III-V HBT modeling with HICUM

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Introduction

III-V HBT technology

- GaAs HBTs dominate PA handset market
- InP HBTs are among fastest transistors built (record for f_T, f_{max})
- InP HBTs are suitable for high-speed electronics ***and*** optoelectronics applications
- Integration of InP HBTs with silicon appears possible

... however ...

- compact models mostly based on external extensions of SGP model due to its availability in all circuit simulators (incl. special microwave simulators)
- single device parameter extraction => discrete models (vs. scalable in silicon)
  => no circuit optimization through simple device sizing
- no efficient statistical modeling possible although more needed than for silicon technologies

Important physical effects

... in III-V HBTs

- current blocking and charge storage due to conduction band spikes
- collector-base capacitance variation due to III-V electron velocity profile
- velocity overshoot and/or negative differential mobility in low-current transit time
- thermionic emission and tunneling (dep. on composition grading in BE junction)

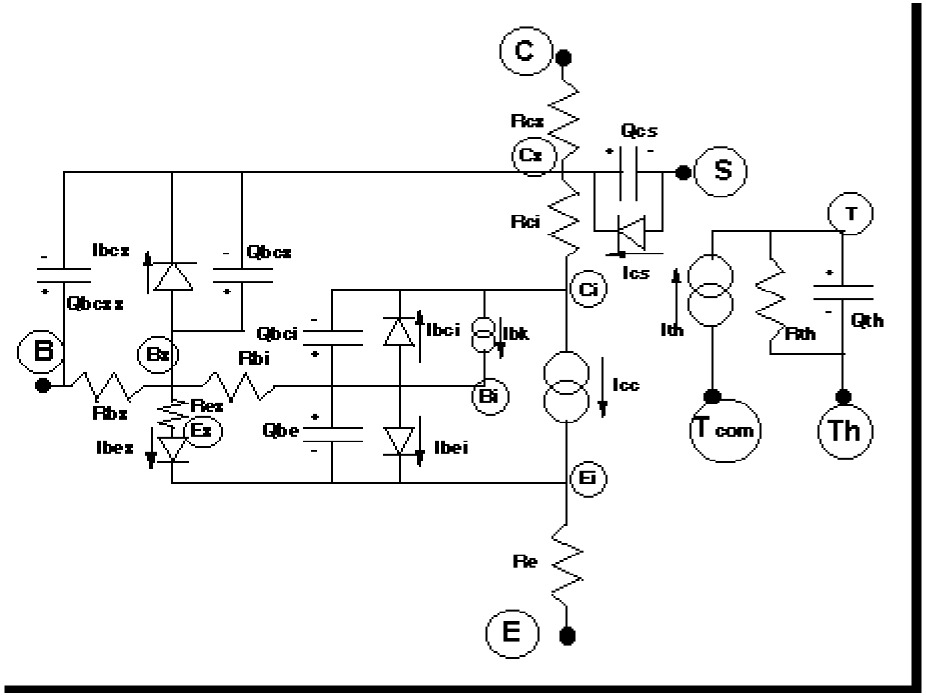
... and in advanced HBTs in general

- collector-base depletion capacitance punch-through
- self-heating
- impact ionization
- NQS effects for charge ***and*** transfer current with bias dep. NQS time constants
- bias dependent GICCR weight factors (for graded composition profiles)

=> not covered by (built-in) SGP model

Compact modeling

Typical III-V HBT example: UCSD HBT model



- http://hbt.ucsd.edu/
  - similar to Agilent AHBT model
  - self-heating
  - charge storage in heterojunction
  - BC capacitance punch-through
  - neg. diff. mobility (NDM) in τ_f and C_{BC}
- Missing Effects:
  - NQS effects
  - bias-dependent V_{ER}
  - no scaling available
  - thermionic emission, tunneling
- Issues
  - Discrepancy between small-signal and large-signal values: small-signal charge is obtained by taking τ^*I_{cf}, instead of integral over the term
  - often: III-V HBT models are used only for small-signal modeling
  - often: proprietary models
    => unavailable across simulators, non-uniform and unreliable implementation

Physical effects in compact models

physical effect	UCSD	HICUM/L2	HICUM/L0
current blocking and related charge storage in HICUM: for BC junction in GaAsSb/Inp HBT	√	-	-
current dependent BC depletion capacit.	√	-	-
velocity overshoot / negative diff. mobility	√	-	-
thermionic emission, intraband tunneling	-	-	-
BC depletion capacitance punch-through	√	√	√
self-heating	√	√	√
impact ionization	√	√	√
NQS effects	-	√	-
bias and bandgap dependent Early effect (relevant only for graded composition)	-	√	√

