VBIC Fundamentals

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Outline

- **History**
- **Review of VBIC model**
  - improvements over SGP
  - model formulation
  - observations and comments
- **Parameter extraction**
  - relationship to SGP
  - details of specific steps
- **Practical issues**
  - geometry modeling
  - statistical modeling
- **Code**
  - mechanism for definition and generation

Genesis

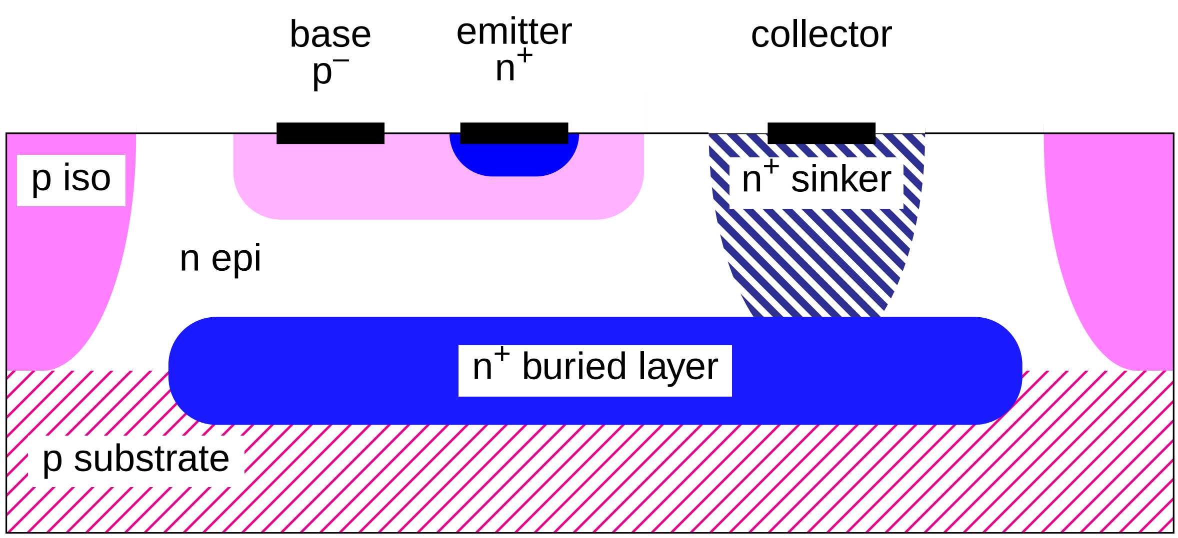
A Direct Descendent of BCTM

- **John Shier and Jerry Seitchik were the prime motivators**

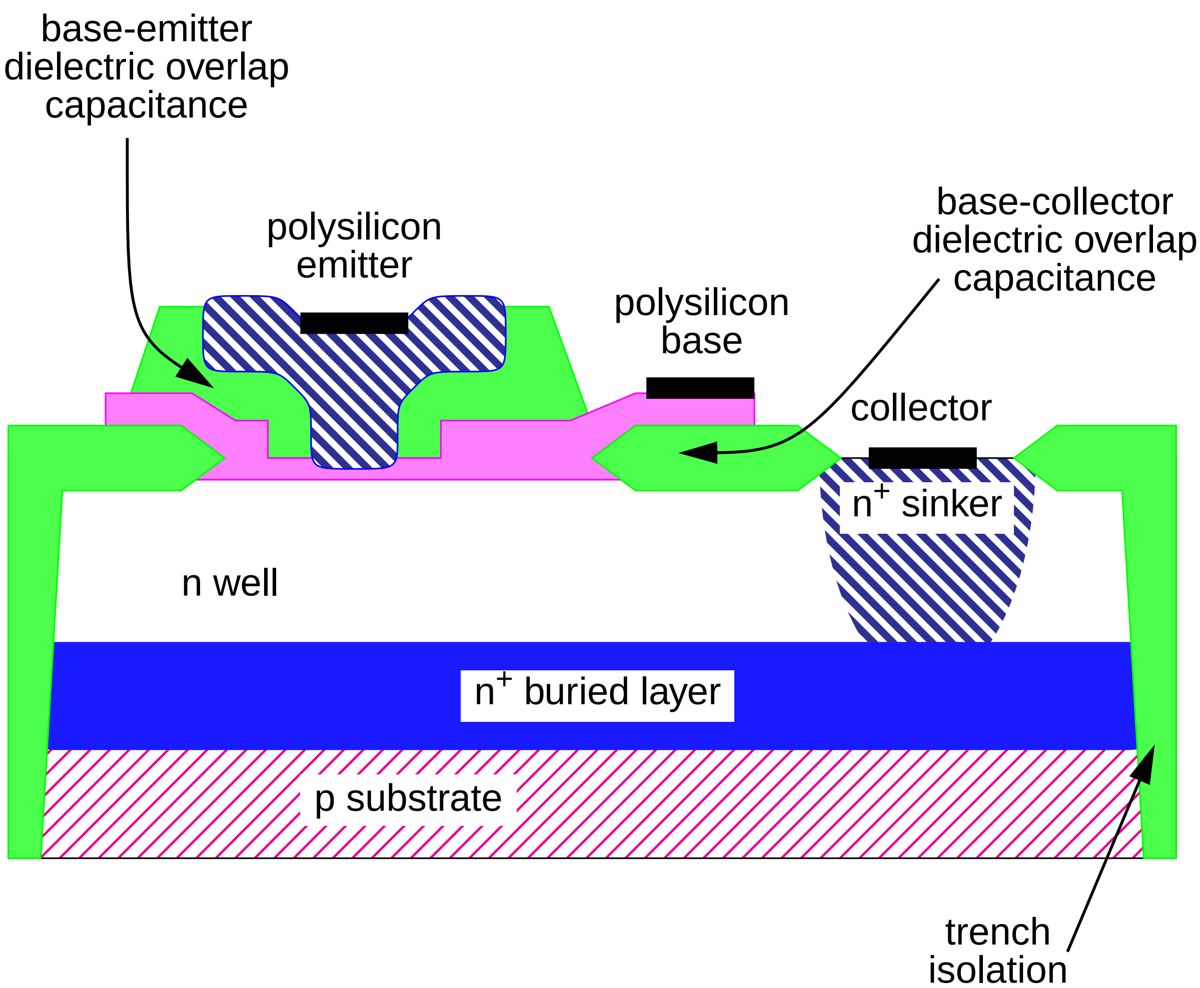
Derek Bowers	Didier Celi
Mark Dunn	Mark Foisy
Ian Getreu	Terry Magee
Marc McSwain	Shahriar Moinian
Kevin Negus	James Parker
David Roulston	Michael Schroter
Shaun Simpkins	Paul van Wijnen
Larry Wagner	

- **many others have provided feedback and suggestions**

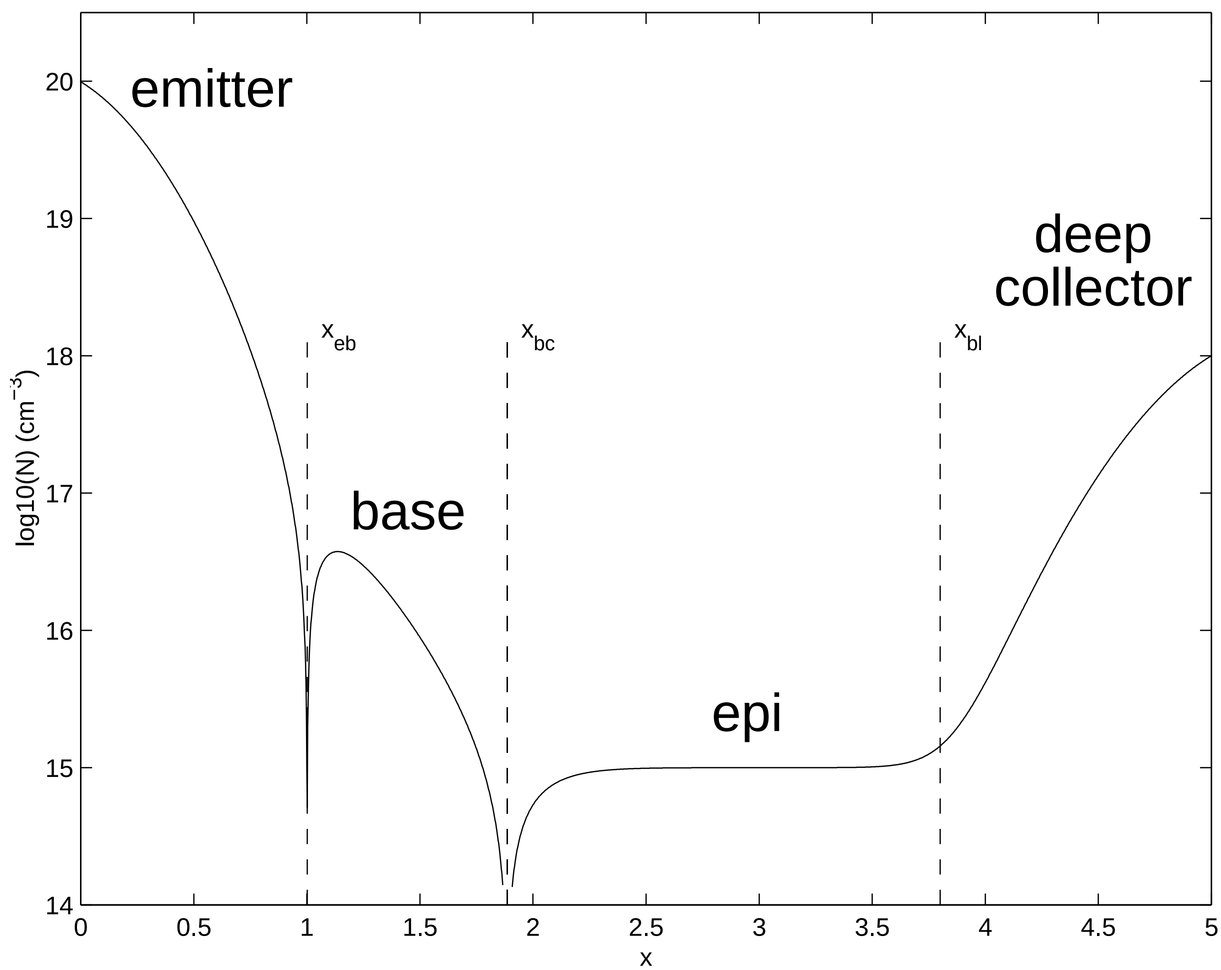
Junction Isolated Diffused NPN



Trench Isolated Double Poly NPN



Doping Profile



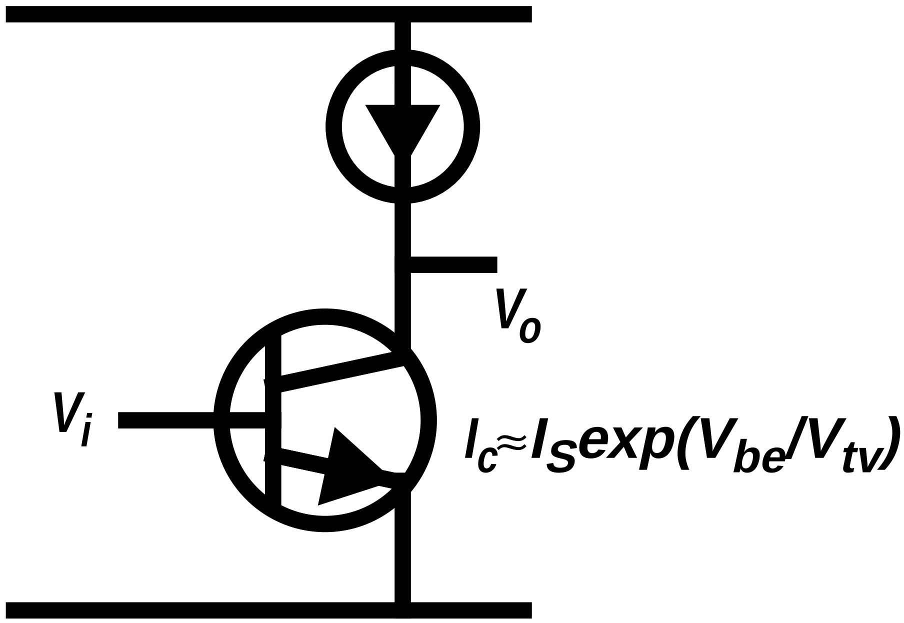
VBIC and SGP

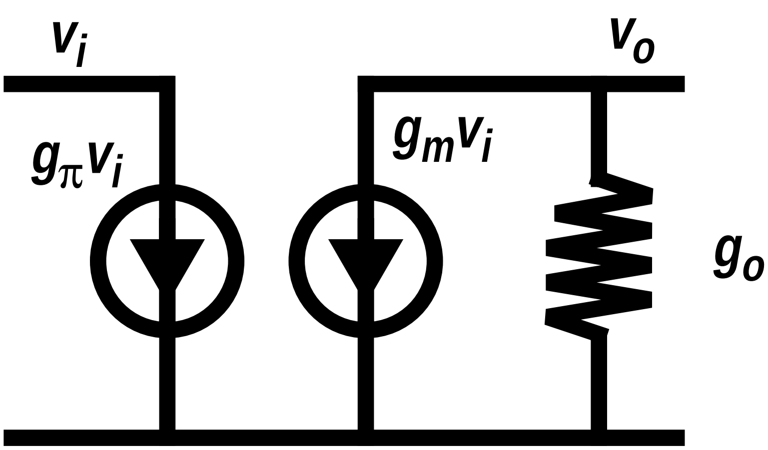
- **improved Early effect modeling**
- **physical separation of I_c and I_b**
  - improved HBT modeling capability
- **improved depletion, diffusion capacitances**
- **parasitic PNP**
- **modified Kull quasi-saturation modeling**
- **constant overlap capacitances**
- **weak avalanche model**
- **base-emitter breakdown**
- **improved temperature modeling**
  - built-in potential does not become negative!
- **self-heating**

- **incompatibilities between VBIC and SGP**
  - Early effect modeling
  - I_{RB} emitter crowding model

Plot and Fit what is Important for Design

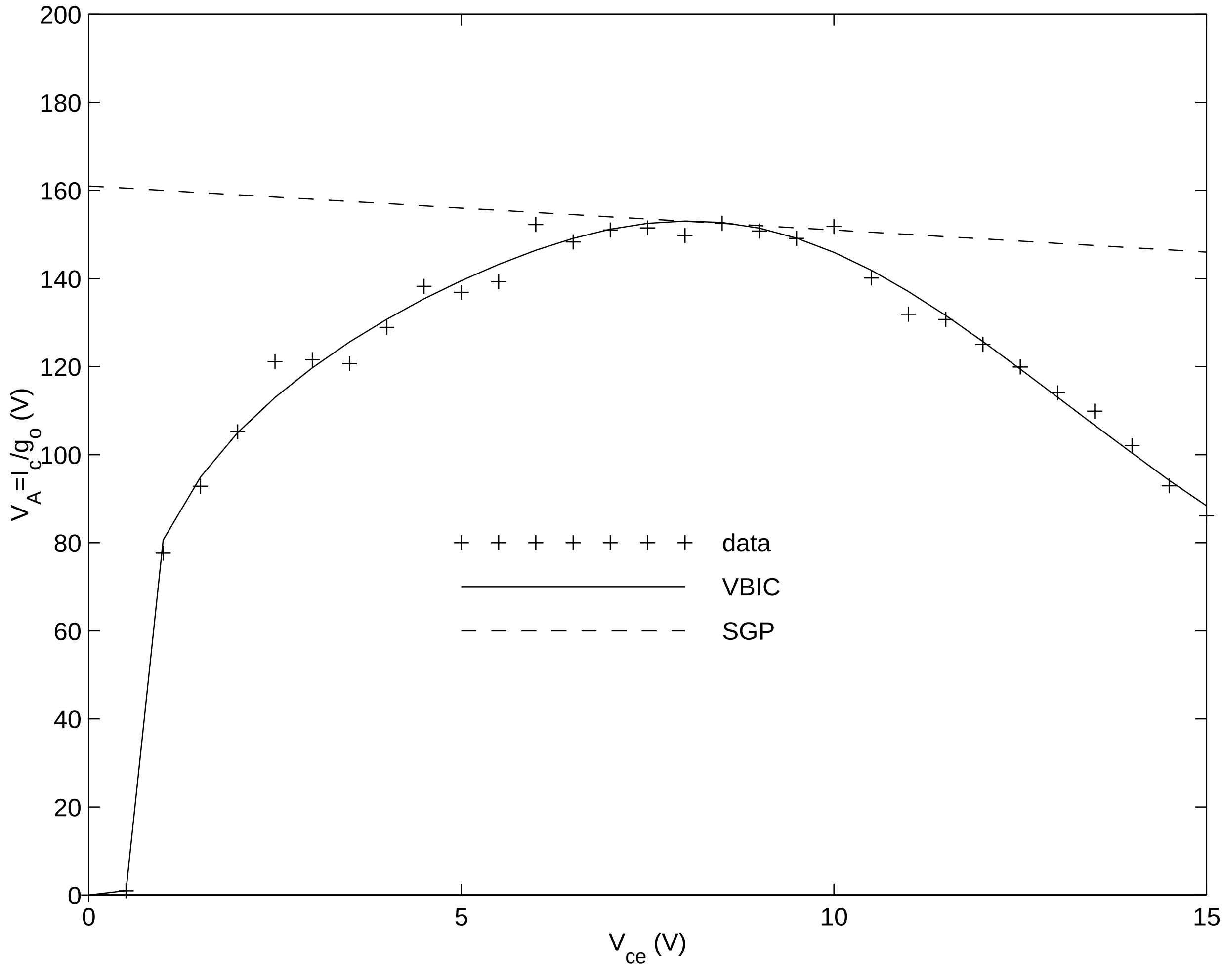
"Good" I_c Fit is Not Sufficient, $I_c r_o$ is Important





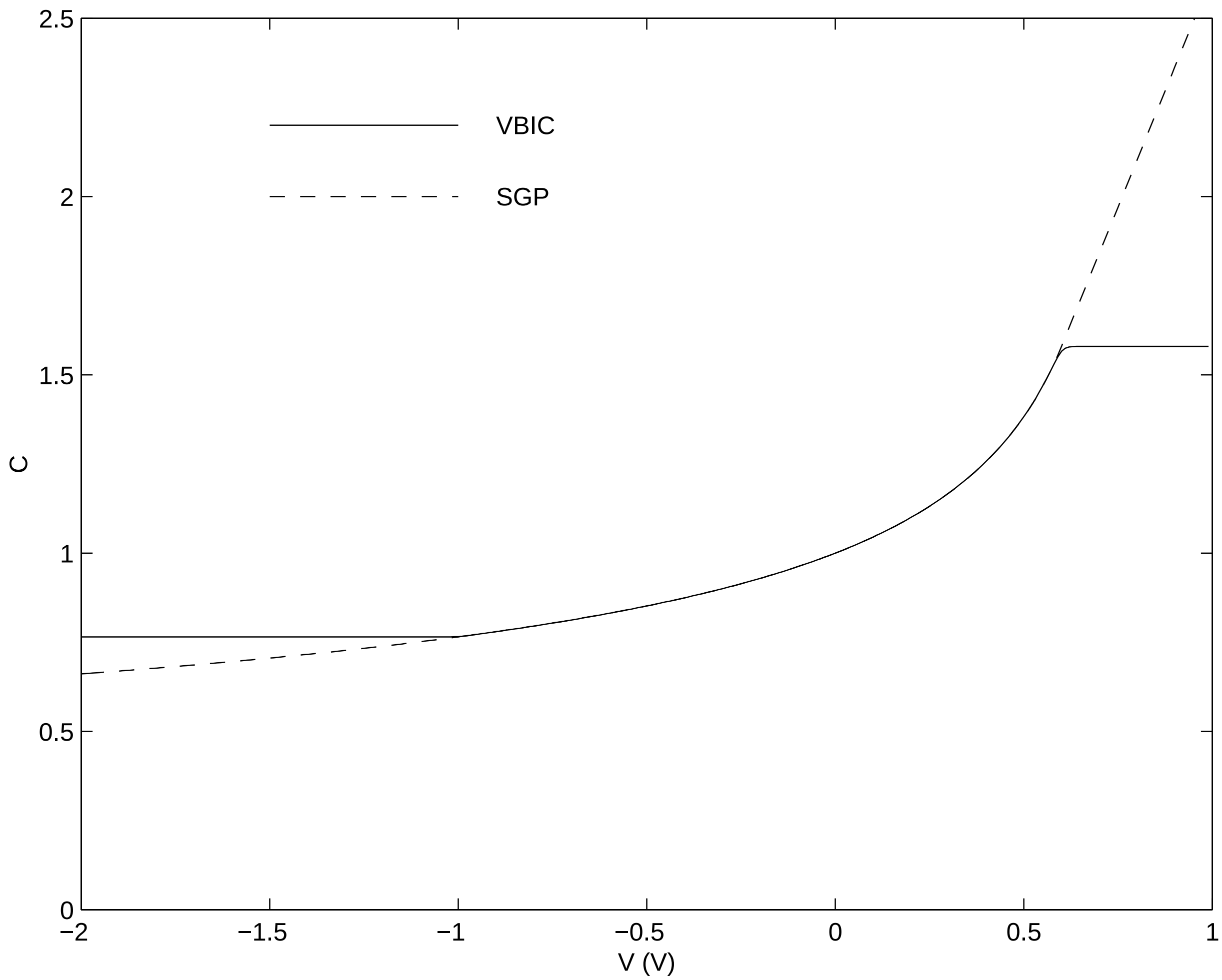
$$\frac{v_o}{v_i} = \frac{g_m}{g_o} \approx \frac{I_c}{V_{tv} g_o}$$

