Bringing THz communication to the mass market: no longer an illusion?

Piet Wambacq, imec Fellow and professor at VUB, Brussels

with thanks to many imec colleagues

THz communication comes in the spotlight

ISSCC 87 THURSDAY

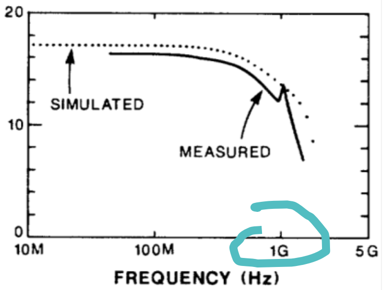
SESSION XIV: WIDEBAND AMPLIFIERS

THAM 14.1: A Matched Impedance NMOS Amplifier*

*Kai-Yap Toh**, Robert G. Meyer*

University of California

Berkeley, CA



ISSCC 2021 / SESSION 22 / TERAHERTZ FOR COMMUNICATION AND SENSING / OVERVIEW

Session 22 Overview:
Terahertz for Communication and Sensing
WIRELESS SUBCOMMITTEE

Tuesday, May 25, 2010
12:00 PM - 01:10 PM • Room 201AB

Silicon at THz Frequencies: A Reality or a Dream?

Chair/Moderator:
Prof. Gabriel M. Rebeiz, University of California, San Diego

ISSCC 2021 / SESSION 23 / THz CIRCUITS AND FRONT-ENDS / OVERVIEW

Session 23 Overview: ***THz Circuits and Front-Ends***
RF SUBCOMMITTEE

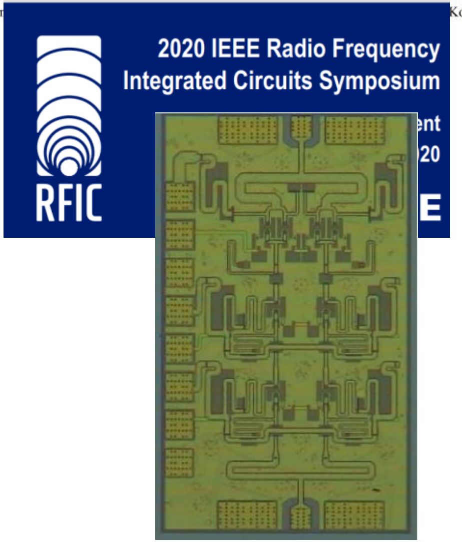
But how close are we to products?

D-band integrated circuits coming to maturity

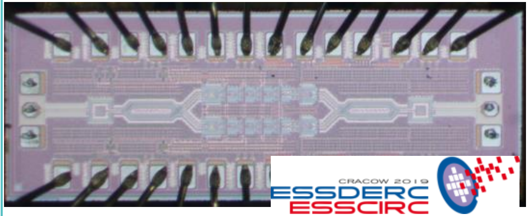
Transceiver functionality, efficient power amplifiers, …

A 140GHz power amplifier with 20.5dBm output power and 20.8% PAE in 250-nm InP HBT technology

Ahmed S. H. Ahmed[#1], Munkyo Seo[*], Ali A. Farid[#], Miguel Urteaga[$], James F. Buckwalter[#], and Mark J. W. Rodwell[#]
[#]Department of Electrical and Computer Engineering, University of California, Santa Barbara, USA
[*]Departr… Korea



130nm BiCMOS

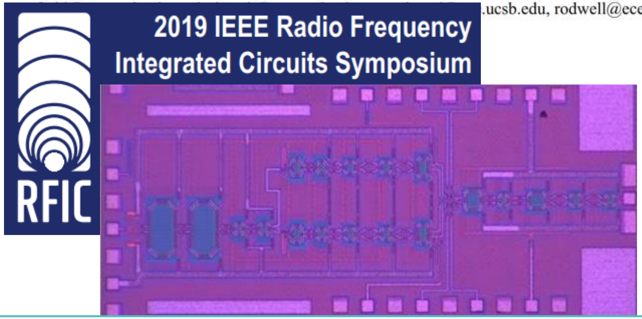


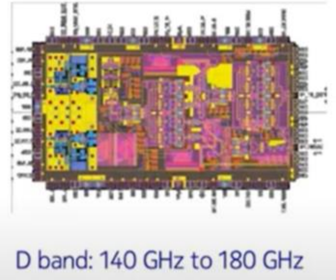
Imec, 140GHz BiCMOS PA, ESSCIRC 2019

34 dB gain, Psat of 17 dBm with 13% PAE

A Broadband Direct Conversion Transmitter/Receiver at D-band Using CMOS 22nm FDSOI

