Recent NGST HEMT Device & MMIC Development

MMIC Array Receivers and Spectrographs Workshop

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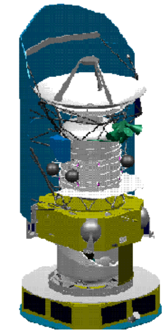
HEMT Technology Development Applicable towards Radiometric Applications at NGST

- *NGST Internal R&D*
  - *Yearly budget > $2M for last 10 years*
  - *First LNAs at various frequencies including 90, 140, 150, 180, 240 GHz*
  - *First 30 dB gain 160-190 GHz amplifier block and full radiometer*
- *DARPA*
  - *MIMIC Phase II W-band GaAs HEMT LNA*
  - *TRP W-band MMW Camera*
  - *MAFET MMW InP HEMT MMIC production*
  - ***SWIFT – 340 GHz Transceiver***
  - ***Hi-Five – 220 GHz Driver***
- *JPL CHOP – focused development of InP HEMT croyogenic LNAs*
  - *FCRAO 94 GHz LNA UMass Amherst*
  - *European Space Agency – ground telescopes MMW LNAs, PINs*
  - *GEOSTAR, **183 GHz SAR***
  - *Deep Space Network, Paul Allen Telescope, Hawaii MMW LNAs*
- *Projects*
  - *Jason (TOPEX/Poseidon) Ka-band LNAs*
  - *ODIN, IMAS, MLS (120 GHz flight)*
  - *Cloudsat (W-band)*
  - *PLANCK and Herschel (MMW, W-band power)*
  - *ALMA (NRAO, X-band LNAs, W-band power)*
  - *CSIRO (Austrailia): Narrabri telescopes, VLA (MMW to 200 GHz)*
  - *NOAA (ATMS, CMIS) development **(MMW to 200 GHz)***
  - *LRR (Goddard – X-band)*
  - ***NRL G-band MMIICs***

DARPA

MLS

Herschel

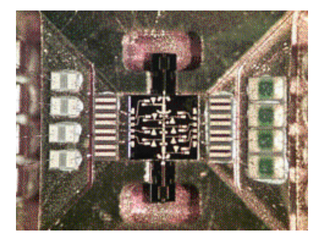


NASA

JPL

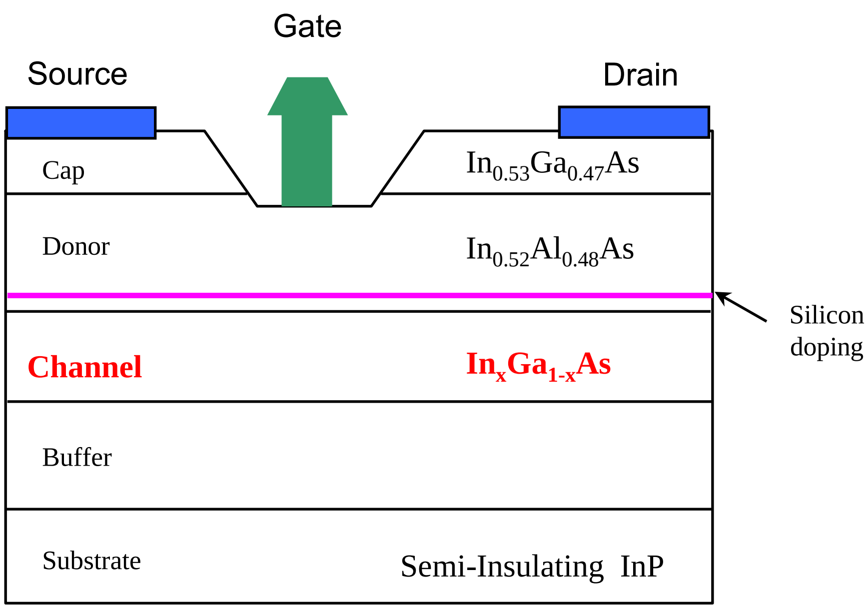
Planck

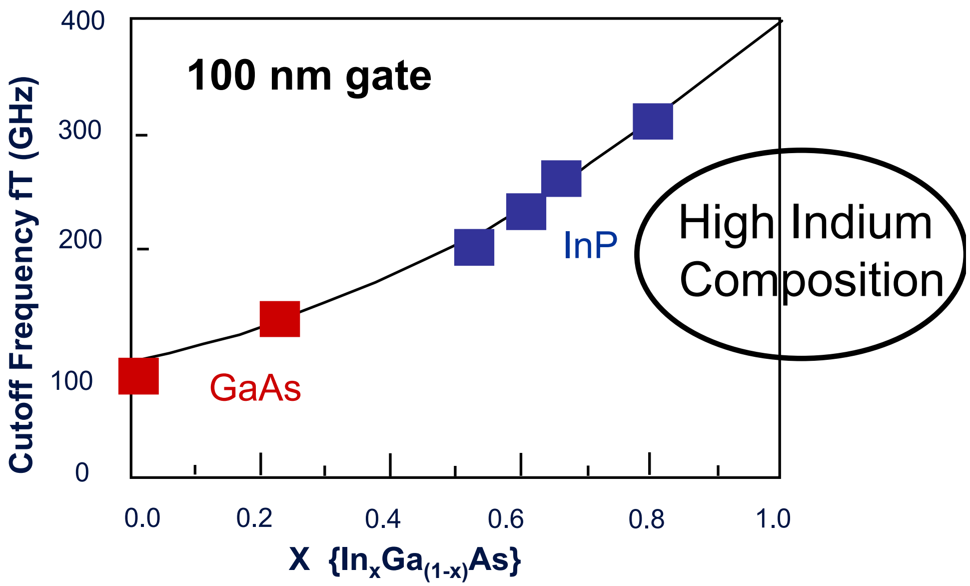
Odin Module



W-band MMW Camera

InP HEMT





Features

- Pseudomorphic growth of InP HEMT layers with MBE
- Mobility, fT improve with higher Indium composition
- Single recess, semi-selective etch process
- SiNx passivation
- 2-level interconnect metal process with airbridges, TFR and MIMCAP
- 50 um thick chips with through via process

InP HEMT Device Structure

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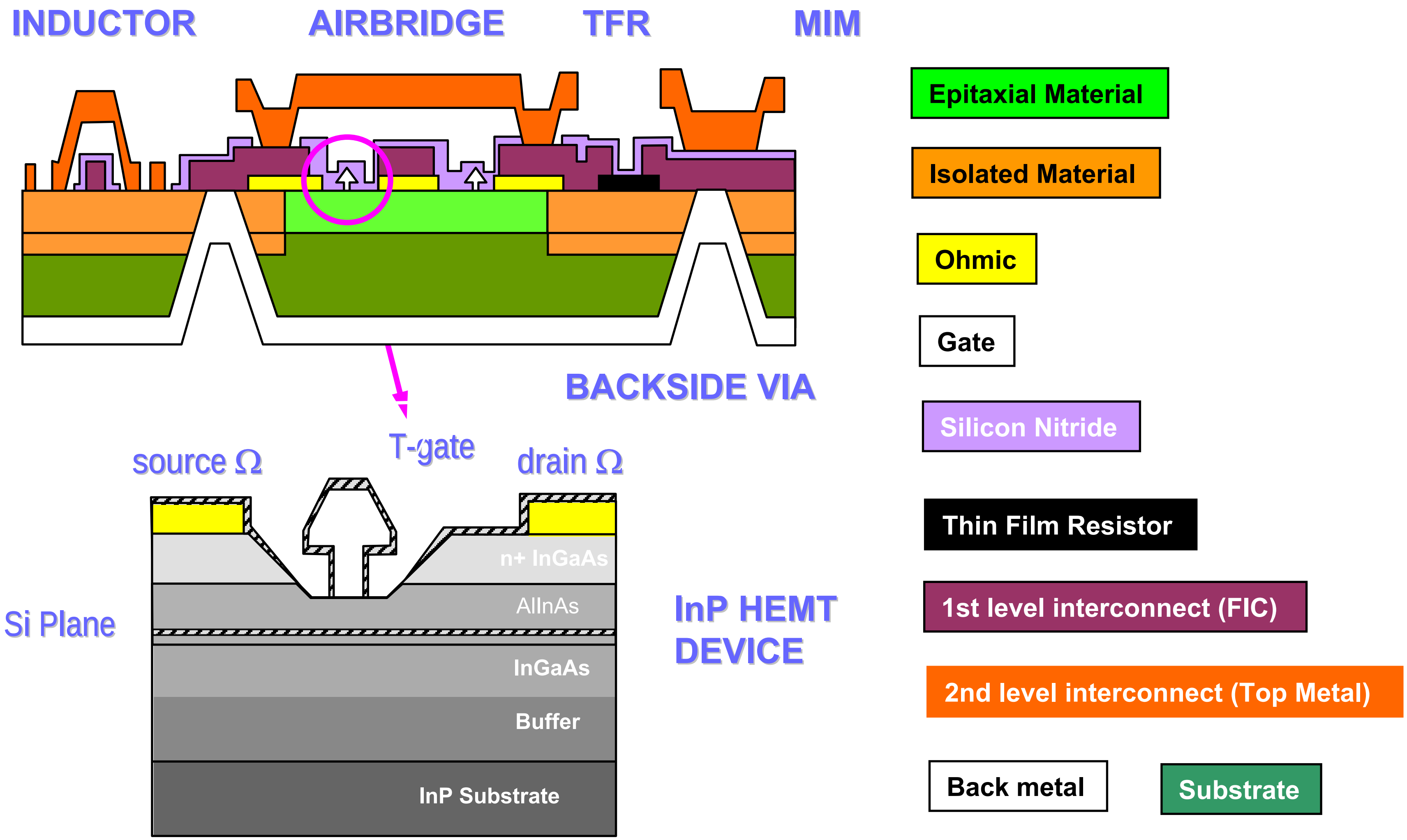

Process commonality between different InP HEMT technologies shortens development cycle