Early Voltage Modeling



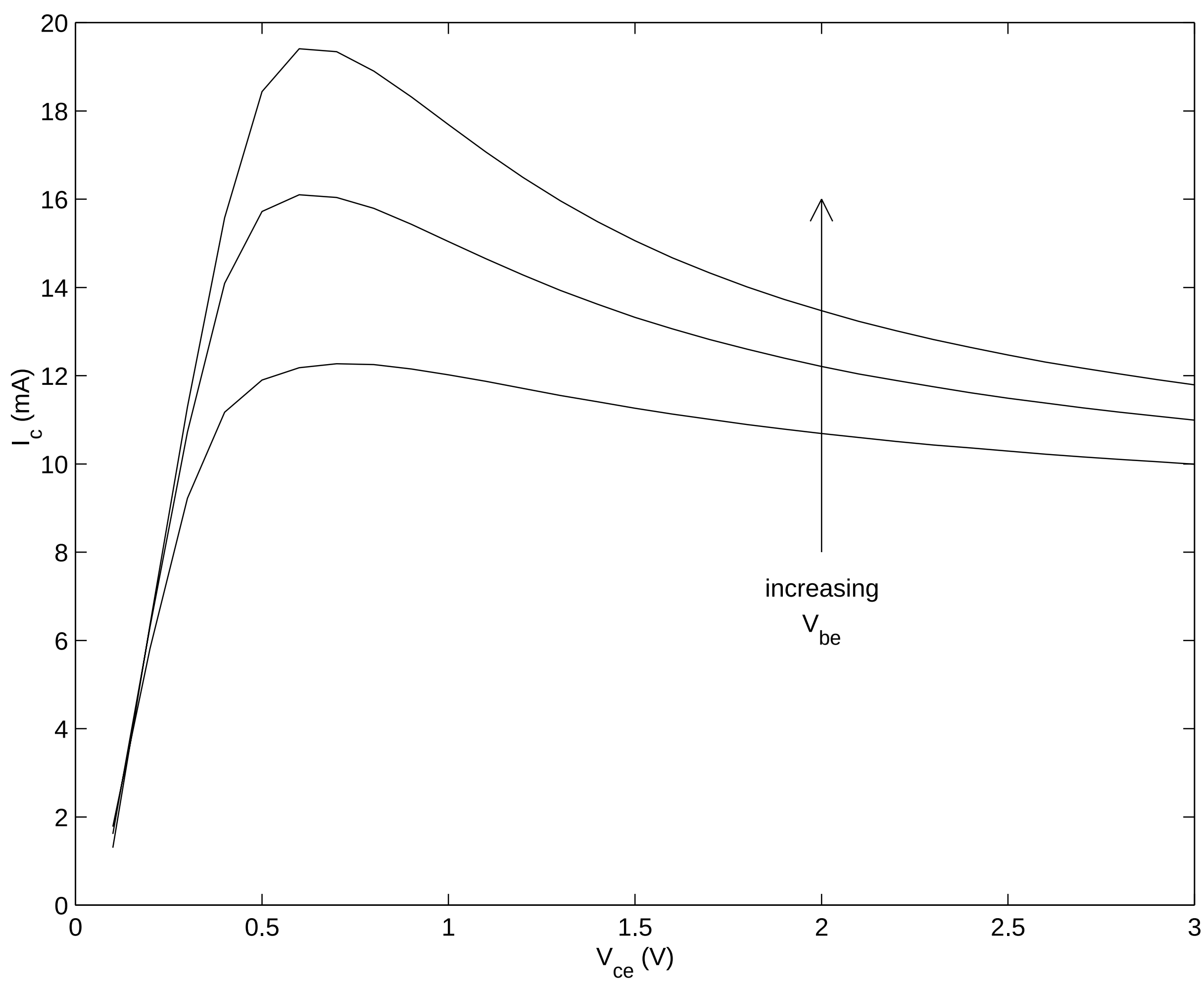
Depletion Capacitance Modeling

- VBIC 1.2 has reach-through model



Problems with Kull

- **negative output conductance at high V_{be}**
- **is caused by velocity saturation model**
- **fixed in VBIC**



Velocity Saturation Modeling

Effect is visible for 50μm long devices!

- **convenient to model as mobility reduction**

  $\mu_{red}(E) = \mu_o / \mu(E)$

  - much more informative than velocity-field plot

- **is 1 for low field, and increase with field E**
- **common models are linear and square-root**

$$\mu_{red} = 1 + \frac{\mu_o}{v_{sat}} \frac{|V|}{L}$$

$$\mu_{red} = \sqrt{1 + \left(\frac{\mu_o}{v_{sat}} \frac{V}{L}\right)^2}$$

$$E_c = v_{sat} / \mu_o$$

- **linear model is often used for analytic simplicity (Kull), square-root model is smooth and continuous, and preferred physically**

Velocity Saturation?

What does self-heating do to a resistor?

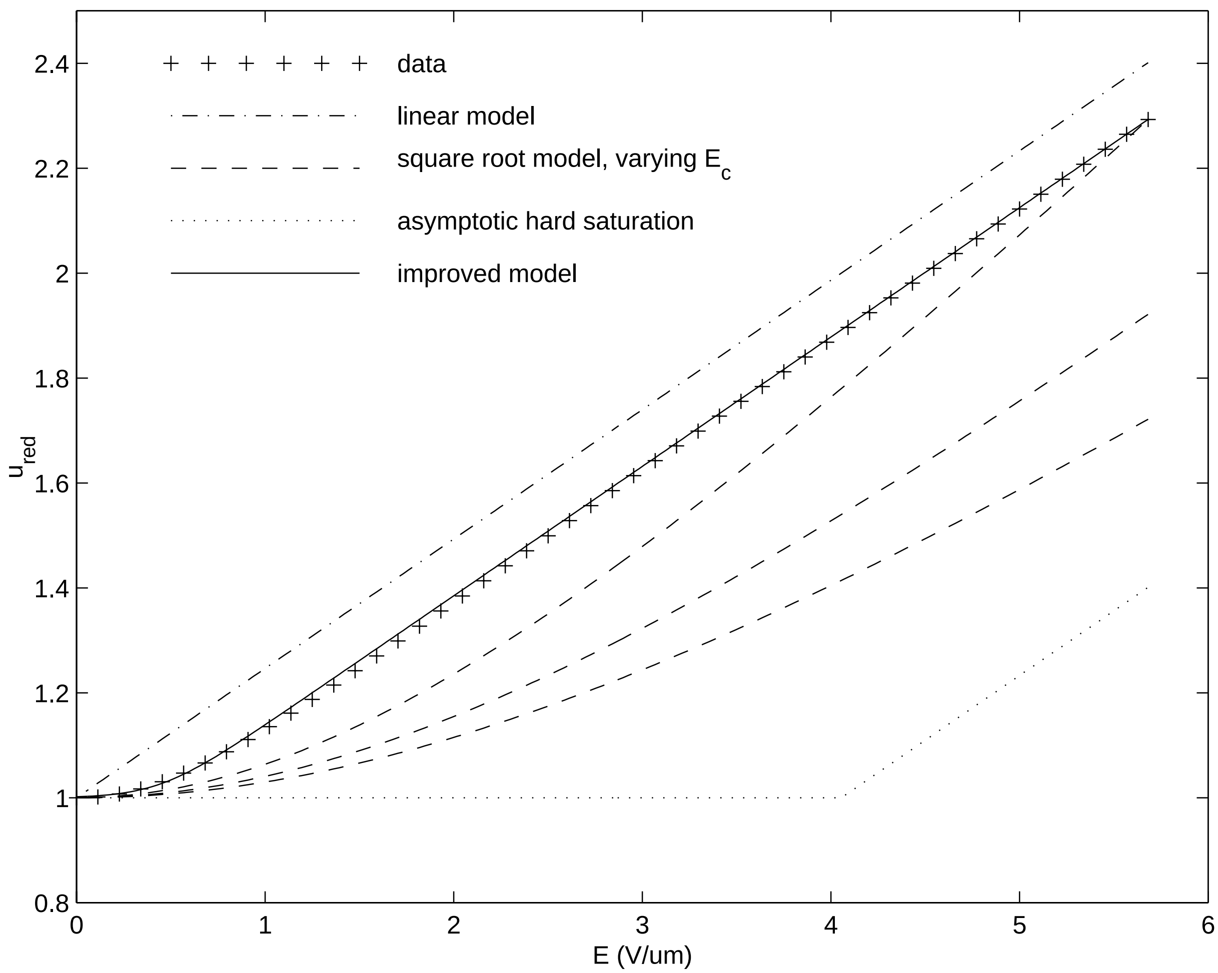
- **resistance change is** $R = R_0(1 + TC_1 \Delta T)$
- **temperature rise is**
  $\Delta T = R_{TH} IV \approx R_{TH} V^2 / R_0$
- R_{TH} **varies nearly as inverse area**
  $R_{TH} = R_{THA} / (LW)$
- **resistance varies as** $R_0 = R_S L / W$
- **putting this together gives an effective mobility reduction**

$$R / R_0 = \mu_{red} \approx 1 + \left(\frac{R_{THA} TC_1}{R_S} \right) \left(\frac{V}{L} \right)^2$$

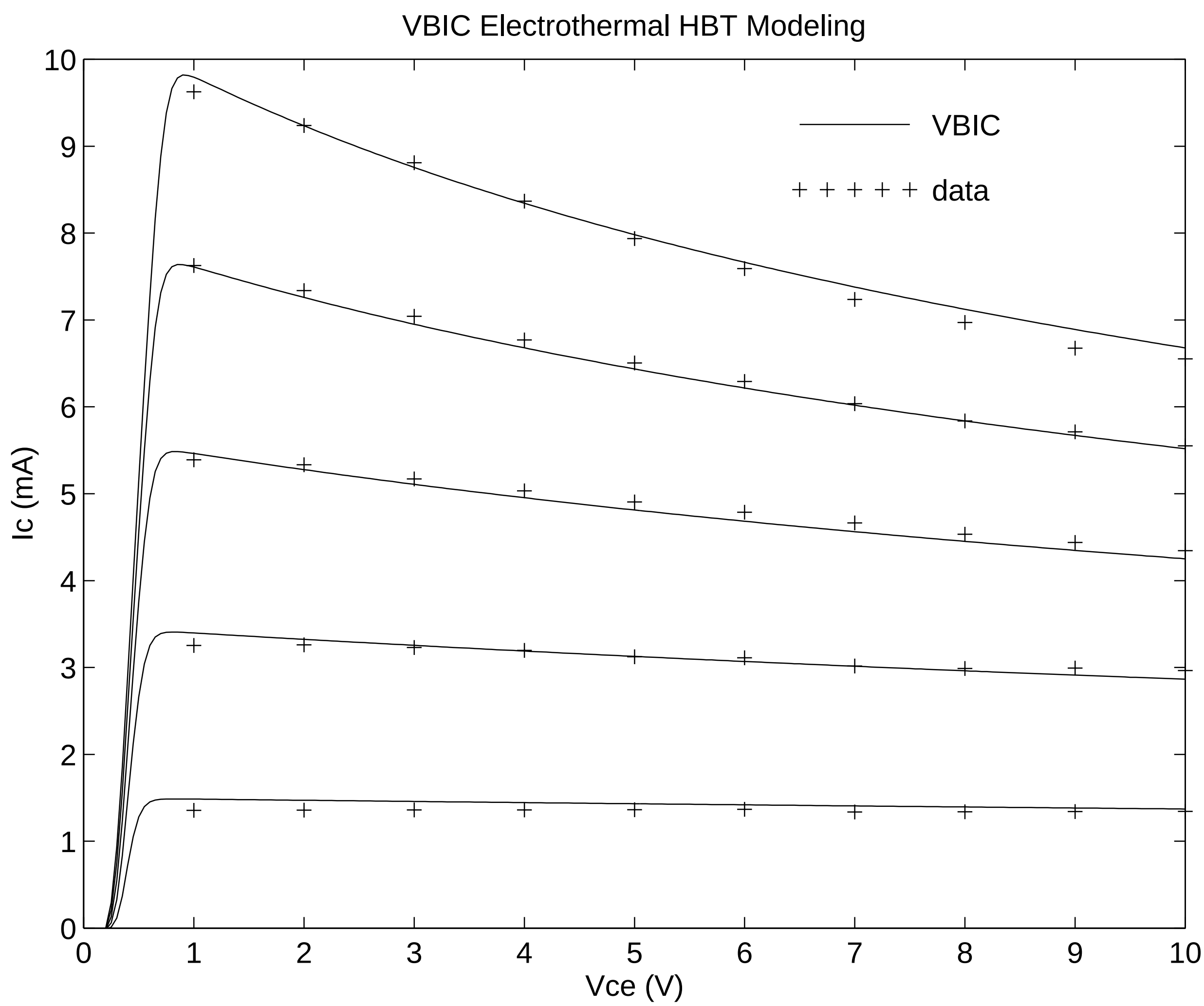
- **the parabolic variation of** μ_{red} **with field is exactly what is seen in the low field data**
- **accurate velocity saturation modeling must be done with a self-consistent self-heating model**

Velocity Saturation

- **common linear and square root models are not accurate**

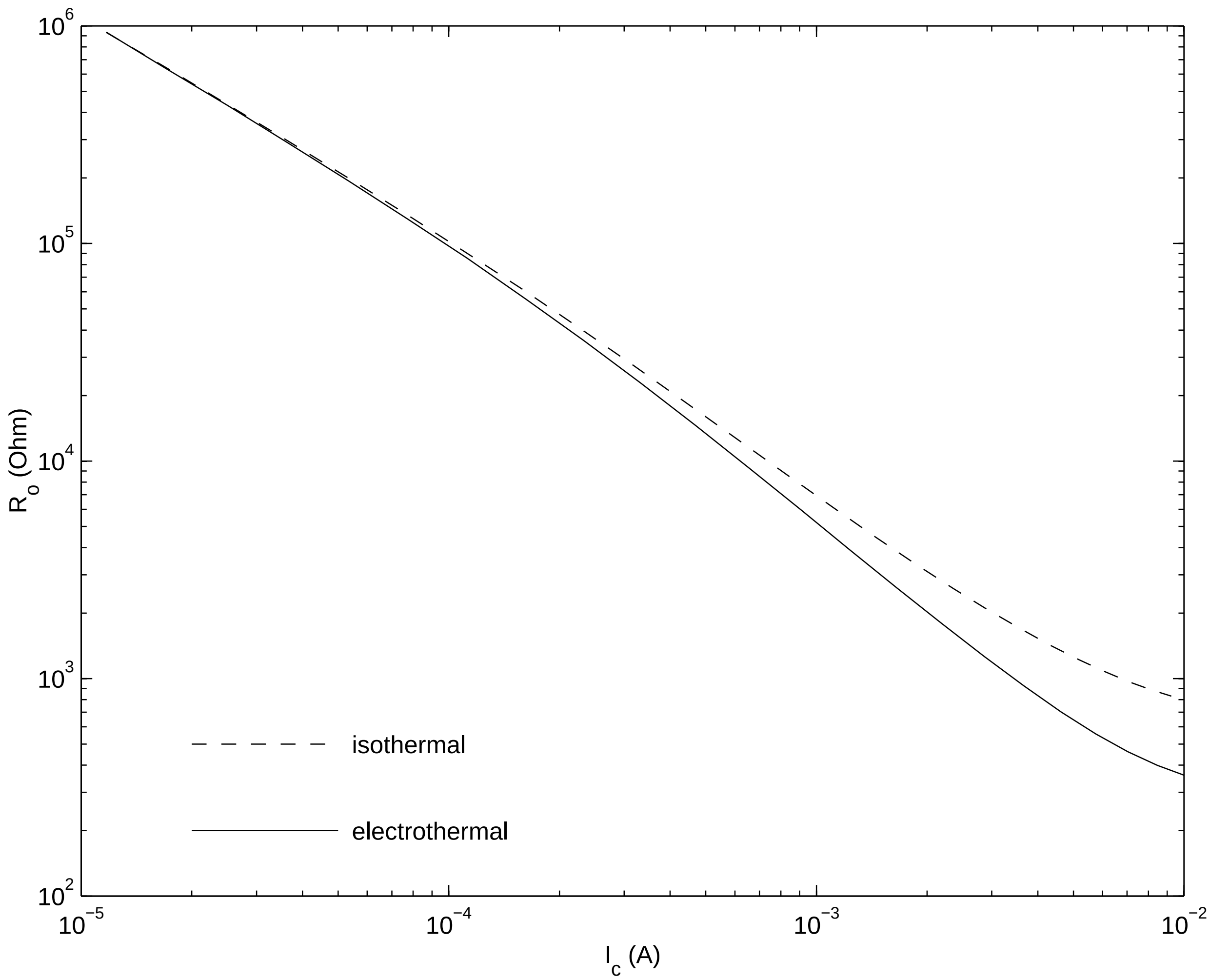


Electrothermal Model

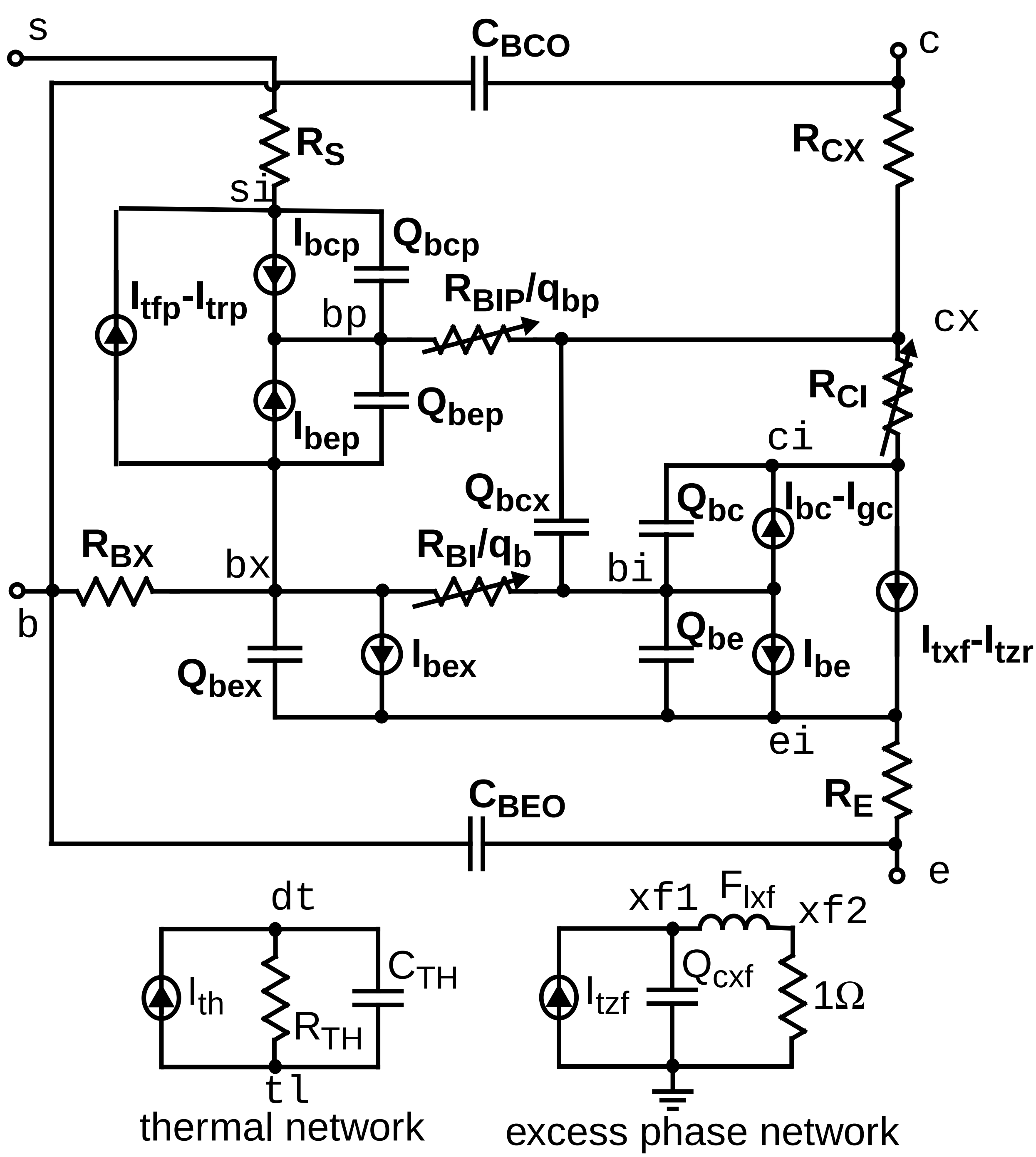


Need for Electrothermal Modeling

■ **output resistance degradation**



VBIC Equivalent Network



Transport Model

- $$I_{cc} = \frac{I_{tf} - I_{tr}}{q_b}$$
- $$I_{tf} = I_S\left(exp\left(\frac{V_{bei}}{N_F V_{tv}}\right) - 1\right)$$
- $$I_{tr} = I_S\left(exp\left(\frac{V_{bci}}{N_R V_{tv}}\right) - 1\right)$$
- $$q_b = q_1 + \frac{q_2}{q_b}$$
- $$q_1 = 1 + \frac{q_{je}}{V_{ER}} + \frac{q_{jc}}{V_{EF}}$$
- $$q_2 = \frac{I_{tf}}{I_{KF}} + \frac{I_{tr}}{I_{KR}}$$

Components of Base Current

Based on Recombination/Generation

- $I_b = I_{bi} + I_{bn}$
  - ideal and non-deal components
- $I_{bi} = I_{BI}\left(exp\left(\frac{V_b}{N_I V_{tv}}\right) - 1\right)$
  - N_I is of order 1
- $I_{bn} = I_{BN}\left(exp\left(\frac{V_b}{N_N V_{tv}}\right) - 1\right)$
  - N_N is of order 2

Basic Modeling Equations

- **continuity equation**

$$q(\partial n / \partial t) - \nabla \bullet \mathbf{J}_e = q(G_e - R_e)$$

- **carrier densities** $V_{tv} = kT / q$

$$n = n_{ie}\, exp((\psi - \varphi_e) / V_{tv})$$

$$p = n_{ie}\, exp((\varphi_h - \psi) / V_{tv})$$

- **drift-diffusion relations**

$$\mathbf{J}_e = -q\mu_e n \nabla\psi + qD_e \nabla n = -q\mu_e n \nabla\varphi_e$$

$$\mathbf{J}_h = -q\mu_h p \nabla\psi - qD_h \nabla p = -q\mu_h p \nabla\varphi_h$$

- **surface recombination**

$$\mathbf{J}_h = qS_h(p - p_0)$$

- **Shockley-Read-Hall process**

$$R_{srh} = (np - n_{ie}^2) / (\tau_h(n + n_{ie}) + \tau_e(p + n_{ie}))$$

- **Auger process**

$$R_{aug} = (np - n_{ie}^2)(c_e n + c_h p)$$

1-Dimensional Base Analysis

- **steady-state, ignore recombination/gen.**

$$J_{ex} = \text{const}$$

- **for electron quasi-Fermi potential**

$$\frac{\partial\, exp(-\varphi_e / V_{tv})}{\partial x} = -\frac{exp(-\varphi_e / V_{tv})}{V_{tv}} \frac{\partial \varphi_e}{\partial x}$$

