

The IAF mHEMT-Technology for low-noise mm-Wave and cryo-MMICs

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From Room-Temperature to Cryogenic Applications

- Status of the IAF-HEMT-Technology :
 - IAF well established as european source for MMICs
 - MMICs from 1 GHz to 500 GHz
 - State of the art RT noise figure

- Motivation:
 - Crosslink with radioastronomy
 - Increasing demand for Cryo-MMICs
 - Scientific Challenge

- Objective:
 - Cryo-Optimization of low noise HEMT-Technology

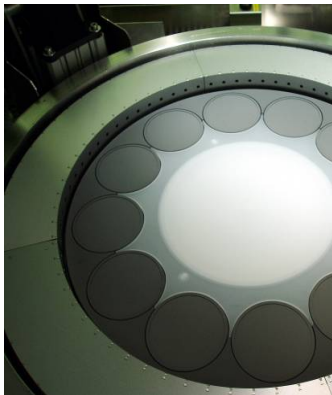
Outline

- IAF Facilities for High Frequency Electronics
- The IAF mHEMT Process
- MMICs for RT applications
- Process Monitoring
- Assessment of the potential for Cryo-MMICs
- Modelling
- Summary

IAF Expertise High-Frequency Electronics

European Source for HF-devices, -circuits and -modules

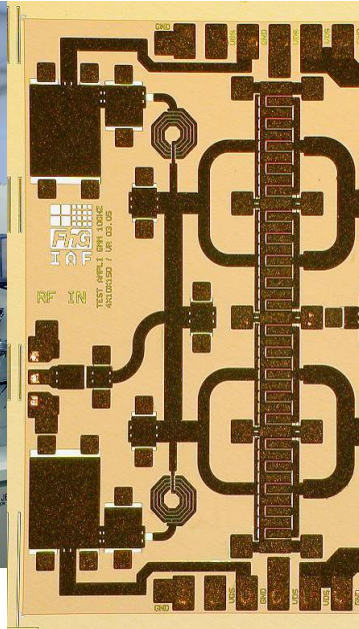
**Material
Epitaxy**



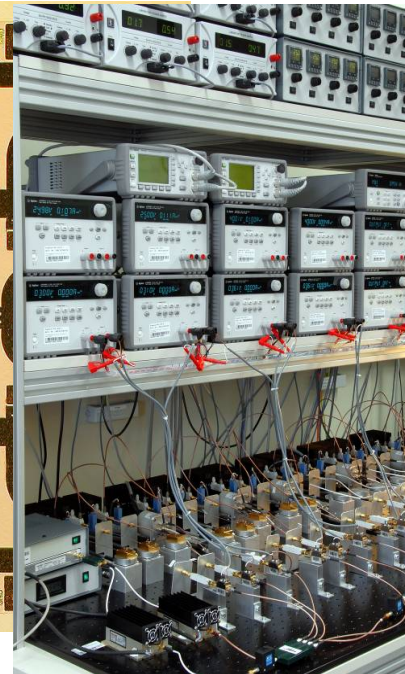
**Process
Technology**



**Design
MMICs**



**Measurement
Reliability**



**Packaging
Modules**

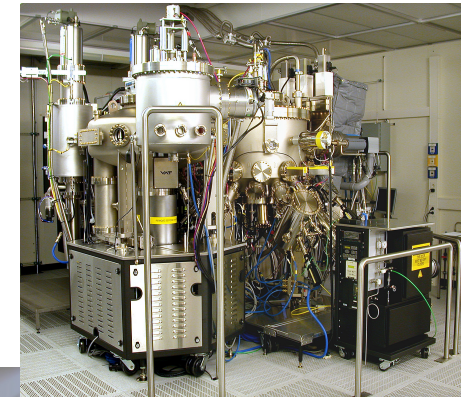


Processing Equipment used for the IAF Technology

- 4 x 4" Wafer MBE "GEN 200"
- Jeol JBX 9300 Electron Beam Lithography
- Canon 5000+ wafer stepper

Automatic Batch Tools for

- Wafer Coating and Developing
- Plasma Etching
- Plasma Deposition
- Thermal Annealing
- Metal Deposition (Sputtering, Evaporation, Galvanisation)



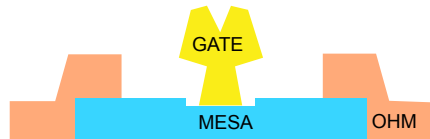
IAF mHEMT-Technology: Processing

MESA

wet etched MESA



GeAu Ohmic contacts

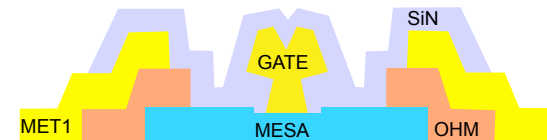


PtTiPtAu e-beam gate

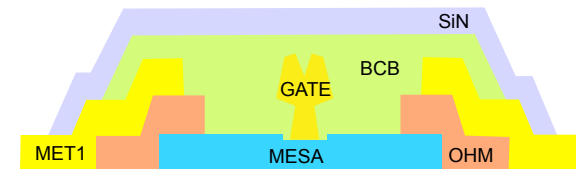


1. Metall

100 nm technology



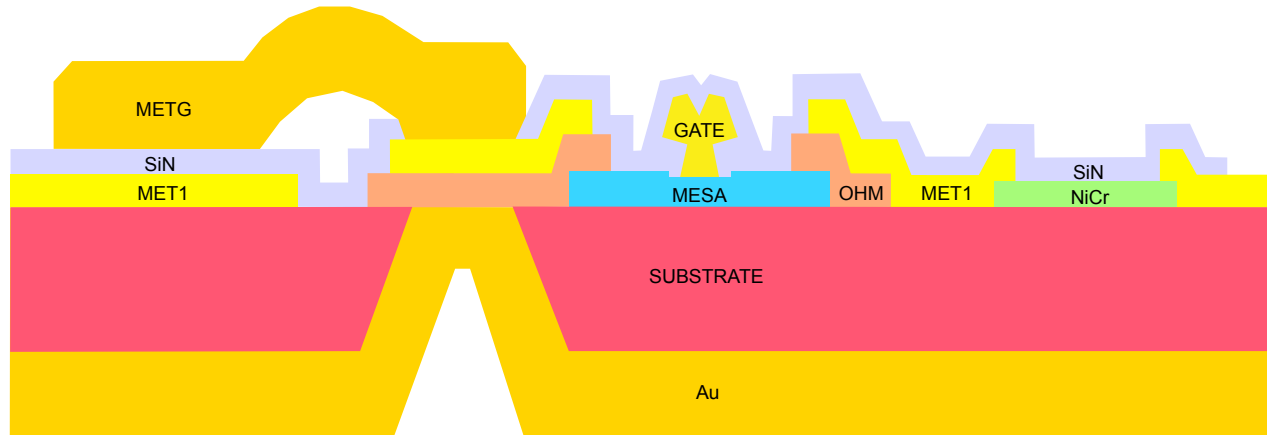
250 nm SiN passivation



250 nm SiN passivation on BCB

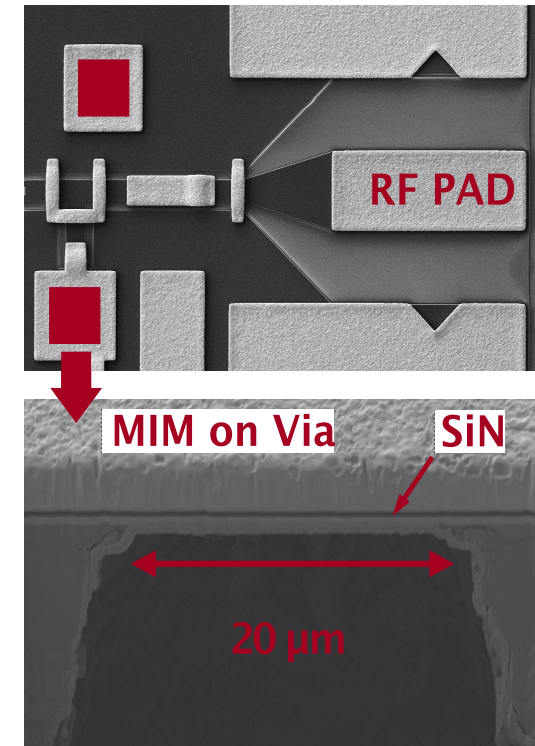
50/35 nm
technology

IAF mHEMT Technology für MMICs



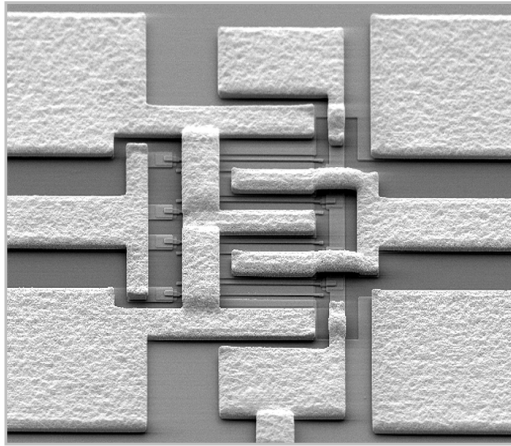
Characteristic features

- 2 Metallization layers
- 2.7 μm Au air bridges
- 225 pF/mm² MIM capacities
- 50 $\Omega/\square$ NiCr resistors
- 250 nm CVD SiN passivation
- Back side process (thinning and via-holes)



Transmission environment:
Grounded Coplanar

IAF mHEMT Processes



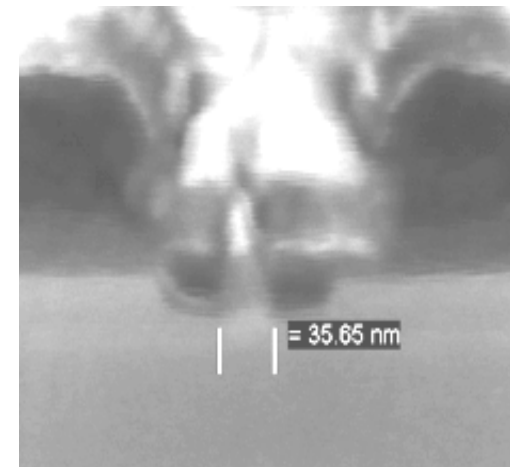
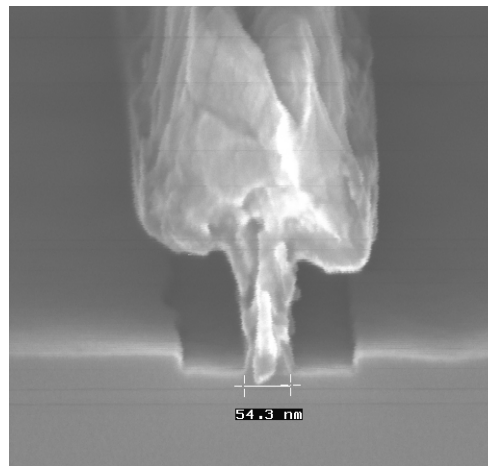
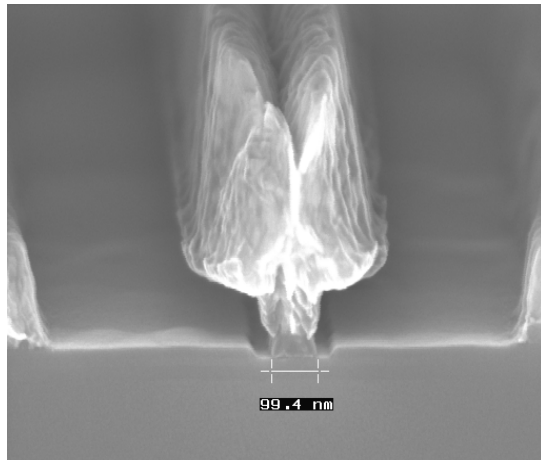
$L_G = 100$ nm
established