Cryogenic InP HEMT

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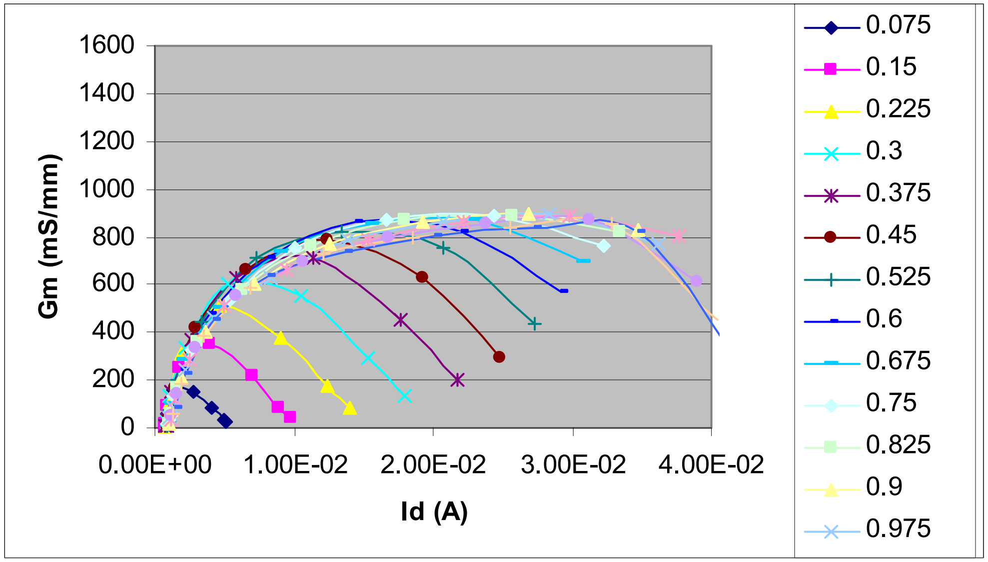
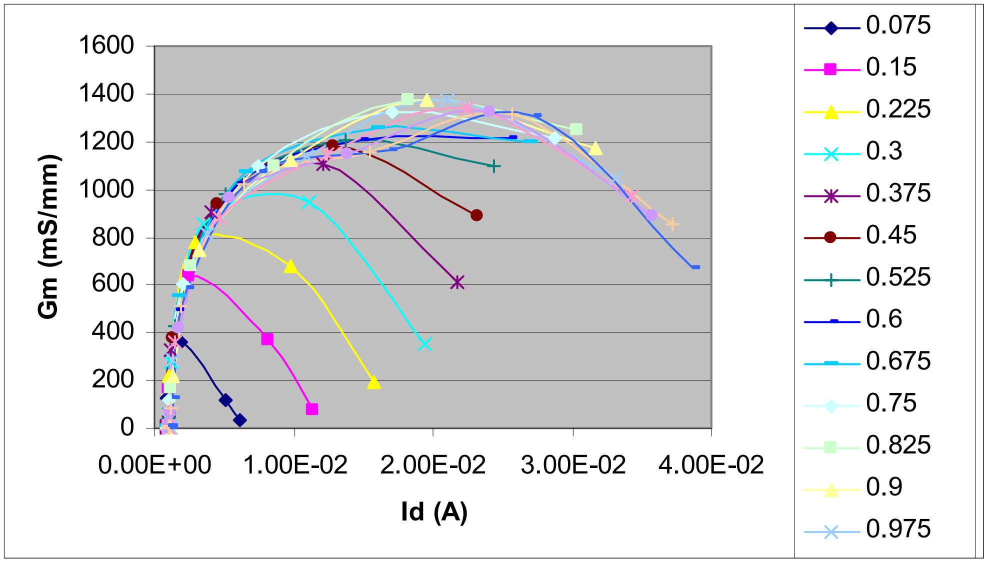
Cryo-4 300K



Ref. T. Gaier et. al. 2005

Cryo-4 60K



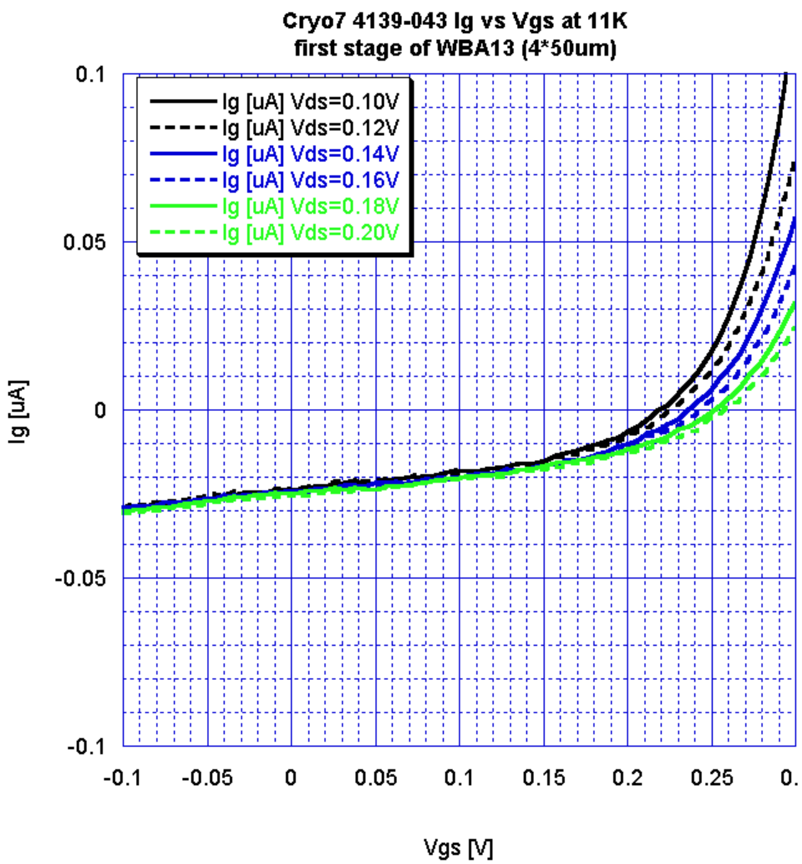
- *Key to achieving best cryogenic LNA NFmin is highest Gm for lowest Id*

