# HICUM Workshop

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# Improved $T_f$ and $f_T$ determination

prepared by

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# Overview

- Introduction
- Parameter extraction according to the conv. method (CM)
- Improved method (IM) - theory
- Parameter extraction according to the IM
- Deviation of the transit frequency in the high-current region
- Summary

# Introduction - The conventional method (CM)

- relation between transit frequency and transit time:

$$\frac{1}{2\pi f_T} = \tau_f(V_{BC}, I_C) + (r_{Cx} + r_E)C_{jC}(1 + 1/\beta_0) + \frac{C_{jC}(1 + 1/\beta_0) + C_{jE}}{I_C} V_T m_{Cf}$$

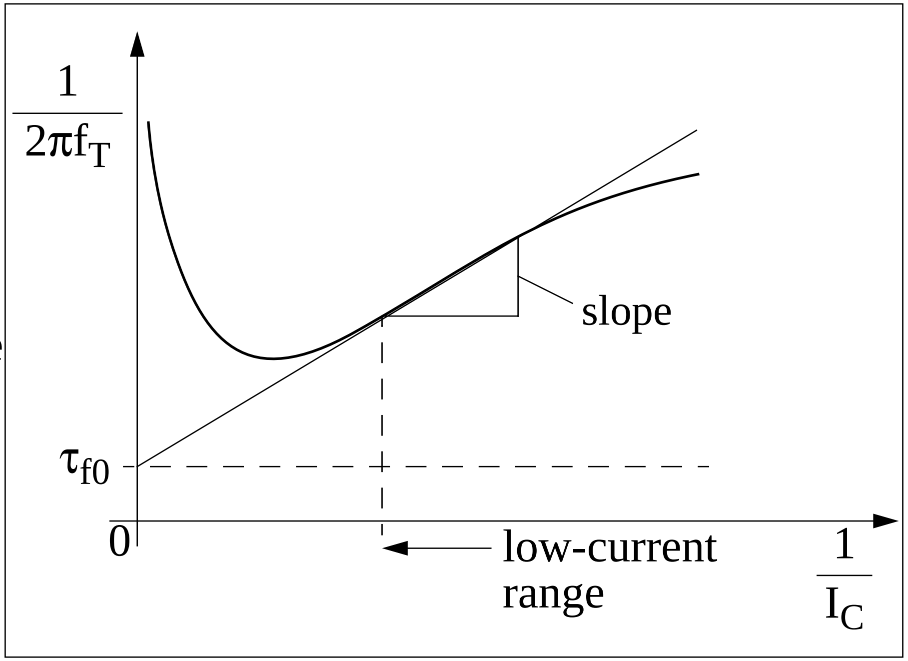
- CM for extracting transit time:

  - find inflection point in plot $\frac{1}{2\pi f_T}$ vs. $\frac{1}{I_C}$

  - calculate a tangent at the inflection point

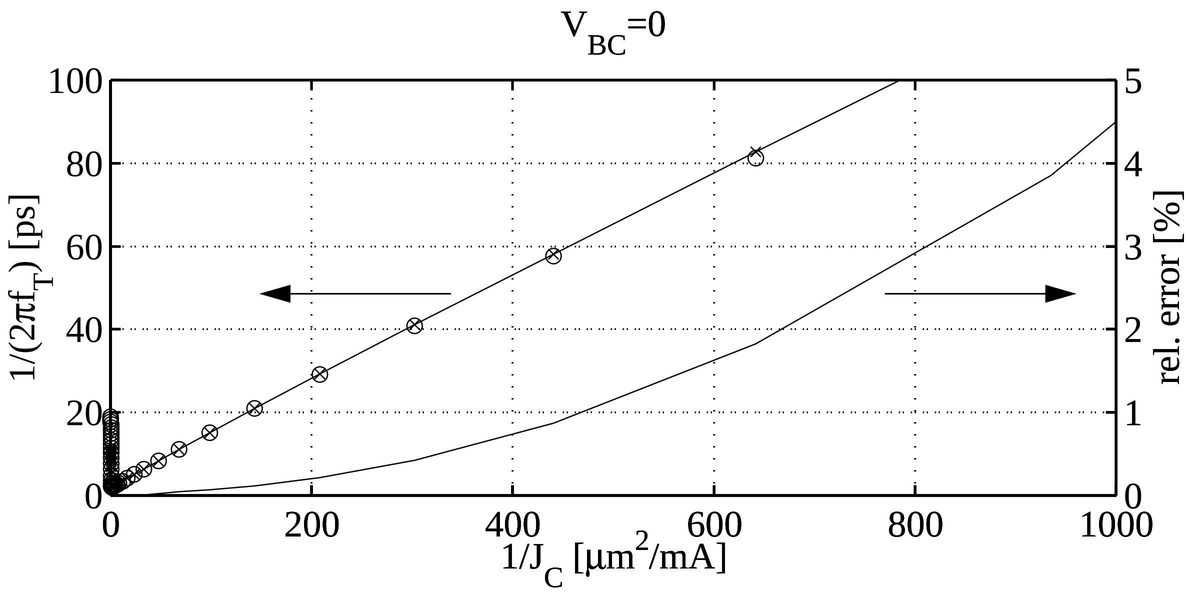
  - $\tau_{f0}$ = intersection of tangent with ordinate

