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Improved Noise Models for High-Speed SiGe HBT RF Circuit Design

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SRC Task 1133.001 (2003-2006)

Task Overview

- **Task Description**
- **Task Objectives / Deliverables**
- **Task Leader**
- **Students with Grad Date**
- **Industrial Liaisons**
- **Past year accomplishments**
  - **New extraction based model**
  - **Scalability modeling**

Task Objectives

- Development of more accurate RF noise models for SiGe RFIC design
  - Methodologies of RF noise source extraction
  - Evaluation of existing models
  - New model and parameter extraction development
  - Model verification on 50 / 120 / 200 GHz HBTs for SRC member companies
- Tools for application of new model in circuit design
  - Matlab codes for model parameter extraction
  - Verilog-A based models (VBIC based) for application of the new model in circuit design

Personnel

- PI and Co-PI
  - Guofu Niu (Auburn) and John Cressler (Georgia Tech)
- Students
  - Kejun Xia (Auburn, PhD, to graduate Fall 2005, presenter)
  - Qingqing Liang (Georgia Tech, PhD, graduated Spring 2005, now at IBM)
- Industrial Liaisons
  - David Sheridan (IBM)
  - Shaikh F. Shams and Hernan A. Rueda (Freescale)

Industry Interaction and Knowledge Transfer

- Extensive collaboration and transfer of research result to IBM and Freescale
  - New model
  - Parameter extraction methods
- The PI visited Freescale in Dec 2004
  - Presentation of results
  - Transfer and demonstration of noise extraction and modeling matlab codes
- Numerous interactions with IBM Modeling group
- Student internship
  - Summer 2004 at IBM, Burlington – with Scott Parker

Past Year Accomplishments

- Noise source extraction / parameter extraction methods
- Major models evaluated
- Connections between different models established
- A new expression for noise crowding effect derived
- Noise crowding effect quantified experimentally
- A new model for all noise sources is developed
  - Explicit modeling of frequency dependence through w or w^2
  - Explicit modeling of current dependence through gm
  - Scalable over multiple geometries
  - Extensive verification using measured and simulated data on 50 GHz HBTs
  - Initial investigation on 200 GHz HBTs

Publications

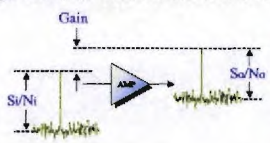
- G.F. Niu, K. Xia, D. Sheridan and S. Sweeney, "RF Noise Modeling in SiGe HBTs," *International Conference on Noise and Fluctuations (ICNF), Spain*, 2005 (Invited talk).
- G.F. Niu, "Noise in SiGe HBT RF Technology: Physics, Modeling and Circuit Implications," Review Paper, Special Issue of *Proceedings of the IEEE on SiGe Technology*, to appear, 2005
- G.F. Niu, K. Xia, D. Sheridan and S. Sweeney, "Physics and Modeling of RF Noise in SiGe HBTs," invited talk, *Workshop on Compact Modeling*, May 2005.
- G. F. Niu, K. Xia, D. Sheridan, D. Harame, "Experimental Extraction and Model Evaluation of Base and Collector Current RF Noise in SiGe HBTs ," *Tech. Digest of IEEE Radio Frequency Integrated Circuits Symposium (RFIC)*, pp. 615-618, June 2004.
- K. Xia and G.F. Niu, "Ratio based small signal parameter extraction of SiGe HBTs," *Proc. IEEE BCTM*, pp. 144--147, Sep. 2004.
- G.F. Niu, "Bridging the Gap Between Microscopic and Macroscopic Theories of Noise in Bipolar Junction Transistors," *IEEE Topical Meeting on Si Monolithic Integrated Circuits in RF Systems*, pp. 227 – 230, 2004.

Publication cont.

- K. Xia, G. Niu, D. Sheridan and S. Sweeney, ``Frequency and bias dependent modeling of correlated base and collector current RF noise in SiGe BTs", under review, *IEEE Trans. Electrons Devices*.
- K.Xia, G. Niu, D. Sheridan and S. Sweeney, ``Input non-quasi Static effect in SiGe HBTs and its impact on Noise Modeling", accepted, *IEEE BCTM* 2005.