- **from the drift-diffusion relation**

$$\mathbf{J}_e = q\mu_e n_{ie} V_{tv}\, exp(\psi / V_{tv}) \frac{\partial\, exp(-\varphi_e / V_{tv})}{\partial x}$$

- **rearranging and integrating across base**

$$\mathbf{J}_e \int_0^w \frac{exp\left(-\frac{\psi(x)}{V_{tv}}\right)}{\mu_e(x) n_{ie}(x)} dx =$$

$$qV_{tv}\left(exp\left(-\frac{\varphi_{ew}}{V_{tv}}\right) - exp\left(-\frac{\varphi_{e0}}{V_{tv}}\right)\right)$$

Gummel ICCR

- **now φ_h is constant across the base, so multiplying by** $exp(\varphi_h / V_{tv})$ **and noting that junction biases are** $\varphi_h - \varphi_e$

$$I_{cc} = \frac{I_S\left(exp\left(\frac{V_{bei}}{V_{tv}}\right) - exp\left(\frac{V_{bci}}{V_{tv}}\right)\right)}{q_b}$$

- **saturation current is** $I_S = qA_eV_{tv}/G_{b0}$
- **normalized based charge is** $q_b = G_b/G_{b0}$ **(**G_{b0} **is** G_b **at zero applied bias)**
- **scaled base charge (Gummel number) is**

$$G_b = \int_0^W p/(\mu_e n_{ie}^2)dx$$

- **physical basis of BJT behavior is apparent**

Quasi-Neutral Emitter Base Current

- **in the emitter** $\varphi_e \approx 0$ **and** $n \approx N_{de}$**, so** $p \ll n$ **and** $np \gg n_{ie}^2$
- **recombination rates are**

$$R_{qn,\,srh} = \frac{p}{\tau_h} = \frac{n_{ie}^2 \, exp(\varphi_h / V_{tv})}{\tau_h N_{de}}$$

$$R_{qn,\,aug} = c_e n^2 p = c_e N_{de} n_{ie}^2 \, exp(\varphi_h / V_{tv})$$

- **in the emitter** $\varphi_h \approx V_{bei}$**, so integration over the emitter gives**

$$I_{be,\,qn} \propto exp(V_{bei} / V_{tv})$$

- **this is an ideal component of base current**

Emitter Contact Base Current

- **recombination at the emitter contact**

$$\mathbf{J}_{h,\,ec} = qS_h(p_{ec} - p_{ec0}) = qS_h p_{ec}$$

- **hole density at emitter side of base-emitter junction is**

$$p_{e,\,b} = n_{ie}^2 \mathit{exp}(V_{bei}/V_{tv})/N_{de}$$

- **for a shallow emitter**

$$\mathbf{J}_h = qD_h(p_{e,\,b} - p_{ec})/w_e$$

- **hole density at the emitter**

$$p_{ec} = n_{ie}^2 \mathit{exp}(V_{bei}/V_{tv})/(N_{de}(1 + S_h w_e/D_h))$$

- **surface recombination is an ideal component of base current**

$$I_{be,\,ec} \propto \mathit{exp}(V_{bei}/V_{tv})$$

Space-Charge Region Base Current

- **in base-emitter space-charge region** $np \gg n_{ie}^2$ **but both** n **and** p **are relatively small: Auger process is negligible**

- $$R_{sc,\,srh} = \frac{n_{ie}\,exp(V_{bei}/V_{tv})}{\tau_h\left(exp\dfrac{\psi}{V_{tv}} + 1\right) + \tau_e\left(exp\dfrac{V_{bei} - \psi}{V_{tv}} + 1\right)}$$

- **this rate is maximized when**
  $$\psi = 0.5(V_{bei} - V_{tv}log(\tau_h/\tau_e))$$

- **for approximately equal lifetimes**
  $$R_{sc,\,srh} = (n_{ie}/(\tau_h + \tau_e))\,exp(0.5V_{bei}/V_{tv})$$

- **space-charge recombination contributes to non-ideal component of base current**
  $$I_{be,\,sc} \propto exp(V_{bei}/(2V_{tv}))$$

Intrinsic Collector Model

- **integrate across the epi region**

$$J_{ex} = -\frac{q\mu_e}{w}\int_{\varphi_{e0}}^{\varphi_{ew}} n\,d\varphi_e$$

- **in the collector** $n = p + N$**,** φ_h **is constant**

$$np = p(p+N) = n_{ie}^2\,exp\left(\frac{\varphi_h - \varphi_e}{V_{tv}}\right)$$

- **differentiating w.r.t. position** x **gives**

$$(2p+N)\frac{\partial p}{\partial x} = -\frac{n_{ie}^2}{V_{tv}}\,exp\left(\frac{\varphi_h - \varphi_e}{V_{tv}}\right)\frac{\partial \varphi_e}{\partial x}$$

$$(2p+N)dp = -\frac{np}{V_{tv}}(d\varphi_e)$$

$$n\,d\varphi_e = -V_{tv}\left(2 + \frac{N}{p}\right)dp$$

Intrinsic Collector Model (cont'd 1)

- **substitute in integral**

$$J_{ex} = \frac{qV_{tv}\mu_e}{w}\int_{p_0}^{p_w}\left(2 + \frac{N}{p}\right)dp$$

$$I_{epi0} = \frac{qAV_{tv}\mu_e}{w}\left(2(p_w - p_0) + N\,log\left(\frac{p_w}{p_0}\right)\right)$$

- $n = p + N$ **implies** $p_w - p_0 = n_w - n_0$ **so**

$$\frac{p_w}{p_0} = \frac{n_0}{n_w}\,exp\left(\frac{V_{bcx} - V_{bci}}{V_{tv}}\right)$$

- **standard quasi-neutrality gives**

$$n_0 = \frac{N}{2}\left(1 + \sqrt{1 + \frac{4n_{ie}^2}{N^2}\,exp\left(\frac{V_{bci}}{V_{tv}}\right)}\right)$$

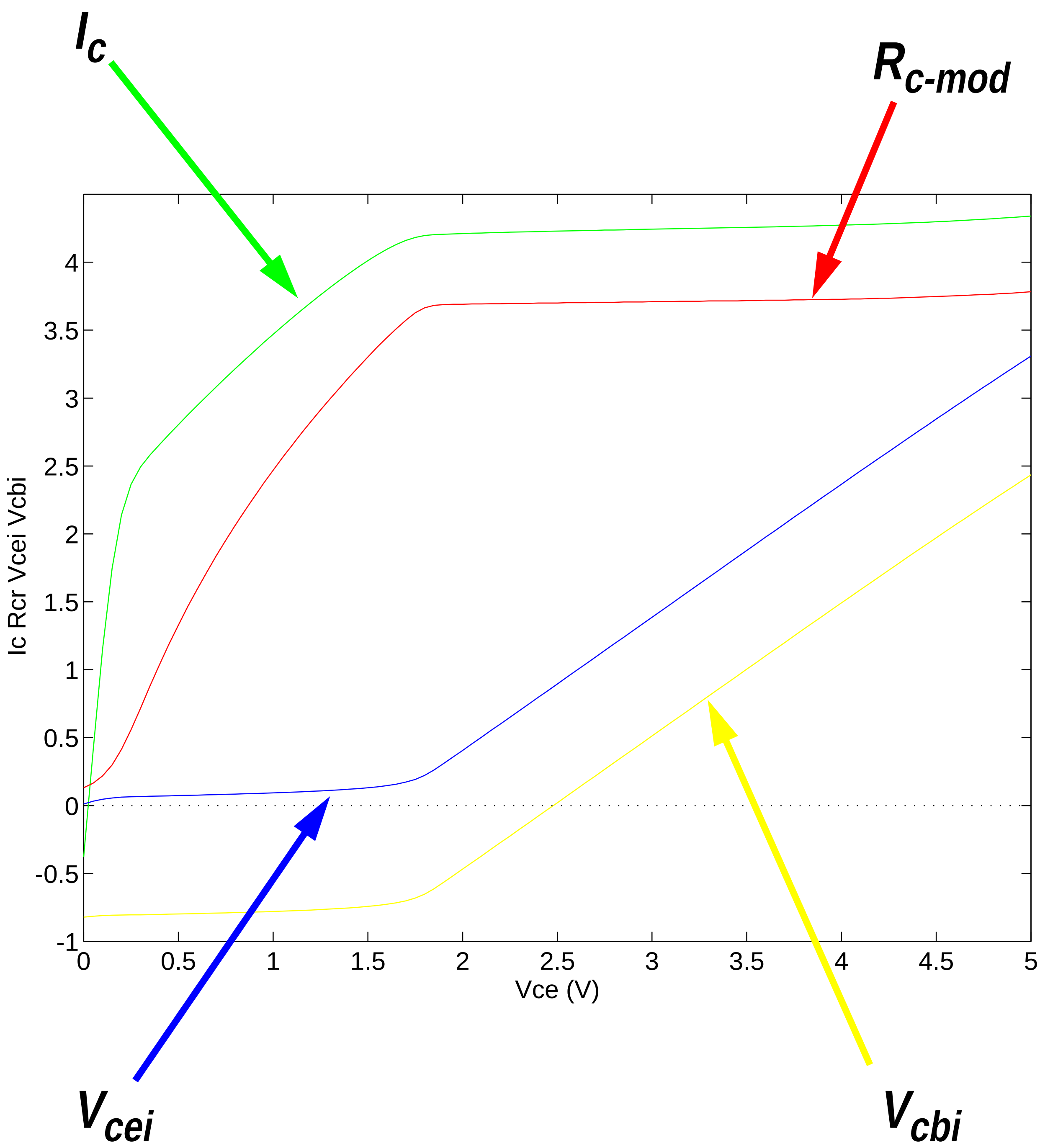
and similarly for n_w **as a function of** V_{bcx}

Intrinsic Collector Model (cont'd 2)

Final model

- $$I_{epi0} = \frac{V_{rci} + V_{tv}\left(K_{bci} - K_{bcx} - \mathit{log}\left(\frac{K_{bci}+1}{K_{bcx}+1}\right)\right)}{R_{CI}}$$
- $$K_{bci} = \sqrt{1 + G_{AMM}\,\mathit{exp}(V_{bci}/V_{tv})}$$
- $$K_{bcx} = \sqrt{1 + G_{AMM}\,\mathit{exp}(V_{bcx}/V_{tv})}$$
- $$I_{rci} = \frac{I_{epi0}}{\sqrt{1 + \left(\frac{R_{CI} I_{epi0}/V_O}{1 + \left(\sqrt{0.01 + V_{rci}^2}\right)/(2V_O H_{RCF})}\right)^2}}$$
- **empirical modification of velocity saturation model to prevent negative** g_o **and include high bias effects**

Quasi-saturation Modeling



Passivity

- **in forward operation, ignoring base current, q_b modulation, and parasitics, the power dissipated is**

$$I_S\left(exp\left(\frac{V_{be}}{N_F V_{tv}}\right) - exp\left(\frac{V_{bc}}{N_R V_{tv}}\right)\right)V_{ce}$$

- **this is proportional to**

$$1 - exp\left(\frac{V_{be}}{V_{tv}}\left(\frac{1}{N_R} - \frac{1}{N_F}\right)\right)exp\left(-\frac{V_{ce}}{N_R V_{tv}}\right)$$

- **Because V_{be} and V_{ce} are positive, passivity requires**

$\frac{1}{N_R} - \frac{1}{N_F} \le 0$**, i.e.** $N_F \le N_R$

Passivity (cont'd)

- **Similar analysis for reverse operation leads to**

  $N_R \leq N_F$

- **This implies** $N_R \equiv N_F$

- **The analysis is more restrictive than necessary, and HBTs most definitely have** $N_R \neq N_F$**, however this shows that with certain parameter values VBIC (and SGP, and any other BJT model with separate forward and reverse ideality factors) can be non-passive!**
  - it is preferred if a model enforces physically realistic behavior regardless of parameter values
  - VBIC has N_F and N_R for SGP compatibility and HBT modeling accuracy

Electrothermal Modeling

- **significantly increases complexity of model**
- **simpler approaches have proposed (e.g. V_{be} and β correction) but these are not physically consistent**
- **all branch constitutive relations become functions of local temperature as well as branch voltages**
  - self-consistent with temperature model
- **I_{th} is computed as the sum over the non-storage elements of the product of current and voltage for every branch**
  - cannot simply multiply terminal currents and voltages because of energy storage elements

VBIC Parameters from SGP

Core Model Similar to SGP

- program `sgp_2_vbic` available
- simple translations from SGP to VBIC
  - $R_{BX} = R_{BM}$
  - $R_{BI} = R_B - R_{BM}$
  - $C_{JC} = C_{JC} X_{JC}$
  - $C_{JEP} = C_{JC}(1 - X_{JC})$
  - $T_D = \pi T_F P_{TF} / 180$

VBIC Parameters from SGP (cont'd)

Early Effect Model is Different

- **specify** V_{be} **and** V_{be} **for matching** g_o

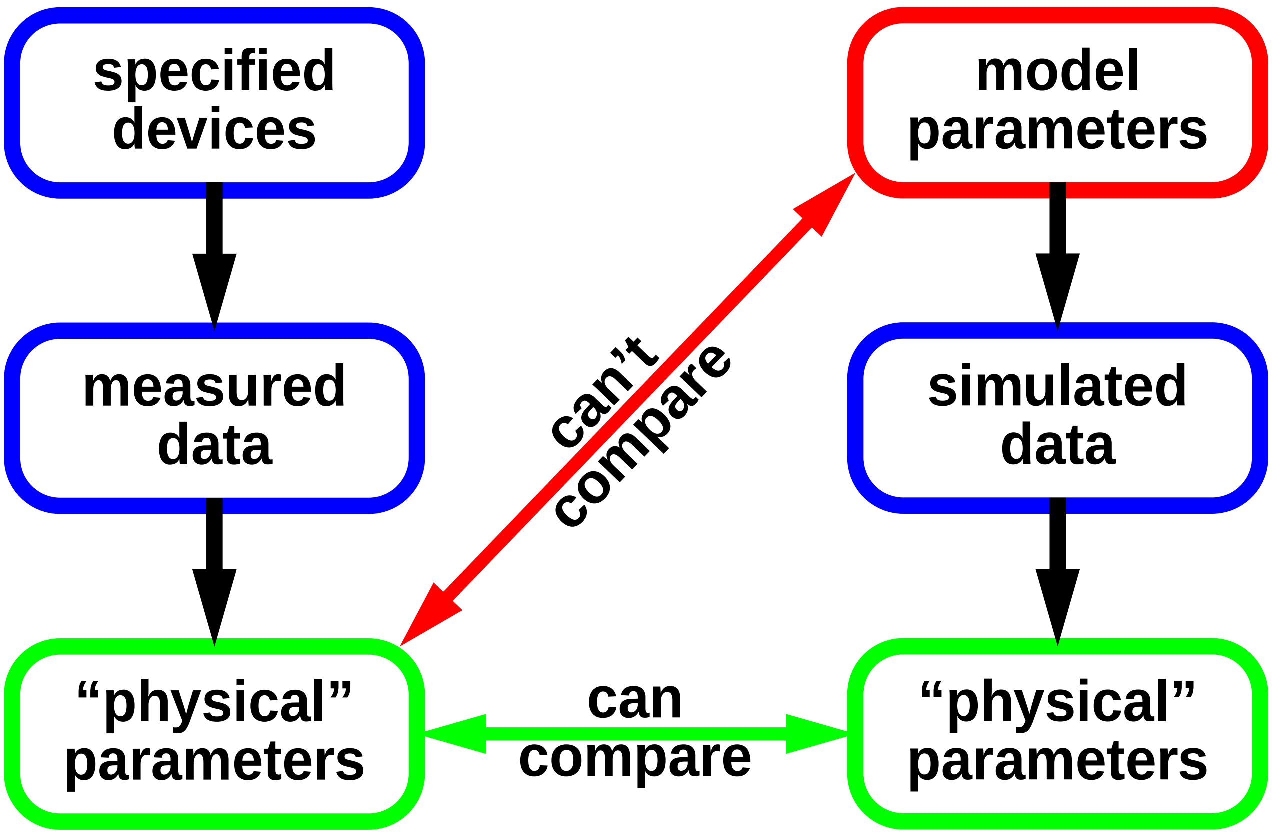
$$\frac{g_o^f}{I_c} = \frac{1/V_{AF}}{1 - V_{be}^f/V_{AR} - V_{bc}^f/V_{AF}}$$

$$\frac{g_o^r}{I_e} = \frac{1/V_{AR}}{1 - V_{be}^r/V_{AR} - V_{bc}^r/V_{AF}}$$

- **from analysis of output conductance in forward and reverse operation**

$$\begin{bmatrix} q_{bcf} - \dfrac{c_{bcf}}{(g_o^f/I_c)} & q_{bef} \\ q_{bcr} & q_{ber} - \dfrac{c_{ber}}{(g_o^r/I_e)} \end{bmatrix} \begin{bmatrix} \dfrac{1}{V_{EF}} \\ \dfrac{1}{V_{ER}} \end{bmatrix} = \begin{bmatrix} -1 \\ -1 \end{bmatrix}$$

What is a Parameter?



Direct Extraction vs. Optimization

- **direct extraction is uses simplifications of a model, it does not give the “best” fit of the un-simplified model to data**
- **direct extraction is based on manipulation of a model and data, the quantities fitted are NOT the most important quantities as far as circuit performance is concerned**
  - **the goal of characterization is accurate simulation of important measures of performance of circuits, not of unrelated metrics of individual devices (at sometimes strange biases)**
- **models are approximations and trade-offs must be made during characterization to reflect the modeling needs of target circuits for a technology**
- **to optimize the trade-offs you need to fit multiple targets (g_m/I_d or I_c/g_o), and these must be weighted over geometry and bias**

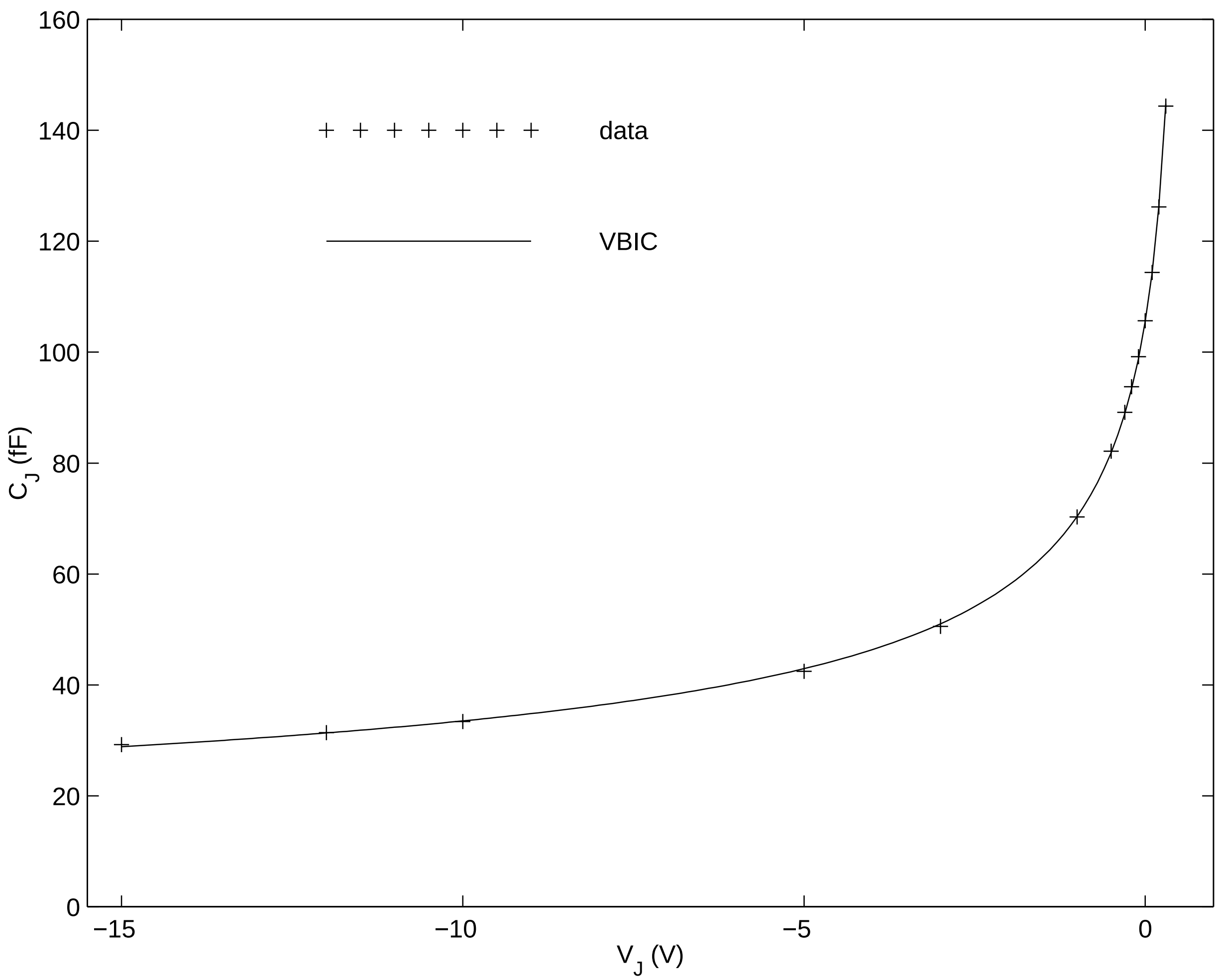
VBIC Parameter Extraction

- **based on a combination of parameter initialization (extraction) and optimization**
- **both steps use a subset of data and subset of the model parameters**
- **you can NEVER directly equate a number derived from simple manipulation of measured data to a a model parameter**
  - $V_A = V_{AF}^{SGP} - V_{be}\left(1 + \frac{V_{AF}^{SGP}}{V_{AR}^{SGP}}\right)$
  - proper equivalence involves EXACTLY simulating and processing data
- **initial parameters are refined when the approximate model used as a basis to determine a parameter is not sufficiently accurate**

