Receivers & Array Workshop 2010
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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 Device-Test 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*

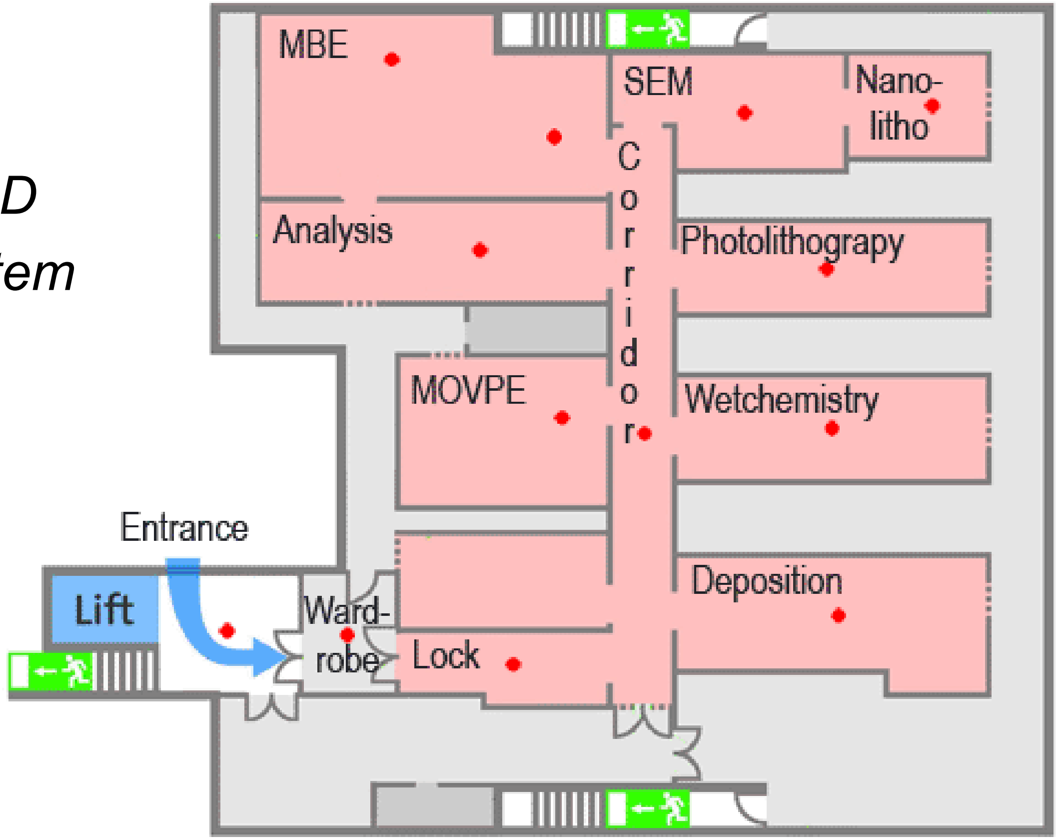
Introducing ETH / FIRST Cleanroom

FIRST – Frontiers in Research Space and Time

- ***In Operation Since 2002***
- ***400 m^2 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-Profiler / Hall Effect System*
- *Ellipsometer / Alphastep*
- *MA6 / MJB3 / DUV Aligners*
- *3 Optical Microscopes*
- *Wet Bench Area / Litho Area*
- *…*



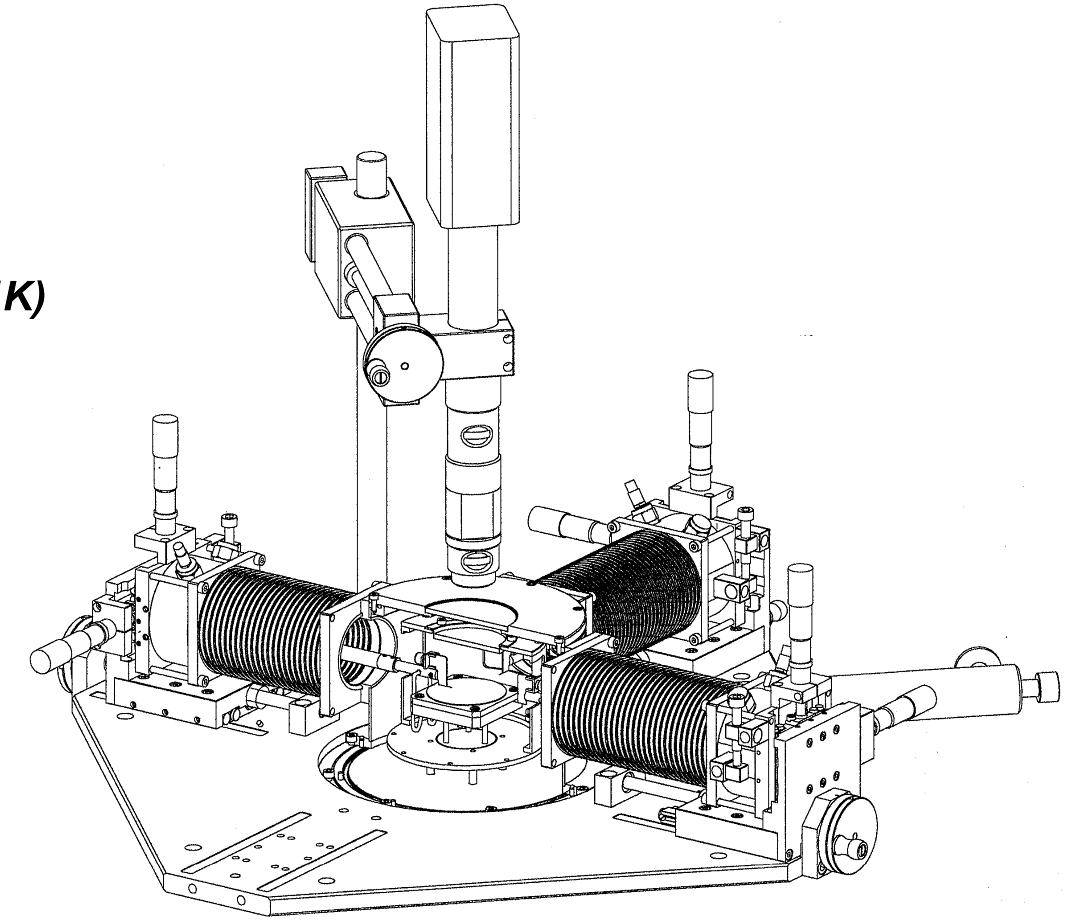
Introducing ETH / MWE "Measurement Lab"

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 Cryo-System***
  - ***Open-Cycle lHe Cryostat***
  - ***Vacuum Level: <10e-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***
  - ***lN_2 shielded lHe Cryostat***
- ***Feedthrough:***
  - ***4 RF Cables (SMA-connectors)***
  - ***2 DC Wires/Cables (16 pin)***
- ***Probes***
  - ***Any Probe Type/Size Fitting on the Copper Plate (Ø17cm x 10 cm)***

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ETH HEMT History

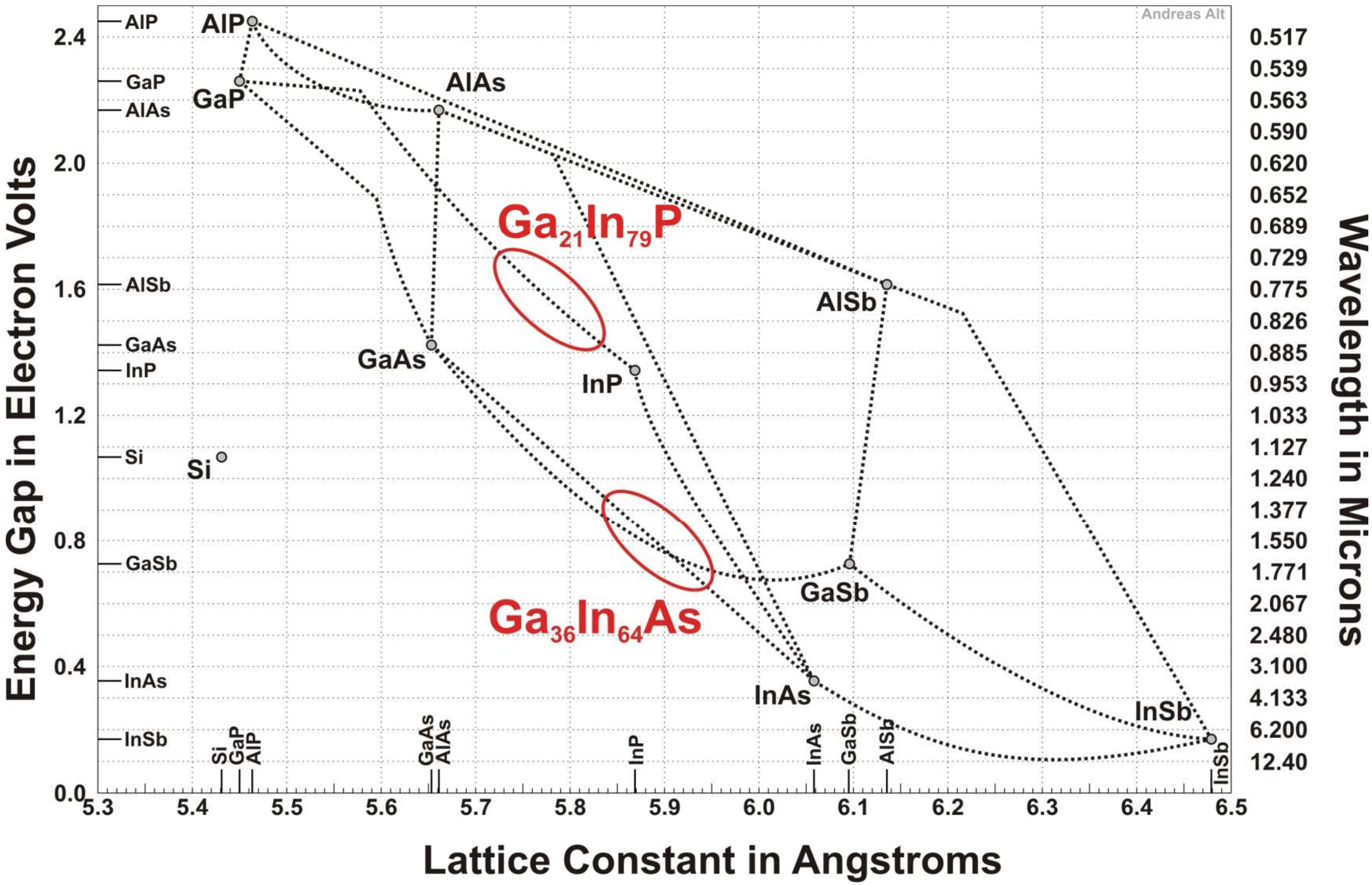
- *1991 Development of 0.25µm ETH AlInAs/GaInAs/InP HEMT Transistor-Process by C. Bergamaschi under Prof. Bächtold*
- *1998 First ESA-Project Involving ETH-HEMTs and YEBES for Design & Fabrication of X-Band Amplifier*
- *…Transistor Supply for Various Projects*
- *2006-2008 Process Transfer from In-House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

ETH InP HEMT Work Today

- ***Evolve "Conventional" AlInAs/GaInAs/InP HEMT Technology***
  - ***Understand & Improve "Conventional" Devices***
- ***InAs Channel Insets Without Antimonide Related Problems***
- ***"Aluminum Free" GaInP/GaInAs pHEMT Concept for Improved [1]:***
  - *Reliability*
  - *High-Frequency Power Performance*
  - *LF-Noise*
  - *Cryogenic Performance*
  - *Breakdown Behavior*
  - *Improved Etch-Selectivity of GaInAs/GaInP (Recess)*

[1] A. Mesquida Küsters and K. Heime, "Al-Free InPBased High Electron Mobility Transistors: Design, Fabrication and Performance," Solid-State Electronics, vol. 41, pp. 1159-1170, 1997