Noise Figure: Definition and Importance

- Noise Figure (NF) = (Si/Ni)/(So/No) > 1 as amplifier adds noise
- NF determines Minimum Detectable Signal and hence sensitivity of a wireless system
- Cost and density of base station infrastructure are directly determined by receiver noise figure
- 1dB degradation in Noise Figure is a big deal – for cell phones, it means 26% more additional base stations

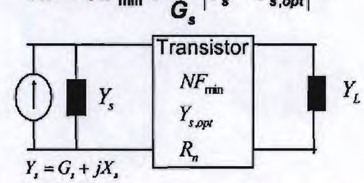


Minimization of noise through bandgap engineering as well as accurate modeling of noise are important!

Noise Parameters That Determining Noise Figure (NF)

- NF determined by transistor noise parameters and source
- NF => NFmin when Ys = Ys,opt (noise matching)
- Rn determines sensitivity to deviation from Ys,opt

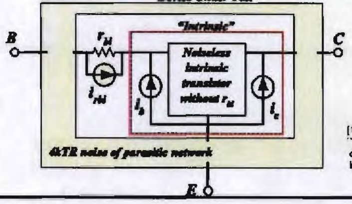
$$NF = NF_{\min} + \frac{R_n}{G_s}\left|Y_s - Y_{s,opt}\right|^2$$



What fundamentally determines transistor noise parameters?

Noise Sources In Transistor And Expected Modeling Improvement

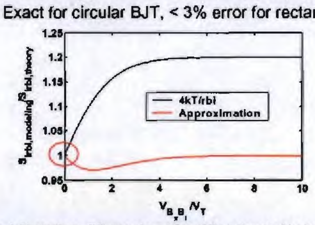
- 4kTR thermal noise for Rbx, Rcx and Re - well understood
- Thermal-like noise for intrinsic base resistance rbi
  - Crowding effect, quantification needed
- 2qI shot-like noise (white) for base and collector current
  - Experimental extraction of ib and ic noise clearly needed!
  - Our extraction has shown strong frequency dependence of IB noise, and strong correlation between IB and IC noises.



[1] K. Xia, G. Niu, D. Sheridan and S. Sweeney ``Frequency and bias dependent modeling of correlated base and collector current RF noise in SiGe HBTs," to be published.

Intrinsic Base Resistance Noise With Crowding Effect

- Theoretical results is given by J. C. J. Paasschen in [2]
  - Expressed with two parameter Vbxbi and Rbv.
  - Generally Vbxbi = several Vt (=kT/q), difficult to extract
- Newly proposed approximation $S_{irbi} = 4kT/r_{bi} - 2qI_B/3$ [1]
  - Based on [2], more convenient when using small signal ckt
  - Exact for circular BJT, < 3% error for rectangular BJT



[2] J. C. J. Paasschens, ``Compact modeling of the noise of a bipolar transistor under DC and AC current crowding conditions," IEEE Trans. Electron Devices, Vol. 51, No. 9, pp. 1483-1495, 2004.

How Crowding Effect affects SiGe Intrinsic Base Resistance Noise ?

- Sirbi=4kT/rbi-2qI_B/3
- Crowding effect on noise is negligible in SiGe HBTs
  - Because of the heavily dope base
    - Small base resistance rbi
    - Small base current I_B

Emitter geometry (μm^2)	r_{bx} (Ω)	r_{bi} at peak f_T (Ω)	$\frac{2qI_B/3}{4kT/r_{bi}}$ at peak f_T (%)
0.24 × 20 × 2	2.70	2.68	0.25
0.24 × 10 × 2	3.70	5.75	0.33
0.24 × 20 × 1	11.5	10.5	0.49
0.48 × 10 × 1	13.0	21.1	1.03

For most cases Less than 1% !

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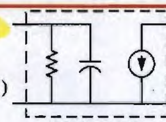
Summary of Important Noise Models

- van Vliet Model

$$S_{ibib^*} = 4kT\Re(Y_{11}) - 2qI_B$$
$$S_{icic^*} = 2qI_C$$
$$S_{icib^*} = 2kT(Y_{21} + Y_{12}^* - g_m)$$



Re(Y11)=gbe=Ic/Vt
QS, Frequency independent !

- Transport Noise Model

$$S_{ibib^*} = 2qI_B + 4qI_C[1 - \Re(e^{j\omega\tau_n})]$$
$$S_{icic^*} = 2qI_C$$
$$S_{icib^*} = 2qI_C(e^{j\omega\tau_n} - 1)$$

- SPICE Model

$$S_{ibib^*} = 2qI_B$$
$$S_{icic^*} = 2qI_C$$
$$S_{icib^*} = 0$$

- Semi-empirical Model. *Sib* modeling is demonstrated here.