  - calculate $C_{jE,max}$ from the tangent slope

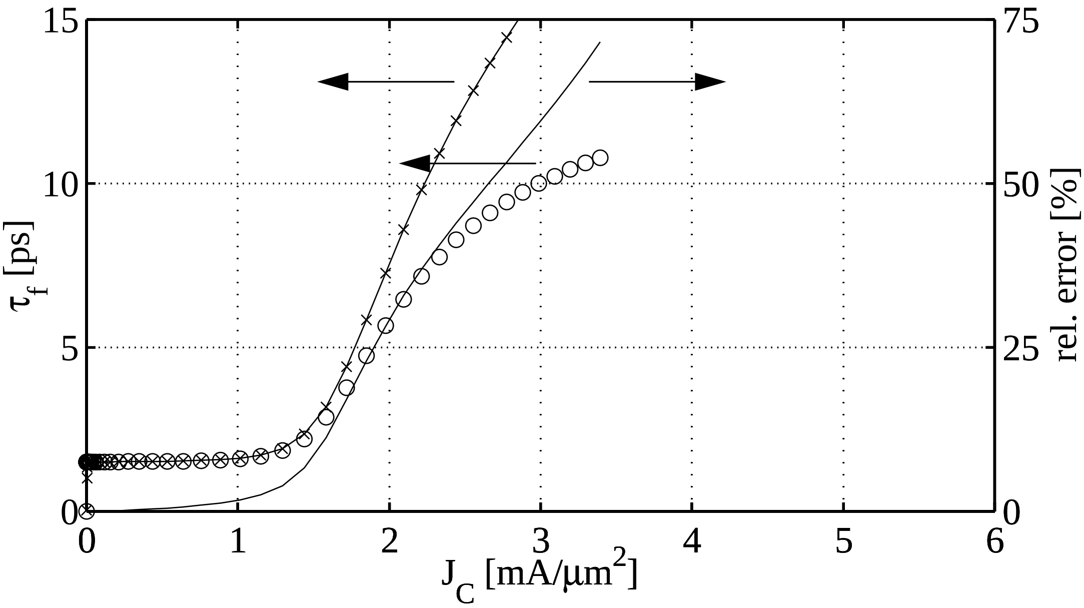


# Verification of the transit frequency relation

- low-current region: the equation approximates the reference




- high-current region: equation <u>does not</u> approximate the reference




⇒ equation has to be revisited for high-current region

# Why using simulation results instead of measurements to verify an extraction methodology?

Advantages:

- model parameters are known: extracted result is easily comparable with parameter setup
- deviation of extracted result is only due to the used methodology and not due to measurement uncertainty

Disadvantages:

- applicability to measured data still must to be verified

## Extraction result according CM at low-current densities

- the rel. error is in the range of 10%

Discussion:

- various causes for inadequacy of the CM (exact result depends on process)

## $\Rightarrow$ extracted result with CM is random

- 1st example:
  proc 1: $C_{jE}(I_{C1}) = C_{jE,\,max}$ and $\Delta\tau_f(I_{C1}/I_{CK1}) > 0$

  proc 2: $C_{jE}(I_{C1}) = C_{jE,\,max}$ and $\Delta\tau_f(I_{C1}/I_{CK2}) = 0$

$I_{C1}$ collector current in inflection point, $I_{CK1}$ and $I_{CK2}$ critical current at $V_{CE1} = V_{CE2}$.

