Correlated Noise Modeling - An Implementation into HICUM

A. Chakravorty, M. Schroter, P. Sakalas, J. Herricht

Chair for Electron Devices and Integrated Circuits (CEDIC)
University of Technology Dresden Germany

Dept. of Electrical and Computer Engin.
University of California at San Diego
USA

chakravo@iee.et.tu-dresden.de, mschroter@ieee.org

http://www.iee.et.tu-dresden.de/iee/eb/hic_new/hic_start.html

Atmel, Heilbronn (Germany)

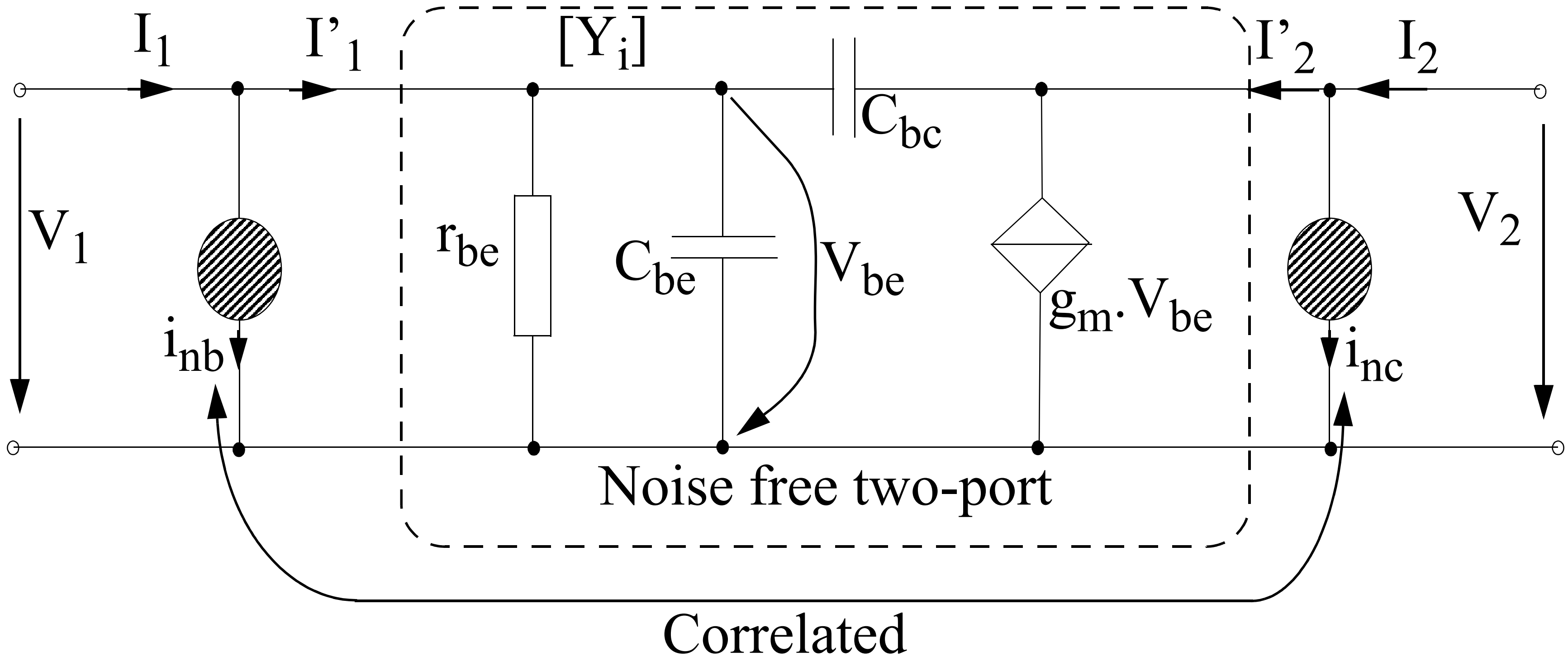
June 2006

Outline

- Correlated Noise in HBTs
- PSD matrix : problems with SPICE
- System theoretical solution
- Implementation challenges
- Implementation into HICUM
- Results

Correlated Noise in HBTs

- Presently in HICUM: thermal noise, shot noise, flicker noise
- Base and collector shot noise sources are actually correlated