Frequency and bias dependent modeling of correlated base and collector current RF noise in SiGe HBTs. K.J. Xia, G. F. Niu, D. Sheridan and S. Sweeney, To be published.

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New Semi-empirical Extraction Based Intrinsic Noise Model

- Pros:
  - Using conventional models without input NQS effect
  - Infrastructure of conventional models can be used
- Cons:
  - Resulting noise currents may not be completely physical
  - Involve several additional parameters dedicated to noise modeling
- Technical approach:
  - Small signal parameter extraction to obtain accurate and physically meaningful values
  - Intrinsic noise sources extraction using de-embedding of all circuit elements step by step using standard noise circuit analysis theory (Hillbrand and Russer)
  - Intrinsic noise sources modeling
  - Geometry scaling examination

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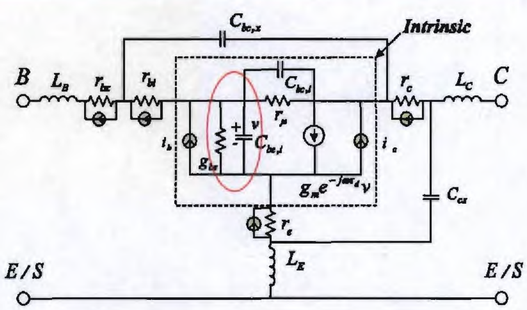
Small Signal CKT – No Input NQS



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Devices and Parameter Extraction

- 50 GHz peak fT SiGe HBTs with different geometries are used to develop noise model and examine noise scaling
  - 0.24x20x2 um^2 (reference device)
  - 0.24x10x2 um^2 (emitter length scaling)
  - 0.24x20x1 um^2 (finger number scaling)
  - 0.48x10x1 um^2 (emitter width scaling)
- SiGe HBT noise simulations are used to provide guidance to model equation development
- Excellent Y-parameters fitting is obtained
  - For all devices
  - Parameters are well consistent with geometry scaling

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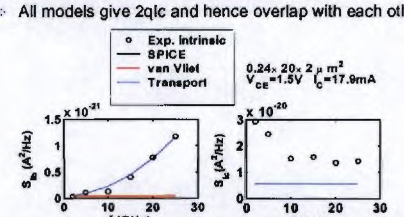
Intrinsic Sib and Sic Extracted

- Extracted Sib > 2qIb and strongly frequency dependent
  - The van Vliet model Sib=2qIb, the same as the SPICE model, when the input NQS effect is not modeled.
  - The transport noise model Sib is fitted to the extraction result with parameter τ_n.
- Extracted Sic > 2qIc and frequency dependent
  - All models give 2qIc and hence overlap with each other.



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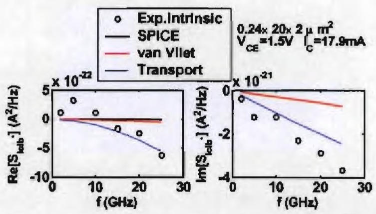
Intrinsic Sicib* Extracted

- Extracted Sicib* is significant and frequency dependent
  - SPICE model, Sicib*=0
  - van Vliet model, much underestimate the value
  - Transport model, Sicib* improves the frequency dependence a lot. However, its Im(Sicib) is not well modeled, as τ_n has been used to fit Sib only.



Modeling Strategy Using Extraction

- For each of Sib, Sic, Im(Sicib*) and Re(Sicib*)
  - Examine the frequency dependence through ω
  - Examine the bias dependence of coefficients through gm
  - Develop new equations guided by
    - noise physics
    - insight from noise simulation
    - Analysis of transport and van Vliet (with input NQS) models
- Normalized correlation c
  - Schwartz inequality
  - How much is c for SiGe HBTs examined ?
- Geometry scaling
  - Rule derivation
  - Verification