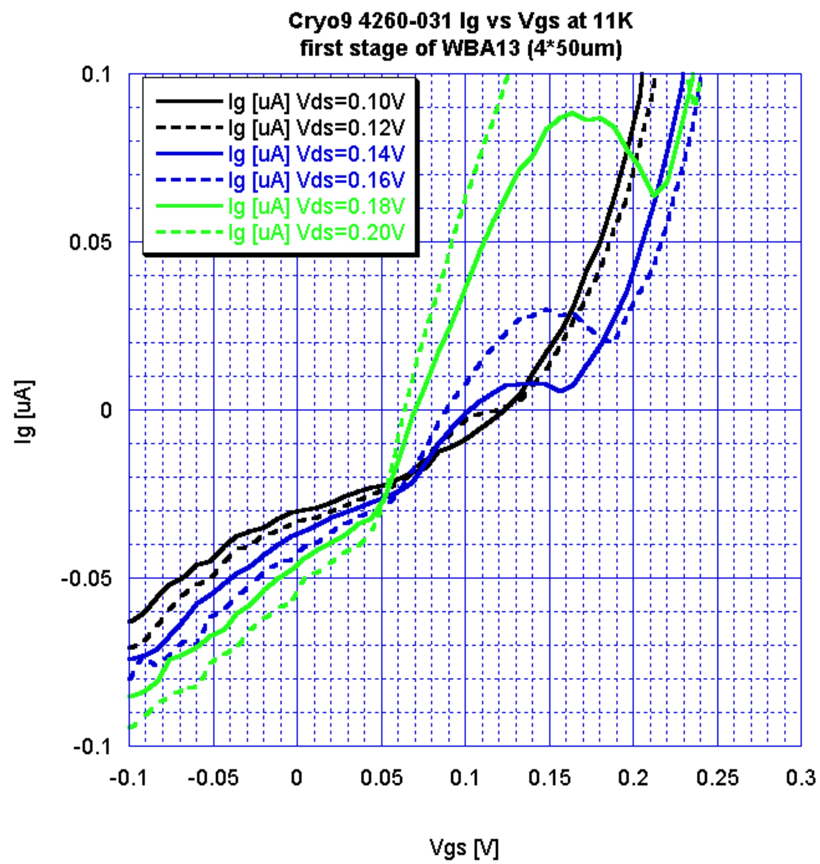
Cryogenic InP HEMT

• *Shot noise due to forward Ig can impact overall NFmin*

Cryo7 4139-043 Cryo 9 4260-31

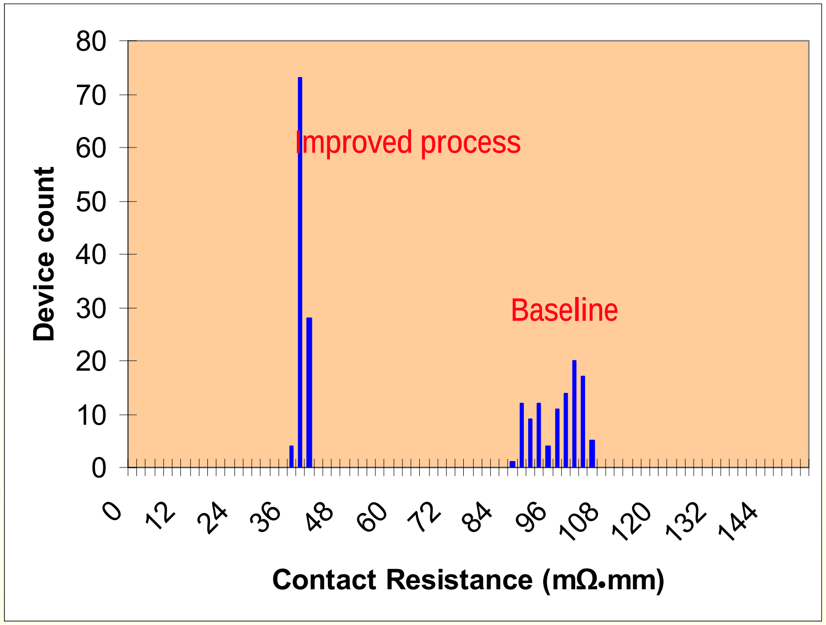
Igs vs Vgs @15K

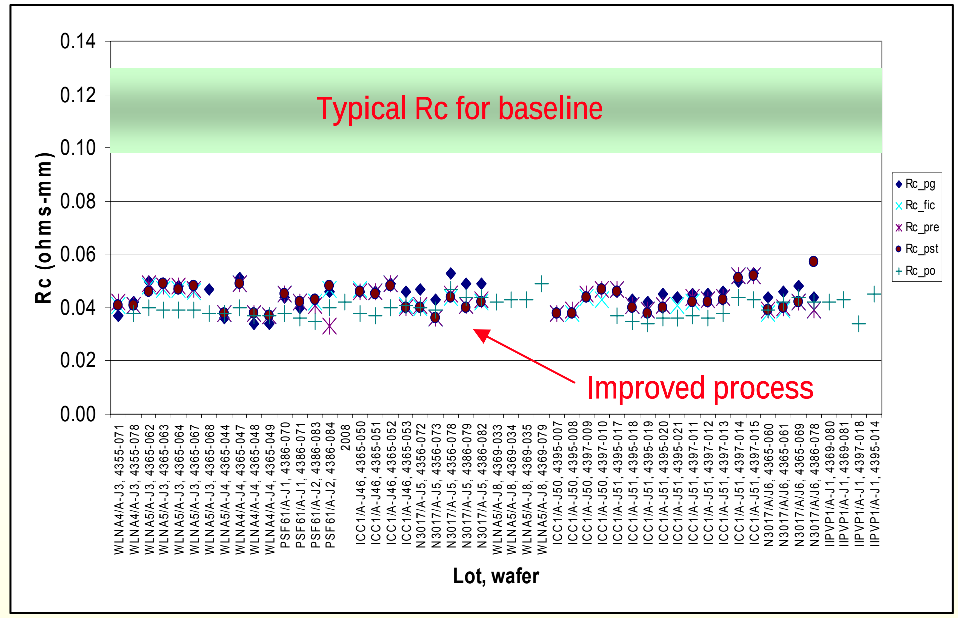




Ref. M. Pospieszalski et. al. 2005

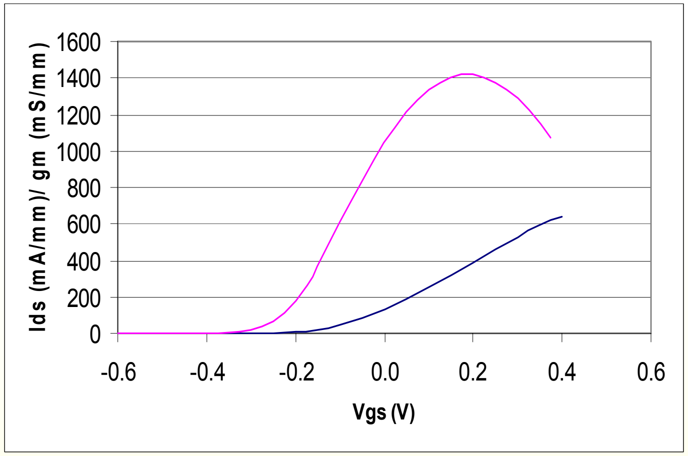
InP HEMT: Ohmic contact improvement



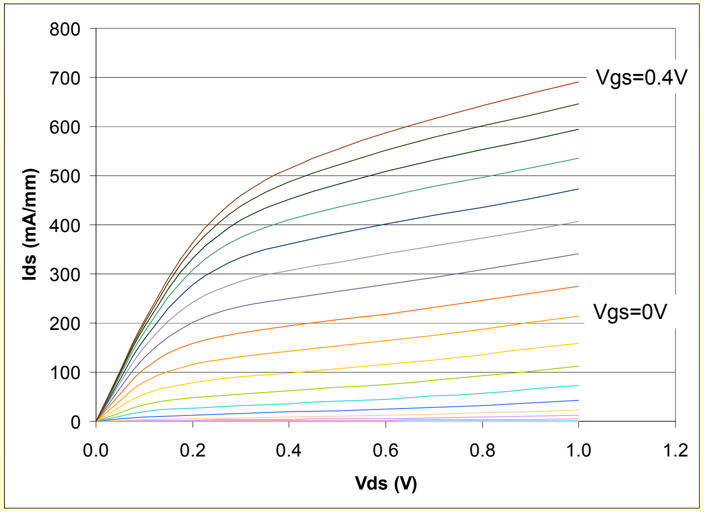


- Ohmic contact process has been optimized
  - Composite n+ cap
  - Non-alloyed Ohmic metal
- Improved Ohmic contact resistance by over 60%
- Good on-wafer uniformity.
- Good lot-to-lot repeatability

DC characteristics of 0.1um InP HEMT with improved Ohmic process



Rc (Ω-mm)	0.04 (Ω-mm)
BVgd	3.5V
Gmp, Vds=1V	1400 (mS/mm)
fT, Vds=1V	230 GHz
MSG @ 26GHz, Vds=1V	17 dB



- 20% improvement in Gmp
- Low V-knee: good for low power performance
- Well controled output conductance
- Good pinch-off characteristics

Low DC Power InP HEMT

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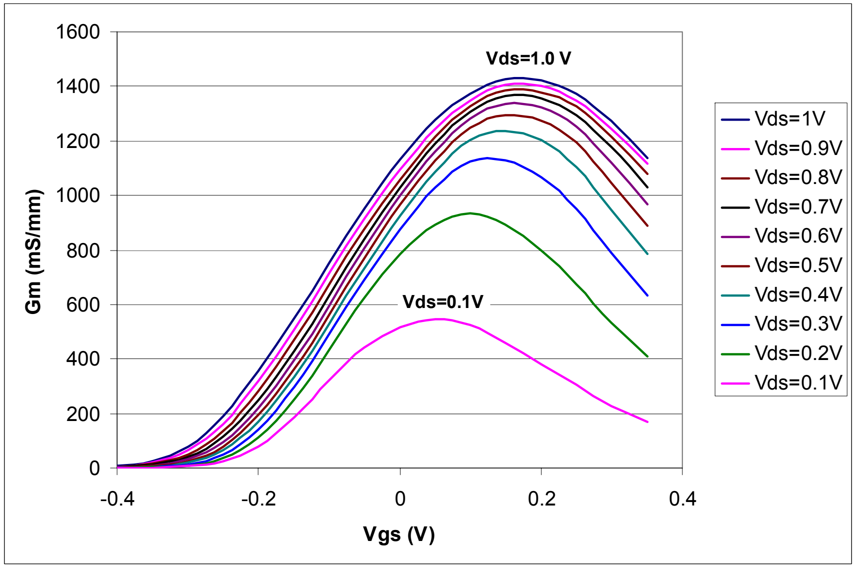
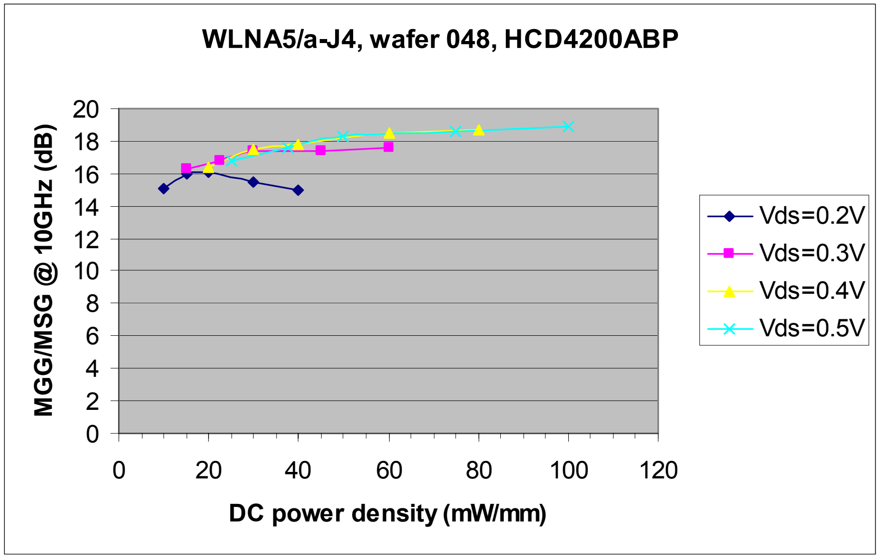
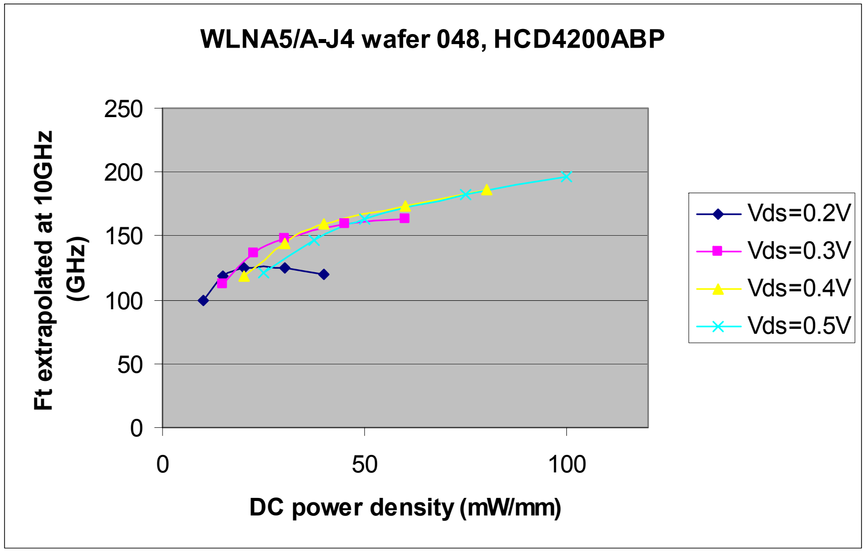
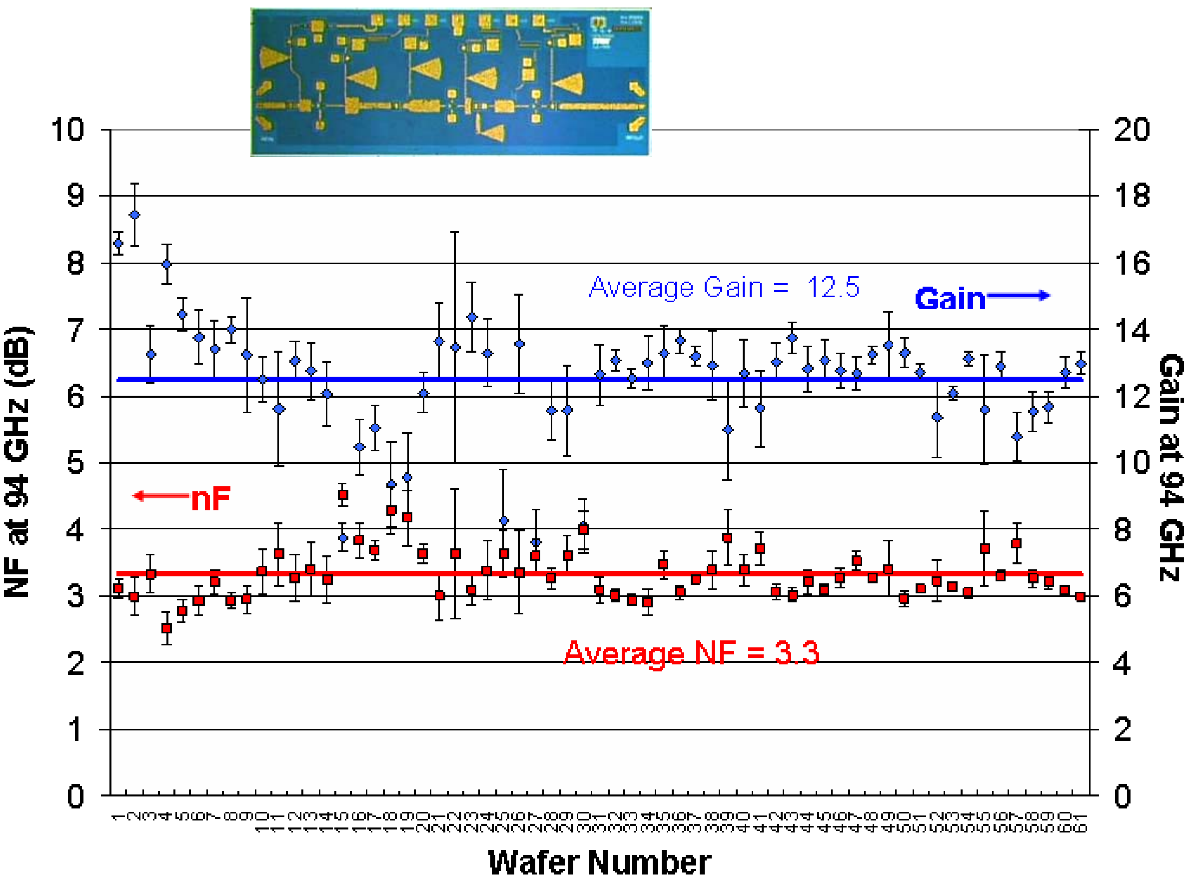