PSD matrix: problems with SPICE

- Output noise power spectral density

$$S_{YY}(j\varpi) = G(j\varpi).S_{XX}(j\varpi).G^{+}(j\varpi)$$

  - $S_{xx}(jw)$: input noise power spectral density
  - $G(jw)$: transfer function matrix, $G^{+}(jw)$: complex conjugate of $G(jw)$

$$S_{XX}(j\varpi) = \begin{bmatrix} S_{i_{nb}} & S_{i_{nb}i_{nc}} \\ S_{i_{nc}i_{nb}} & S_{i_{nc}} \end{bmatrix}$$

- Cross-correlated terms
  - Off-diagonal elements
  - not handled by SPICE simulators
  - crucial from operating frequencies around and above $f_{Tpeak}/10$

System theoretical solution

- Manipulate input noise PSD matrix

$$S_{XX}(j\varpi) = T(j\varpi).S_{\bar{X}}^{N}(j\varpi).T^{+}(j\varpi) \qquad S_{\bar{X}}^{N}(j\varpi) = \begin{bmatrix} S_{\bar{i}_{nb}}^{N} & 0 \\ 0 & S_{\bar{i}_{nc}}^{N} \end{bmatrix} \qquad T(j\varpi) = \begin{bmatrix} 1 & 0 \\ t_{21} & 1 \end{bmatrix}$$

$$S_{YY}(j\varpi) = G(j\varpi).T(j\varpi).S_{\bar{X}}^{N}(j\varpi).T^{+}(j\varpi)G^{+}(j\varpi)$$