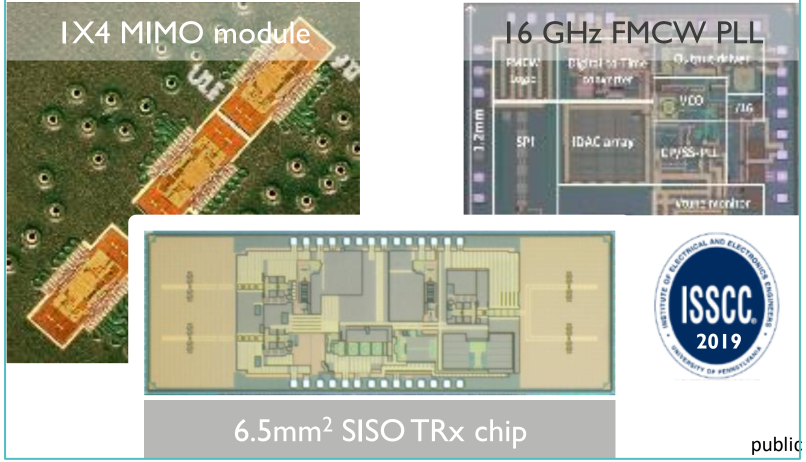
Ali A. Farid, Arda Simsek, Ahmed S. H. Ahmed, Mark J. W. Rodwell
ECE Department, University of California Santa Barbara, CA 93106
….ucsb.edu, rodwell@ece.ucsb.edu





Nokia, European 5G Conference 2021

imec, 40GHz radar transceiver 28nm CMOS



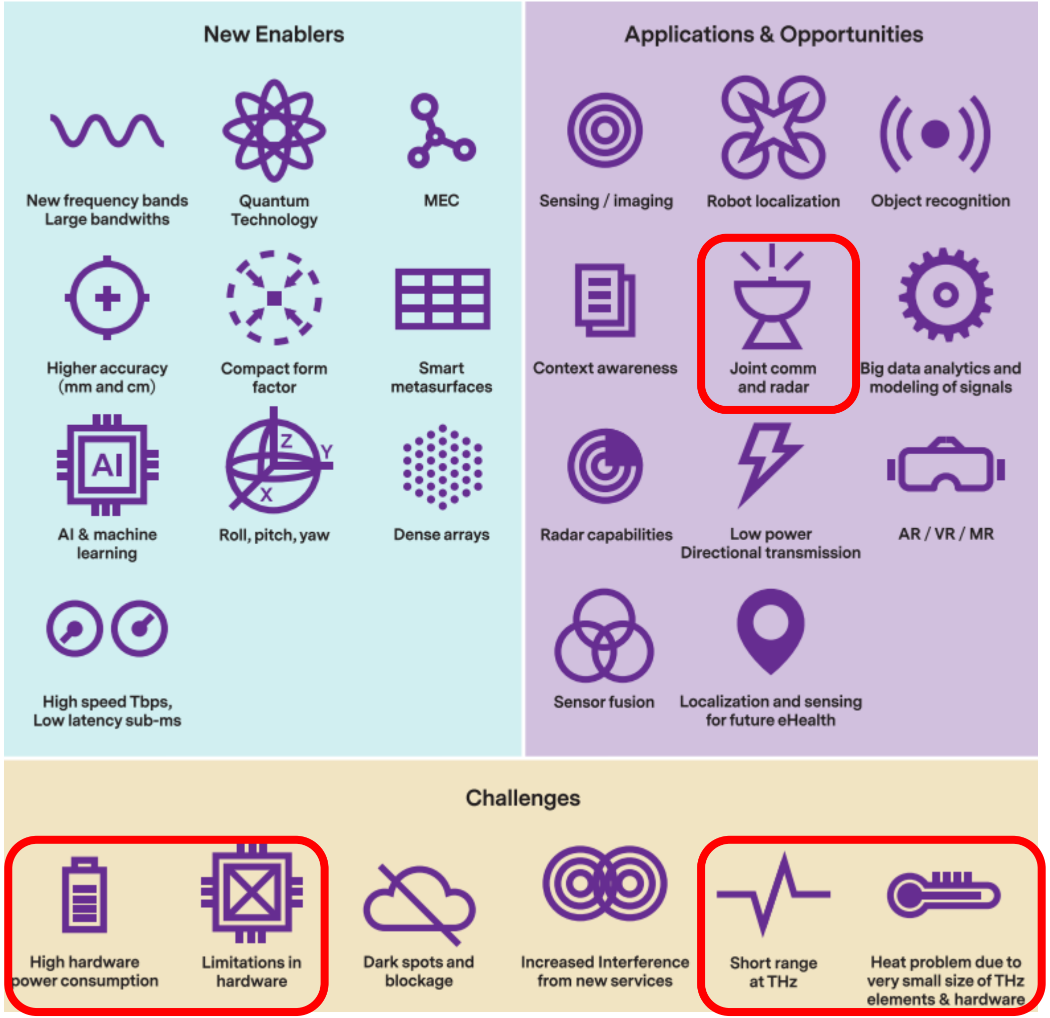
Can we make mass markets 6G systems with these circuits?