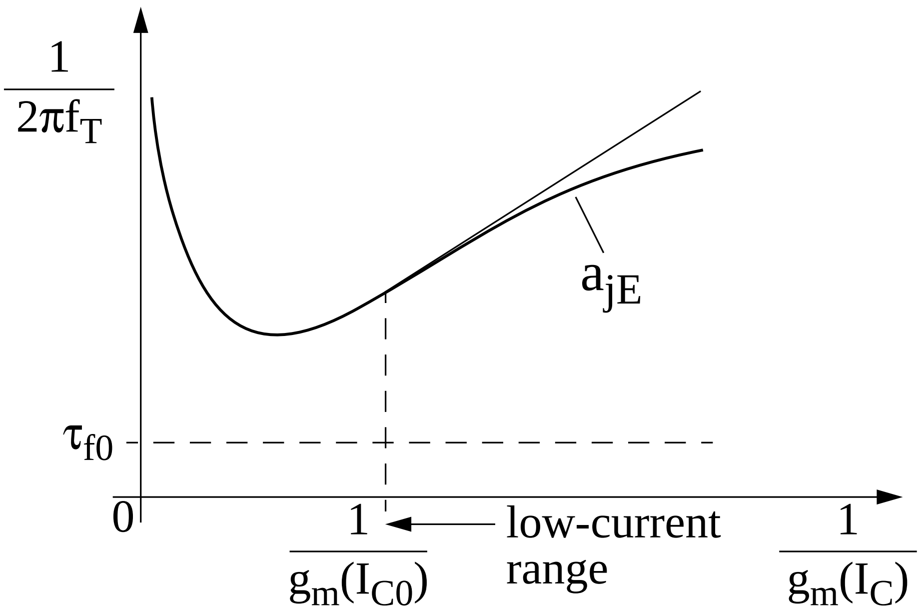
$\Rightarrow$ calculating $C_{jE,max}$ in proc 1 from slope is impossible because of influence of $\Delta\tau_f$ and $I_{CK1} < I_{CK2}$

- 2nd example: same setup as in example 1

$\Rightarrow$ a deviation in the slope will cause a deviation in the extrapolated value of $\tau_{f0}$