- mHEMT

- metamorphic High Electron Mobility Transistor

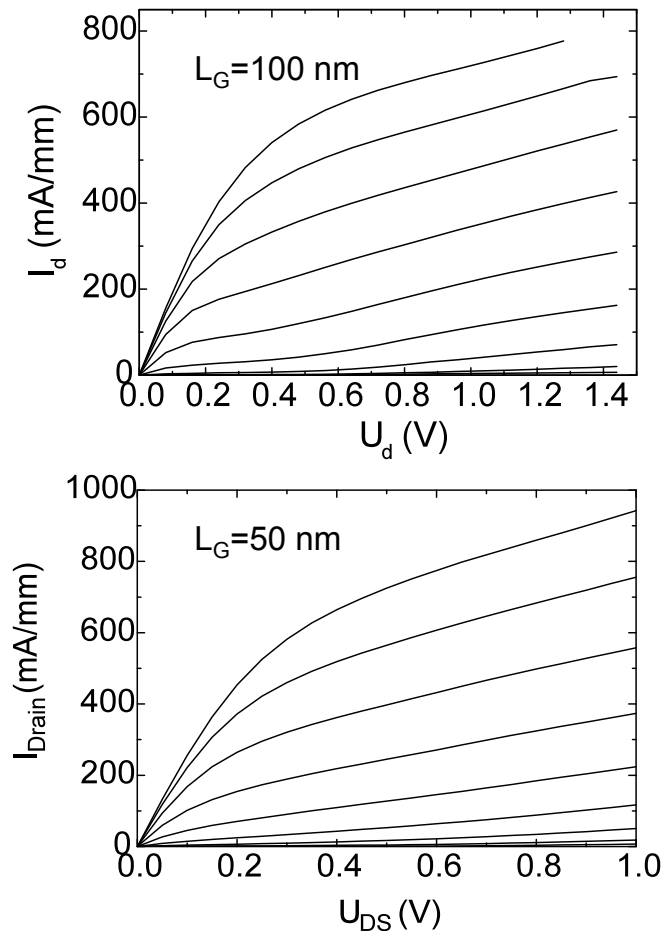
- Comparison with InP-HEMTs :

- different substrates
 - identical active layer structure



IAF mHEMT Technologies: DC- und RF-Parameters

Characteristic Parameters for 35, 50 and 100 nm $\text{In}_x\text{Ga}_{1-x}\text{As}$ mHEMTs



	35 nm	50 nm	100 nm
x (%)	80	80	65
R_C (Ωmm)	0.03	0.05	0.07
R_S (Ωmm)	0.10	0.15	0.23
R_g (Ω/mm)	250	250	400
$I_{D,\text{max}}$ (mA/mm)	1600	1200	900
V_{BD} (V)	2.0	2.5	4
$G_{m,\text{max}}$ (mS/mm)	2500	1800	1300
f_T (GHz)	550	380	220
f_{max} (GHz)	~900	~600	300

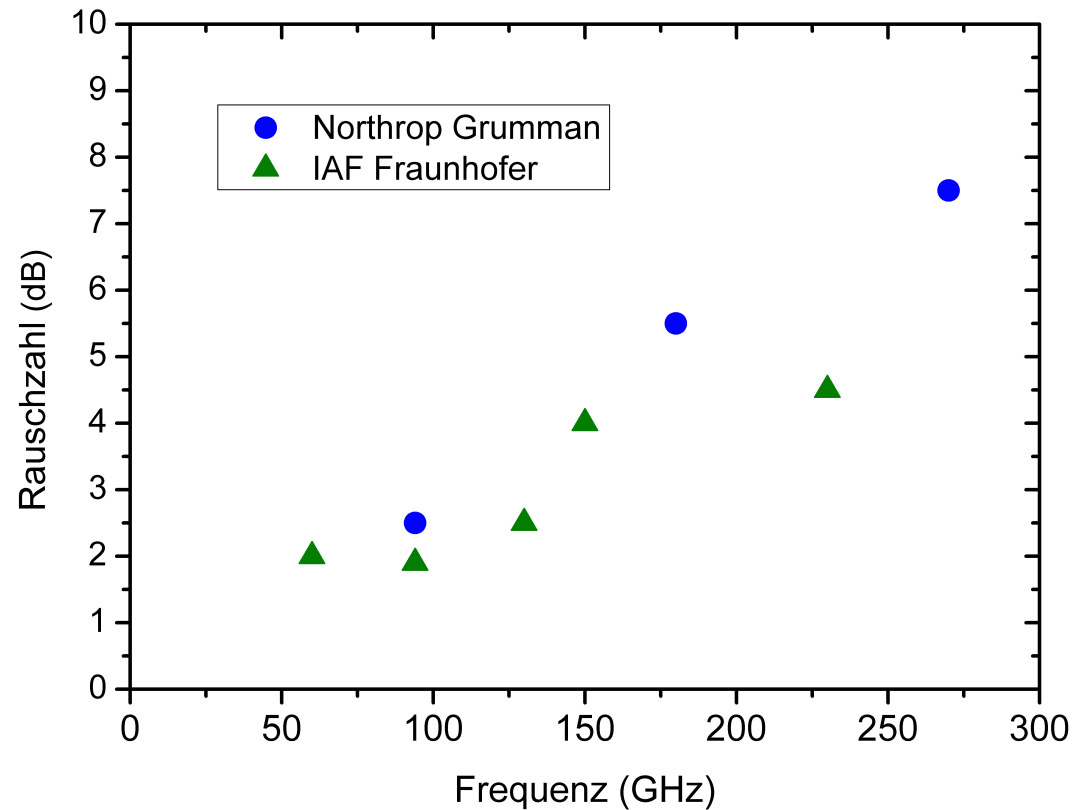
$$T_{\text{min}} = \sqrt{T_{\text{amb}} T_{\text{CE}}} \frac{f}{f_{\text{max}}}$$

für $f \ll f_{\text{max}}$

M.W. Pospieszalski, *IEEE Microwave Magazine*, vol. 6, no. 3, 62, 2005

RT-Performance of the IAF-LNAs

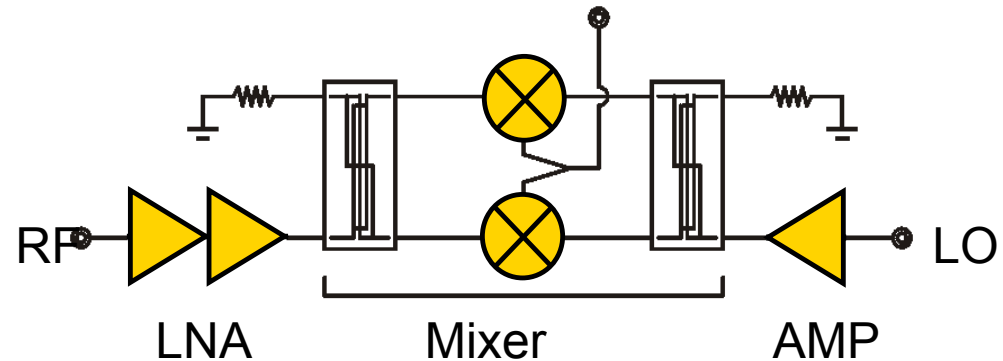
- Within Europe: leading position IAF
- Worldwide: neck-and-neck race with NGC



Data up to 2008

Multifunktional MW Circuits

W-Band Heterodyne Receiver MMIC



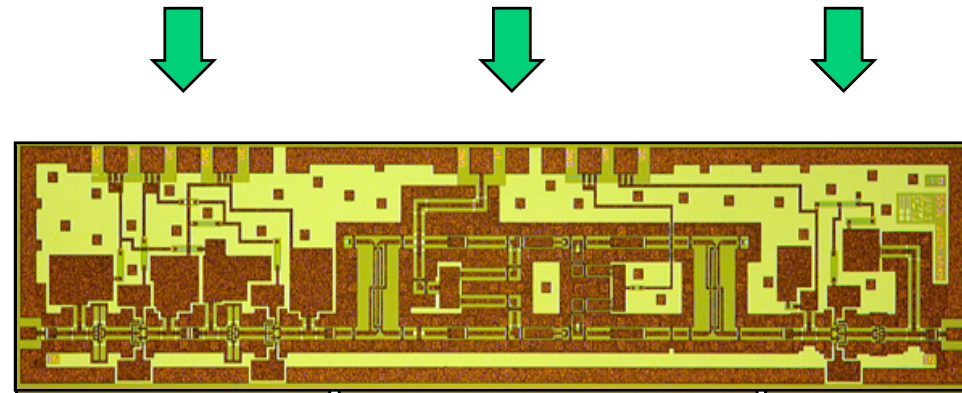
Building blocks :

two-stage low-noise amplifier

balanced resistive mixer
(2 Lange coupler)

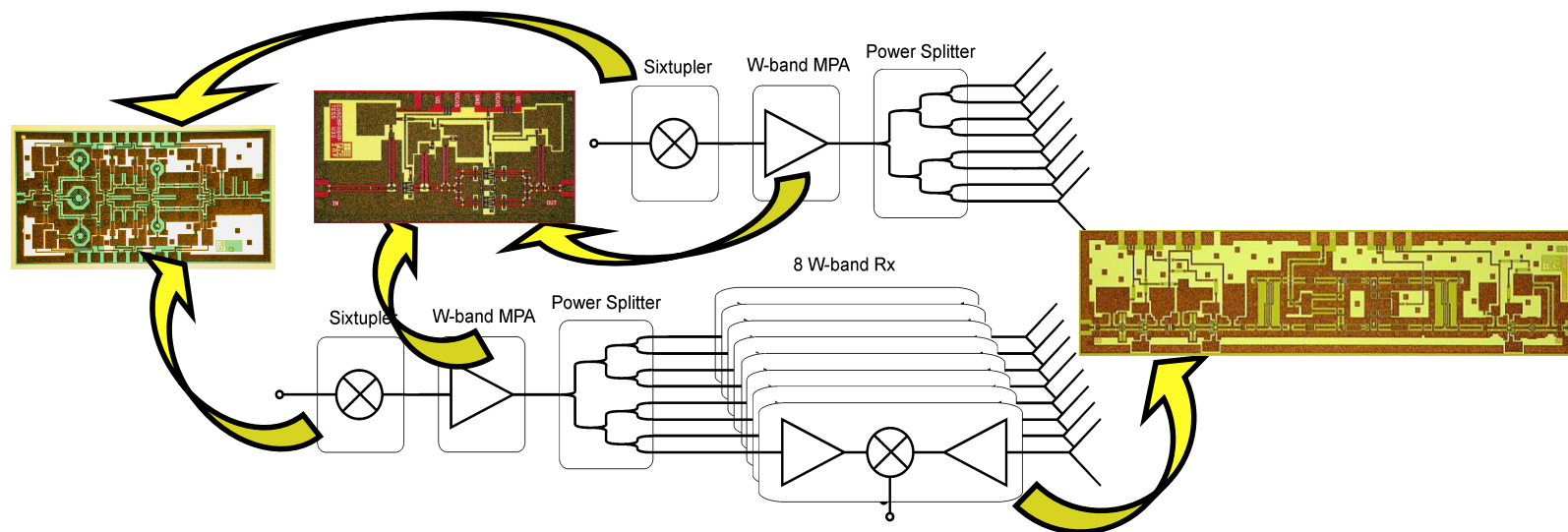
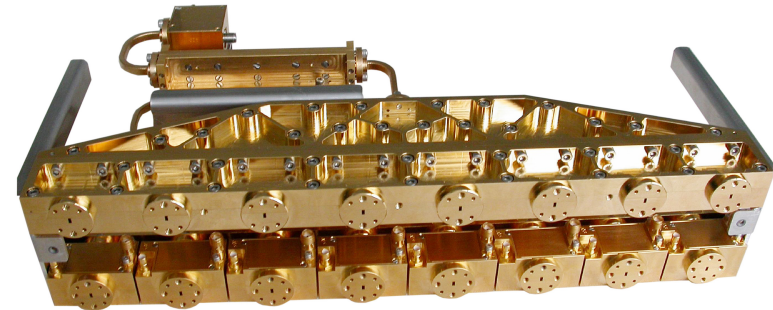
single-stage LO driver amplifier

