Project: IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs)

Submission Title: Current Status of Semiconductor Technologies and Circuits for THz applications

Date Submitted: July 2008

Source: Jae-Sung Rieh, Korea University
Address
Voice: FAX: E-Mail: jsrieh@korea.ac.kr

Re:

Abstract: Current Status of Semiconductor Technologies and Circuits for THz applications

Purpose:

Current Status of Semiconductor Technologies and Circuits for THz applications

2008. 7.16

Jae-Sung Rieh
School of Electrical Engineering
Korea University

Outline

- Introduction
- Components for THz Communication Systems
- Semiconductor Technologies for THz
- Circuit Examples for THz
- Summary

Introduction

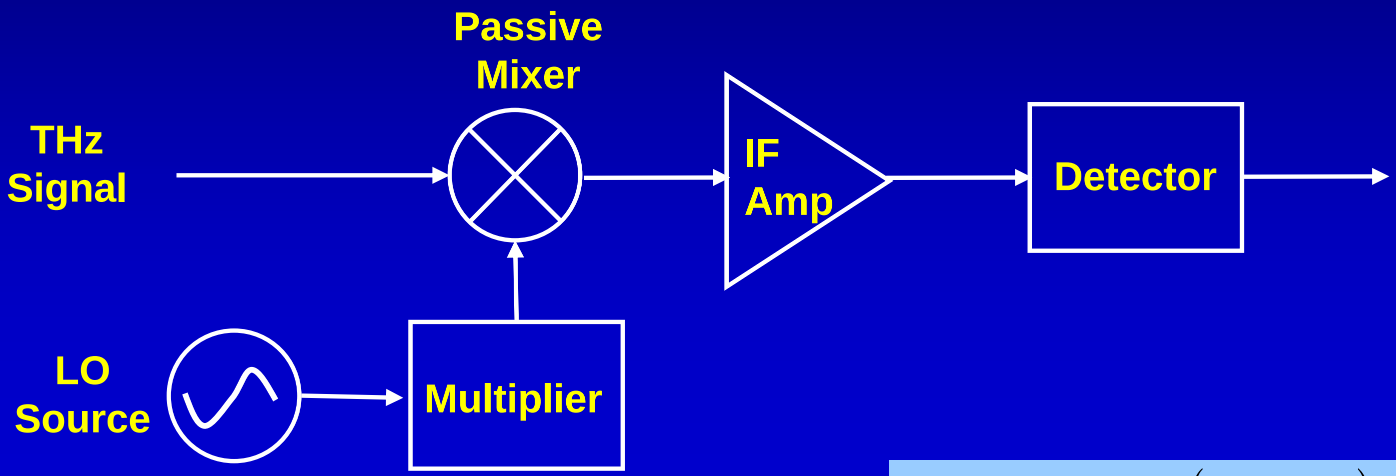
- Two main approaches for THz system implementation
  - Optical approach
    - Challenge: lowering the operation frequency
  - Electrical approach
    - Challenge: raising the operation frequency

- Electrical approaches
  - Diode approach

    → Passive and no gain provided
  - Transistor approach

    → Operation frequency still not sufficient but growing

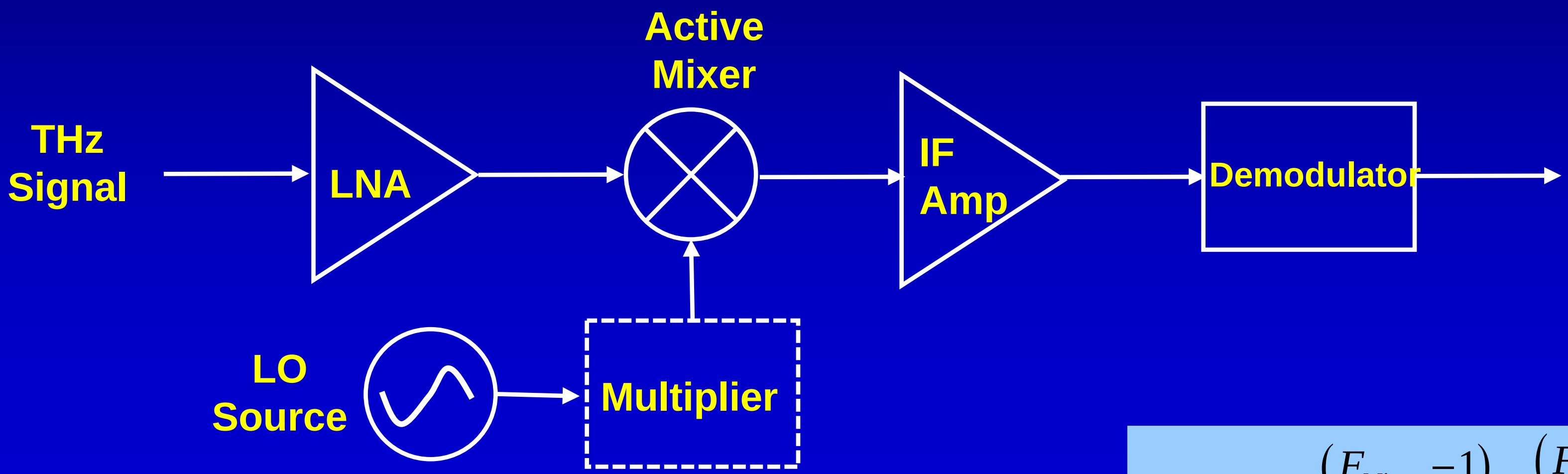
Traditional Diode-Based THz Receiver


Passive Mixer
THz Signal
IF Amp
Detector
LO Source
Multiplier

$$F = F_{mixer} + L_{Mixer}\left(F_{IFamp} - 1\right) + \ldots$$

- Issues
  - Absence of LNA
    - → Noise from mixer and IF amp not suppressed
  - Passive nature of mixer
    - → No gain provided. Noise from IF amp not suppressed
  - LO source
    - Typically not integration-ready

Transistor-Based THz Receiver



$$F = F_{LNA} + \frac{(F_{Mixer} - 1)}{G_{LNA}} + \frac{(F_{IFamp} - 1)}{G_{LNA} G_{Mixer}} + \ldots$$

- Widely accepted architecture for low frequency receivers
  - Addition of LNA
  - Active mixer with gain or reduced loss
  - Integration-friendly LO

→ Enabled by transistor-based semiconductor technologies

→ Can this architecture be applied to THz receivers, too?

Semiconductor Technologies for THz

- III-V technologies
  - HBT (heterojunction bipolar transistor) technologies
  - HEMT (high electron mobility transistor) technologies
- Si-based technologies
  - SiGe HBT technologies
  - RFCMOS technologies

	Bipolar	**FET**
III-V	III-V HBT	III-V HEMT
Si	SiGe HBT	RF CMOS

Technology Comparison

GaAs/InP
HBT or HEMT

- Very high operation speed
- High cost
- Reliability issues

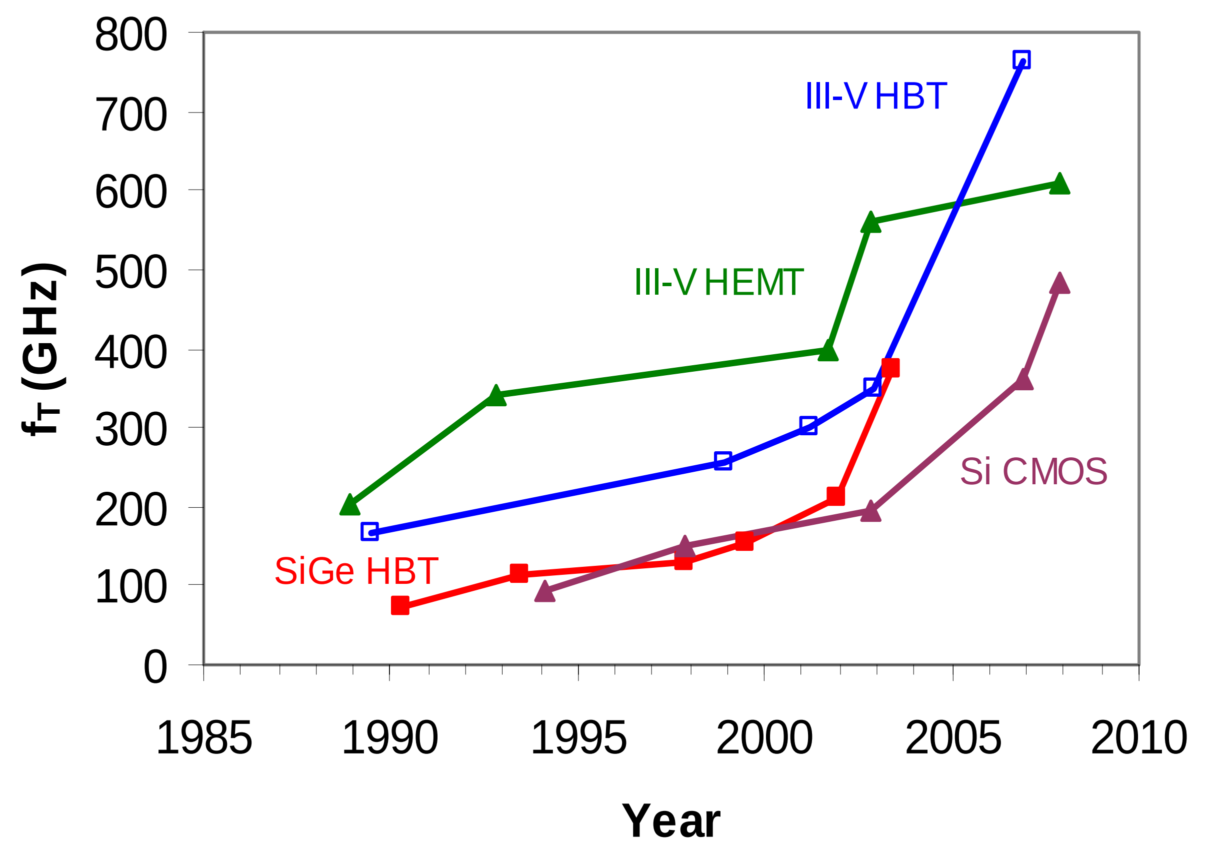
SiGe BiCMOS

- High operation speed
- CMOS-technology compatible
- High reliability
- Extra mask steps on base CMOS technology

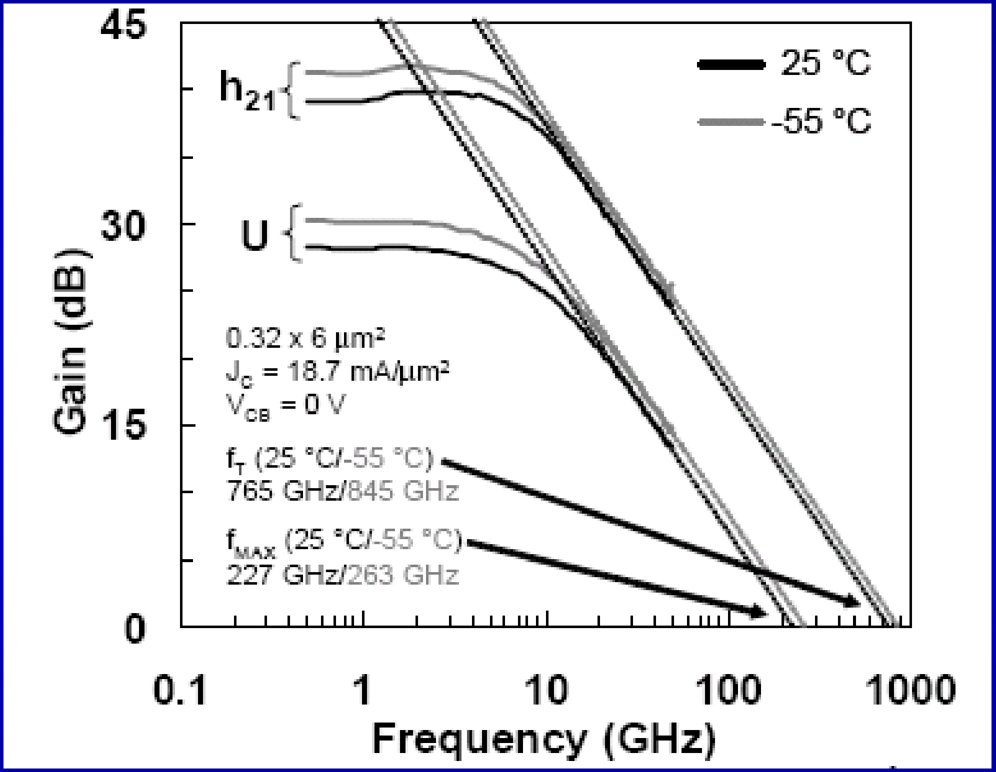
CMOS

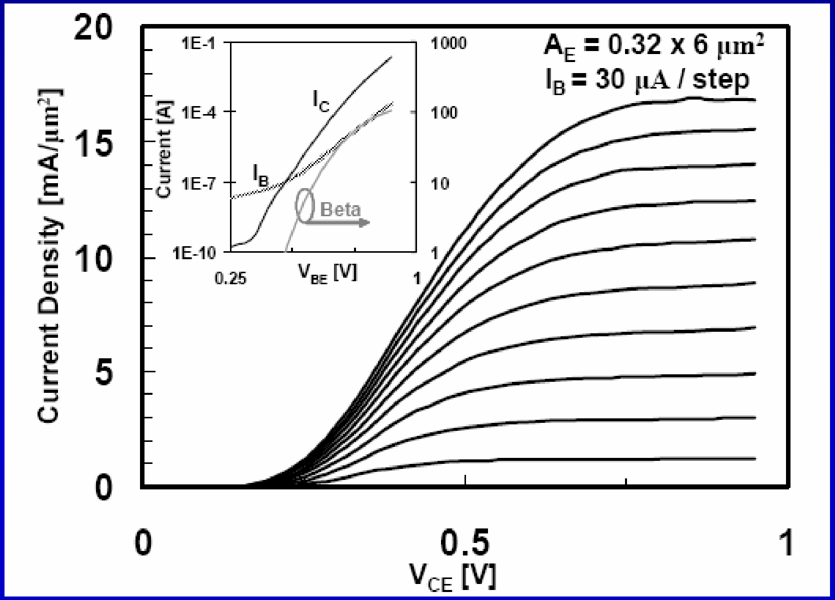
- Acceptable operation speed
- Low cost and high reliability
- Relatively low g_m
- Poor device matching