  - Cross-correlated terms inside the transfer function

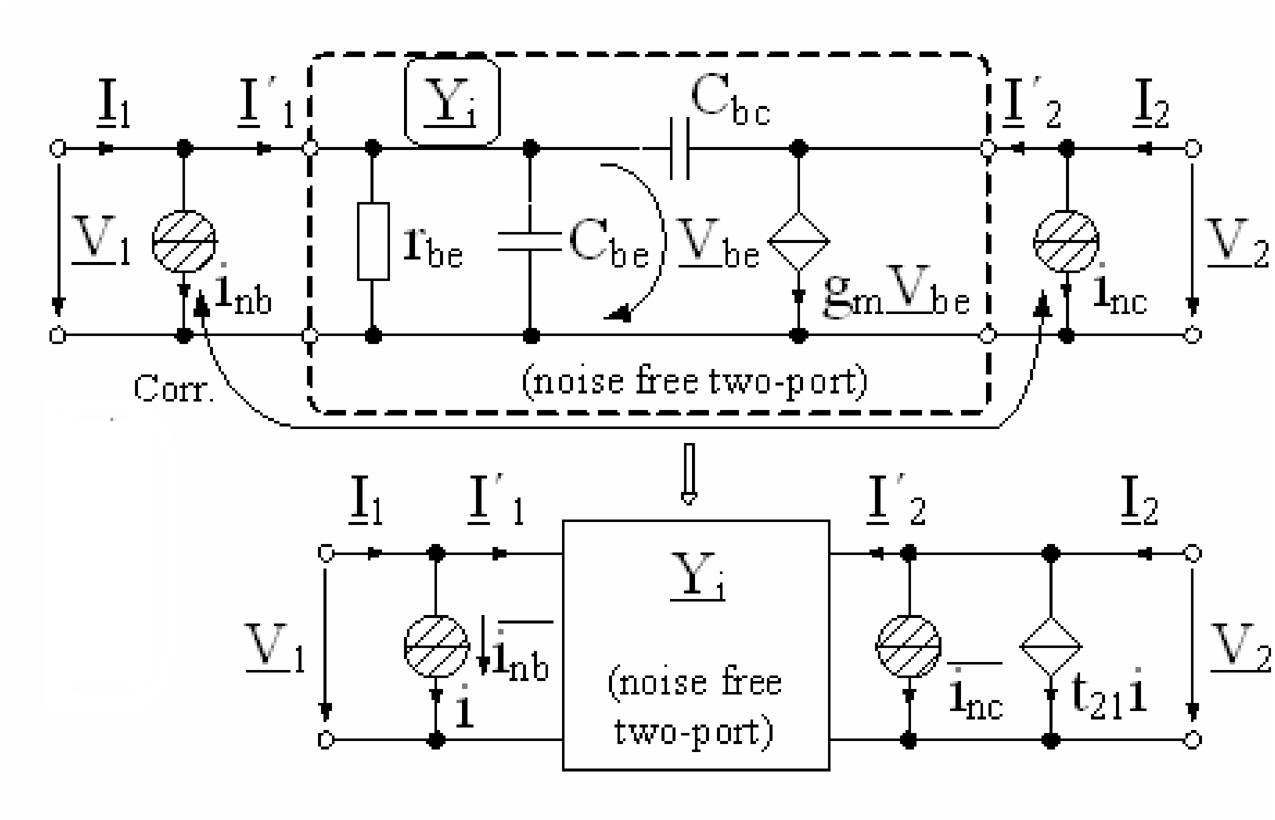
- From matrix element comparison

$$S_{\bar{i}_{nb}}^{N} = S_{i_{nb}} \qquad S_{\bar{i}_{nc}}^{N} = S_{i_{nc}} - S_{i_{nb}} \left| t_{21} \right|^{2}$$

and

$$t_{21} = \frac{S_{i_{nc} i_{nb}}}{S_{i_{nb}}} = \frac{-2qI_{C}(j\varpi\tau_{B}/3)}{2qI_{B}} = -j\varpi\frac{\tau_{B}}{3}\frac{I_{C}}{I_{B}}$$

System theoretical solution (cont'd)



- Original noise PSD matrix: two correlated noise sources
- After manipulation: three uncorrelated noise sources with different PSDs

Implementation challenges

- Problem at first look
  - frequency dependent PSD at output

$$S_{\bar{i}_{nc}}^{N} = S_{i_{nc}}\left(1-\beta_{dc}\left(\frac{\varpi\tau_B}{3}\right)^2\right) \qquad S_{\bar{i}_{new}}^{N} = \left|\varpi\frac{\tau_B}{3}\beta_{dc}\right|^2 S_{i_{nb}}$$

- solution
  - time derivative of noise source: operator *"ddt( )"* produces *"jw*" in frequency domain
- Further problem
  - negative sign inside PSD
  - impossible by simple addition/subtraction of noise sources
  - addition/subtraction of noise PSD not possible
  - multiplication of noise sources not permitted in SPICE

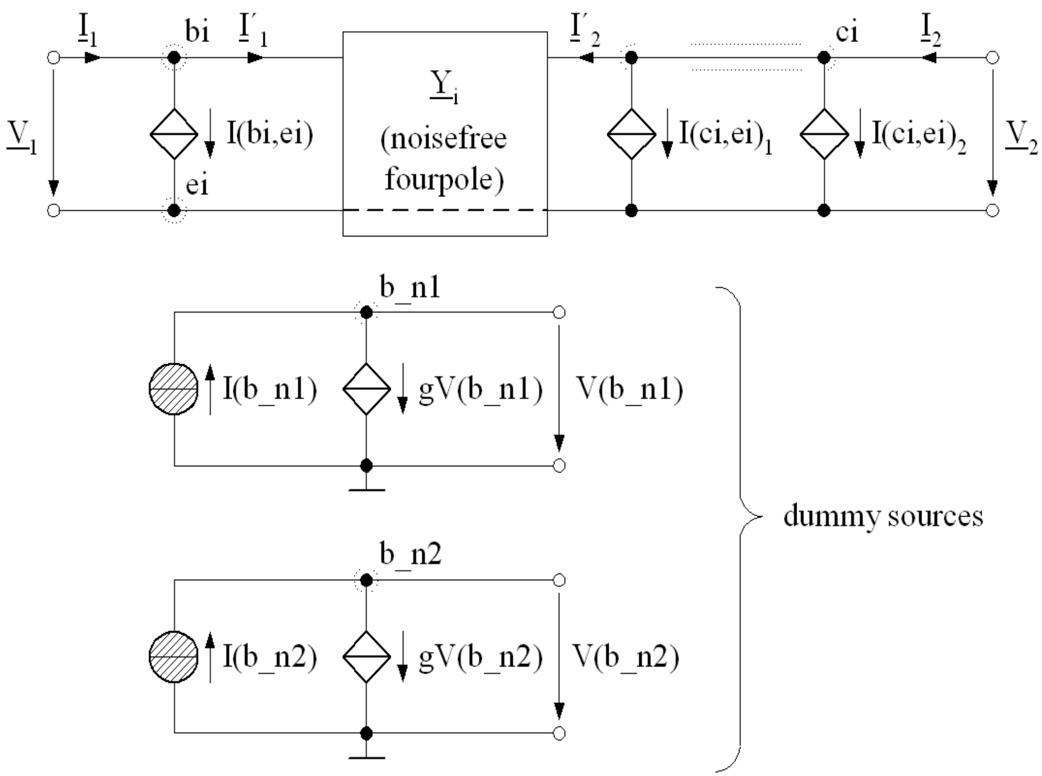
Implementation into HICUM

- One source at input side: same as before
- Two sources at output side
  - one requires derivative w.r.t. time of the input noise source
  - for the remaining one, following PSD proposed