Chip Size: 1 x 4 mm²

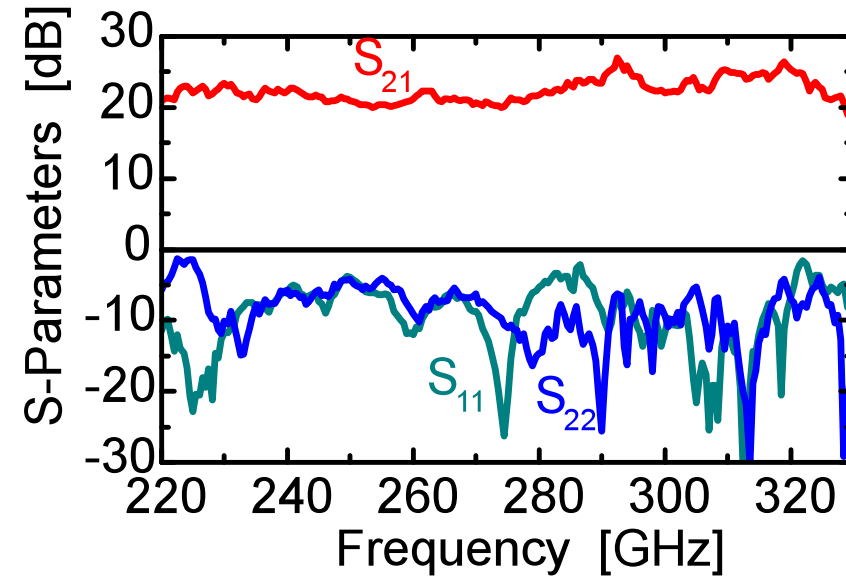
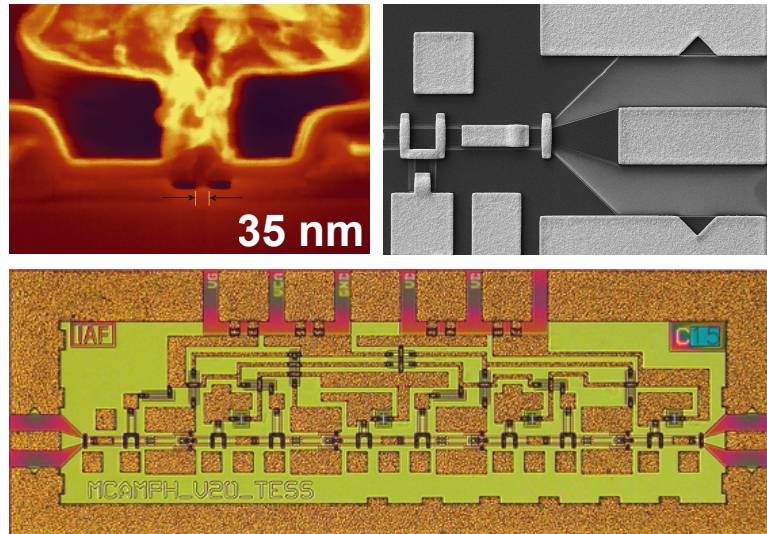


Module for Imaging Radar System at 94 GHz

- 8-Channel-Radar for W-Band (75...110 GHz)
- Frontend MMIC built from IAF modules:
 - Frequency-Sixtupler: BW = 83...105 GHz
 - Driver Amplifier: $P_{\text{out}} = 14 \text{ dBm}$
 - 1:8 Power Divider: $A = 13 \text{ dB}$
 - Receiver: $G_{\text{conv}} = 6 \text{ dB}$, $\text{NF} = 4 \text{ dB}$

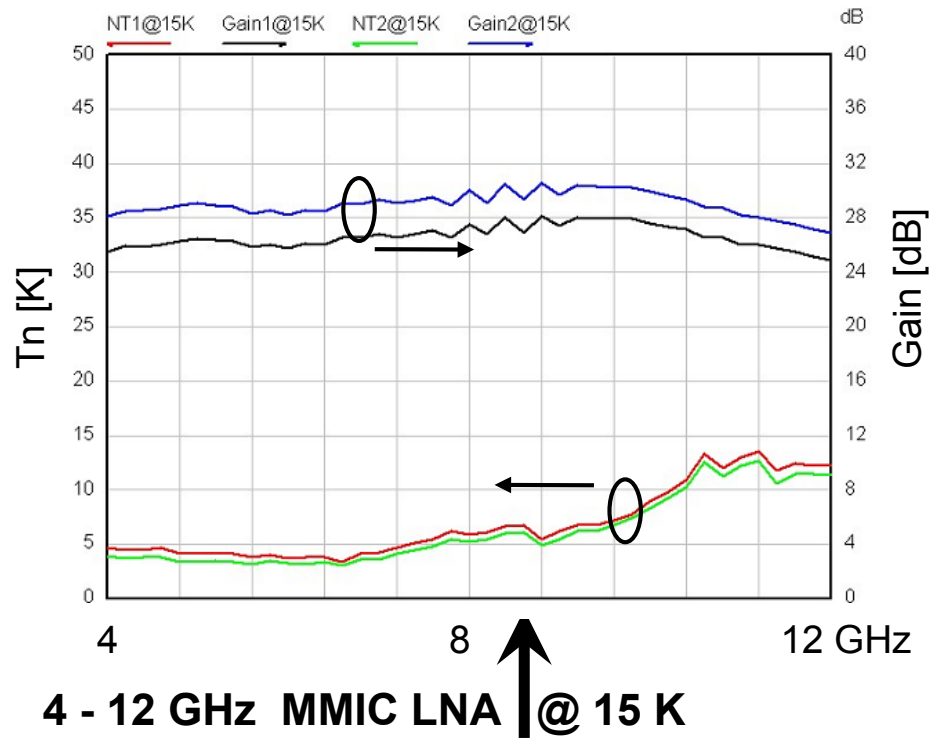


UWB Submillimeter-Wave Amplifier MMIC



- 35 nm gate length mHEMT
- four-stage cascode LNA
- chip size 0.5 x 1.2 mm²
- gain: > 20 dB @ 220...325 GHz
- noise figure: 6.9 dB (sim.)
- power consumption: 50 mW

IAF MMICs for Radioastronomic Receivers

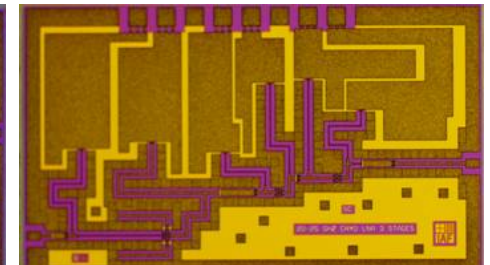
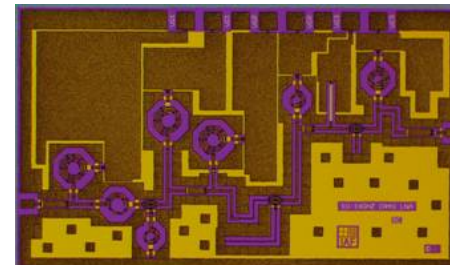
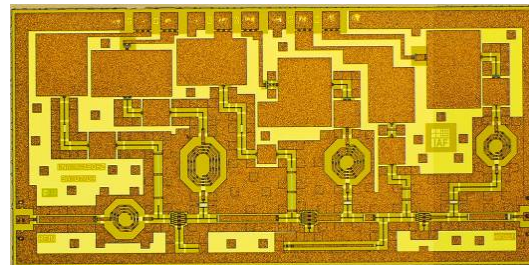
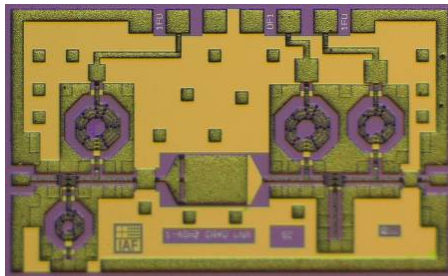


First cooperation project IAF / MPIfR / IRAM
Goal: Cryo-Test of the existing 100 nm mHEMT Technology IAF M39

- **Result: More insight required**
- **Development of four IF amplifiers**

Frequenz [GHz]	Gain [dB]	S_{11}, S_{22} [dB]	T_N [°K] (*)	P_{DC} [mW]
1-4	>27	< -15, -10	$T_N \sim 1..2$	<15
4-12	>27	< -15, -10	$2 < T_N < 4$	<15
10-18	>30	< -15, -10	$5 < T_N < 9$	<15
20-25	>30	< -15, -10	$10 < T_N < 12$	<15

(*) Best effort, goal is InP performance



Mappings R732b W149

LNA 4-12 GHz EXT

LNA 4-12 GHz EXT on IAF 732b

Wafer: 149

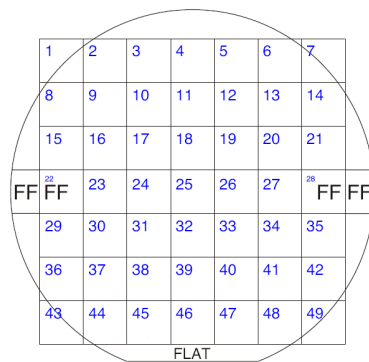
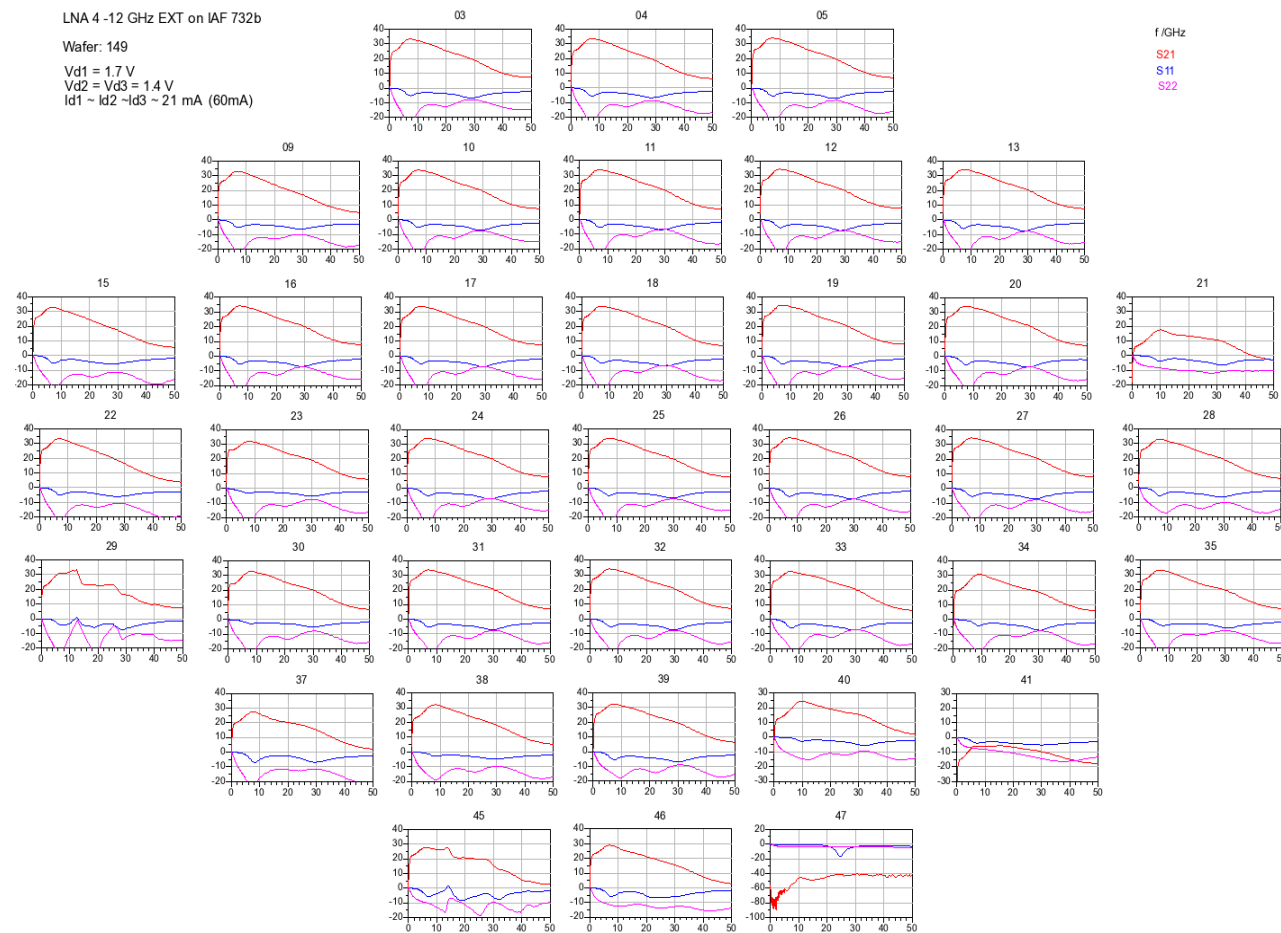
Vd1 = 1.7 V