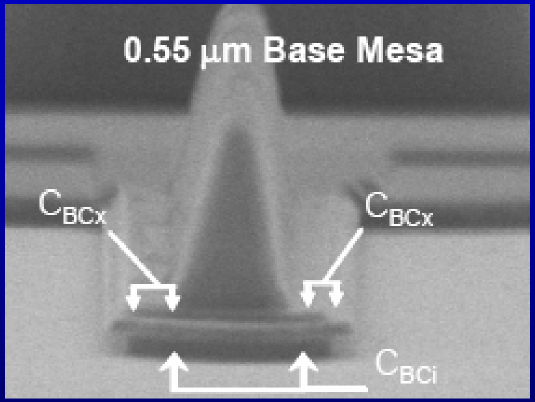
Operation Speed Trend of Technologies



III-V HBT Record Performance



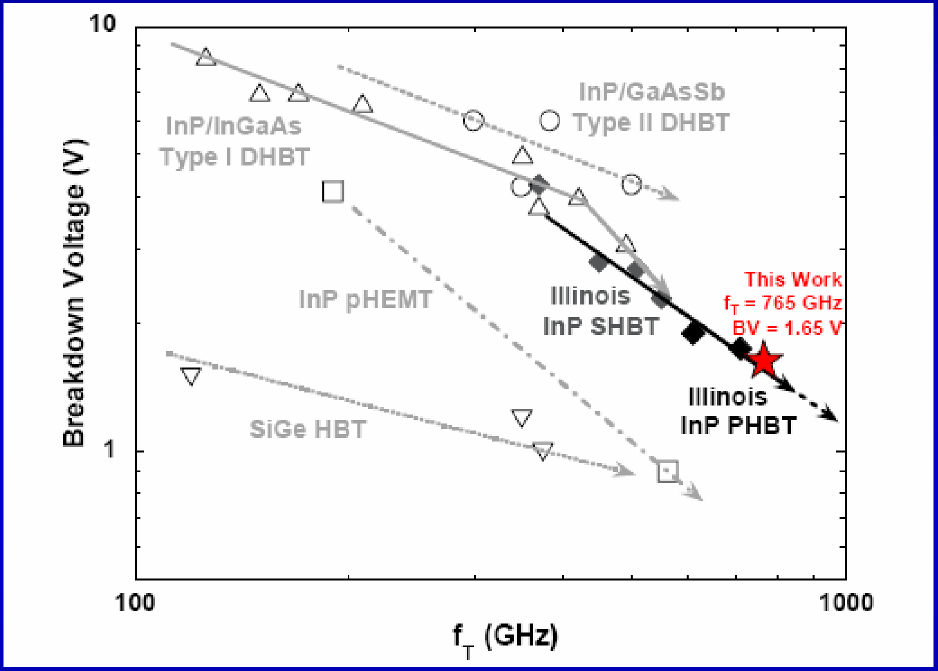


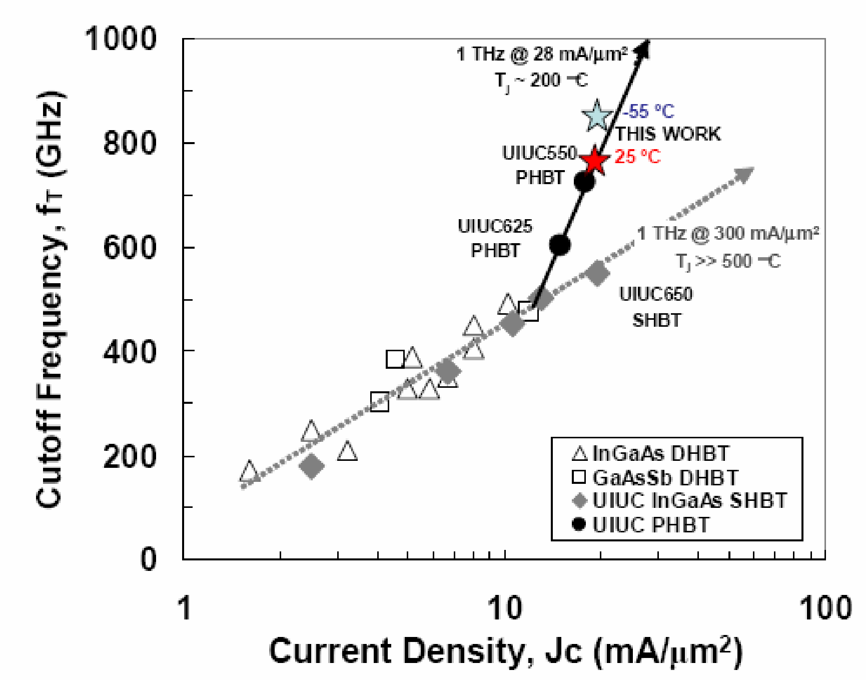


- UIUC
- Peak f_T = 765 GHz at 25C
- Peak f_T = 845 GHz at -55C

Snodgrass et al IEDM 2006

III-V HBT Performance Issues

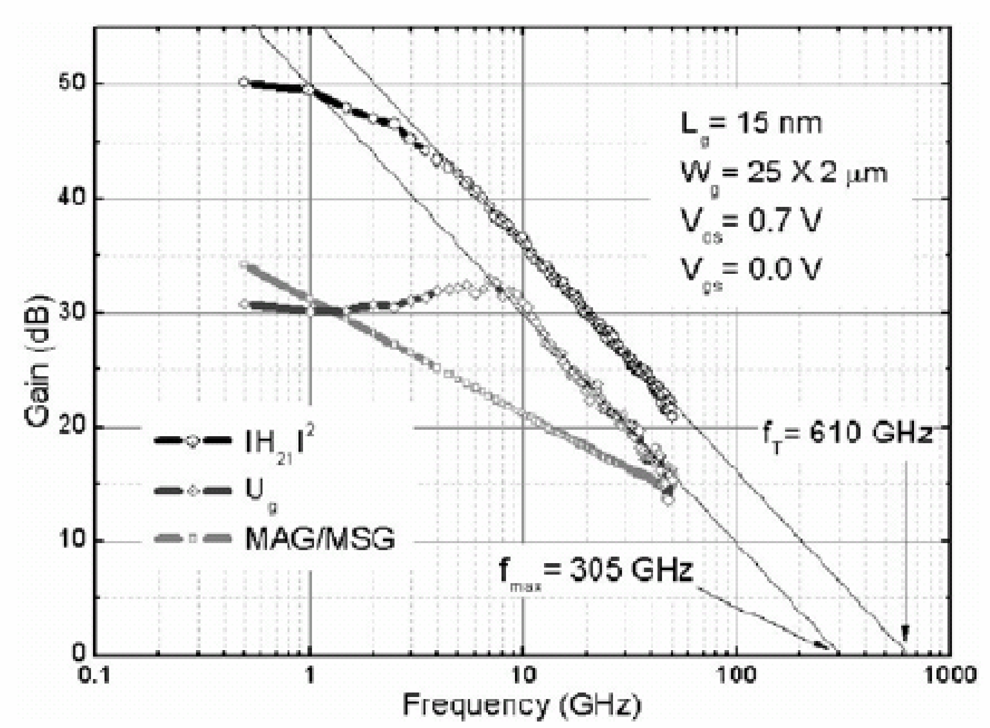


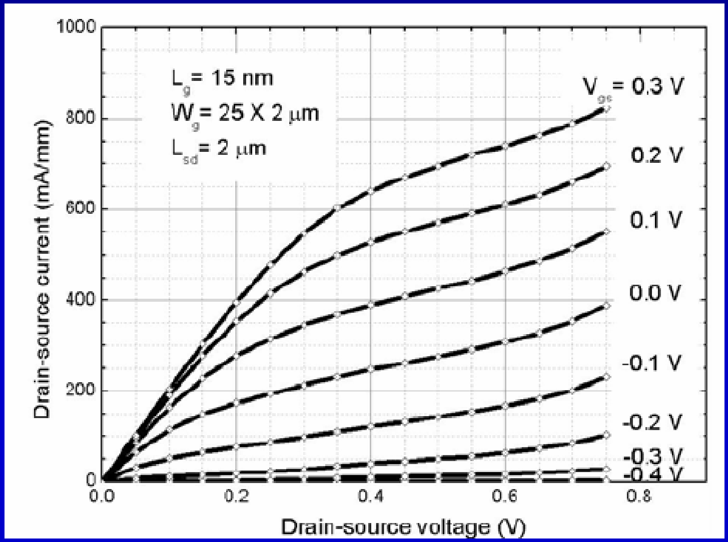


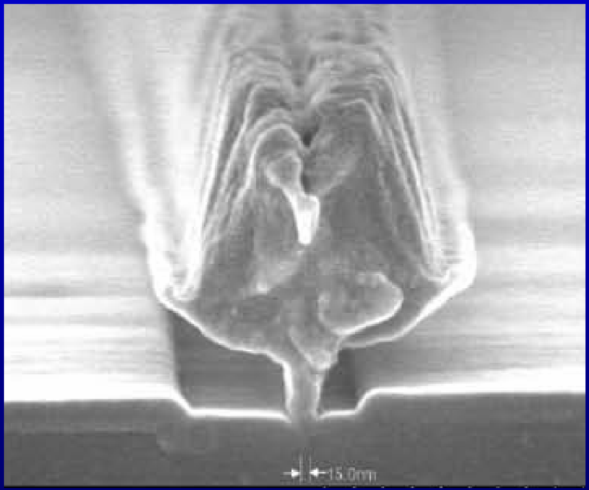
- Issues with increasing operation frequency
  - Reduction in breakdown voltage → Limits safe operation region
  - Increase in collector current density → Influences reliability

