50-500GHz Wireless Technologies: Transistors, ICs, and Systems

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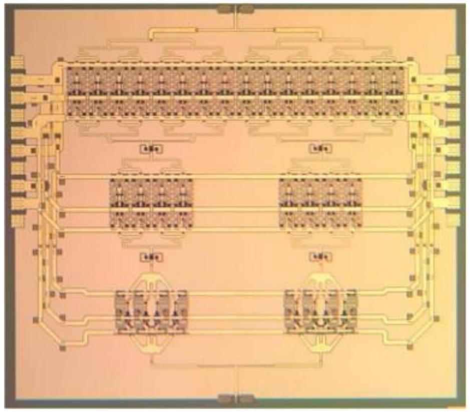
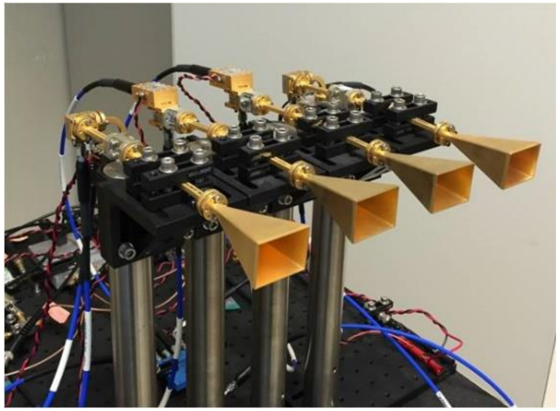
M. Seo: ***Sungkyunkwan University***

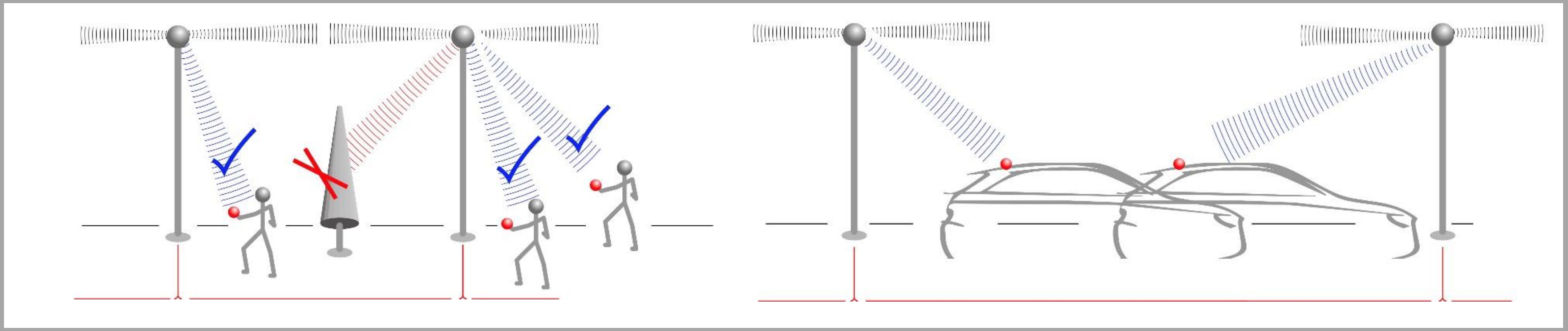
** Now with Intel*

Why mm-wave wireless ?

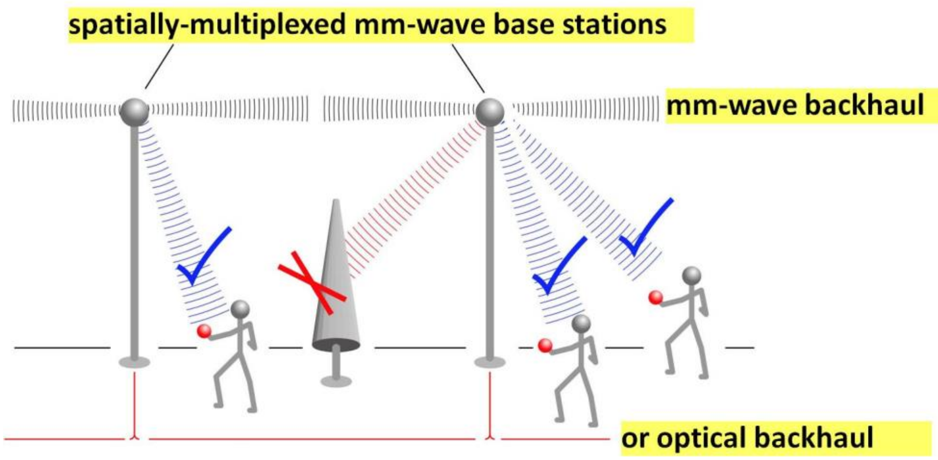


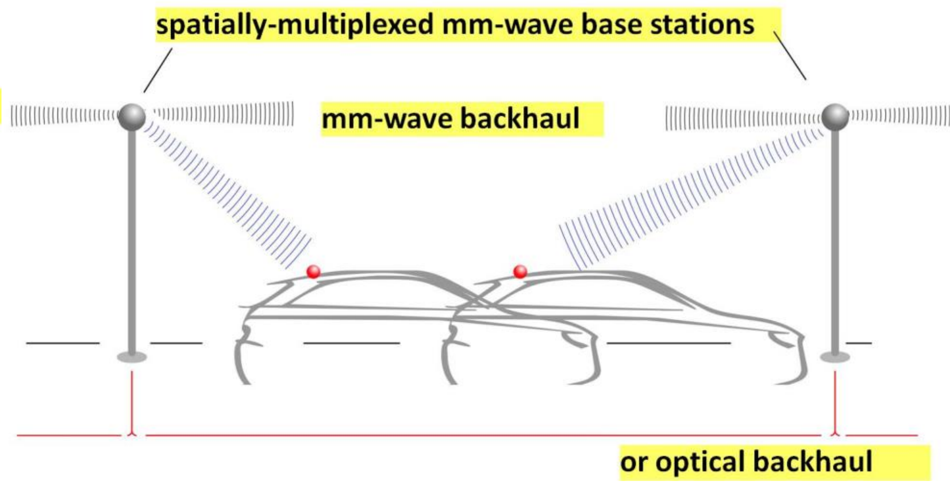


Links

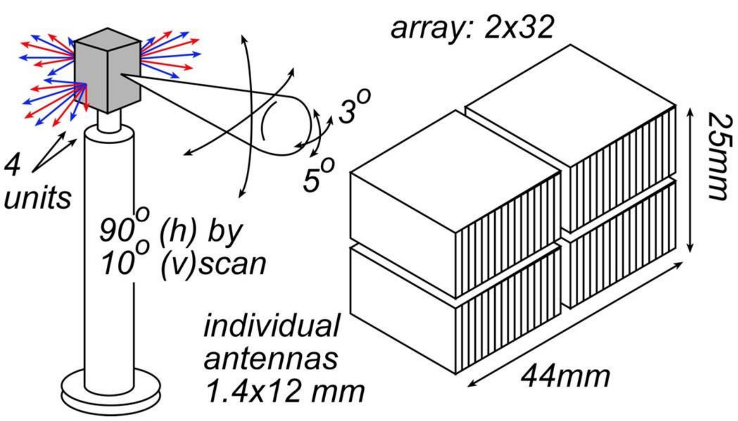


mm-Waves: high-capacity mobile communications

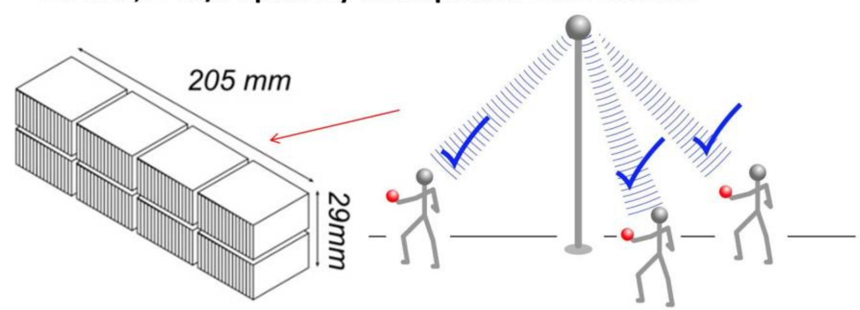




140 GHz, 10 Gb/s Adaptive Picocell Backhaul



60 GHz, 1 Tb/s Spatially-Multiplexed Base Station



128 users/face, 512 total users, each beam 2Gb/s

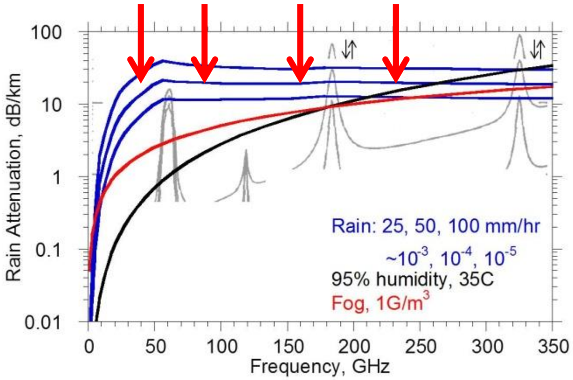
Needs→ research:

RF front end: phased array ICs, high-power transmitters, low-noise receivers

IF/baseband: ICs for multi-beam beamforming, for ISI/multipath suppression, ...

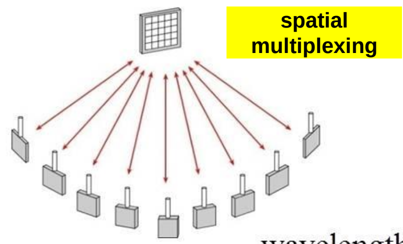
mm-Waves: benefits & challenges

Large available spectrum

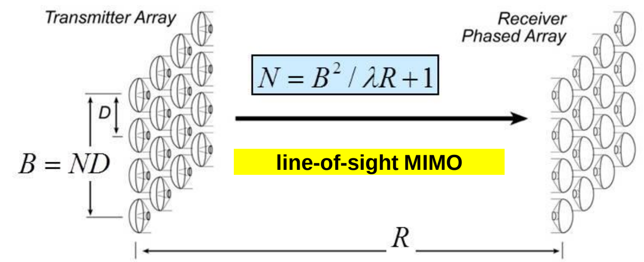


(note high attenuation in foul weather)

Massive # parallel channels

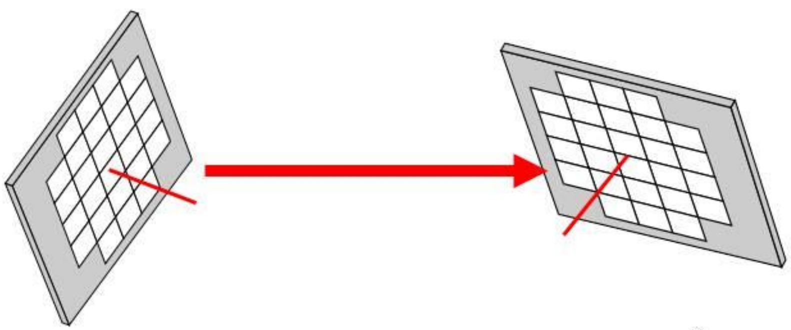


$$\text{angular resolution} \approx \frac{\text{wavelength}}{\text{array width}}$$



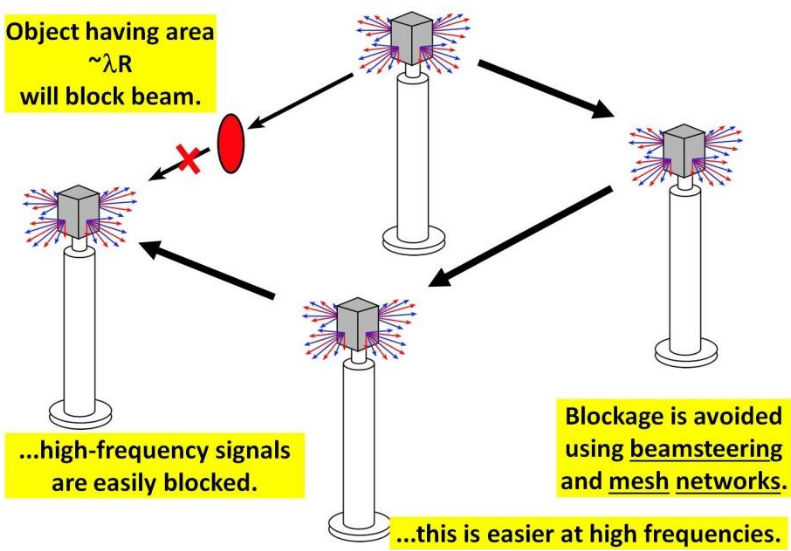
$$\#\text{channels} \propto (\text{aperture area})^2 / (\text{wavelength} \cdot \text{distance})^2$$

Need phased arrays (overcome high attenuation)

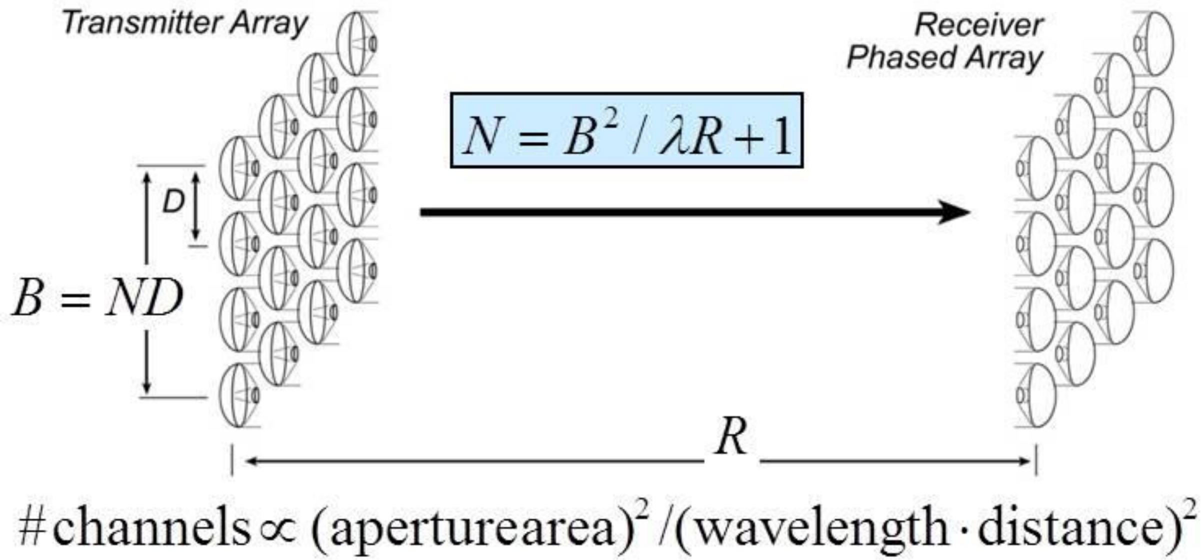


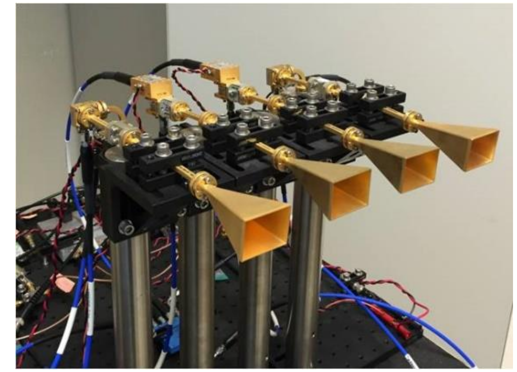
$$\frac{P_{received}}{P_{transmit}} \propto N_{receive} N_{transmit} \frac{\lambda^2}{R^2} e^{-\alpha R}$$

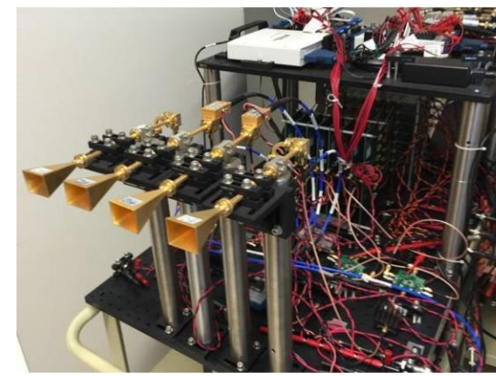
Need mesh networks

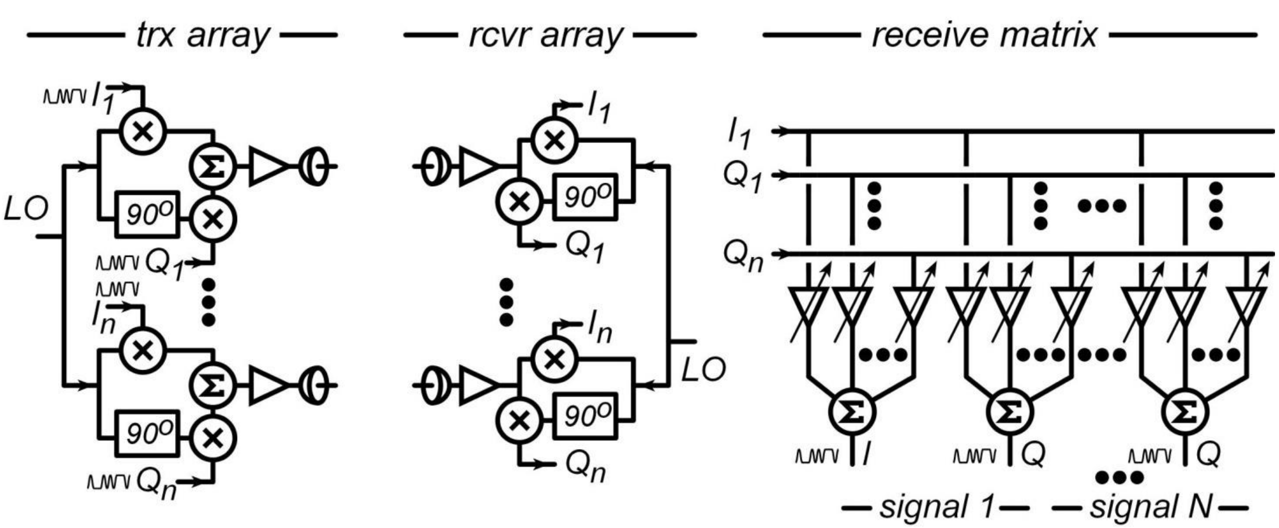


mm-Wave LOS MIMO: multi-channel for high capacity







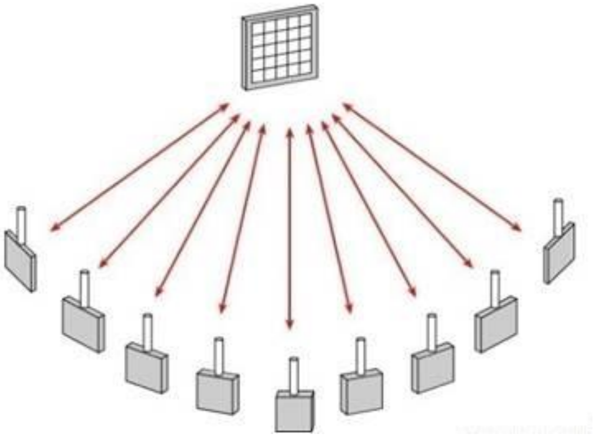


Torklinson : 2006 Allerton Conference
Sheldon : 2010 IEEE APS-URSI
Torklinson : 2011 IEEE Trans Wireless Comm.

