Modeling of 70nm GaAs mHEMT Process for MMIC Amplifier Design up to 220GHz

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Yinhe596 S&T Campus

- **Location:**
  - Shuangliu District, Chengdu

- **Strategic new tech research centers:**
  - info tech, advanced manufacturing, new materials,...
Microsystem and Terahertz Research Center (MTRC)

- 4 research labs
- Latest EDA platform for design, state of the art THz characterization & measurement equipment
- In-house fabrication facility with 3000+ m² cleanroom for III-V, MEMS & system integration
MT03: THz Application Technology Research Laboratory

- Yinhe596
  - MTRC
    - MT03

- Active in research fields
  - THz communications, radar, imaging systems
  - THz components, THz ICs, THz microsystems integration
Outline

Modeling of 70nm GaAs mHEMT Process for MMIC Amplifier Design up to 220GHz

- Background & Motivation
- Test chip & Characterization
- Modeling Methodologies & Results
- Summary
Background & Motivation

THz gap
- huge bandwidth, high data rate, applications in high speed communication

III-V transistor speed
- InP HEMTs with $f_{\text{max}} > 1$THz, amplifier even work at 1THz by NGC
- Few COTS modules available

Foundry process
- 70nm GaAs mHEMT
- $f_{\text{max}} > 400$GHz
- amplifiers beyond 100GHz
Background & Motivation

- **PDK model**
  - only verified up to 50GHz
  - unknown uncertainty for THz
  - high risk and costly redesign

- **Evaluation of devices is necessary**
  - for beyond 100GHz design
    - small components value sensitive to variation and modeling error
  - passives and transistors
    - passives: EM helps but need calibration and verification
    - transistor modeling as an integral part of the amplifier design flow
Test Chip

Test structures for evaluation and modeling

- compact design
  - 1x3mm$^2$
- CPW environment
  - G-G 40μm, signal trace 20μm for 50Ohm TXL
Typical Test Structures

- mHEMTs
- Resistors
- Capacitors
- Inductors
- TXLs...
- GSG pads 75-100um
- 200um separation
Devices Characterization

- On-wafer banded s-parameters measurements
  - 100um GSG probes
  - 10MHz~67GHz (x3)
  - VNA frequency extenders
    - 75GHz~110GHz (x2)
    - 10MHz~110GHz
    - D: 110GHz~170GHz
    - G: 140GHz~220GHz
  - 6 setups measurement systems in 5 labs
Devices Characterization

- Measured on probe station with:
  - dies glued on copper carrier by silver epoxy
  - to mimic the targeted working environment
Devices Characterization

- Calibration and De-embedding [1]
  - 1st tier calibration using LRRM with ISS
  - OPEN/SHORT/PAD dummies for OS, POS de-embedding
  - on-wafer multiline TRL calibration


Comparison of calibration and de-embedding effect on transconductance
Devices Characterization

- Calibration and De-embedding
  - POS up to 67GHz
  - mTRL is used in other bands
    - generally effective

- Some problems
  - discontinuities
  - unreal artifacts
  - Incorrect sign
  - originate from data

Adopted calibration and de-embedding applied on transconductance for reference
Measurement Non-idealities

- Raw $S_{11}$ of PAD dummy
  - especially obvious for magnitude of s-parameters

- Ref[2]
  - Parasitic scattering and coupling

Parasitic Scattering & Coupling

- E-Field distribution for a CPW transmission line
  - 100GHz
  - 200GHz
  - 300GHz
Parasitic Scattering & Coupling

- full test chip EM simulation

- @ 200GHz

- unwanted coupling to adjacent test structures

- results in degraded data
Parasitic Scattering & Coupling

- Some characteristics and test structures are less sensitive
  - Effective inductance, capacitance, phase of transmission terms
  - Long transmission line
    - Effective L, Phase
Modeling Methodologies

- Considering the data degradation up to 220GHz

- Following strategies are used:
  - **Systematic calibration of EM simulation**
    - For parasitics extraction and measurement verification
  - **Feeding network modeling**
    - replace de-embedding and on-wafer calibration
  - **Recursive Modeling[3] of mHEMT**
    - previously extracted equivalent circuit model (ECM) used recursively in later extractions