Snodgrass et al IEDM 2006

HEMT Record Performance



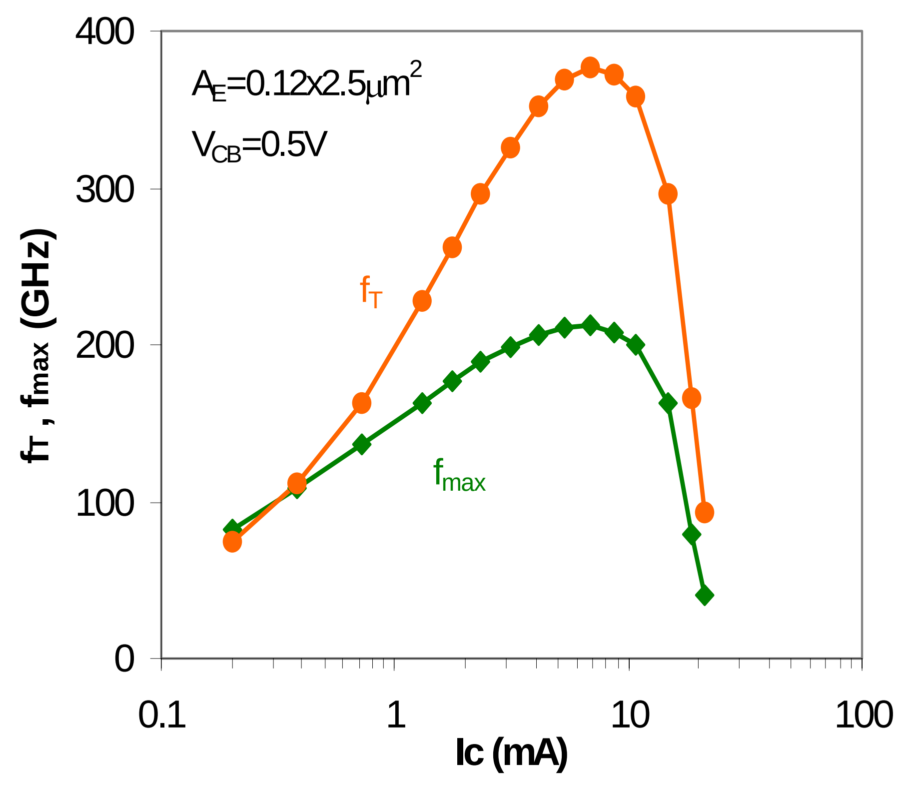


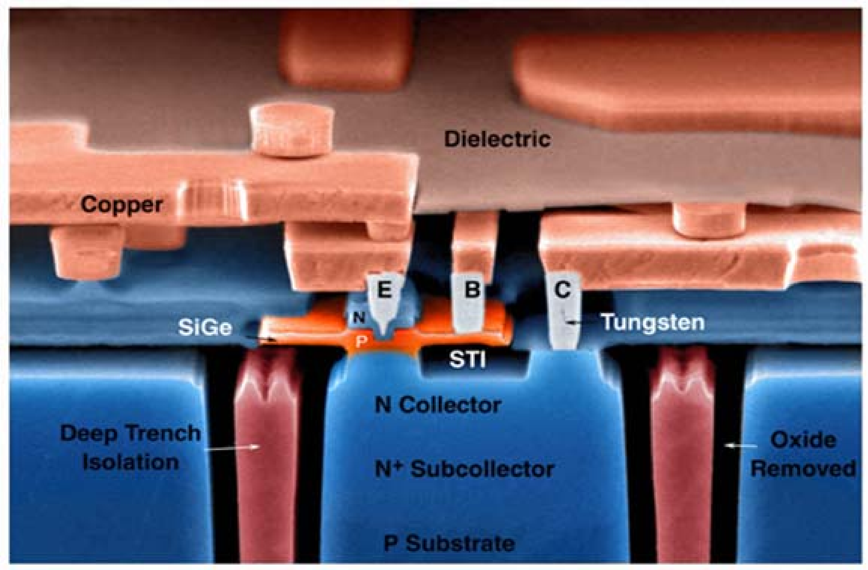


- Seoul National Univ.
- 15 nm gate length InP HEMT
- Peak f_T / f_{max} = 610/305 GHz

Yeon et al IEDM 2007

SiGe HBT Record Performance

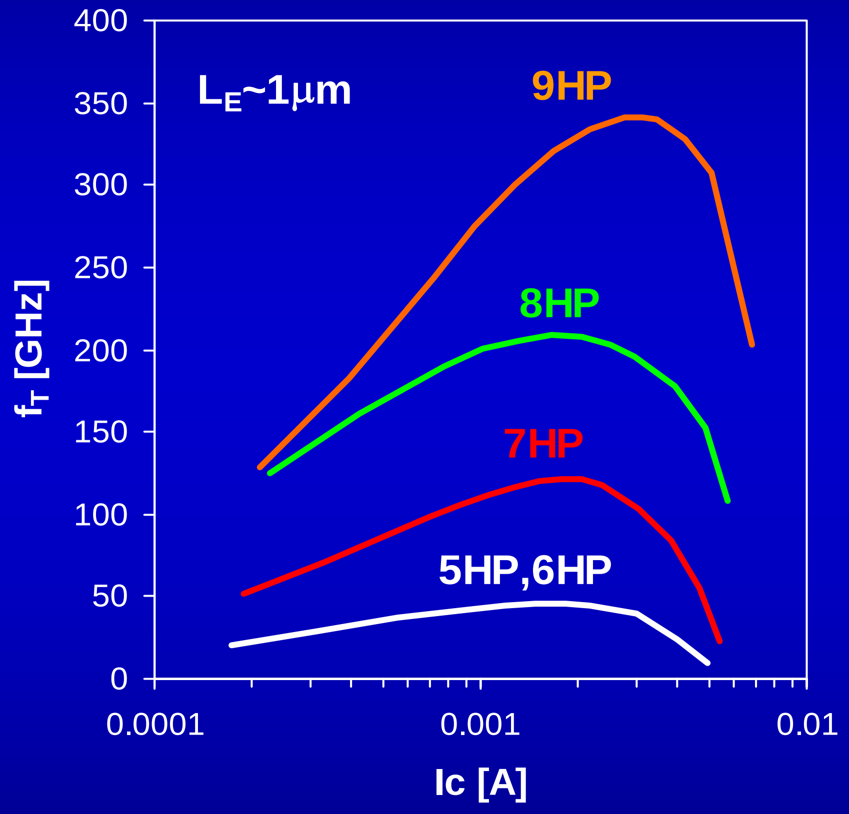




- IBM
- 0.12 um SiGe HBT
- Peak f_T / f_{max} = 375/210 GHz

Rieh et al IPRM 2003

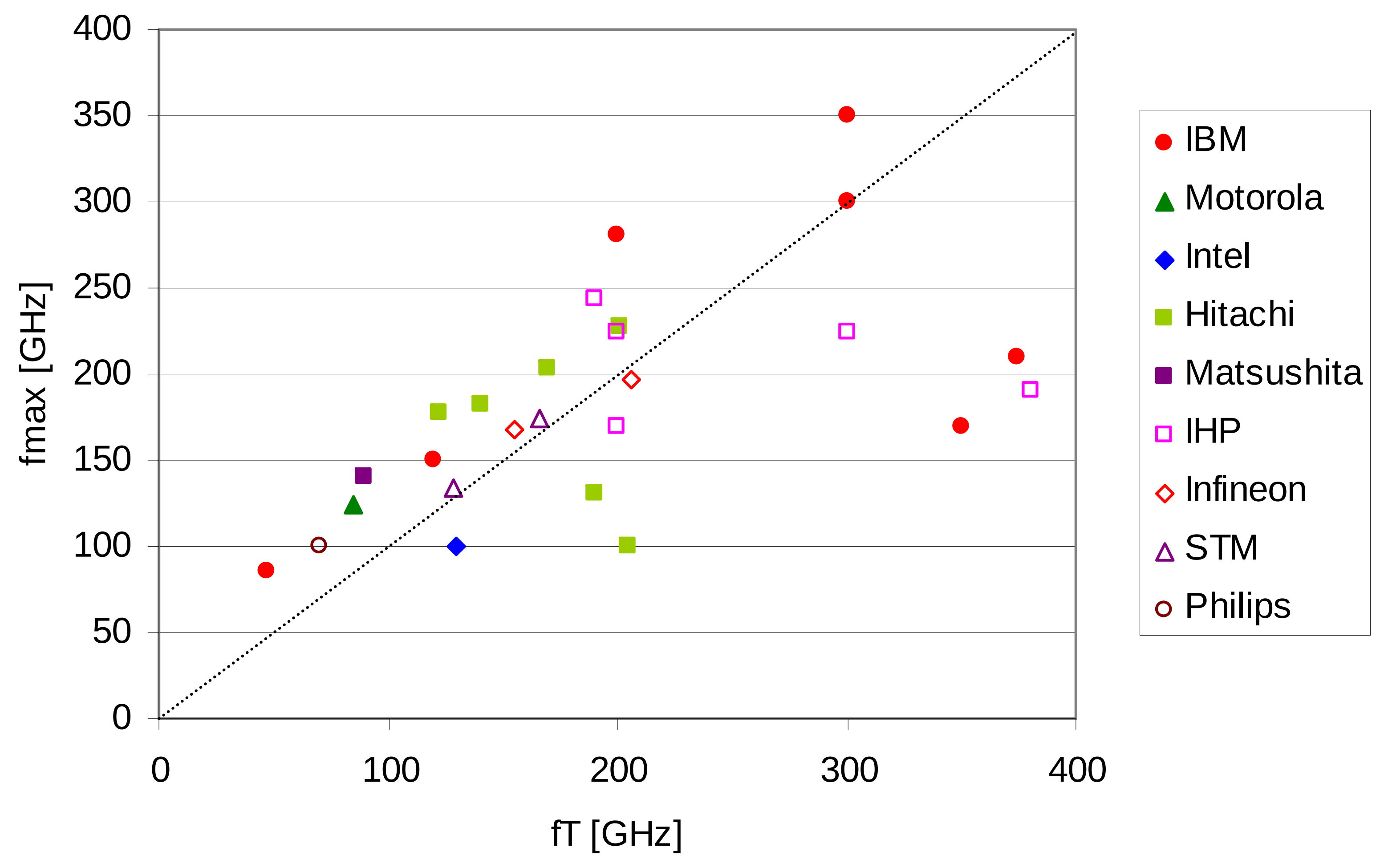
SiGe HBT Performance Trend



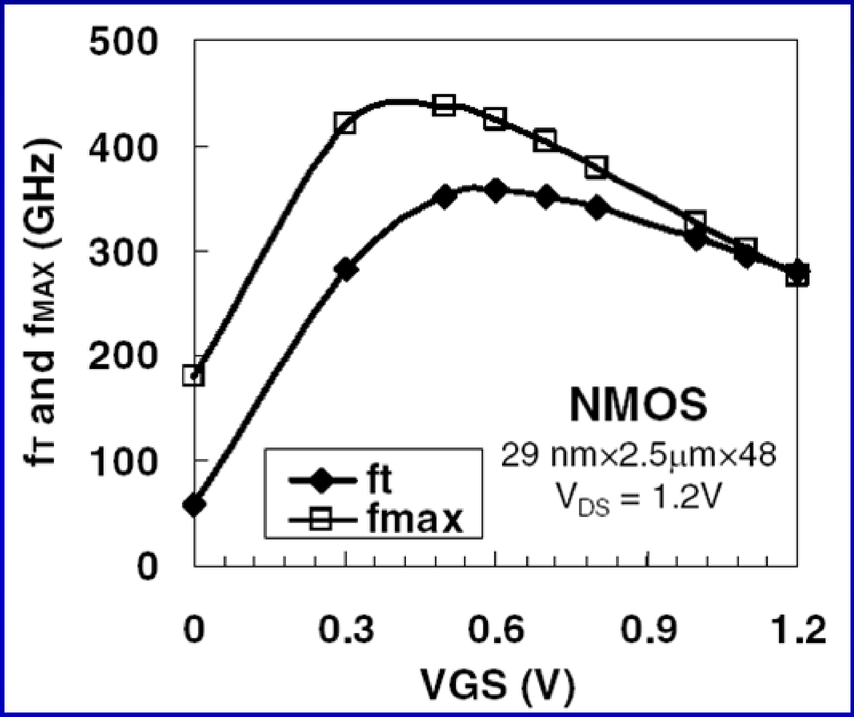
	5HP 6HP	7HP	8HP	9HP
f_T [GHz]	47	120	210	350
f_{max} [GHz]	85	150	285	300
$J_{C,p}$[mA/μm²]	~1.5	~8	~12	~19
BV_{CEO} [V]	3.4	1.8	1.7	1.7
BV_{CBO} [V]	10.5	6.5	5.5	5.6
Beta	100	300	300	650

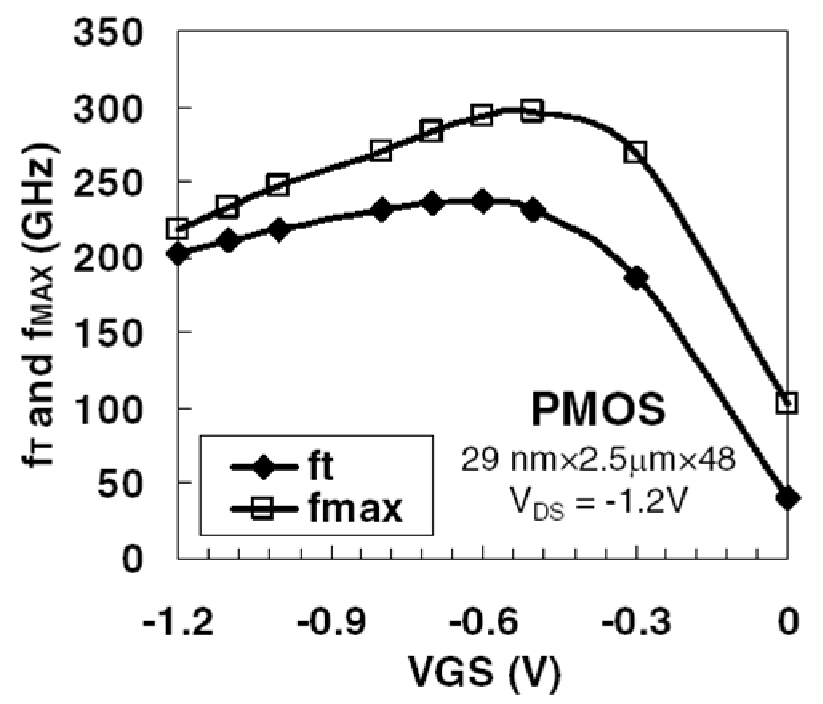
- Trend of IBM SiGe HBTs

SiGe HBT f_T and f_{max}



RFCMOS Record Performance (I)