# Improved method for extracting $\tau_f$ at low-current densities



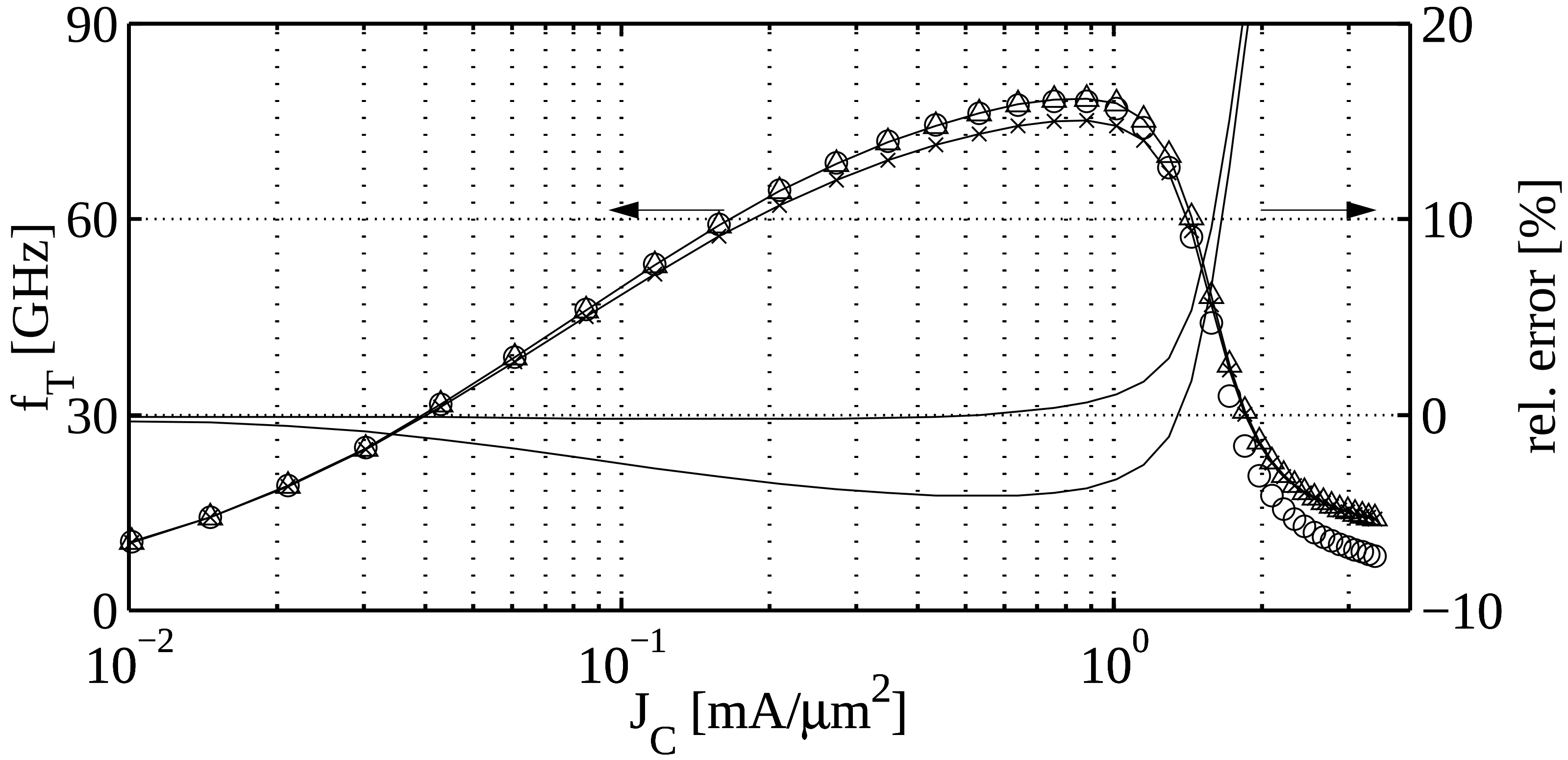

$$g_m = \frac{\Re(y_{21})}{1 - r_E \Re(y_{21})}$$

Improved method:

- determine $I_{C0}$ from tangent in inflection point
  $\Rightarrow$ lower bound
- fit equation at sufficiently low-current densities
  $\Rightarrow$ parameters $\tau_{f0}$, and $a_{jE}$

$$\left.\frac{1}{2\pi f_T}\right|_{\frac{1}{g_m} \geq \frac{1}{g_m(I_{C0})}} = \tau_{f0} + \left.\frac{C_{jC} + a_{jE} C_{jE0} f(V_{BE})}{g_m(I_C)}\right|_{\frac{1}{g_m} \geq \frac{1}{g_m(I_{C0})}}$$