C. De Lima et al., "Convergent Communication, Sensing and Localization in 6G Systems: An Overview of Technologies, Opportunities and Challenges," in IEEE Access, vol. 9, pp. 26902-26925, 2021, doi: 10.1109/ACCESS.2021.3053486.

6G

Convergence of

- Communication
- Sensing
- Localization

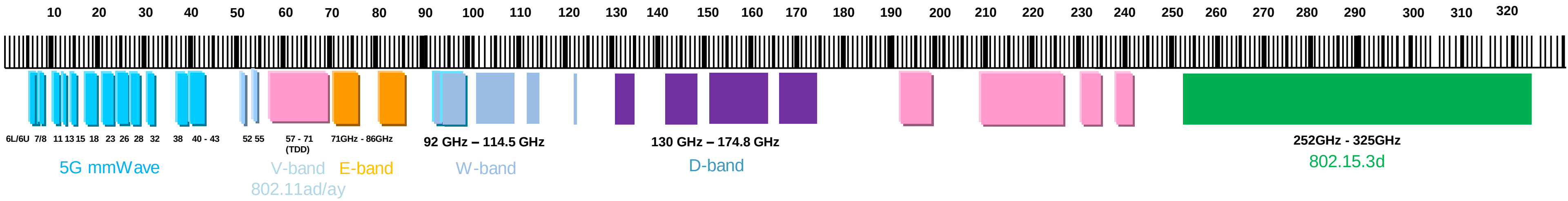


Outline

- The application level
- The challenge level
  - Active circuits
  - Antennas and packaging
  - Getting rid of the heat
- Conclusions

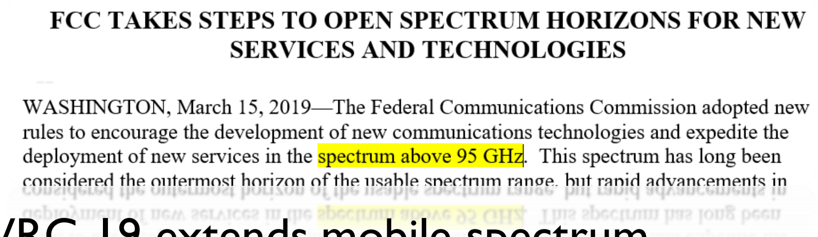
New radio spectrum to meet the 6G capacity demands