STEPS: C_{be}, C_{bc}, C_{cs}

Junction Depletion Capacitance Extraction

- **for each junction measure capacitance (forward bias is important for C_{be})**
- **use optimization to fit model to data**



STEP: V_A

Coupled Early Voltage Extraction

- **measure forward output (FO) at a moderate V_{be}, high enough to get reasonable data but below where series resistance and high-level injection effects are dominant**
- **measure reverse Gummel (RG) data at two values of V_{eb} (0 and 1)**
- **differentiate FO data to get $g_o = \partial I_c / \partial V_{ce}$**
- **compute I_c / g_o and find its maximum value**
- **from RG data compute $I_{el} / (I_{eh} - I_{el})$ where added subscripts mean low and high V_{eb}**
- **select one point from the RG data in the region between where noise and high bias effects are observable (the “flat” region”)**
  - should be at $V_{bc} < F_C P_C$ if possible

STEP: V_A (cont'd)

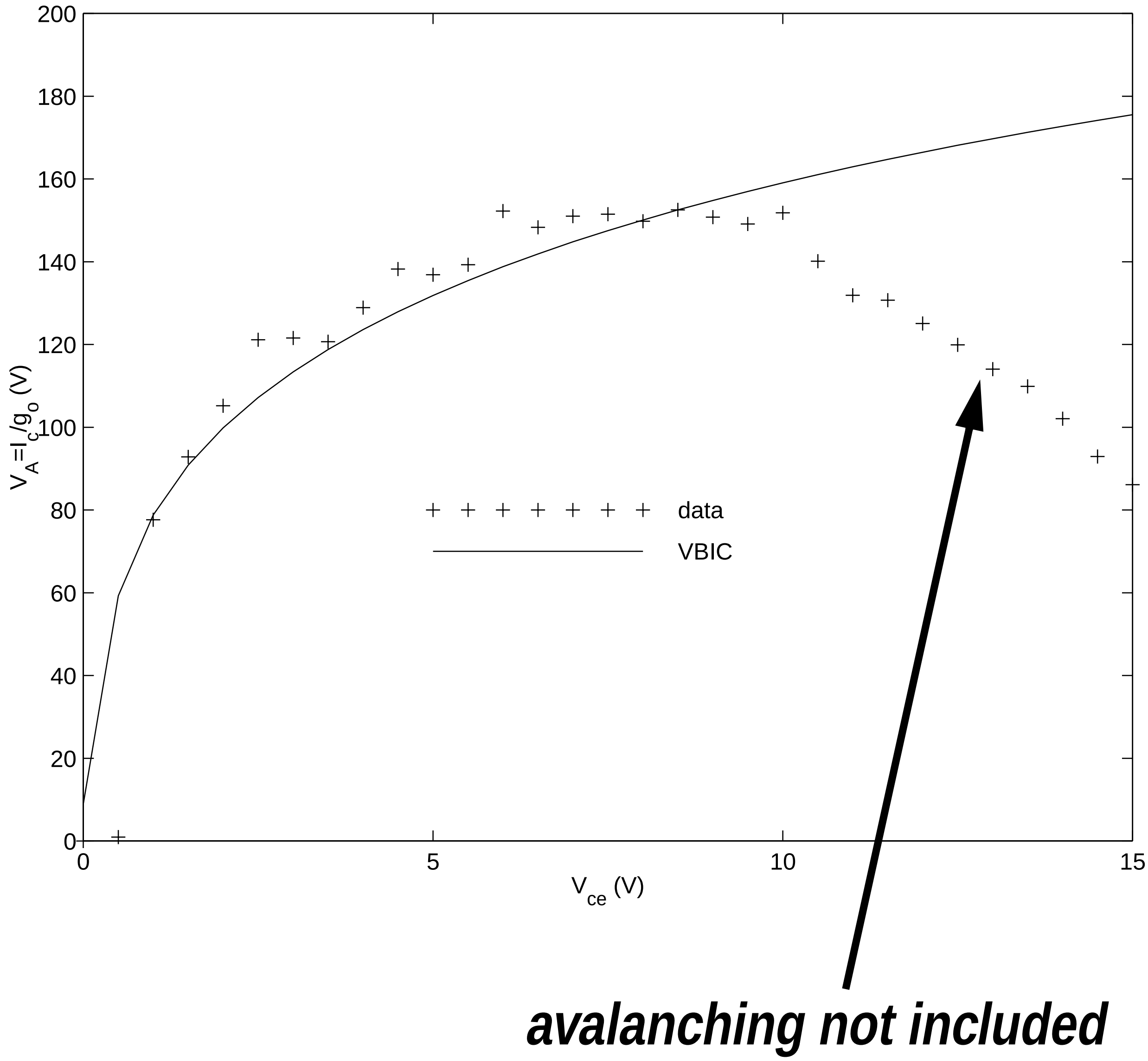
- compute junction depletion charges and capacitances at the selected forward and reverse biases
- form and solve the equations

$$\begin{bmatrix} q_{bcf} - \dfrac{c_{bcf}}{(g_o^f / I_c)} & q_{bef} \\ q_{bcr} & q_{berh} - \dfrac{(q_{berl} - q_{berh})I_{el}}{(I_{eh} - I_{el})} \end{bmatrix} \begin{bmatrix} \dfrac{1}{V_{EF}} \\ \dfrac{1}{V_{ER}} \end{bmatrix} = \begin{bmatrix} -1 \\ -1 \end{bmatrix}$$

- this directly follows from the transport current formulation
- you can mix and match derivatives or differences for each component, picking maximum I_c / g_o is useful for FO data as it avoids data that has a significant avalanche component

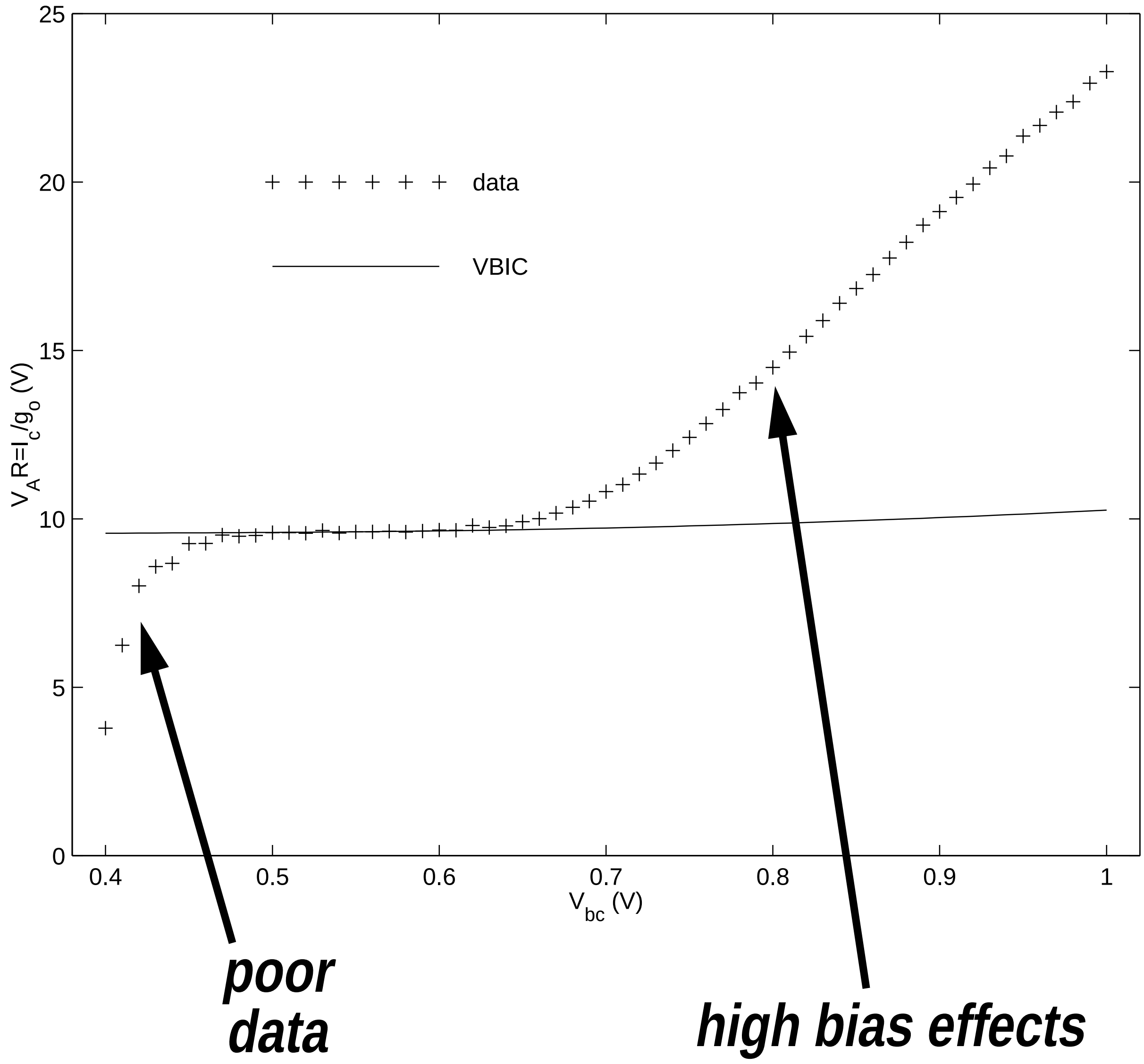
STEP: V_A (cont'd)

Forward Early Effect



STEP: V_A (cont'd)

Reverse Early Effect



STEP: I_{BCIP}

Substrate Current Analysis

- **in Forward Gummel (FG) data at $V_{cb} = 0$ the parasitic base-collector turns on at high V_{be} because of R_C de-biasing**
- **under these conditions**

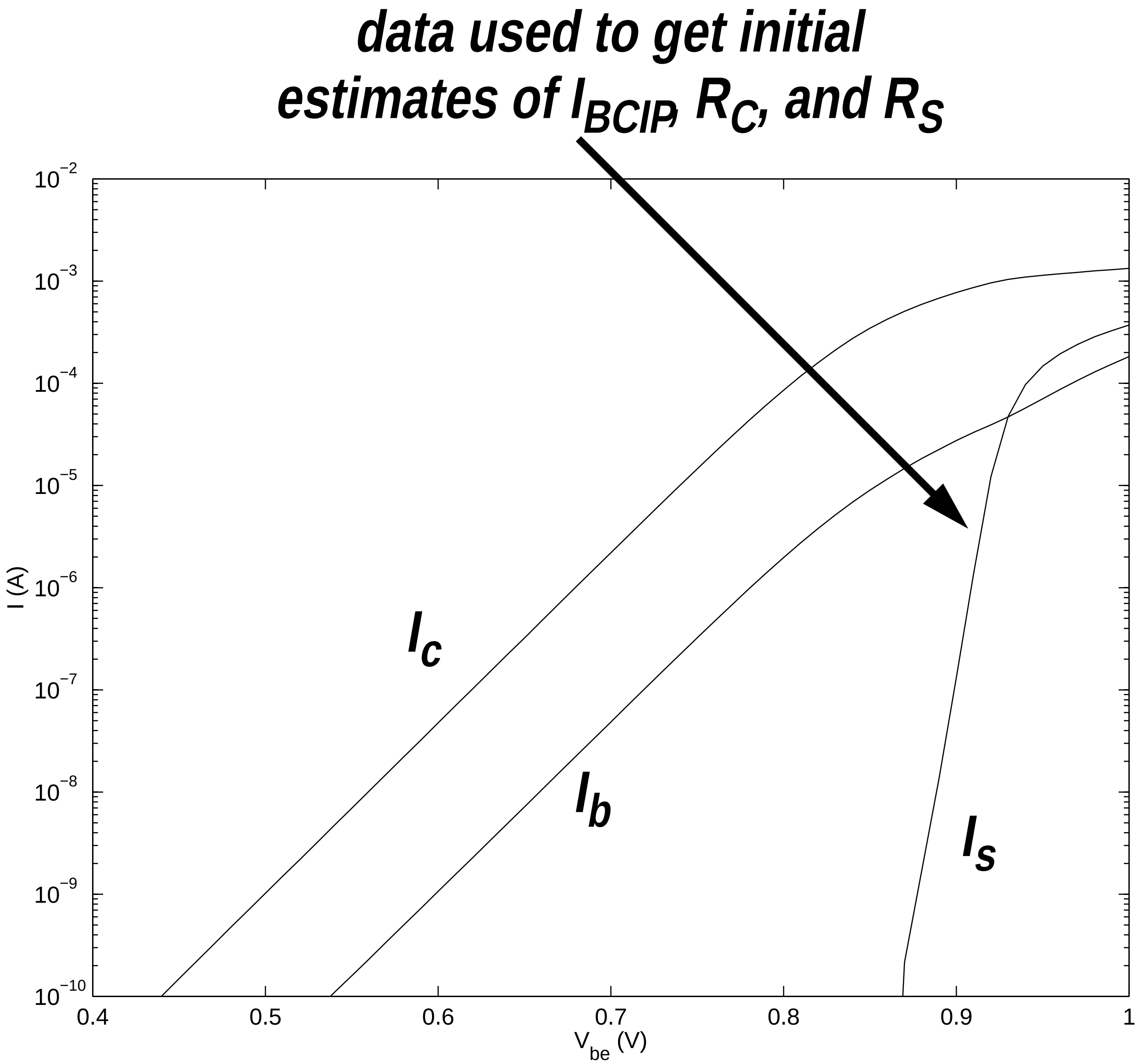
$$I_s = I_{BCIP}\,exp\left(\frac{I_c R_C}{N_{CIP} V_{tv}}\right)$$

  - at this stage assume that $N_{CIP} = 1$

- **from the "ideal" region of $I_s(I_c)$ the intercept and slope give I_{BCIP} and R_C**
- **from the deviation from ideality at high I_c the substrate resistance R_S can be calculated**
  - really the sum $R_S + R_{BIP}$

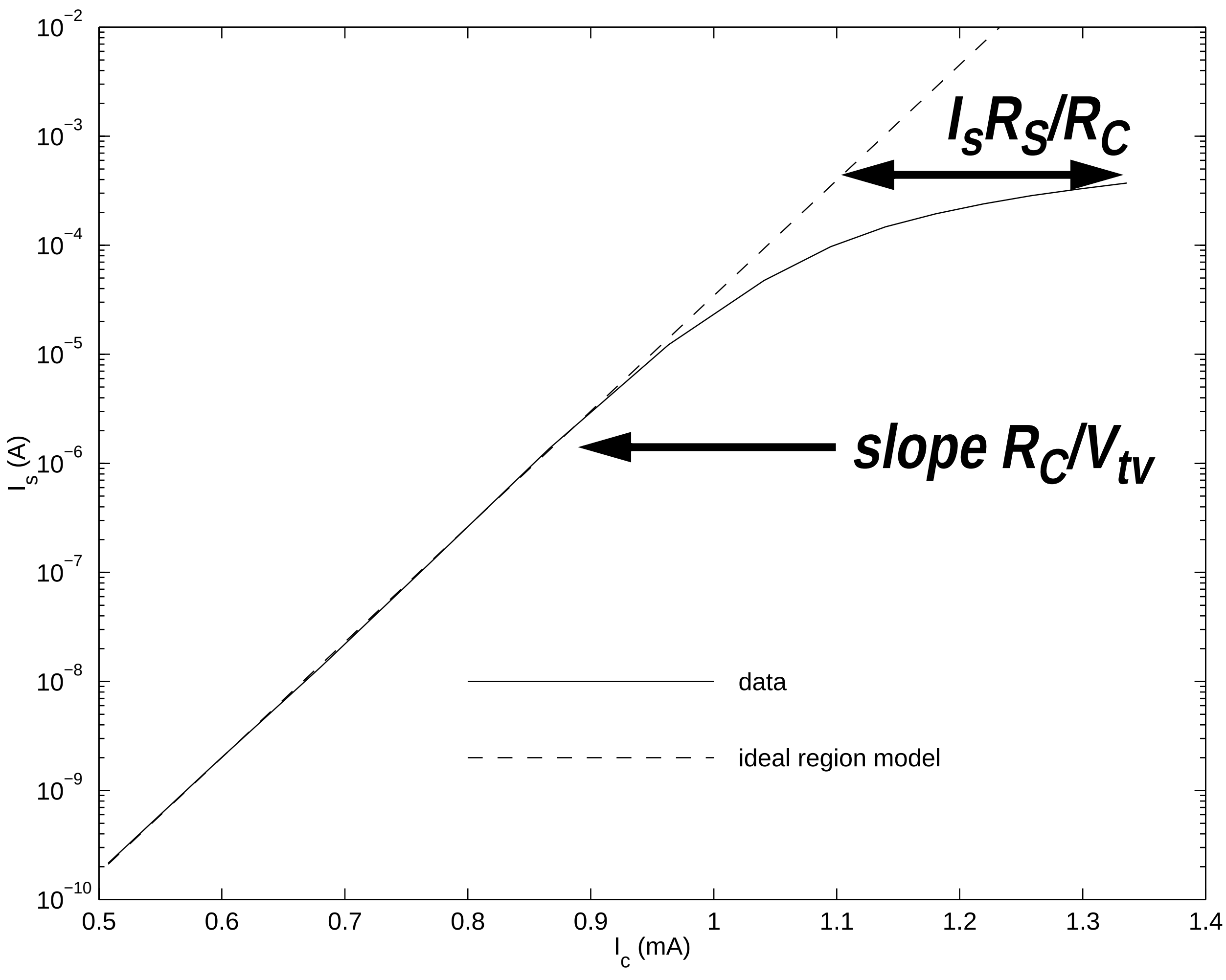
STEP: I_{BCIP} (cont'd)

High Bias FG Data



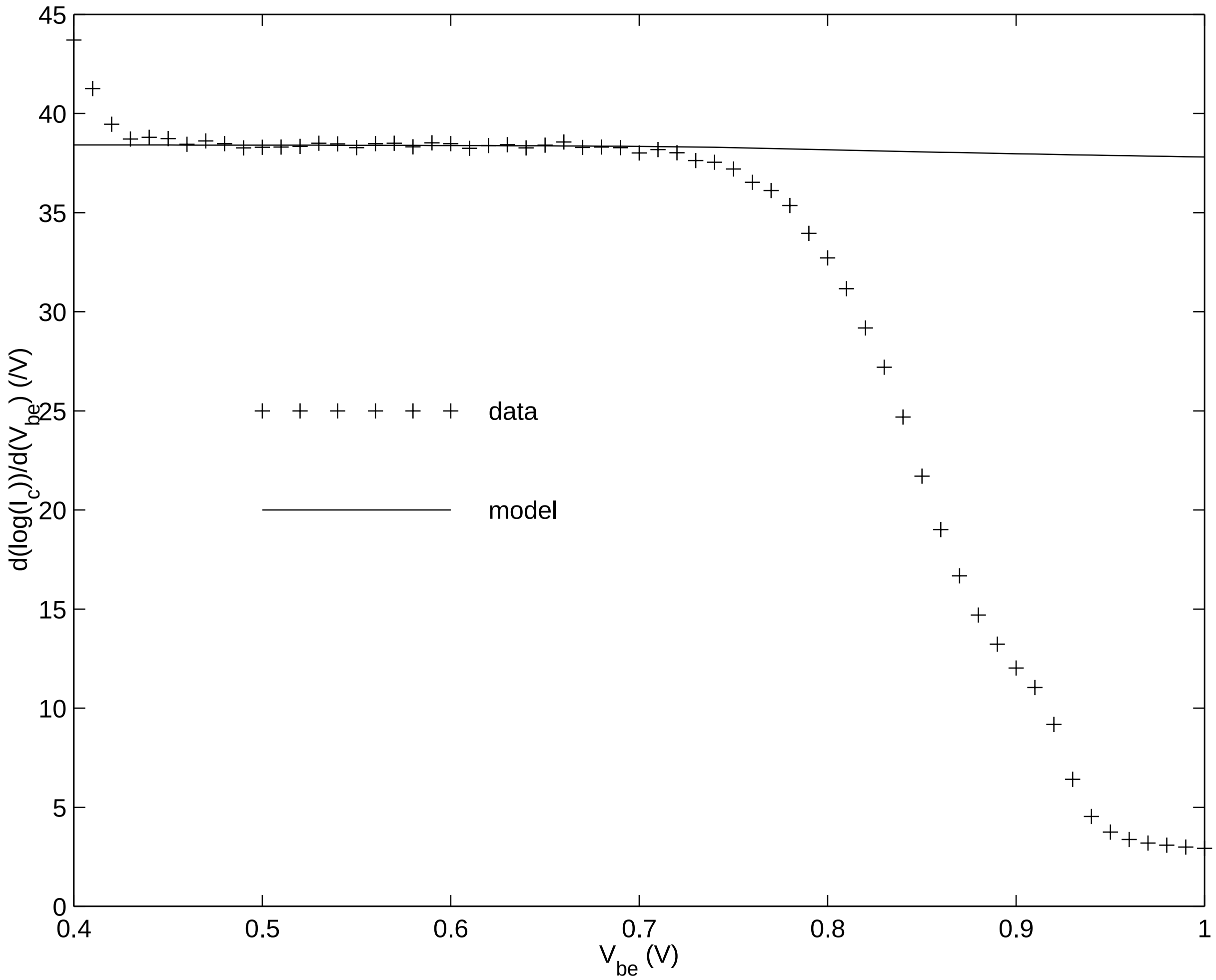
STEP: I_{BCIP} (cont'd)