Goal

Extend Si-based standard model to III-V HBTs

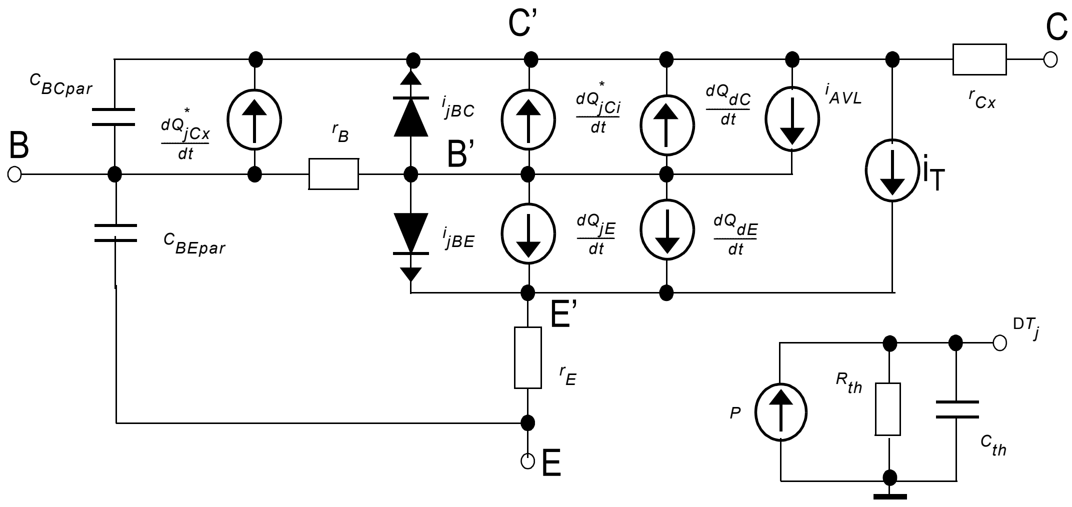
Benefits

- Unified standard model => large knowledge pool for parameter extraction methods
- available in all mainstream circuit simulators
- III-V models incapable of modeling Si
- Experience with standardized extraction schemes
- Test structure development experience

=> Establish comprehensive model suitable for all bipolar technologies

(possibly model hierarchy)

Starting point: HICUM/L0 v1.3

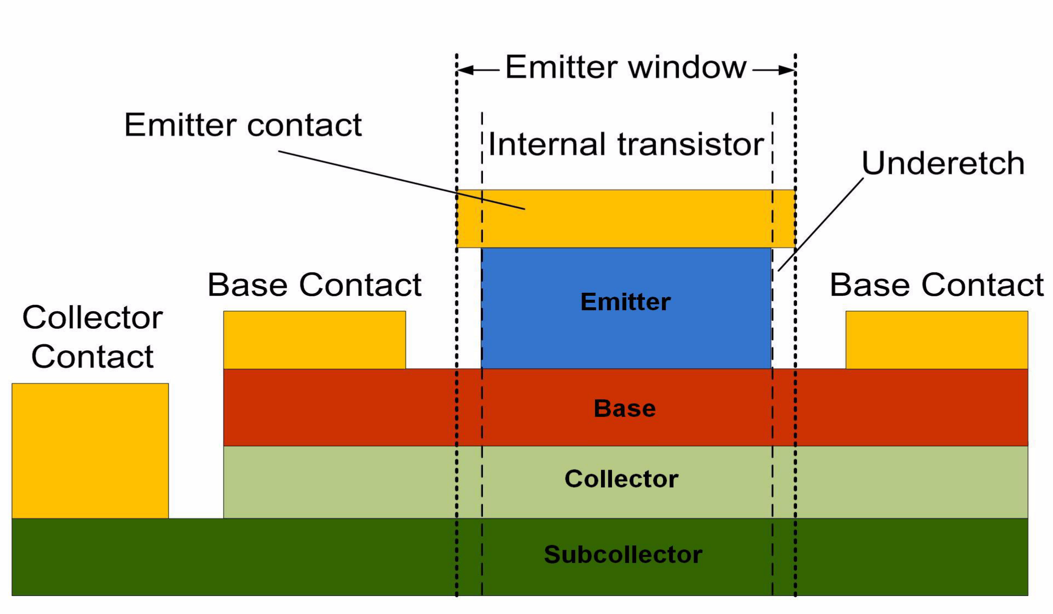


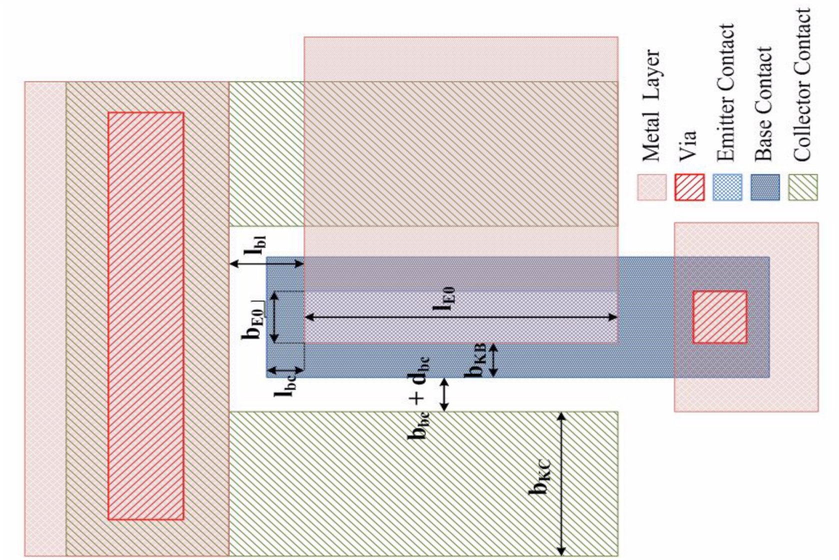
- Effects included
  - self-heating
  - BC capacitance punch-through
  - bias-dependent V_{ER}
  - impact ionization
- Missing
  - NDM-caused changes in charge and transit time
  - NQS effects
  - current blocking at BE junction, explicit BC barrier effect