Vd2 = Vd3 = 1.4 V

Id1 ~ Id2 ~ Id3 ~ 21 mA (60mA)

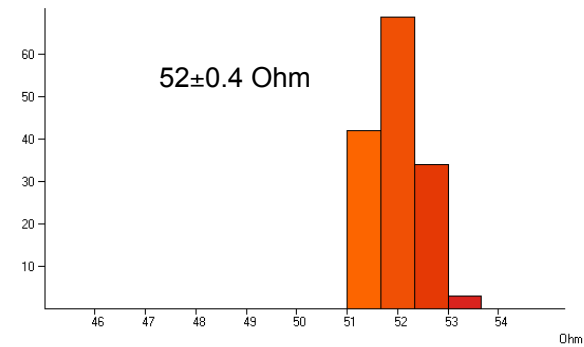
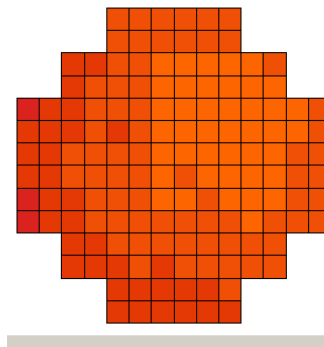
f /GHz

S21
S11
S22

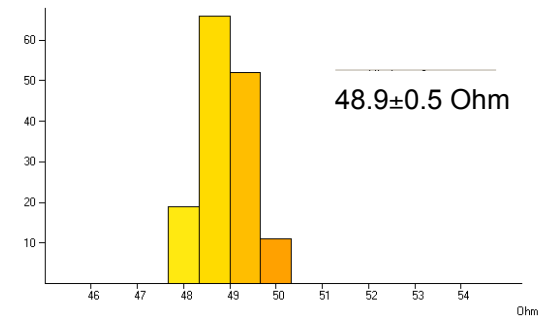
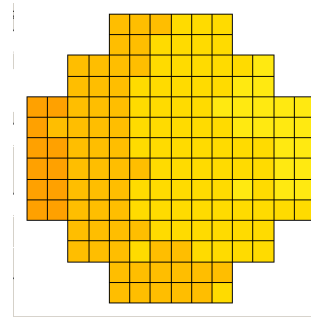


R729 NiCr Sheet

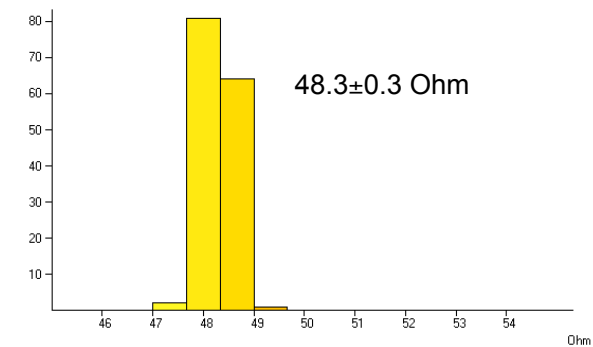
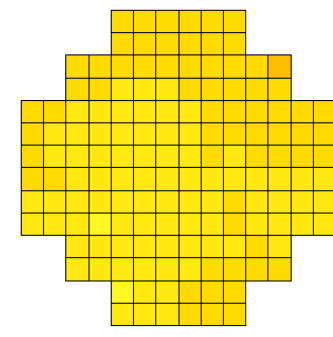
W87



W55

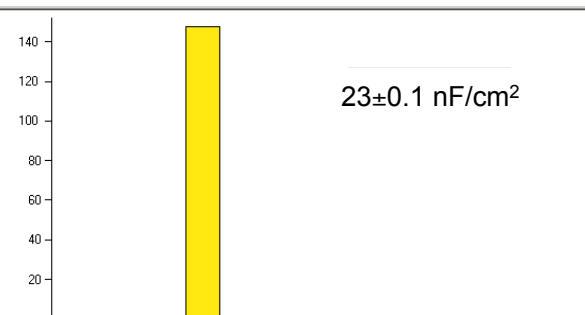
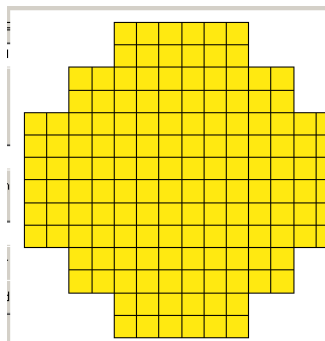


W88

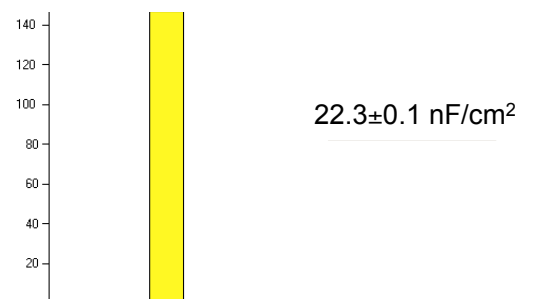
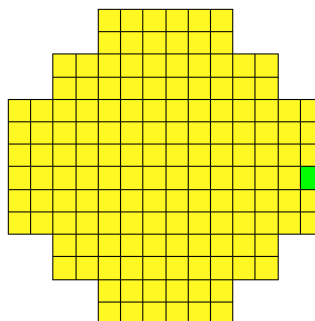


R729 MIM Capacities

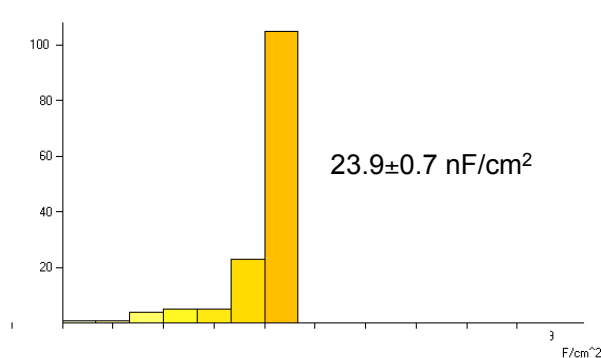
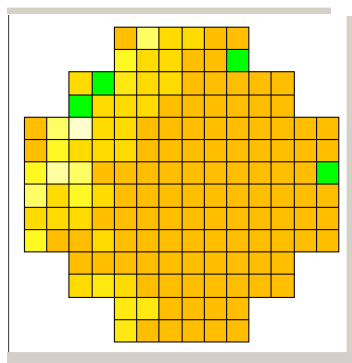
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W55

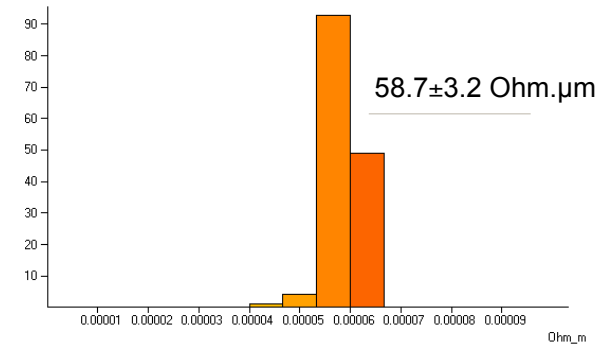
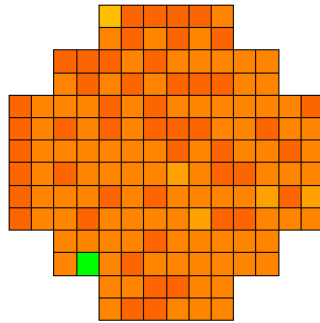


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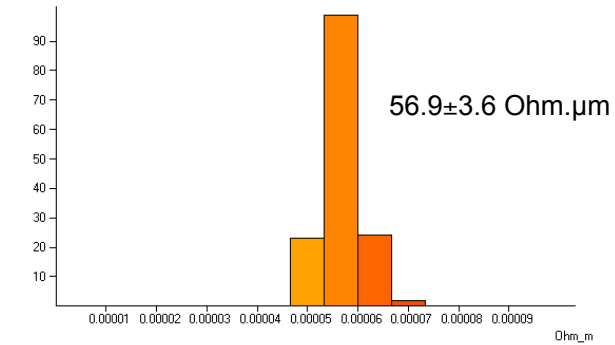
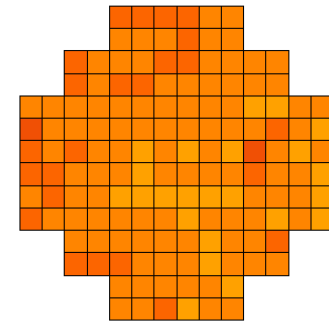


R729 Contact Resistance

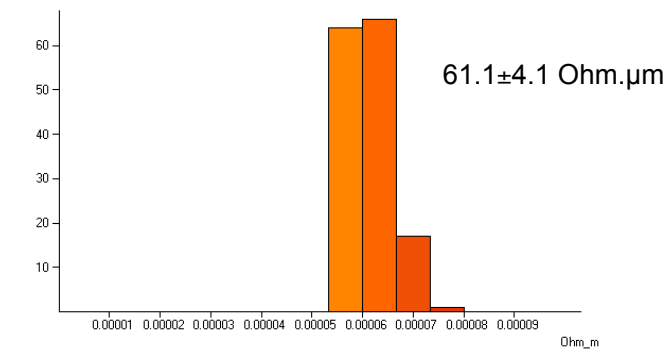
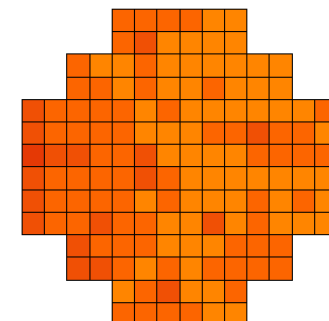
W87



W55

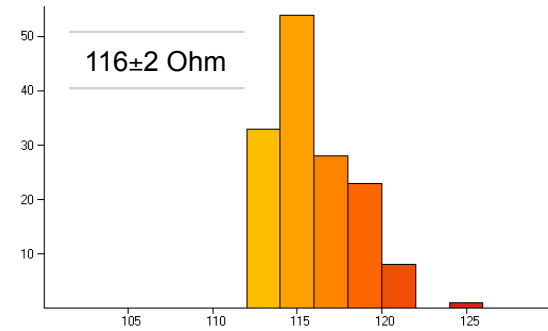
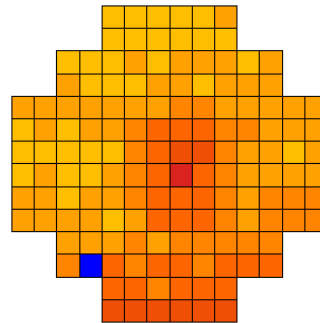