High Bias FG Data, $I_s(I_c)$



FG Data Analysis for I_S and N_F

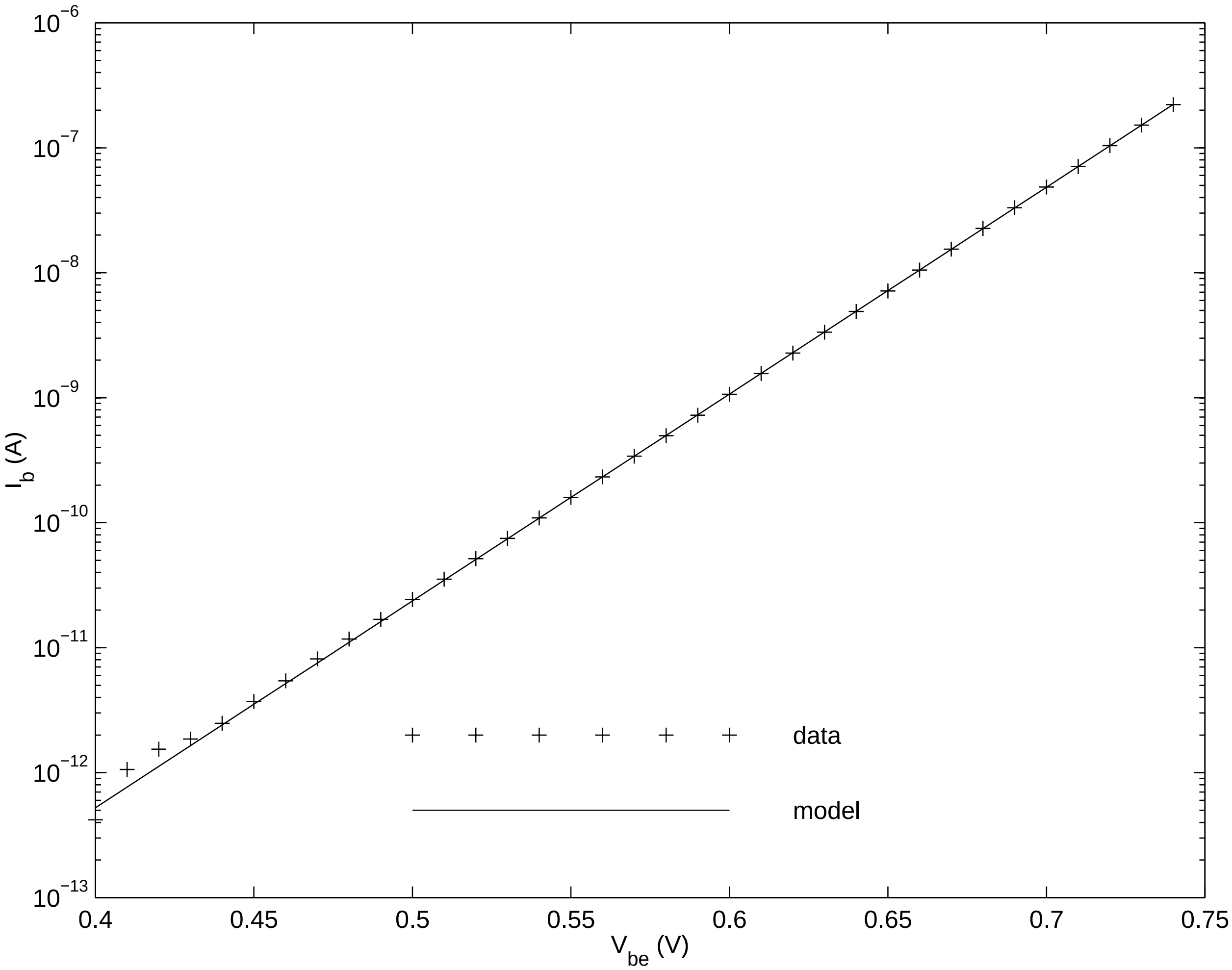
- select "ideal" region FG I_c data, calculate q_1, form $q_1 I_c$ (accounts for Early effect)
- extract I_S and N_F from slope and intercept



STEP: I_B

From FG I_b or RG I_b-I_s Data

- **select ideal region data, I_{BI} and N_I follow from slope and intercept**
- **at low bias, subtract ideal component to get non-ideal component, fit this**



STEP: I_{SP}

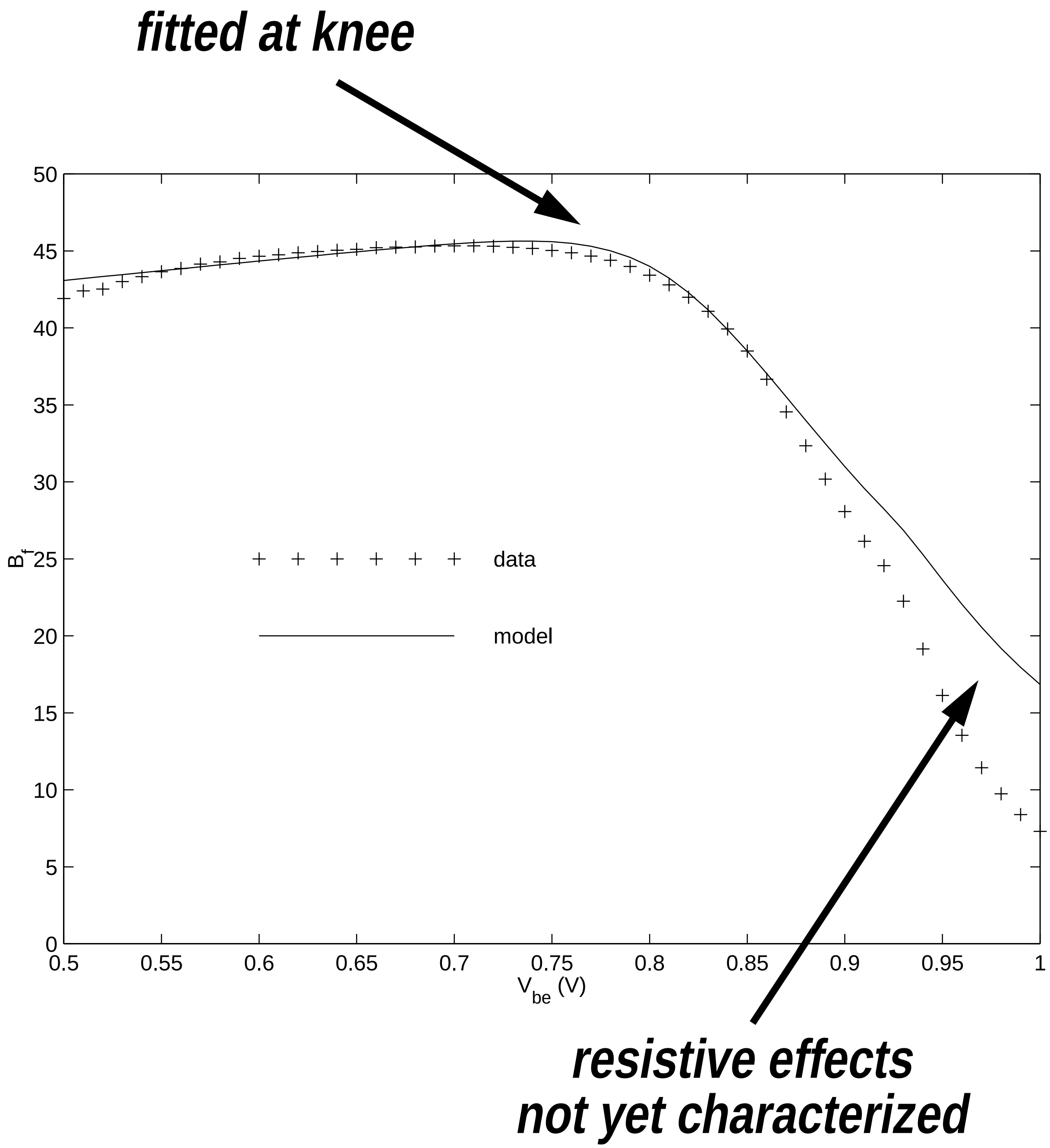
- **from ideal region RG** I_e **data extract** N_R **from the slope of** $q_1 I_e$
- **from ideal region RG** I_e **data extract** I_{SP} **and** N_{FP} **from slope and intercept**
  - there is no Early effect in the model for the reverse transport current, so no correction for this is necessary

STEP: I_{KF}

Same Technique is Used for I_{KR} and I_{KP}

- **select FG high bias data to avoid the region where the non-ideal component of base current is significant**
- **from the ideal component of base current calculate the intrinsic base-emitter voltage** V_{bei}
- **calculate** q_1 **from intrinsic biases**
  - approximation: do not know base-collector de-biasing, so assume $V_{bci} = V_{bc}$
- **from** $I_c = I_S exp(V_{bei}/(N_F V_{tv}))/q_b$ **calculate** q_b
- **calculate** $q_2 = q_b(q_b - q_1)$
- **then** $I_{KF} = I_S exp(V_{bei}/(N_F V_{tv}))/q_2$

STEP: I_{KF}



fitted at knee
50
45
40
35
30
25
20
15
10
5
0
B_f
data
model
0.5
0.55
0.6
0.65
0.7
0.75
0.8
0.85
0.9
0.95
1
V_be (V)
resistive effects
not yet characterized

STEP: R_B

Base and Emitter Resistance Characterization

- **the open collector (Giacolleto) method is used to determine** R_E
  - must be done at very high I_b
- **initial estimates of** R_{BX} **and** R_{BI} **are made from Ning-Tang analysis**
- R_{BX}, R_{BI}, I_{IKF}, R_C **and** N_{CIP} **are optimized to fit high bias FG data**
  - all of I_c, I_b and I_s are fitted
  - the residual is $\dfrac{y - \hat{y}}{|y| + |\hat{y}|}$, which is symmetric with respect to relative error, and insensitive to outliers
- **proper residual calculation is a key to robust optimization**

Open Collector Method for R_E

Done at high bias

- **physical analysis**

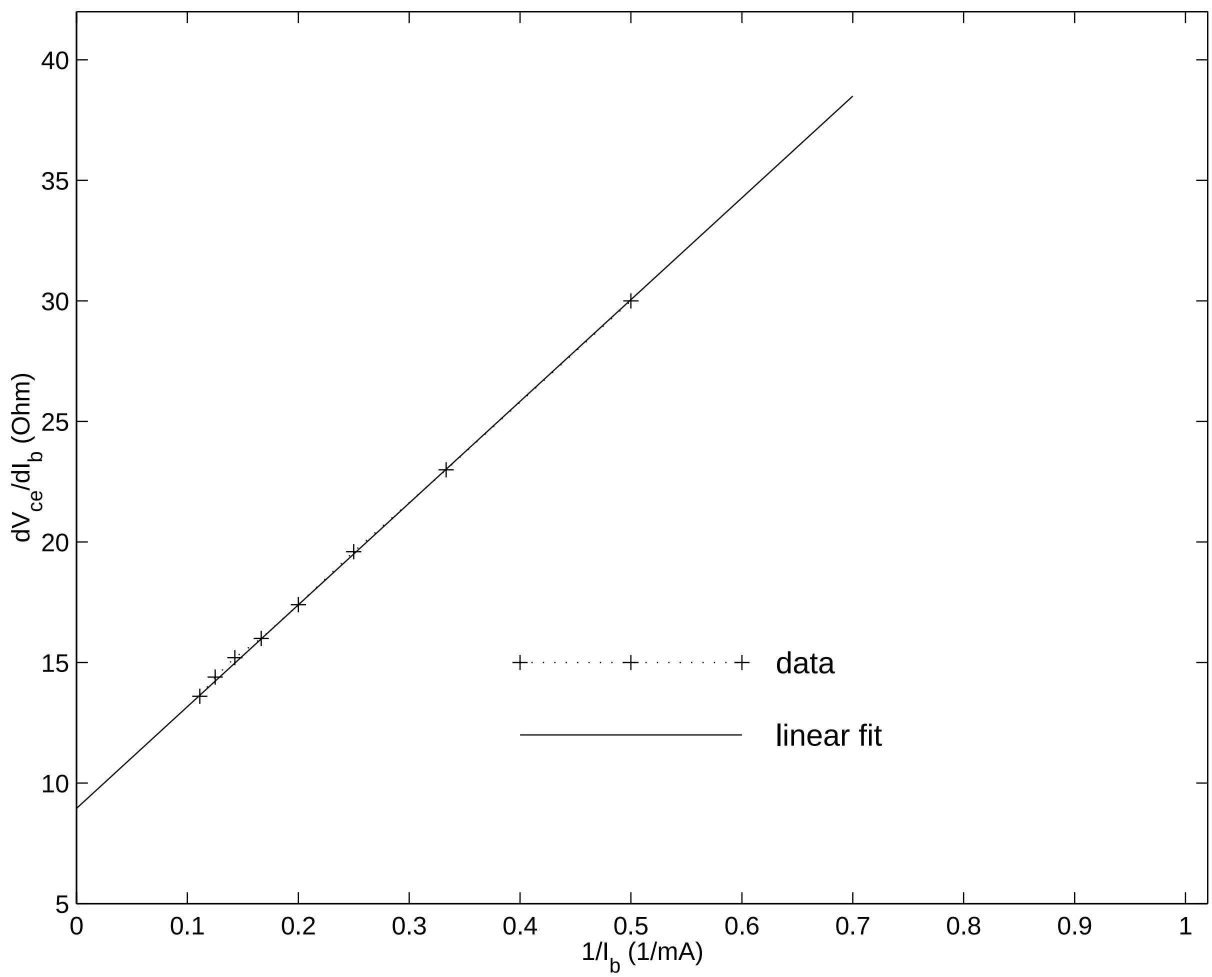
$$V_{ce} = I_b R_E + K\, ln\left(1 + \sqrt{I_b / I_{OS}}\right)$$

- **derivative is**

$$\frac{\partial V_{ce}}{\partial I_b} = R_E + \frac{0.5K}{\sqrt{I_b}\left(\sqrt{I_b} + \sqrt{I_{OS}}\right)} \approx R_E + \frac{K}{2I_b}$$

- **take derivative, plot versus** $1/I_b$
- **abscissa intercept gives** R_E**, slope gives** K
- **optimization is used to refine parameters**

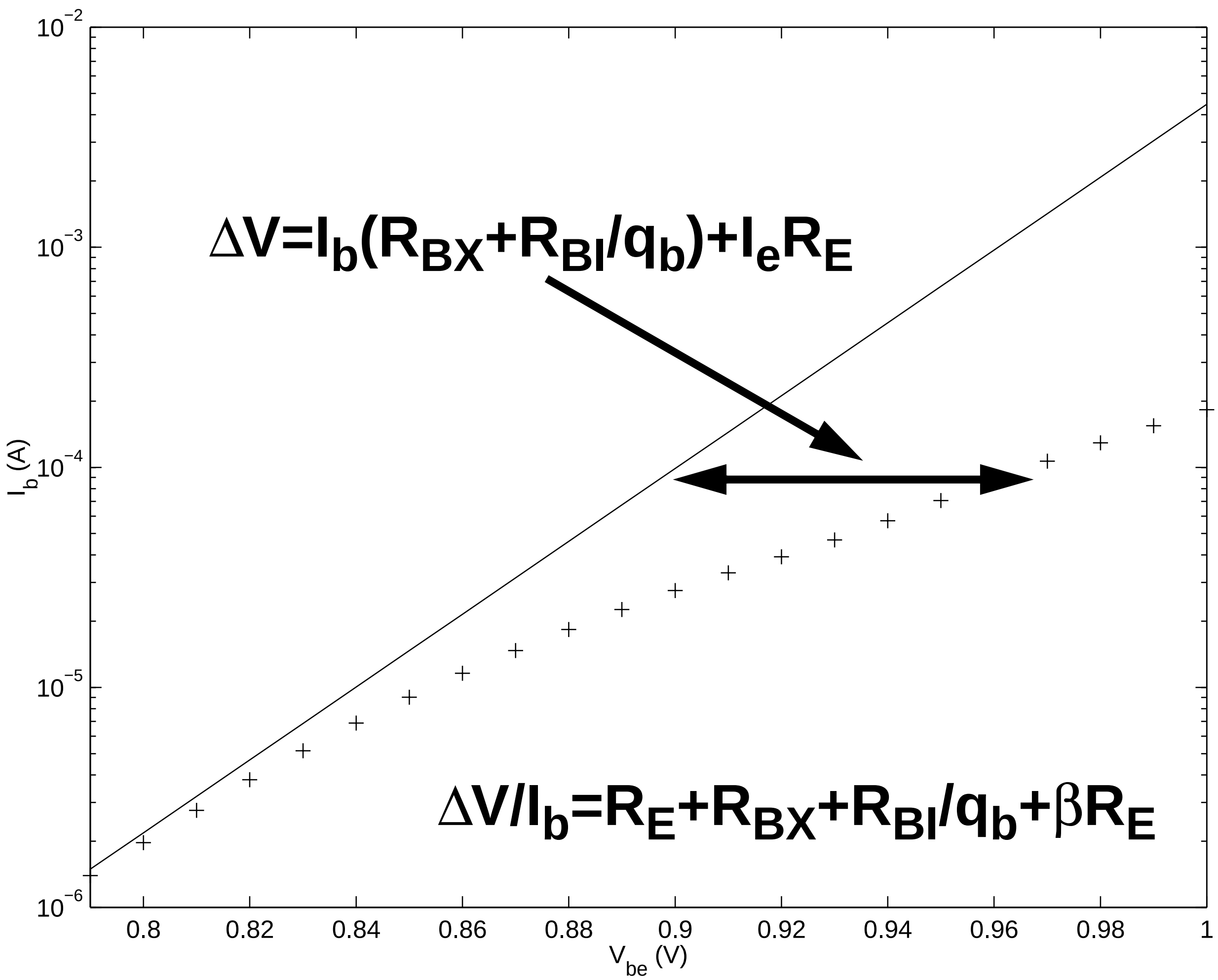
R_E Extraction Plot



Base Resistance DC

Ning-Tang Analysis

- **determine** V_{bei} **from** I_b
  - avoid region where I_{bc} is significant
- **calculate** $\Delta V / I_b$ **at three high bias points**



Base Resistance DC (cont'd)

- **get system of linear equations to solve**

$$\begin{bmatrix} \left(\frac{\Delta V}{I_b}\right)_1 \\ \left(\frac{\Delta V}{I_b}\right)_2 \\ \left(\frac{\Delta V}{I_b}\right)_3 \end{bmatrix} = \begin{bmatrix} 1 & \frac{1}{q_{b,1}} & \beta_1 \\ 1 & \frac{1}{q_{b,2}} & \beta_2 \\ 1 & \frac{1}{q_{b,3}} & \beta_3 \end{bmatrix} \begin{bmatrix} R_E + R_{BX} \\ R_{BI} \\ R_E \end{bmatrix}$$

- **however, at high bias $\beta \approx \beta_{low} / q_b$, therefore the matrix is poorly conditioned**
- **need additional information**
  - AC data
  - physical calculation for R_{BI} (Ning-Tang)
  - R_E from open collector method

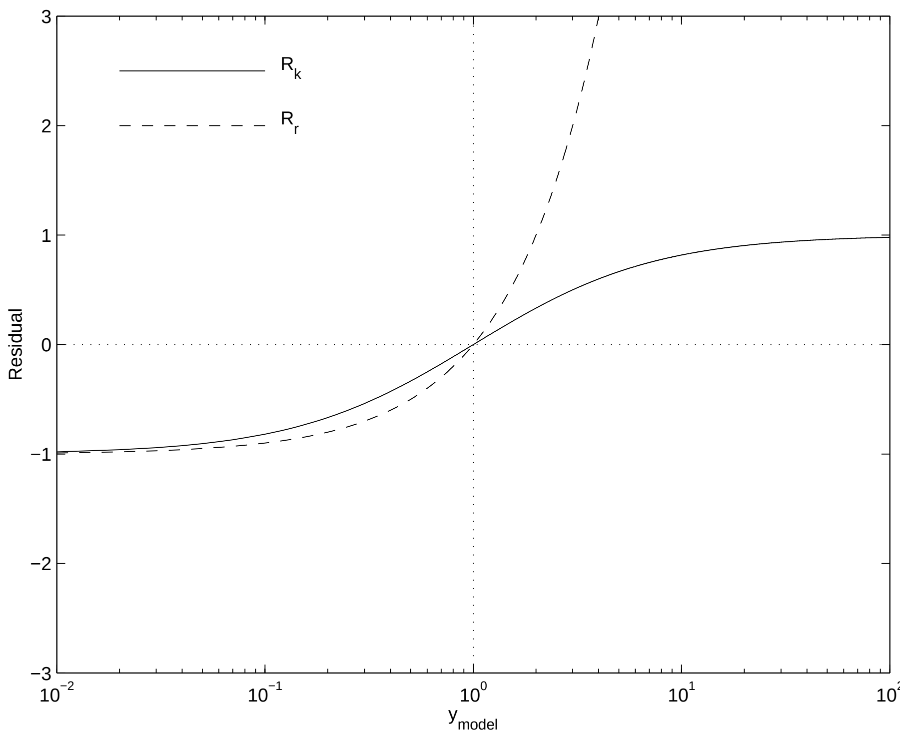
Base Resistance AC

Impedance Circle Method

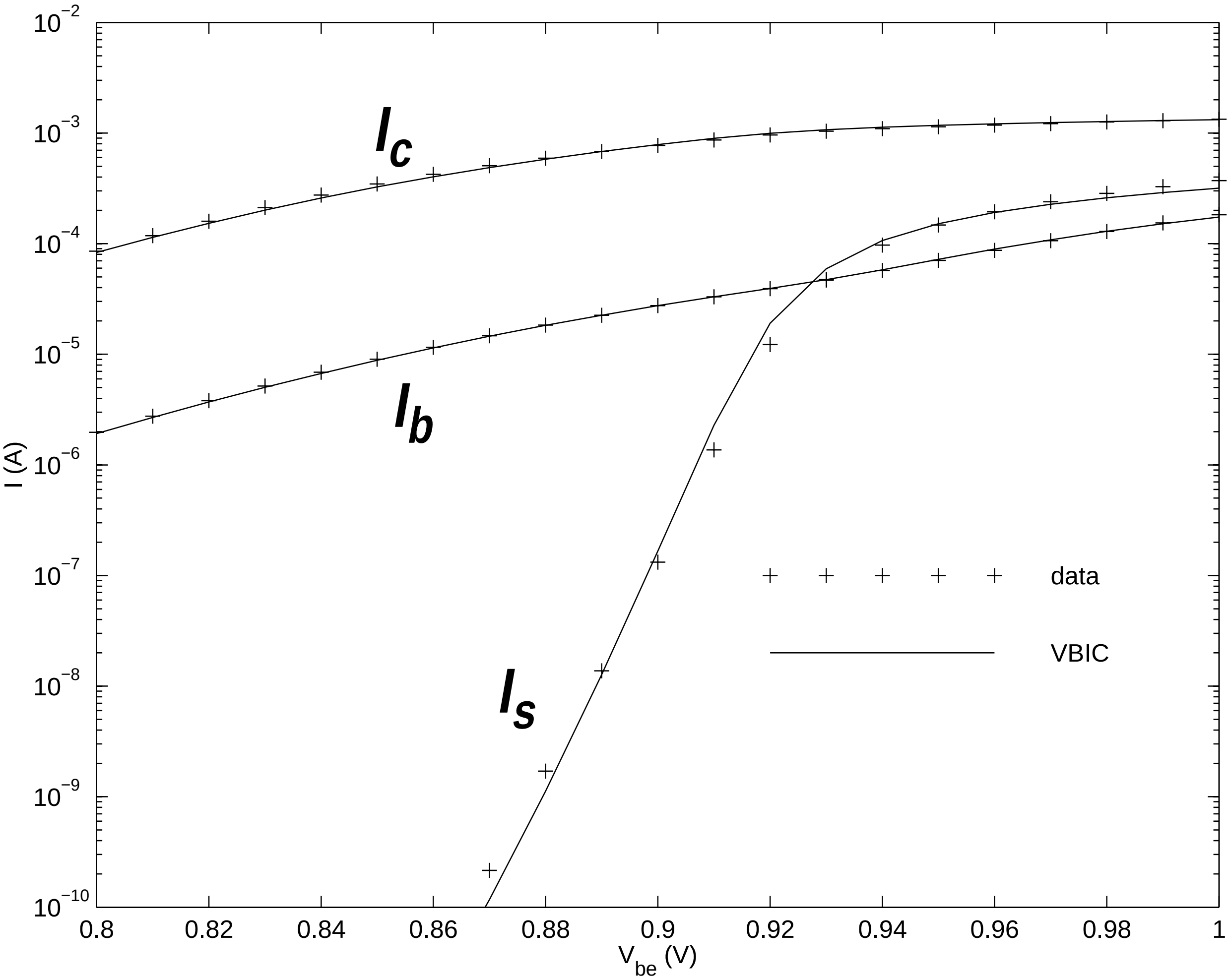
- **indeterminacy in DC data can be broken with AC data**
  - adds orthogonal information
- **simple theory gives low frequency asymptote as** $R_B + r_\pi + (1 + \beta_{ac})R_E$ **and high frequency asymptote as** $R_B + R_E$
  - because of deviations at high frequency from a circle the high frequency asymptote is extrapolated from low frequency data
- **however, detailed simulations with a realistic small-signal model show that the radius of the low frequency data depends strongly on all components of the small-signal model**
  - simple extraction from the impedance circle is not possible
- **still should look at this data for extraction**