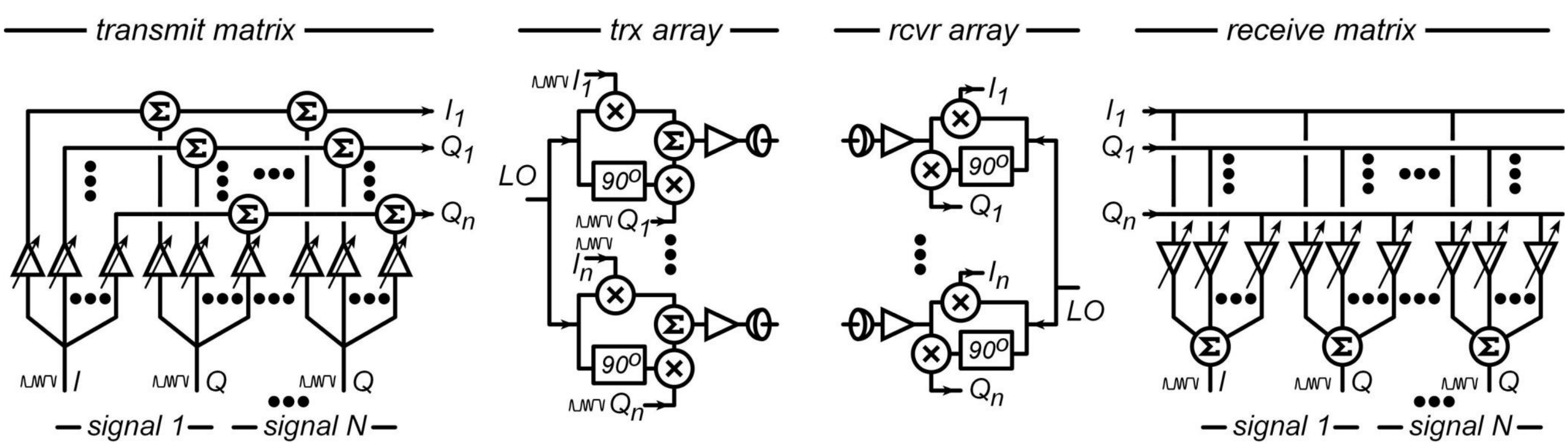
Spatial Multiplexing: massive capacity RF networks

multiple independent beams

each carrying different data
each independently aimed
beams = # array elements

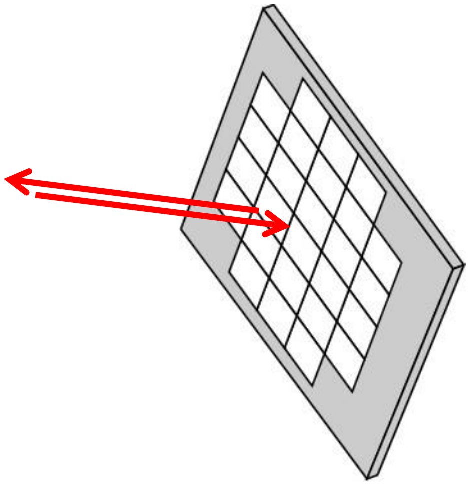


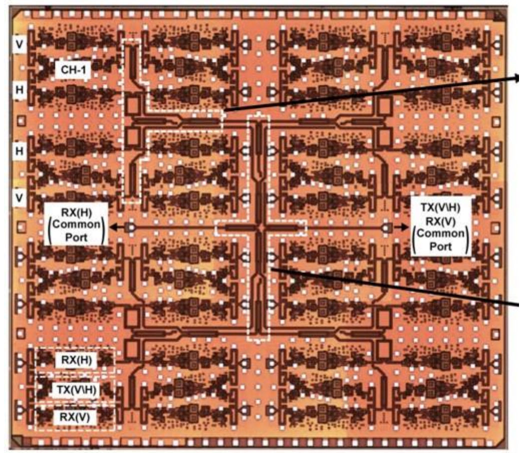
Hardware: multi-beam phased array ICs



Millimeter-wave imaging

10,000-pixel, 94GHz imaging array→ 10,000 elements



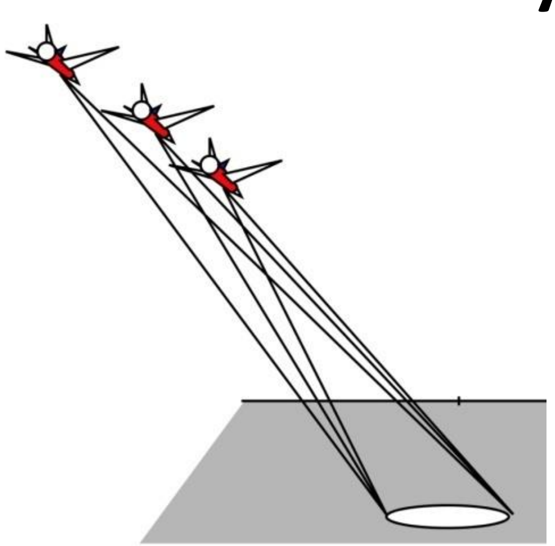


Golcuk: Trans MTT, Aug 2014

Demonstrated:
SiGe, 1.3 kW (UCSD/Rebeiz)

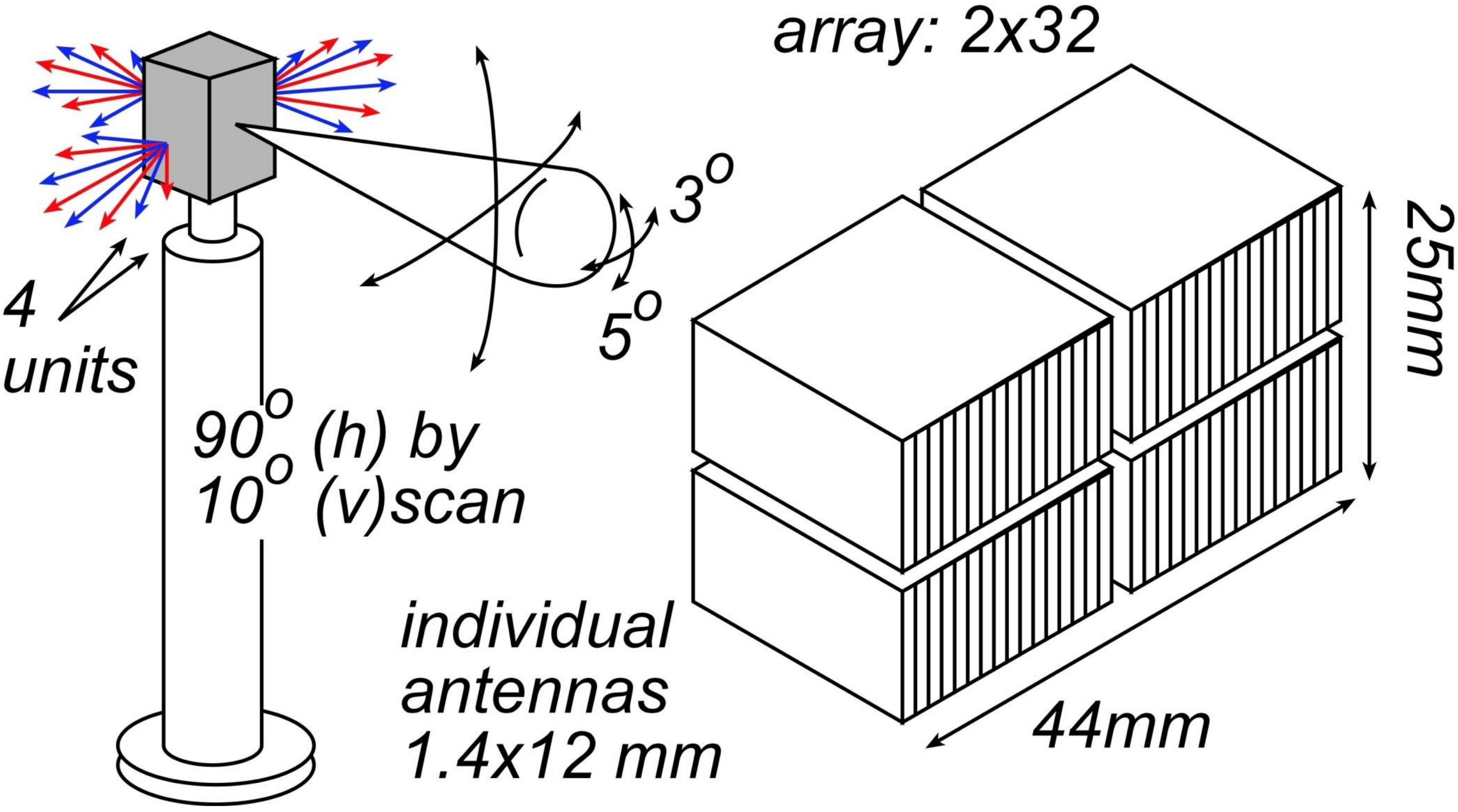
Lower-power designs:
InP, CMOS, SiGe
(UCSB, UCSD, Virginia Poly.)

235 GHz video-rate synthetic aperture radar

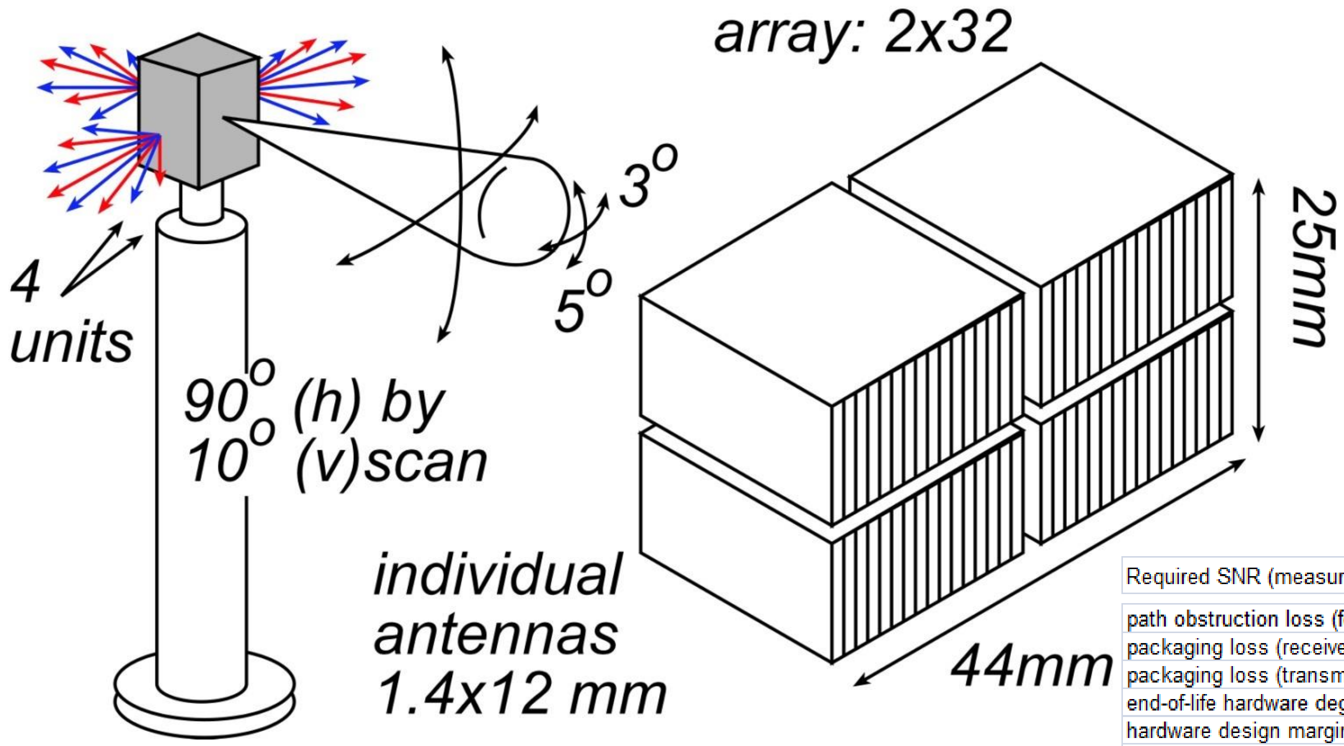


1 transmitter, 1 receiver
100,000 pixels
20 Hz refresh rate
5 cm resolution @ 1km
50 Watt transmitter
(tube, solid-state driver)

140 GHz, 10 Gb/s Adaptive Picocell Backhaul



140 GHz, 10 Gb/s Adaptive Picocell Backhaul



Required SNR (measured as Eb/No)	6.8	dB
path obstruction loss (foliage, glass)	5.00	dB
packaging loss (receiver)	3	dB
packaging loss (transmitter)	3	dB
end-of-life hardware degradation	3	dB
hardware design margin	3	dB
beam aiming loss (edge of beam)	3	dB
systems operating margin	10	dB
PA backoff for OFDM	7.00E+00	dB

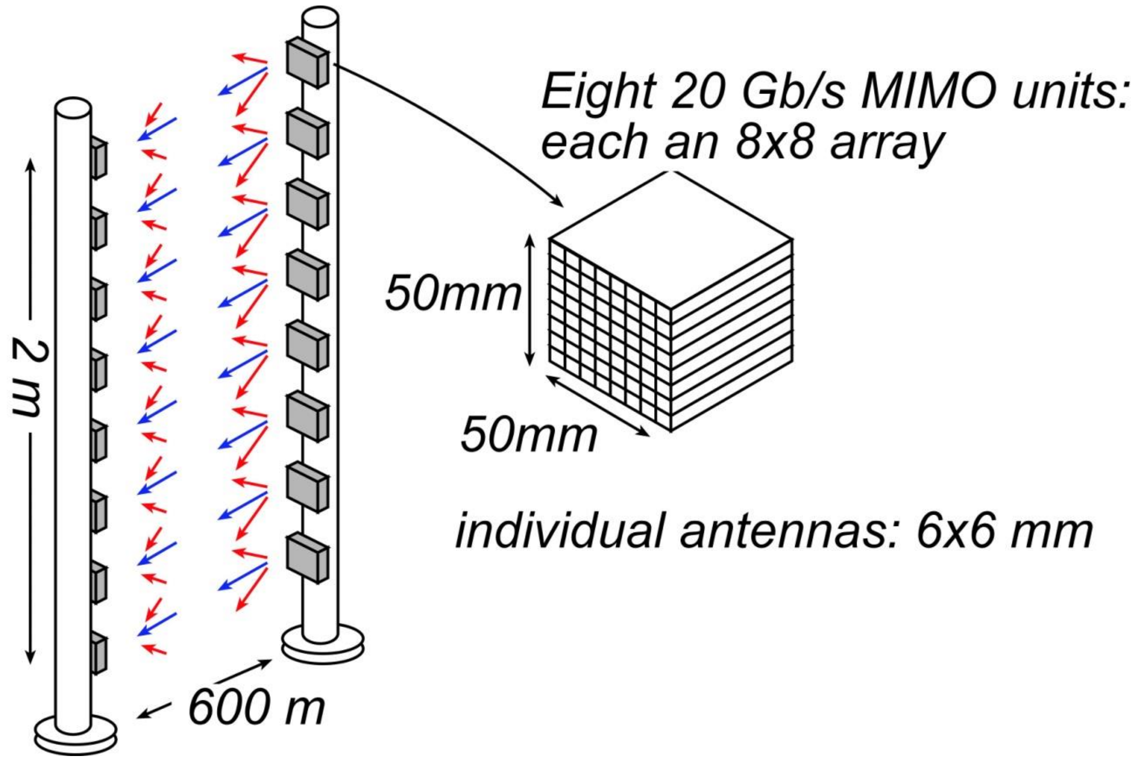
350 meters range in 50mm/hr rain

Realistic packaging loss, operating & design margins

PAs: 24 dBm P_{sat} (per element)→ GaN or InP

LNAs: 4 dB noise figure → InP HEMT

340GHz, 160Gb/s spatially multiplexed backhaul



1° beamwidth; 8° beamsteering

600 meters range in 50 mm/hr rain

Realistic packaging loss, operating & design margins

PAs: 14 dBm P_{sat} (per element)→ InP

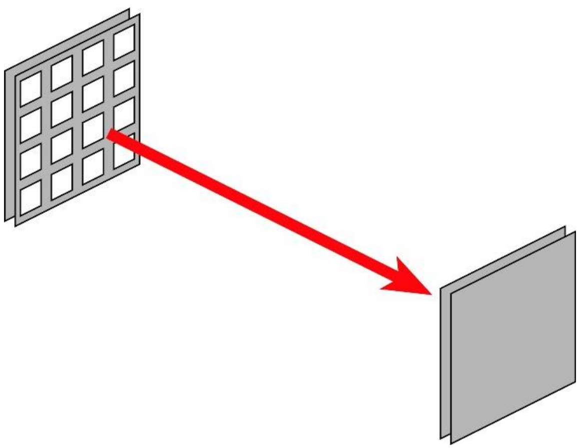
LNAs: 7 dB noise figure → InP HEMT

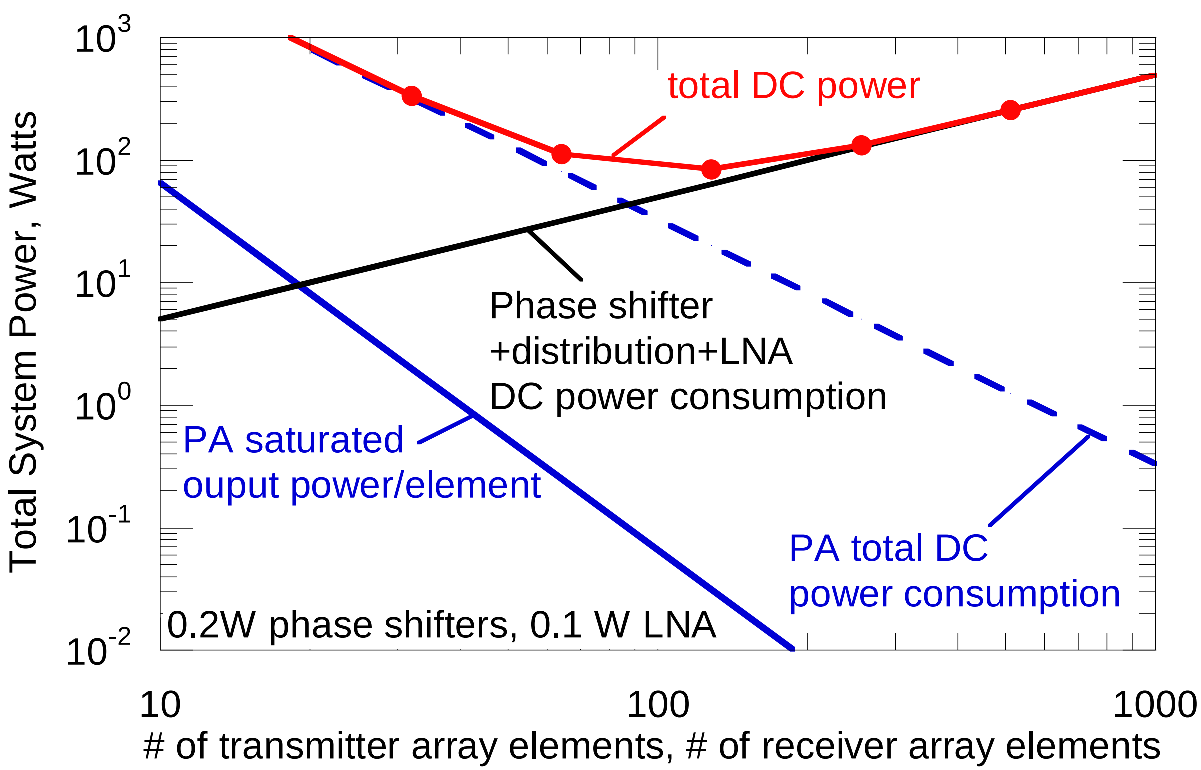
Optimum array size for low system power

$$\frac{P_{receive}}{P_{transmit}} \propto N^2 \frac{\lambda^2}{R^2} \longrightarrow P_{transmit} \propto \frac{1}{N^2}$$

Do large arrays save power ?