Sib and "induced" base current noise

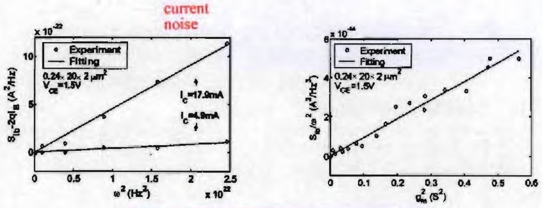
Frequency dependence:

$$S_{ib} = 2qI_B + C_{ib}\omega^2$$

induced base current noise

Bias dependence:

$$C_{ib} = K_{bb} \cdot g_m^2$$

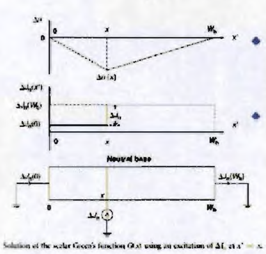


$$\boxed{S_{ib} = 2qI_B + K_{bb} \cdot g_m^2 \omega^2}$$

Understanding "Induced" Base Current Noise

- I = dQ/dt

$$\frac{d}{dt} \xrightarrow{frequency\_domain} j\omega \xrightarrow{PSD} \omega^2$$



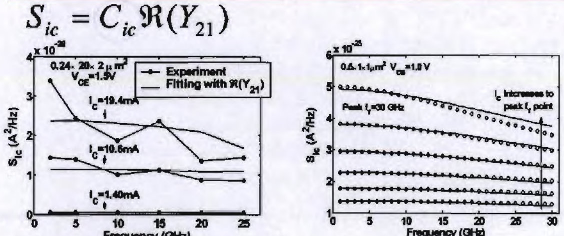
- Freq dependence is consistent with van Vliet model and transport model
- Bias dependence different

$$S_{ib}^{van} \approx 2qI_B + 4kTC_{bei}^2 r_d \omega^2$$

$$S_{ib}^{tran} \approx 2qI_B + 2qI_C \tau_n^2 \omega^2$$

Frequency Dependence of Sic

$$S_{ic} = C_{ic} \Re(Y_{21})$$



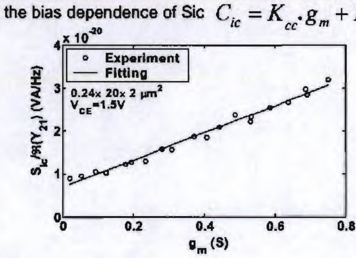
Experimental data

Less accuracy of Sic extraction at low frequencies, system noise plays a bigger role

Simulation data

Sic – Collector Current Noise

- Firstly, the bias dependence of Sic $C_{ic} = K_{cc} \cdot g_m + B_{cc}$.



- Therefore

$$\boxed{S_{ic} = (K_{cc} \cdot g_m + B_{cc}) \Re(Y_{21})}$$

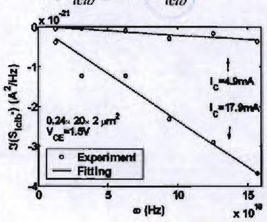
Im(Sicib*) – Imaginary Correlation

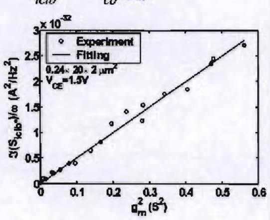
Frequency dependence:

$$\Im(S_{icib^*}) = -C^i_{icib^*}\omega$$

Bias dependence:

$$C^i_{icib^*} = K^i_{cb}g_m^2$$





$$\boxed{\Im(S_{icib^*}) = -K^i_{cb}g_m^2\omega}$$

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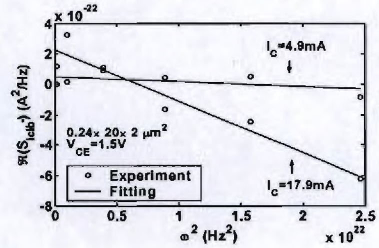
Frequency dependence of Re(Sicib*)

$$\Re(S_{icib^*}) = C^{r1}_{icib^*} - C^{r2}_{icib^*}\omega^2$$



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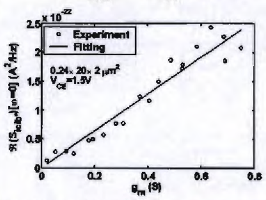
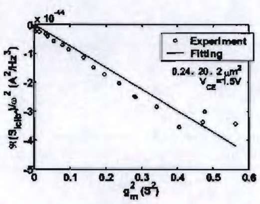
Re(Sicib*) – Real Correlation