- **applied to InP HBTs**
- **no special test structures available for geometry scaling**

=> single device extraction necessay

InP DHBT structure



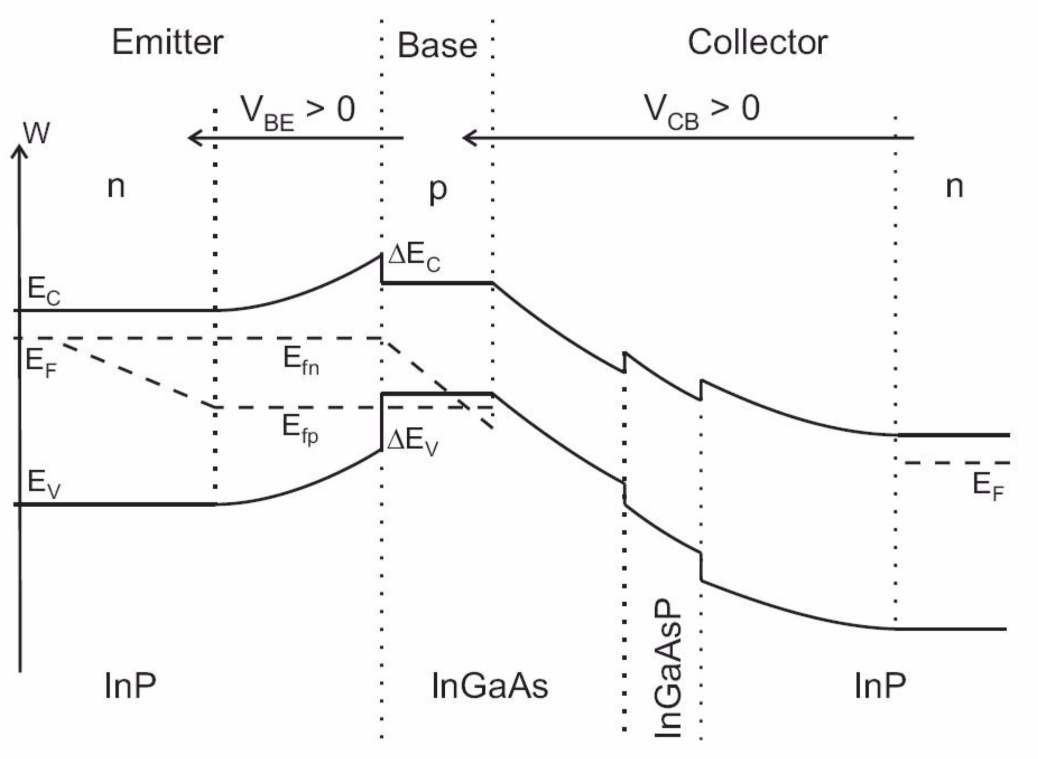


InP-InGaAs DHBT [3]			
Layer	Material	Size	Doping
Emitter	InP	40	6e17
Base	InGaAs	30	5e19
Collector	InGaAs	50	2e16
Collector	InGaAsP	20	2e16
Collector	InP	20	2e17
Collector	InP	70	2e16

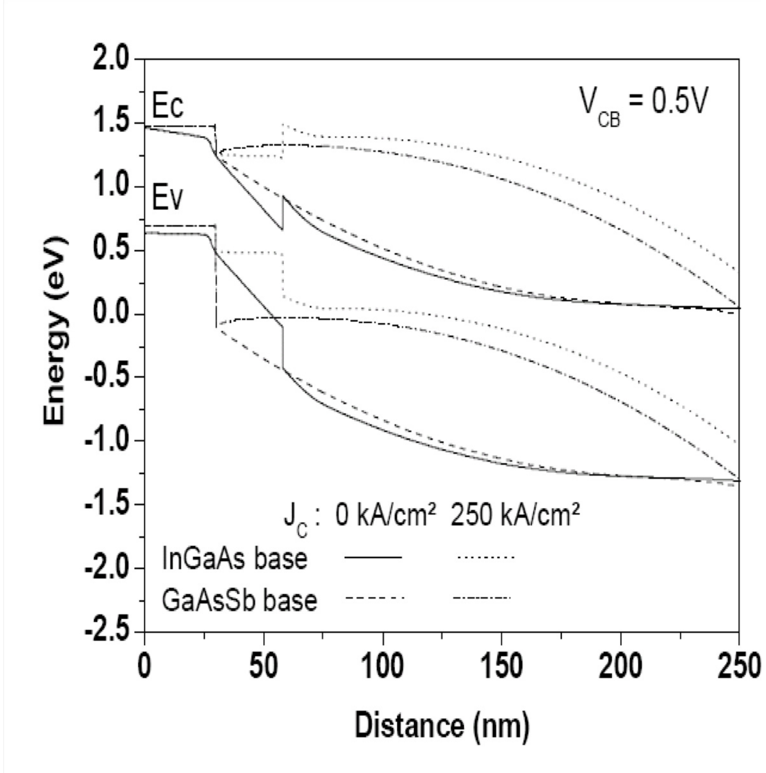
InP-GaAsSb DHBT [4]			
Layer	Material	Size	Doping
Emitter	InP	25	6e17
Emitter	GaInP	15	6e17
Base	GaAsSb	20	8e19
Collector	InP	75	2e16
Collector	InP	50	1e19