# Comparison of the extracted results

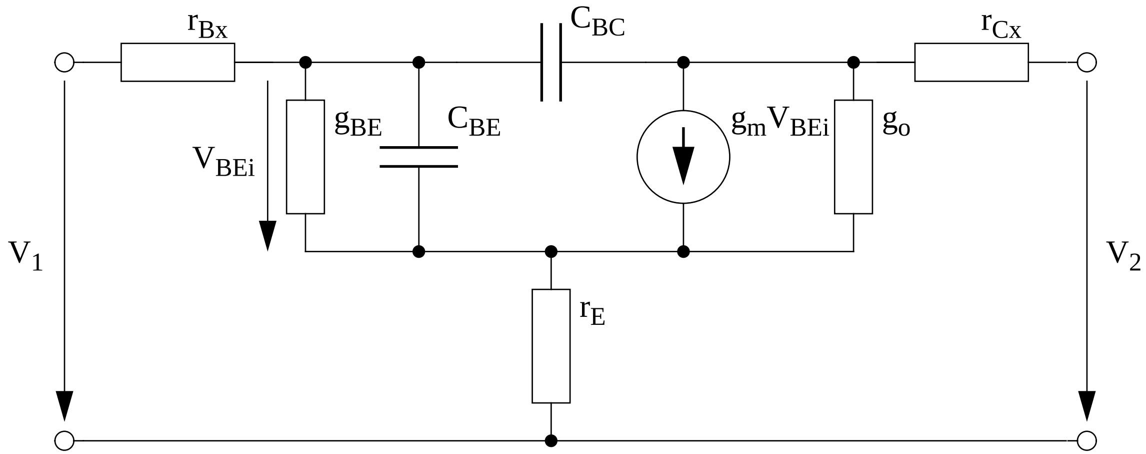



Discussion:

- more accurate result than in case of extraction according CM
- remaining deviation at high-current densities caused by inadequate standard equation for $1/(2\pi f_T)$

# Transit frequency relation including external elements

- small signal equivalent circuit




$$C_{BC} = C_{jC} + C_{dC}$$

$$C_{BE} = C_{jE} + C_{dE}$$

$$C_{dC} = \tau_f g_o$$

$$C_{dE} = \tau_f g_m$$

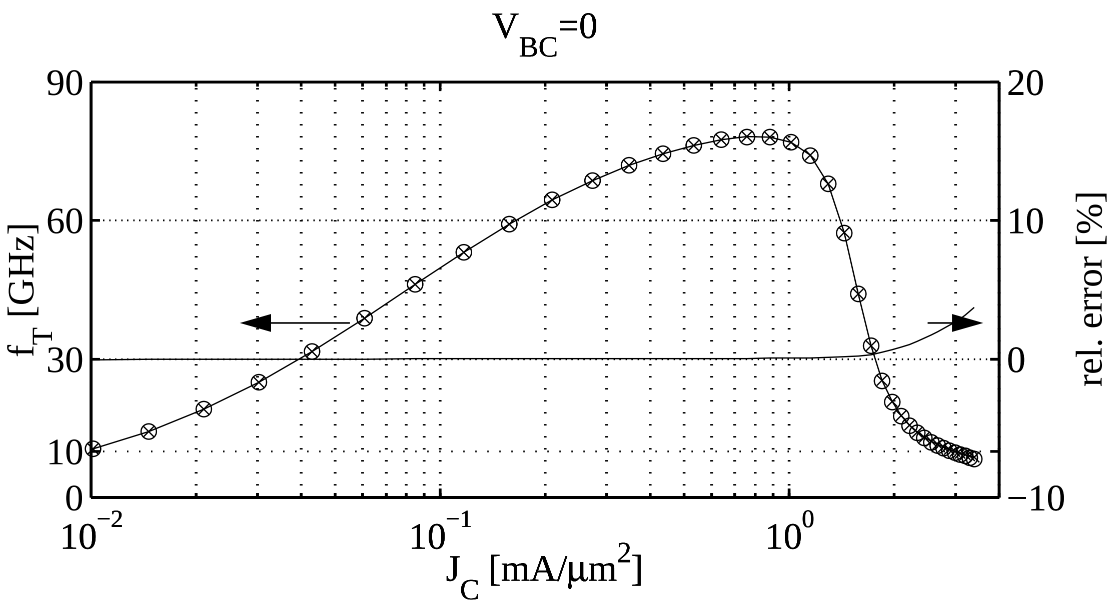
- simplified equation (from symbolic analysis)