$$S^N_{\bar{i}_{nc}} = S_{i_{nc}}\left(1-\frac{\beta_{dc}}{2}\left(\frac{\varpi\tau_B}{3}\right)^2\right)^2 = S_{i_{nc}}\left(1-\beta_{dc}\left(\frac{\varpi\tau_B}{3}\right)^2+\left(\frac{\beta_{dc}}{2}\left(\frac{\varpi\tau_B}{3}\right)^2\right)^2\right)$$

- Last term reflects the error
  - for this PSD, accurate upto $f_{Tpeak}/3$
  - combining all PSDs, accurate upto f_{Tpeak}
  - very small in all practical purposes

Implementation into HICUM (cont'd)



- Time derivative: capacitive
- Total transit time used
- Incorporated into HICUM
- simulated with ADS 2004A
- Tested against 150GHz HBT

- Source 1:

$$I(bi,ei) = g.V(b\_n1)$$

$$V(b\_n1) = \frac{1}{g}\sqrt{2qI_B}$$

- Source 3:

$$I(ci,ei)_2 = \beta_f k \tau_f \frac{d}{dt}\left(-g.V(b\_n1)\right)$$

- Source 2:

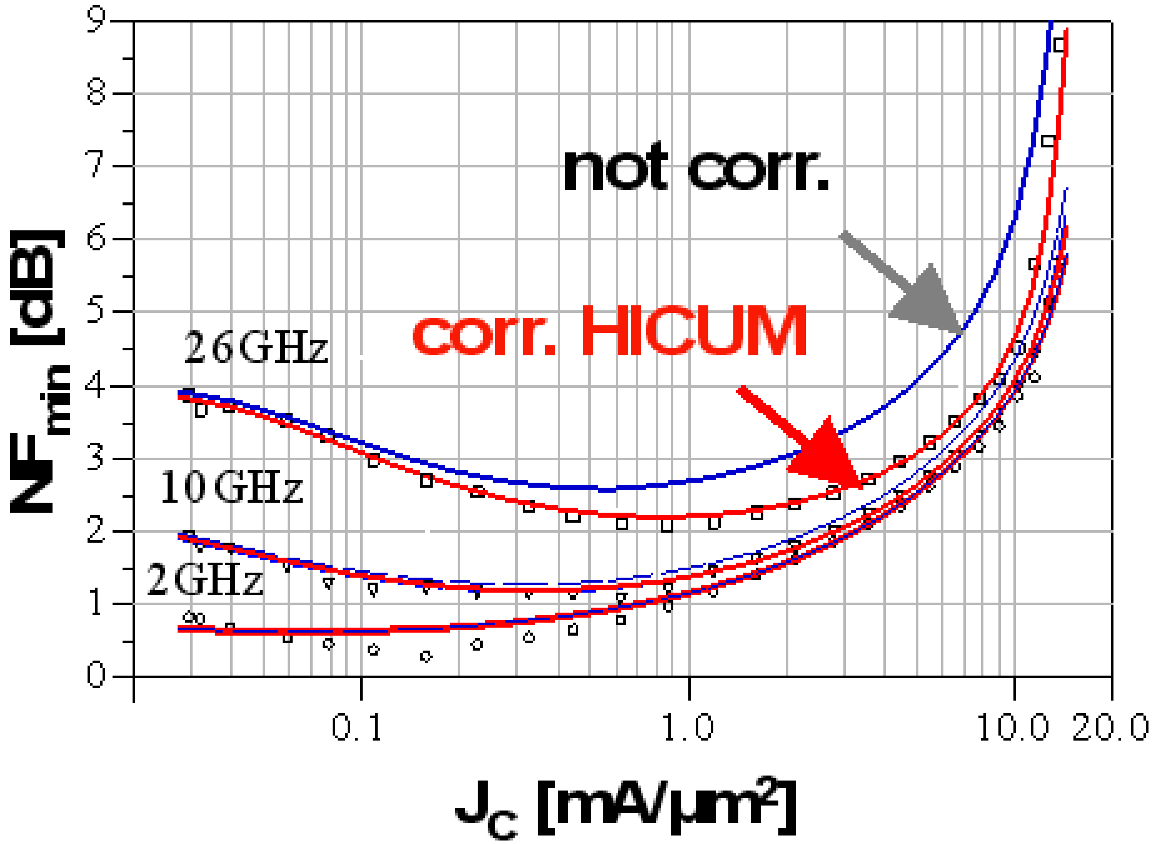
$$I(ci,ei)_1 = g.V(b\_n2) + \frac{\beta_f}{2}\left(k\tau_f\right)^2 \frac{d^2}{dt^2}\left(g.V(b\_n2)\right) \quad V(b\_n2) = \frac{1}{g}\sqrt{2qI_C}\ ,$$