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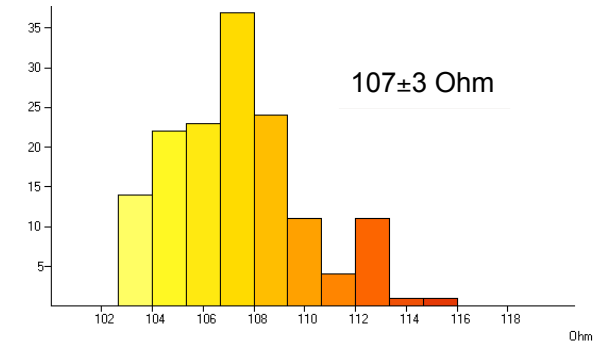
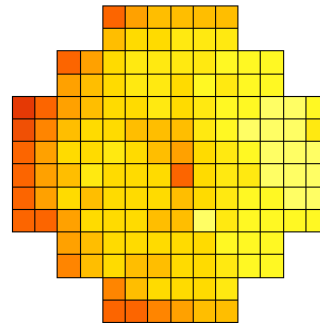


R729 Sheet Resistance

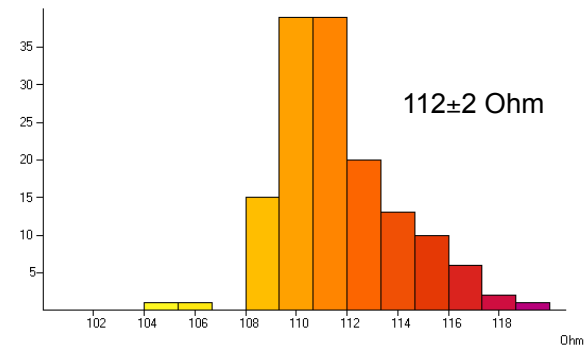
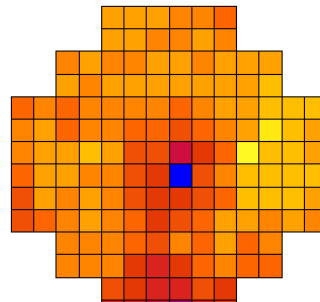
W87



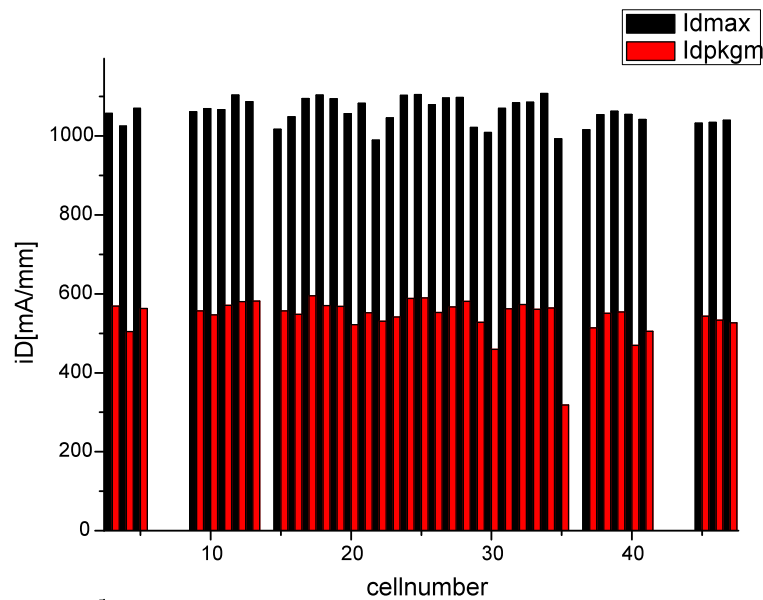
W55



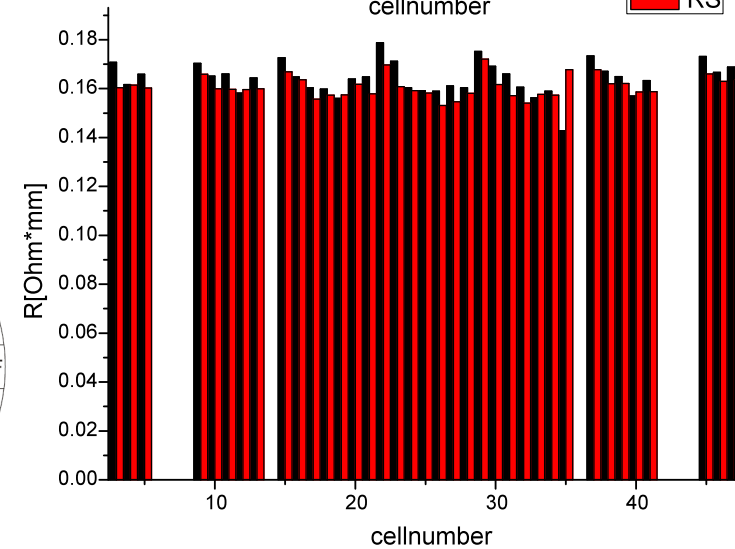
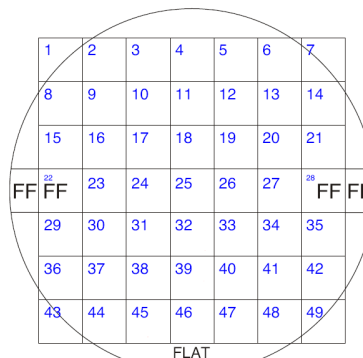
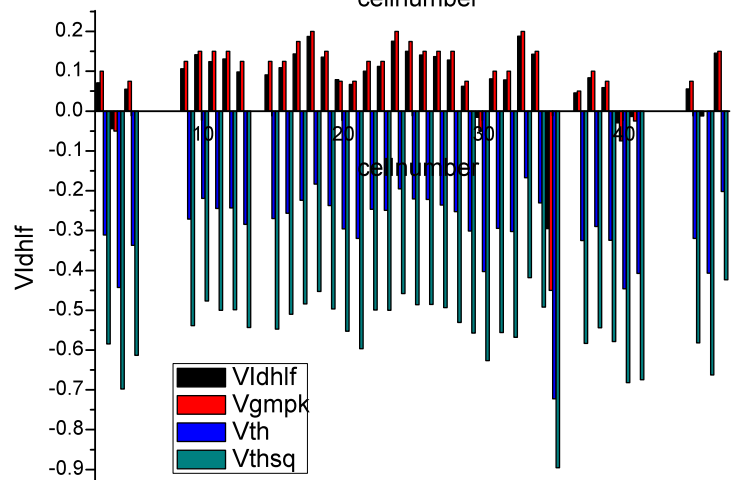
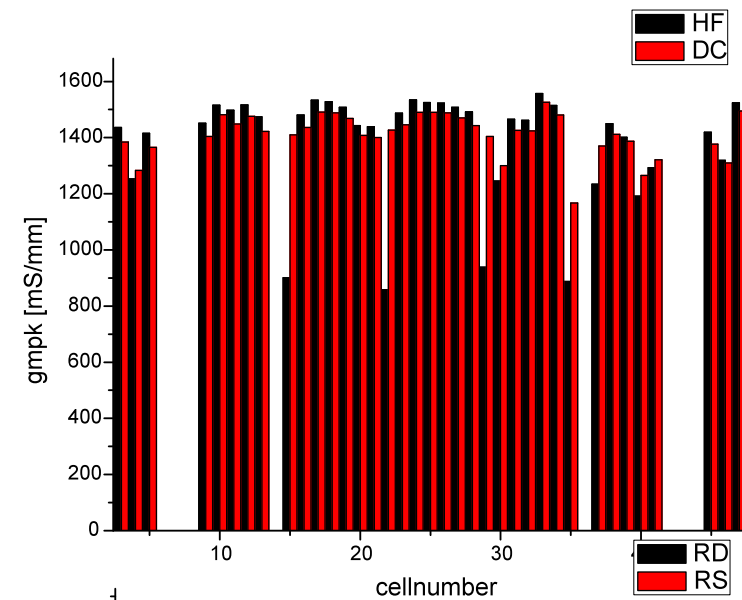
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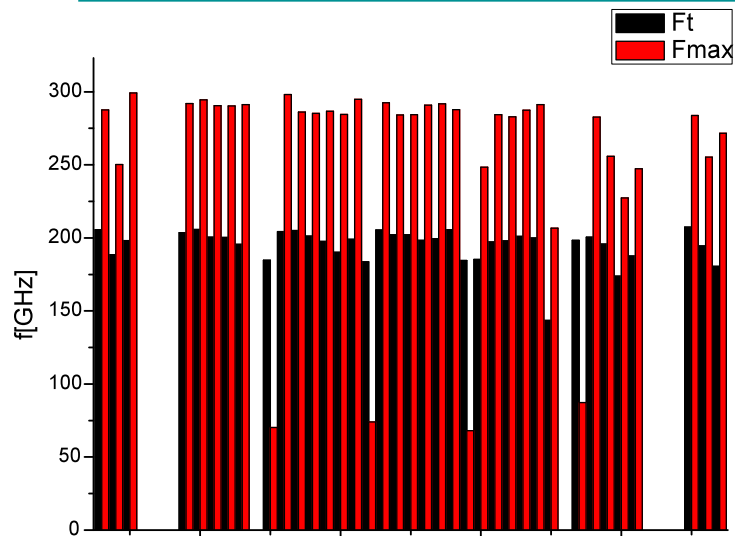
PCM Transistor Mapping DC