- The bias dependence of coefficients are

$$C^{r1}_{icib^*} = K^{br}_{cb}g_m \qquad C^{r2}_{icib^*} = K^{kr}_{cb}g_m^2$$





- Therefore

$$\boxed{\Re(S_{icib^*}) = K^{br}_{cb}g_m - K^{kr}_{cb}g_m^2\omega^2}$$

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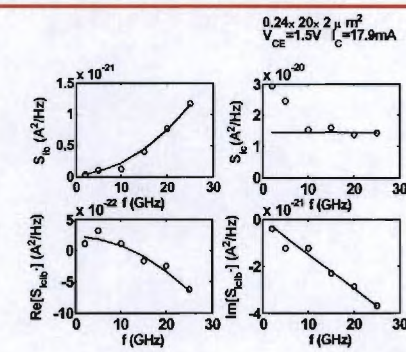
Intrinsic Noise Sources Modeling Results



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Normalized Correlation c

- By definition

$$c \equiv \frac{S_{icib^*}}{\sqrt{S_{ib}S_{ic}}}$$

- Schwartz inequality must be satisfied:

$$|c| \le 1$$

- If this is not satisfied
  - Double check Y-parameters extraction
  - Double check noise extraction

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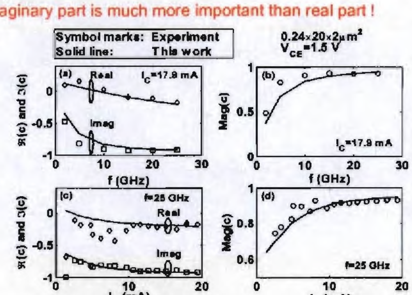
Extracted c And Modeling Results

- |c| is about 0.9 at high Ic. The correlation is important for SiGe HBTs examined
- Imaginary part is much more important than real part !



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Generalized Model Equations

- $\alpha_{bb^*} \approx 2$, $\alpha_{cc^*} \approx 1$ and $\alpha^i_{cb^*}$ is between 1 and 2
- Bbb* and Bcb* are close to zero, Bcc* is about 2KT
- Only a slight accuracy loss in Bopt by setting Re(Sicib*)=0, reduce to nine parameters
- Schwartz inequality is not satisfied automatically.

$$S_{ib} = 2qI_B + (K_{bb^*} g_m^{\alpha_{bb^*}} + B_{bb^*})\omega^2$$

$$S_{ic} = (K_{cc^*} g_m^{\alpha_{cc^*}} + B_{cc^*})\Re(Y_{21})$$

$$\Re(S_{icib^*}) = K^{br}_{cb^*} g_m - K^{kr}_{cb^*} g_m^2 \omega^2$$

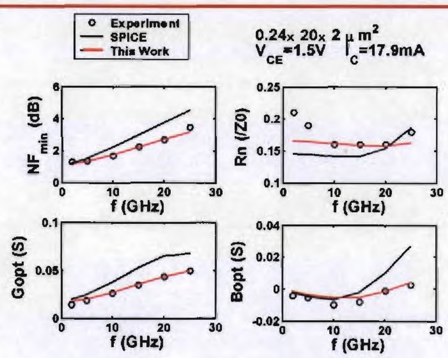
$$\Im(S_{icib^*}) = -(K^i_{cb^*} g_m^{\alpha^i_{cb^*}} + B^i_{cb^*})\omega$$

Extracted Model Parameters

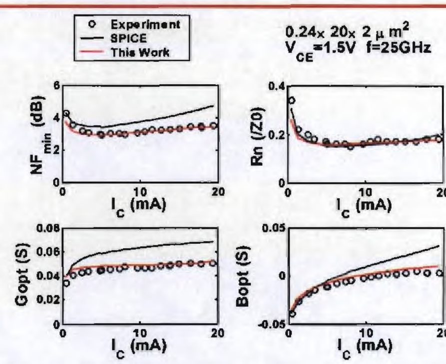
- AE=0.24x20x2 um² (the reference transistor)
- Parameters are in MKS unit

Parameter	Value	Parameter	Value
α_{bb^*}	2	K_{bb^*}	1.0245×10^{-43}
$\alpha^i_{cb^*}$	1.8	$K^i_{cb^*}$	4.6690×10^{-32}
α_{cc^*}	1	K_{cc^*}	1.6345×10^{-20}
B_{bb^*}	0	$B^i_{cb^*}$	1.0209×10^{-34}
$K^{br}_{cb^*}$	3.0369×10^{-22}	$K^{kr}_{cb^*}$	8.1213×10^{-44}
B_{cc^*}	8.2843×10^{-21}		