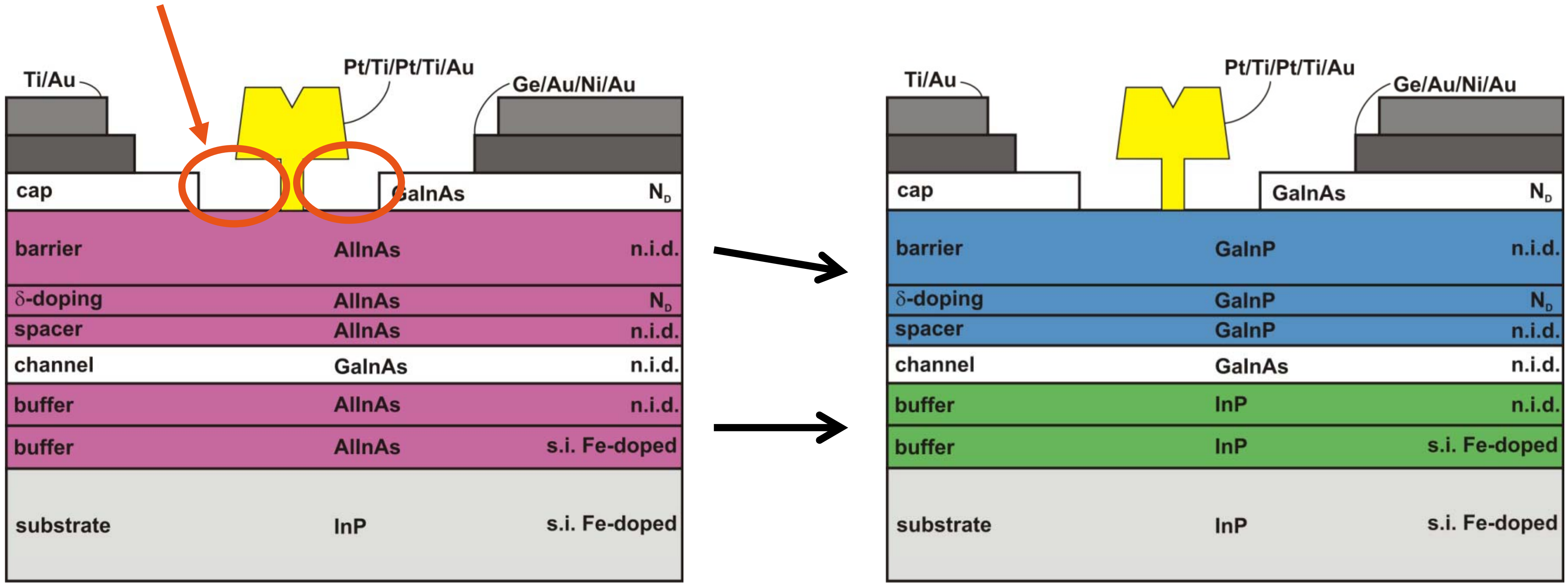
“Aluminum free” HEMT Concept



"Aluminum free" HEMT Concept

Goal: Eliminate AlInAs from HEMT-Epi

Sensitive Region, Even when Passivated!



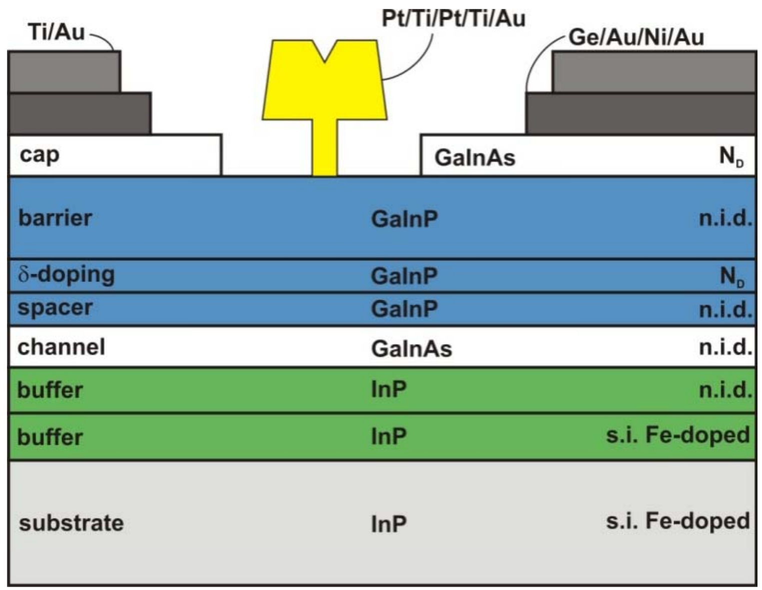
"Aluminum free" HEMT Concept

Difficulties to Consider when Replacing AlInAs with GaInP and InP

- *Growing Insulating InP-Buffer on InP*
- *Achieving High Sheet Densities and High Mobilities*

while

- *Aiming for High Conduction Band Offset*



Al-Free InP pHEMTs Motivation:

- ***AlInAs Can Be Chemically Unstable***
  - *Traps Present (Residual Oxygen, already in MOCVD Al Source)*
  - *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 AlInAs/GaInAs HEMTs*
  - *Did Not Gain Acceptance*

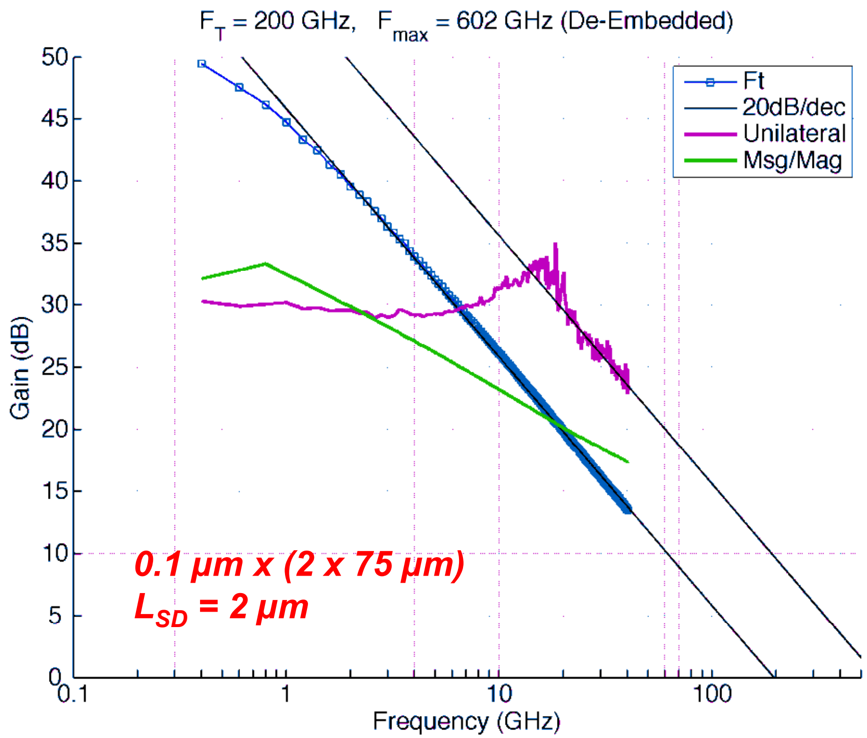
Al-Free InP pHEMTs (ETH-Grown)

f_{MAX} > 600 GHz (100 nm)

Peak f_T Bias:
$f_T = f_{MAX}$ = 250 GHz

Peak f_{MAX} Bias: V_{DS} = 1.5 V
f_T = 200 GHz / f_{MAX} = 602 GHz

Non-Optimized Layers on InP:Fe
μ = 8,300 cm²/Vs $N_s < 1 \times 10^{12}$ /cm²

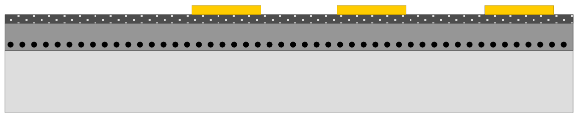


The GaInP/GaInAs Al-Free pHEMT on InP:Fe

is Very Promising!

Typical Device Fabrication Process

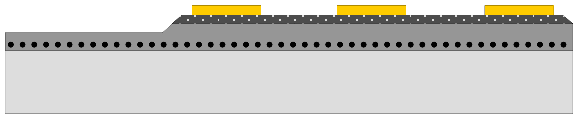
Ohmic Contacts



Ge/Au Annealed Contacts: <0.1 Ωmm

↓

Device Isolation



Phosphoric Acid Based Solutions

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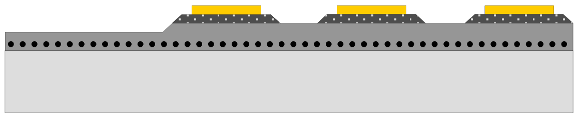
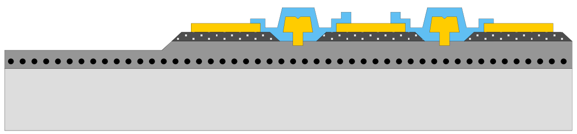
Gate Recess