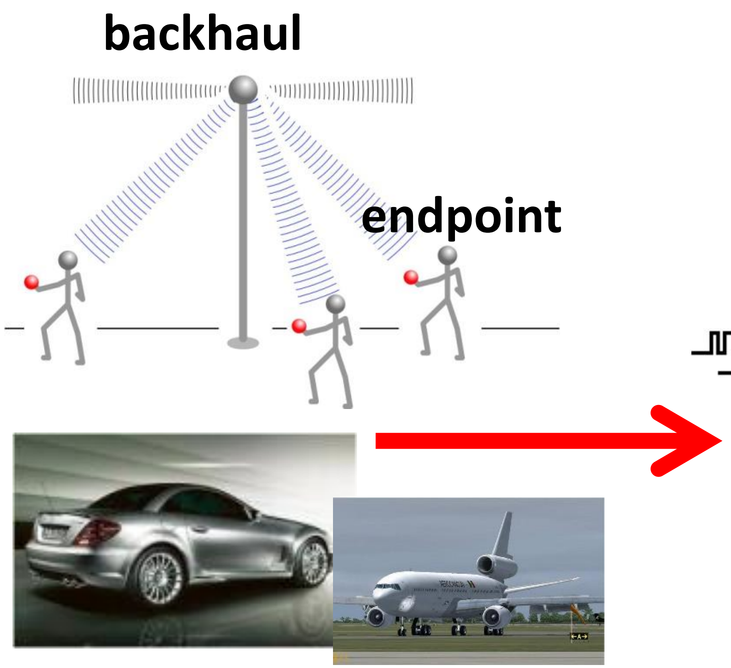
$$\text{Total system power} = \frac{P_{transmit}}{\text{efficiency}} + N(\text{power of LNA, phase shifters...})$$

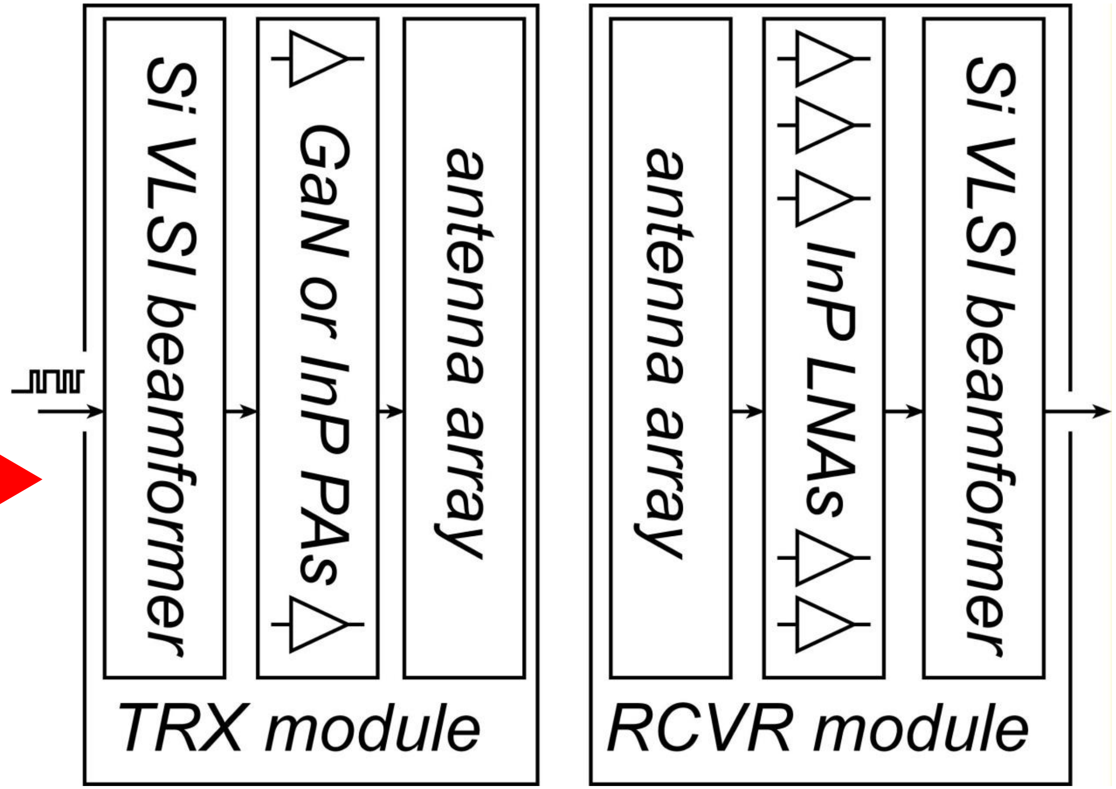




At optimum-size array, target PA output power is typically 10-200 mW

50-500 GHz Wireless Transceiver Architecture



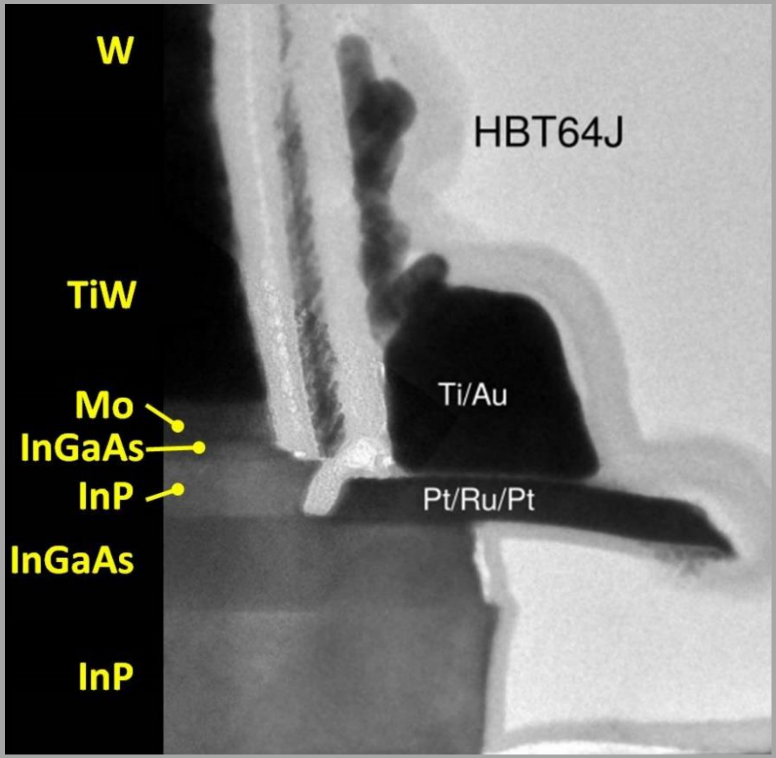


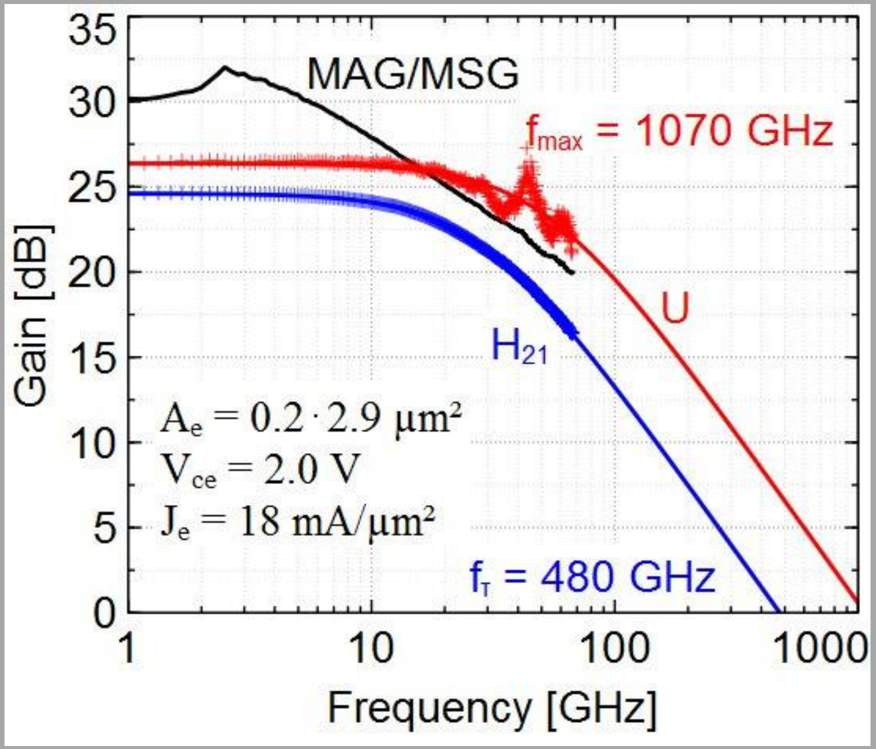
III-V LNAs, III-V PAs → power, efficiency, noise
Si CMOS beamformer→ integration scale

...similar to today's cell phones.

High-gain antenna → large area
→ much too big for monolithic integration

Transistors

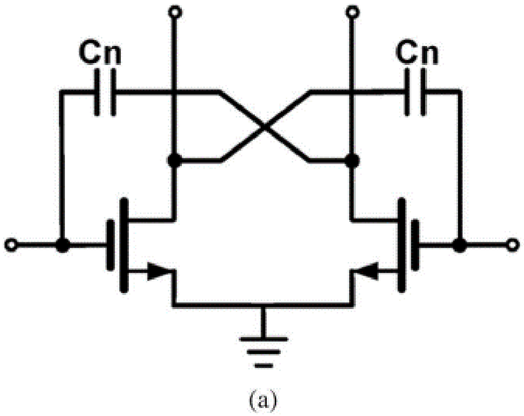


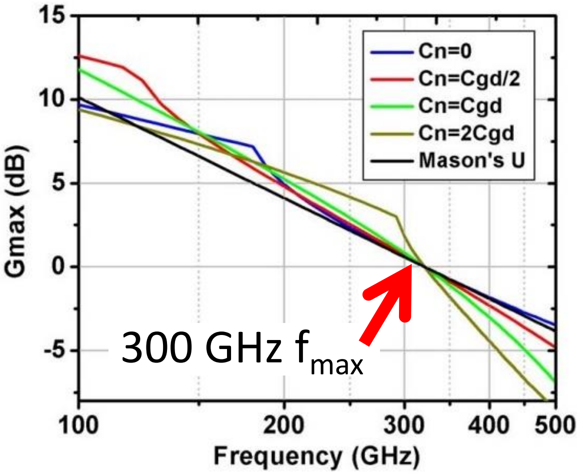


mm-wave CMOS (examples)

210 GHz amplifier: 32 nm SOI, positive feedback, 15 dB, 3 stages

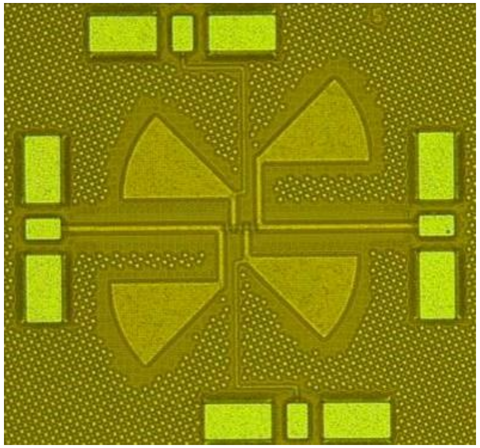
Wang et al. (Heydari), JSSC, March 2014

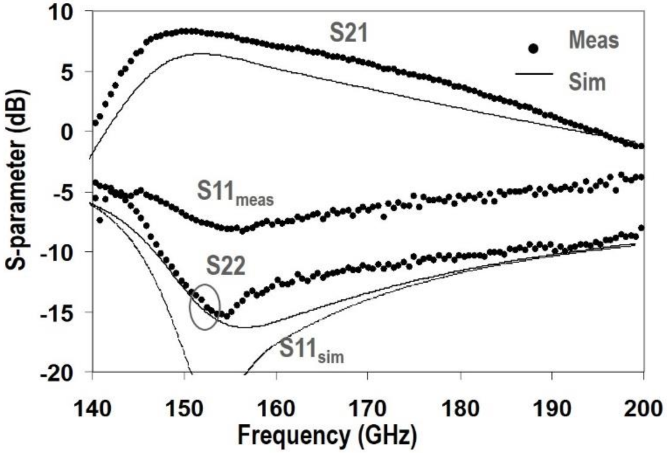




150 GHz amplifier: 65 nm bulk CMOS, 8.2 dB, 3 stages (250GHz f_{max})

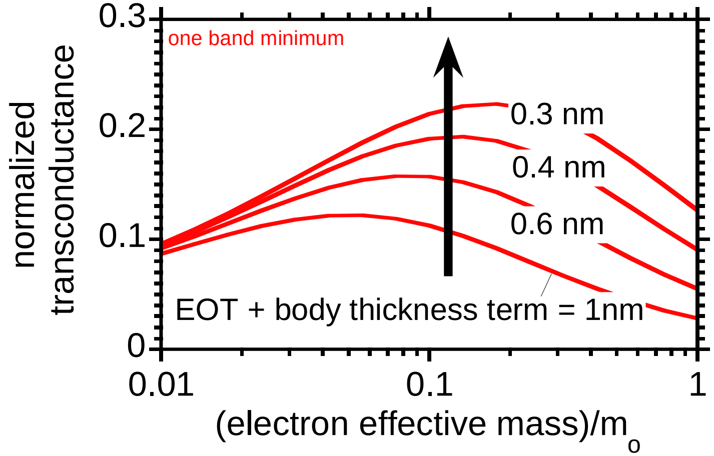
Seo et al. (UCSB), JSSC, December 2009



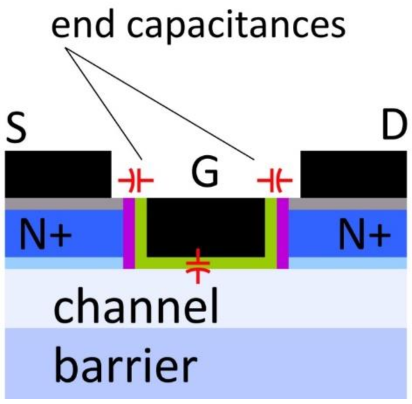


mm-Wave CMOS won't scale much further

Gate dielectric can't be thinned
→ on-current, g_m can't increase



Shorter gates give no less capacitance
dominated by ends; ~1fF/μm total

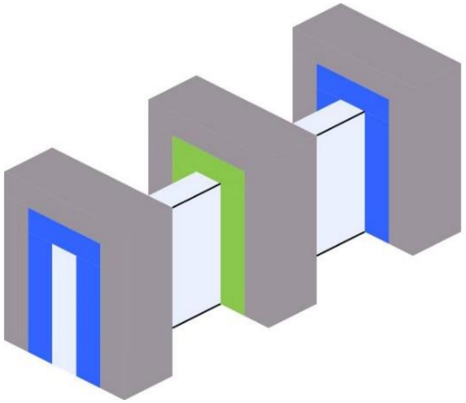


Maximum g_m, minimum C→ upper limit on f_τ.
about 350-400 GHz.