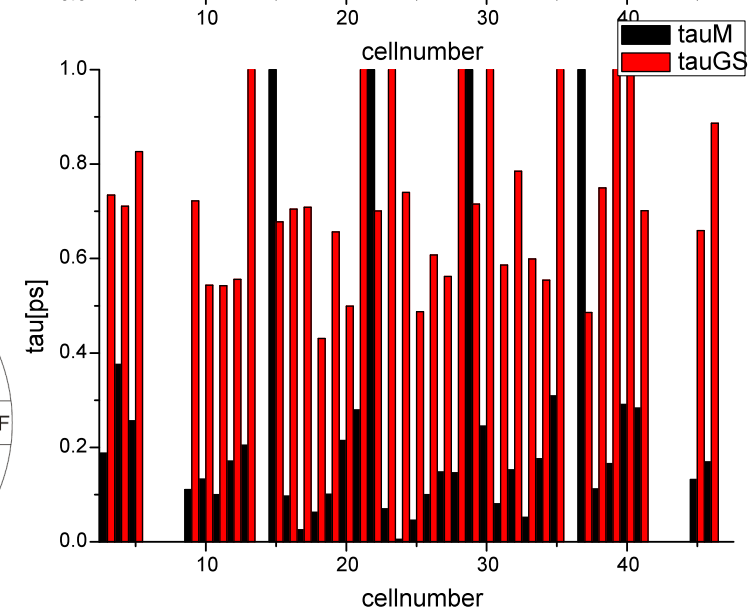
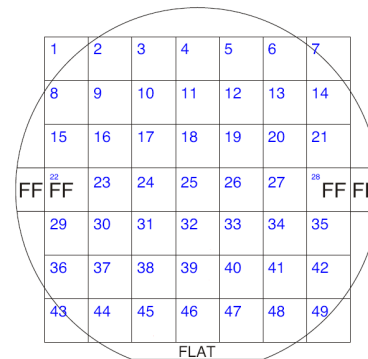
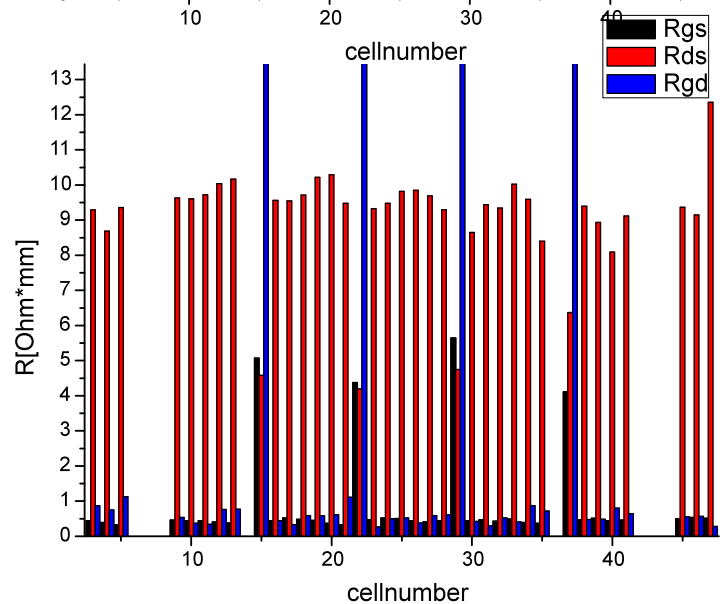
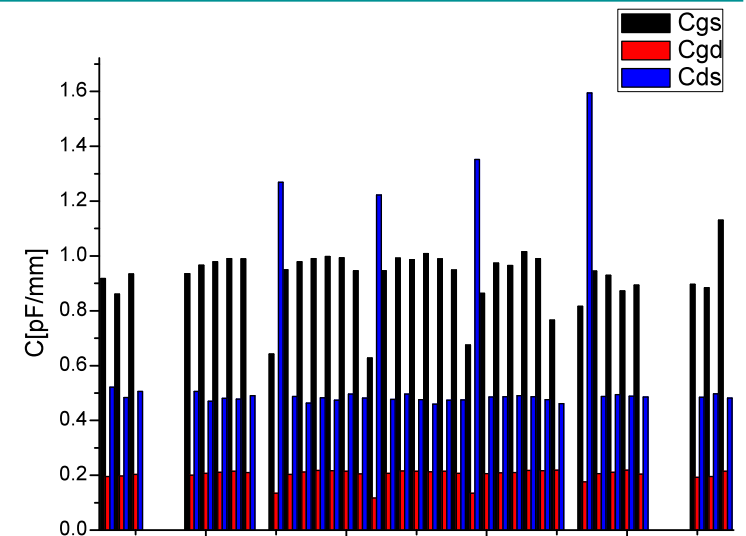
R729a
 (AL090721)
 M39
 LG=100 nm
 F2x30 Wafer 55



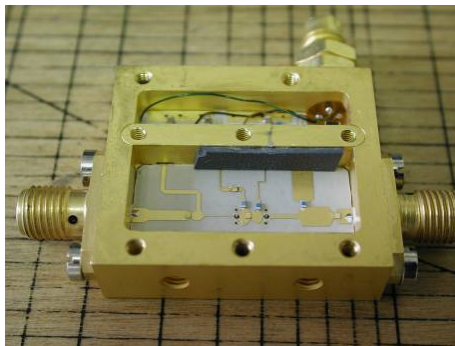
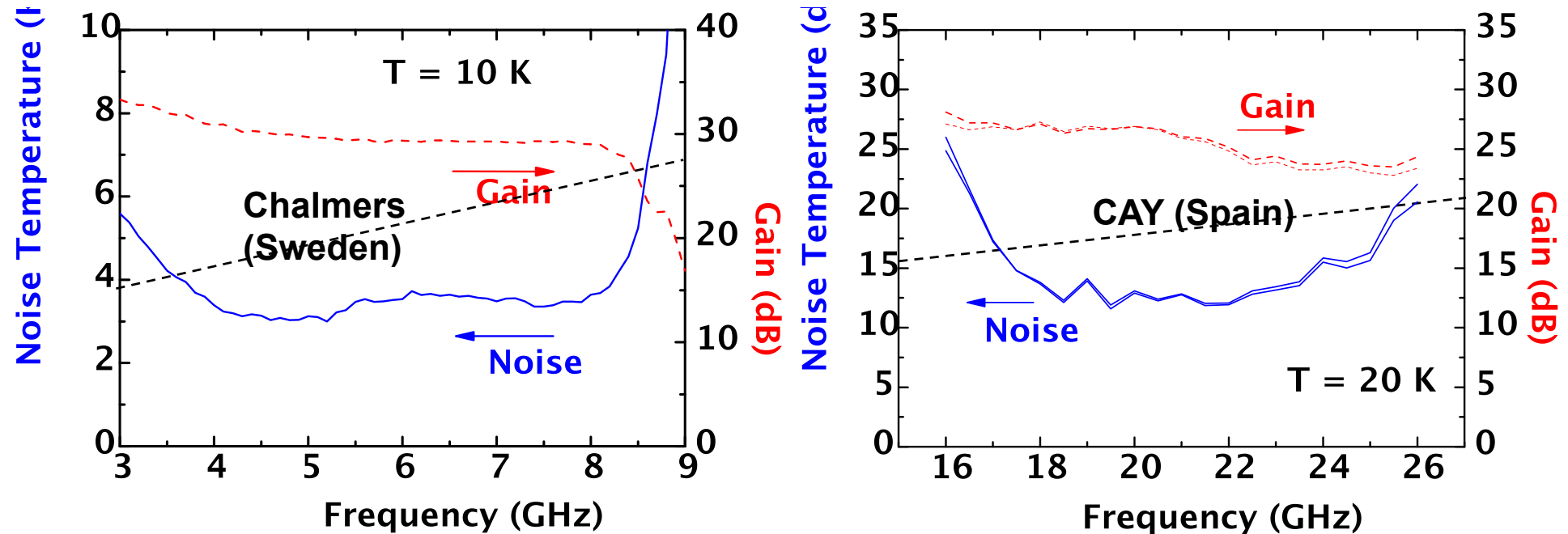
PCM Transistor Mapping HF



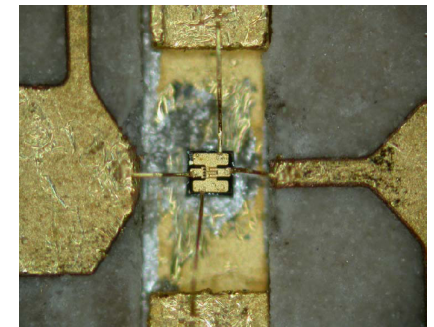
R729a
(AL090721)
M39
LG=100 nm
F2x30 Wafer 55



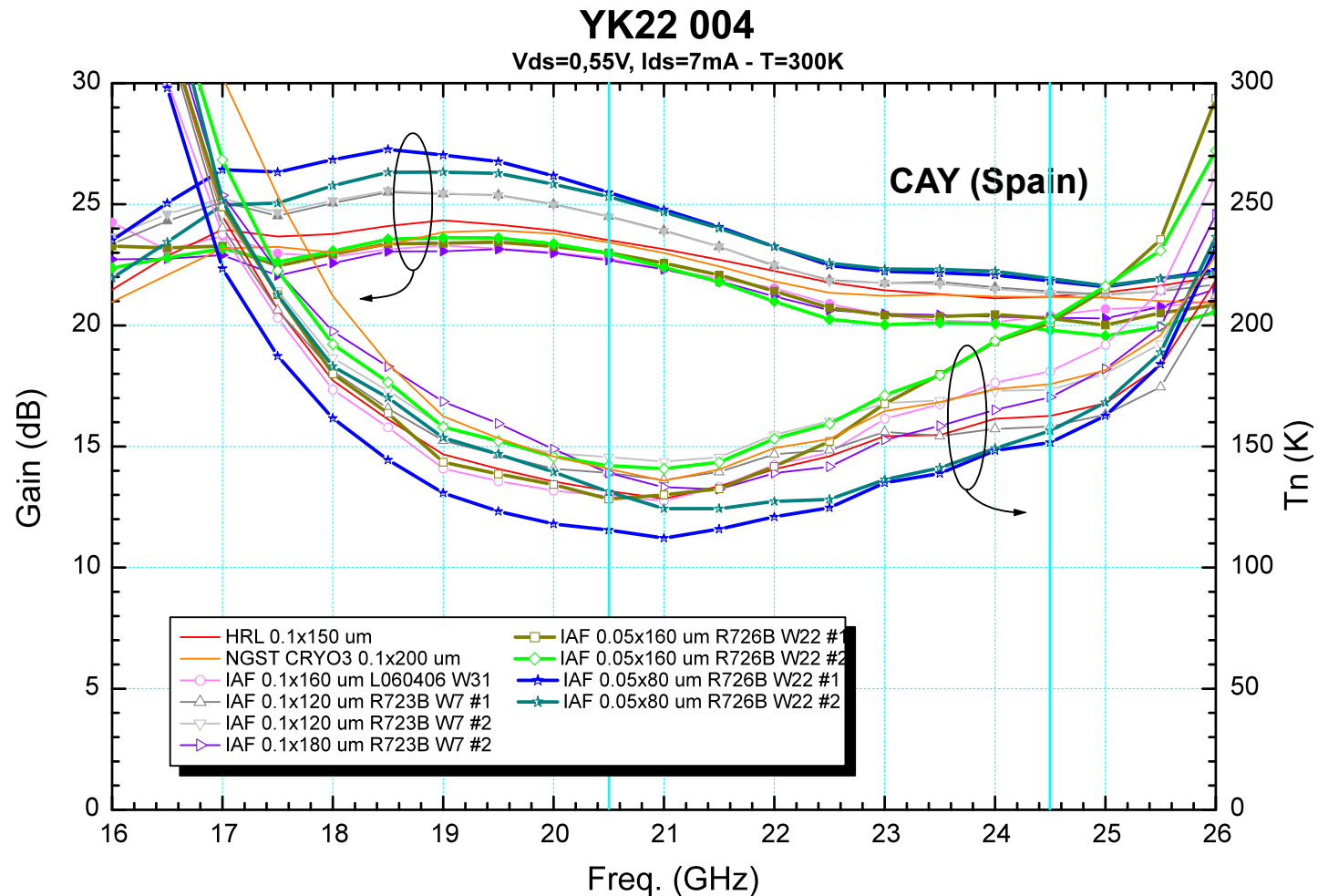
Performance of IAF mHEMTs at Cryogenic Temperatures



- Test in hybrid amplifiers
- Comparable with best InP-based HEMT performance ($T_N [K] \sim f [GHz] / 2$)