Band diagrams of DHBTs

InP-InGaAs DHBT band diagram at forward active bias (from [3])



type I vs type II BC band diagram at zero and forward bias (from [5])



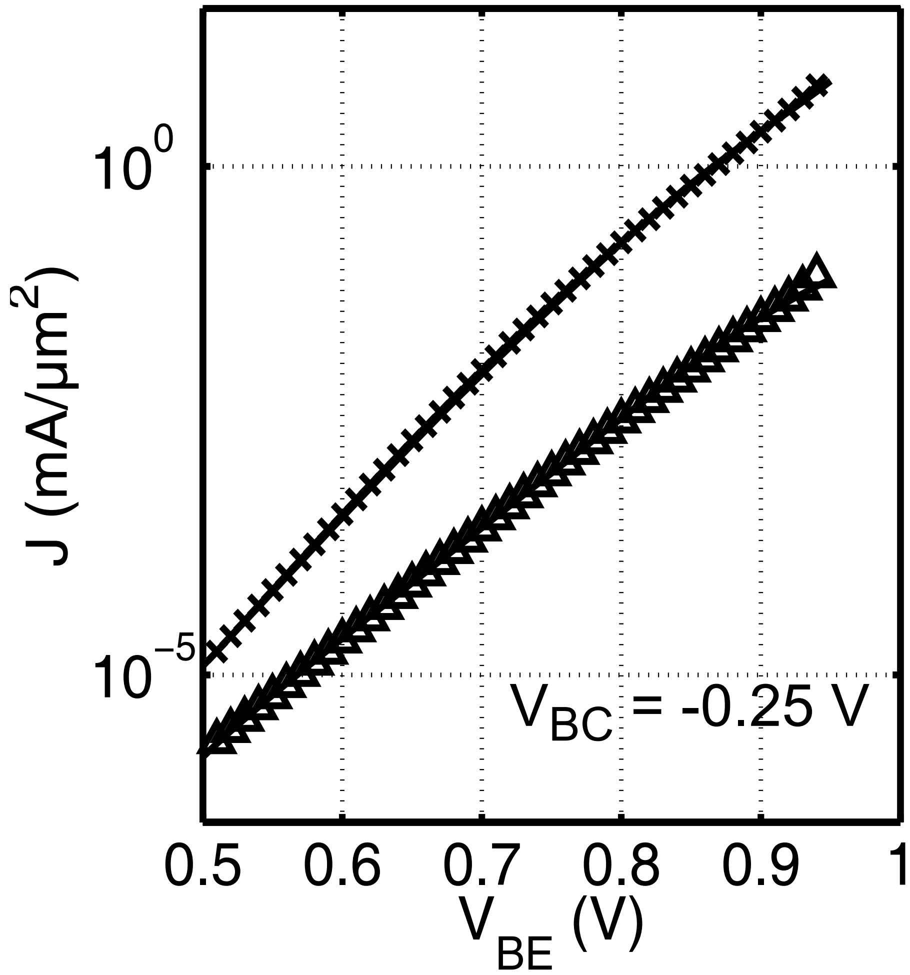
=> GaAsSb base is more attractive approach