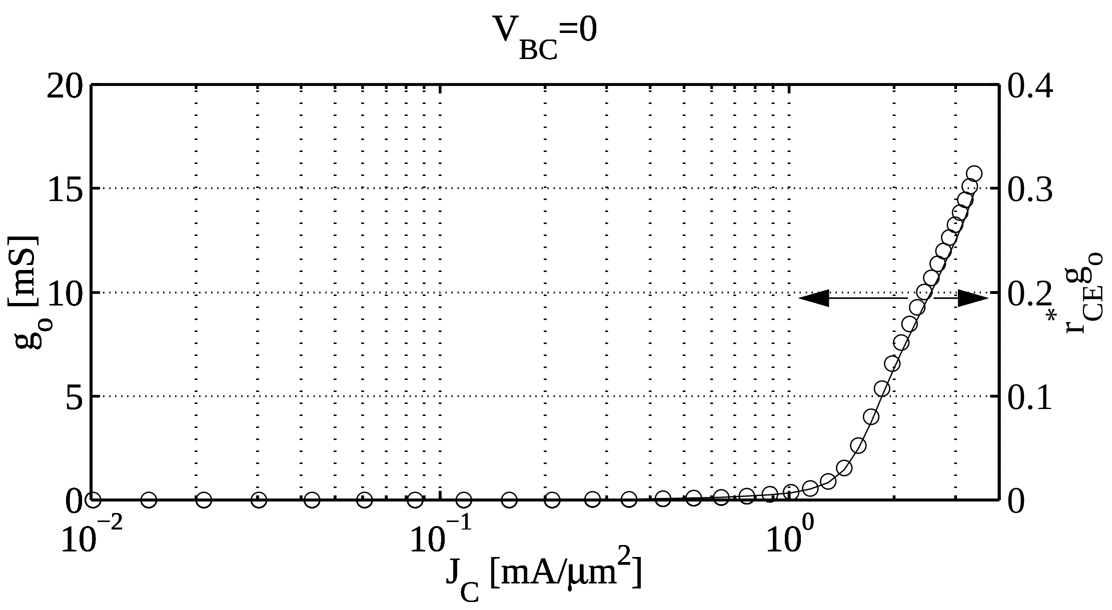
$$\frac{1}{2\pi f_T} = \tau_f(1 + r_{CE}^* g_o) + r_{CE}^* C_{BC}(1 + 1/\beta_0) + \frac{(C_{jE} + C_{BC})(1 + r_{CE}^* g_o) + C_{BC} 1/\beta_0}{g_m}$$

$$r_{CE}^* = r_{Cx} + r_E(1 + 1/\beta_0)$$

# Verification of the new equation



## Using the new equation

- inserting $C_{BC} = C_{jC} + C_{dC}$, $C_{dC} = \tau_f g_o$ in the new eq. and a rearrangement leads to

$$\frac{1}{2\pi f_T} = \tau_f\left(1 + r^*_{CE} g_o\left(2 + \frac{1}{\beta_0} + \frac{g_o}{g_m}\right) + \left(1 + \frac{1}{\beta_0}\right)\frac{g_o}{g_m}\right) + r^*_{CE} C_{jC}\left(1 + \frac{1}{\beta_0}\right) + \frac{(C_{jE} + C_{jC})(1 + r^*_{CE} g_o) + C_{jC}/\beta_0}{g_m}$$

- with exception of $g_m$ and $g_o$ all values are known from measurements or previous extraction steps (same as in CM).

- $g_m = \dfrac{\Re(y_{21})}{1 - r_E \Re(y_{21})}$ and $g_o = \Re(y_{22})$ at low frequencies

$$\frac{1}{2\pi f_T} = \tau_f f(g_o, g_m) + h(g_o, g_m, a_{jE}) = \tau_{f0} f(g_o, g_m) + \Delta\tau_f f(g_o, g_m) + h(g_o, g_m, a_{jE}) \quad (*)$$

$$\left.\frac{1}{2\pi f_T}\right|_{\frac{1}{g_m} \geq \frac{1}{g_m(I_{C0})}} = \tau_{f0} f(g_o, g_m) + h(g_o, g_m, a_{jE})\Big|_{\frac{1}{g_m} \geq \frac{1}{g_m(I_{C0})}} \quad (**)$$

- use (**) in low-current range and fit simultaneously the parameters $a_{jE}$, $\tau_{f0}(\tau_0, \Delta\tau_0, \tau_{Bfvl})$
- calculate $\Delta\tau_f$ from (*) and fit the high-current component of the transit time

# Summary

- The conventional method for extracting the transit time is inadequate (rel. error in the order of 10% and 60% at low to high current densities)
- An improved method has been suggested and applied on simulated data (rel. error < 0.5%)
- In high-current region the influence of $g_o$ and $C_{dC}$ can be significant.
- A new simplified equation has been shown and successfully verified (rel. error < 4%)