Tungsten via resistances reduce the gain

Inac et al, CSICS 2011

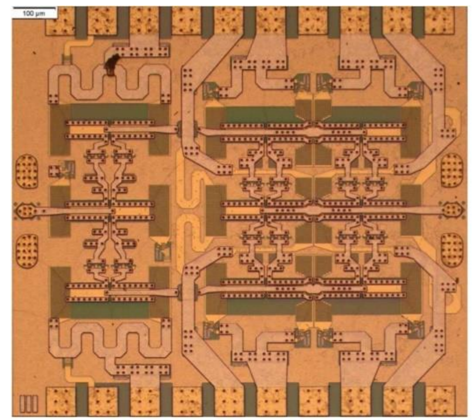
Present finFETs have yet <u>larger</u> end capacitances



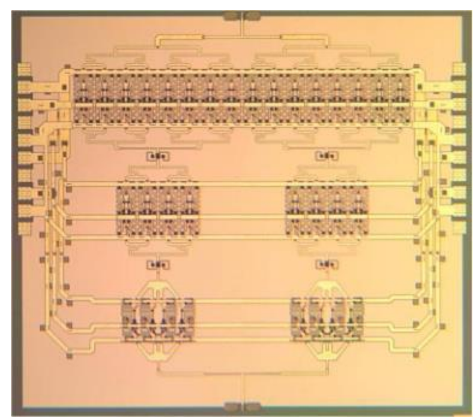
III-V high-power transmitters, low-noise receivers

Cell phones & WiFi:
GaAs PAs, LNAs

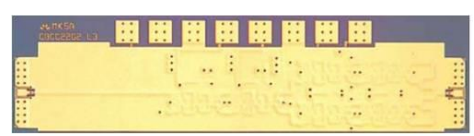
mm-wave links need
high transmit power,
low receiver noise



0.47 W @86GHz
H Park, UCSB, IMS 2014

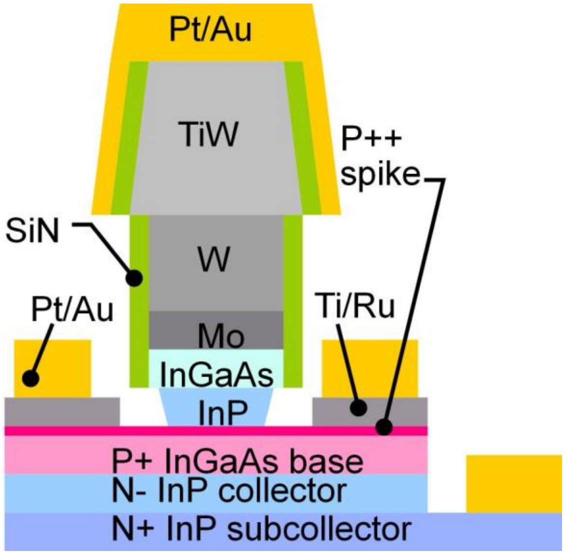


0.18 W @220GHz
T Reed, UCSB, CSICS 2013



1.9mW @585GHz
M Seo, TSC, IMS 2013

Making faster bipolar transistors



to double the bandwidth:	change
emitter & collector junction widths	decrease 4:1
current density (mA/μm^2)	increase 4:1
current density (mA/μm)	constant
collector depletion thickness	decrease 2:1
base thickness	decrease 1.4:1
emitter & base contact resistivities	decrease 4:1

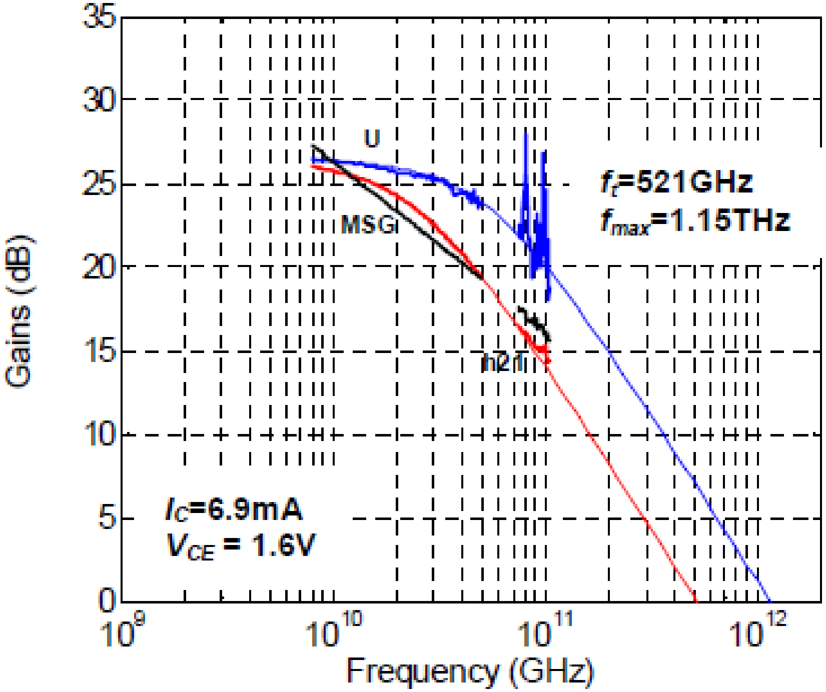
Narrow junctions.

Thin layers

High current density

Ultra low resistivity contacts

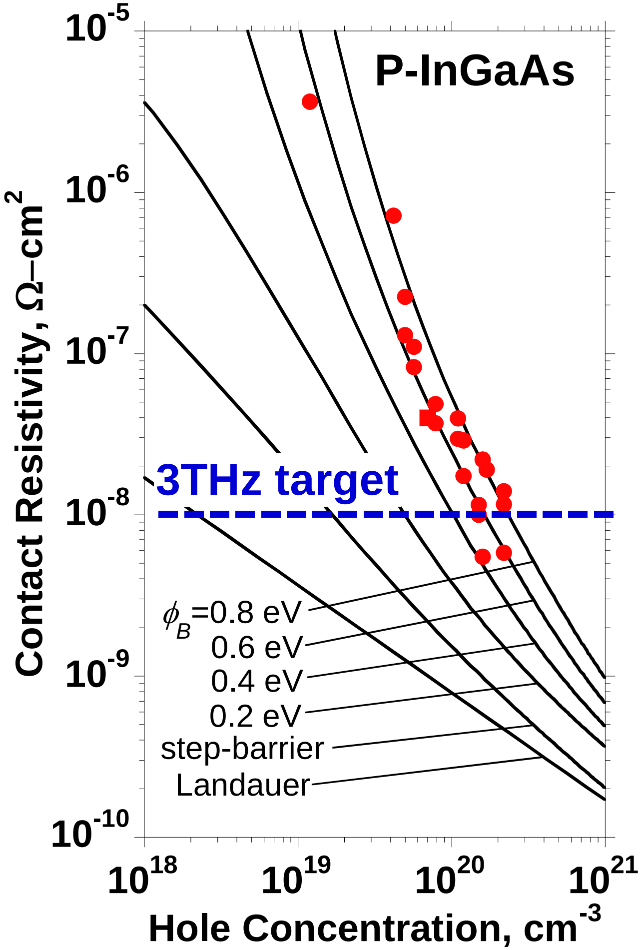
Teledyne: M. Urteaga *et al*: 2011 DRC



THz HBTs: The key challenges

Obtaining good base contacts

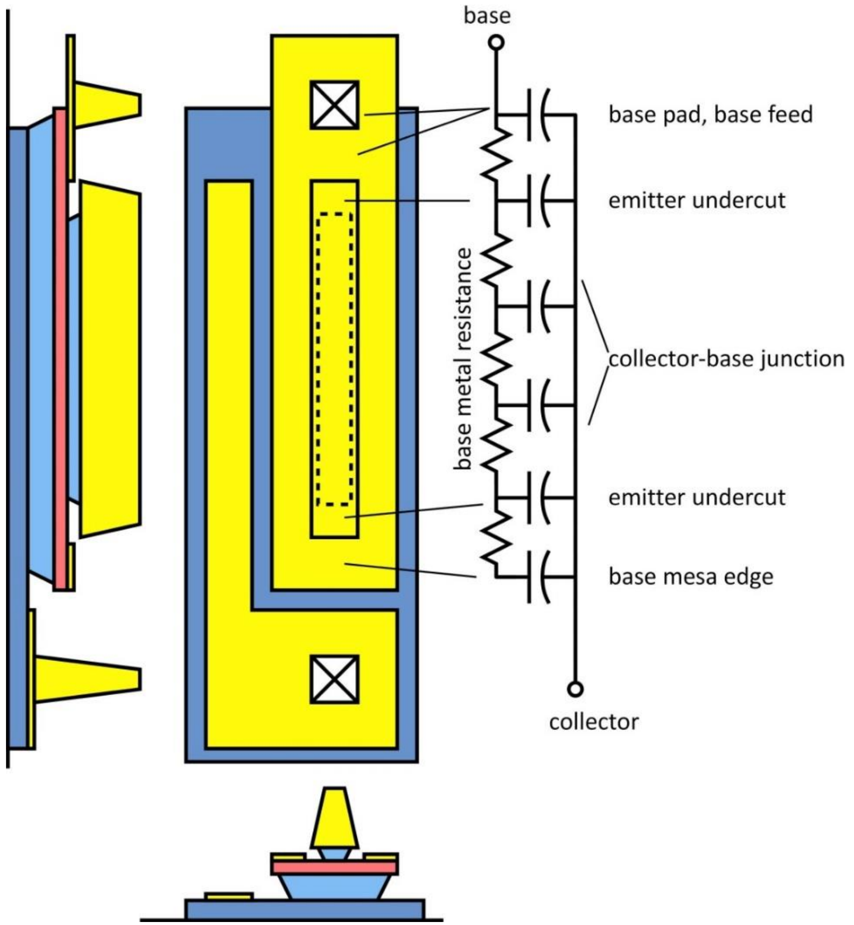
in HBT vs. in contact test structure
(emitter contacts are fine)



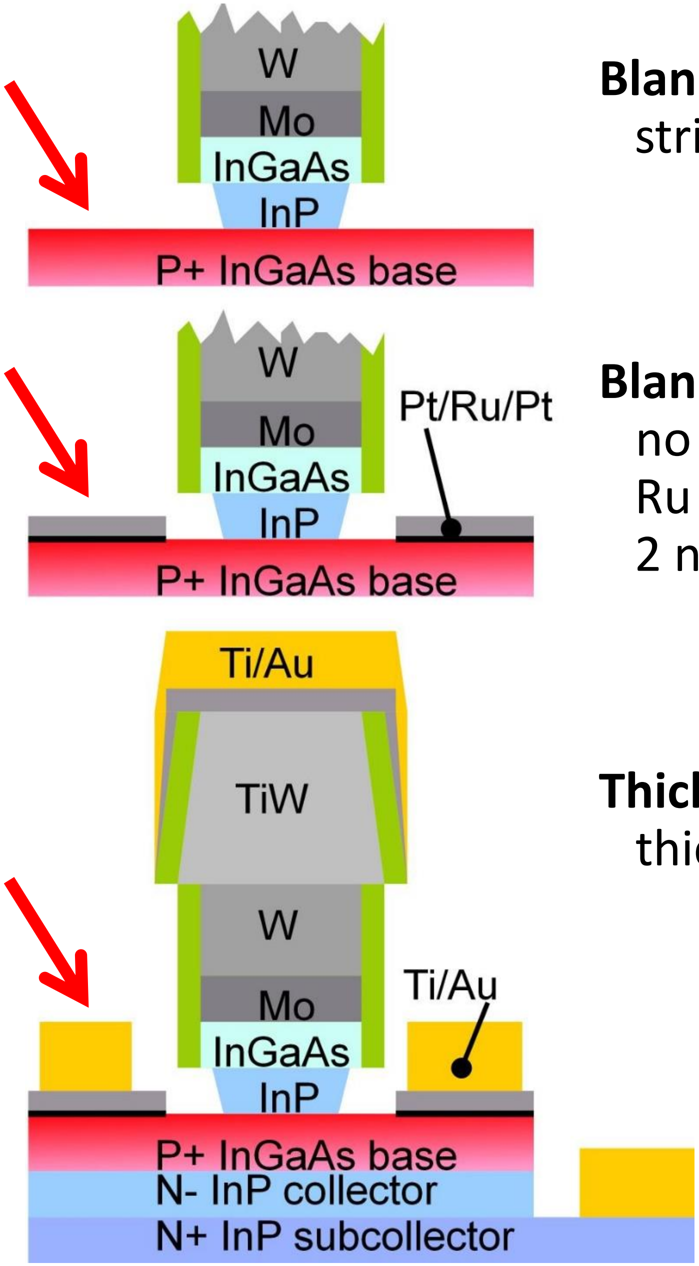
Baraskar *et al*, Journal of Applied Physics, 2013

RC parasitics along finger length

metal resistance, excess junction areas



THz HBTs: double base metal process



Blanket surface clean (UV O_3 / HCl)
strips organics, process residues, surface oxides

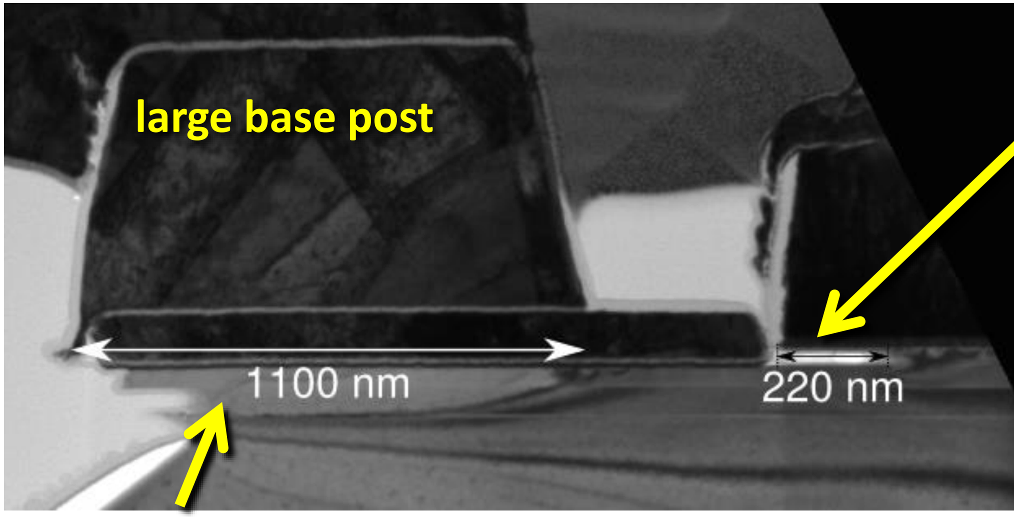
Blanket base metal
no photoresist; no organic residues
Ru refractory diffusion barrier
2 nm Pt : penetrates residual oxides

