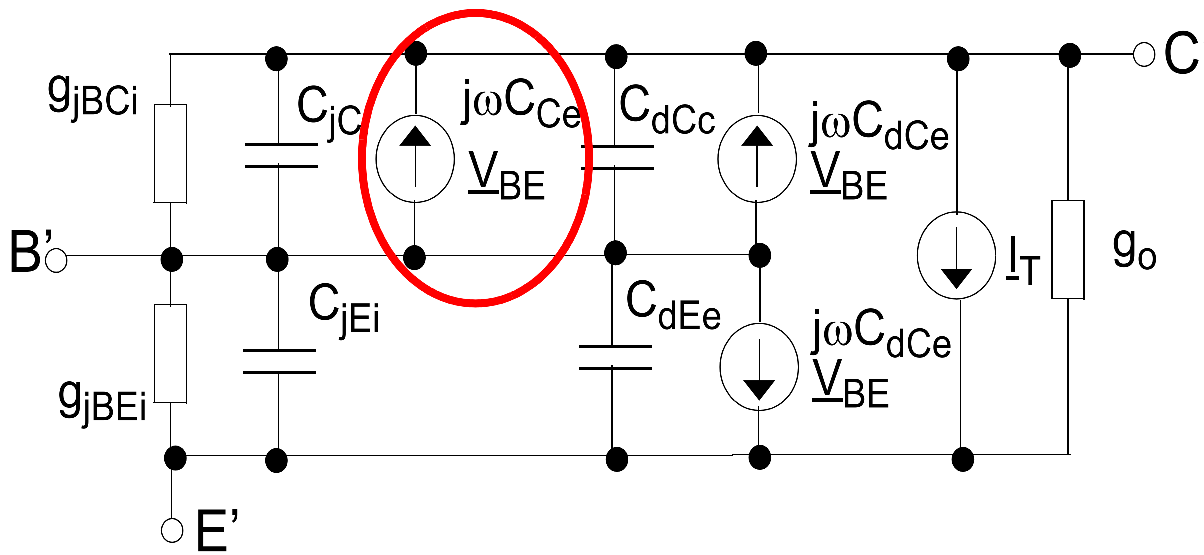
Modeling the collector field

- Goal: model Q_{jCi} (and w_{BC}) by bias dependent electric field E_{jC} at the BC-junction:

$$Q_{BCi} = \varepsilon E_{jC}(V_{BCi}, i_{Tf})$$

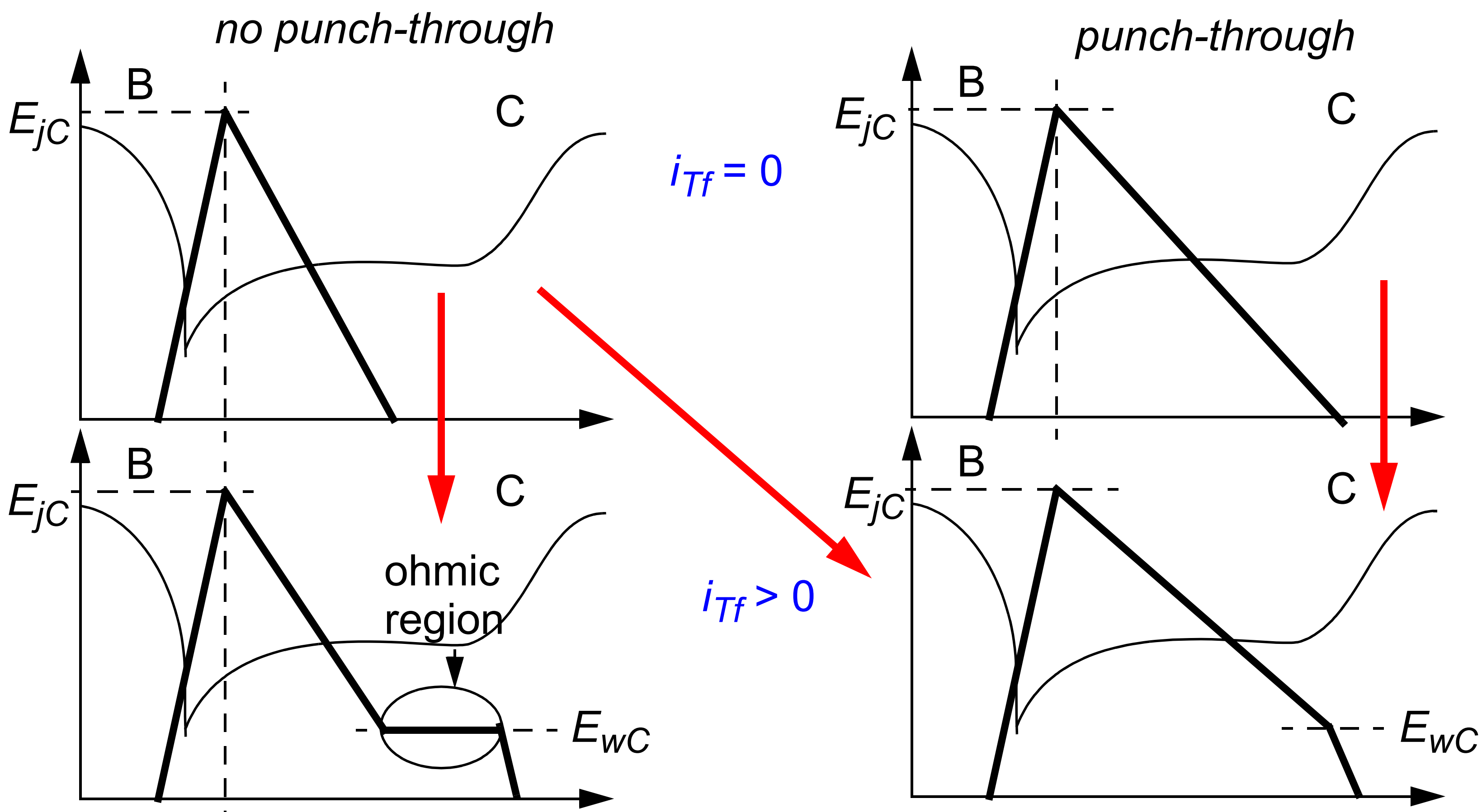
$$\Rightarrow \quad C_{jCi} = \varepsilon \left.\frac{dE_{jC}(V_{BCi}, i_{Tf})}{dV_{BCi}}\right|_{V_{B'E'}} \quad \text{and} \quad C_{Ce} = \varepsilon \left.\frac{dE_{jC}(V_{BCi}, i_{Tf})}{dV_{BEi}}\right|_{V_{B'C'}}$$

=> corresponding small-signal equivalent circuit



Brief review of bias dependent field

- Poisson eq. for low-bias electric field in collector: $\frac{dE}{dx} = \frac{q}{\varepsilon}(N_{Ci} - n)$ with $n = J_C / q v_c$
- Resulting field shape under different operating conditions (note change of field sign)



Modeling the electric field

- Poisson equation with current dependence: $\frac{dE}{dx} = \frac{q}{\varepsilon}(N_{Ci} - n) = \frac{q}{\varepsilon}\left(N_{Ci} - \frac{J_T}{qv_n}\right)$
- simplified model for electron velocity: $v_n = v_{sn}\frac{E}{E_{lim} + E}$
- solution: $\frac{E_{jC} - E(x)}{a} - \frac{b}{a^2}\ln\left(\frac{aE(x) - b}{aE_{jC} - b}\right) = x$ (valid only in SCR)

  with $a = \frac{qN_{Ci}}{\varepsilon}\left(1 - \frac{J_T}{J_{lim}}\right)$ and $b = \frac{qN_{Ci}}{\varepsilon}\frac{J_T}{J_{lim}}E_{lim}$
- Boundary condition from $V_{Ci} = -\int_0^{w_{Ci}} E(x)dx$

  => $V_{Ci} = \frac{1}{2a}(E_{jC}^2 - E_{wC}^2) + \frac{b}{a}w_{Ci}$ (valid at all biases)