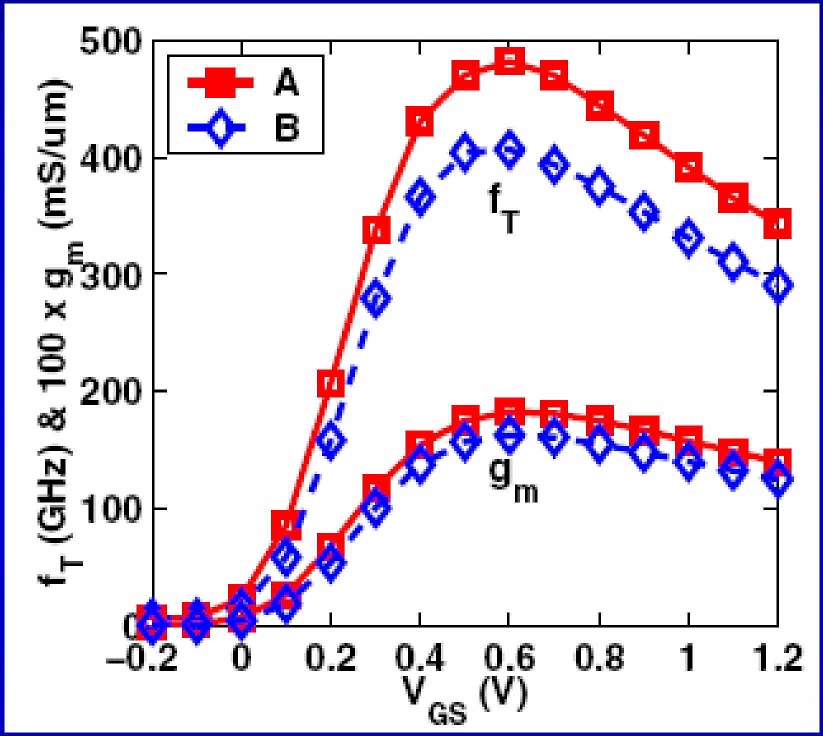


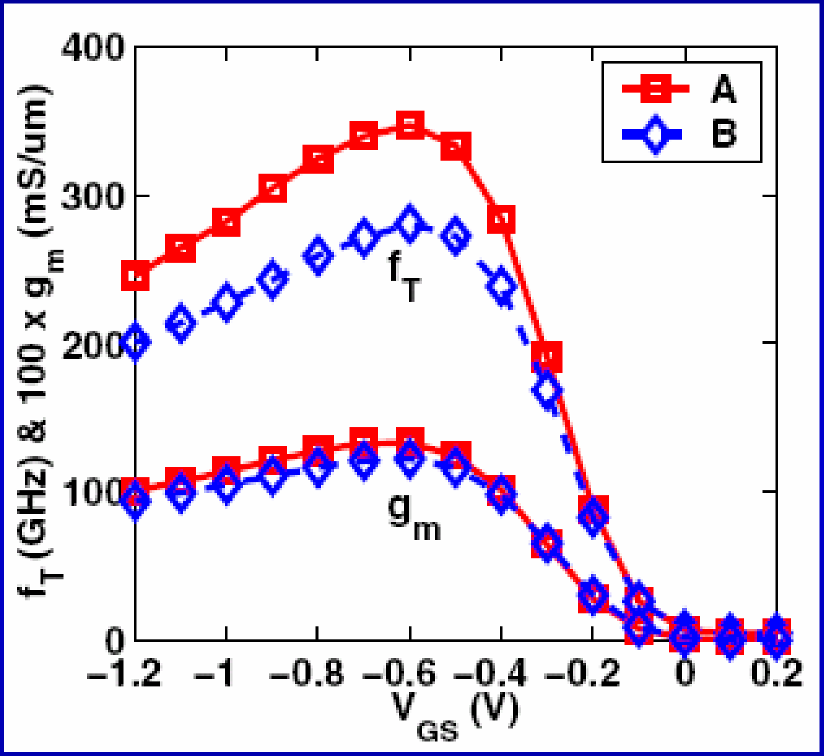
- 65 nm SOI NFET (L_{poly}=29 nm)
- Peak f_T / f_{max} = 360/420 GHz

- 65 nm SOI PFET
- Peak f_T / f_{max} = 238/295 GHz

Post et al IEDM 2006

RFCMOS Record Performance (II)





- NFET: 45 nm SOI (L_{poly}=29 nm)
- Peak f_T = 485 GHz

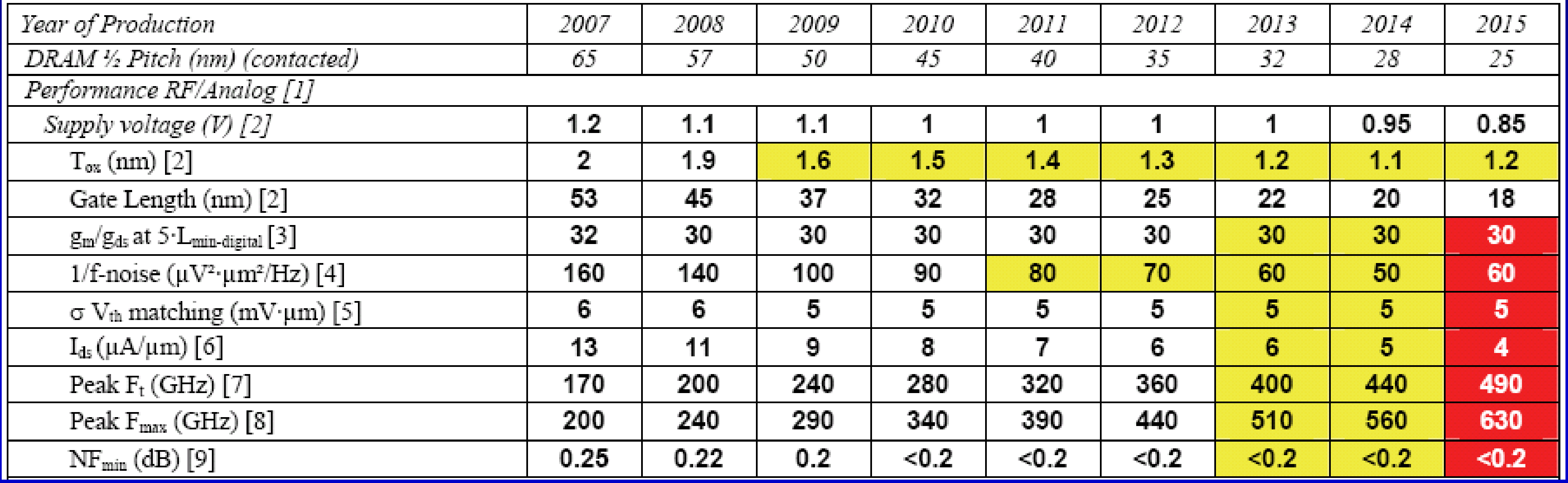
- PFET: 45 nm SOI (L_{poly}=31 nm)
- Peak f_T = 345 GHz

A: Relaxed poly pitch, B: Minimum poly pitch

Lee et al IEDM 2007

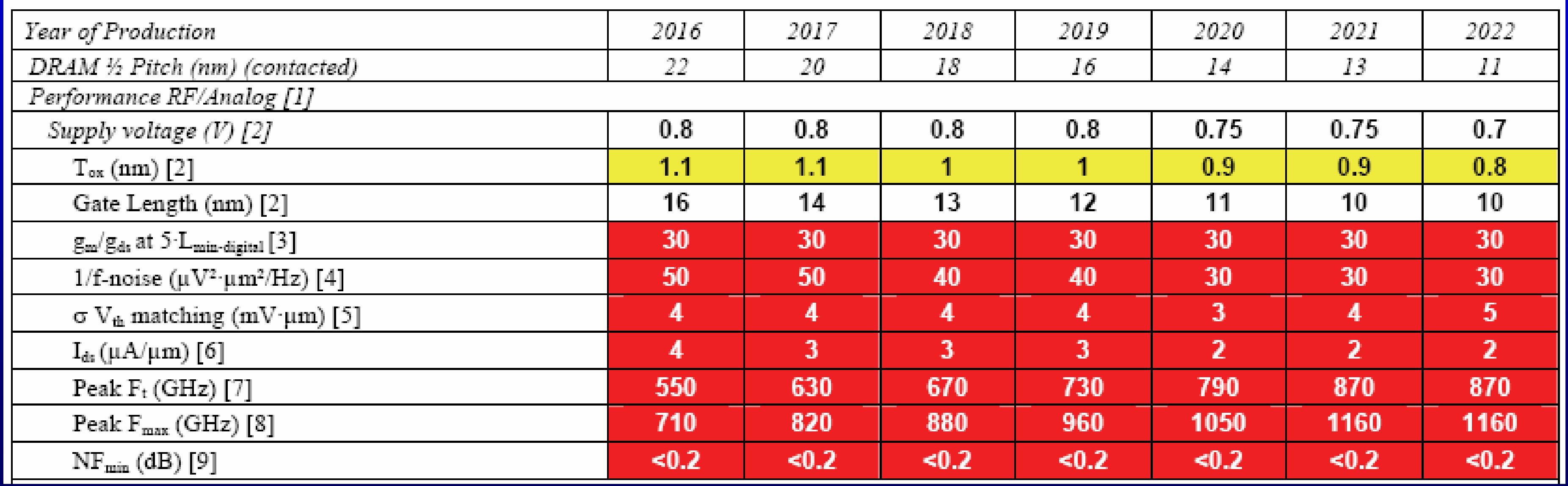
ITRS Roadmap 2007 for RFCMOS

Near-term



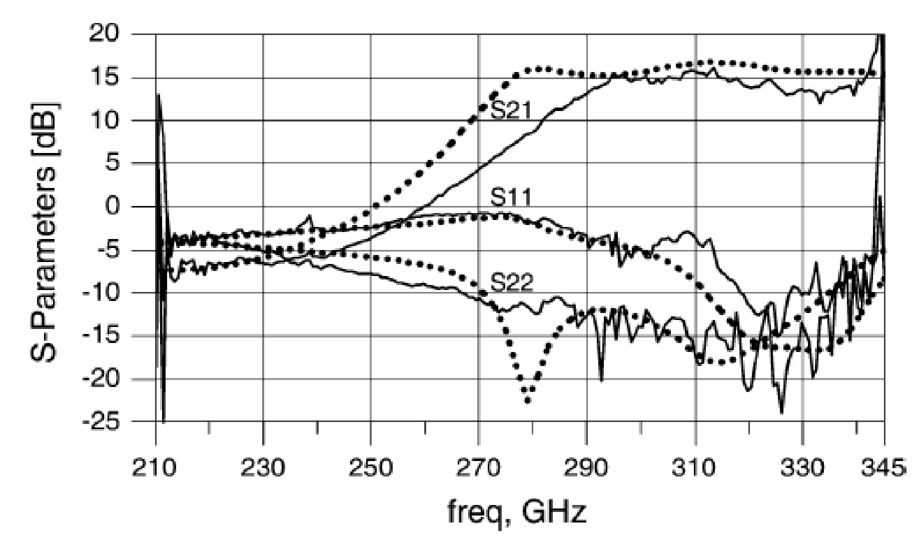
Year of Production	*2007*	*2008*	*2009*	*2010*	*2011*	*2012*	*2013*	*2014*	*2015*
DRAM ½ Pitch (nm) (contacted)	*65*	*57*	*50*	*45*	*40*	*35*	*32*	*28*	*25*
Performance RF/Analog [1]									
Supply voltage (V) [2]	1.2	1.1	1.1	1	1	1	1	0.95	0.85
T_{ox} (nm) [2]	2	1.9	1.6	1.5	1.4	1.3	1.2	1.1	1.2
Gate Length (nm) [2]	53	45	37	32	28	25	22	20	18
g_m/g_{ds} at $5 \cdot L_{min\text{-}digital}$ [3]	32	30	30	30	30	30	30	30	30
1/f-noise ($\mu V^2 \cdot \mu m^2$/Hz) [4]	160	140	100	90	80	70	60	50	60
σ V_{th} matching (mV·μm) [5]	6	6	5	5	5	5	5	5	5
I_{ds} (μA/μm) [6]	13	11	9	8	7	6	6	5	4
Peak F_t (GHz) [7]	170	200	240	280	320	360	400	440	490
Peak F_{max} (GHz) [8]	200	240	290	340	390	440	510	560	630
NF_{min} (dB) [9]	0.25	0.22	0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2