Organic Acids

↓

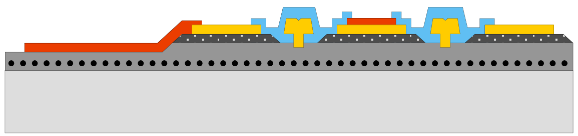
T-Gates



30-500nm Ebeam T-Gates + SiN_x Passivation

↓

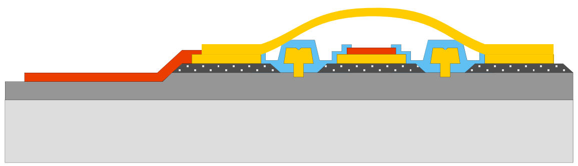
Metallization



Overlay Metallization

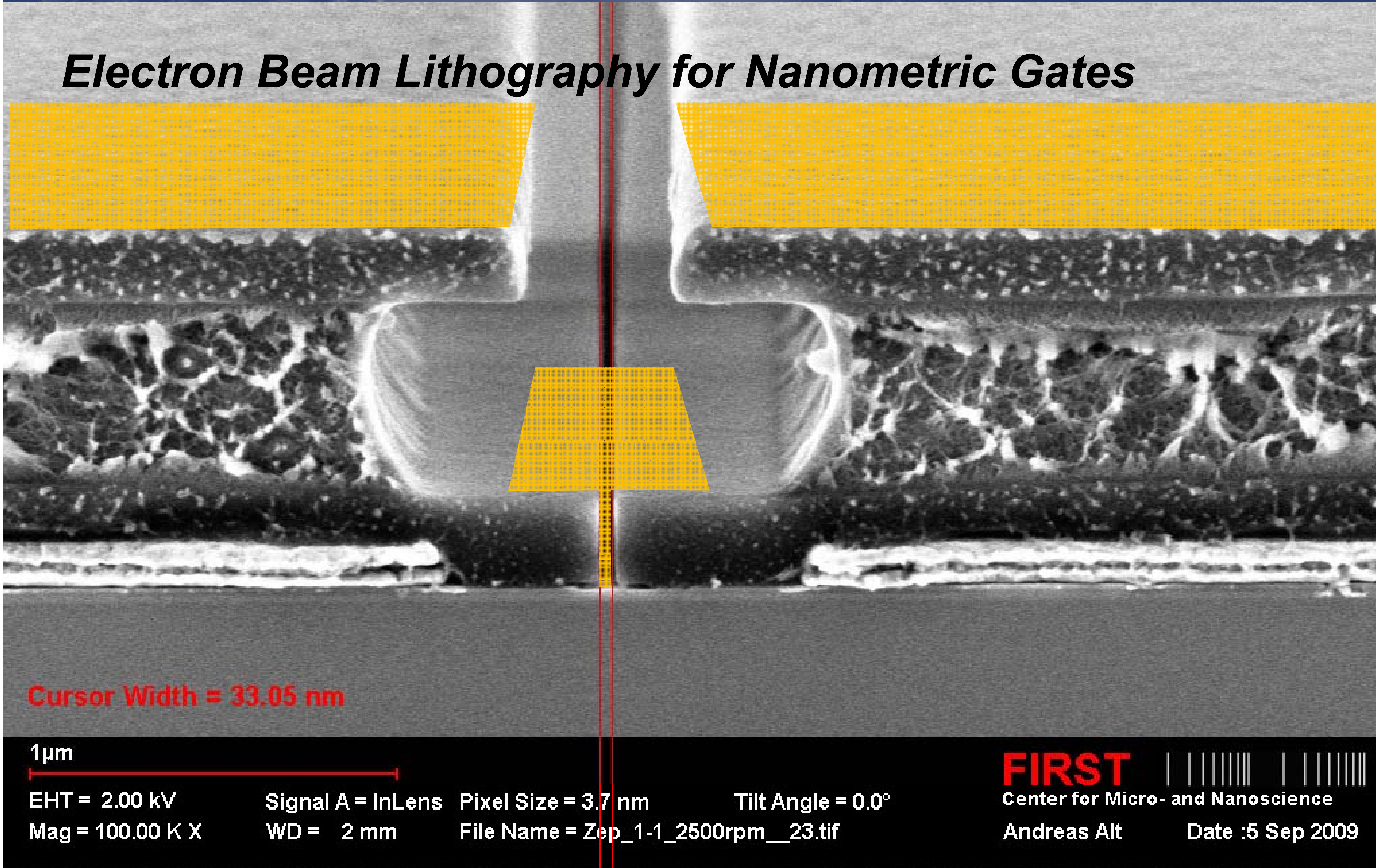
↓

Electroplating

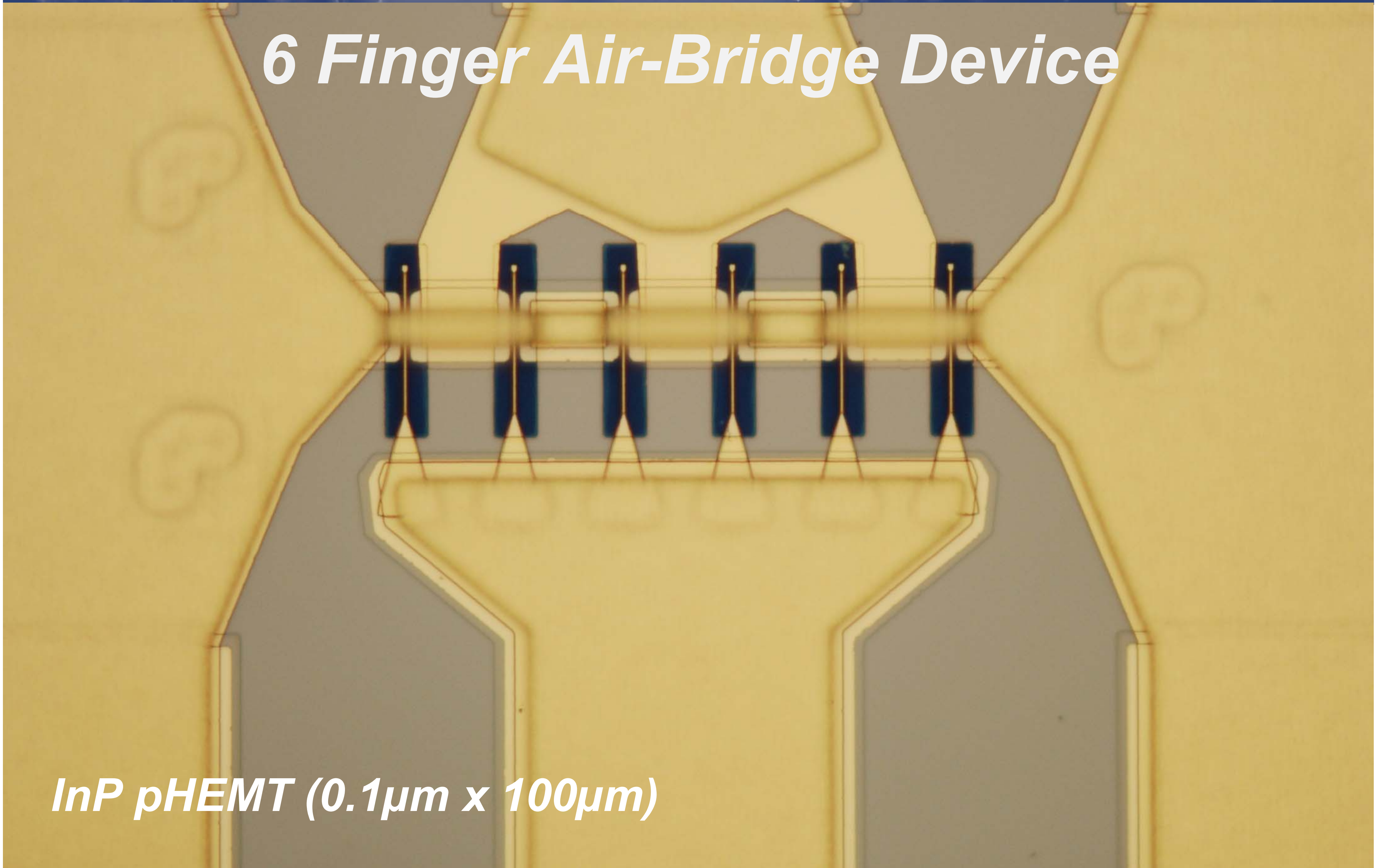


Airbridges +Thick Pad-Metal Followed by Thinning to 100µm + Dicing

Electron Beam Lithography for Nanometric Gates

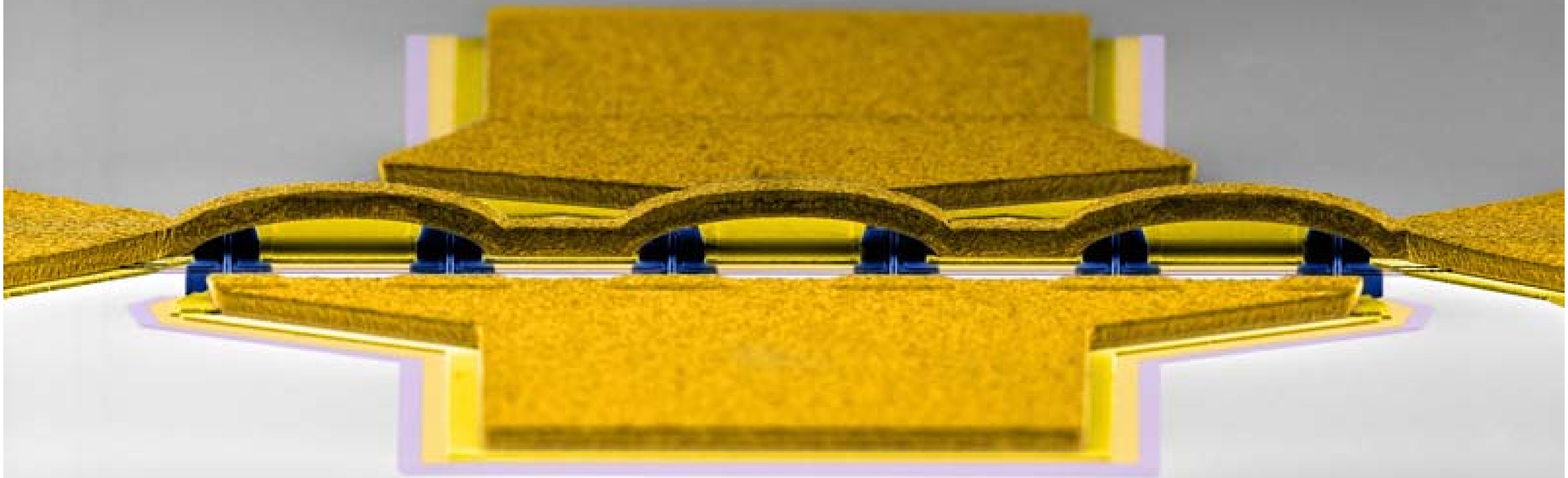


6 Finger Air-Bridge Device



InP pHEMT (0.1µm x 100µm)

6 Finger Air-Bridge Device



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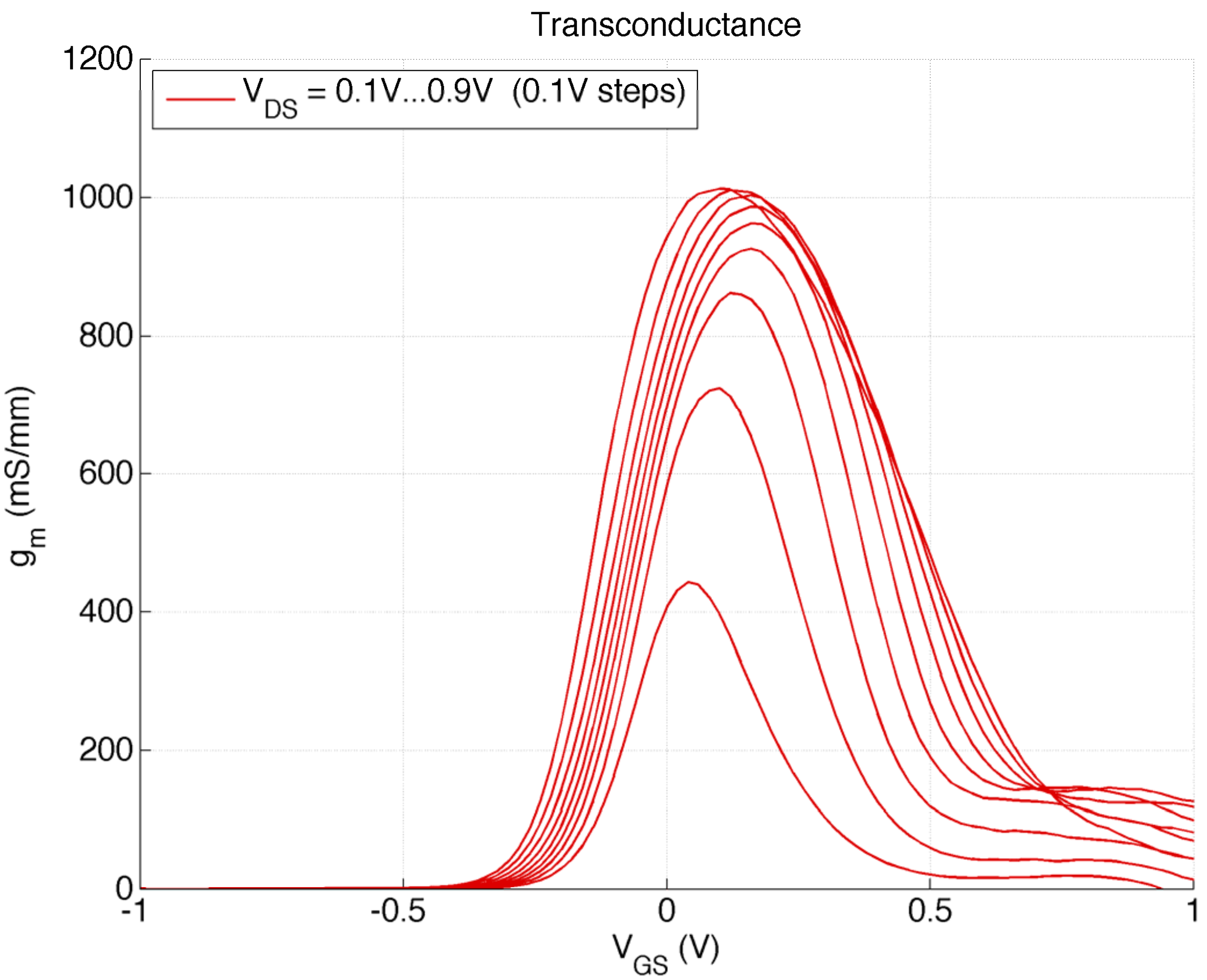
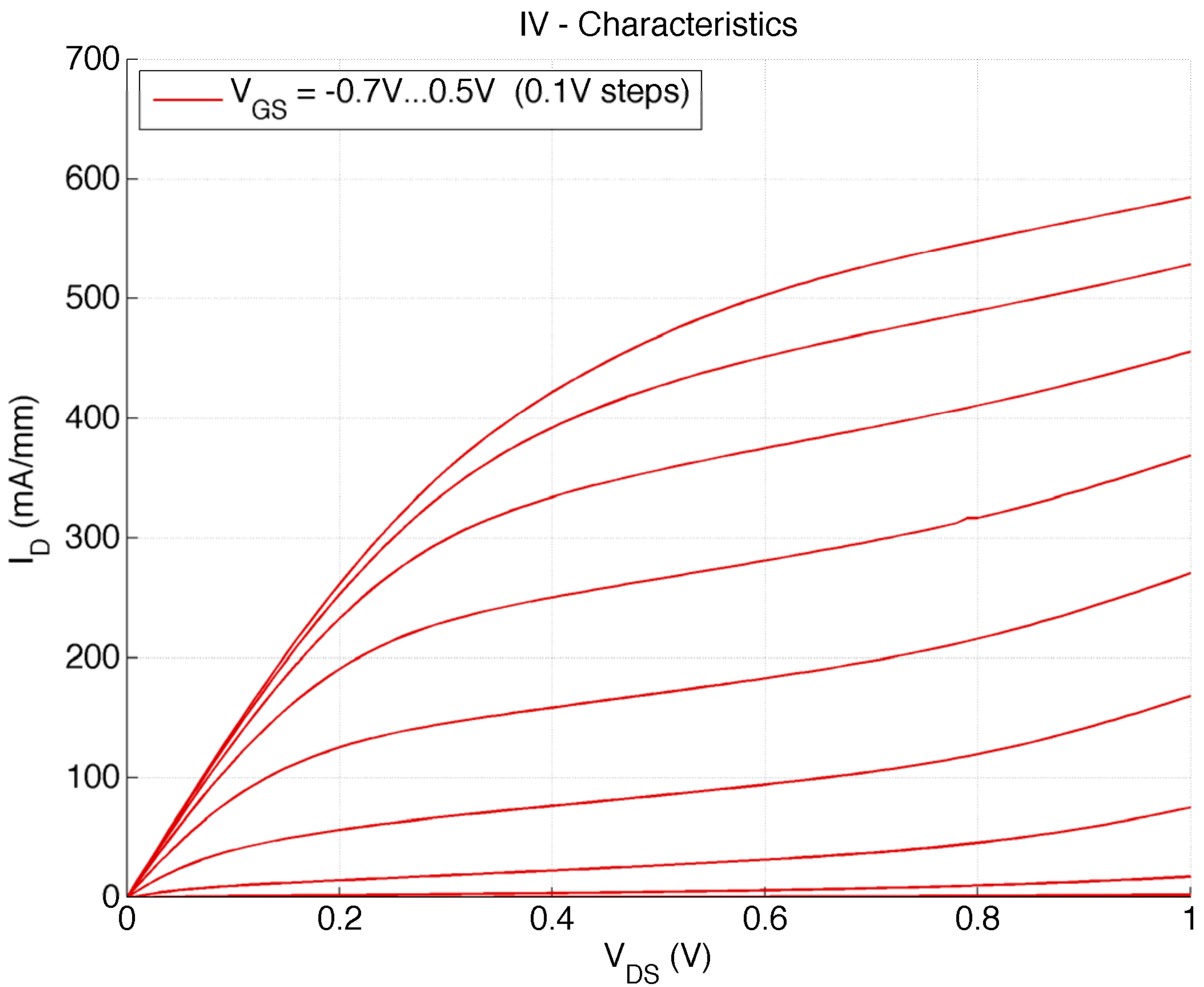
DC Device Characteristics @ RT