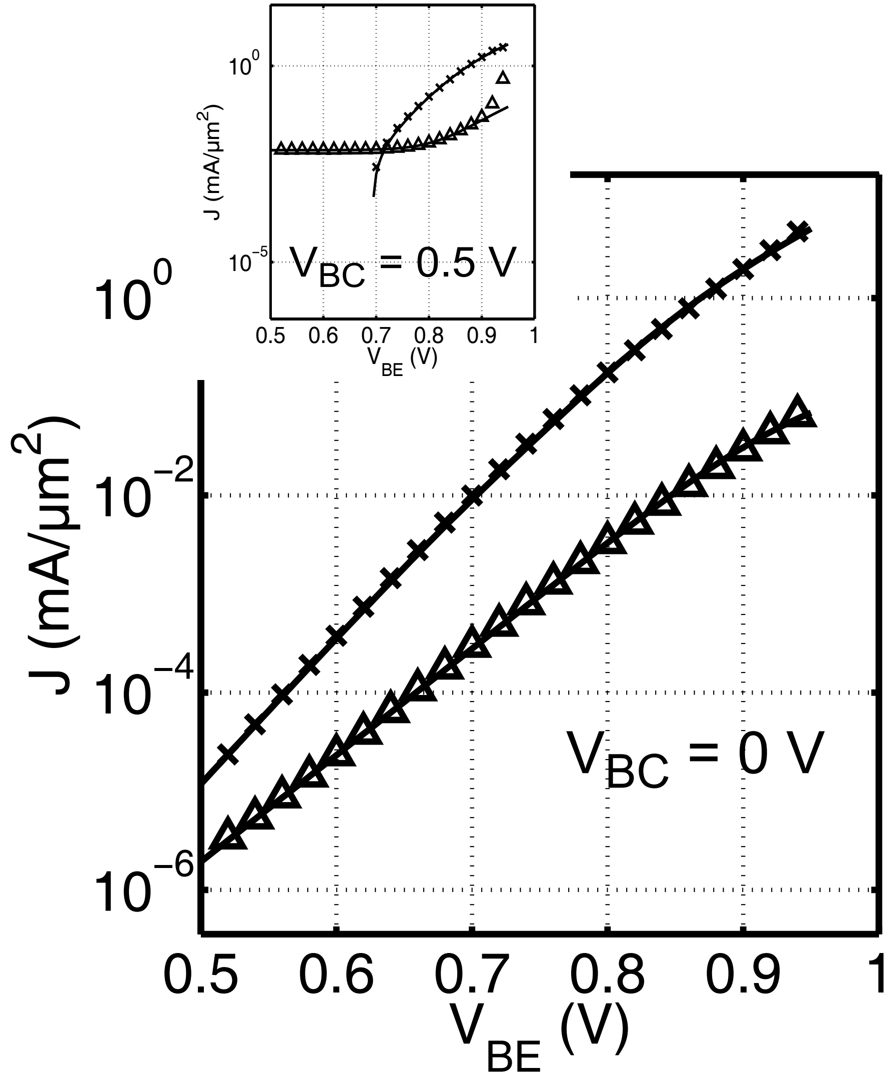
InGaAs/InP technology

- Transistors provided by Fraunhofer IAF
- $f_T \approx 350$ GHz, $f_{max} \approx 400$ GHz
- HICUM/L0 version 1.3 used [2]
  - physical formulation for bias dependent V_{ER} (relevant for compositional grading)
  - temperature dependence of V_{ER}
- no test structures or scaling, automated extraction with manual improvement
  - calculation of series resistances from theory and sheet resistance
  - measurements at various ambient temperatures available for extraction of temperature related parameters
- for more information see CSICS 2011 [6]

Experimental results

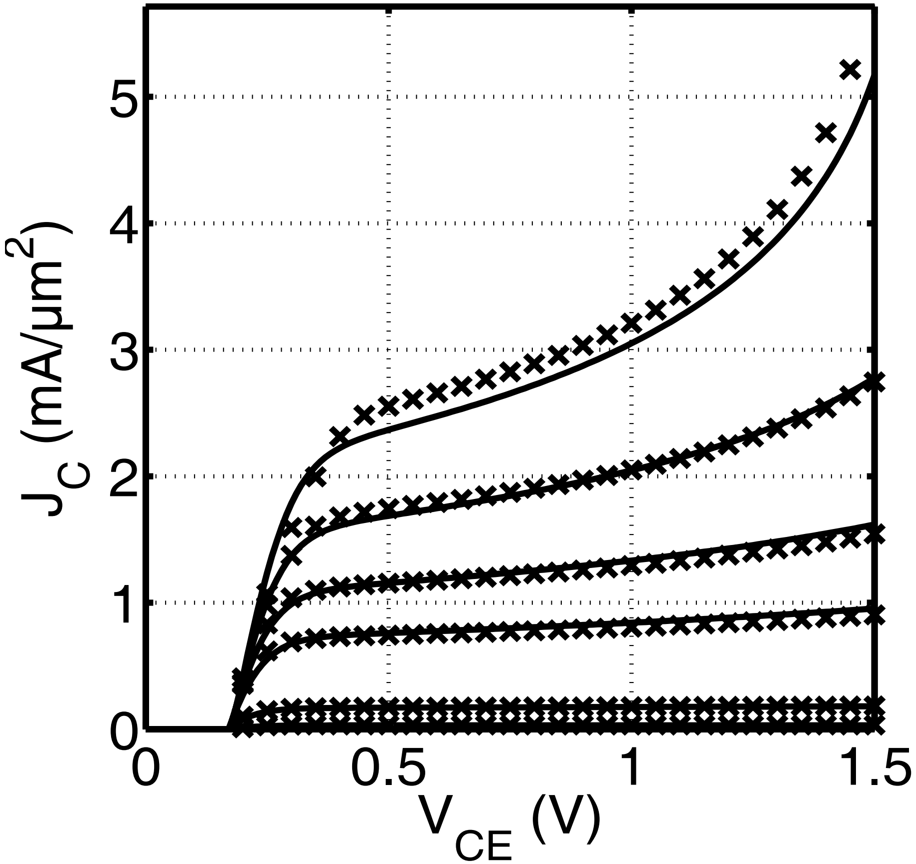
Gummel characteristics at different V_{BC}