Thick Ti/Au base pad metal liftoff
thick metal→ low resistivity

Rode et al., IEEE TED, Aug. 2015

Reducing Emitter Length Effects

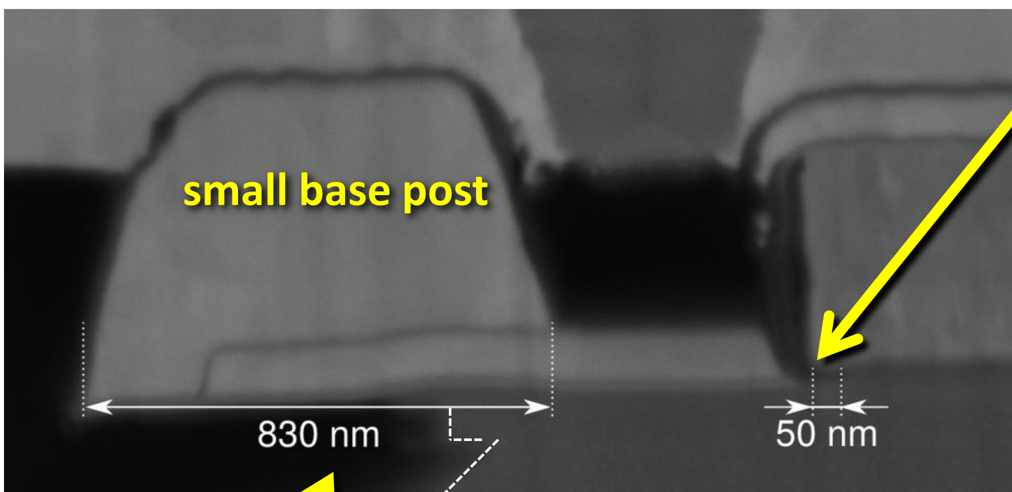
before



large emitter end undercut

small base post undercut

after

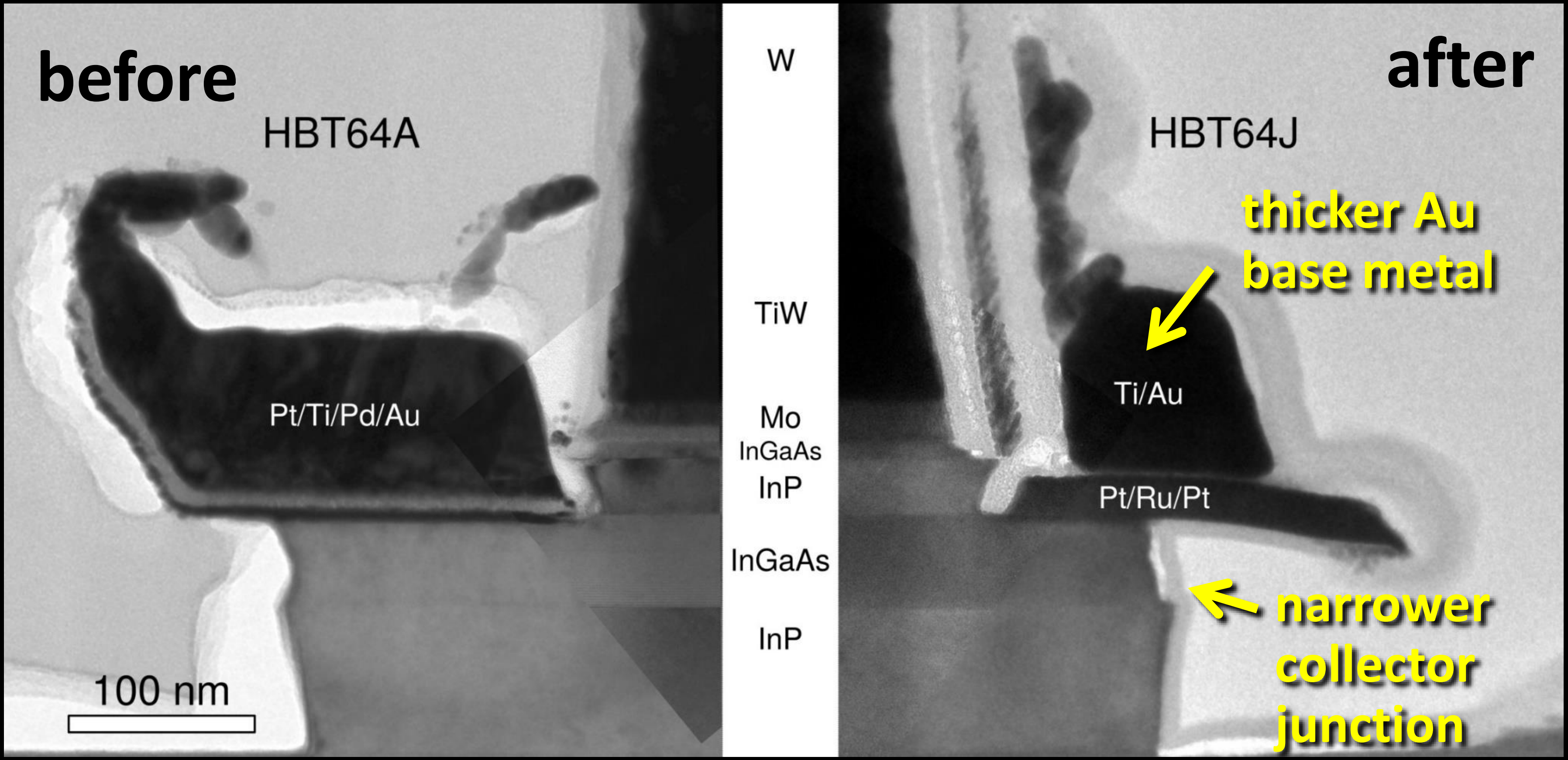


small emitter end undercut

large base post undercut

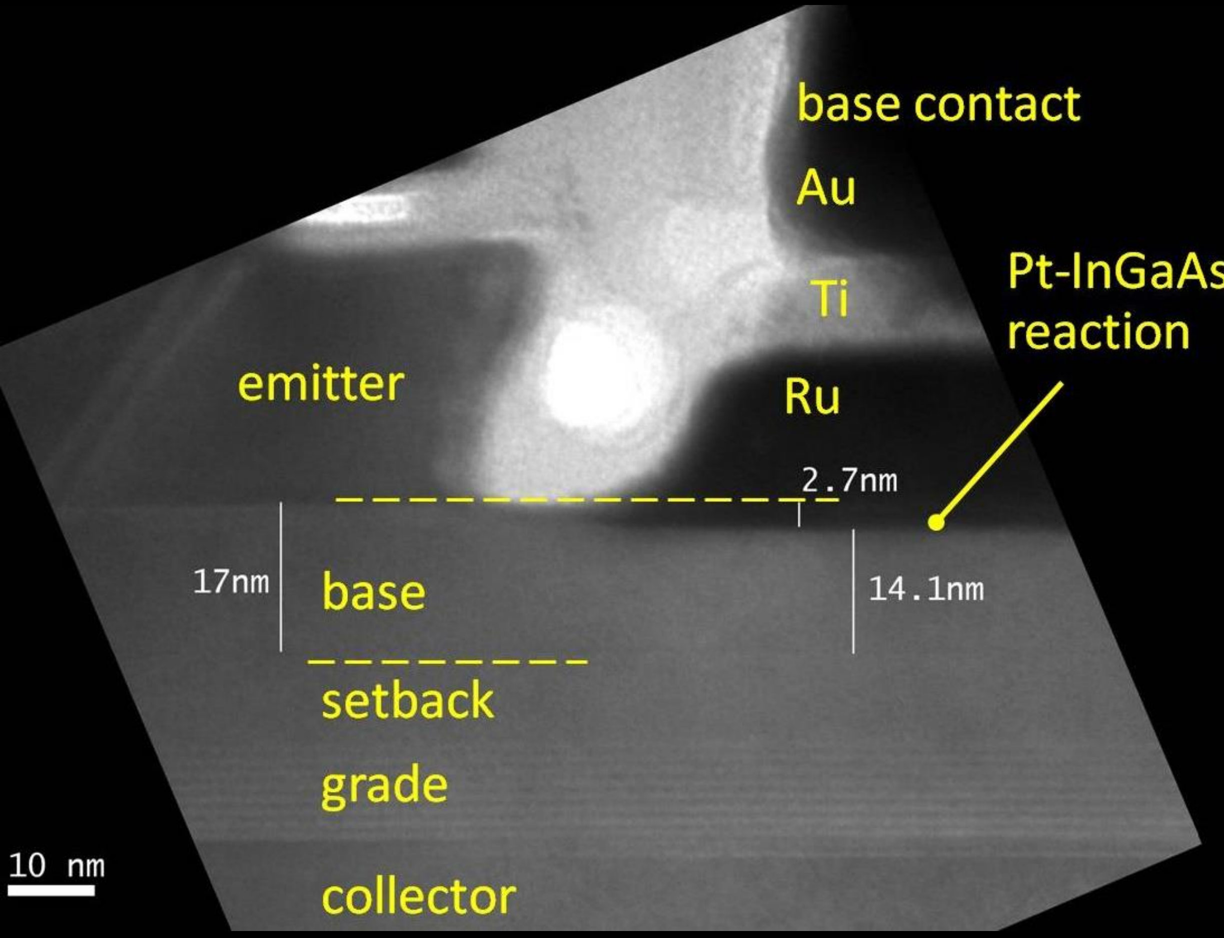
Rode et al., IEEE TED, Aug. 2015

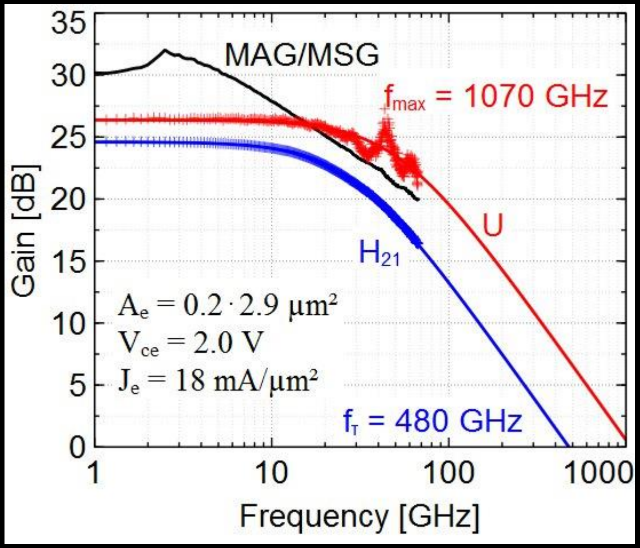
Reducing Emitter Length Effects

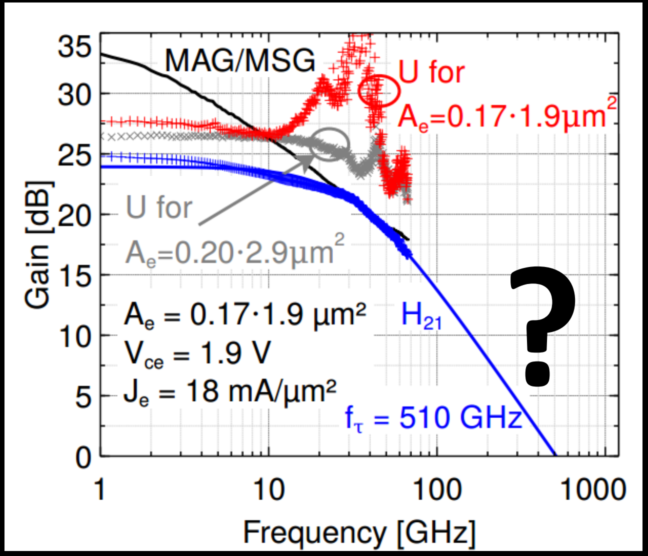


Rode et al., IEEE TED, Aug. 2015

InP HBTs: 1.07 THz @200nm, ?? @ 130nm





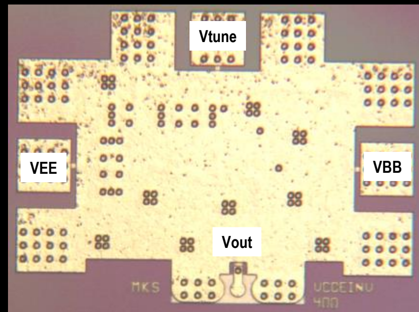


Rode et al., IEEE TED, Aug. 2015

130nm /1.1 THz InP HBT: ICs to 670 GHz

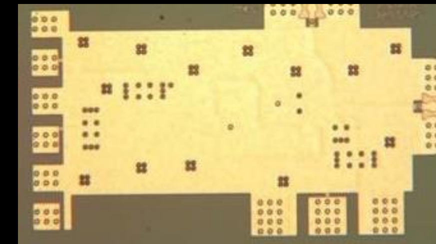
614 GHz fundamental VCO

M. Seo, TSC / UCSB



340 GHz dynamic frequency divider

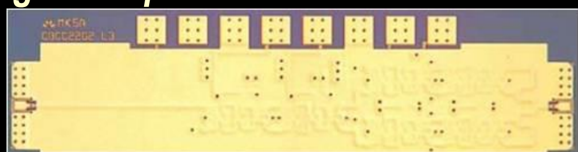
M. Seo, UCSB/TSC
IMS 2010



620 GHz, 20 dB gain amplifier

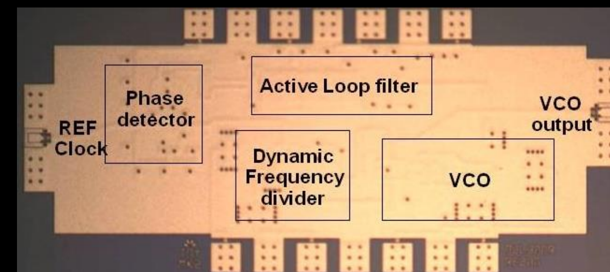
M Seo, TSC
IMS 2013

also: 670GHz amplifier
J. Hacker , TSC
IMS 2013 (not shown)



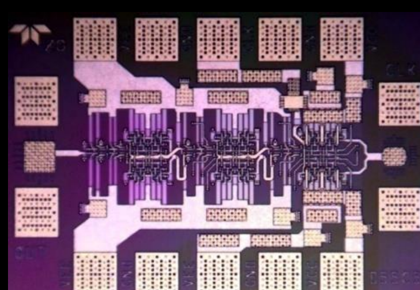
300 GHz fundamental PLL

M. Seo, TSC
IMS 2011



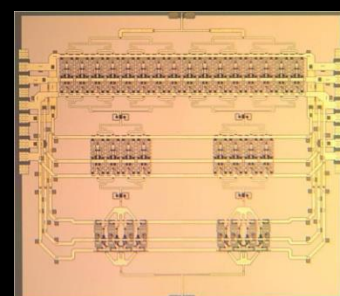
204 GHz static frequency divider (ECL master-slave latch)

Z. Griffith, TSC
CSIC 2010



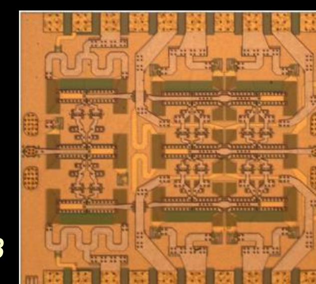
220 GHz 180 mW power amplifier

T. Reed, UCSB
CSICS 2013

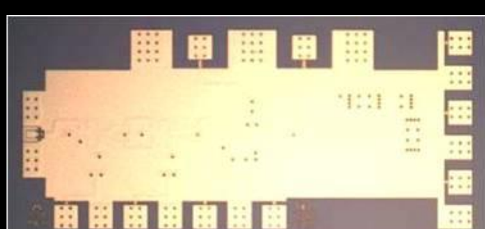


81 GHz 470 mW power amplifier

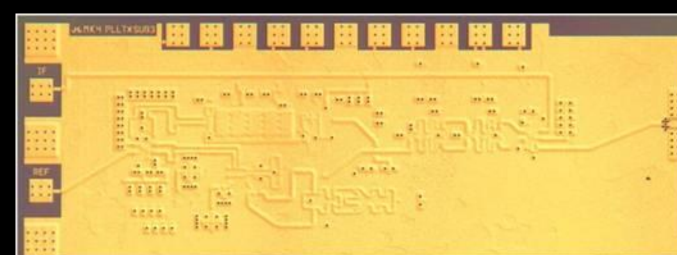
H-C Park UCSB
IMS 2014



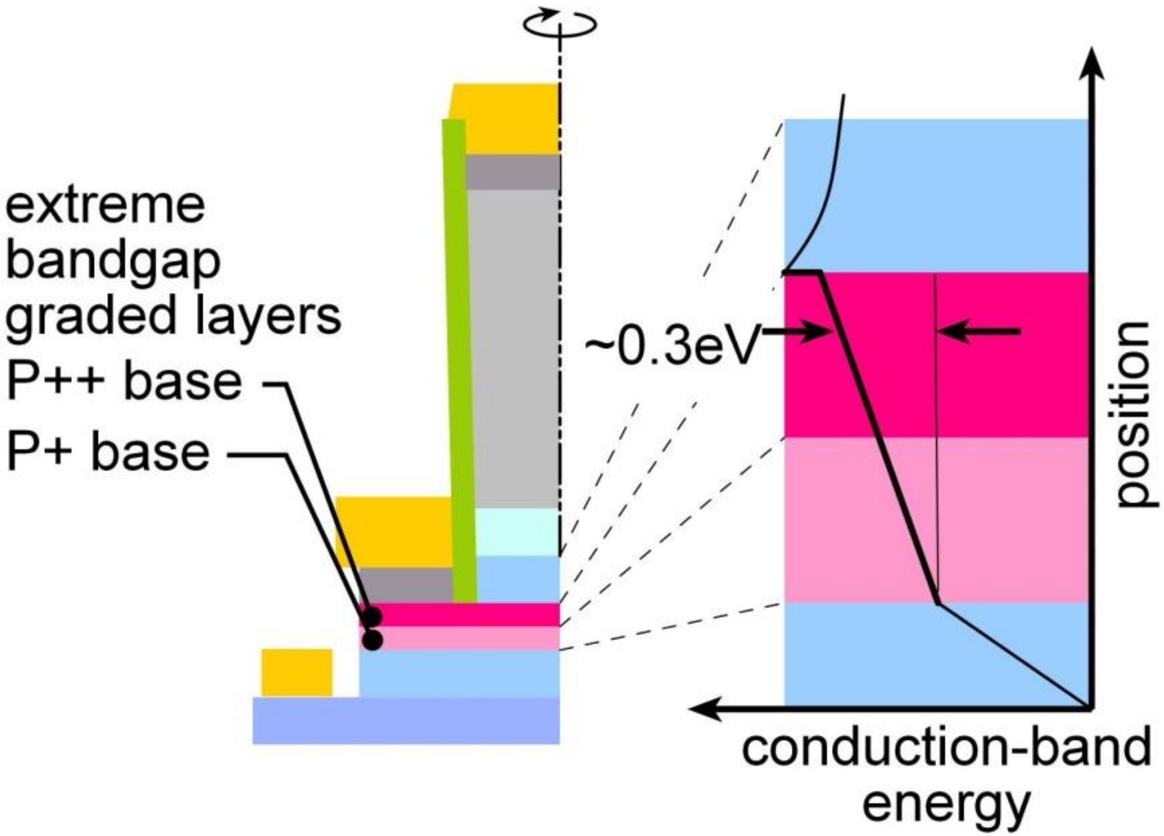
Integrated 300/350GHz Receivers:
LNA/Mixer/VCO
M. Seo TSC

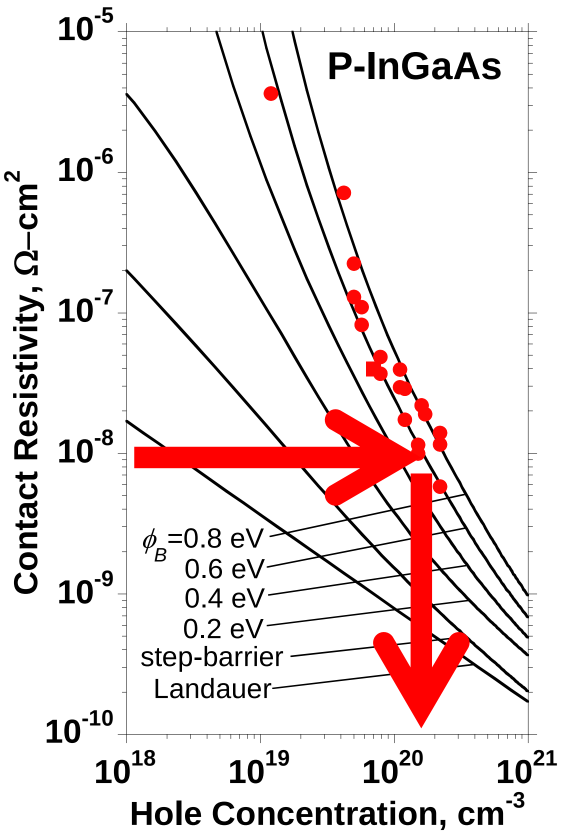


600 GHz Integrated Transmitter
PLL + Mixer
M. Seo TSC



Towards a 3 THz InP Bipolar Transistor





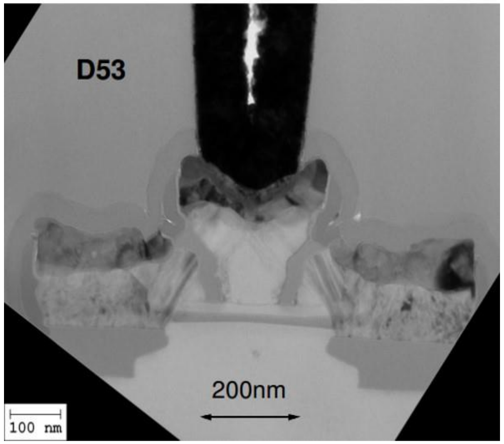
Extreme base doping→ low-resistivity contacts→ high f_{max}

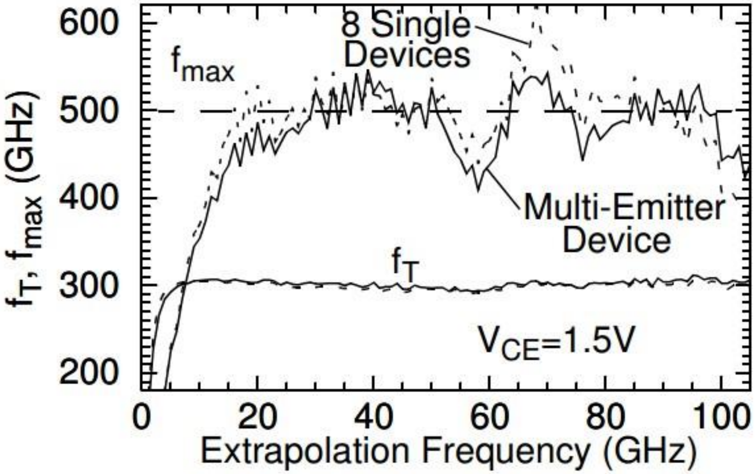
Extreme base doping→ fast Auger (NP^2) recombination→ low β.