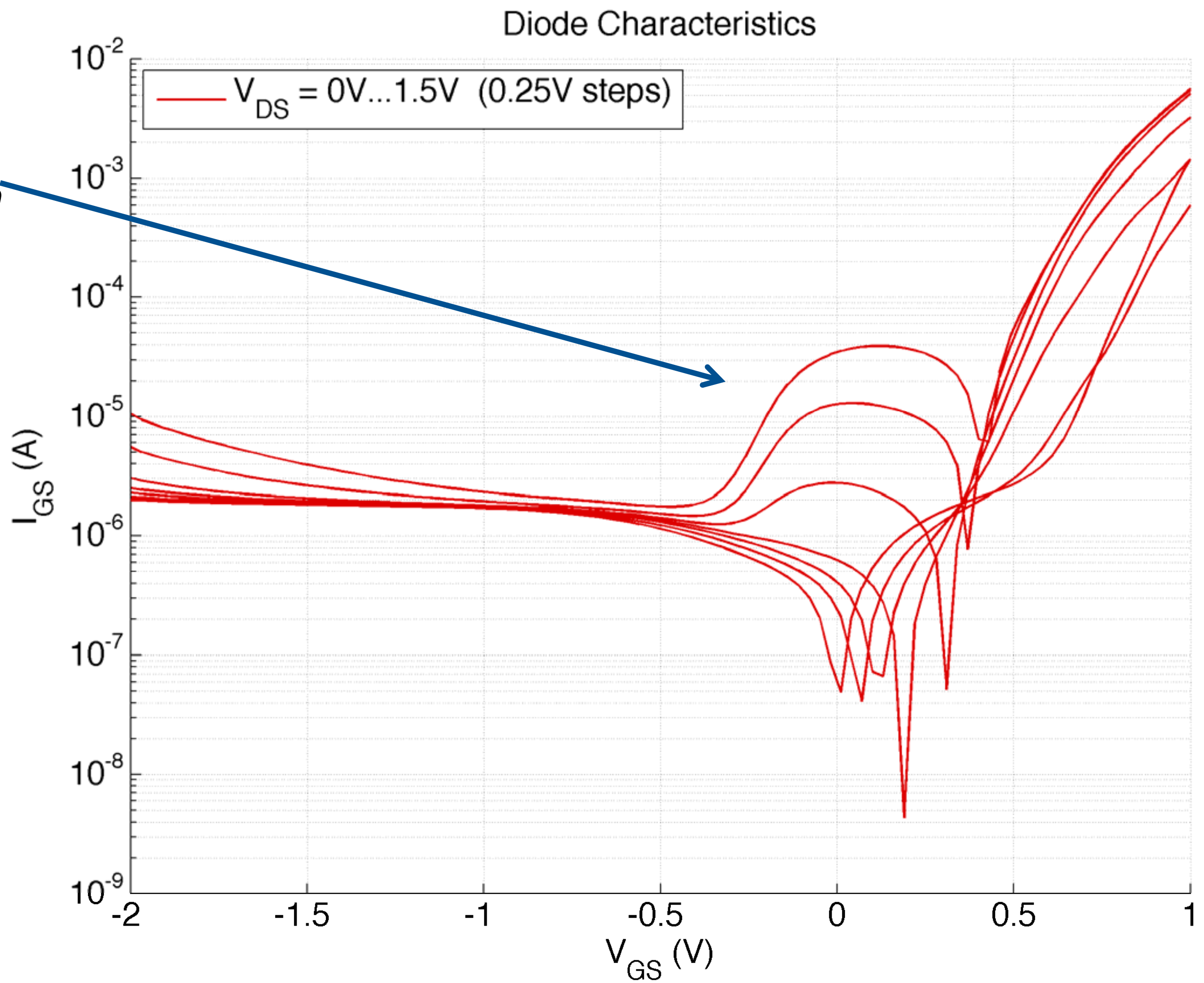


DC Device Characteristics @ RT



DC Device Characteristics @ RT

Impact Ionization (V_{DS} ≥ 1V



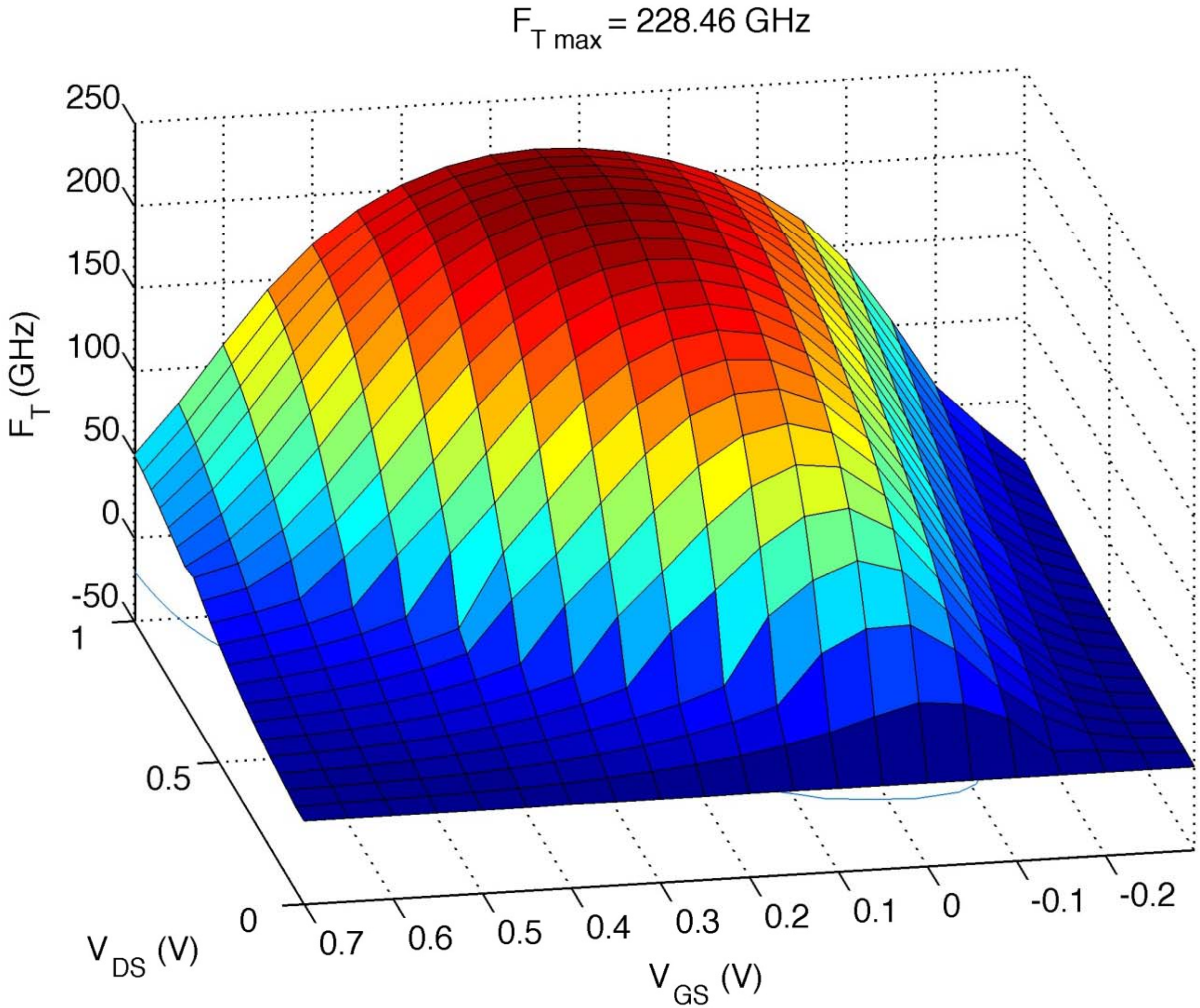
RF Device Characteristics @ RT

- *Bias Sweep*

  Without *Removing*

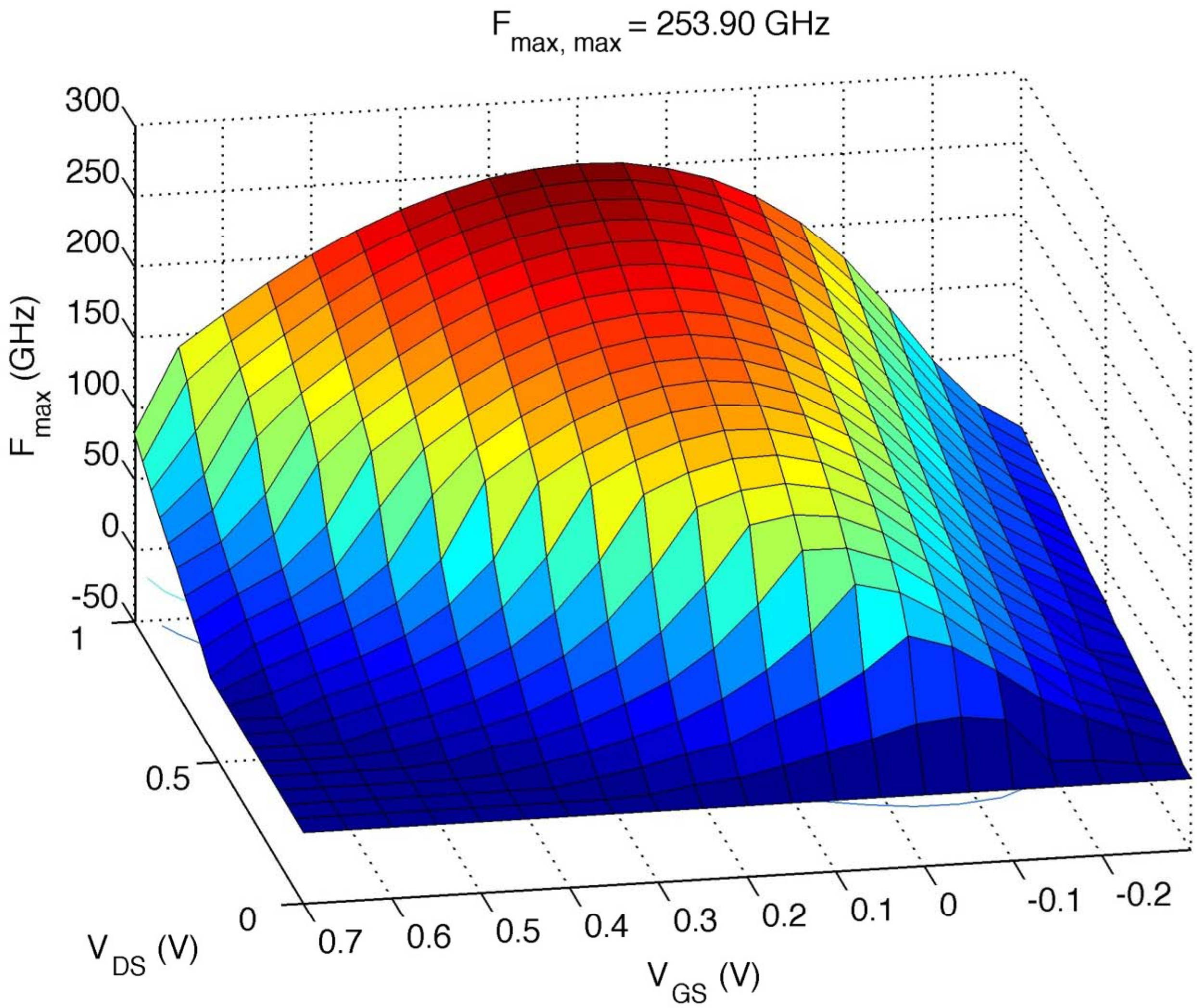
  Pad-Parasitics!