Modeling Methodologies

- Modeling in flowchart

1. **Characterization Data**
2. **Meas, Sim PAD, SHORT, OPEN**
3. **EM Calibration**
4. **ECM of feeding networks**
5. **ECM of mHEMT**
6. **Meas R, L of SHORT, LINE C of OPEN, CAP**
7. **Meas Low freq for intrinsic High freq for extrinsic**
EM Calibration

- Systematic EM calibration[4]
  - Simplified process cross-section profile
  - Based on measurement data of SHORT, LINEs and Caps structures
  - HFSS and Momentum
    - Materials parameters
    - Thickness

EM Calibration Results

- 100fF $C_{\text{mim}}$
  - $\text{Si}_3\text{N}_4$, $\text{SiO}_2$ dielectric from 2 Caps
  - verified up to 170GHz
EM Calibration Results

- Transmission lines
  - Conductivity from effective resistance
  - GaAs substrate dielectric from LINEs
  - HFSS and ADS similar results
EM Calibration Results

- 200Ohm Resistor
  - Thin film metal resistor
  - verified up to 110GHz
Feeding network modeling

- 2x20um mHMET with feeding parasitics
  - Reference planes
Feeding network modeling

- Feeding network modeling
  - based on PAD, SHORT and OPEN dummy structures
Feeding network modeling

- Extraction recursively
  - Each extracted ECM is used as part of the subsequent ECM
  - PAD $\rightarrow$ SHORT $\rightarrow$ OPEN
Feeding Networks Results

- PAD dummy
  - EM vs. data
  - $C_{pg}, C_{pd}$

![Graph showing $C_{pad}$ vs. GHz]
Feeding Networks Results

- SHORT dummy
  - EM vs. data
  - $R_g, L_g$
  - $R_{g1}, L_{g1}$
  - $R_d, L_d$
  - $R_{d1}, L_{d1}$
Feeding Networks Results

- OPEN Dummy
  - EM vs. data
  - $C_{pg1}, C_{pg2}$
  - $C_{dg1}, C_{dg2}$
Recursive Modeling

- **mHEMT model**
  - Pi-network embedded in the feeding ECM
  - used raw measurement data as targets

![Diagram of mHEMT model]
Extrinsic Elements Extraction

- Cold-FET for terminal parasitics
  - source parasitics and res at G,D ignored
- $L_{ge}, L_{de}$
  - Recursive methods, fitting to raw data (>110GHz)
Intrinsic ECM Extraction

- Intrinsic elements
  - starting value: extracted from low frequency de-embedded data (<110GHz)
  - then fitting together with feeding network ECM
Meas vs. Sim Results

- mHEMT 2x20um \( V_g = 0 \text{V} \) \( V_d = 1 \text{V} \) (close to peak transconductance)

\[ g_m, C_m \]
Meas vs. Sim Results

- mHEMT 2x20um $V_g=0V$ $V_d=1V$
  - $C_{gs}$, $\text{re}(Y_{11}+Y_{12})$
Meas vs. Sim Results

- mHEMT 2x20um $V_g=0$V $V_d=1$V

$C_{ds}$, $1/R_{ds}$
Meas vs. Sim Results

- mHEMT 2x20um $V_g=0V$ $V_d=1V$
  - $C_{gd}$, $\text{re}(1/Y_{12})$
Meas vs. Sim Results

- mHEMT 2x20um $V_g=0V$ $V_d=1V$
  - MAG
  - S-parameters Smith plots
Model Application

- 3-stage CS amplifier
  - T-junction matching
  - Gain > 20dB@140GHz
Summary

- Test chip & Characterization
  - Compact, CPW style
  - On-wafer banded measurements with non-idealities

- Modeling Methodologies & Results
  - EM calibration for parasitics extraction and verification of measurement
  - Feeding network modeling instead of de-embedding and calibration
  - Recursive modeling of mHEMT up to 220GHz, to be used in amplifier design
Ref & Acknowledgement

References


Acknowledgement

- This work was supported by Challenge Program under grant no. TZ2018003.
- The authors would like to thank Prof. Yan Wang, Wenyuan Zhang of Tsinghua University, Miao Li, Haibin Zhao of Platform Design Automation Inc, Prof. Jun Liu of Zhangzhou Dianzi University, Zhifu Hu, Meilin He of CETC13 for their help and technical discussions.
Thanks for your attention.

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