Solution: very strong base compositional grading→ high β

1/2-THz SiGe HBTs

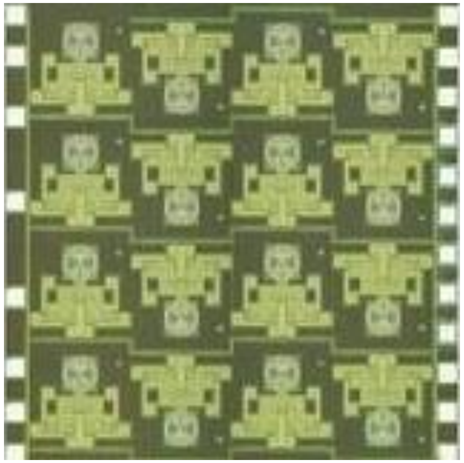
500 GHz f_{max} SiGe HBTs Heinemann et al. (IHP), 2010 IEDM





16-element multiplier array @ 500GHz (1 mW total output)

U. Pfeiffer et. al. (Wuppertal / IHP) , 2014 ISSCC



Towards a 2 THz SiGe Bipolar Transistor

Similar scaling
InP: 3:1 higher collector velocity
SiGe: good contacts, buried oxides

Key distinction: Breakdown
InP has:
thicker collector at same f_τ,
wider collector bandgap

Key requirements:
low resistivity Ohmic contacts
note the high current densities

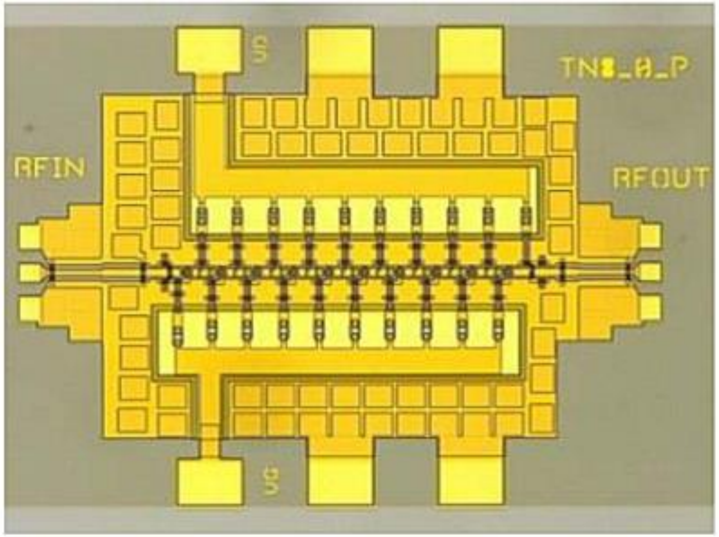
	InP	SiGe	
emitter			
junction width	64	**18**	nm
access resistivity	2	**0.6**	Ω–μm^2
base			
contact width	64	18	nm
contact resistivity	2.5	**0.7**	Ω–μm^2
collector			
thickness	53	15	nm
current density	36	**125**	mA/μm^2
breakdown	2.75	1.3?	V
f_τ	1000	1000	GHz
f_{max}	2000	2000	GHz

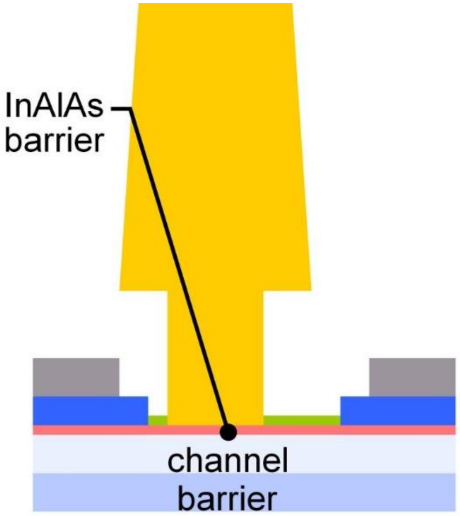
Assumes collector junction 3:1 wider than emitter.
Assumes SiGe contacts no wider than junctions

Towards at 2.5 THz HEMT

First Demonstration of Amplification at 1 THz Using 25-nm InP High Electron Mobility Transistor Process

Xiaobing Mei, et al, IEEE EDL, April 2015 **(Northrop-Grumman)**



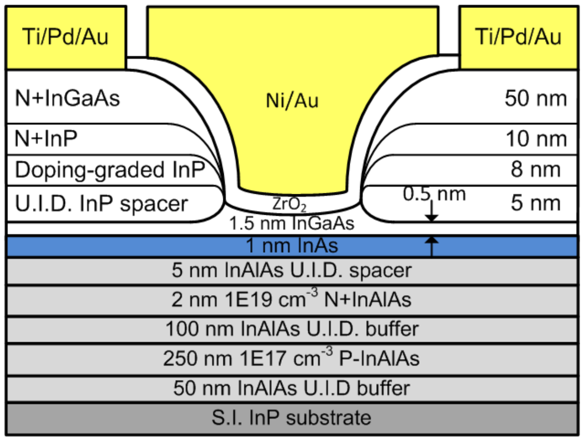


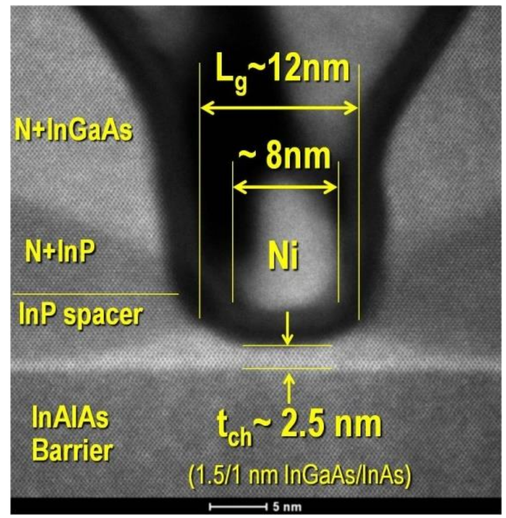
FET scaling laws; 2:1 higher bandwidth	change
gate length	decrease 2:1
current density (mA/mm), g_m (mS/mm)	increase 2:1
transport mass	constant
gate-channel capacitance density	increase 2:1
contact resistivities	decrease 4:1

Need thinner dielectrics, better contacts

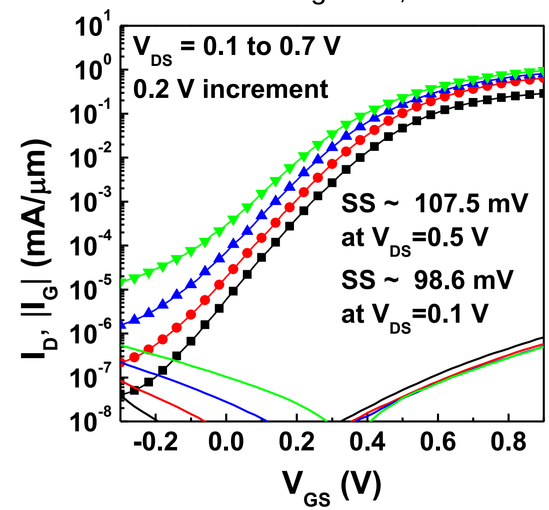
Towards at 2.5 THz HEMT

VLSI III-V MOS

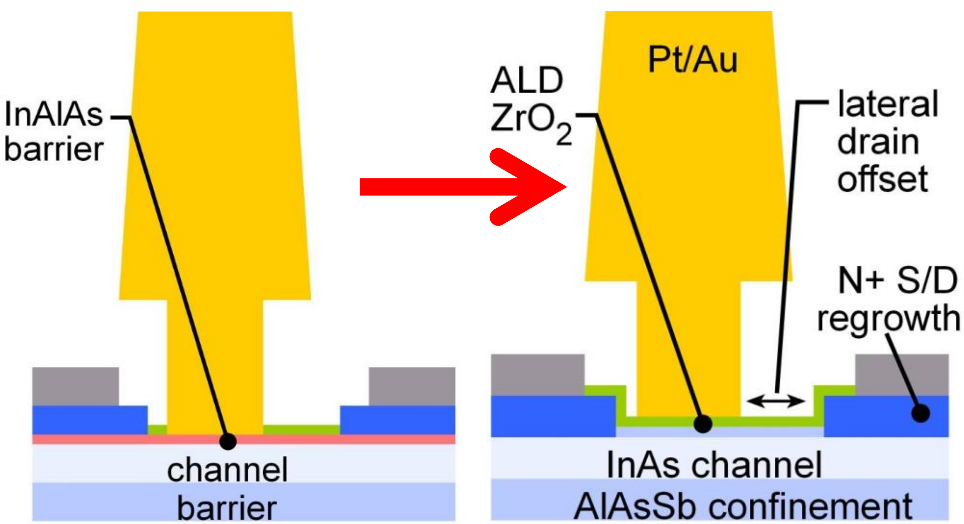




C. Y. Huang et al., DRC 2015

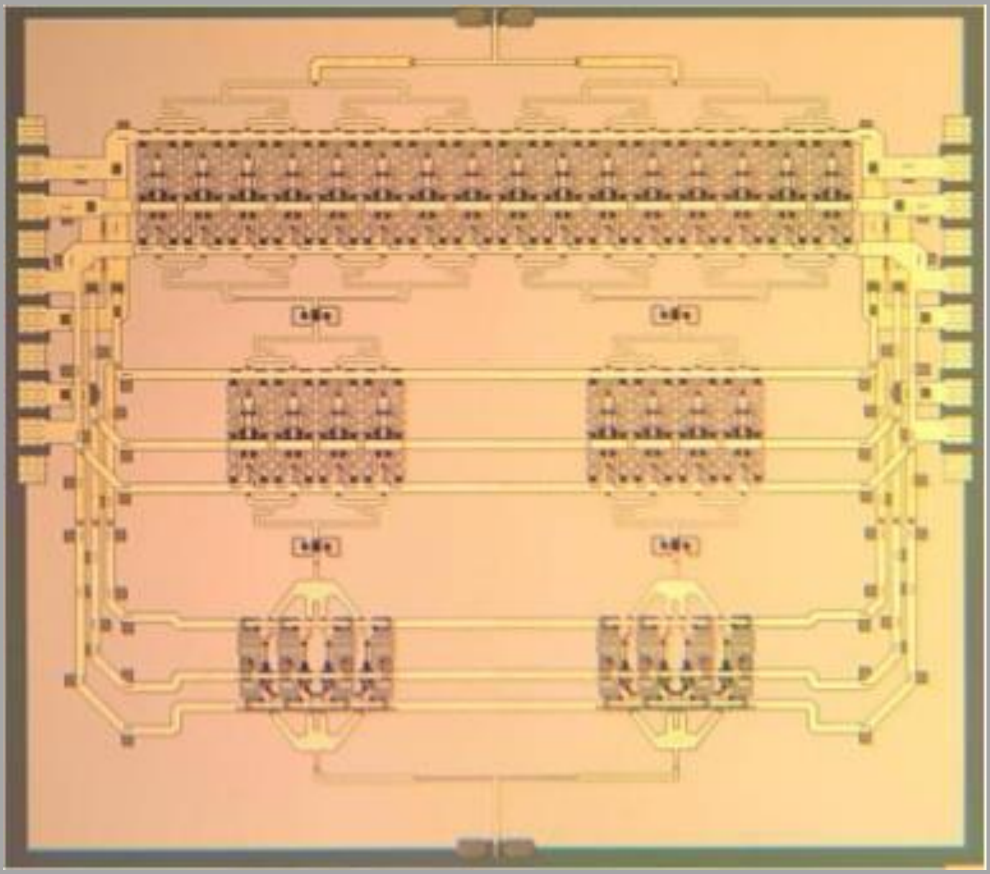


THz III-V MOS



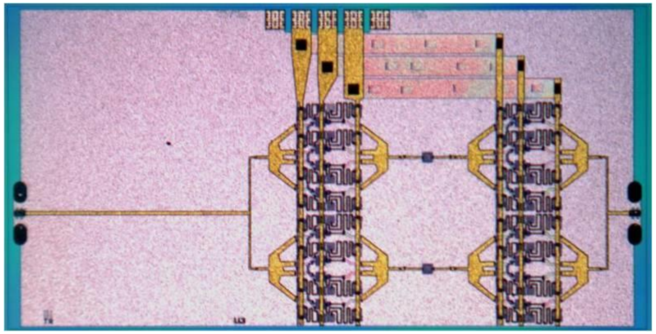
gate length	36	18	9	nm
EOT	0.8	0.4	0.2	nm
well thickness	5.6	2.8	1.4	nm
effective mass	0.05	0.08	0.08	times m_0
# bands	1	1	1	--
S/D resistivity	150	74	37	Ω-μm
extrinisic g_m	2.5	4.2	6.4	mS/μm
on-current	0.55	0.8	1.1	mA/μm
f_τ	0.70	1.2	2.0	THz
f_{max}	0.81	1.4	2.7	THz

Power Amplifiers

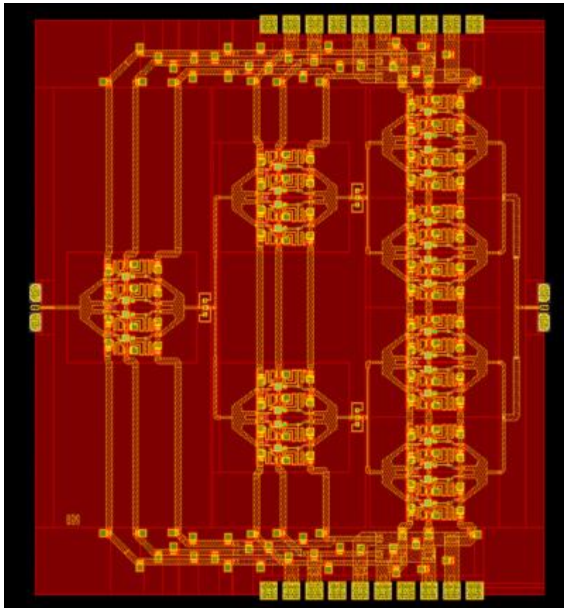


220 GHz power amplifiers; 256nm InP HBT

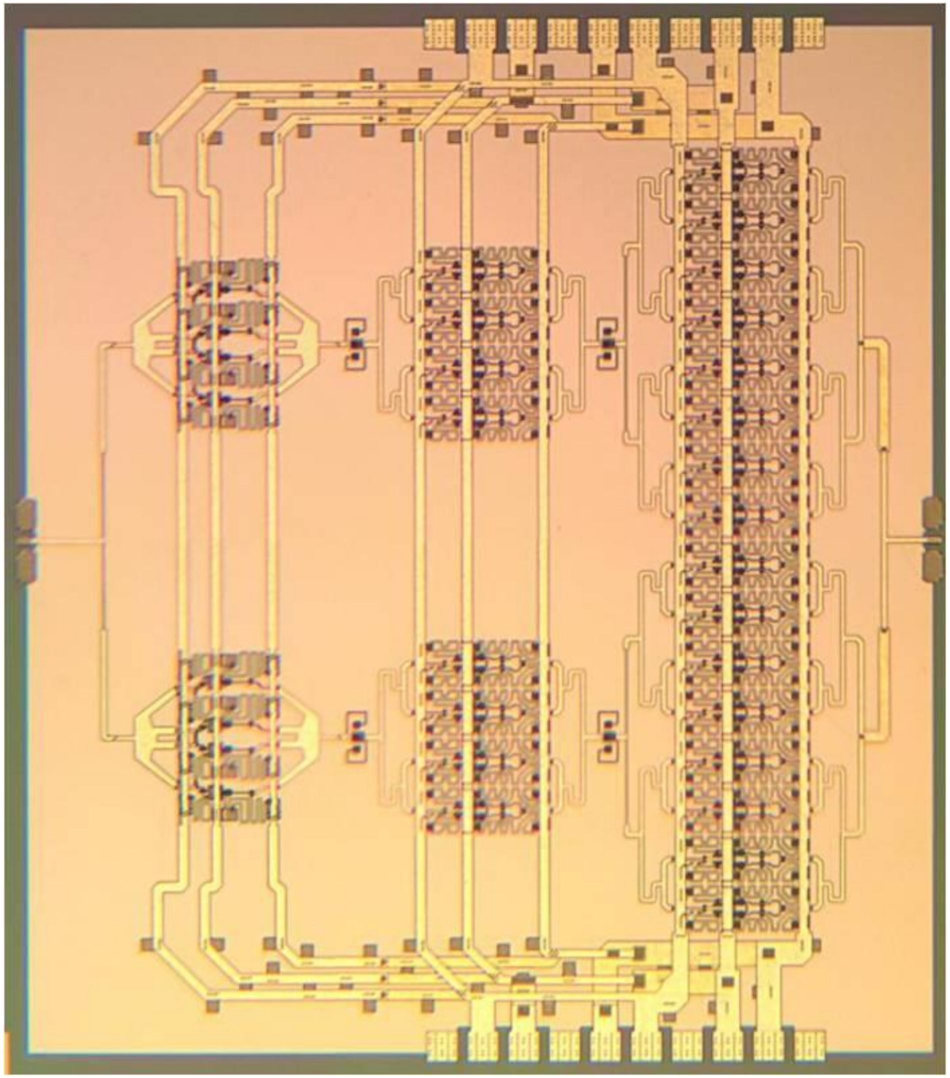
90 mW



164 mW, 0.43 W/mm, 2.4% PAE



180 mW (330 mW design; thermally limited)



T. Reed (UCSB), Z. Griffith (TSC), IEEE CSIC 2012 & 2013; Teledyne 256nm InP HBT

mm-Wave Power Amplifier: **Challenges**

needed: High power / High efficiency / Small die area (low cost)

<u>Extensive</u> power combining

<u>Compact</u> power-combining

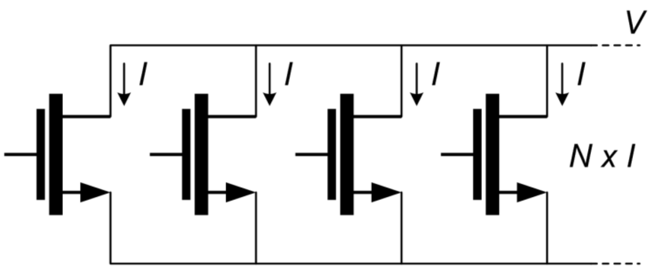
$$\mathrm{PAE} = \eta_{\substack{\mathrm{drain/} \\ \mathrm{collector}}} \left(1 - \frac{1}{\mathrm{Gain}}\right) \cdot \eta_{\substack{\mathrm{power-} \\ \mathrm{combiner}}}$$

Class E/D/F are poor @ mm-wave
insufficient f_{max} ,
high losses in harmonic terminations

<u>Efficient</u> power-combining

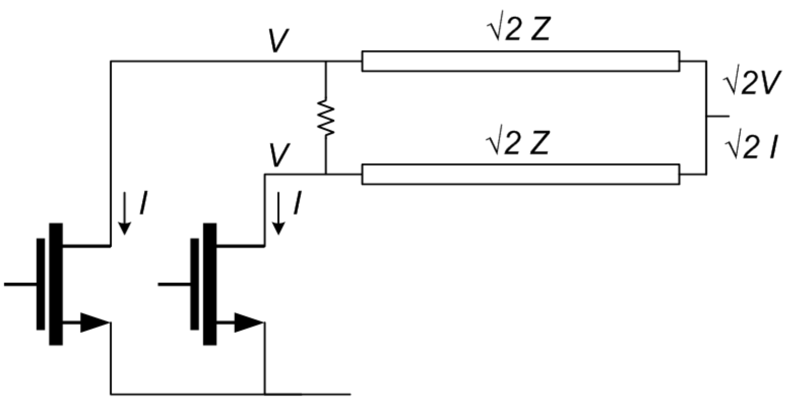
Goal: efficient, compact mm-wave power-combiners

Parallel Power-Combining



Output power: P_{OUT} = **N** x V x I
Parallel connection increases P_{OUT} ✓

Load Impedance: Z_{OPT} = V / (**N** x I)
Parallel connection decreases Z_{opt} ✗

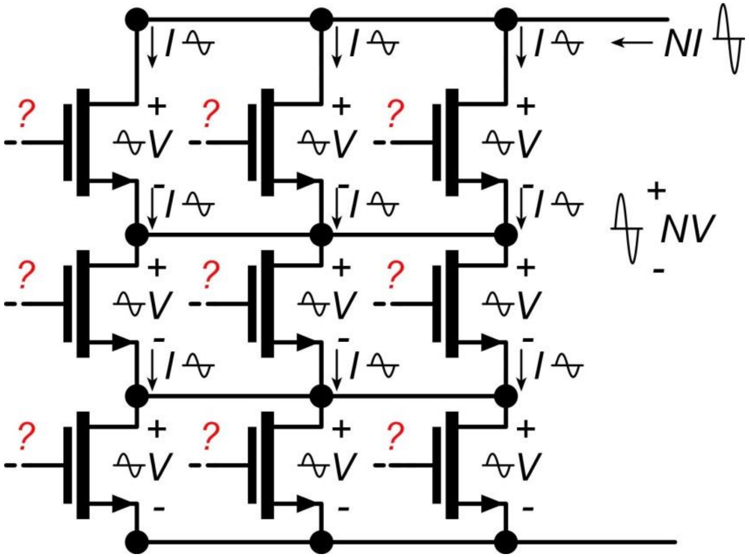


High P_{OUT} → Low Z_{opt}

Needs impedance transformation:
lumped lines, Wilkinson, ...