- *0.1µm x 150µm*

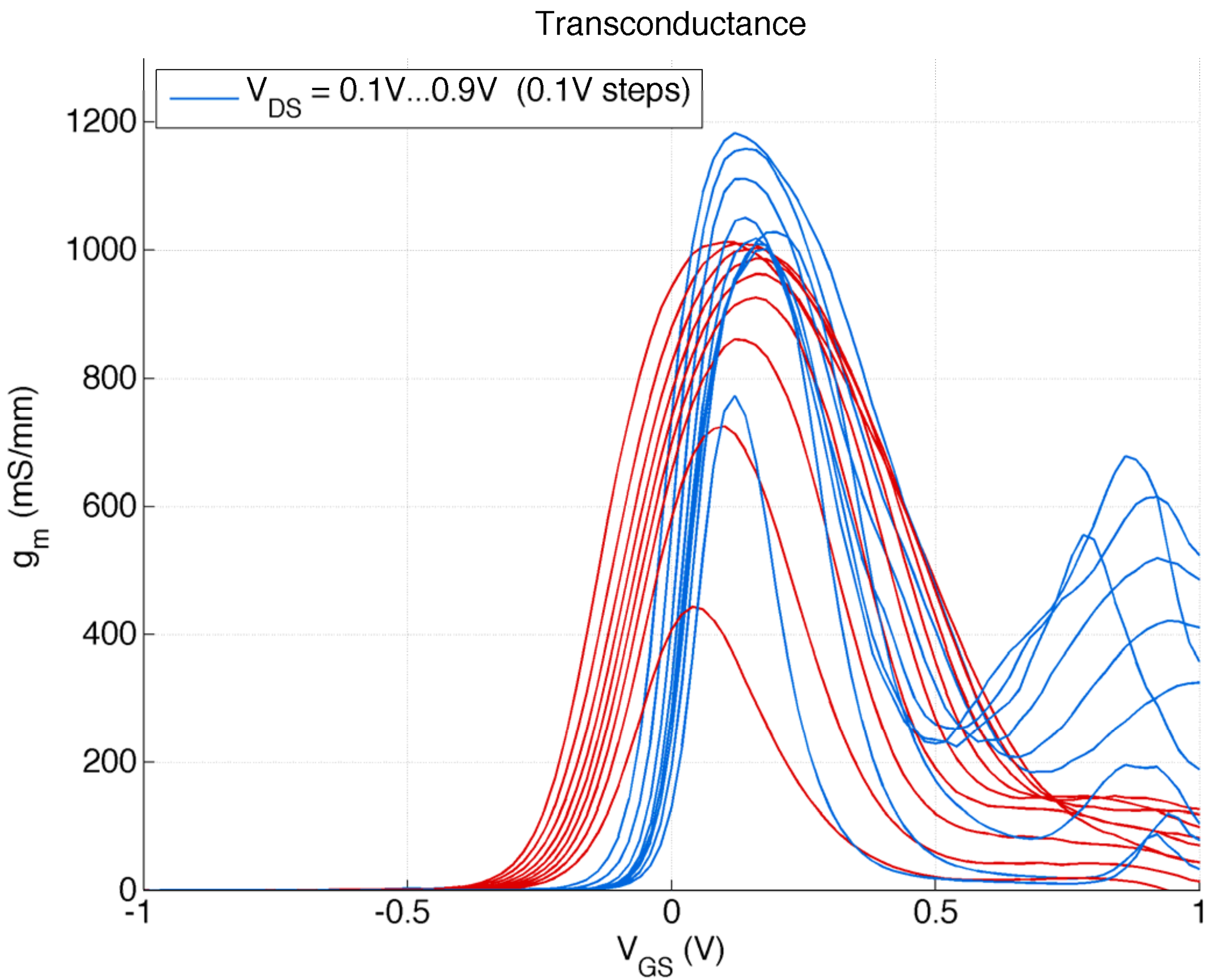


RF Device Characteristics @ RT

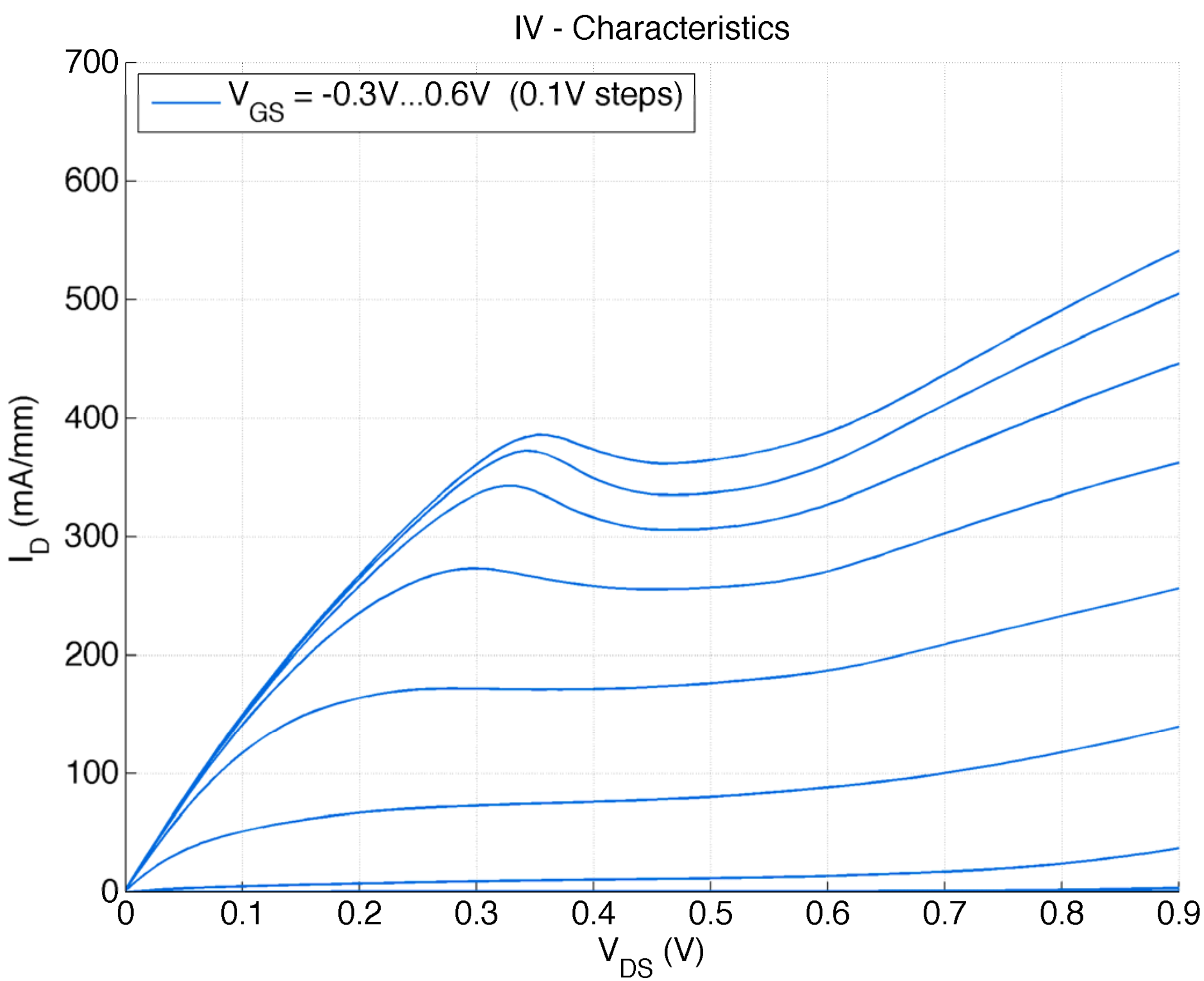
- *Bias Sweep*
  Without *Removing Pad-Parasitics!*
- *0.1µm x 150µm*



DC Device Characteristics @ 15K vs. 300K



DC Device Characteristics @ 15K



DC Device Characteristics @ 15K vs. 300K

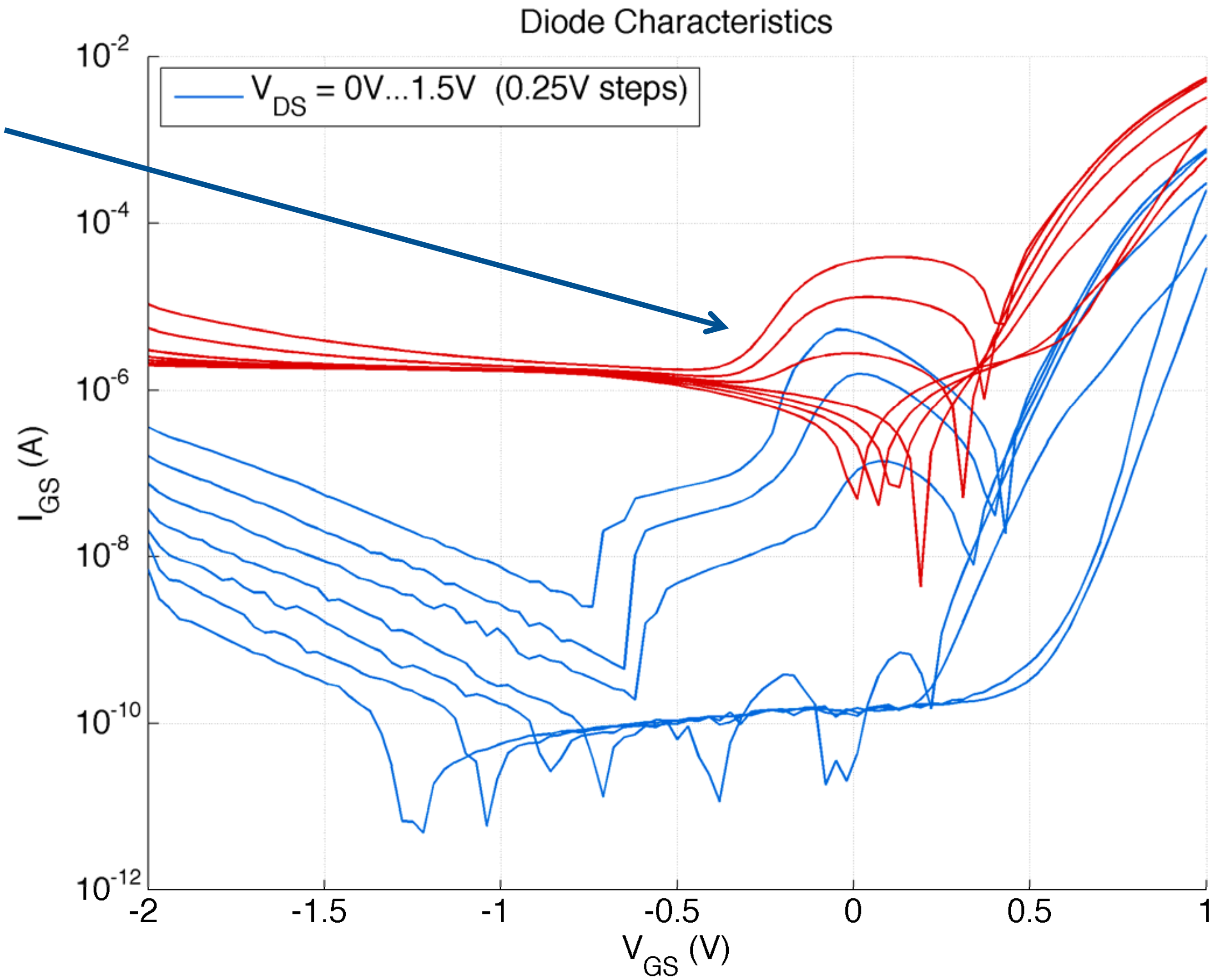
Impact

Ionization

(V_{DS} ≥ 1V

I_G↓ by 4 Orders

of Magnitude!



