Recent ETHZ-YEBES Developments in Low-Noise pHEMTs for Cryogenic Amplifiers

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Outline

- Group and Lab Introduction
- ETH HEMT Process & Fabrication
- Device Characteristics
- YEBES Amplifier Results
- Conclusion
Introducing MWE Group

- **Established in 2006**

- **Members (9 Researchers + 1 Prof)**
  - 7 Ph.D. Candidates
  - 2 Postdocs
  - 1 Measurement Engineer + 1 Process Engineer

- **Research Areas**
  - **HEMTs (InP, Group III-N)**
  - InP/GaAsSb DHBTs
  - MOCVD (InP, GaInP, GaAsSb)
  - Circuit Design + Characterization
Introducing ETH / FIRST Cleanroom

FIRST – Frontiers in Research Space and Time

- In Operation since 2002
- 400 m² of class 10-10’000
- State of the Art Equipment
- Managed by 11 Professors
- Run by 9 perm. Employees
Introducing ETH / FIRST Cleanroom Equipment

- 3 MBEs / MOVPE
- 2 X-Ray / PL Mapper
- 2 Zeiss SEMs / AFM
- 2 Raith 30kV EBLs
- PECVD / RIEs / ICP / LPCVD / ALD
- 3 EB-Evaporation / 1 Sputter System
- Rapid Thermal Annealer
- CV-Profilier / Hall Effect System
- Ellipsometer / Alphastep
- MA6 / MJB3 / DUV Aligners
- 3 Optical Microscopes
- Wet Bench Area / Litho Area
- …
Introducing ETH / MWE “Measurement Lab”

Measurement Tools & Capabilities

- Vector Network Analyzers (0.045 – 110 GHz + 140 – 220 GHz)
- Power Analysis (0.045–110 GHz)
- Spectrum Measurements up to 90 GHz
- Antenna Measurements
- Noise Figure Measurements up to 75 GHz
- Noise Parameters up to 20 GHz
  - Up to 50 GHz by End of 2010
  - Multiharmonic Load-Source Pull by End of 2010
Introducing ETH / MWE “Cryo Lab”

- **On-Wafer Calibration System**
  - Open-Cycle Cryostat
  - Vacuum Level: <10^-6 Torr
  - Temperature Range: 5 K to 400 K (±0.1K)
  - PID Temperature Controller
  - Temperature Sensors: Si Diode (Chuck) and Pt Thermometer (Probe Arm)

- **Feedthrough:**
  - RF Cables (K- and 2.4mm-connector)
  - DC Wires/Cables (10 pin)

- **Probes**
  - Cryogenic RF Probes (K- and 2.4mm connector)
  - Multi-Contact-Wedge Probe (9 pin)
Introducing ETH / MWE “Cryo Lab”

- Cryo Dewar System
  - Temperature Range: 10 K to 400 K

- Feedthrough:
  - 4 RF Cables (SMA-connectors)
  - 2 DC Wires/Cables (16 pin)

- Probes
  - Any Probe Type Fitting on the Copper Plate
    (Ø17cm x 10 cm)
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ETH HEMT History

- 1991 Development of 0.25µm ETH AllInAs/GaInAs/InP HEMT Transistor-Process by C. Bergamaschi under Prof. Bächtlold
- 1998 First ESA-Project Involving ETH-HEMTs and YEBES for Design & Fabrication of X-Band Amplifier
- 2006-2008 Process Transfer from In-House Cleanroom to FIRST
- Currently: ESA Ka-Band Amplifier Project with ETH Devices and YEBES for Amplifier Design & Fabrication (S. Halté)
ETH InP HEMT Work Today

- Evolve “Conventional” AlInAs/GaInAs/InP HEMT Technology
- InAs Channel Insets Without Antimonide Related Problems
- “Aluminum Free” GaInP/GaInAs pHEMT Concept for Improved:
  - High-Frequency Power Performance
  - Reliability
  - LF-Noise
  - Cryo Performance
  - Breakdown Behavior
  - Improved Etch-Selectivity of GaInAs/GaInP (Recess)
"Aluminum free" HEMT Concept