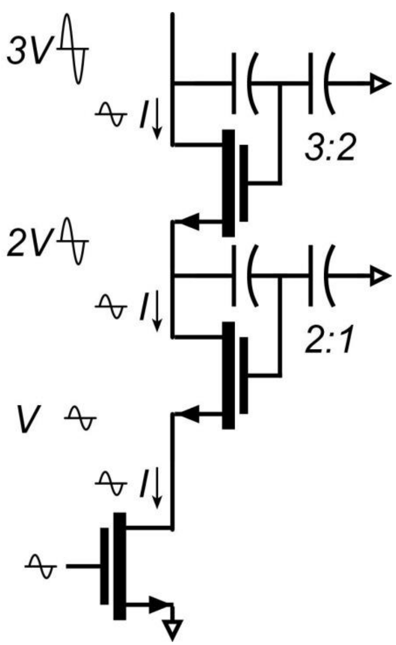
High insertion loss ✗
Small bandwidth
Large die area

Series Power-Combining & Stacks



Parallel connections: I_{out}=N x I
Series connections: V_{out}=N x V

Output power: P_{out}=**N^2** x V x I
Load impedance: Z_{opt}=V/I ✓
Small or zero power-combining losses ✓
Small die area ✓
How do we drive the gates ?

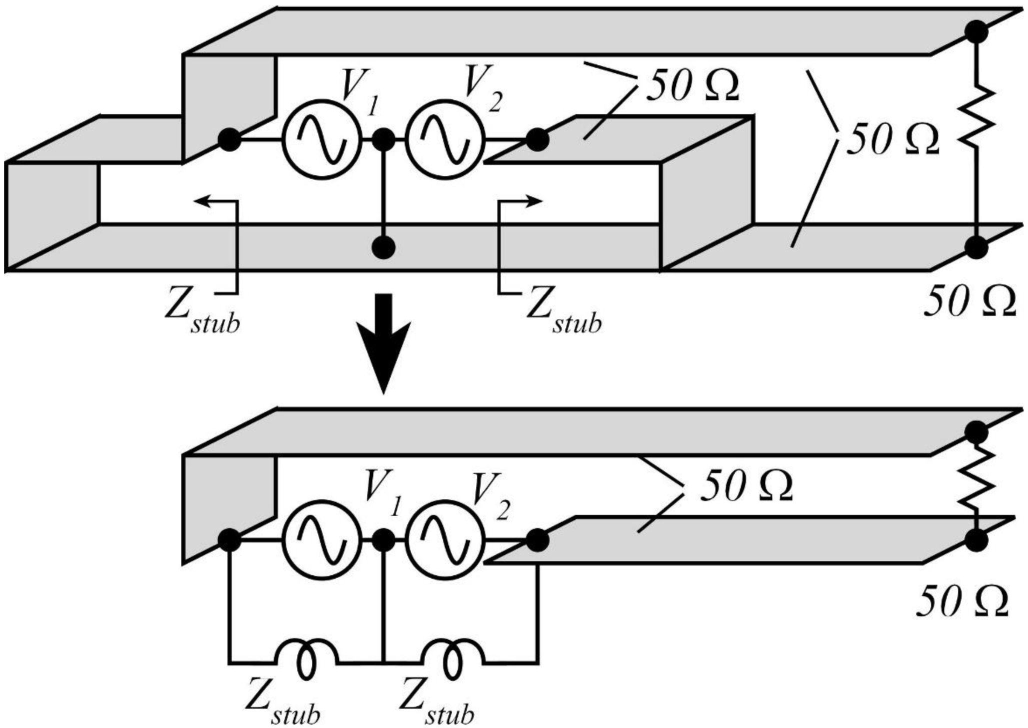


Local voltage feedback:
drives gates, sets voltage distribution

Design challenge:
need uniform RF voltage distribution
need ~unity RF current gain per element
...needed for simultaneous compression of all FETs.

Shifrin *et al.*, 1992 IEEE-IMS; Rodwell *et al.*, U.S. Patent 5,945,879, 1999; Pornpromlikit *et al.*, 2011 CSICS

Sub-λ/4 Baluns for **Series** Combining



Balun combiner:
2:1 series connection ✓
each source sees 25 Ω
→ 4:1 increased P_{out} ✓

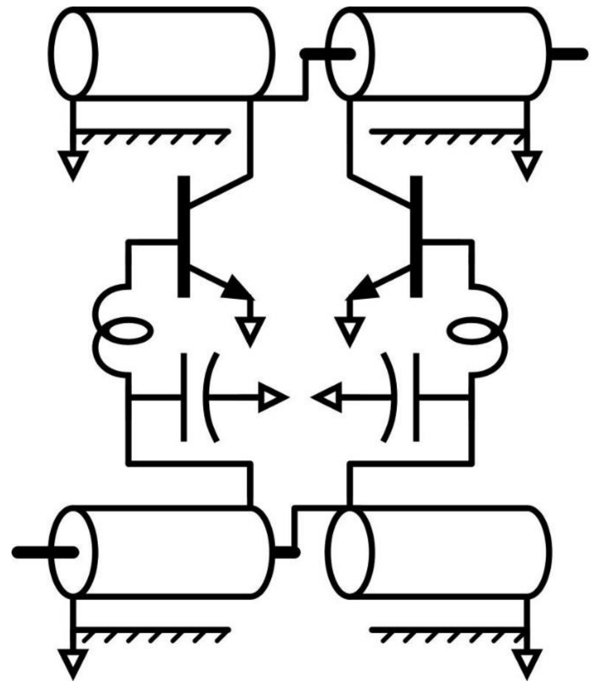
Standard λ/4 balun :
long lines
→ high losses ✗
→ large die ✗

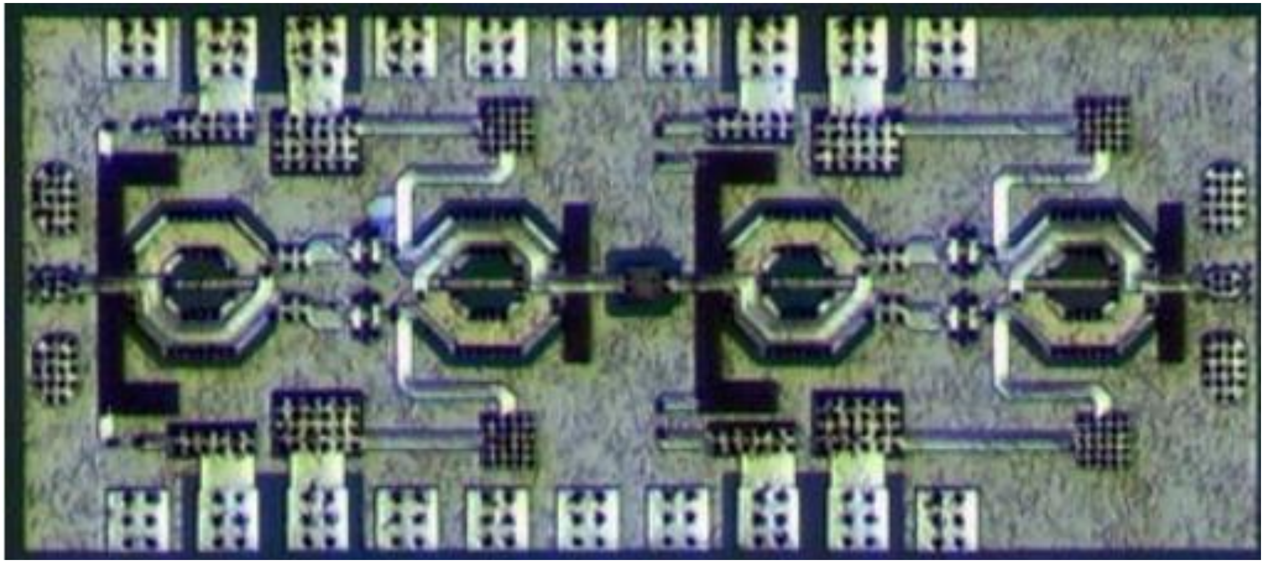
Sub-λ/4 balun :
stub→ inductive
tunes transistor C_{out} ! ✓
short lines→ low losses ✓
short lines → small die ✓

Park *et al.*, 2013 CSICS, 2014 IEEE-IMS

2:1 series-connected 86GHz power amplifier

20 dB Gain
188mW P_{sat}
1.96 W/mm
32.8% PAE
Teledyne 250 nm InP HBT
2 stages, 1.0 mm^2





Daneshgar *et al.*, 2014 IEEE-IMS

4:1 series-connected 81GHz power amplifier

Park *et al.*, 2014 IEEE-IMS

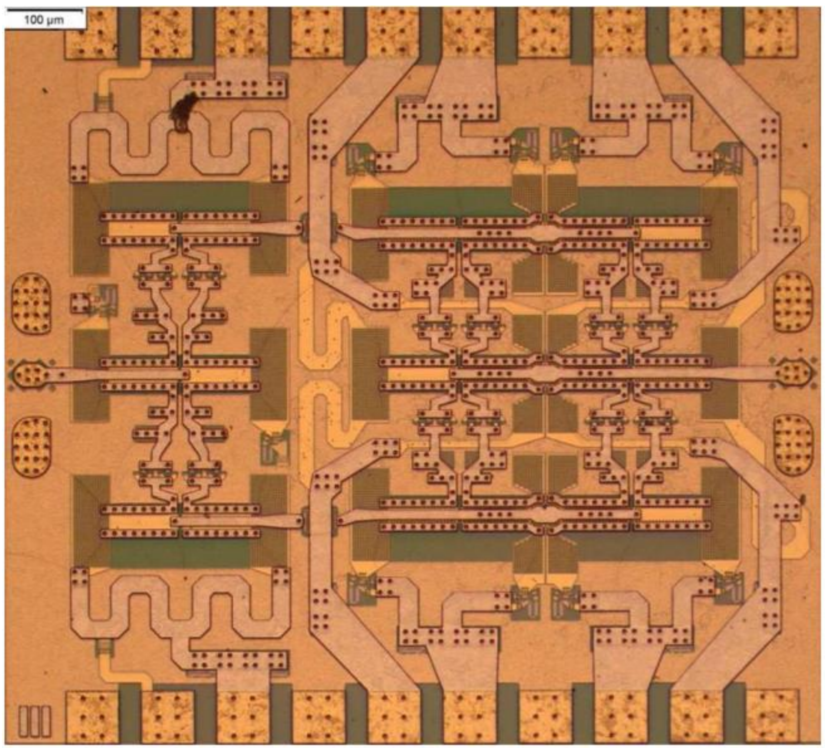
17 dB Gain

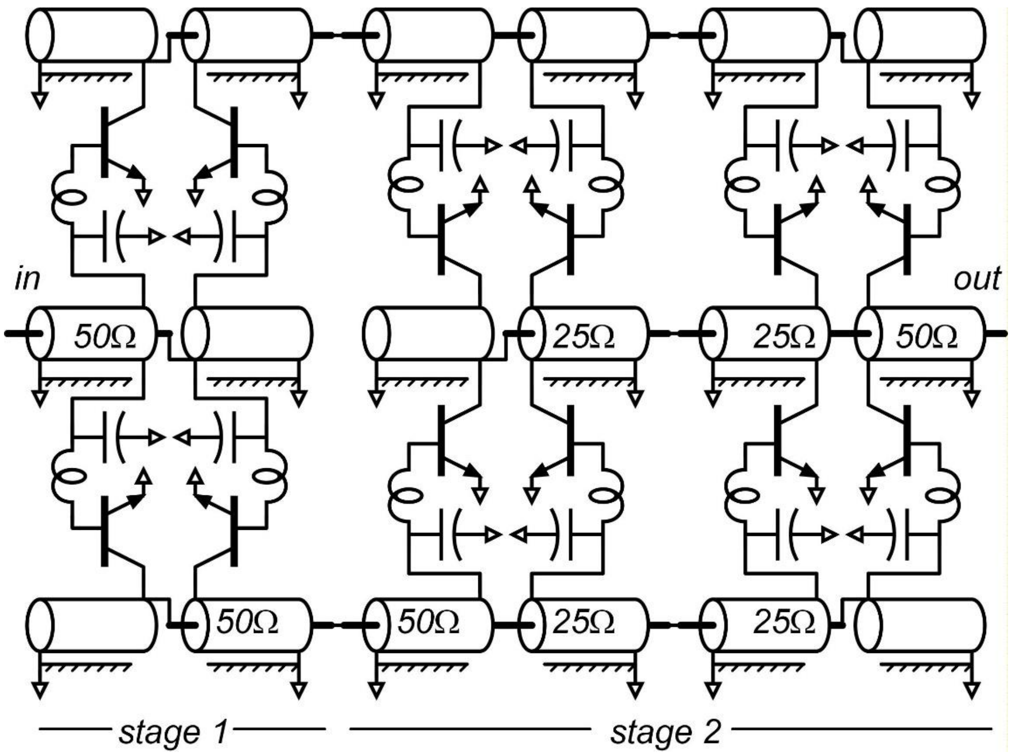
470 mW P_{sat}

23% PAE

Teledyne 250 nm InP HBT

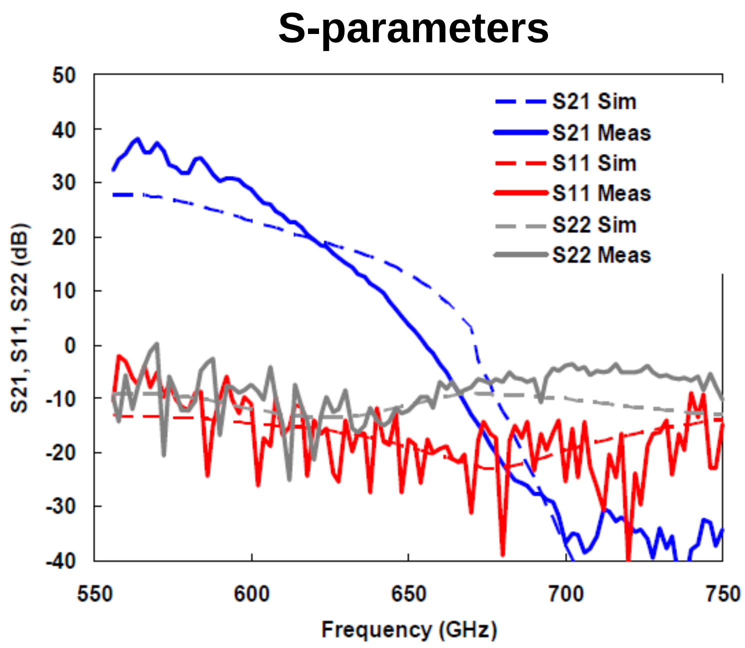
2 stages, 1.0 mm^2(incl pads)

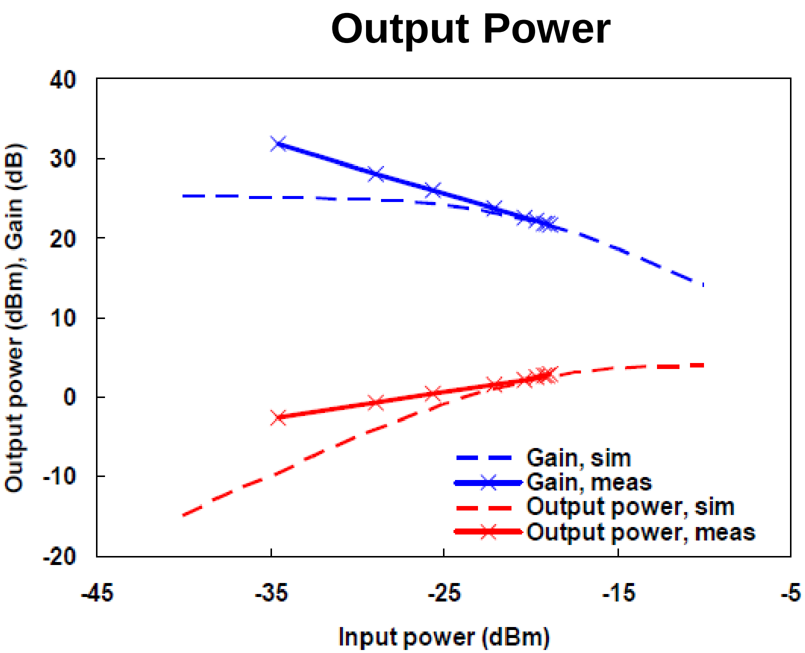




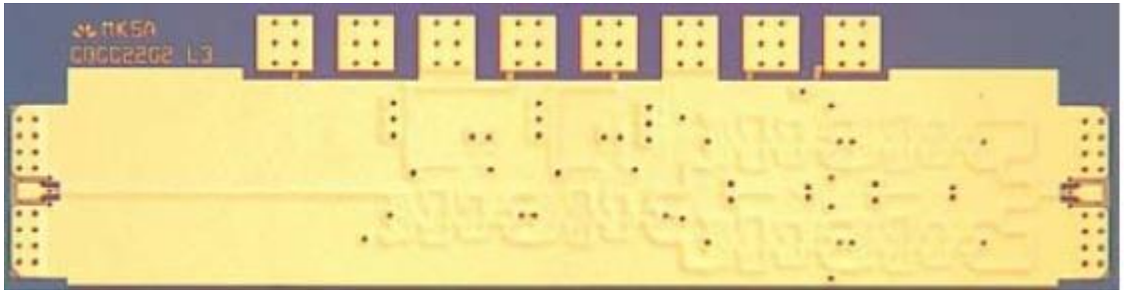
Teledyne: 1.9 mW, 585 GHz Power Amplifier

M. Seo *et al.*, Teledyne Scientific: IMS2013





- 12-Stage Common-base
- 2.8 dBm P_{sat}
- >20 dB gain up to 620 GHz



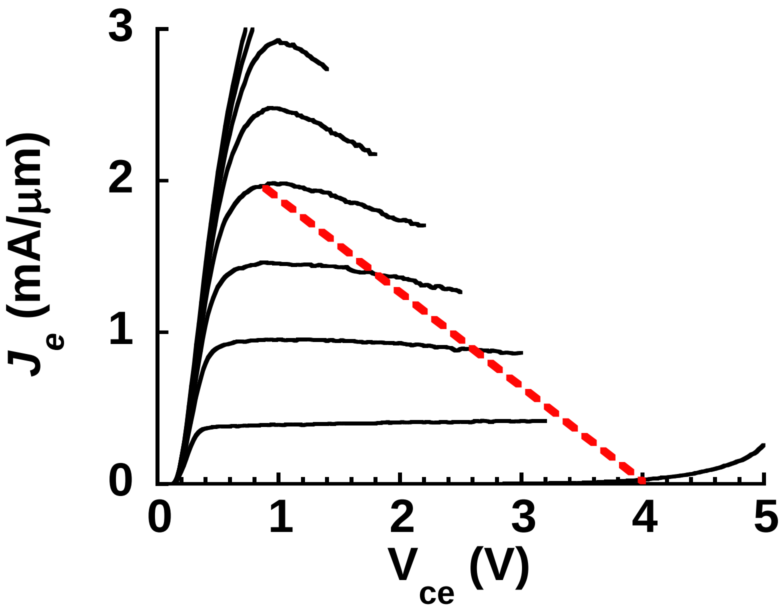
What limits output power in sub-mm-wave amplifiers ?