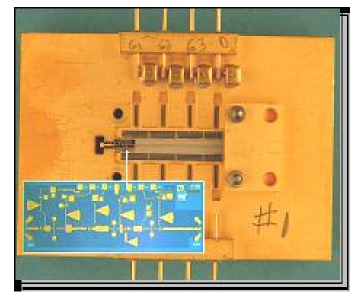


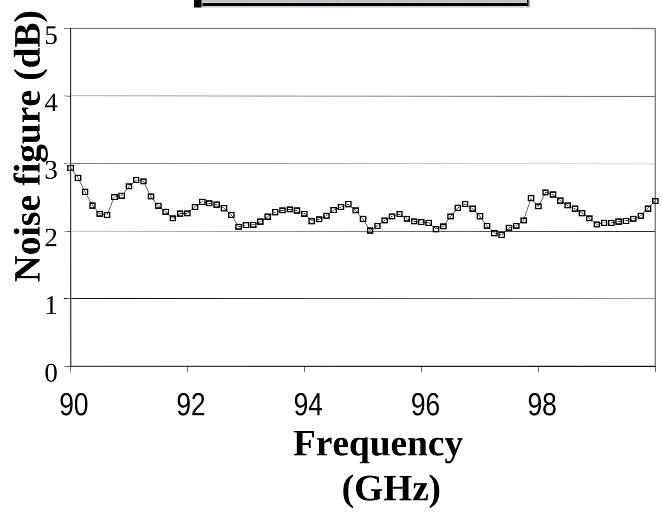
- Peak Gm>900mS/mm at Vds=0.2V
- Ft >140 GHz at a DC power of 20mW/mm
- Good choice for low DC power applications

InP HEMT Production W-band MMIC Performance

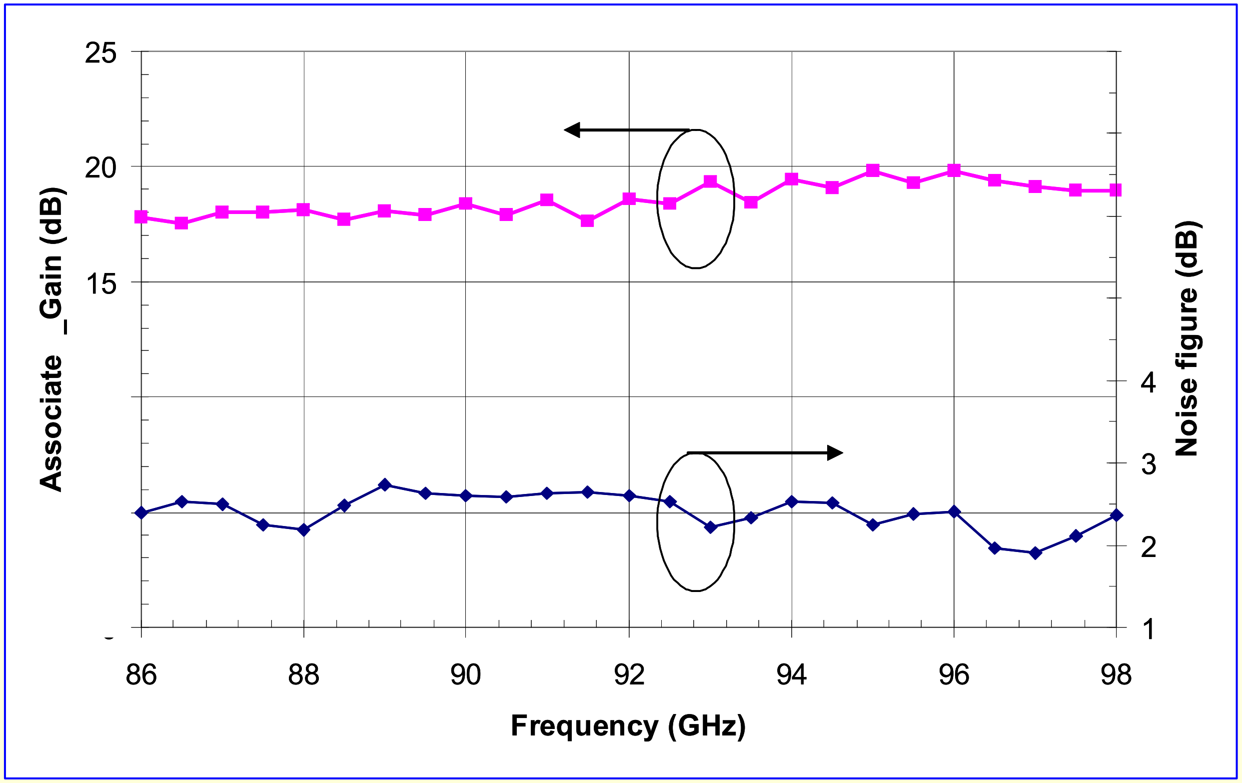


- 100 mm InP HEMT
- 60 wafers/20 sites per wafer
- On-wafer testing
- Fixture testing NF is better than on-wafer data by 0.5 dB