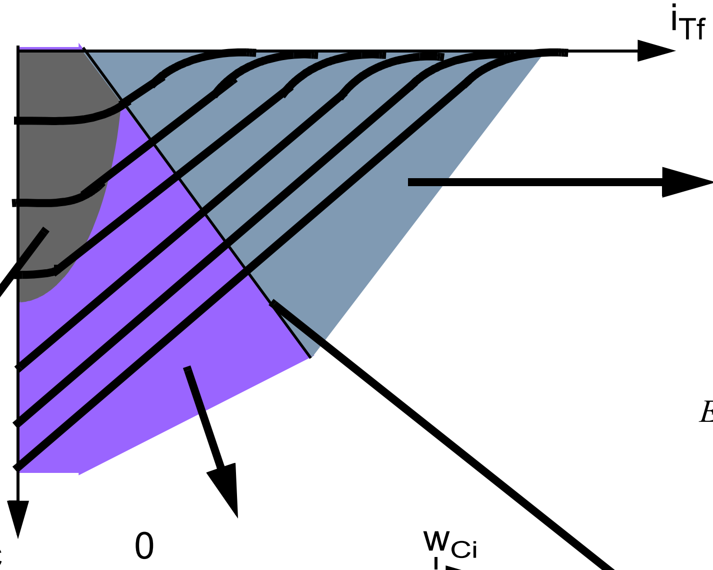
Compact collector field model

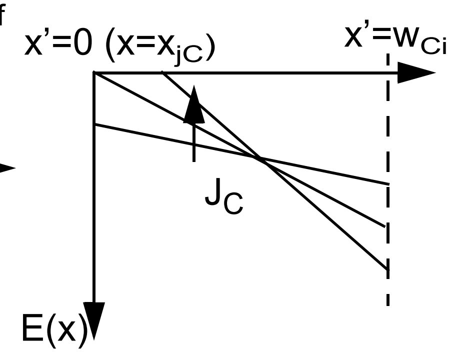
low-current electric field at V_{BC}=0:

$$E_{jC00} = -\frac{Q_{jCi}(V_{DCi})}{\varepsilon A_E}$$

Low-current electric field:

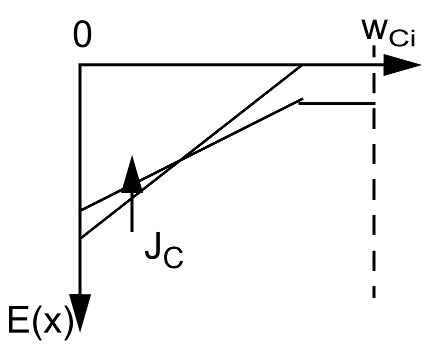
$$E_{jC0}(V_{BC}) = E_{jC00} - \frac{Q_{jCi}(V_{BC})}{\varepsilon A_E}$$





$$E_{jC}(V_{BC}, i_{Tf}) = E_{CKl} - \frac{V_{PT}}{w_{Ci}}\frac{i_{Tf}-I_{CKl}}{I_{lim} f_0 f_\infty}$$

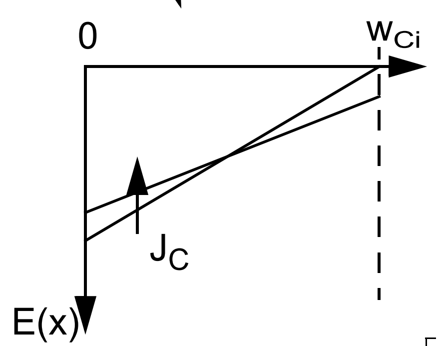
$$f_\infty = \cos\left(\left(\frac{I_T}{2I_{CK}}\right)^\beta\right)$$



$$E_{jC}(V_{BC}, i_{Tf}) = \sqrt{2(aV_{Ci}-bw_{Ci})+E_{wC}^2}$$

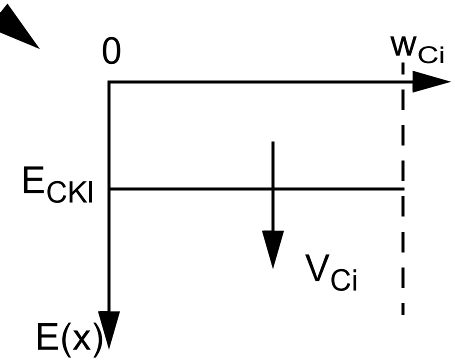
with

$$E_{wC} = E_{lim}\frac{i_{Tf}/I_{lim}}{1-i_{Tf}/I_{lim}}$$



$$E_{jC}(V_{BC}, i_{Tf}) = \begin{bmatrix}E_{jC0}\\E_{PT}\end{bmatrix} - \frac{V_{PT}}{w_{Ci}}\frac{i_{Tf}-\begin{bmatrix}0\\I_{PT}\end{bmatrix}}{I_{lim}f_0}$$