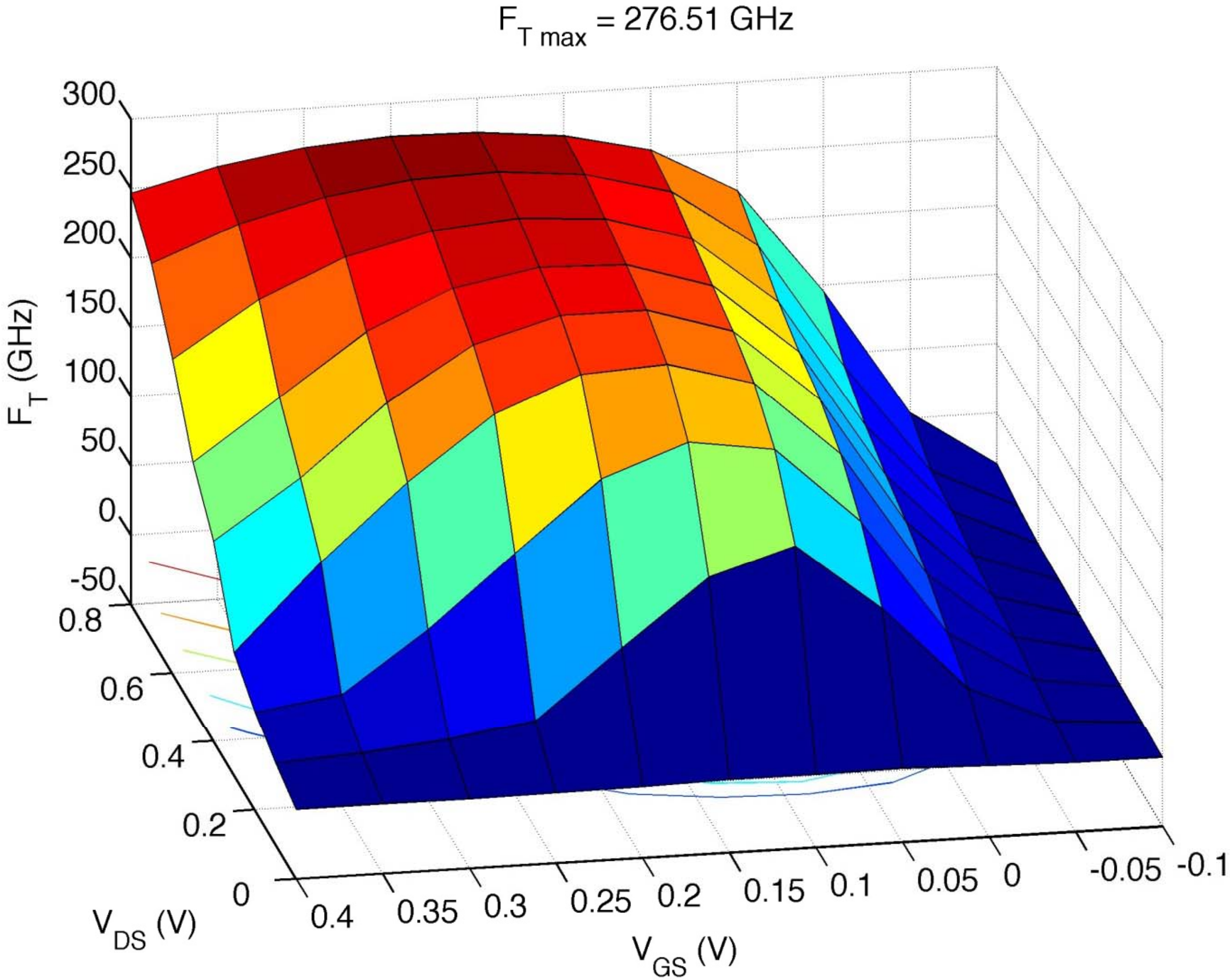
RF Device Characteristics @ 15K

- *Bias Sweep*

  Without *Removing*

  Pad-Parasitics

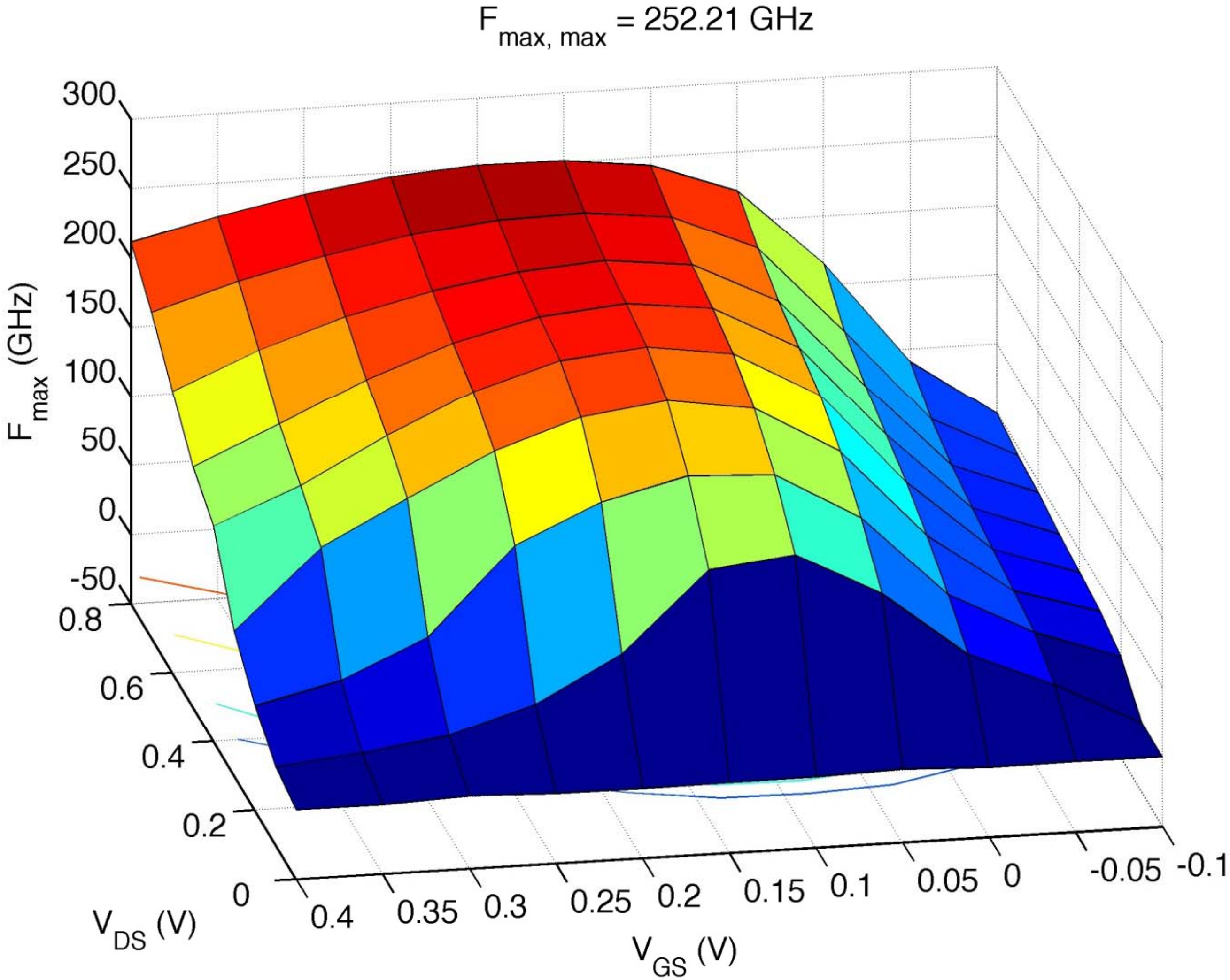
- *0.1µm x 150µm*



RF Device Characteristics @ 15K

- *Bias Sweep*

  Without *Removing Pad-Parasitics*
- *0.1µm x 150µm*



RF Device Characteristics @ 15K

- *RF Data*

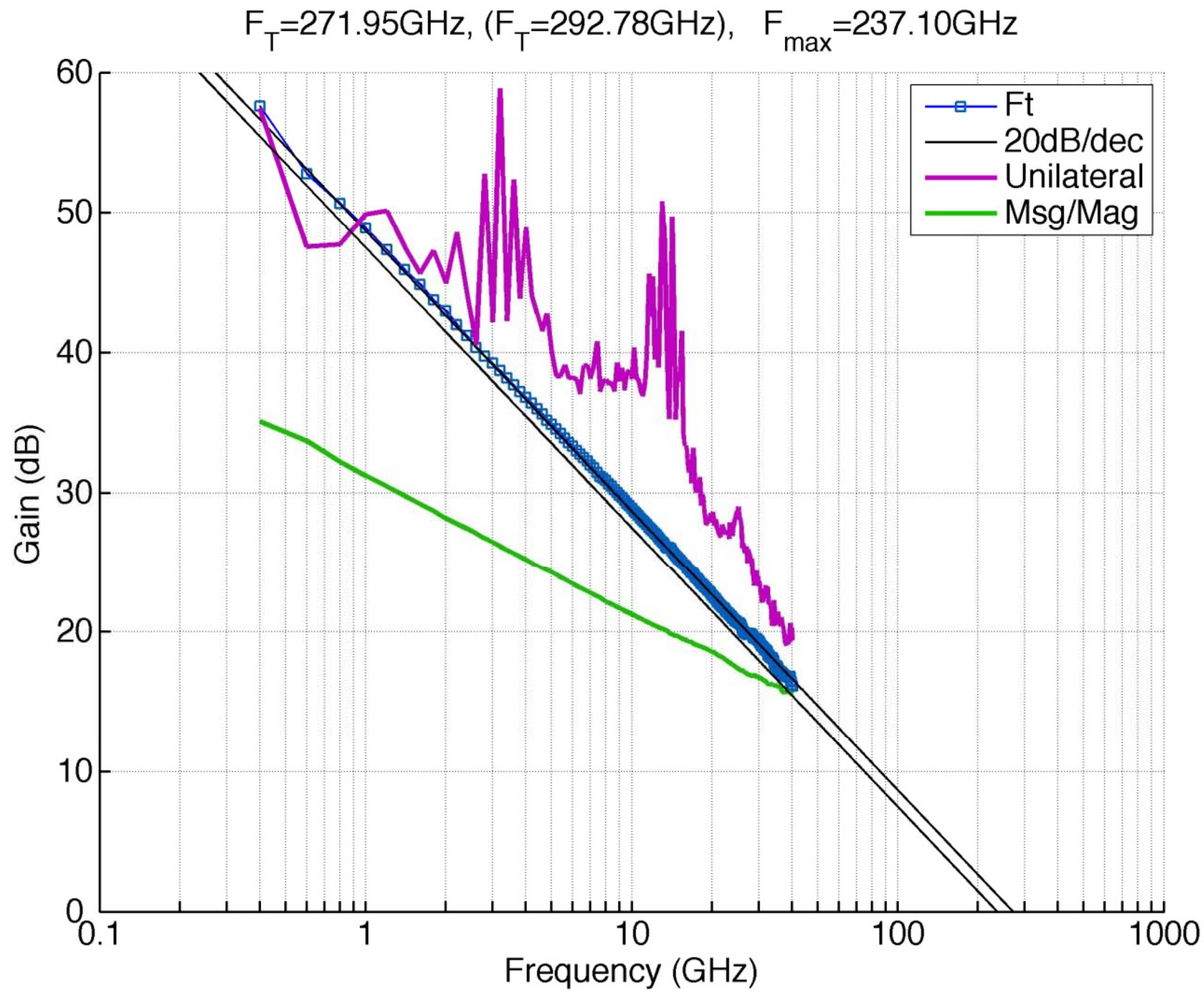
  ***Without** Removing*

  Pad-Parasitics!

- *F_T of 272 GHz @*

  0.7V V_{DS}, 0.2V V_{GS}

  *31mA I_{DS}, **0.12nA I_{GS}***



RF Device Characteristics @ 15K

- *RF Data*

  Without *Removing*

  Pad-Parasitics!