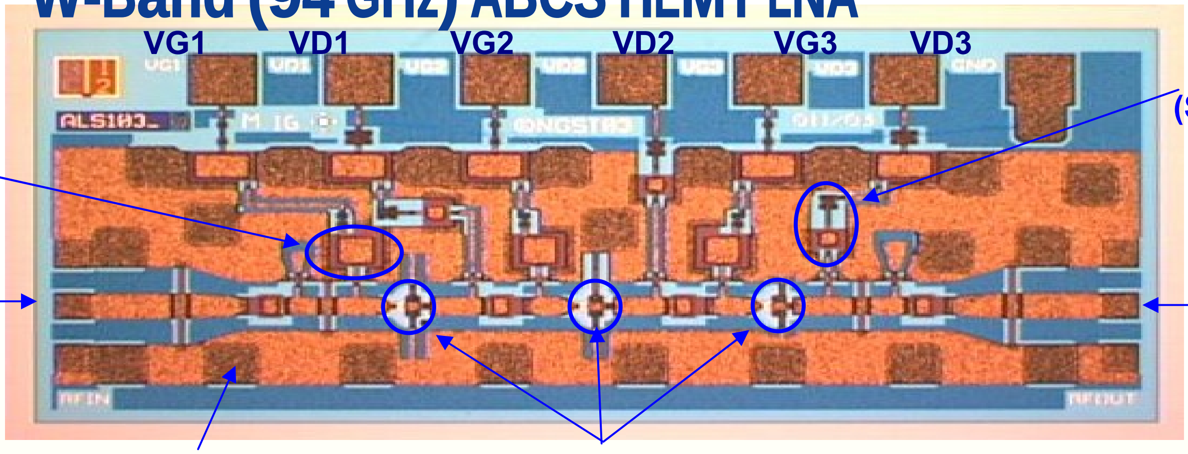


Noise figure of a 3-stage W-band LNA MMIC

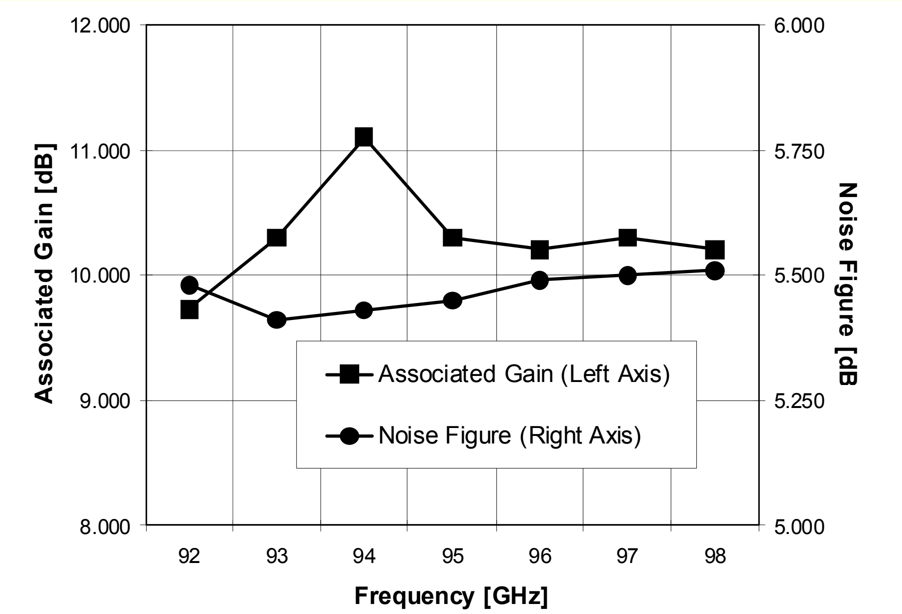


- Vds=1V, Ids=18mA
- 2.5 dB noise figure at 94GHz
- 19.4dB associate gain

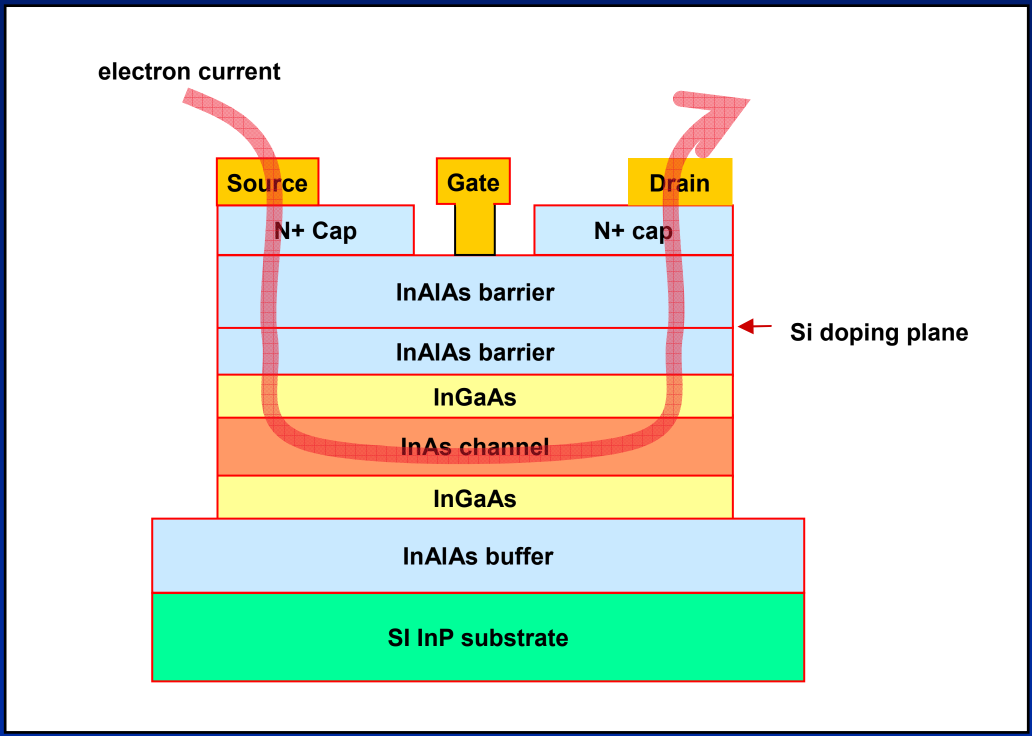
W-Band (94 GHz) ABCS HEMT LNA



- Broadband Three-Stage Amplifier
  - Grounded Coplanar Waveguide (GCPW), with 100-µm substrate
- Low Power, Low-Noise Results
  - 5.4 dB Noise Figure with 11.1 dB Assosciated Gain at 94 GHz
  - Total DC Power only 1.8 mW
  - 0.6 mW per stage

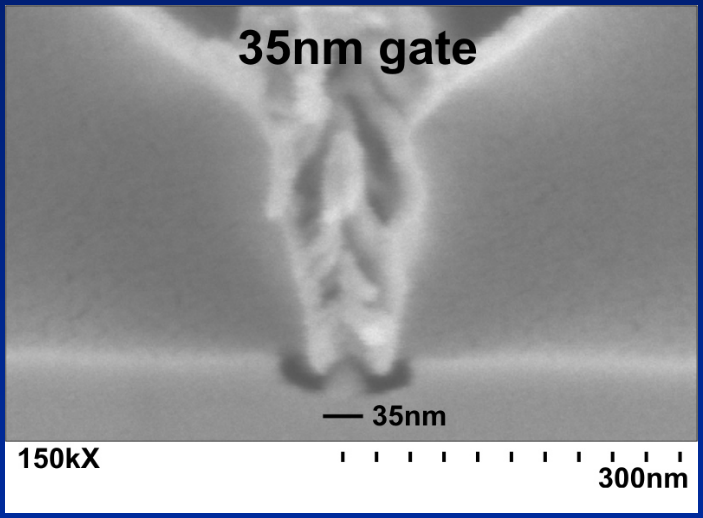


InAs channel Design



- Composite channel with InAs/InGaAs
- Hall mobility of 16,000 cm^2/V-sec and 3.5 x $10^{12}/cm^2$ sheet charge
- Highly doped cap layer for low ohmic contact/access resistance
- Layer structure scaled for 35 nm gate length

Sub 50 nm T-gate



- >5:1 ratio gate top to gate length for low Rg
- Single recess, 100 nm length typical
- 20 KeV exposure, two layer resist scheme

THz InP HEMT

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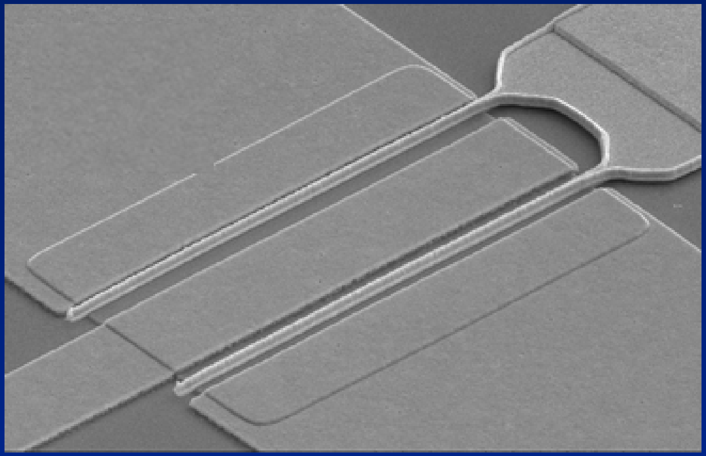
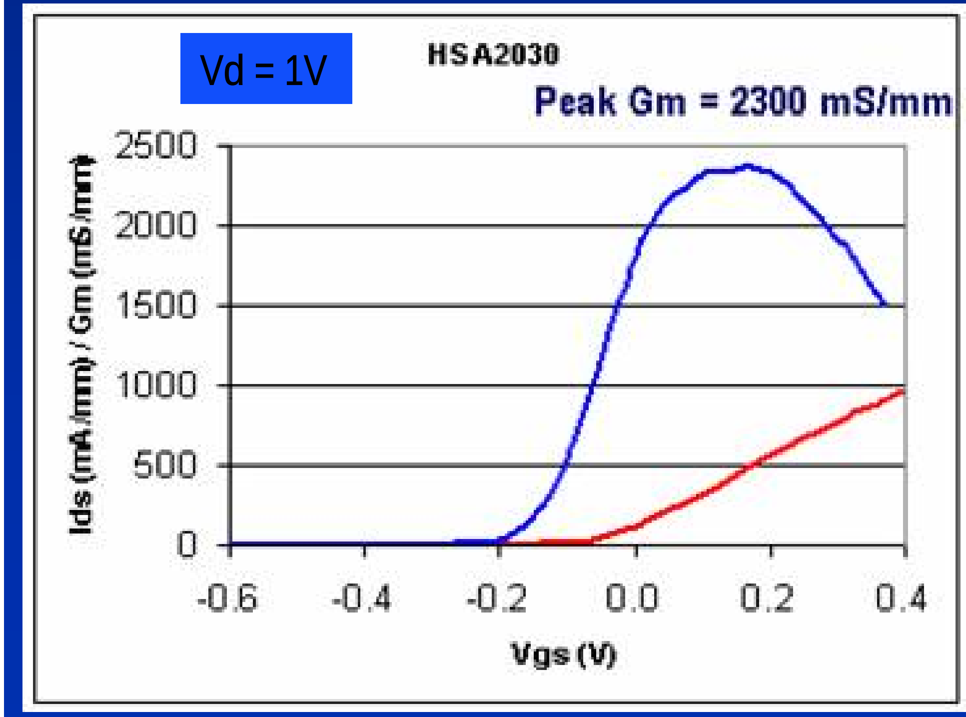
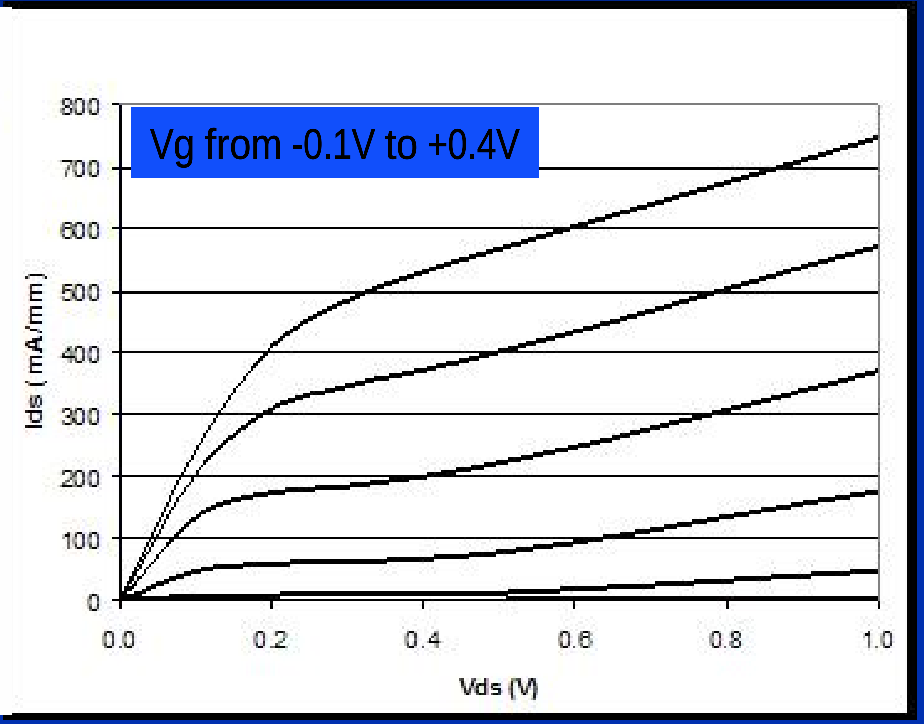


- 2 and 4 finger devices
- Typical d.c. Gmp > 2 S/mm @1V Vds
- Low on-resistance and knee voltage
- Good pinchoff & output resistance