g : 1 Siemens

Results

$T=300K, A_E=(0.2*10.16)\mu m^2, V_{CE}=1.5V$

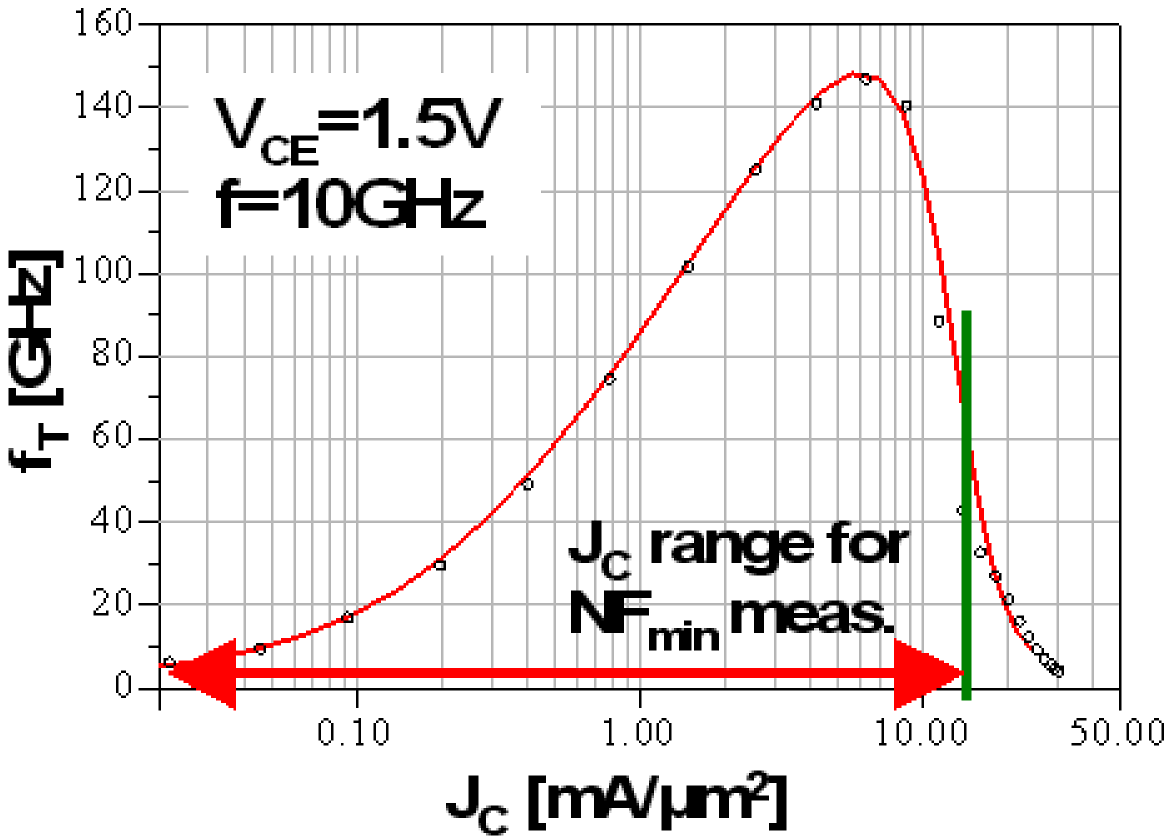
measurement: symbols,   simulation: lines



Results (cont'd)