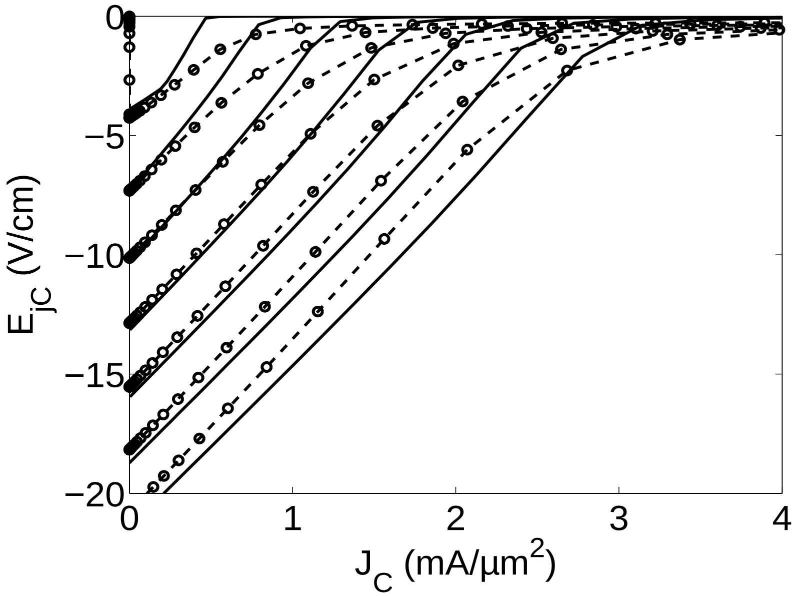
$$f_0 = \begin{cases} a-(a-b)\dfrac{I_T-I_0}{I_{lim}} \\ b \end{cases} \quad \text{with} \quad a = \frac{E_0}{E_{lim}+E_0}, \quad b = \frac{E_{CKl}}{E_{lim}+E_{CKl}}$$

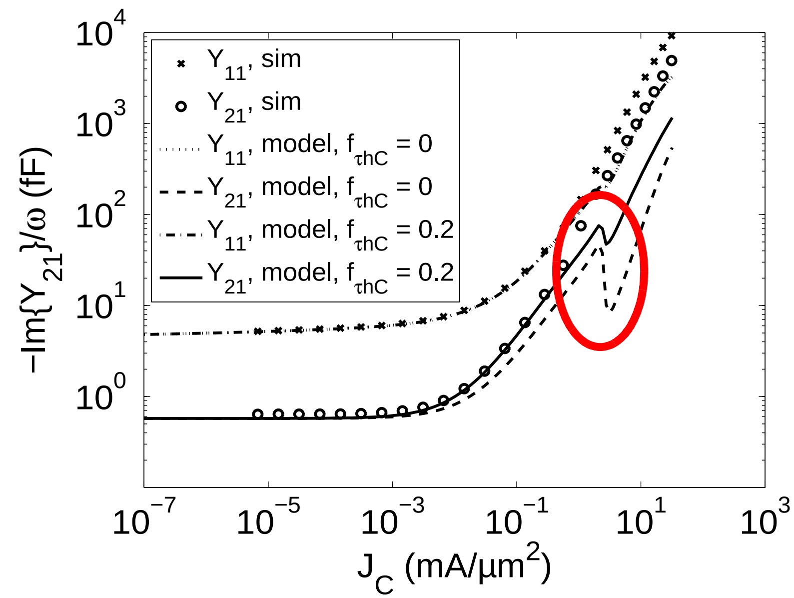


$$E_{jC}(V_{BC}) = E_{CKl} = \frac{V_{Ci}}{w_{Ci}}$$

Results

1D device simulation





=> good results for y_{21}, especially when combining with charge partitioning model

- Issues to be solved yet
  - numerical problems for $J_C > J_{CK}$ still exist
  - Different extraction method necessary, since dQ_{jCi}/di_T is generally included in τ_f determination and parameter extraction

=> field model will allow to also include non-local effects and will be more predictive

Conclusions

- Observations
  - 1D device simulation shows bias dependence and additional phase shift of Im{y_{21}}
  - measurements seem to show slightly larger y_{21} phase shift than model
- Discrepancies traced back to
  - current dependence of internal BC depletion charge Q_{jCi} and
  - lumping mobile charge in BC SCR into BE diffusion capacitance
- Physics-based modeling approach for both elements
  - BC SCR charge portion of Q_f was moved to the internal BC-branch
  - current dependence of Q_{jCi} modeled via electric field in the collector

=> combining both approaches leads in very good results

- Further work necessary
  - field model to be made numerically smooth
  - verify BC SCR charge model in BC branch for different technologies
  - need parameter extraction method for determining $Q_{jCi}(J_C)$ and BC SCR charge
  - couple field model to non-local avalanche breakdown and tunneling current calculation