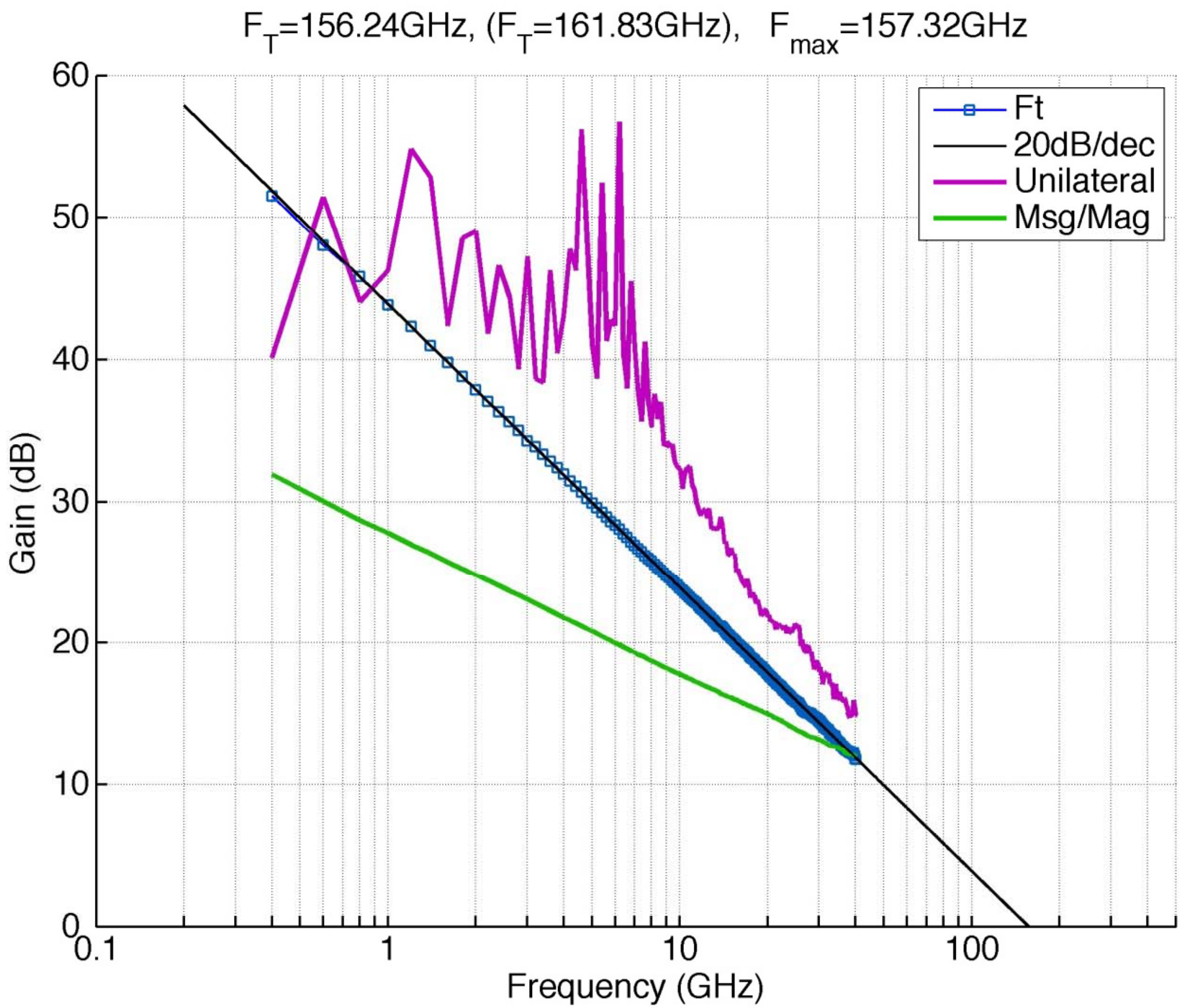
- ***Typical Low-Noise***

  Bias Point @

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

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

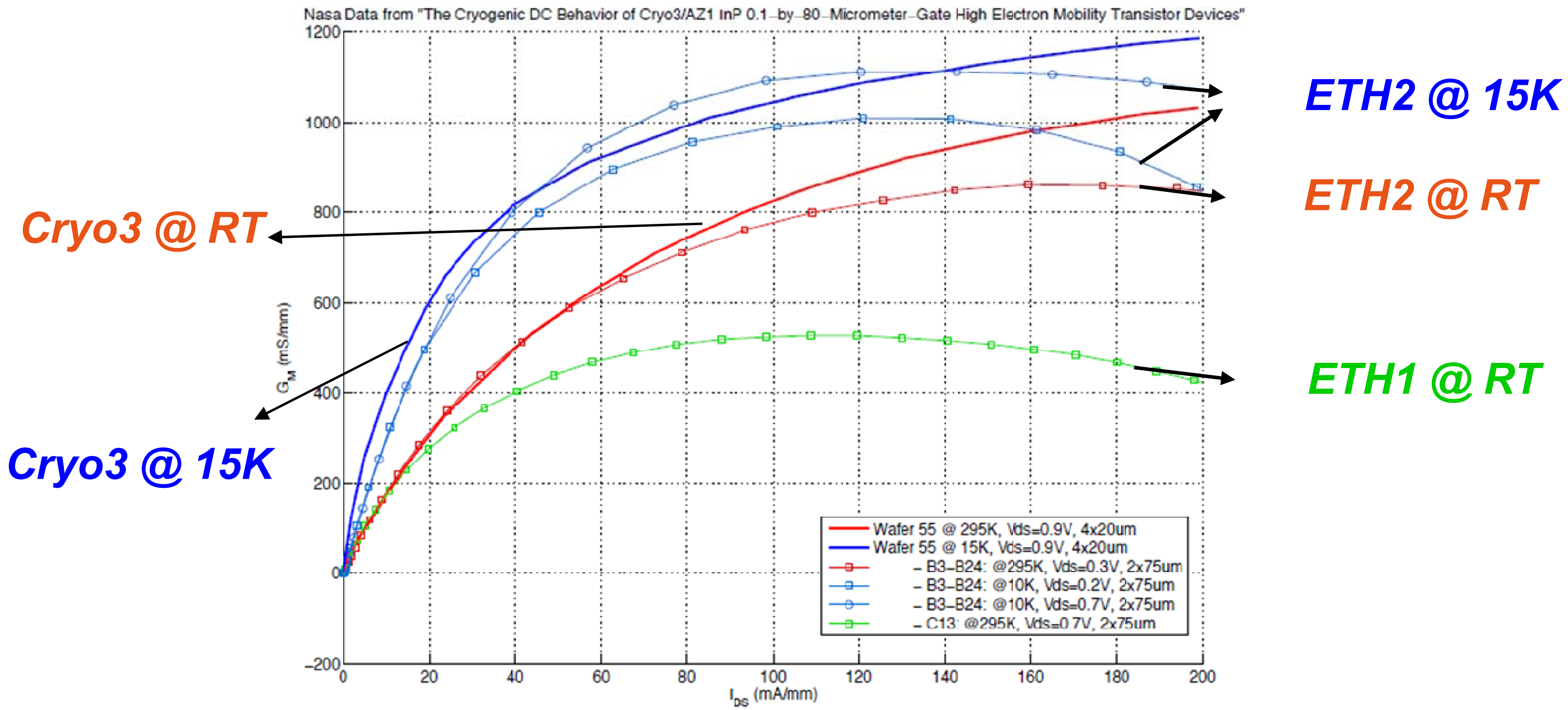
  F_T = 156 GHz



How Judge on Cryo-Noise Performance - Without Building the Amplifier ?

Cryo3 (4x20µm) vs. ETH (2x75µm)

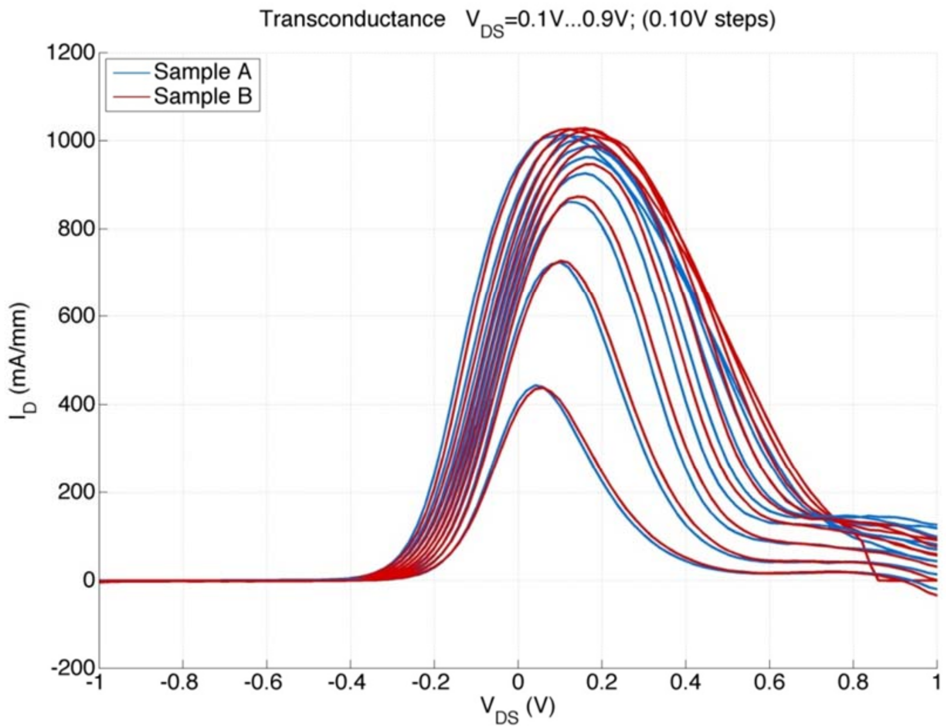
(Not Quite Fair 4F vs. 2F!)

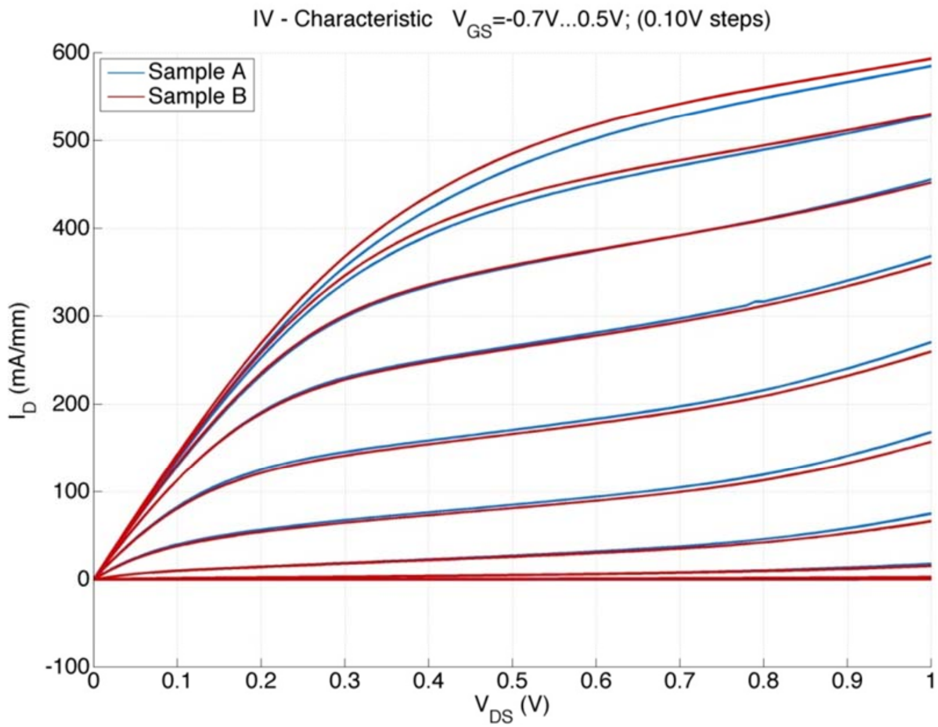


Processing Impact on Device Characteristics

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

(Everything Else Kept the Same)