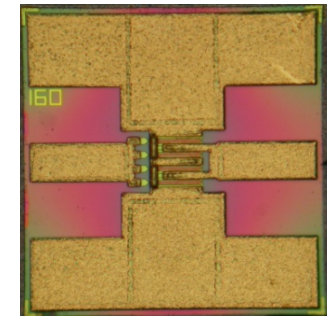
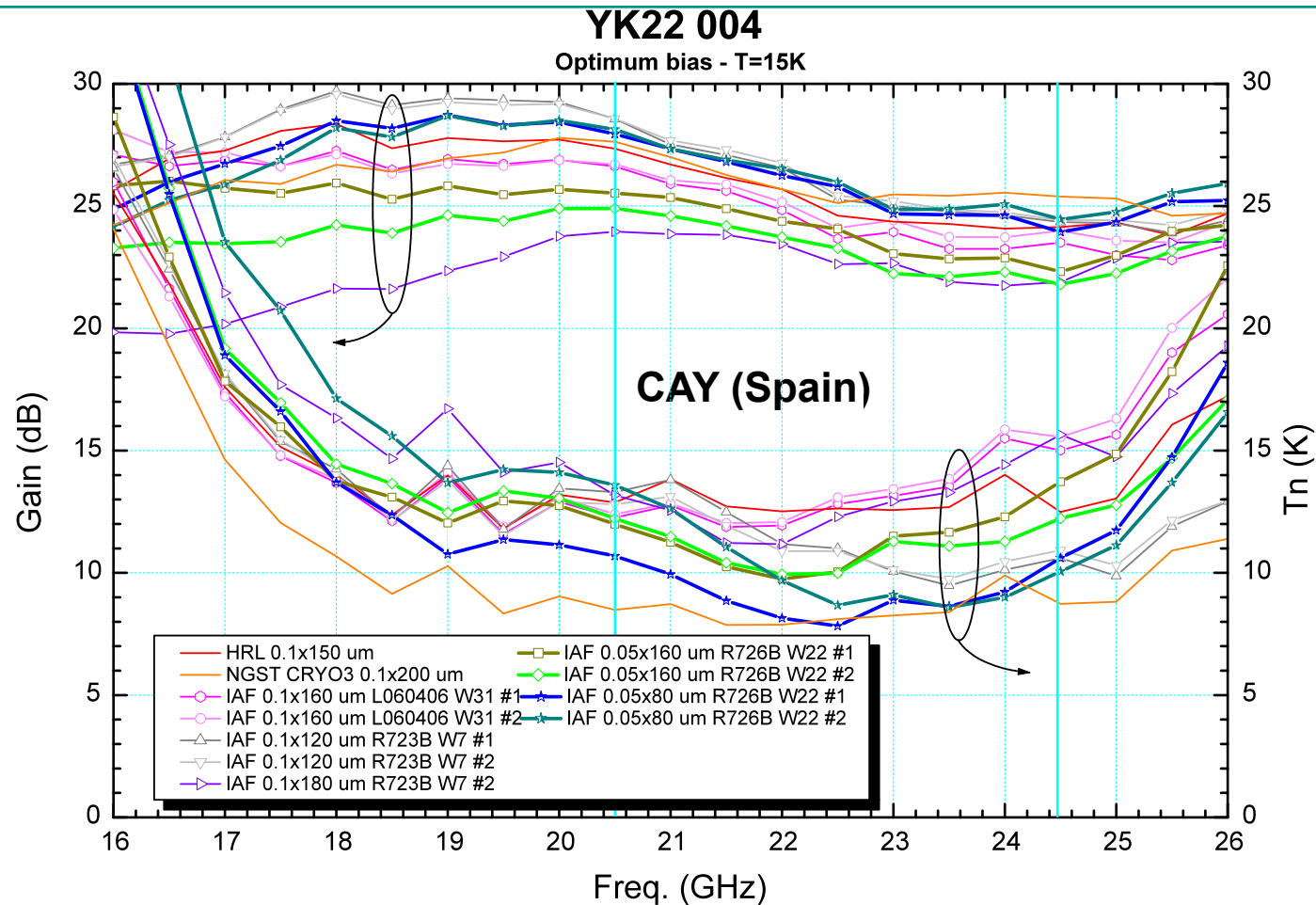


Performance of IAF mHEMTs at Room Temperature



- Test in hybrid amplifiers at room temperature
- Better than best InP-based HEMT performance

Performance of IAF mHEMTs at Cryogenic Temperatures

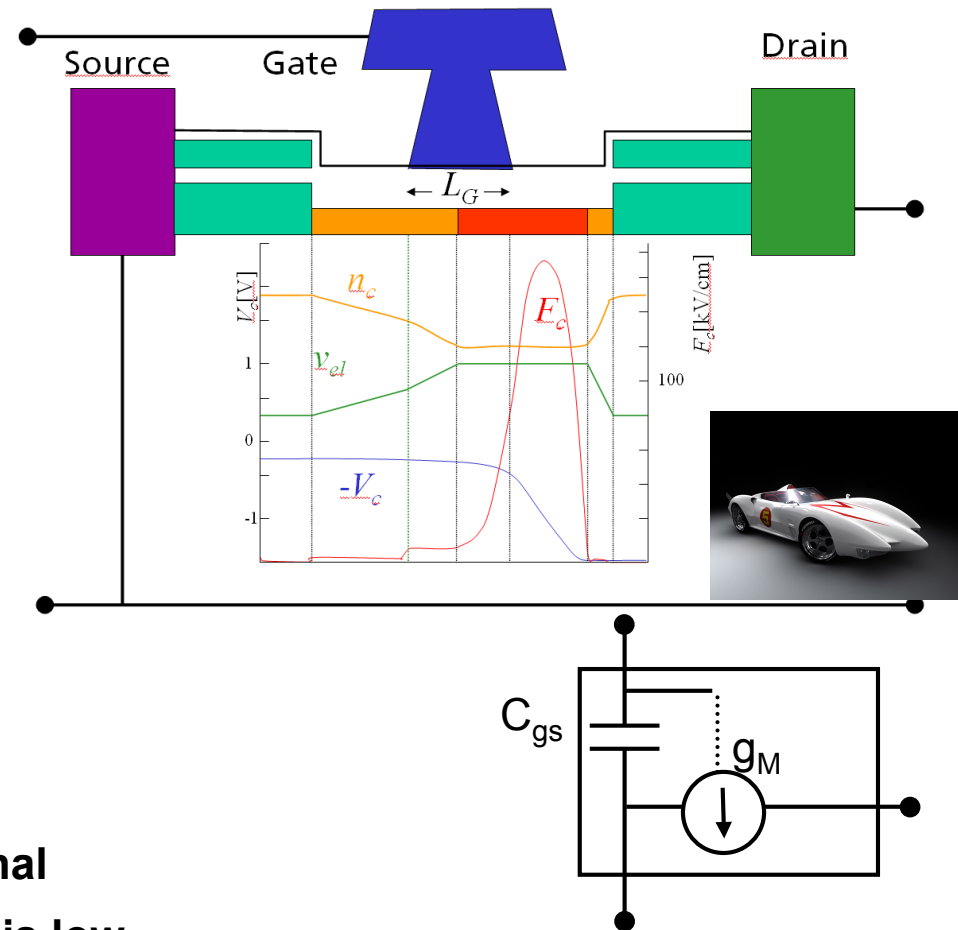
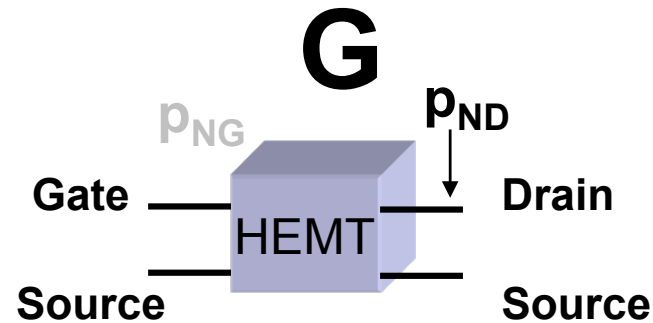


- Test in hybrid amplifiers at T = 15 K
- Equivalent to best InP-based HEMT performance (Cryo3)

Technology Assessment for Cryo-Applications

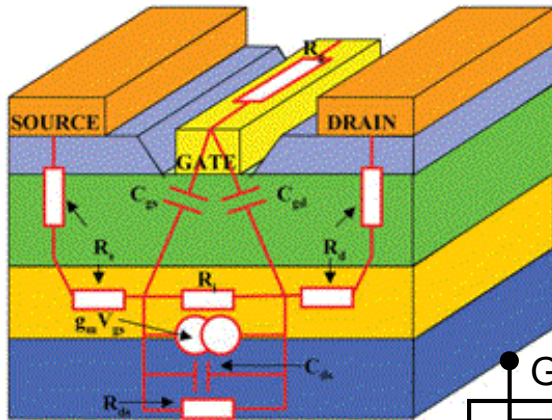
- cryo-performance of Transistors:
mHEMT (GaAs) and pHEMT-Transistors (InP) comparable !!!!
- Passive elements:
Cryo-behavior is under investigation
Cryo-compatibility?
Grounded Coplanar vs Microstrip?
- MMICs
First cryo-MMICs designed, fabricated and tested

Low Noise Properties of the HEMT



- High electron velocity
⇒ high gain
- INPUT: Capacitive coupling of signal
⇒ resistive noise contribution is low
- OUTPUT: Hot electrons in the high-field zone between gate and drain
⇒ little effect on signal due to high gain and low conductance

Small Signal Model Topology



Parasitics:

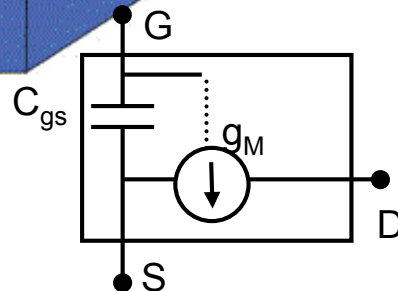
$L_g, L_d, L_s, R_g \sim \text{WF}/\text{nF}$
 $R_d, R_s \sim 1/(\text{nF WF})$
 $C_{pgs}, C_{pgd}, C_{pds} \sim \text{nF} + \text{const}$

Noise:

4 resistive elements

Input: $R_g[T_A], R_s[T_A]$

Output: $g_{DS}[T_{CE}], R_d[T_A]$



Intrinsics (bias dependent)

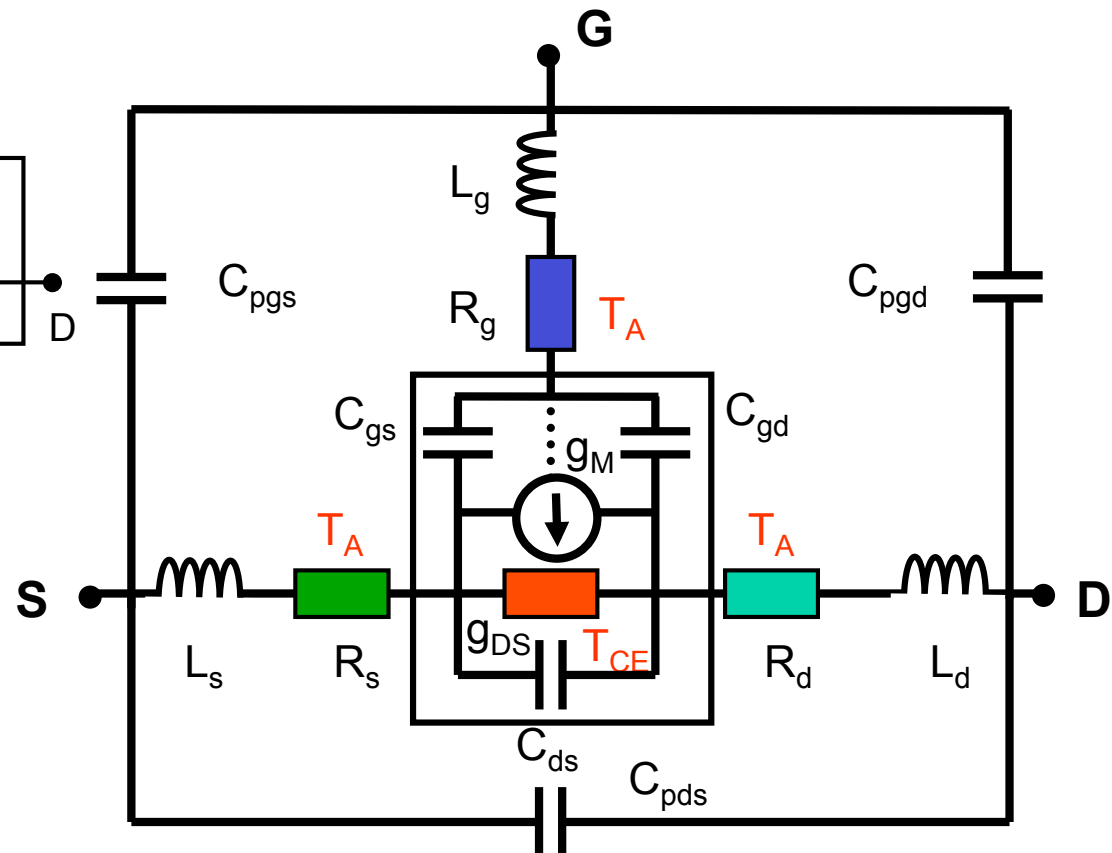
$C_{gs}, C_{gd}, C_{ds} \sim 1/(\text{nF WF})$