**Goal: Eliminate AlInAs from HEMT-Epi**

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<tr>
<th>Layer</th>
<th>Material</th>
<th>Doping</th>
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<td>s.i. Fe-doped</td>
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<tr>
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Al-Free InP pHEMTs Motivation:

- AllInAs Can Be Chemically Unstable
  - Traps Present (Residual Oxygen)
  - Device Instabilities/Non-Idealities (e.g. Kink, Light Sensitivity, etc.)
  - Reliability Limiter

- InP Buffer Layer Advantages
  - Al-Free
  - 10x Higher Thermal Conductivity wrt Alloys

- Old Idea: Explored by K. Heime in 1990’s
  - $f_T = 150$ GHz
  - Claimed to Offer Lower Noise than AllInAs/GaInAs HEMTs
  - Did Not Gain Acceptance
**Al-Free InP pHEMTs (ETH-Grown)**

$f_{\text{MAX}} > 600 \text{ GHz (100 nm)}$

**Peak $f_T$ Bias:**

$f_T = f_{\text{MAX}} = 250 \text{ GHz}$

**Peak $f_{\text{MAX}}$ Bias:** $V_{\text{DS}} = 1.5 \text{ V}$

$f_T = 200 \text{ GHz} / f_{\text{MAX}} = 602 \text{ GHz}$

**Non-Optimized Layers on InP:Fe**

$\mu = 8,300 \text{ cm}^2/\text{Vs} \quad N_s < 1 \times 10^{12} /\text{cm}^2$

The GaInP/GaInAs Al-Free pHEMT on InP:Fe is Very Promising!
Typical Device Fabrication Process

**Ohmic Contacts**: Ge/Au Annealed Contacts: <0.1 Ωmm

**Device Isolation**: Phosphoric Acid Based Solutions

**Gate Recess**: Organic Acids

**T-Gates**: 30-500nm Ebeam T-Gates + SiNx Passivation

**Metallization**: Overlay Metallization

**Electroplating**: Airbridges + Thick Pad-Metal Followed by Thinning to 100μm + Dicing
**InP pHEMT with \( L_G = 100 \text{ nm} \)**

Electron Beam Lithography

**30 nm T-Gate in ZEP-Based Tri-Layer**

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Raith150-Two: Installed End 2008
Nanometric Gates

Cursor Width = 33.05 nm

EHT = 2.00 kV
Mag = 100.00 K X
Signal A = InLens
WD = 2 mm
Pixel Size = 3.7 nm
Tilt Angle = 0.0°
File Name = Zep_1-1_2600rpm__23.tif

Center for Micro- and Nanoscience
Andreas Alt
Date: 5 Sep 2009
6 Finger Air-Bridge Device

InP pHEMT (0.1µm x 100µm)
6 Finger Air-Bridge Device
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DC Device Characteristics @ RT

Transconductance

\[ V_{DS} = 0.1V \ldots 0.9V \ (0.1V \text{ steps}) \]

\[
\begin{array}{c}
g_m \text{ (mS/mm)} \\
\end{array}
\]

\[
\begin{array}{c}
V_{GS} \text{ (V)} \\
\end{array}
\]
DC Device Characteristics @ RT

IV - Characteristics

$V_{GS} = -0.7V...0.5V$ (0.1V steps)
DC Device Characteristics @ RT

![Diode Characteristics Graph](image)

- $V_{DS} = 0V...1.5V$ (0.25V steps)

$V_{GS}$ (V) vs $I_{GS}$ (A)
RF Device Characteristics @ RT

- **Bias Sweep**
- **Without Removing** Pad-Parasitics!
- **0.1µm x 150µm**
RF Device Characteristics @ RT

- **Bias Sweep**
  - **Without Removing** Pad-Parasitics!
- **0.1µm x 150µm**

![Graph showing RF device characteristics](image_url)