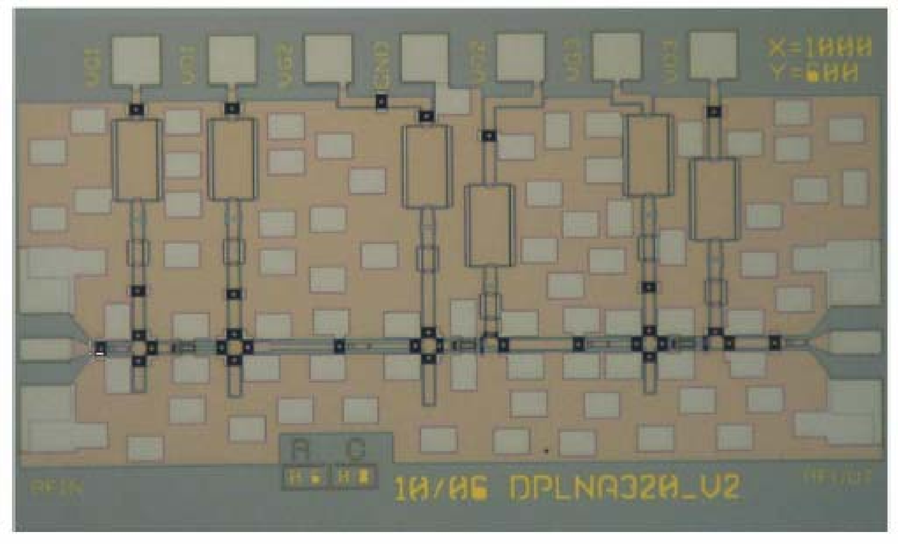
Long-term



Year of Production	*2016*	*2017*	*2018*	*2019*	*2020*	*2021*	*2022*
DRAM ½ Pitch (nm) (contacted)	*22*	*20*	*18*	*16*	*14*	*13*	*11*
Performance RF/Analog [1]							
Supply voltage (V) [2]	0.8	0.8	0.8	0.8	0.75	0.75	0.7
T_{ox} (nm) [2]	1.1	1.1	1	1	0.9	0.9	0.8
Gate Length (nm) [2]	16	14	13	12	11	10	10
g_m/g_{ds} at $5 \cdot L_{min\text{-}digital}$ [3]	30	30	30	30	30	30	30
1/f-noise ($\mu V^2 \cdot \mu m^2$/Hz) [4]	50	50	40	40	30	30	30
σ V_{th} matching (mV·μm) [5]	4	4	4	4	3	4	5
I_{ds} (μA/μm) [6]	4	3	3	3	2	2	2
Peak F_t (GHz) [7]	550	630	670	730	790	870	870
Peak F_{max} (GHz) [8]	710	820	880	960	1050	1160	1160
NF_{min} (dB) [9]	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2

320 GHz InP HEMT Amplifier

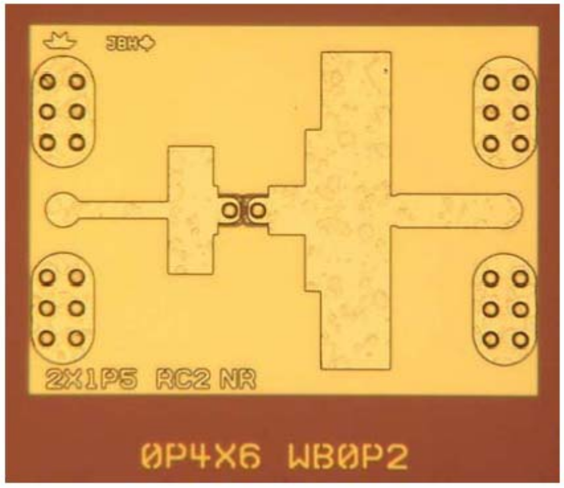




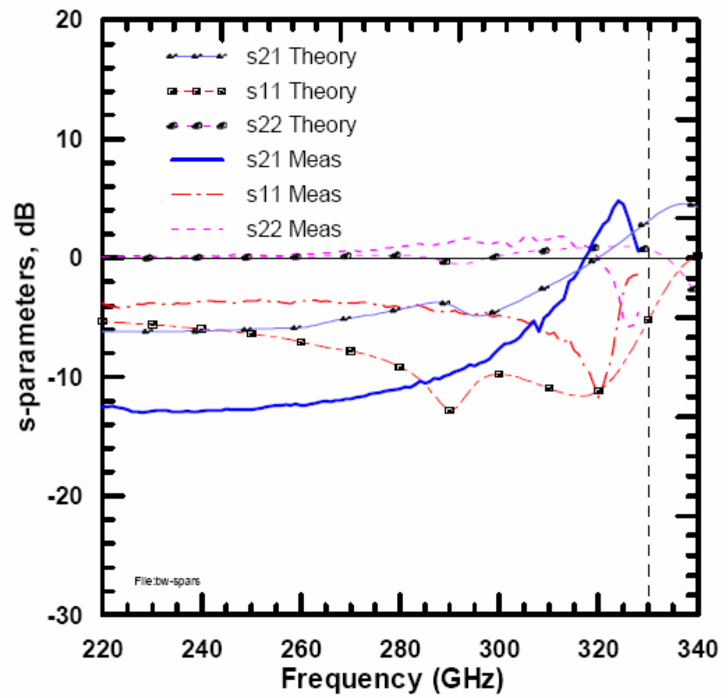
- NGC
- 35 nm NGC InP HEMT
- 3 stage
- P_{Diss} = 43 mW
- Gain = 13-15 dB for 295-340 GHz

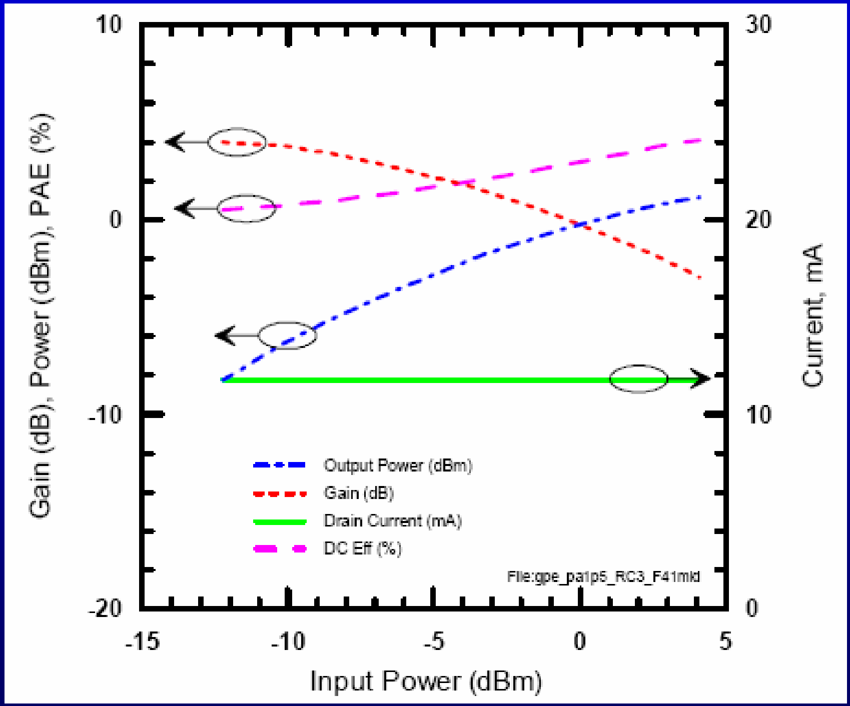
Pukala et al MWCL 2008

324 GHz InP HBT Amplifier



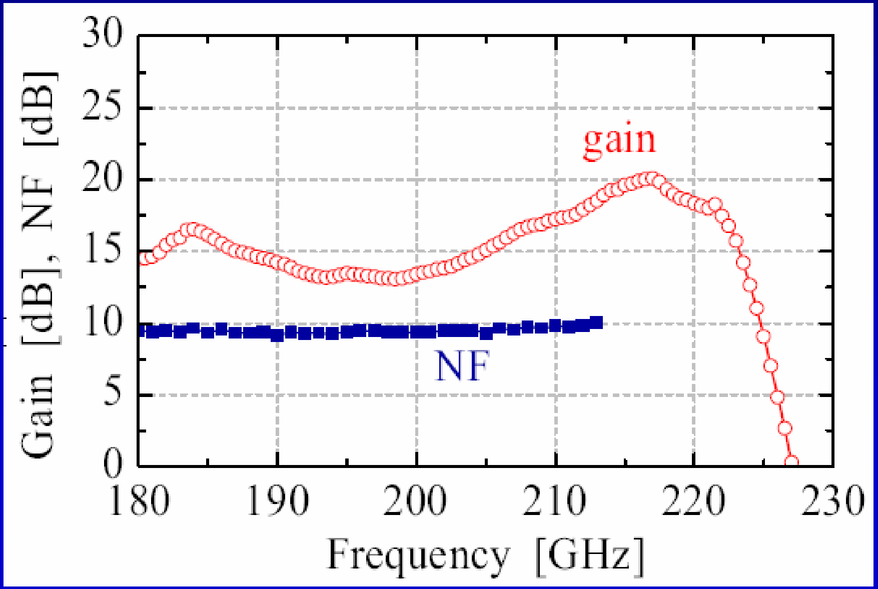
- Teledyne
- 250 nm Teledyne InP HBT
- Single stage common base
- Gain = 4.8 dB at 324 GHz
- Saturated P_{out} = 1.13 dBm