THz Fmax

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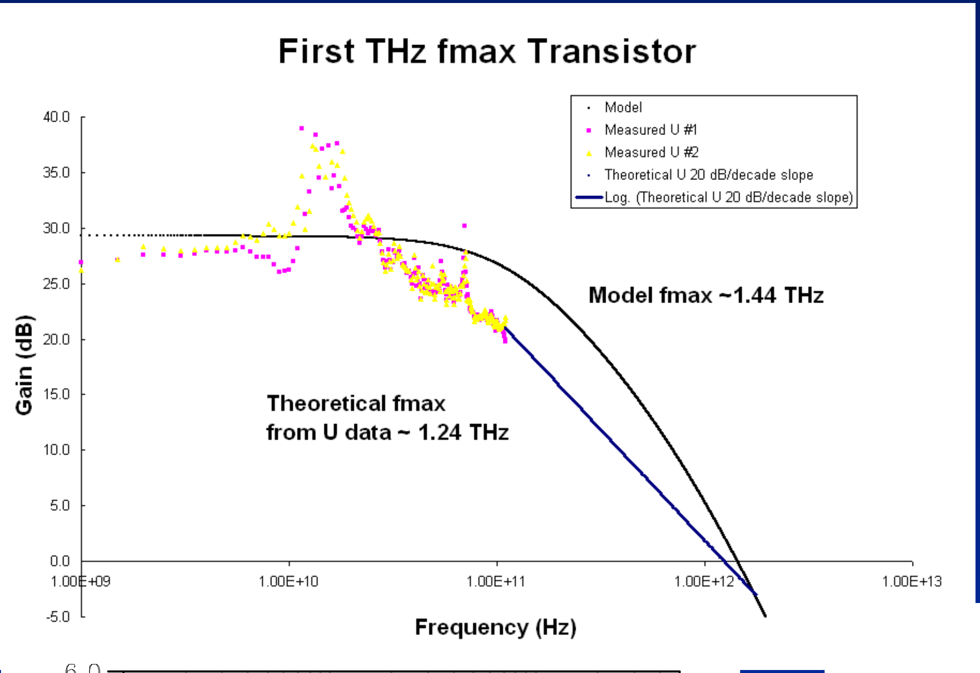
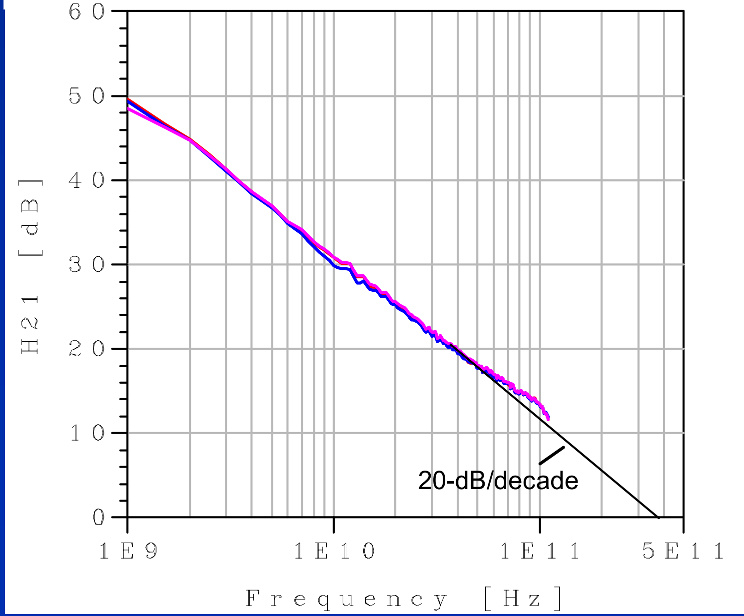
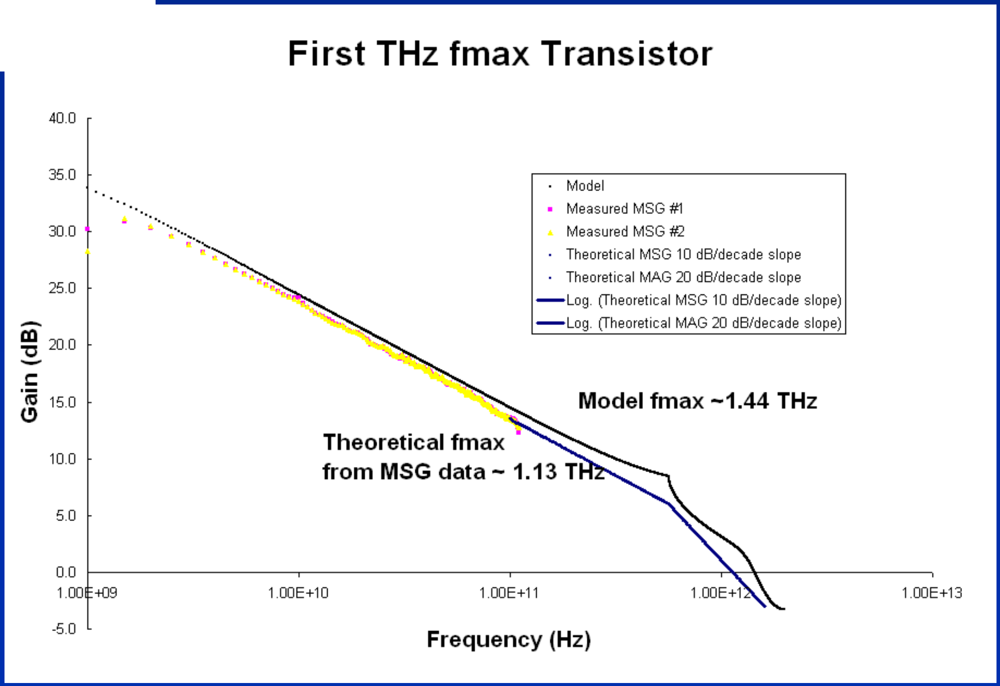


- 2f 20 um InP HEMT
- SOLT calibration
- Vd = 1V, Id = 6 mA
- U@100 GHz ~ 22 dB
- MSG@100 GHz ~ 14 dB
- Model predicts even higher performance



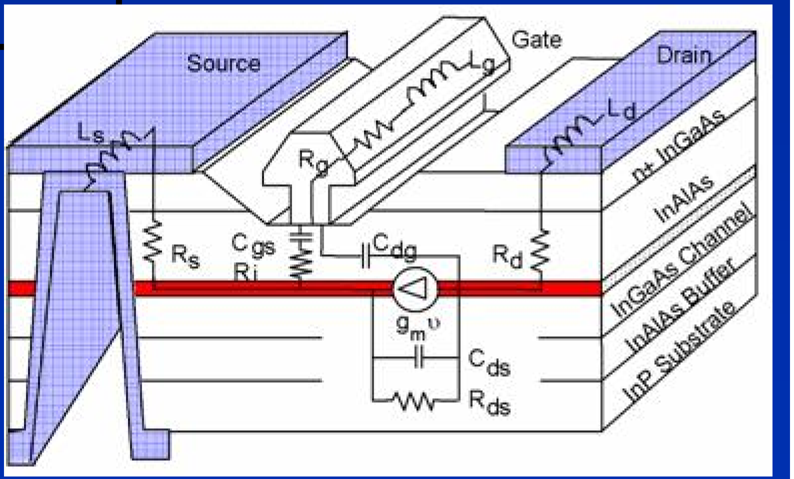


Small Signal Model

		InP HEMT Small-Signal Model				
Param.	Unit	**100 nm**	**70 nm***	**35 nm**		Comments
RF G_m	mS/mm	1125	1500	**2600**		Epitaxy; threshold voltage
C_{gs}	pF/mm	0.90	0.83	**0.80**		Lg reduction; higher Cgs due to shorter gate to channel design
C_{ds}	pF/mm	0.63	0.60	**0.30**		
C_{dg}	pF/mm	0.16	0.18	**0.13**		Improved Cdg
R_{ds}	Ω-mm	10.4	7.2	**6.0**		Epitaxy; threshold voltage
R_g	Ω-mm	120	150	**250**		
f_T	THz	0.2	0.35	**0.45**		Simulated from model
f_{max}	THz	0.4	0.7	**1.4**		Simulated from model
MSG@340 GHz	dB	1	4	**10**		Simulated from model

- Sub 50 nm InP HEMT
- Vd = 1V, Id = 300 mA/mm
- Derived from measurements on 2f10 um, 2f20 um, 2f30 um devices for 340 GHz s-MMIC amplifiers

*reported IEDM 2000



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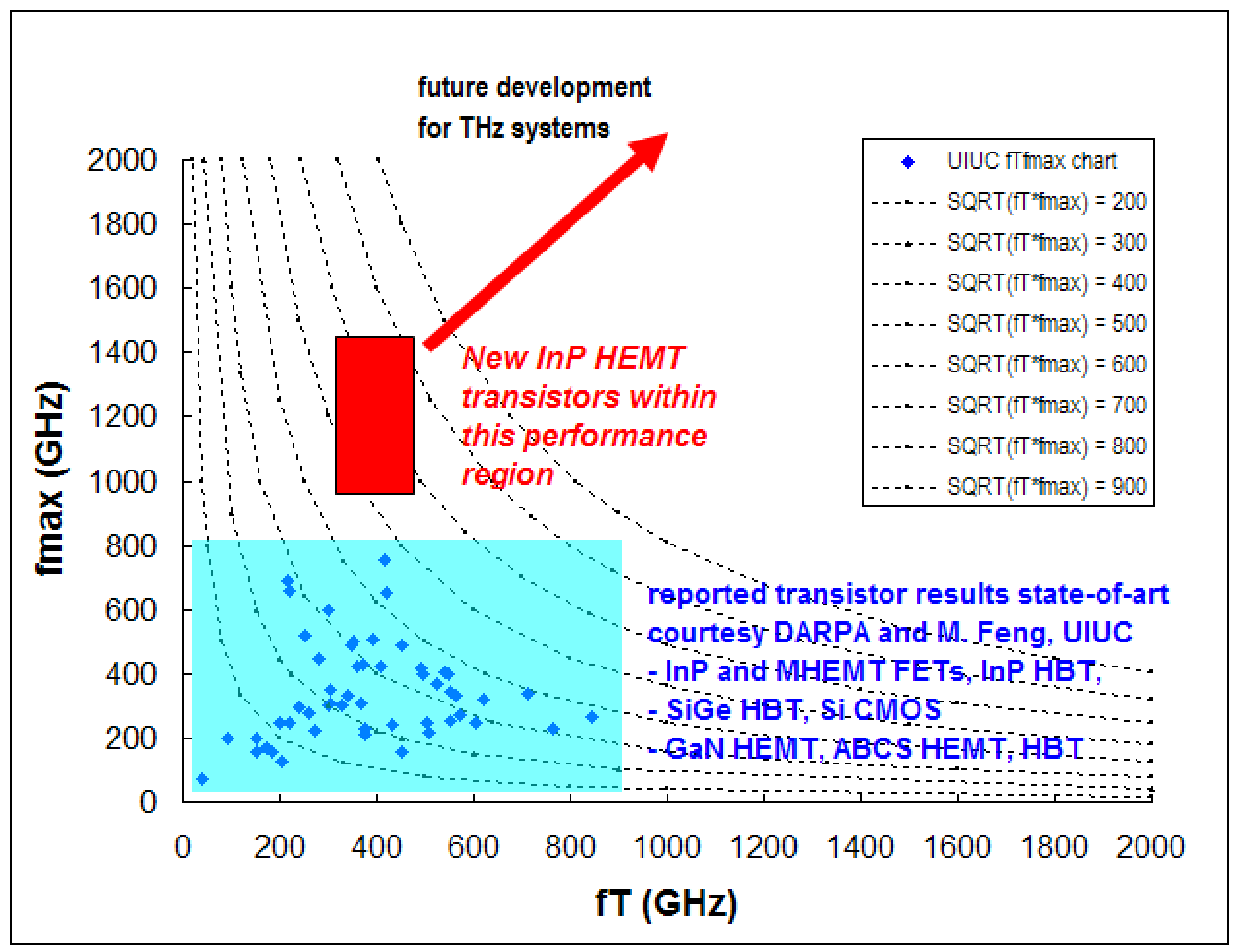