Robust, Symmetric Residuals

	$-\infty$	$\frac{y_{data}}{n}$	$\frac{y_{data}}{2}$	$2y_{data}$	ny_{data}	$+\infty$
R_r	$-\infty$	$-1+\frac{1}{n}$	$-\frac{1}{2}$	$+1$	$n-1$	$+\infty$
R_k	-1	$-1+\frac{2}{(1+n)}$	$-\frac{1}{3}$	$+\frac{1}{3}$	$1-\frac{2}{(1+n)}$	$+1$

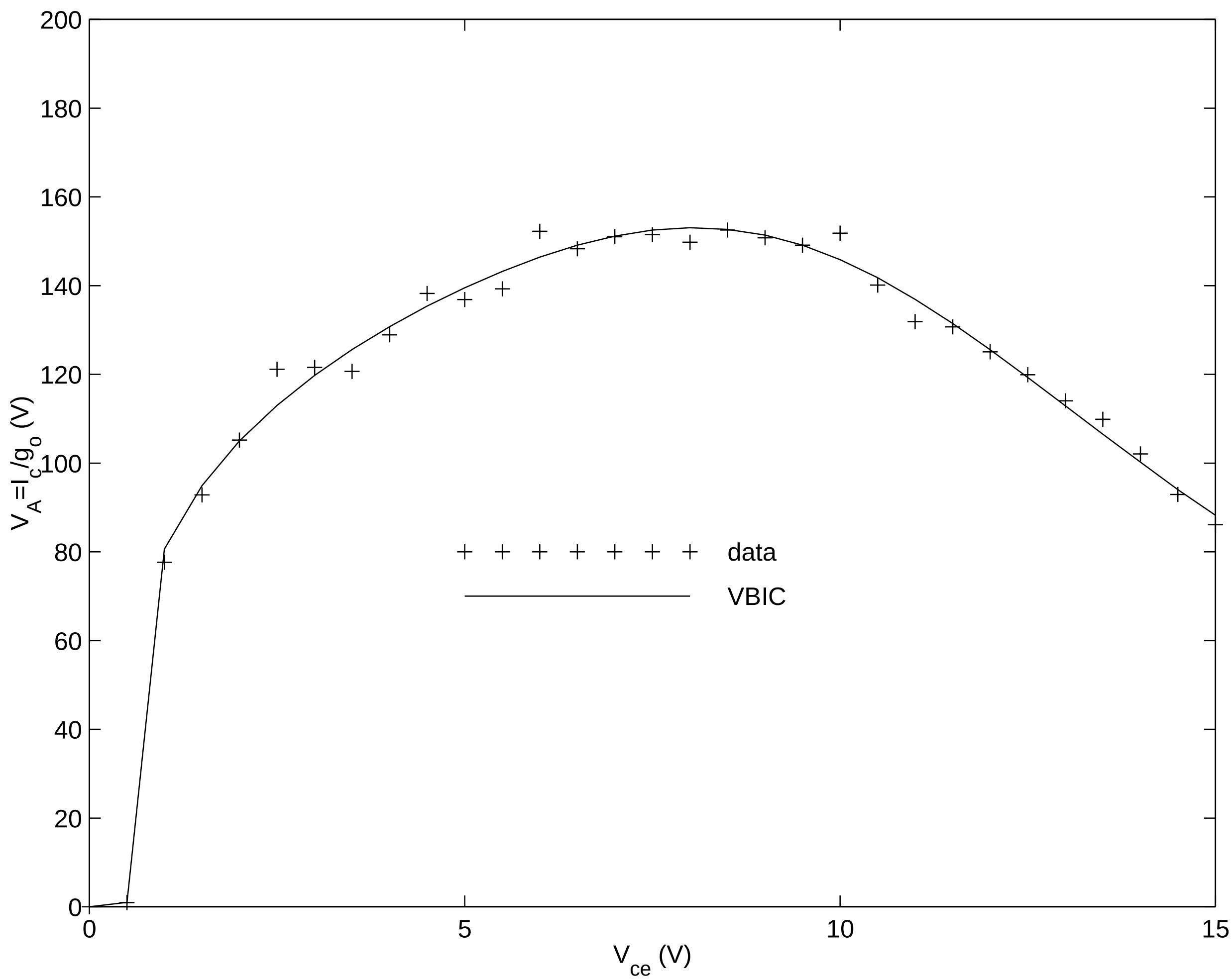


STEP: R_B (cont'd)



Avalanche Parameter Extraction

- compute initial A_{VC1} and A_{VC2} from FO data at highest V_{ce}
- optimize to fit $V_A = I_c / g_o$



Activation Energy Characterization

- $I_S(T) = I_S(T_{nom})$

$$\left(\left(\frac{T}{T_{nom}}\right)^{X_{IS}} exp\left(\frac{-E_A}{k/q}\left(\frac{1}{T} - \frac{1}{T_{nom}}\right)\right)\right)^{\frac{1}{N_F}}$$

- **select a target current level in the ideal operating region, calculate at each T**

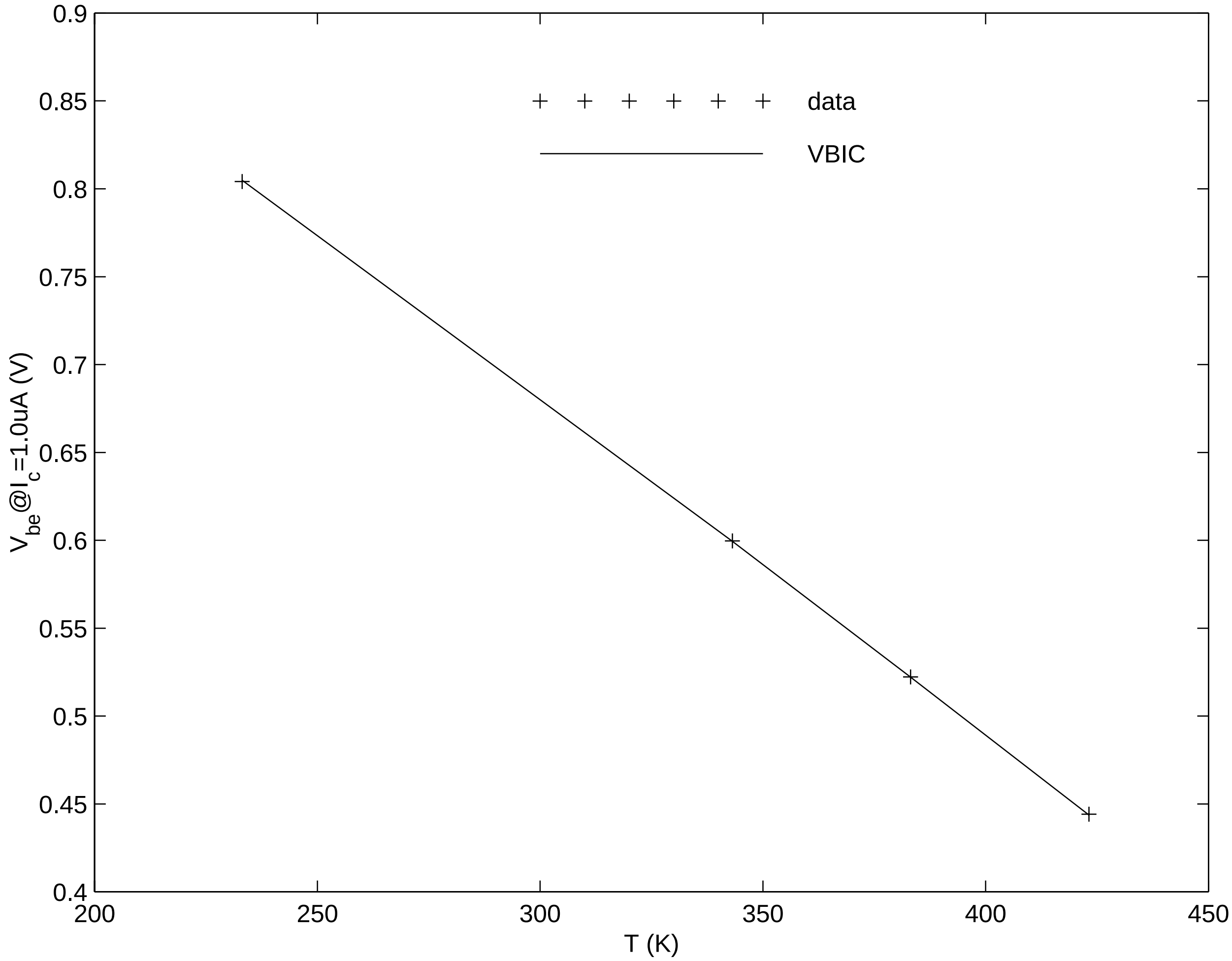
$$I_S = \frac{q_1 I_c}{exp(V_{be}/(N_F V_{tv}))}$$

  - account for q_1 temperature dependence

- **slope of** $N_F log I_S - X_{IS} log T$ **vs.** $1/T$ **is** $-qE_A/k$ **from which** E_A **can be calculated**
- X_{IS} kept at default value

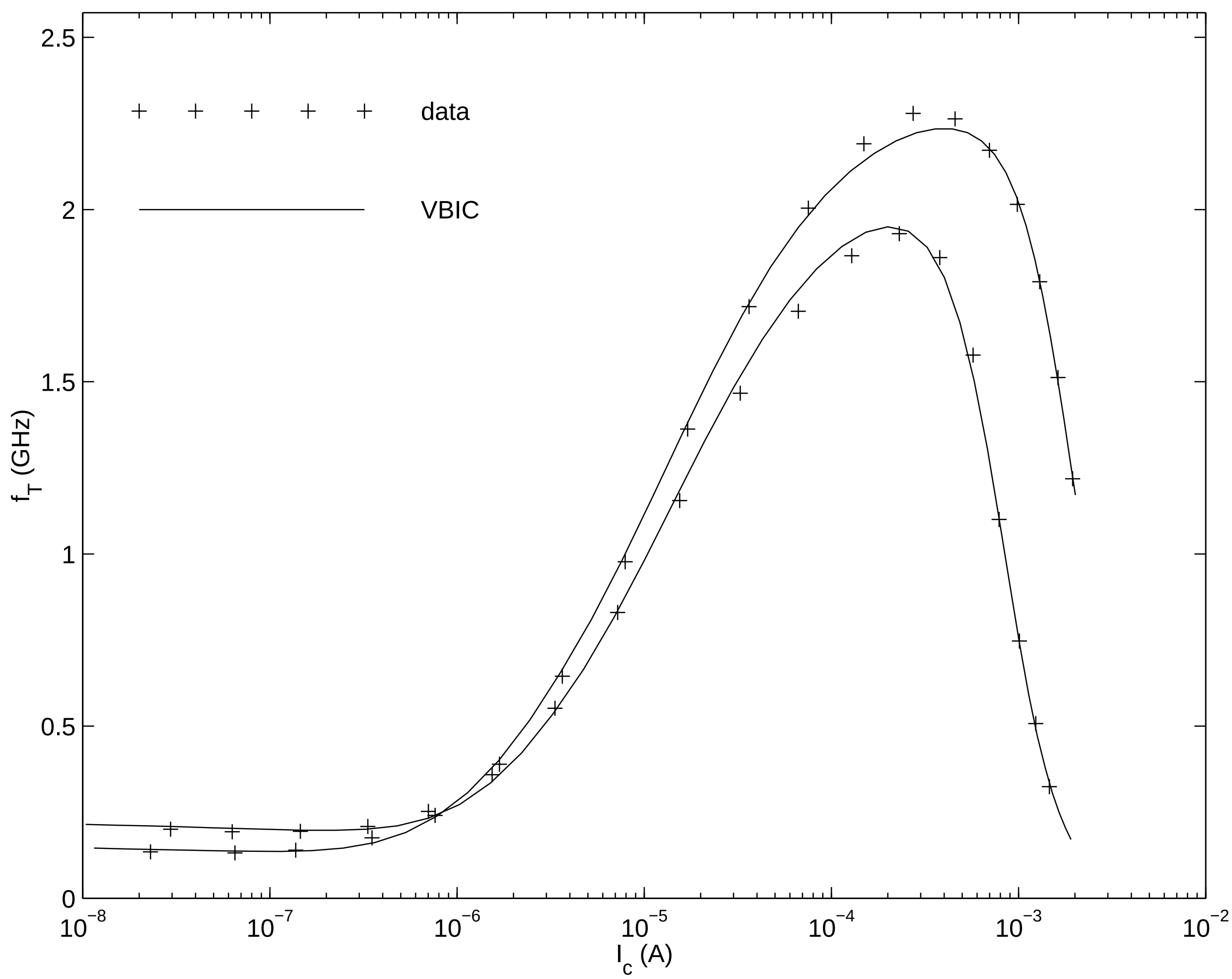
V_{be} vs. Temperature

Important for Bandgap Design



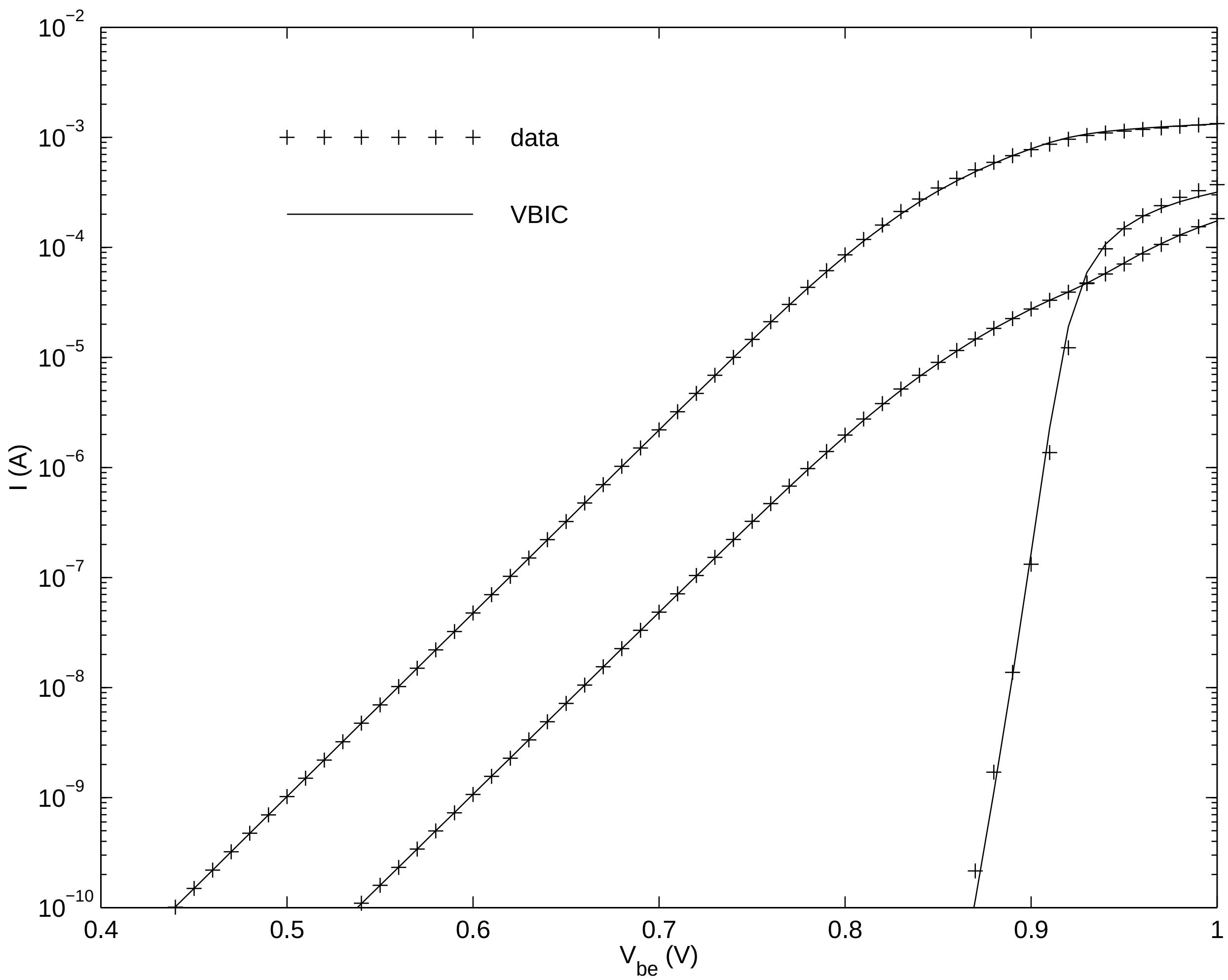
$f_T(I_c)$ Characterization

- **initialize** T_F **and** I_{TF} **from** $1/f_T$ **vs.** $1/I_c$
- **optimize to fit data**
- include c_{be} shape parameters and Q_{TF}

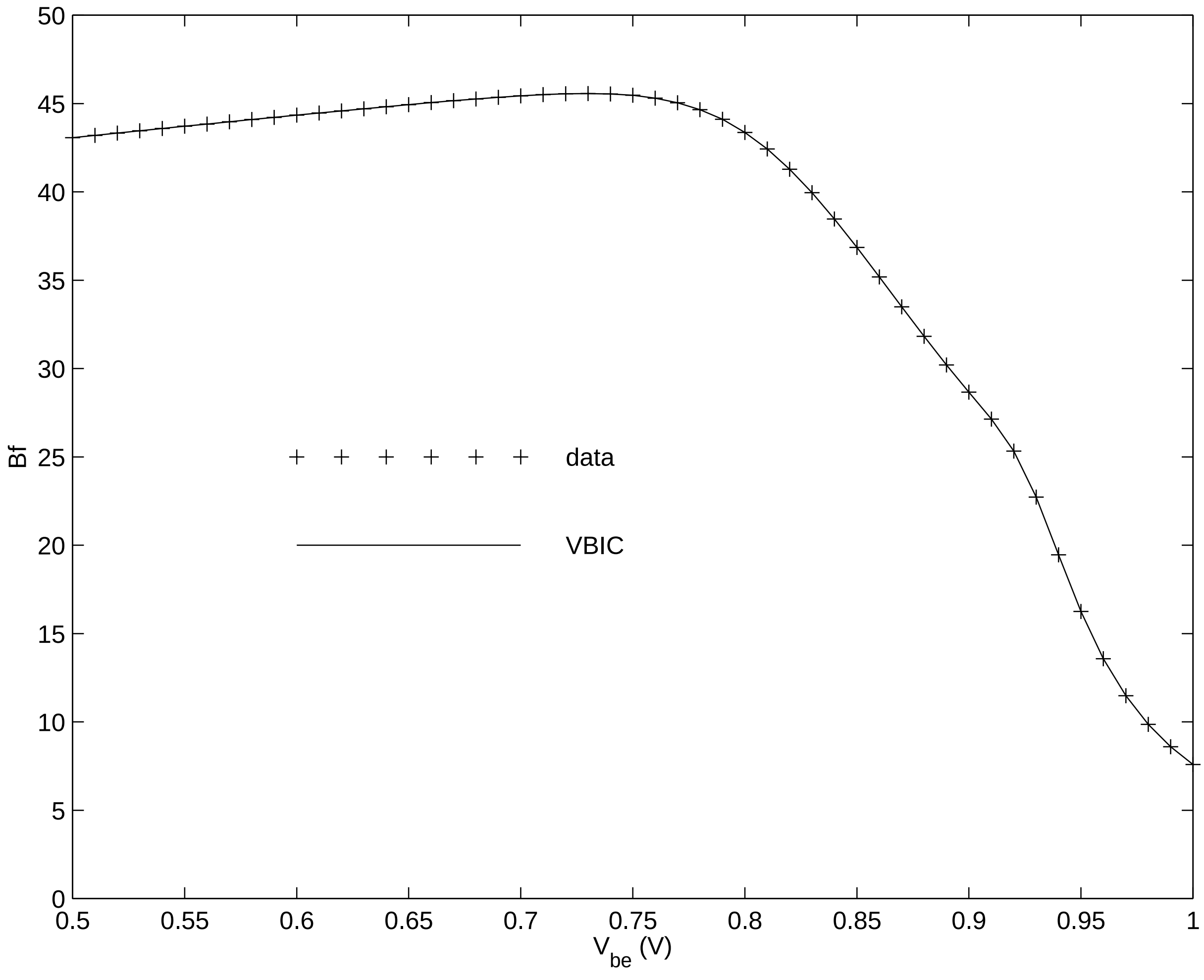


Miscellaneous

- **further optimization is used to fit VBIC to data over the complete bias range**
- **temperature coefficients are determined by extracting temperature dependent parameters at different temperatures and then extracting TC's from the parameters**
  - resistance TC's from sheet resistance test structures and measurements
- **all "standard" extraction data should be without self-heating**
  - low bias or pulsed measurements
  - over temperature
- **thermal resistance is extracted by optimization to fit high $I_c V_{ce}$ data**
- **the transit time model is identical to that of SGP and so existing techniques can be directly used for $f_T(I_c)$ or s-parameter modeling**