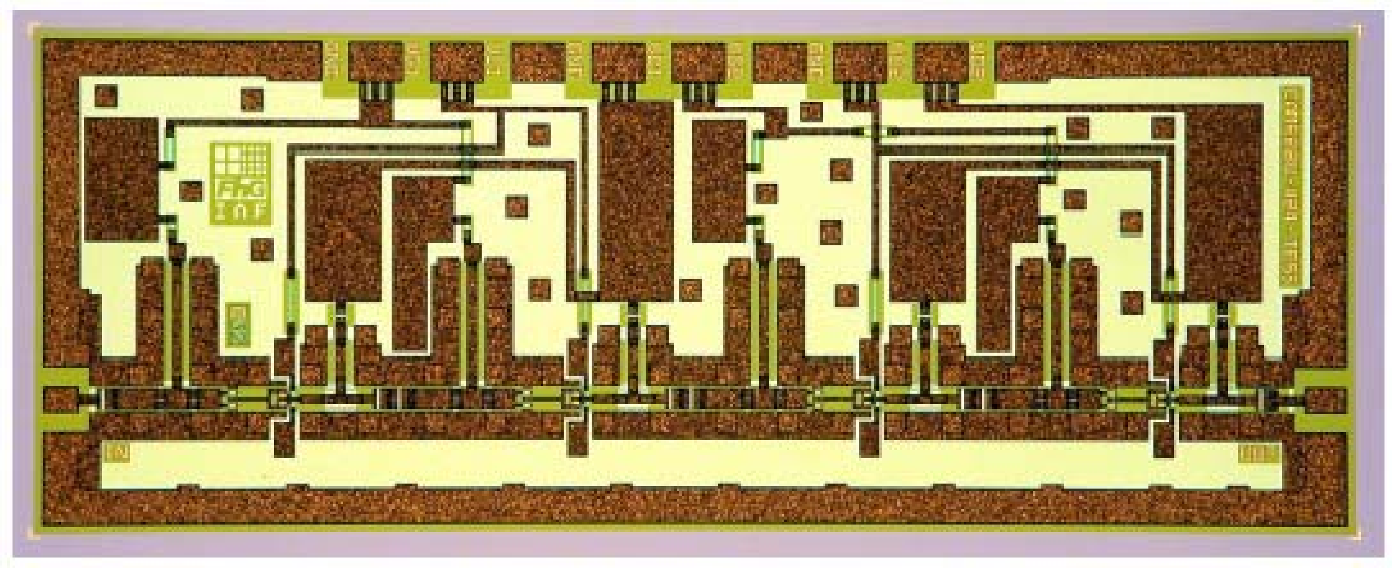


Hacker et al IMS 2008

220 GHz GaAs MHEMT LNA

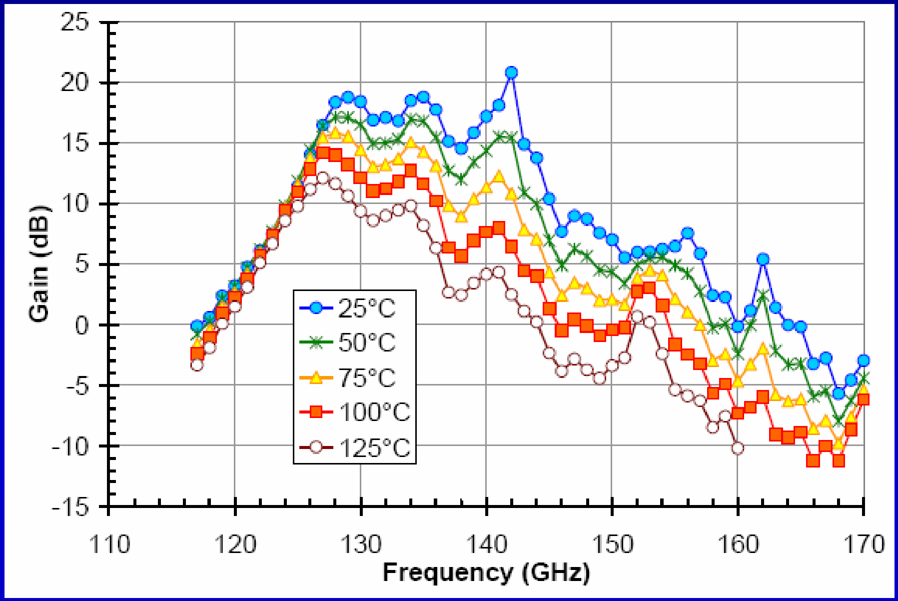


- Franhofer
- 0.1 um Franhofer GaAs mHEMT
- 4 stage cascode
- Peak gain = ~20 dB
- NF = 9.4 dB up to 213 GHz

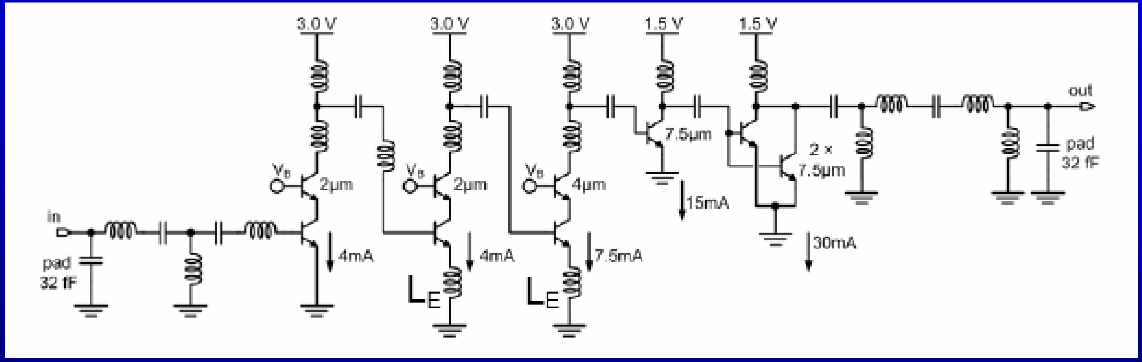


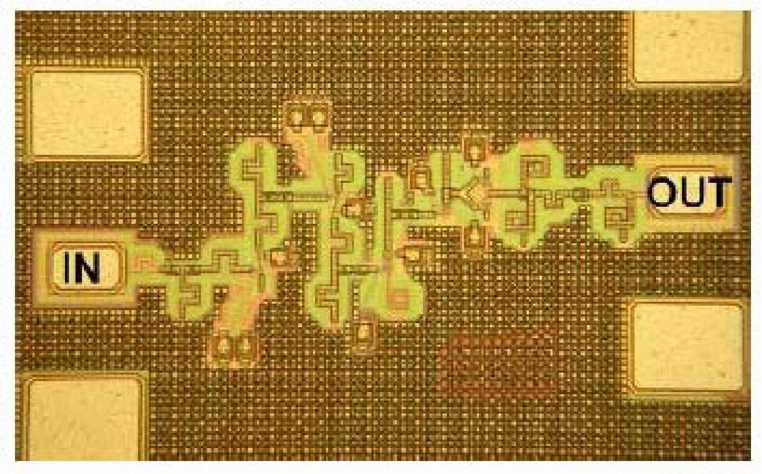
Pukala et al MWCL 2008

140 GHz SiGe HBT Amplifier



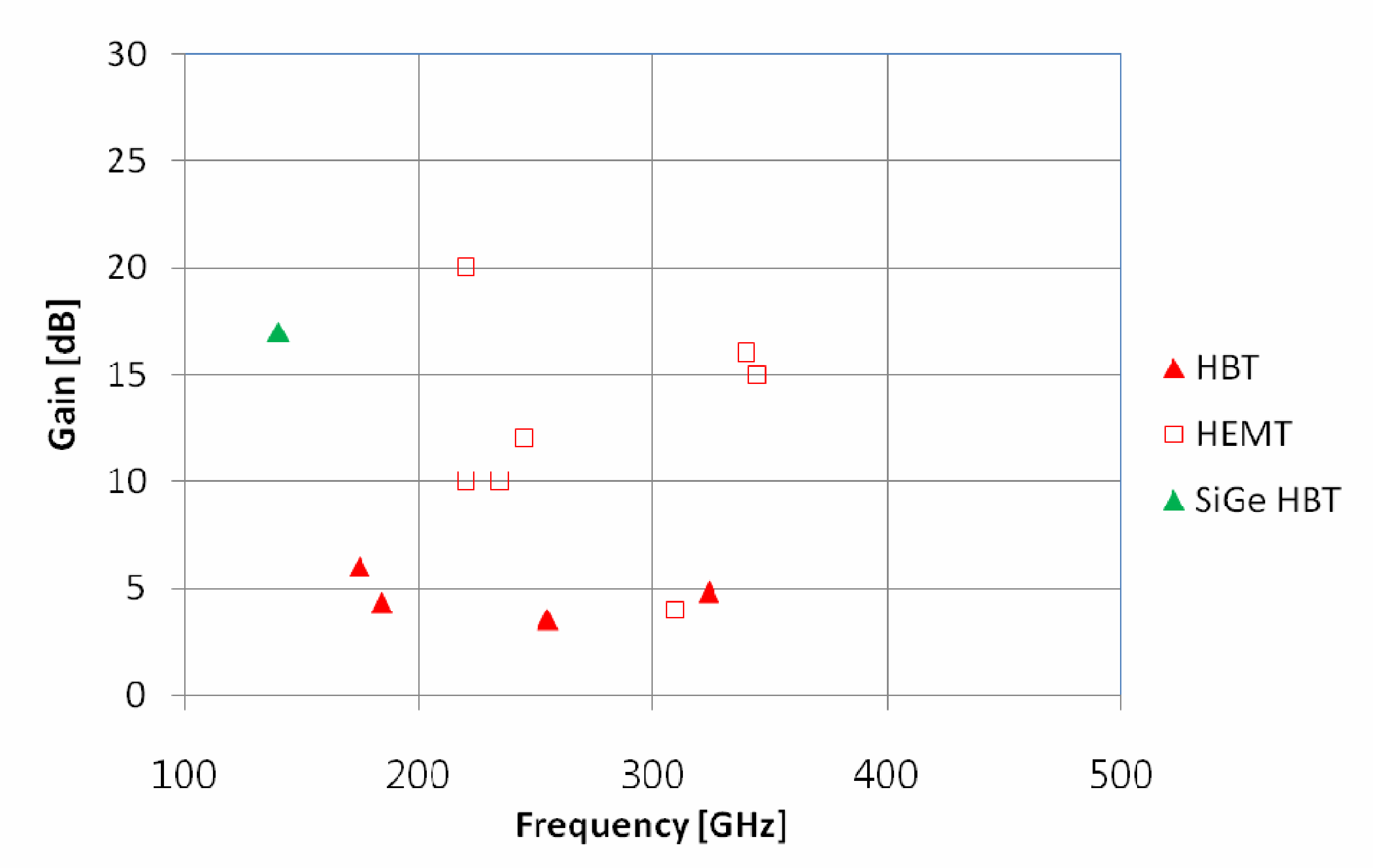
- Univ. of Toronto
- STM SiGe BiCMOS
- 5 stage cascode
- P_{Diss} = 112 mW
- Gain = 17 dB at 140 GHz



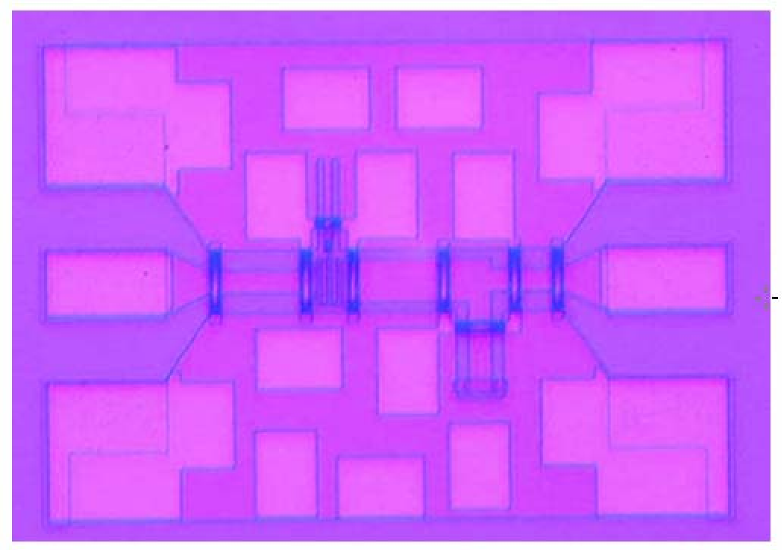


Laskin et al IMS 2007

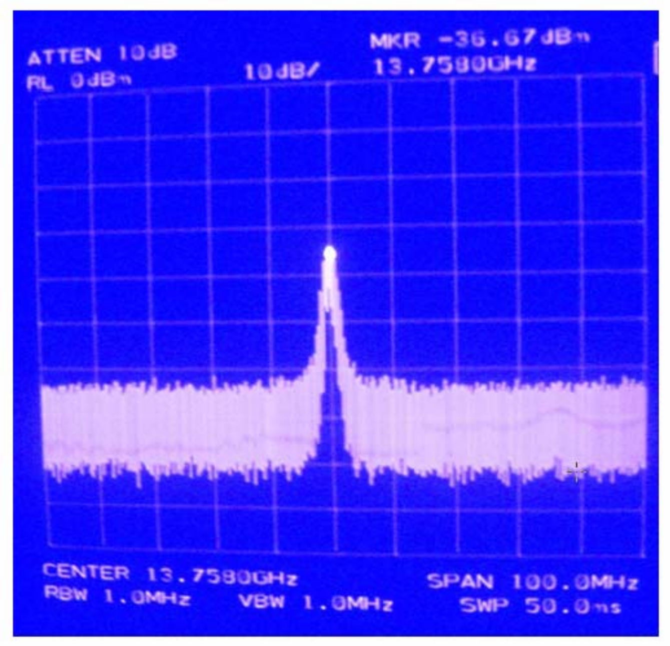
Accumulated Performance: Amplifiers

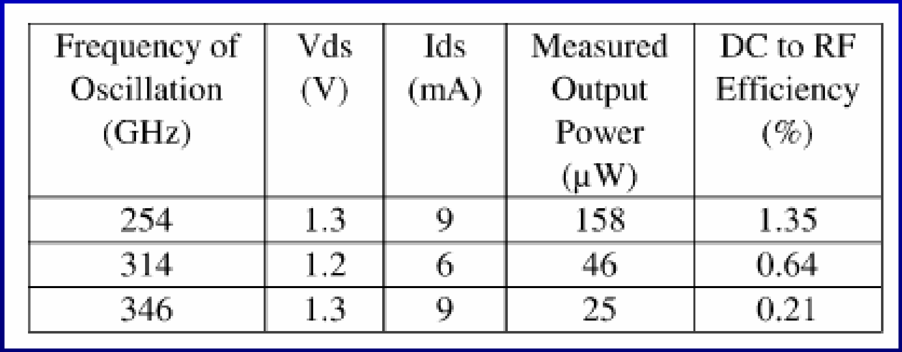


346 GHz InP HEMT Fundamental Oscillator



- NGC
- 35 nm NGC InP HEMT
- DC power = 11.7 mW
- Output power = -16 dBm at 346 GHz