$g_{DS}, g_M \sim 1/(\text{nF WF})$

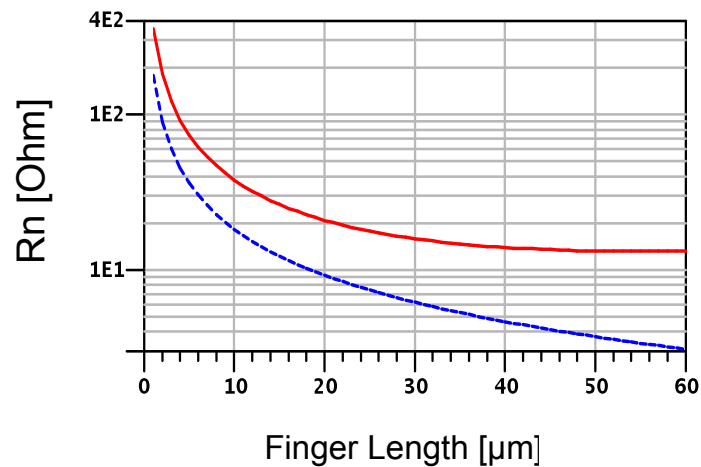
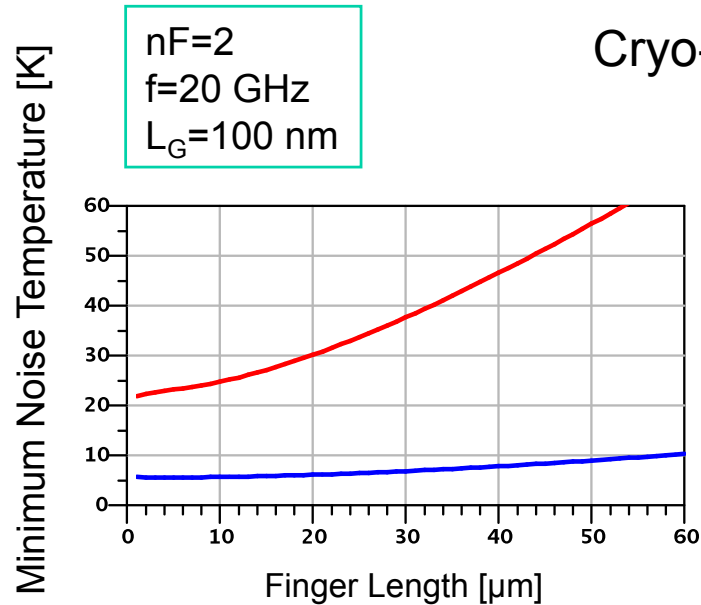
T_{CE} indep. of geometry

■ Taylor expansion in i_D, V_{DS}

■ Quadratic terms

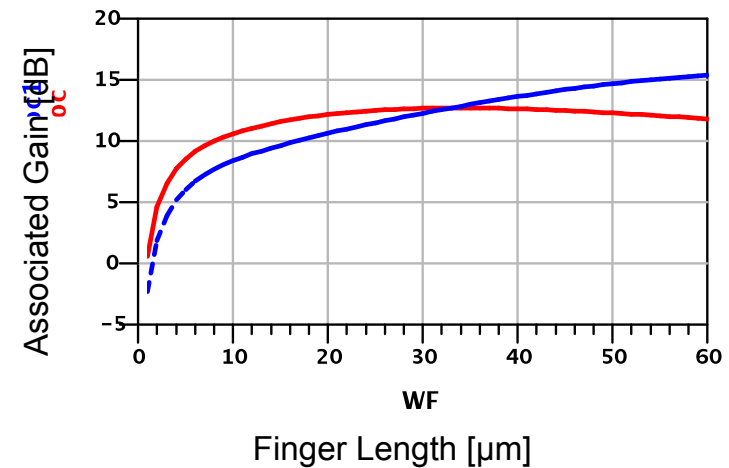
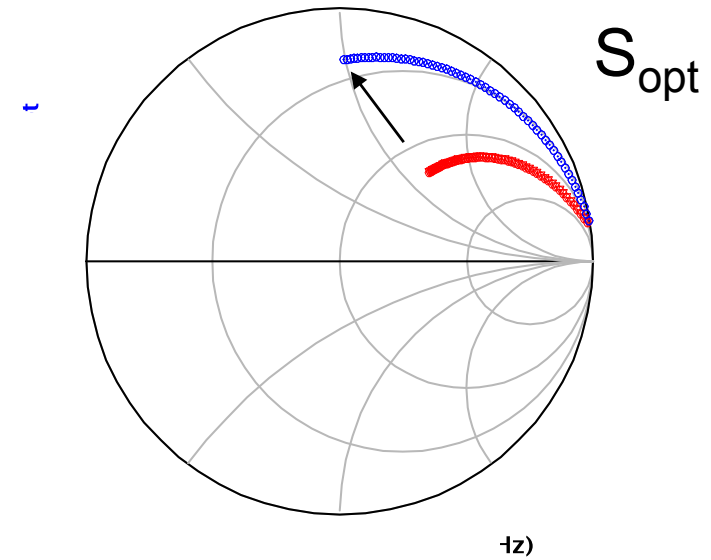


Noise Parameters vs. Finger Length



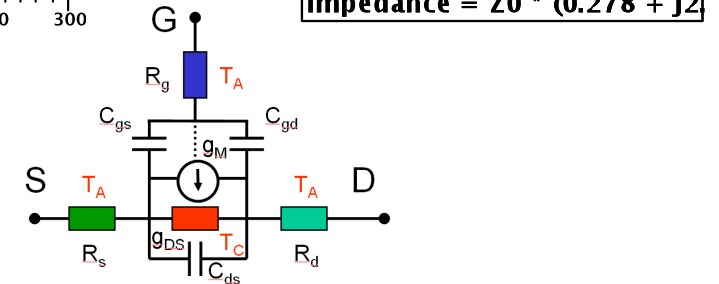
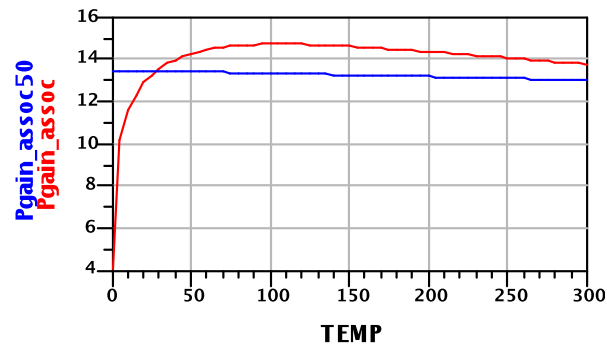
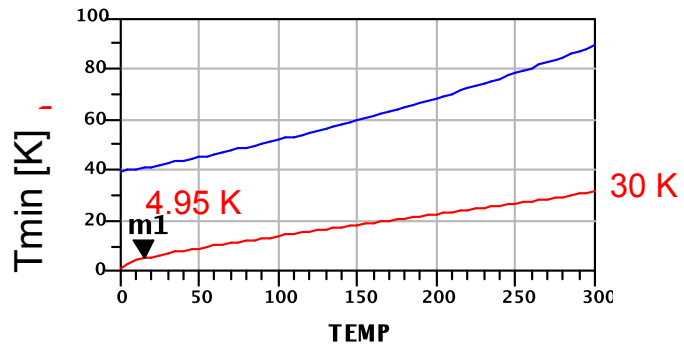
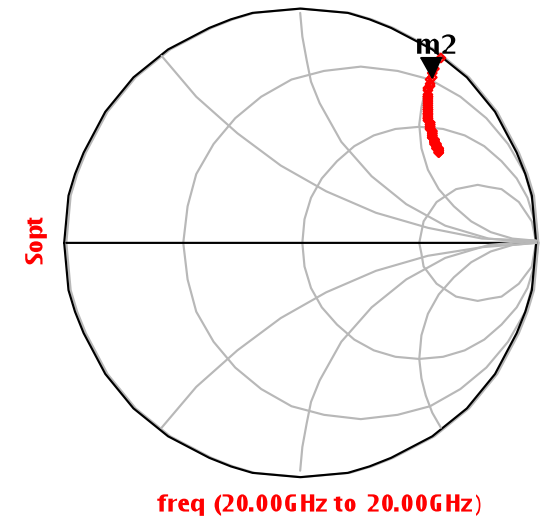
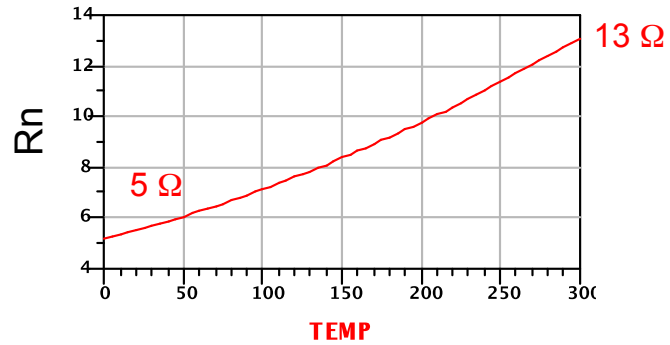
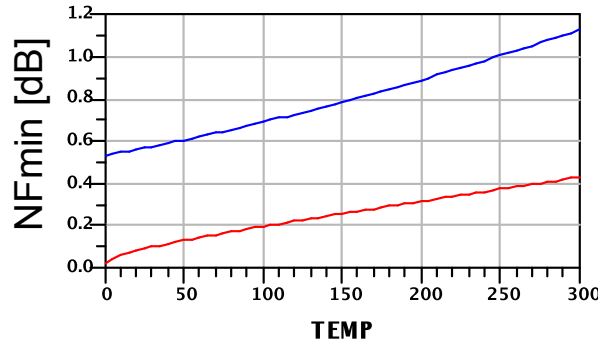
Cryo-LNA design with RT-Model???

$T=300\text{ K}$
 $T=16\text{ K}$



Model: Noise Performance vs. Temperature

F2x40: LG=50 nm; i_d =150 mA/mm; V_d =1 V; f =20 GHz



On-Going Cryo-mHEMT-Programs



- RADIONET

- AMSTAR+

- APRICOT



Fraunhofer
IAF



- Cooperation Projects with European Partners

- IRAM, MPIfR

- IGN, CAY



Max-Planck-Institut
für Radioastronomie



- Max-Planck-Fraunhofer Cooperation Project:

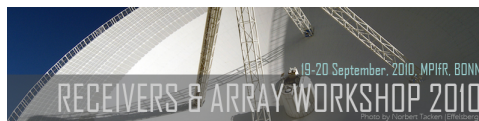
- Optimization of the mHEMT Process for Cryo-Applications

- dedicated Cryo-Runs



MAX-PLANCK-GESELLSCHAFT

 **Fraunhofer**



Summary Infrastructure

- IAF
 - Institution for Applied Research (not a foundry!)
 - Quality Management ISO 9001:2000
 - Quasi-Industrial Standards

- MMIC Design
 - ADS Designkits
 - (Cryo-)Model Library
 - Autolayout

- MMIC Processing
 - Epitaxy
 - mHEMT Processing for 100, 50, 35 nm Gates
 - Wafer-Mapping of Transistors and Circuits

- MMIC Packaging
 - Laser Dicing and „Pick and Place“ Instrumentation
 - Waveguide Module Design and Fabrication

Summary and Outlook

- State of the art RT mHEMT process
 - $NF=2$ dB($TN=177$ K) @94 GHz (300 K)
- Promising Cryo MMIC results
 - $TN=5$ K @ 8 GHz (15 K)
- Potential to further process-optimization for cryo applications
- Improvement/Refinement of Cryo-Models