- $F_{\text{max, max}} = 253.90$ GHz
DC Device Characteristics @ 15K

Transconductance

$V_{DS} = 0.1V...0.9V$ (0.1V steps)
**DC Device Characteristics @ 15K**

**IV - Characteristics**

\[
I_D (mA/mm) \quad V_{DS} (V) \quad V_{GS} = -0.3V...0.6V \quad (0.1V \text{ steps})
\]

- Graph showing the IV characteristics of a device at 15K, with current density vs. voltage across the device.
**DC Device Characteristics @ 15K**

**Impact**

**Ionization**

\( V_{DS} \geq 1V \)
Effect of Temperature on DC

Transconductance

\[ V_{DS} = 0.1V \ldots 0.9V \ (0.1V \ steps) \]
Effect of Temperature on DC

Diode Characteristics

$V_{DS} = 0V...1.5V$ (0.25V steps)
RF Device Characteristics @ 15K

- **Bias Sweep**
  - Without Removing Pad-Parasitics!
- **0.1µm x 150µm**
**RF Device Characteristics @ 15K**

- **Bias Sweep**
  - **Without Removing Pad-Parasitics!**
- **0.1µm x 150µm**

![Graph showing F_{max, max} = 252.21 GHz]

\[ F_{\text{max, max}} = 252.21 \text{ GHz} \]
RF Device Characteristics @ 15K

- **RF Data**
  - **Without Removing Pad-Parasitics!**
  - $F_T$ of 272 GHz @
    - $0.7V \, V_{DS}$, $0.2V \, V_{GS}$
    - $31mA \, I_{DS}$, $0.12nA \, I_{GS}$

![Graph showing RF device characteristics at 15K.](image)
RF Device Characteristics @ 15K

- **RF Data**

  *Without Removing Pad-Parasitics!*

- **Typical Low-Noise Bias Point @**

  0.3V $V_{DS}$, 0.05V $V_{GS}$

  4.3mA $I_{DS}$, **0.014nA** $I_{GS}$

  $F_T = 156$ GHz
Processing Impact on Device Characteristics

A Single Process Step Can Have a Dramatic Impact on Gate Leakage!

(Everything Else Kept the Same)
**Processing Impact on Device Characteristics**

A Single Process Step Can Have a Dramatic Impact on Gate Leakage!

*(Everything Else Kept the Same)*
Processing Impact on Device Characteristics

In this Experiment the Processing Change Solely Influenced the Gate Leakage which is a Key Factor for the Noise Performance!
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Result Considerations

- **CRYO3 is Considered the Best Transistor Ever Measured**

- **Devices Presented Here are not Yet “Optimal”:**
  - Source-Drain Distance is 2µm; Better Performance Expected for 1µm

- **Noise Characterization Over 16–26 GHz by YEBES**

- **YEBES Used ETH Devices in the First Stage of their YK22 004 Amplifier, Comparing Against HRL and NGST Devices**
YEBES Amplifier Results @ 300K

Graph showing the variation of gain (dB) with frequency (GHz) for different conditions at 300K. The graph includes data from various sources such as HRL and CRYO3.
YEBES Amplifier Results @ 15K

Graph showing the performance of different amplifier configurations at 15K temperature. The graph compares gain (dB) vs frequency (GHz) for various runs labeled as HRL, ETH Run Sep09, ETH Run May10, and NGST CRYO3. The graph highlights the optimum bias for each configuration at T=15K.
ETHZ-YEBES Measurement Results

- Noise Results Obtained with ETH Devices Almost Reach CRYO3
  - The Average in-Band Noise is Slightly Higher than CRYO3
  - The Minimum Noise is in Some Cases Slightly Better than CRYO3
- Gain is Significantly Higher for ETH Devices
- Very Low Gate Leakage at Cryogenic Temperatures
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Conclusion

- ITAR Complicates HEMT Procurement Outside US
- ETHZ Technology as EU Source of High-Performance Devices
  - Radio-Astronomy & Deep Space Network
  - Telecommunications
  - Research Applications
- MWE / ETH Interested in Collaborative Projects
  - Secure/Expand EU Source for Strategic Technology
  - Extend Technological Limits