Towards THz frequencies for TBPS wireless connectivity



- Large aggregated bandwidth available at higher frequencies
  - V-band: > 7GHz
  - E-band: >10GHz
  - W-band: >17GHz
  - D-band: > 30GHz
  - 802.15.3d: > 50GHz

- FCC opens up the higher frequencies



FCC TAKES STEPS TO OPEN SPECTRUM HORIZONS FOR NEW SERVICES AND TECHNOLOGIES

WASHINGTON, March 15, 2019—The Federal Communications Commission adopted new rules to encourage the development of new communications technologies and expedite the deployment of new services in the spectrum above 95 GHz. This spectrum has long been considered the outermost horizon of the usable spectrum range, but rapid advancements in

- WRC-19 extends mobile spectrum, aggregated bandwidth of 137GHz available from 275GHz–450GHz

Beyond 5G and 6G: extreme capacity communication applications

Towards >100GHz frequencies for >100Gbps wireless connectivity

Wireless connectors & meshes

Short range ad-hoc point-to-point for D2D, kiosk, automotive

Mobile hotspot, Multi-User Mixed Reality

Fixed Point-to-Mobile multipoint for next-gen mobile indoor & outdoor

Fixed wireless Access

Fixed point-to-multipoint links as fiber substitute

Wireless Backhaul/Fronthaul

Fixed point-to-point links for cellular networks

50Gb/s | <5m

>10Gb/s per user | 10-100m

>20Gb/s per user | 100m

>500Gb/s | >100m

Sensing and communication: not so far apart

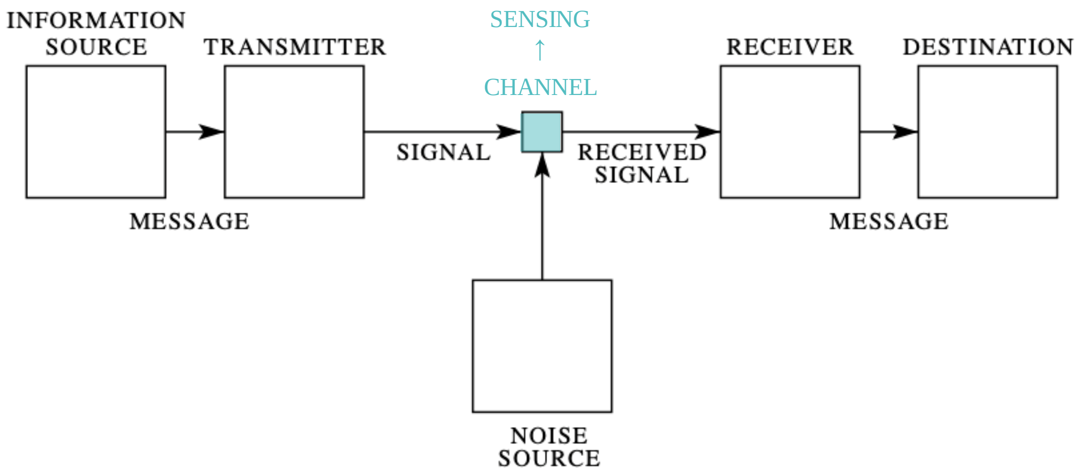


Fig. 1 — Schematic diagram of a general communication system.

C.E. Shannon, The Bell System Technical Journal, Vol. 27, pp. 379–423, 623–656, July, October, 1948.