ABCS compared with 35 nm InP HEMT (SWIFT)

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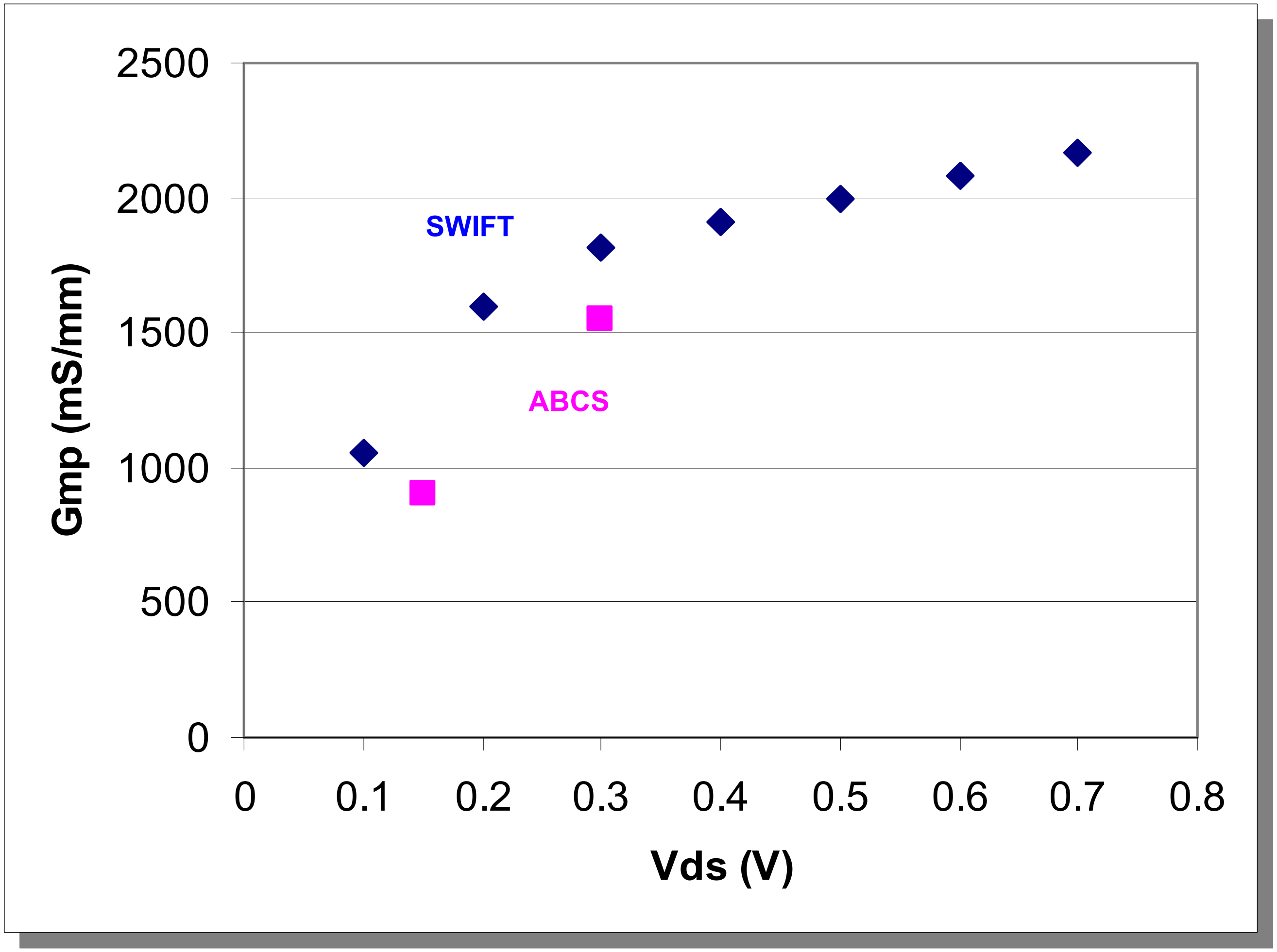
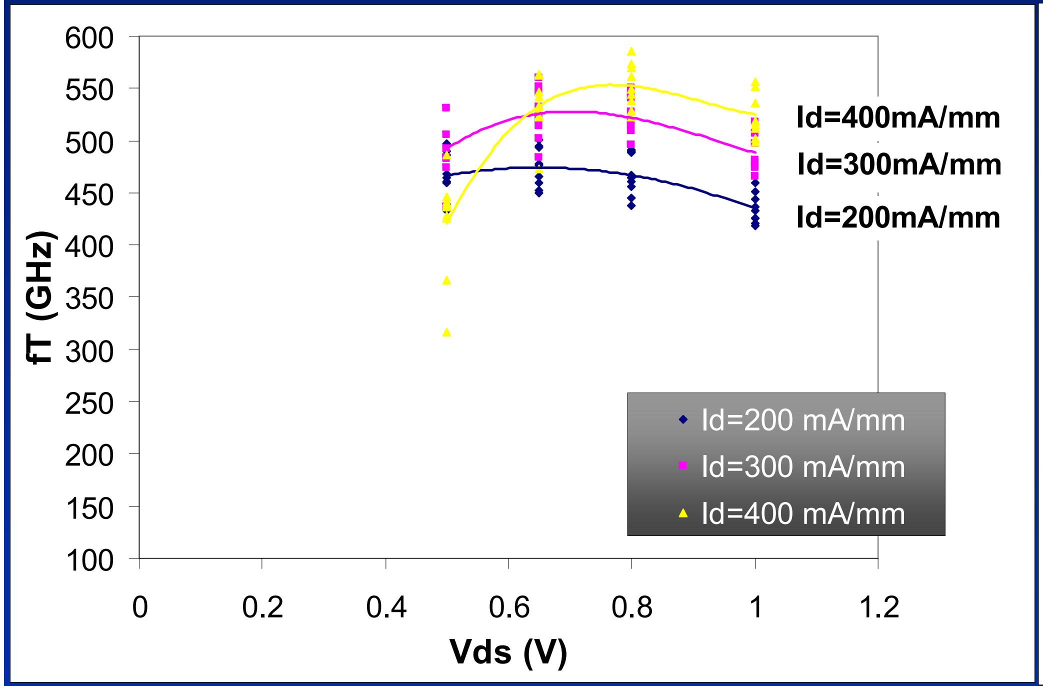
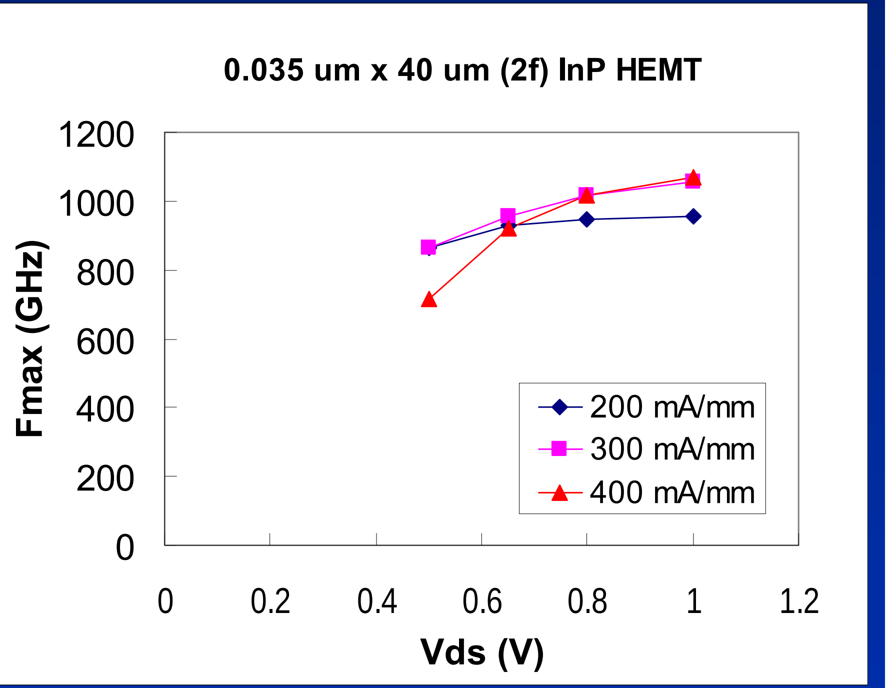