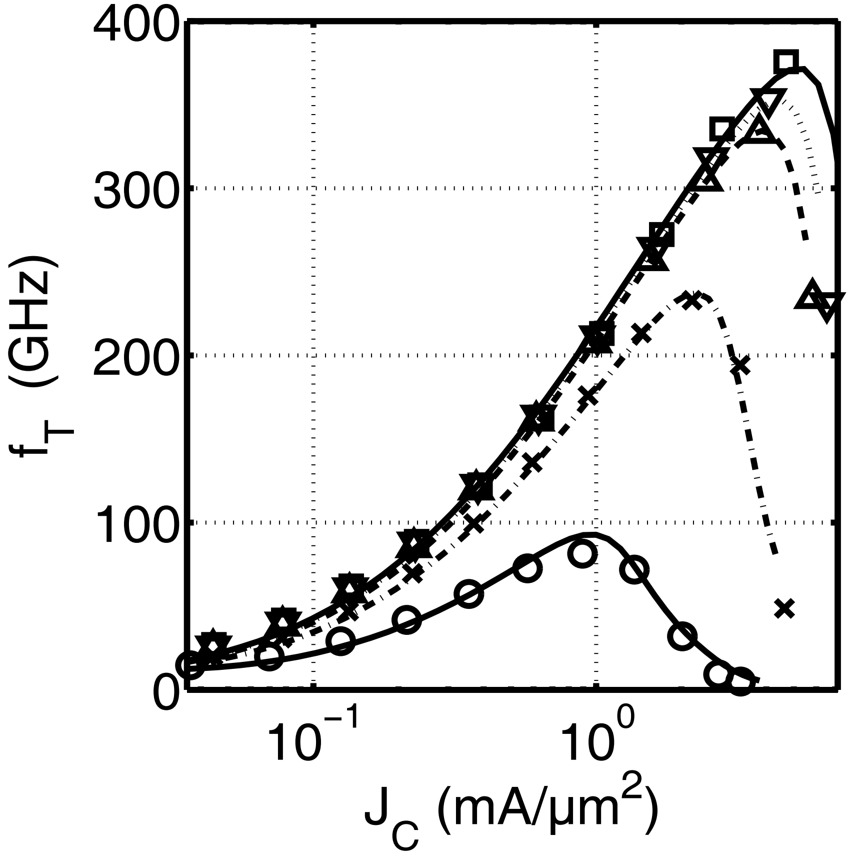
Experimental results

output characteristics



V_{BE} = [0.74, 0.8, 0.86, 0.88, 0.9, 0.92] V

transit frequency V_{BC}

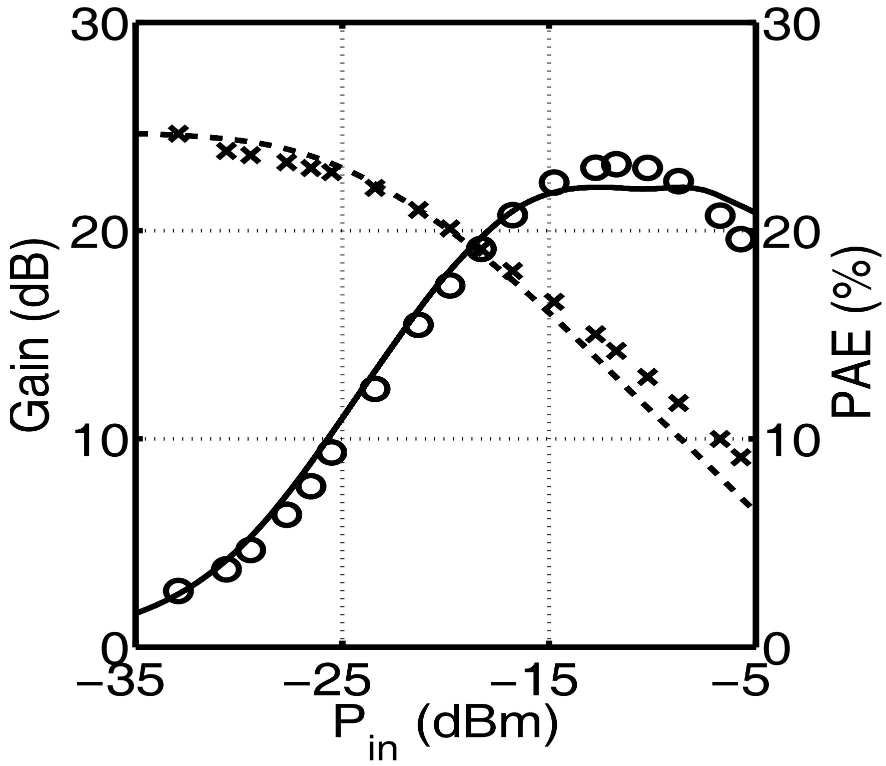


V_{BC} = [-0.25, -0.1, 0, 0.3, 0.5] V

=> very good agreement

Experimental results

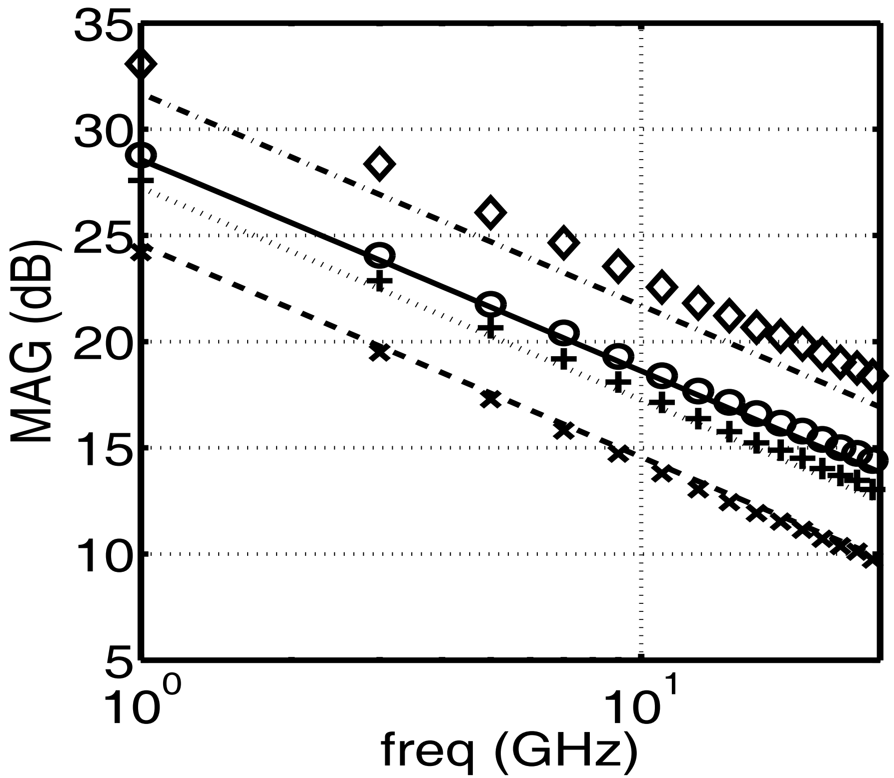
max. available power gain



J_C = 2 mA/µm², V_{BC} = -0.1 V

(≈ 2/3 $f_{t,peak}$)