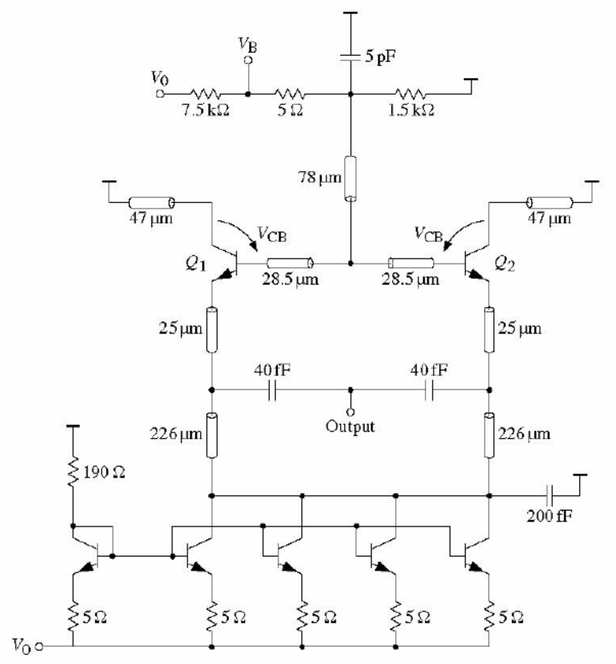




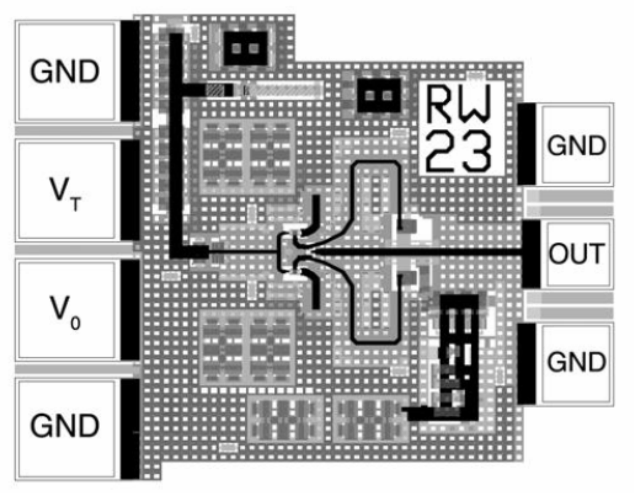
Frequency of Oscillation (GHz)	Vds (V)	Ids (mA)	Measured Output Power (µW)	DC to RF Efficiency (%)
254	1.3	9	158	1.35
314	1.2	6	46	0.64
346	1.3	9	25	0.21

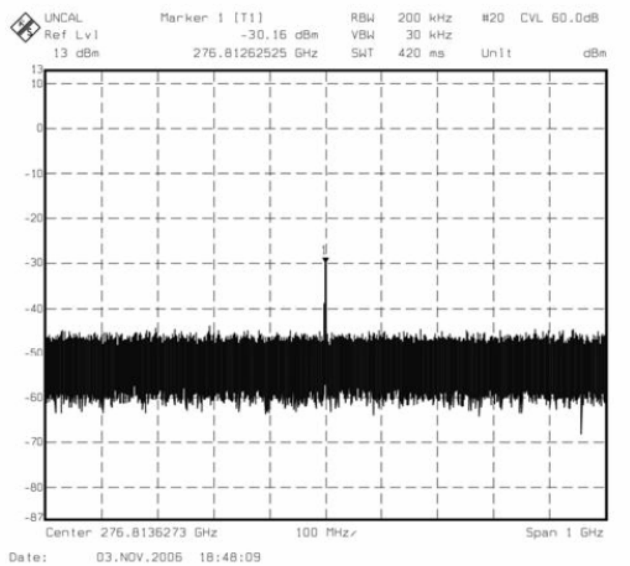
Radisic et al MWCL 2007

278 GHz SiGe HBT Push-Push VCO



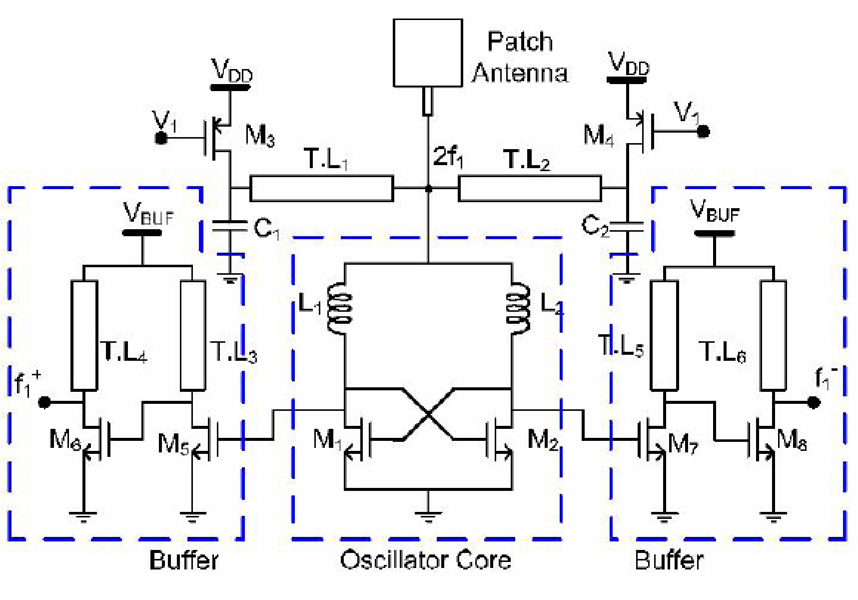
- Technische Univ. Munchen
- Infineon 200 GHz SiGe HBT Technology
- Tuning range: 275.5 - 279.6 GHz
- Output power = -30 dBm at 277 GHz
- DC power = 132 mW



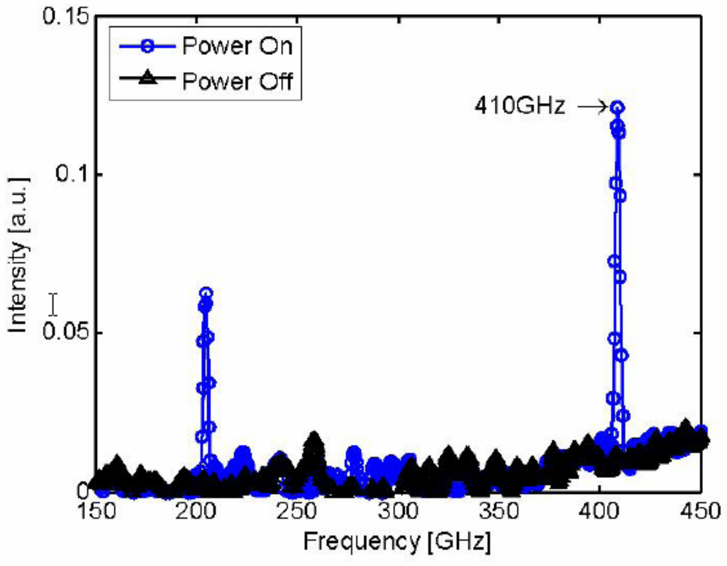


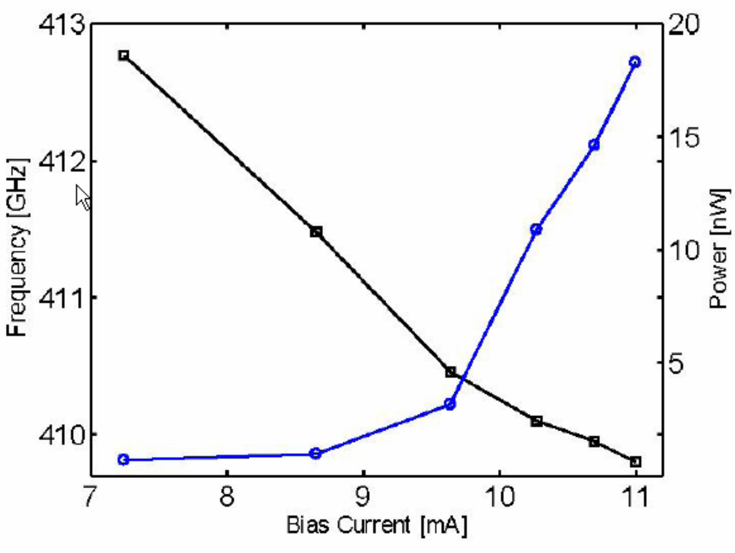
Wanner et al IMS 2007

410 GHz RFCMOS Push-Push VCO



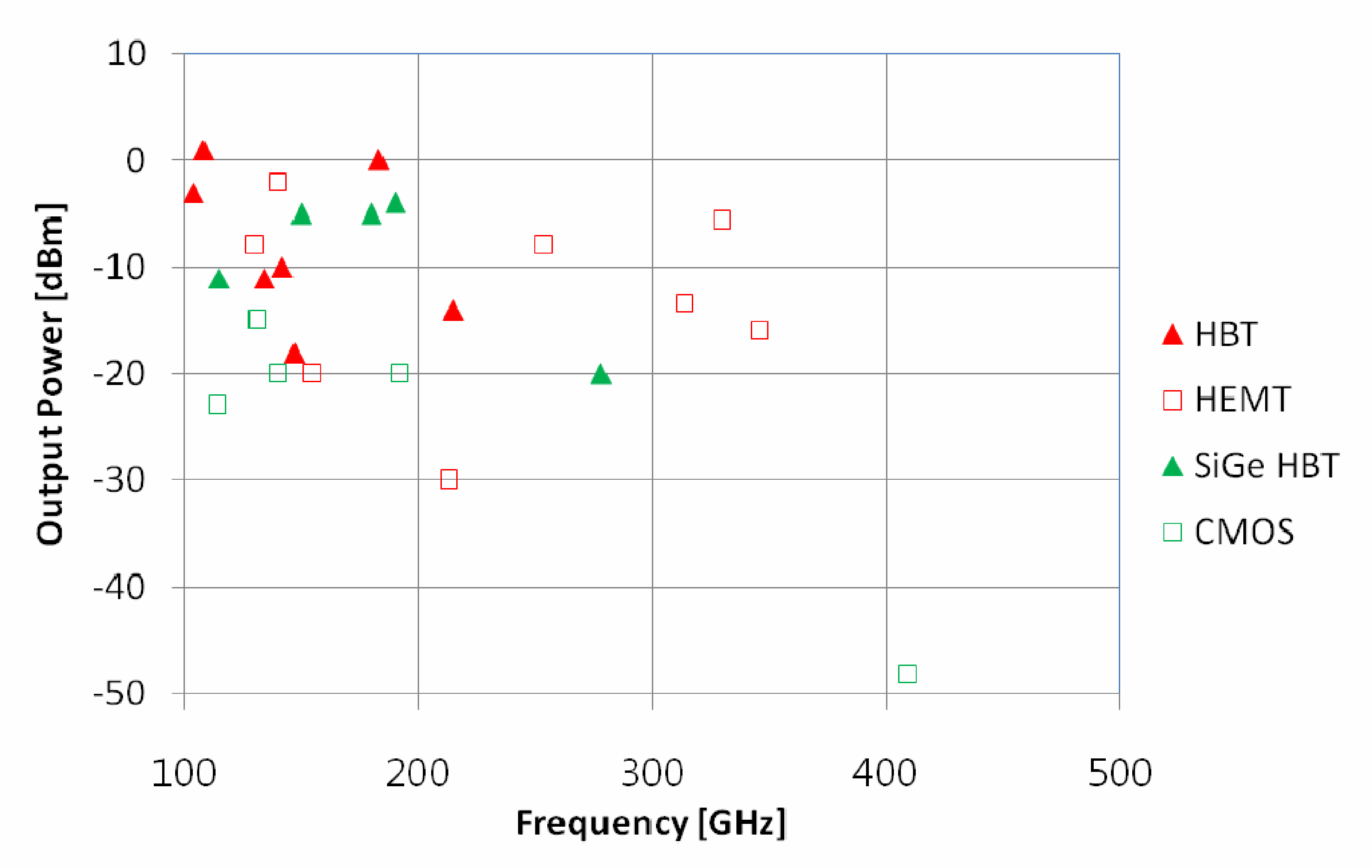
- Univ. of Florida
- 45 nm RFCMOS
- Output power = -47 dBm at 410 GHz
- DC power = 16.5 mW