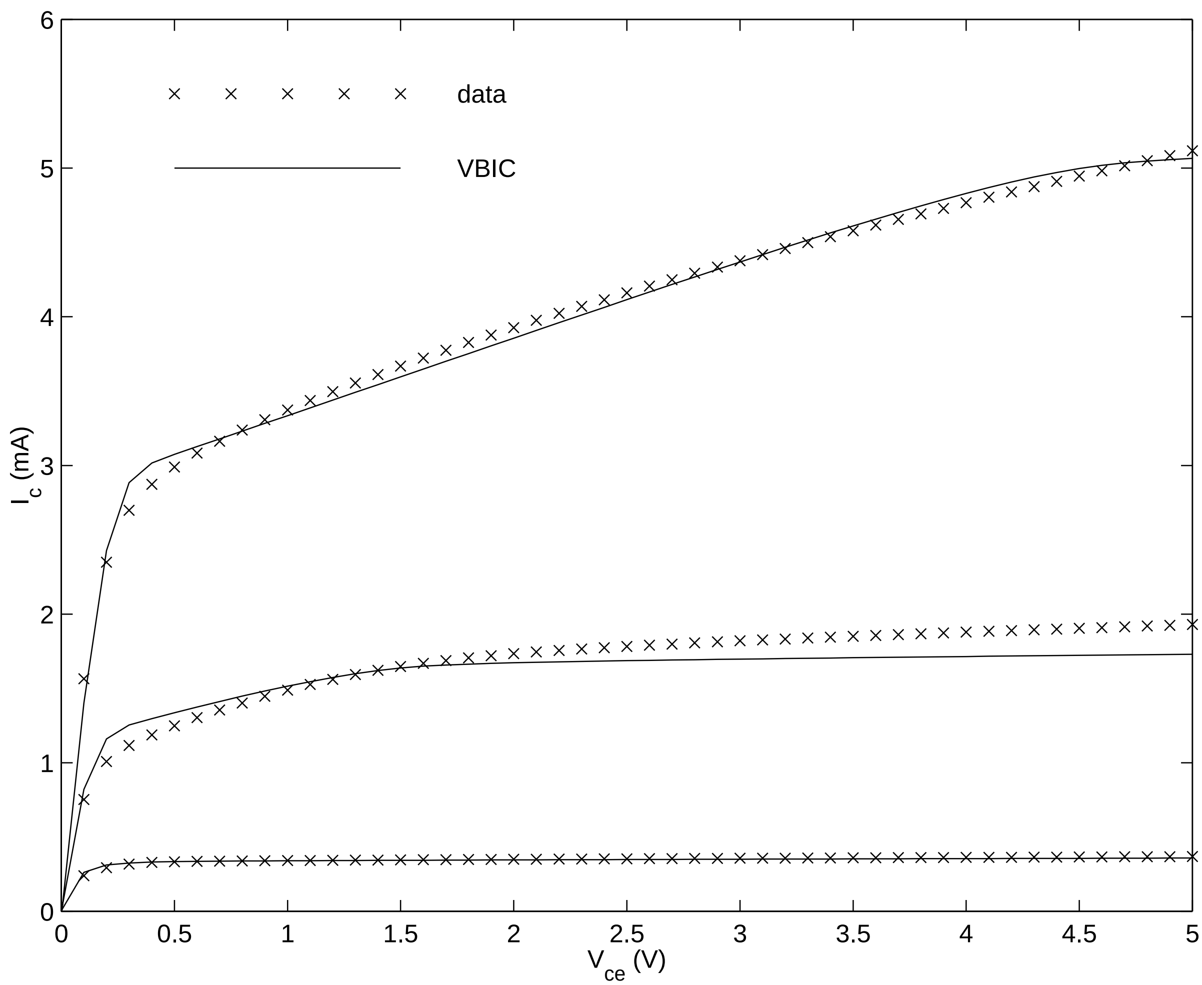

10^−2
10^−3
10^−4
10^−5
10^−6
10^−7
10^−8
10^−9
10^−10
I (A)
0.4
0.5
0.6
0.7
0.8
0.9
1
Vbe (V)
data
VBIC

FG Beta Modeling



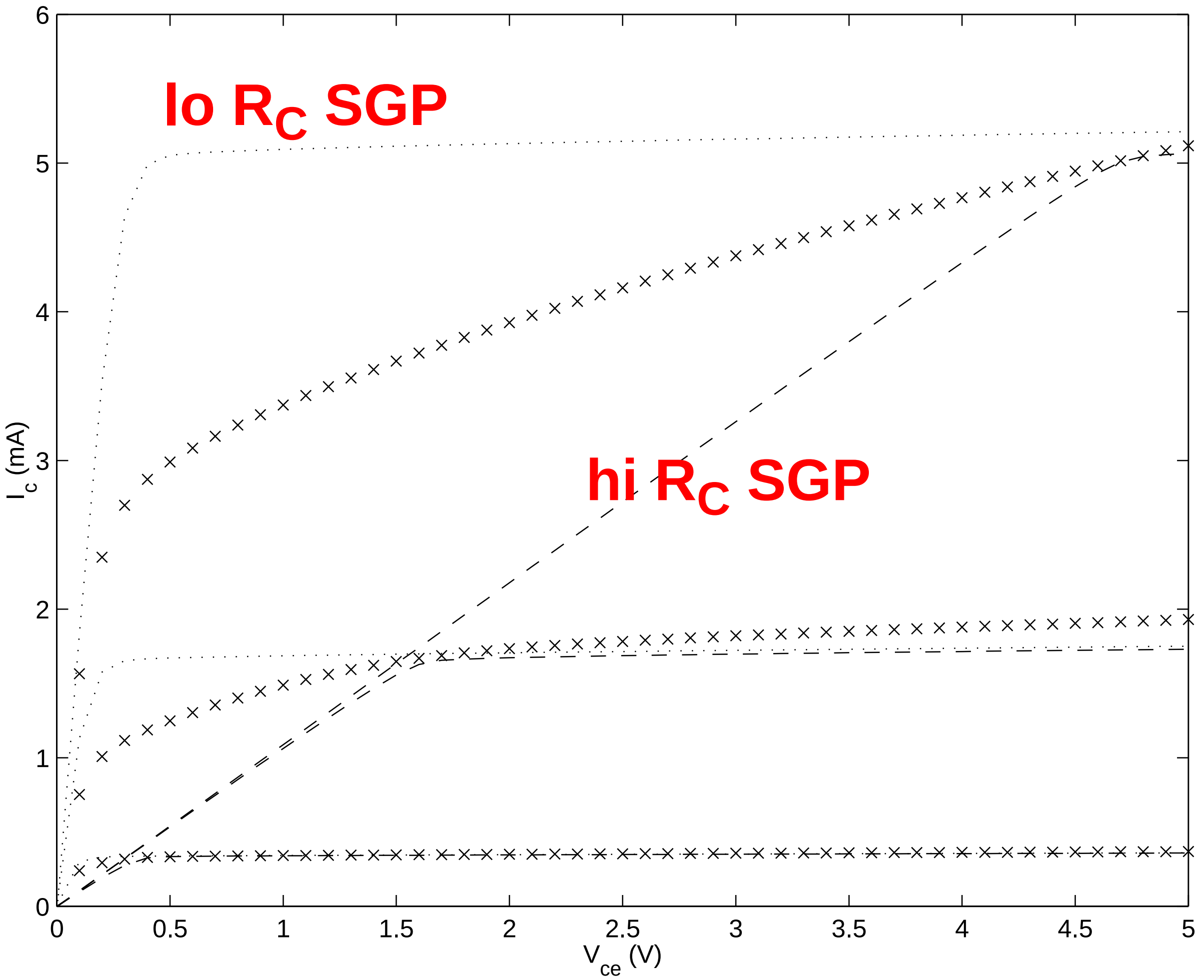
DC Quasi-saturation

- **initialize collector resistance parameters**
  - "smart" way to initialize G_{AMM} and V_O?
- **optimize to fit saturation characteristics**



DC Quasi-saturation

- **quasi-saturation region behavior cannot be modeled well with SGP**



Geometry Modeling

- **all capacitances and currents should be modeled using area and perimeter components (and corner components if necessary), e.g.**

  $$I_S = A_e I_{SA} + P_e I_{SP}$$

- **unless there is a very substantial difference between a masked dimension and an effective electrical dimension, the area and perimeter can be computed as**

  $$A_e = W_e L_e,\ P_e = 2(W_e + L_e)$$

  - it is not possible to distinguish between a "delta" between masked and effective dimensions and variations in the perimeter component

- **forward transit time is also modeled with area and perimeter components**

  $$Q_{diff} \propto A_e I_{SA} T_{FA} + P_e I_{SP} T_{FP} = I_S T_F$$ **so**

  $$T_F = \frac{A_e I_{SA} T_{FA} + P_e I_{SP} T_{FP}}{A_e I_{SA} + P_e I_{SP}}$$

Geometry Modeling (cont'd)

- **similarly from the SGP model the area and perimeter components of collector current are**

$$A_e I_{SA}\, exp\left(\frac{V_{be}}{V_{tv}}\right)\left(1 - \frac{V_{bc}}{V_{AFA}}\right)$$

$$P_e I_{SP}\, exp\left(\frac{V_{be}}{V_{tv}}\right)\left(1 - \frac{V_{bc}}{V_{AFP}}\right)$$

- **want** $I_c = I_S\, exp\left(\frac{V_{be}}{V_{tv}}\right)\left(1 - \frac{V_{bc}}{V_{AF}}\right)$

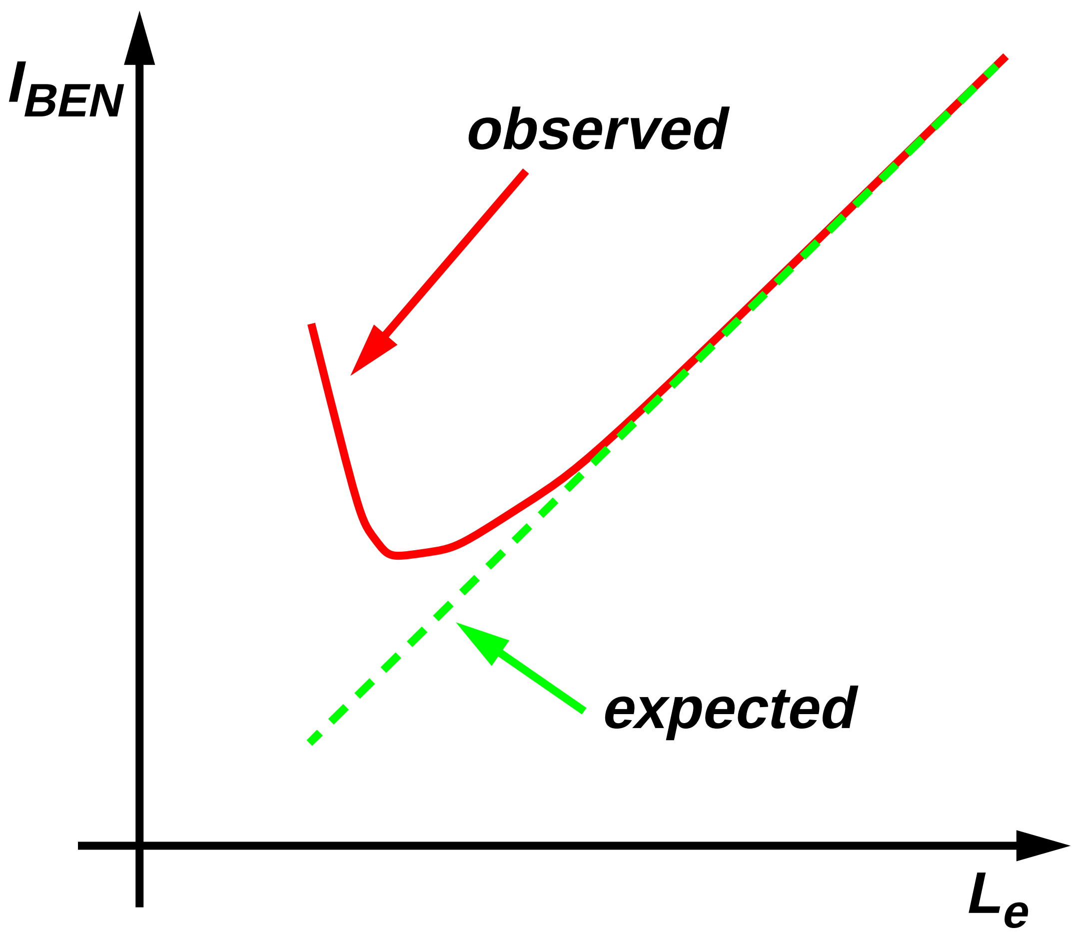
- **equating these gives**

$$\frac{1}{V_{AF}} = \frac{\frac{A_e I_{SA}}{V_{AFA}} + \frac{P_e I_{SP}}{V_{AFP}}}{A_e I_{SA} + P_e I_{SP}}$$

Always Verify Geometry Models

Expect the Unexpected!

- **non-ideal component of base current does not always scale with perimeter**
- **have seen collector resistance increase as emitter length increases**



Resistance Geometry Modeling

This is the most difficult

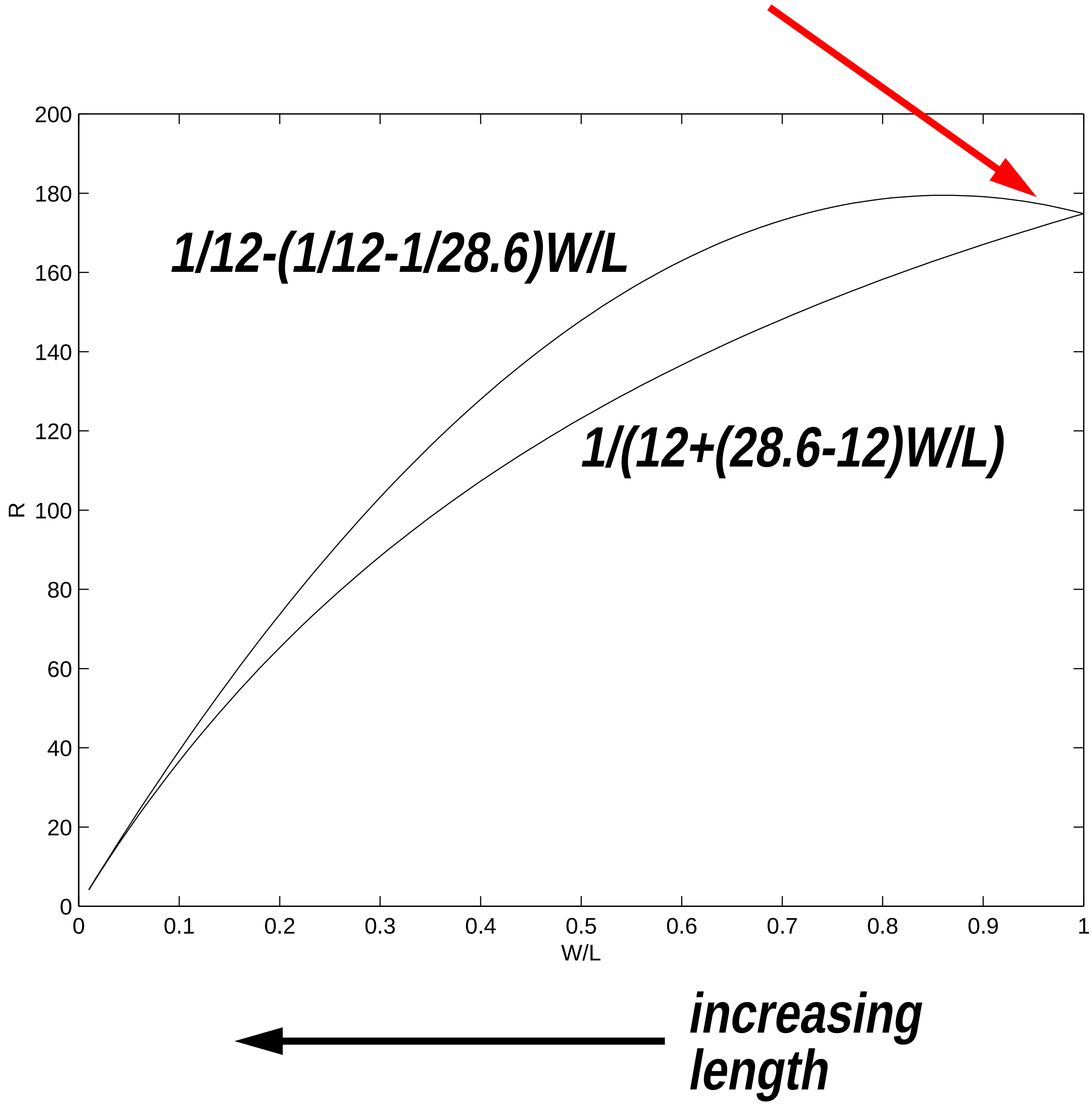
- **think in terms of conductance, not resistance**
- $R_{BI} = k_n \rho_{sbe}(W_e / L_e)$

number of base contacts	1st order theory	physical simulation	reality
n=1	1/3		?
n=2	1/12	1/12	?
n=4	1/32	1/28.6	?

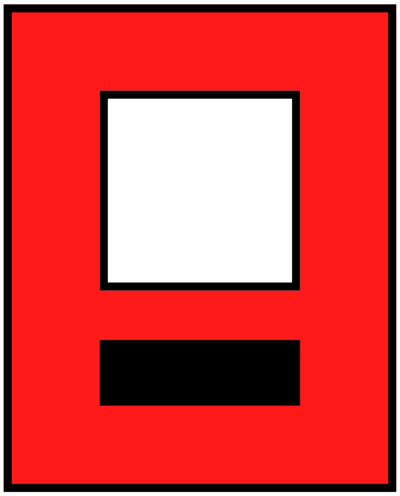
- **for small emitters the n=4 model is reasonable for highly doped base rings**
- **as emitter length increases the effective number of base contacts changes**
- **use** $1/(1/k_1 + (1/k_4 - 1/k_1)(W_e/L_e))$ **rather than** $k_1 - (k_1 - k_4)(W_e/L_e)$ **for monotonic decrease in** R_{BI} **with** L_e

R_{BI} Variation with Geometry

R_{BI} increases as emitter length increases!