power added efficiency



J_C = {0.5, 2.0} and {1.0, 3.8} mA/µm², V_{BC} = {0.3, 0}V (1/2 $f_{t,peak}$, $f_{t,peak}$)

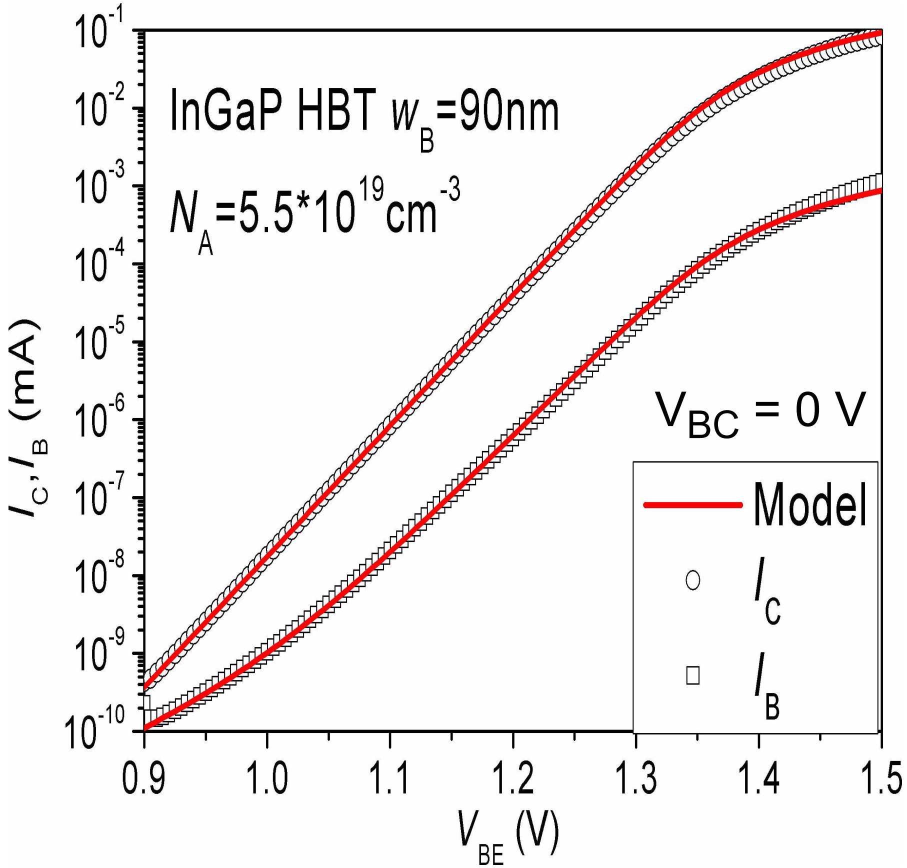
=> already acceptable agreement

InGaP/GaAs technology

- DHBTs provided by Skyworks Inc.
- $f_T \approx 45...60$ GHz, $f_{max} \approx 80...95$ GHz
- three different base widths were investigated: $w_B = \{50, 70, 90\}$ nm
- Focus on noise sources
- for more information see PSS 2011 [7]