Sub-mm-wave PAs: need more current !

3 µm max emitter length (> 1 THz f_{max})
2 mA/µm max current density
I_{max}= 6 mA

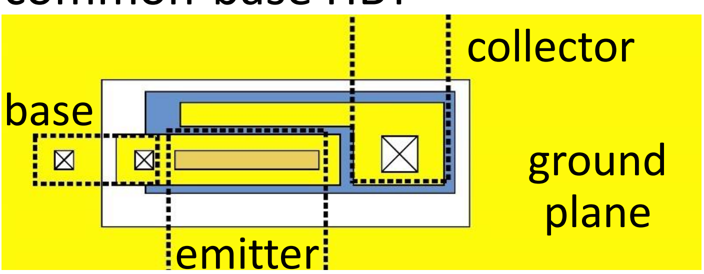
Maximum 3 Volt p-p output

Load: 3V/6mA= 500 Ω

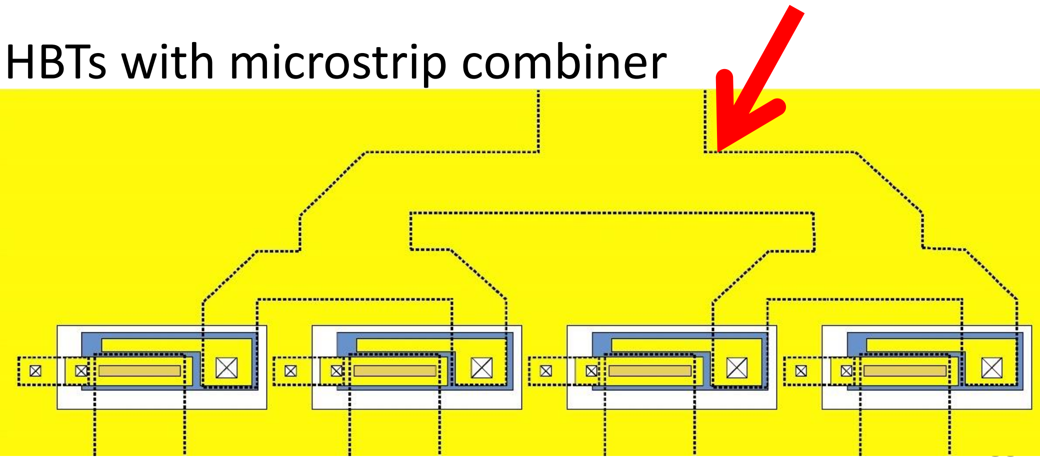


Combiner cannot provide 500 Ω loading

common-base HBT



HBTs with microstrip combiner



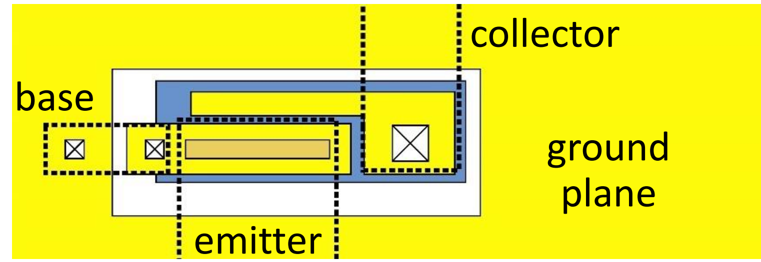
Multi-finger HBTs: more current, lower f_{max}

More current
→ lower cell load resistance

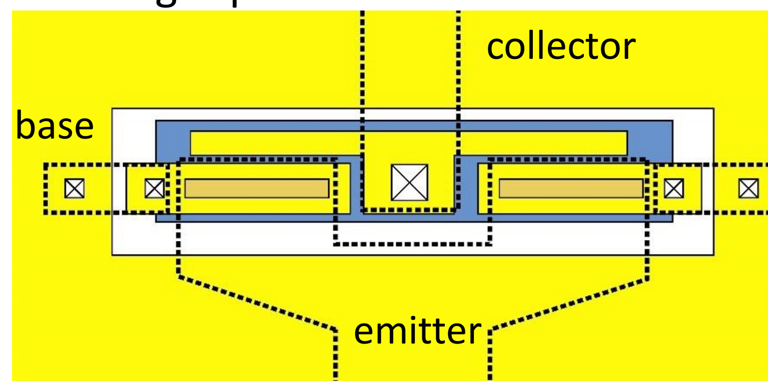
Reduced f_{max}, reduced RF gain:
common-lead inductance→ Z_{12}
feedback capacitance→ Y_{12}
phase imbalance between fingers.

Worse at higher frequencies:
less tolerant of cell parasitics
less current per cell
higher required load resistance
Can optimum load be reached ?

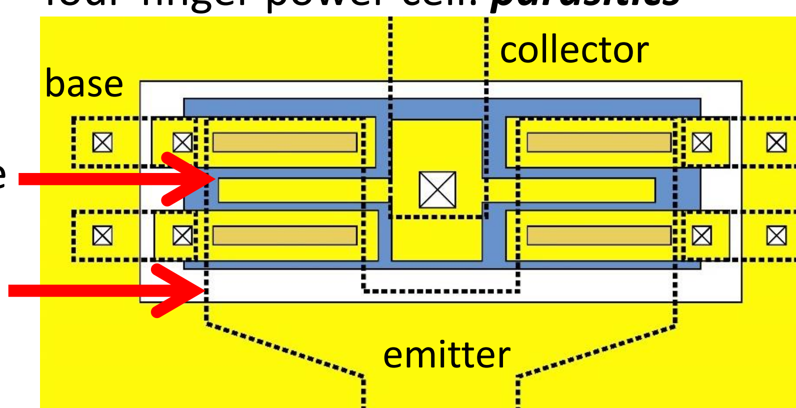
one-finger common-base HBT



two-finger power cell

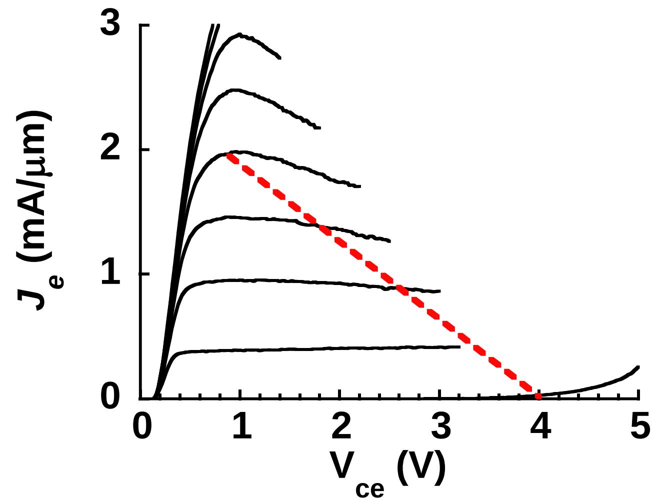


four-finger power cell: ***parasitics***

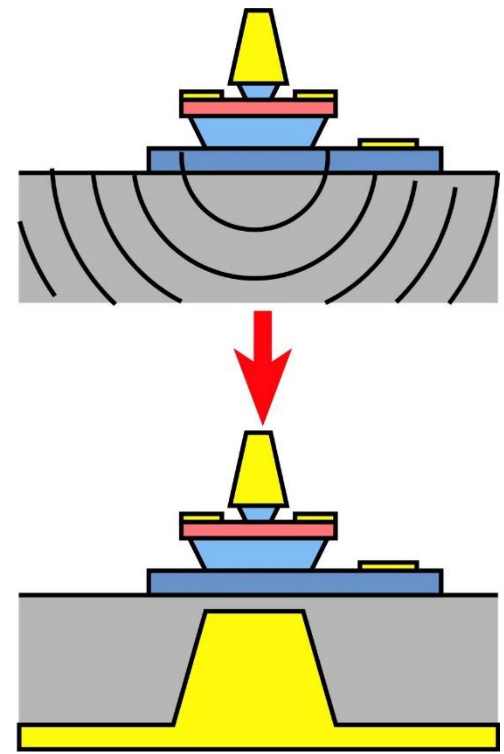


Sub-mm-wave transistors: need more current

InP HBTs:
thinner collector→ more current
hotter→ improve heat-sinking
or: longer emitters→ thicker base metal



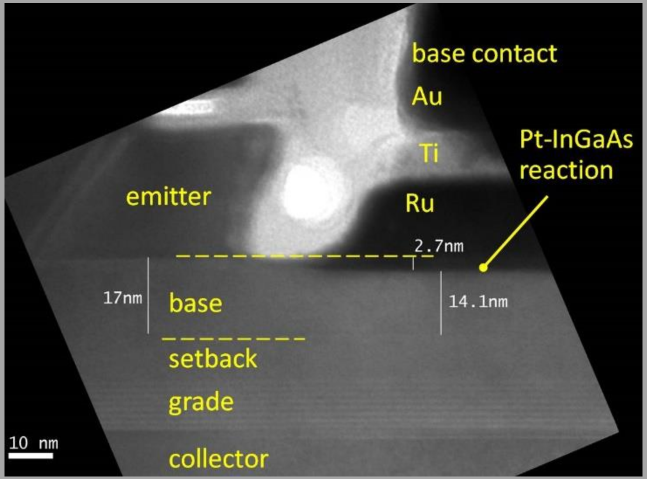
GaN HEMTs:
much higher voltage
100+ GHz: large multi-finger FETs not feasible
Need high current to exploit high voltage.

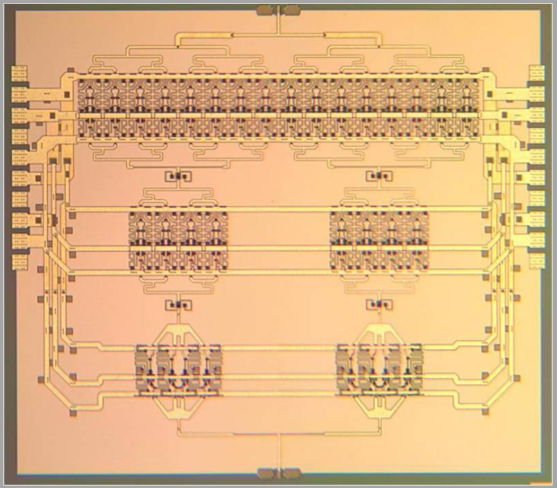


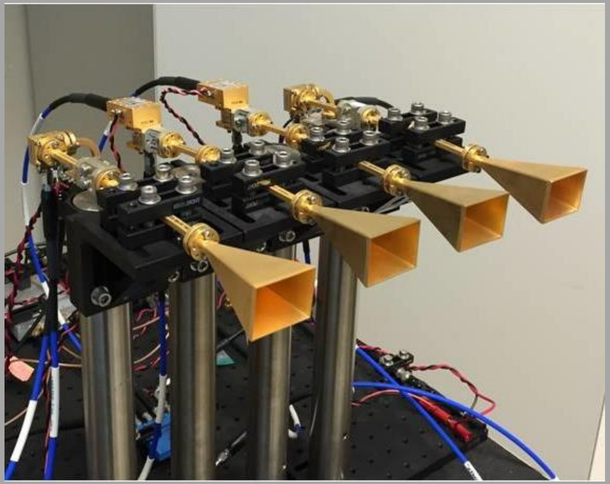
Example:
2mA/μm, 100 μm max gate width, 50 Volts
200mA maximum current
50 Volts/200mA= 250 Ω load→ unrealizable.

Need more mA/μm or longer fingers

50-500GHz Wireless

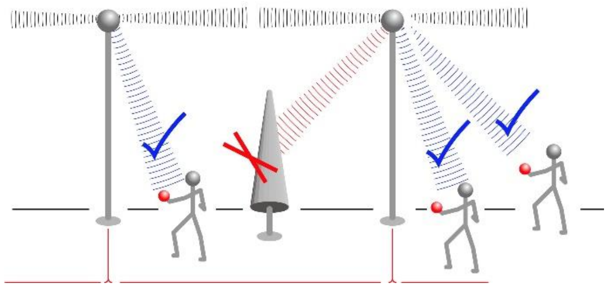


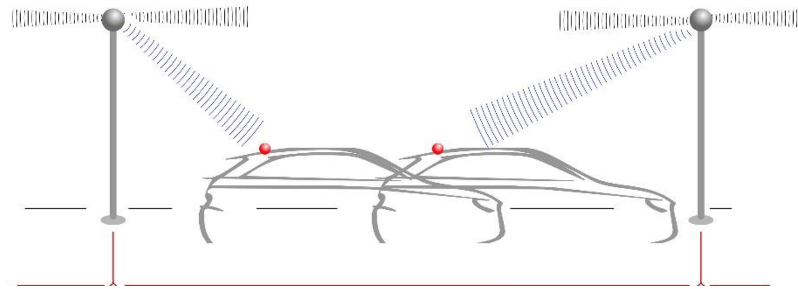




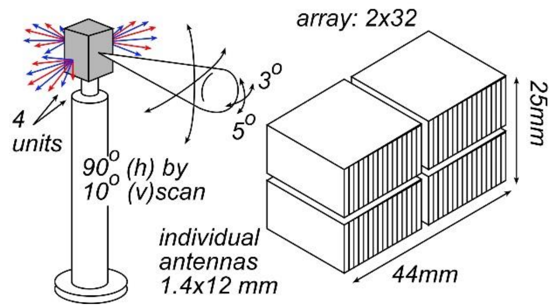
50-500 GHz Wireless Electronics

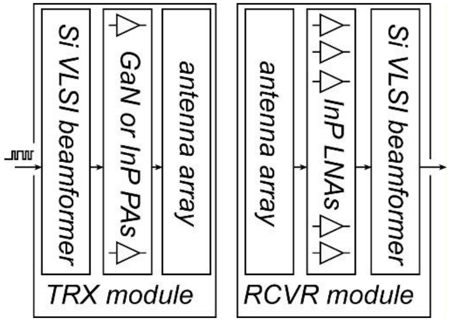
Mobile communication @ 2Gb/s per user, 1 Tb/s per base station





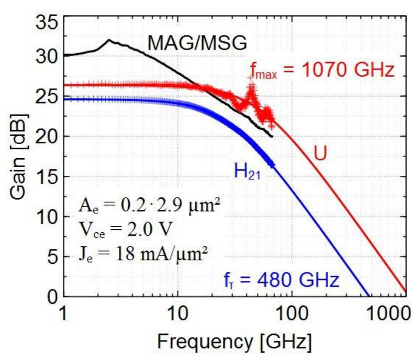
Requires: large arrays, complex signal processing, high P_{out}, low F_{min}

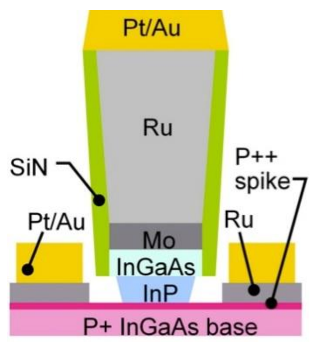


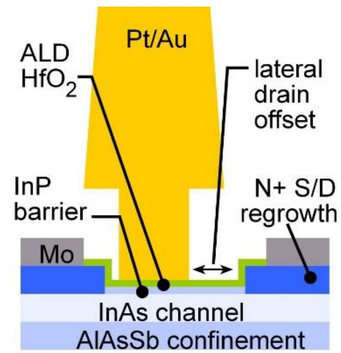


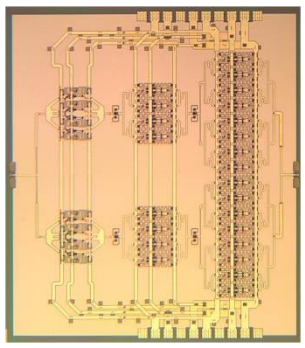
VLSI beamformers
VLSI equalizers
III-V LNAs & PAs

III-V Transistors may perform well enough even for 1 THz systems.









(backup slides follow)

asdfsadfasdfadsf

asdfasdfdfasdf

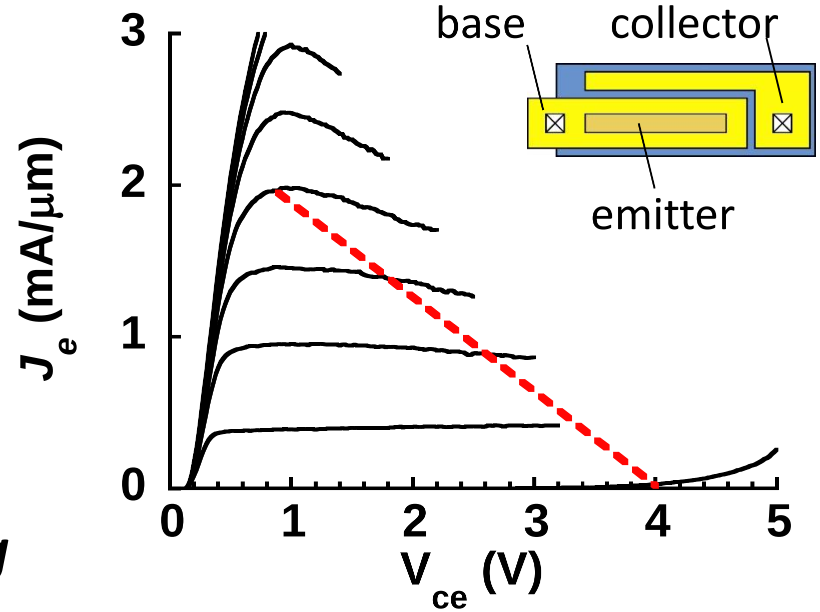
Talk is 40 min plus 10 min for questions…
35-40 slides

Sub-mm-wave PAs: need more current !

<3 μm emitter length for > 1 THz f_{max}
2 mA/μm max current density
I_{max}= 6 mA

Maximum 3 Volt p-p output

Load: 3V/6mA= 500 Ω



Combiner cannot provide 500 Ω loading

ground plane