Bias dependance

fT

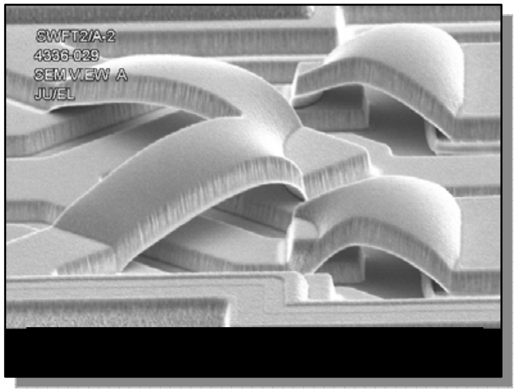


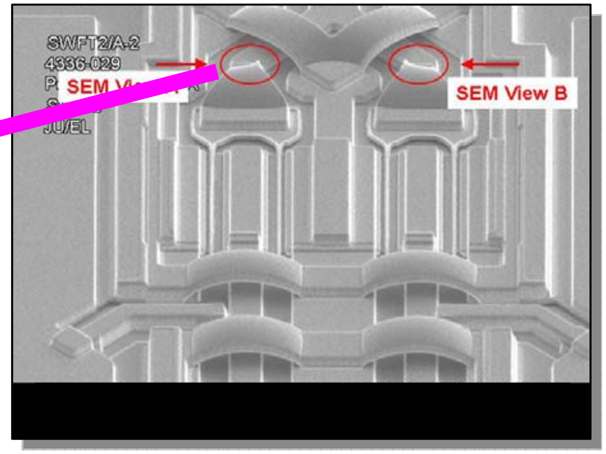
Fmax

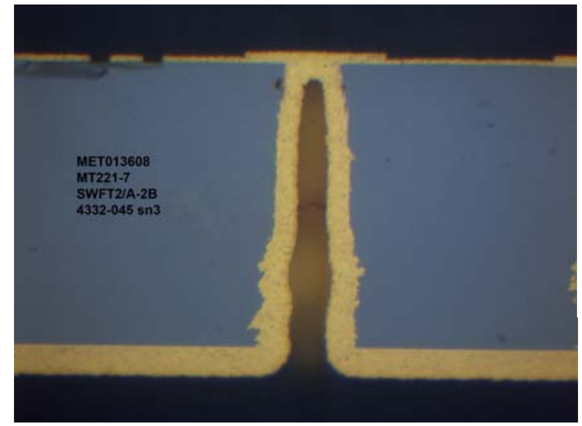


– 2-finger 40um InP HEMT.
– Peak Fmax = 1.1 THz; fT = 550 GHz

Challenging Interconnects and Passives for Sub MMW Integrated Circuits (S-MMICs)

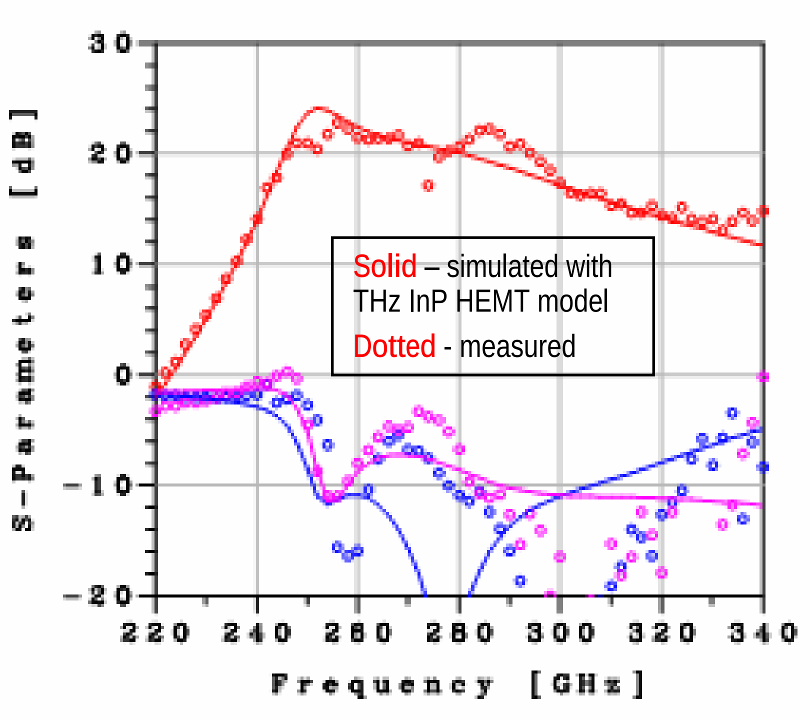






- TFR, MIMCAP, 2 interconnect metal layers with airbridges
- Interconnections scaled down by factor of 5
- Slot via development to 50 um thick InP substrate
- Overall S-MMIC size is ~10x smaller than MMW MMICs

Highest Frequency Circuits



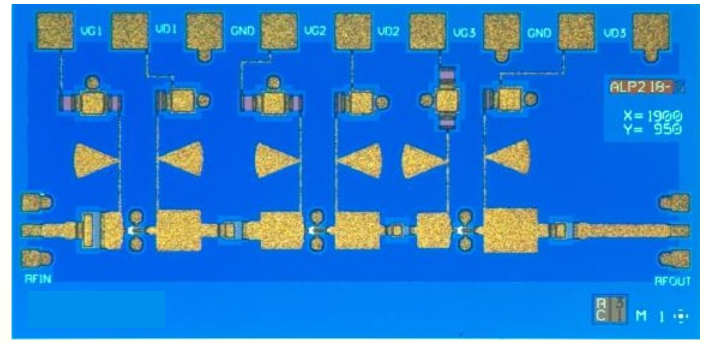
Features

- 35 nm InP HEMT
- 50 um InP with vias
- 3-stage s-MMIC LNA
  - 2f 20 um per stage; 1V, 300 mA/mm
  - 21 dB gain @280 GHz (7 dB/stage)
  - 15 dB gain @340 GHz (5 dB/stage)
  - Best LNAs 18 dB gain@340 GHz
  - NF ~ 7 dB@330 GHz

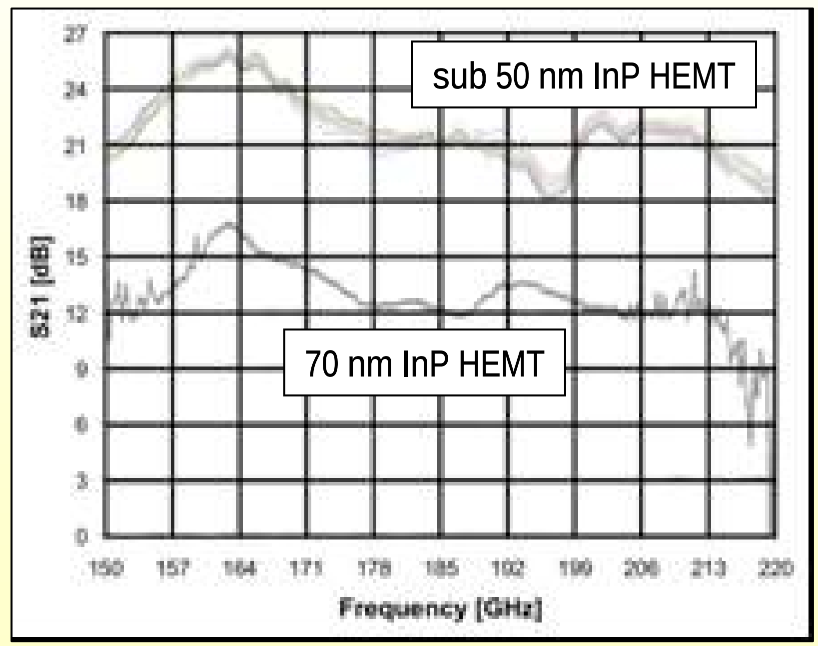
- Highest frequency s-MMIC amplifier ever demonstrated
- Excellent match to simulation validates model
- Validates THz fmax Transistor

G-band LNA performance

- Legacy 3-stage 70 nm InP HEMT G-band LNA MMIC achieved 12 dB gain from 175-210 GHz
  - Singled ended MMIC LNA
  - 2f20 um devices on each of 3 stages
- Same MMIC fabricated on the new sub 50 nm InP HEMT process
- 21 dB gain has been achieved from 175-210 GHz at Vds = 1V and Id = 9 mA
- 18 dB gain was achieved at 220 GHz
- The gain shape with new device is preserved
  - 9 dB higher total gain achieved
  - 3 dB higher gain per stage achieved



Gain vs. Frequency Measurement



Going Forward – HEMT Technology For Radiometers

Understand fundamentals towards cryogenic NF performance

- device stability
- role and reduction of shot noise in cooled devices
- continue to study next generation materials including ABCS HEMT, InAs channels
- apply and continue to push HEMT improvements towards cryogenic performance
- optimization of device technologies for specific frequency bands
    - X-band cryogenic device needs to be different than than W, G-band device

Continue to push the frequency envelope for amplifier technology

- shorter gates, reduced parasitics, InAs channels
- 140 GHz, 220 GHz window for MMW cameras
- 180 GHz for atmospheric sensing
- push 220, 260, 340 GHz and beyond – 1 THz one day?
- advanced packaging concepts

Next generation insertions – larger arrays, cameras, high frequency sensors

- 35, 94 GHz imaging solutions being introduced in commercial market
- 140, 220 GHz active radiometers for next generation cameras
- 180 GHz SAR concepts are being explored
- size, weight, power reduction with wider bandwidth and lower noise figure desired

Going Forward – Proposed Topics of Research for Keck program in next 2-3 years

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Characterize, analysis, optimize InP HEMT device for cryogenic applications

- No systematic study has been conducted on InP HEMT devices to date
- At NGST, InP HEMTs are optimized for room temperature operation and have generally proven to translate to good cryogenic performance
- Several questions have been identified
    - measure and analyze devices to develop correlations to MMIC amplifier results
    - cryogenic leakage current shot noise is significant at lower frequencies
    - device stability with high Indium content channels
    - what gate length and device size is ideal at lower frequencies?
    - 35 nm device improvements at higher frequencies translate to lower freq?
    - do ohmic improvements at room temperature translate to cryogenic advantages?
    - how do recent isolation, gate metal, gate recess and passivation improvements impact cryogenic performance?
    - is there a more ideal device design/process target for cryogenic devices
        - threshold voltage
        - gate length
        - recess process
        - epitaxial design
        - device topologies

Going Forward – Proposed Topics of Research for Keck program in next 2-3 years

Characterize, analysis, optimize InP HEMT device for cryogenic applications (cont.)

- Systematic cryogenic study of existing samples and device/process splits both through MIC amplifiers and cryogenic on-wafer probing measurements
- Study next generation materials including ABCS, InAs channels, new metals and passivation layers
- Update models to set goals and metrics to meet 3x quantum limit noise performance
  - develop correlations to current device and MMIC amplifier results
  - evaluate proposed improvements to these goals

Apply improvements to update latest SOA InP HEMT designs

- develop and adapt new device models towards updated cryogenic LNA designs based on device improvements
- develop new designs to take advantage of performance improvements
  - example – lower Vds, Ids at equivalent gain
- consider splitting device technologies used for specific frequency ranges
- new designs to push higher frequency, wider bandwidth