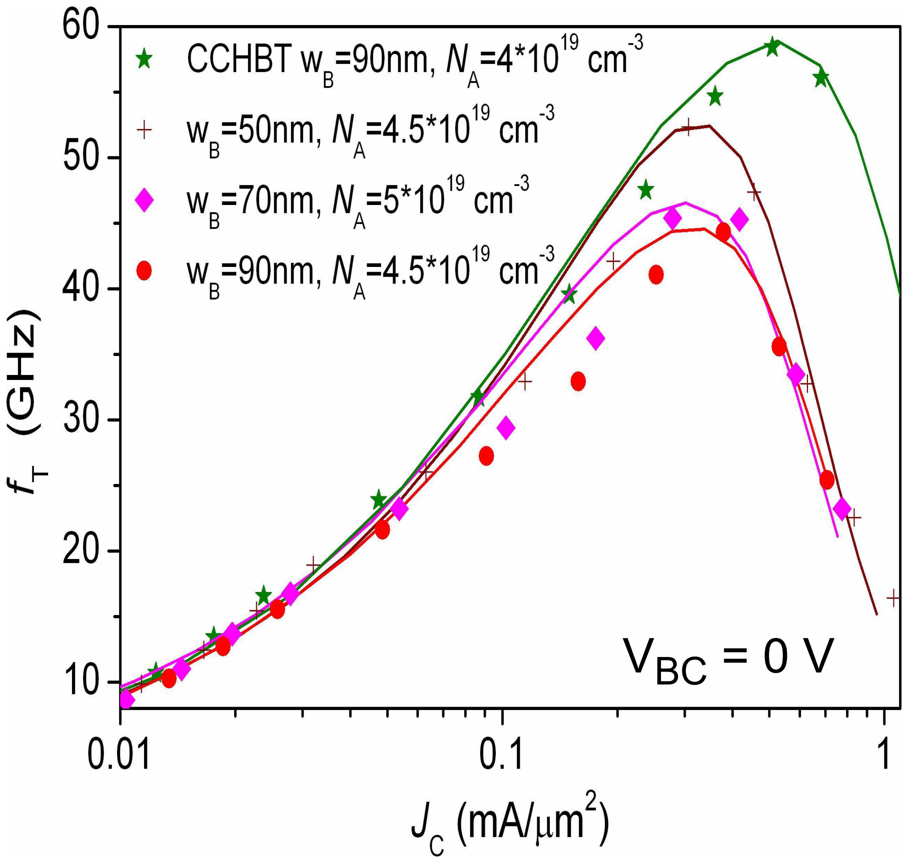
Experimental results

Gummel characteristics



=> good agreement

transit frequency

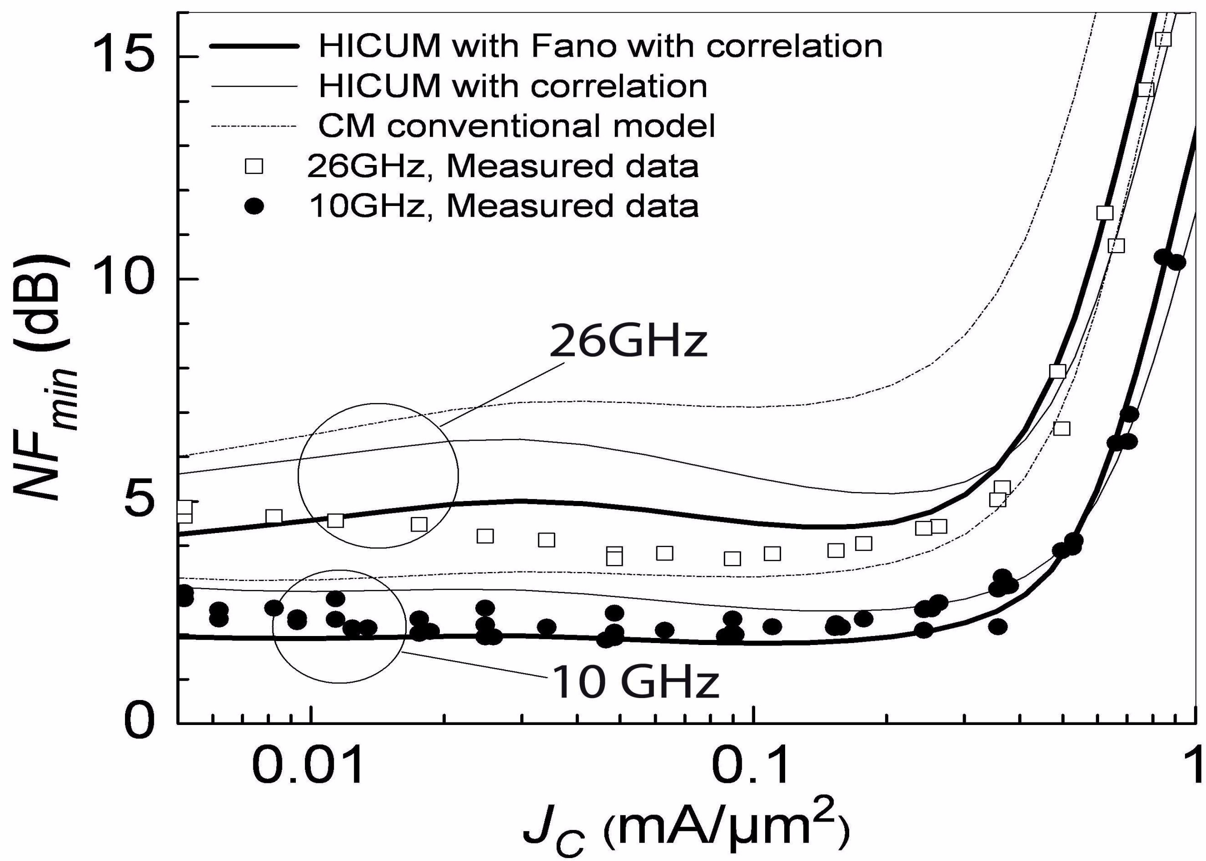


=> deviations at medium J_C

possibly caused by missing velocity overshoot

High-frequency noise results

minimum noise figure vs. frequency



reference device: w_B = 90 nm

=> good agreement for model *with noise correlation* and *Fano factor*

Conclusions

- successfully applied HICUM/L0 to InGaAs/InP HBT, HICUM/L2 to InGaP/GaAs HBT
  - HICUM/L0 required addition of $I_{BC,rec}$, a_{jC}

- Good results for standard characteristics, large-signal, and noise measurements
  - deviations in fT at medium current densities for InGaP/GaAs HBT

- planned: addition of III-V (especially InP) specific features related to
  - carrier transport
  - charge storage (vel. overshoot/neg. diff. mobility, current-dependent C_{jC})
  - device scaling and statistical models

Acknowledgments

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