T=300K,A_E=(0.2∗10.16)μm^2

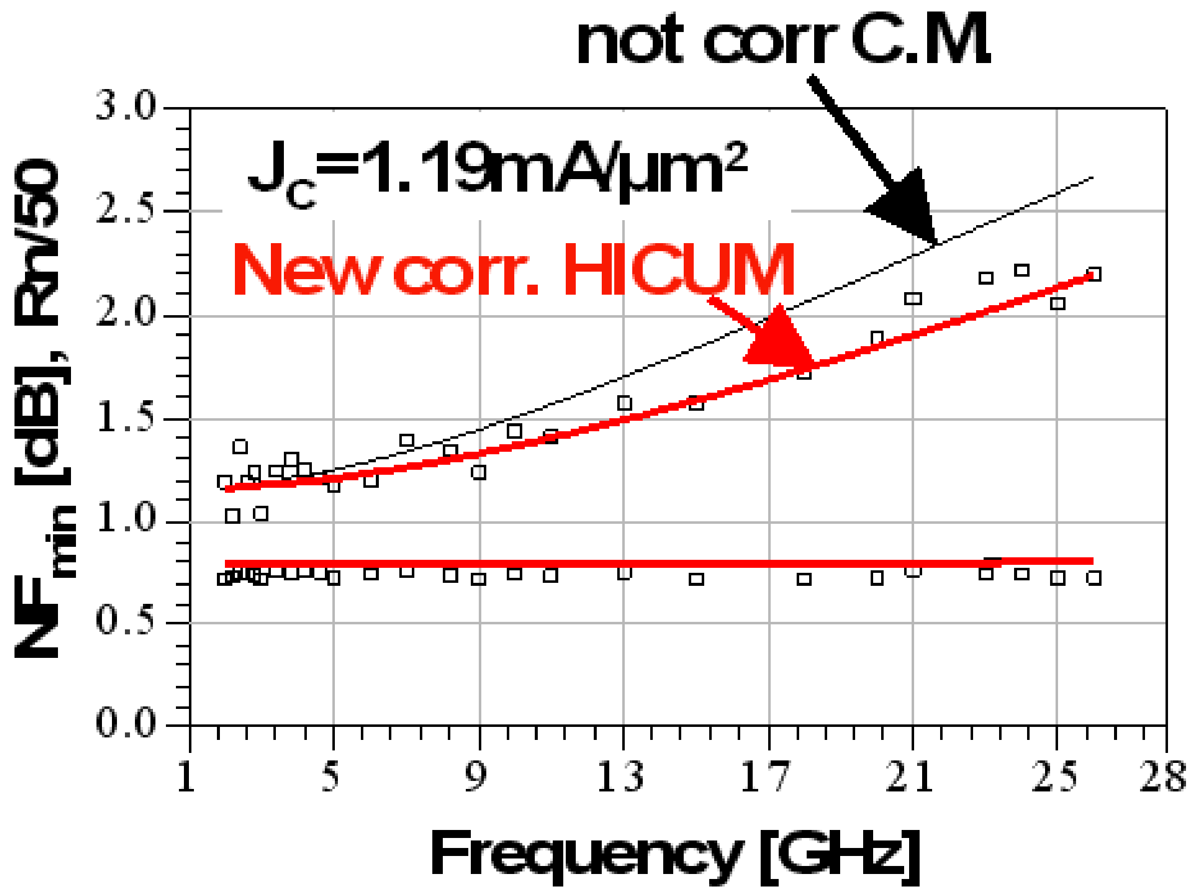
measurement: symbols, simulation: lines



Results (cont'd)

T=300K,A_E=(0.2∗10.16)μm^2,V_{CE}=1.5V,J_C=2.74mA/μm^2

measurement: symbols, simulation: lines



Conclusions

- Relevance of modeling noise correlation in modern HBTs discussed
- SPEICE-specific implementation problems pointed out
- A system theoretical solution proposed
- Corresponding Verilog-A implementation challenges discussed
- Implemented in HICUM and verified with measured data from advanced HBT (fTpeak=150 GHz) process

Acknowledgements

- Jazz Semiconductors Inc.
- C. McAndrew (Freescale Semiconductors)
- G. Coram (Analog Devices)
- M. Mierzinxki (Tiburon Inc.)
- F. Korndoerfer (IHP)
- Financial support from German Research Society (DFG)