Noise Parameters Versus Frequency



Noise Parameters Versus I_C

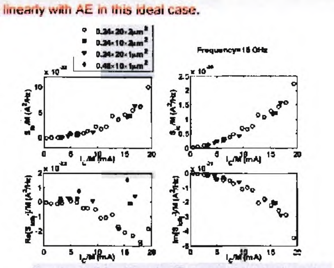


Geometry Scaling Rule For Ideal Transistor With Same Profile

- dc, ac currents and Y-parameters are proportional to emitter area AE (=WE*LE*NE) if biased at same Jc
- Ib, Ic, gm and Re(Y21) can be calculated using scaling factor M (=AE/AE0). AE0 is selected as a reference
- Sib, Sic and Sicib* also scale linearly with AE in this ideal case.

Sib, Sic and Im(Sicib) of different geometries overlap well.

Noise figures are not sensitive to Re(Sicib), thus difficult to extract



X-axis: Ic/M Y-axis: Extracted intrinsic noise

Geometry Scaling Rule Derived

- Sib, Sic and Sicib* scale linearly with AE
- M=AE/AE0
- K parameters with subscript 0 is the model parameters of the reference transistor

$$K_{bb^*} = K_{bb^*0} M^{1-\alpha_{bb^*}} \qquad B_{bb^*} = B_{bb^*0} M$$

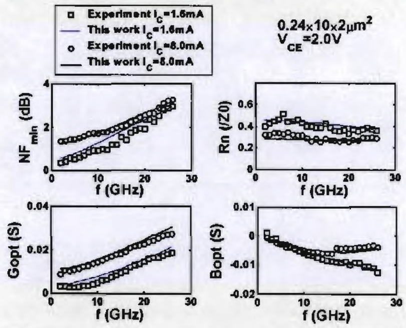
$$K_{cc^*} = K_{cc^*0} M^{-\alpha_{cc^*}} \qquad B_{cc^*} = B_{cc^*0}$$

$$K^{br}_{cb^*} = K^{br}_{cb^*0} \qquad K^{kr}_{cb^*} = K^{kr}_{cb^*0} / M$$

$$K^i_{cb^*} = K^i_{cb^*0} M^{1-\alpha^i_{cb^*}} \qquad B^i_{cb^*} = B^i_{cb^*} M$$

Emitter Length (LE) Scaling

- AE=0.24x10x2 um² (AE0=0.24x20x2 um²)



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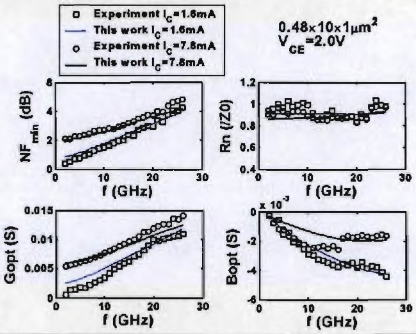
Emitter Width (WE) Scaling

- AE=0.48x10x1 um² (AE0=0.24x20x2 um²)



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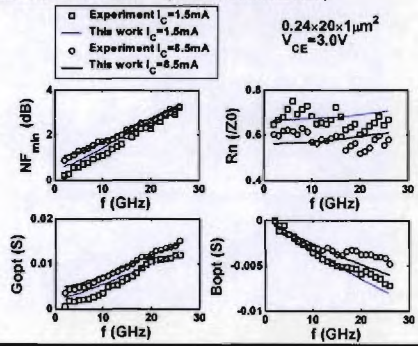
Emitter Finger Number (NE) Scaling

- AE=0.24x20x1 um² (AE0=0.24x20x2 um²)



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Next Year Plan

- Extensive model verification on 200 GHz HBTs
- Develop more efficient parameter extraction
- Develop a simpler model with fewer parameters if at all possible
- New noise test structures for improved measurement accuracy
- Implement the proposed model in our matlab code
- Explore implementation using verilog-A

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Summary of Results

- SiGe HBT noise sources extracted experimentally
- Alternative models evaluated
- Connections between various models established
- New expression obtained for base noise crowding effect
- Noise crowding effect quantified for the first time
- A new noise model has been developed
  - Explicit frequency dependence for Sib, and Sicib*
  - Explicit bias dependence for all through gm
  - Scalable over emitter width, length, and number of fingers
- The new model has been verified on 50/60 GHz HBTs
  - From 2-25 GHz over a wide biasing range beyond peak fT
  - Scalability verified for width, length and finger number

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