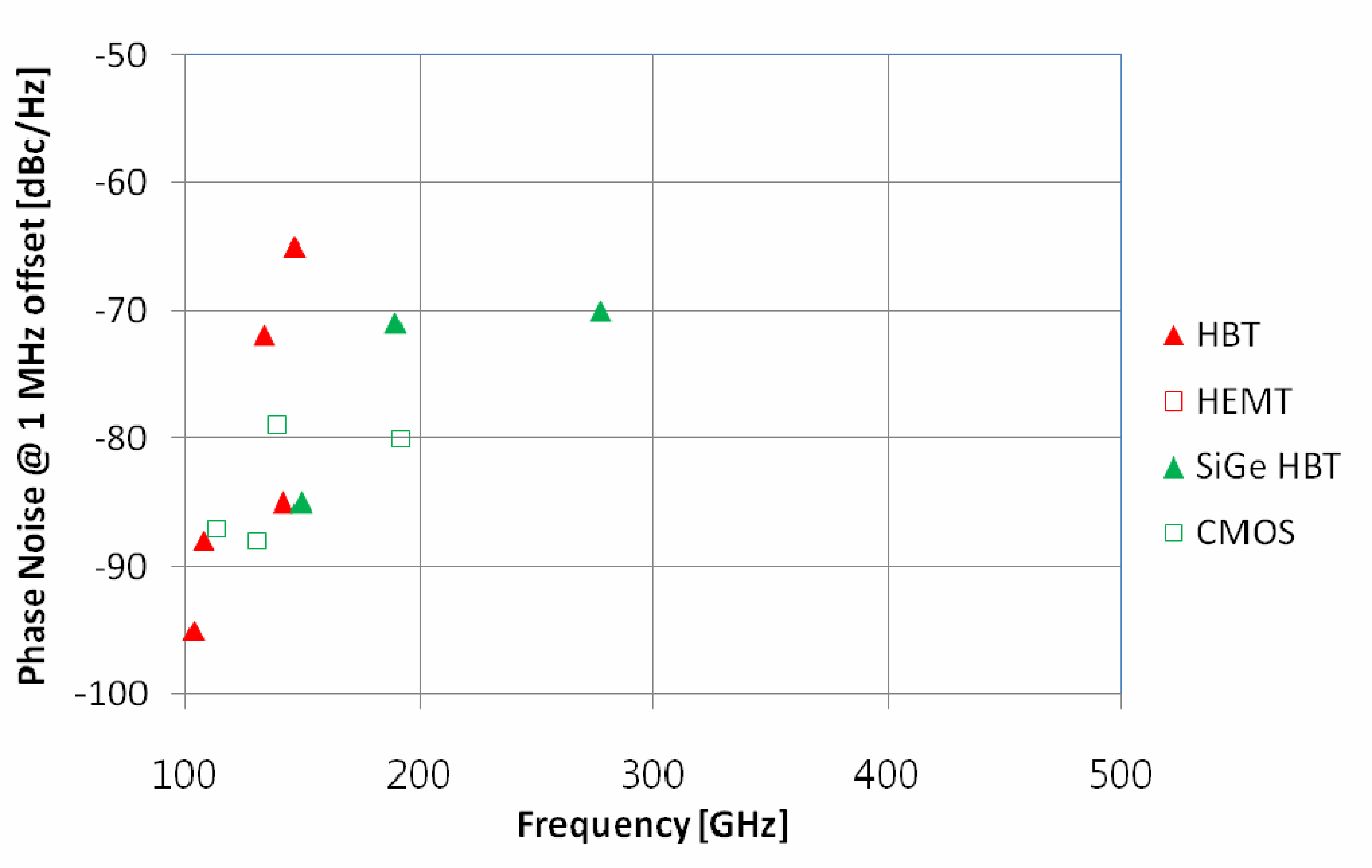
Seok et al ISSCC 2008

Accumulated Performance: Oscillators (I)



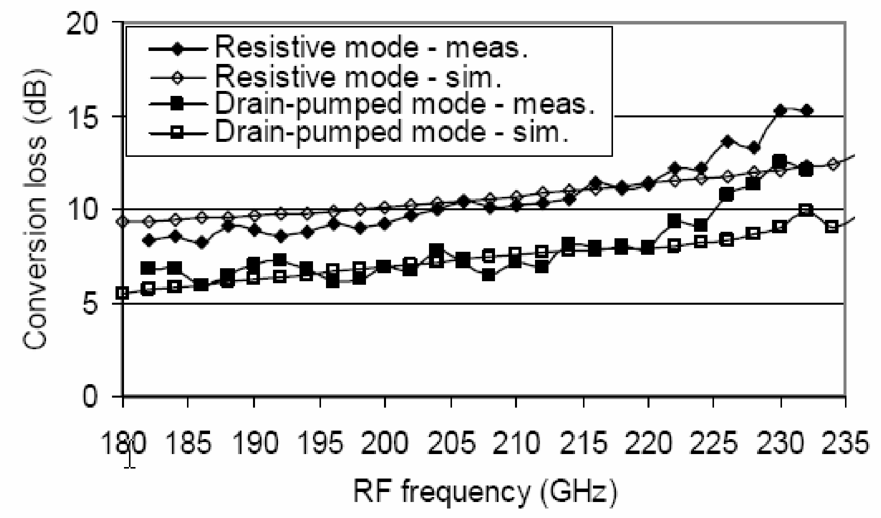
Partially adopted from Wanner et al IMS 2007

Accumulated Performance: Oscillators (II)

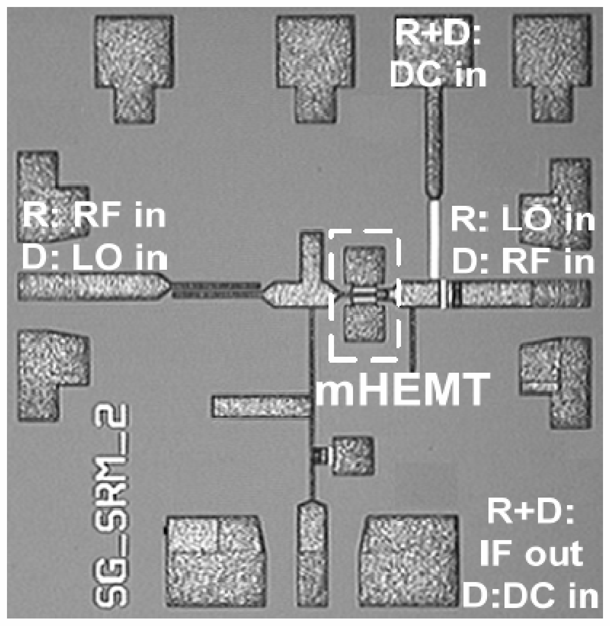


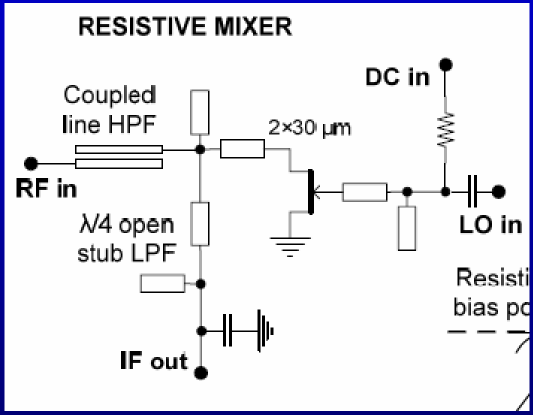
Partially adopted from Wanner et al IMS 2007

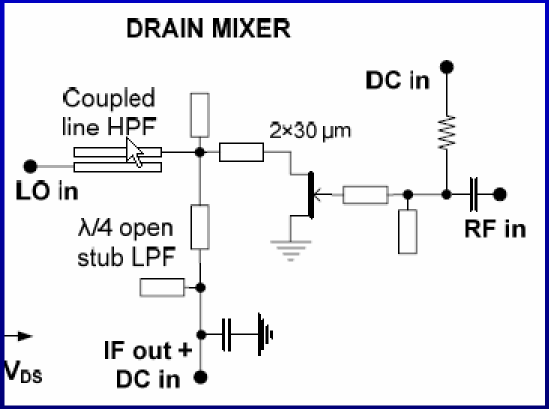
220 GHz MHEMT Active Mixer



- Chalmers University
- 0.1 um GaAs MHEMT
- Conversion loss = ~12 dB for resistive mixer mode
- Conversion loss = ~8 dB for for drain mixer mode

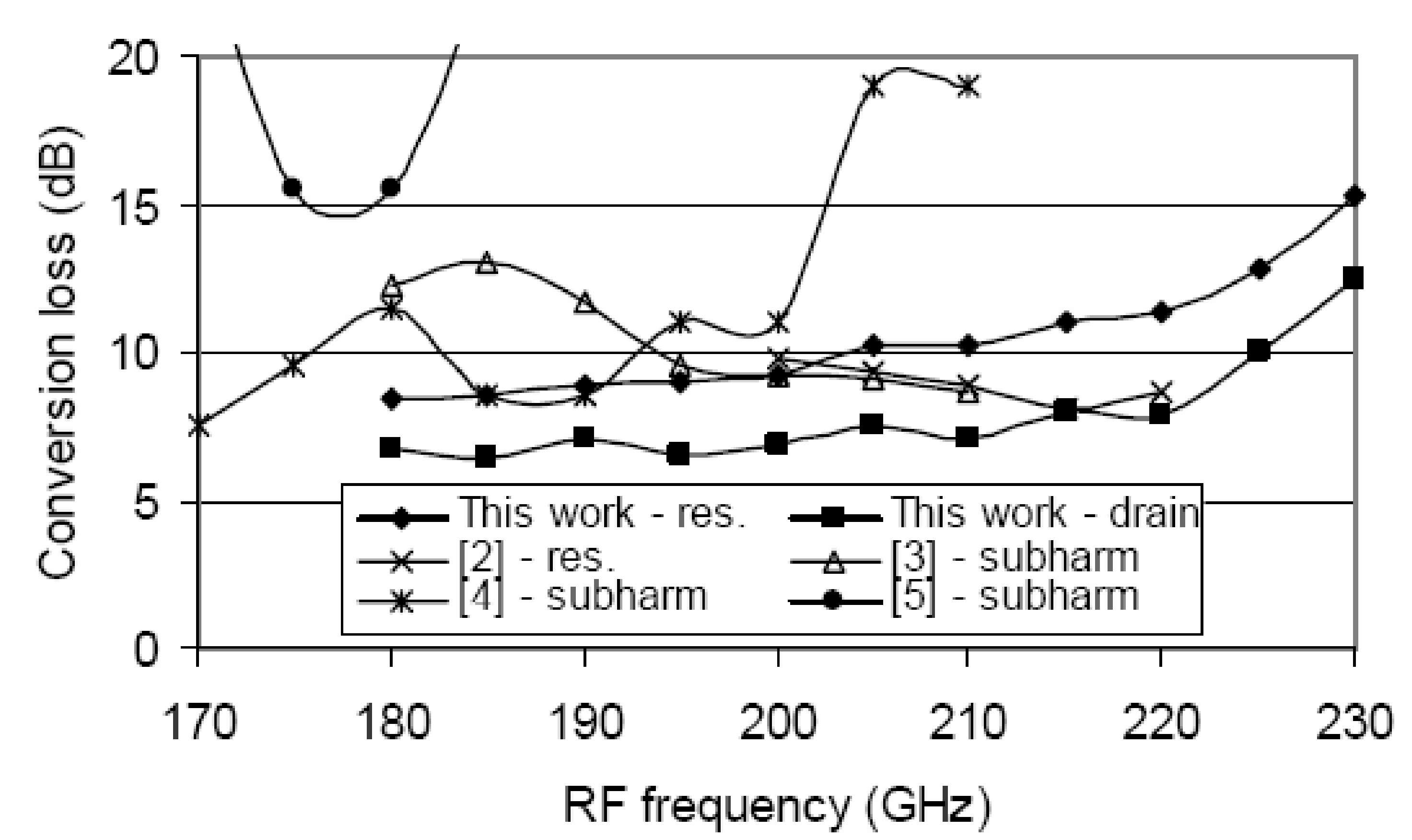






Gunnarsson et al MWCL 2008

Accumulated Performance: Active Mixers



Gunnarsson et al MWCL 2008

Summary

- Current status of semiconductor technologies
  - III-V HBT: f_T ~785 GHz
  - III-V HEMT: f_T ~610 GHz
  - SiGe HBT: f_T ~375 GHz
  - RFCMOS: f_T ~485 GHz
- Current status of circuits
  - Amplifiers: up to 345 GHz (15 dB gain)
  - Oscillators: up to 410 GHz for push-push, 346 GHz for fundamental
  - Active mixers: up to ~220 GHz with conversion loss ~8 dB

→ Transistor-based THz front-end highly promising