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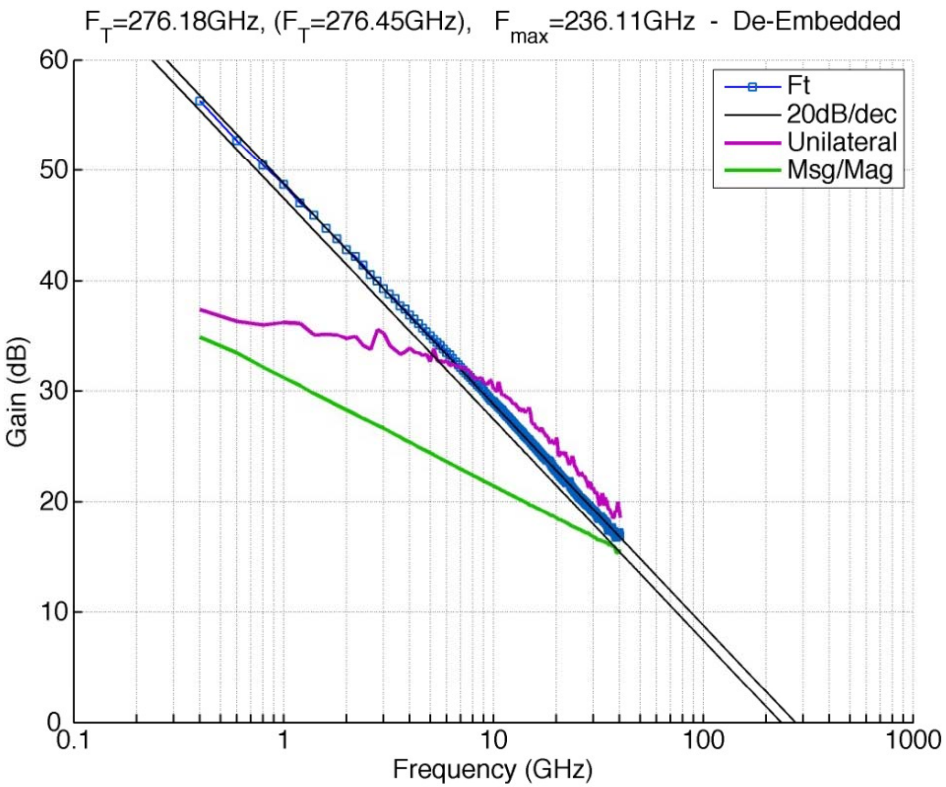
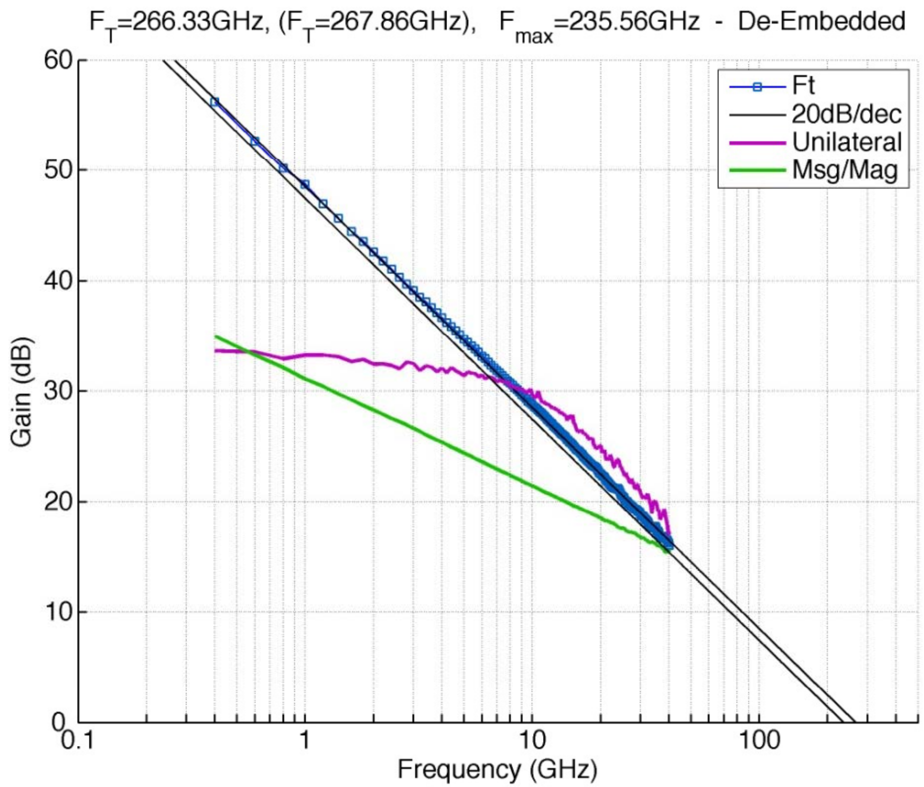
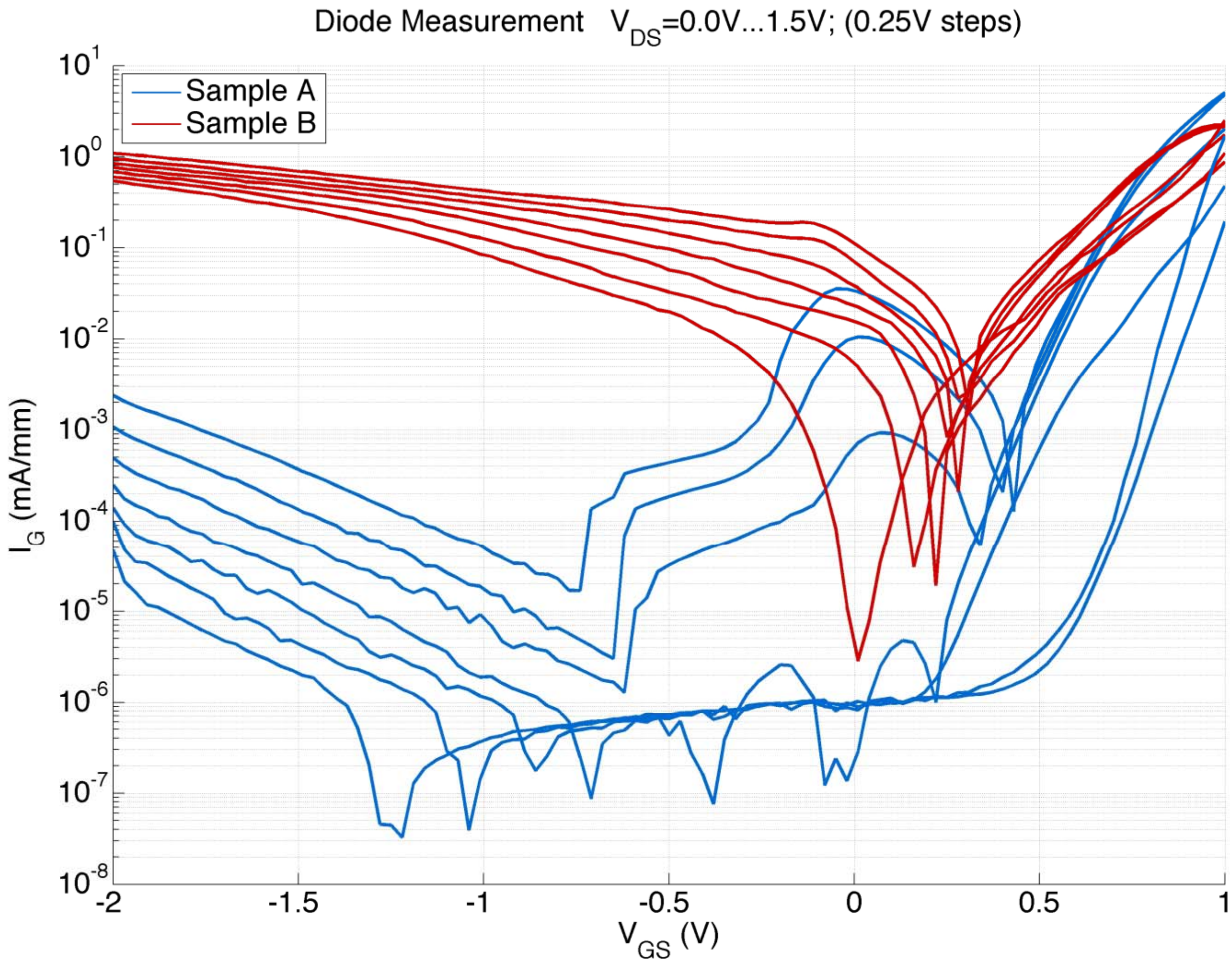




Processing Impact on Device Characteristics

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



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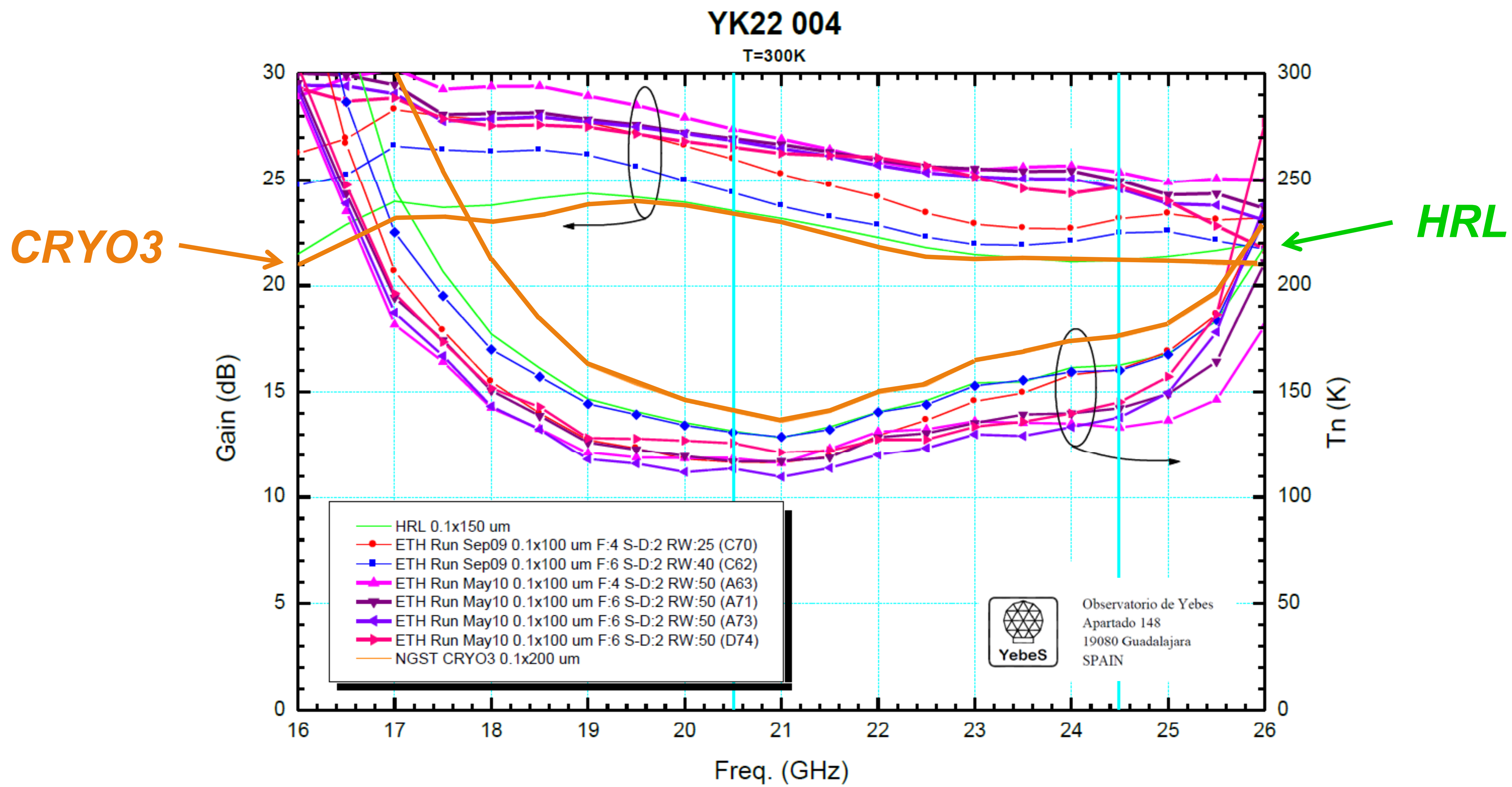
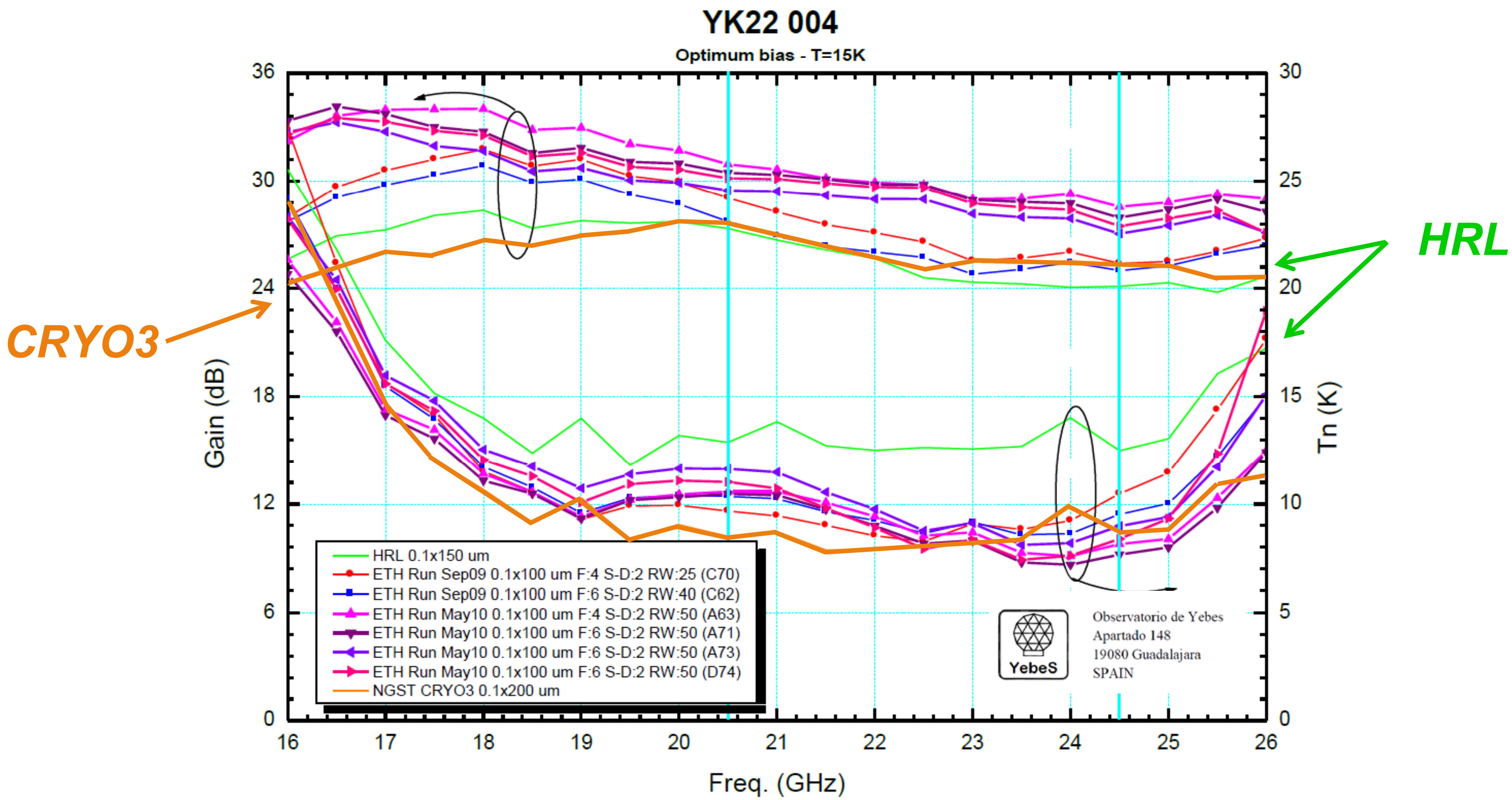
Result Considerations

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



YEBES Amplifier Results @ 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*
- *ETH 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*

End