- **Effective Base Structure Varies with Geometry**



*effectively
4 base contacts*

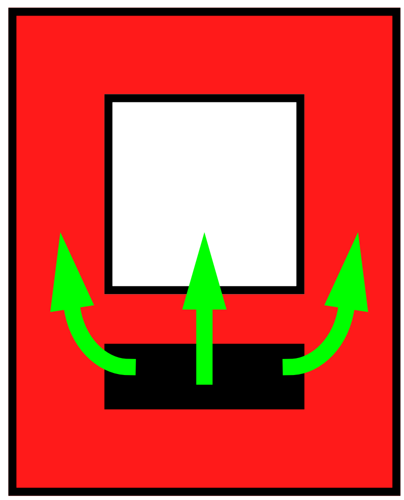
effectively single base contact

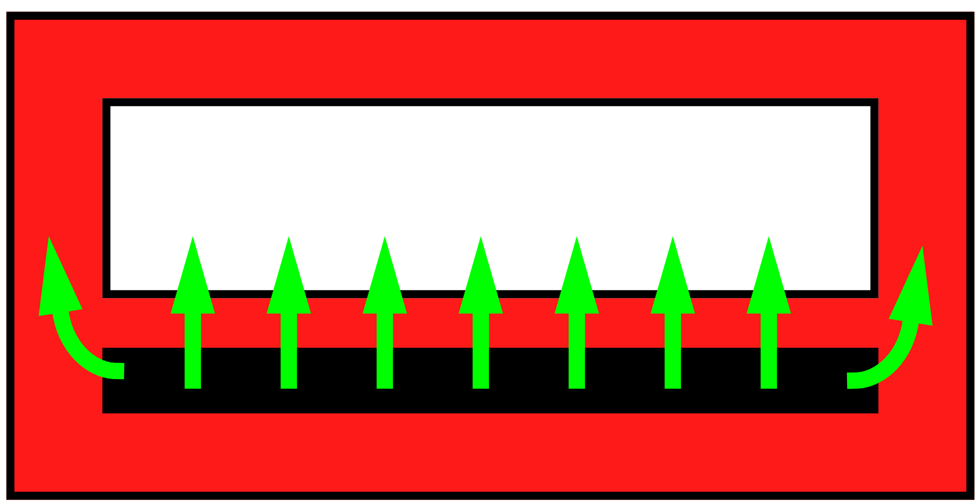
Conductance Increases with Width

Expect a 1/L Dependence for R_{BX}

- $R_{BX} = R_0 + R_L / L$ **????**

$\delta I \propto \delta G \propto \delta L$





- $G_{BX} = 1/R_{BX} = G_0 + G_L L$
  - asymptotically correct as L gets large

Statistical Modeling

- **must be based on process and geometry dependent models**
- **process dependence defined by Ida and Davis, BCTM89**
- **most efficient and accurate way is backward propagation of variance (BPV)**
  - provides Monte Carlo (distributional) and case models
  - for inter-die variation
- **defined in BCTM97 and SISPAD98**
- **exactly the same modeling basis and BPV characterization methodology can be applied to intra-die variation (mismatch), see Drennan BCTM98**

Complete VBIC Code is Available

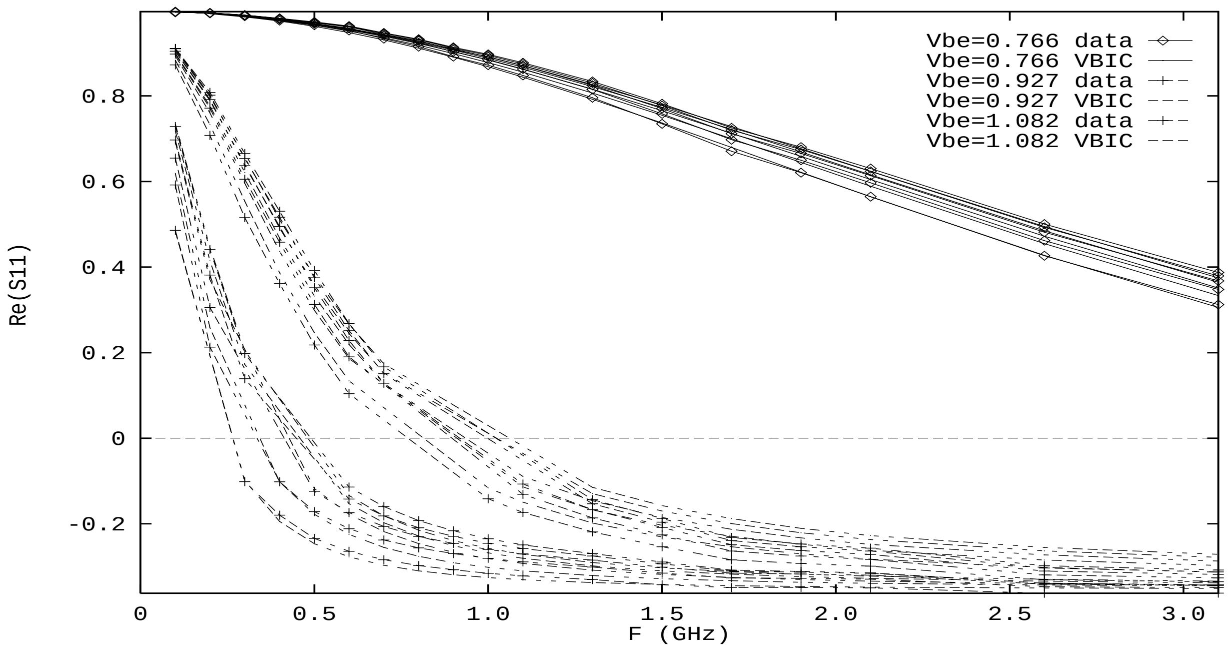
- **the only rational way to define a compact model is in terms of a high-level symbolic description**
  - not through 40 SPICE subroutines
- **historically there have been several proprietary languages and model interfaces**
  - MAST for Saber (Analogy)
  - ADMIT for Advice (Lucent)
  - ASTAP/ASX (IBM)
  - TekSpice (Tektronix/Maxim)
  - MDS (Hewlett-Packard)
  - probably others
  - VBIC had its own symbolic definition
- **VHDL-A looked promising, but appears to have been overtaken by Verilog-A in the industry**

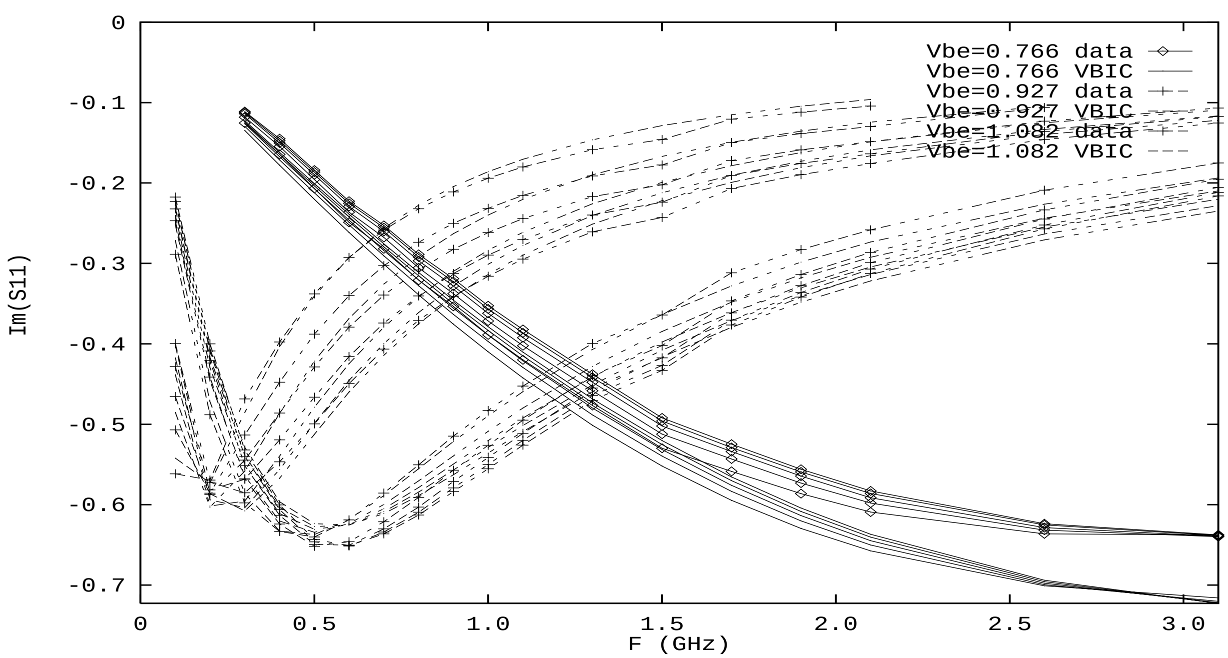
VBIC Code (cont'd)

VBIC is Defined in Verilog-A

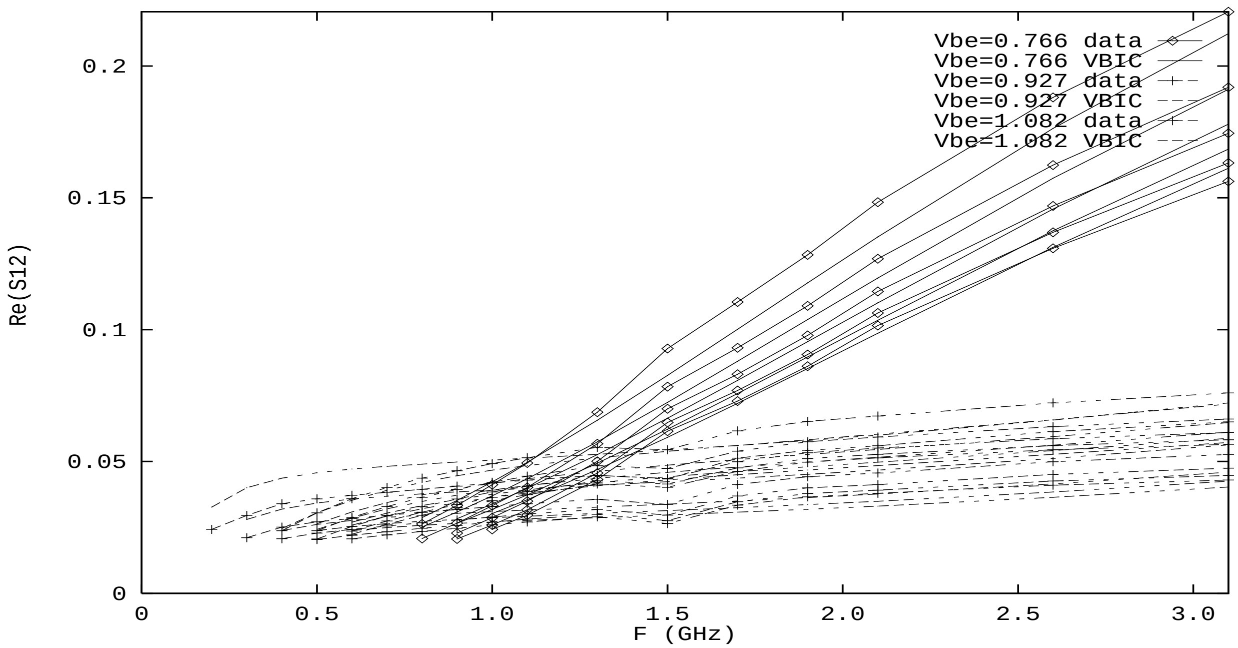
- **well, really in a subset of Verilog-A**
  - conditional definition of 8 separate versions, 3- and 4-terminal, iso-thermal and electro-thermal, and constant- and excess-phase
- **automated tools generate implementable code**
  - FORTRAN and C
  - probably Perl
  - looking at XSPICE
- **DC and AC solvers are provided**
- **transient and other types of analyses depend on simulator algorithms**
  - can use Verilog-A description
  - this can be very slow
- **`http://www-sm.rz.fht-esslingen.de/institute/iafgp/neu/VBIC/index.html`**

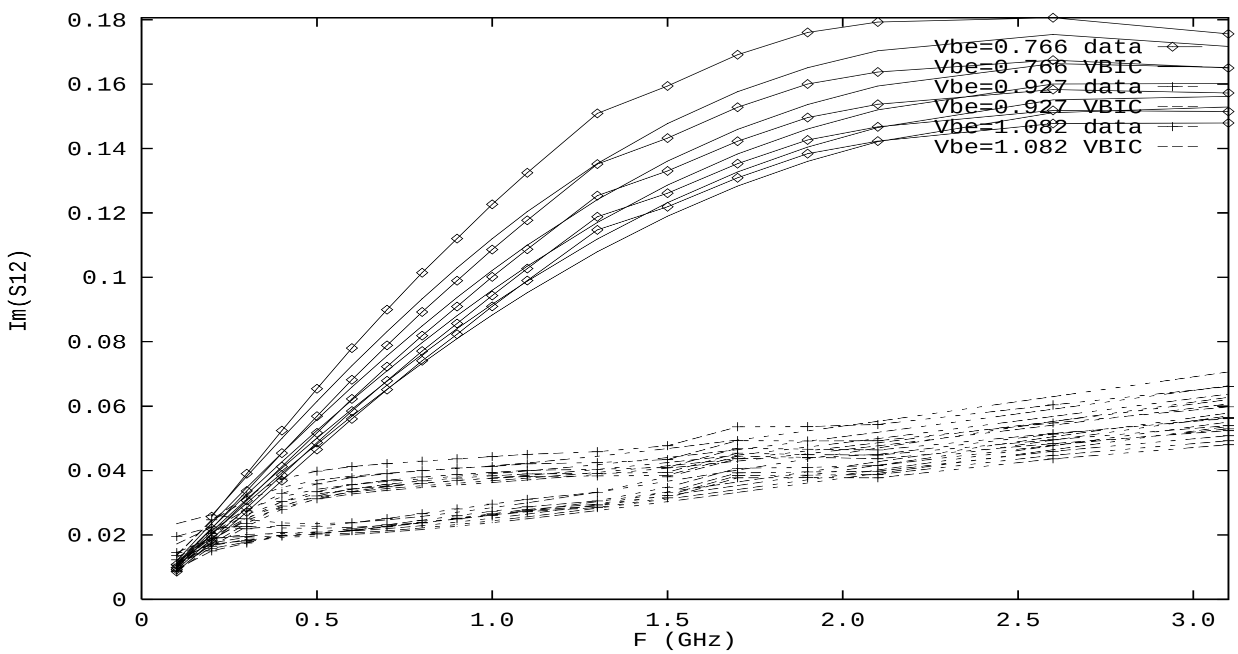
VBIC s11 Modeling



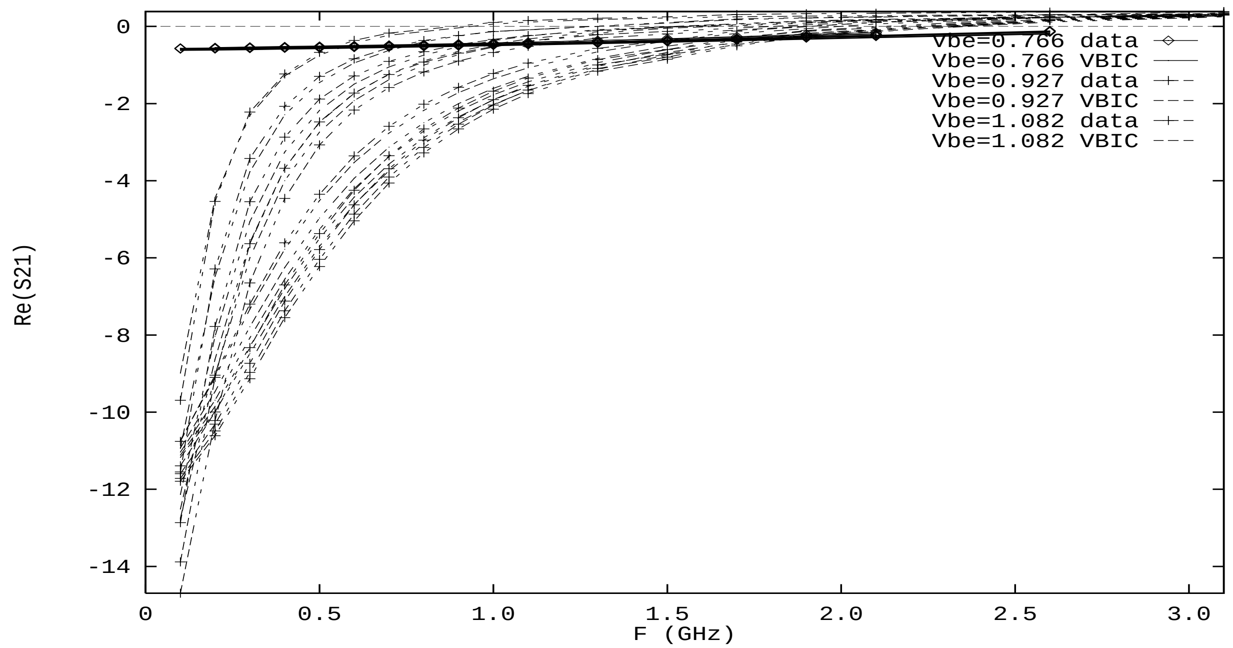


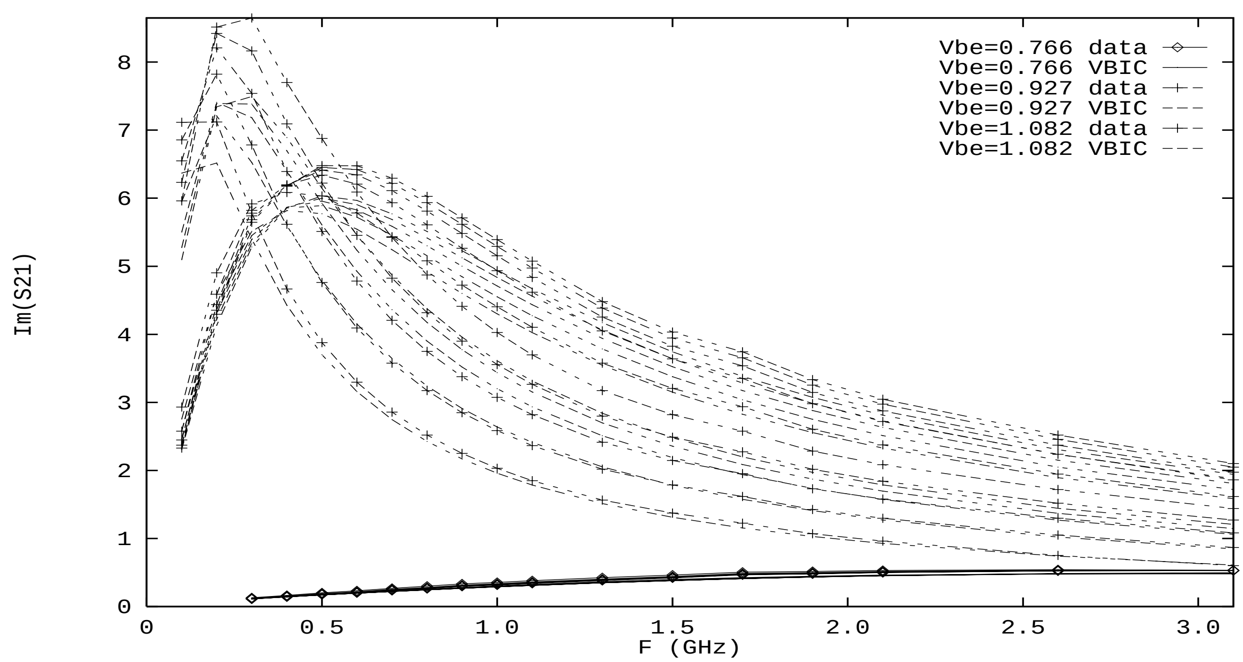
VBIC s12 Modeling



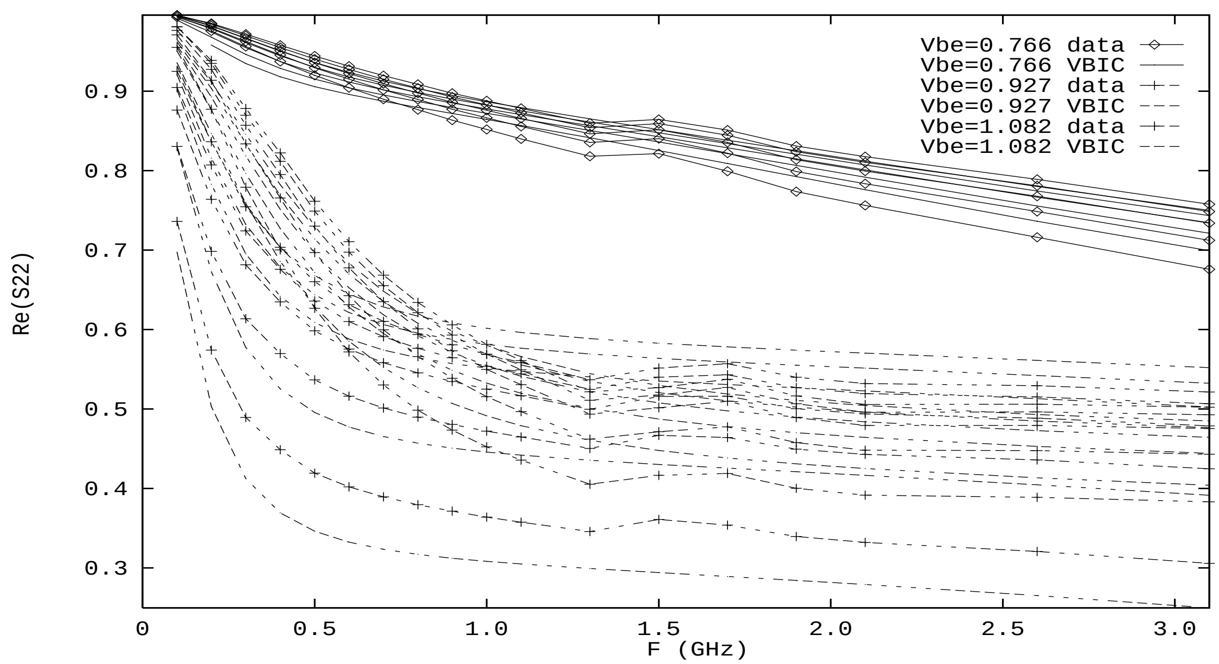


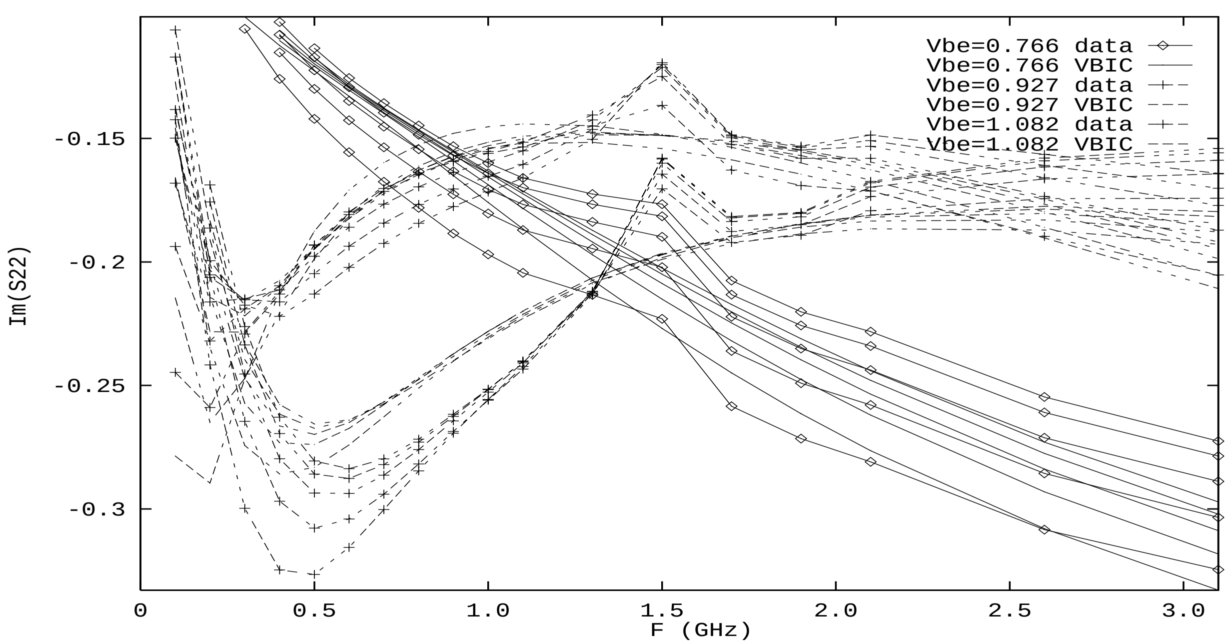
VBIC s21 Modeling





VBIC s22 Modeling





- **s-parameter fits have been done to SGP and VBIC**
  - to the same data
  - in the same optimization tool
- **comparison of RMS errors over bias and frequency**

s-parameter	SGP RMS % error	VBIC RMS % error
$Re(s_{11})$	99.9	7.0
$Im(s_{11})$	65.2	6.2
$Re(s_{12})$	112.6	12.0
$Im(s_{12})$	34.6	6.9
$Re(s_{21})$	209.6	14.3
$Im(s_{21})$	81.6	8.3
$Re(s_{22})$	31.3	8.5
$Im(s_{22})$	63.8	8.5