In sensing the channel is the message

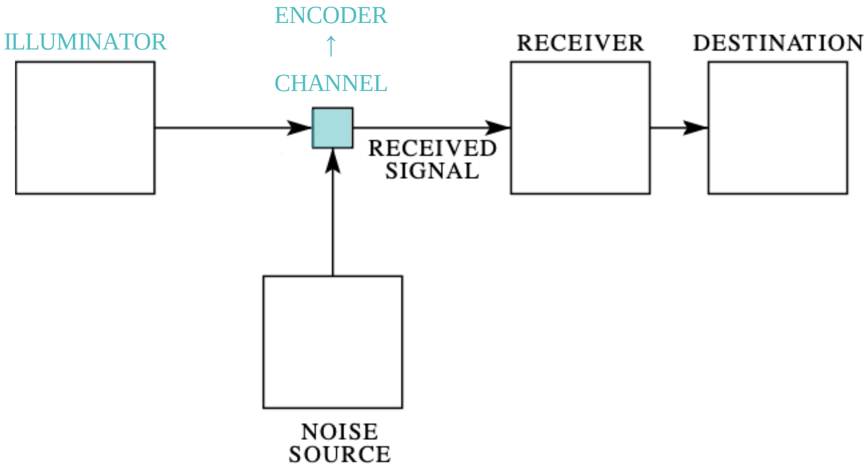


Fig. 1 — Schematic diagram of a general sensing system.

Sensing while communicating (or vice-versa)

Potential items of interest for a 6G system

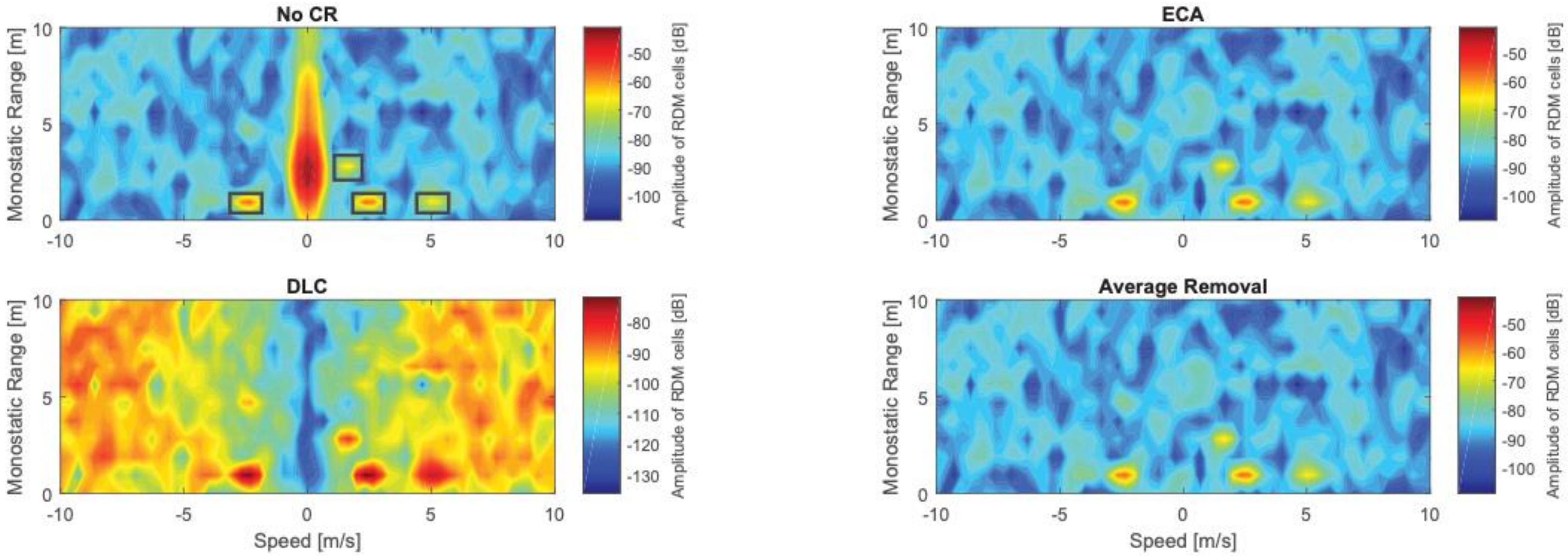
- Range
  - RSS
  - ToF
  - Phase difference
- Angle
  - Arrival/Departure
  - Azimuth/Elevation
- Location
- Speed / velocity
  - Doppler

- Users vs. Nonusers
- User density
- Orientation
- Pose
- Body blocking
- Context
- …

WiFi-based passive bistatic radars

Opportunistic use of known preambles

Need for clutter removal, extensice to 160MHz

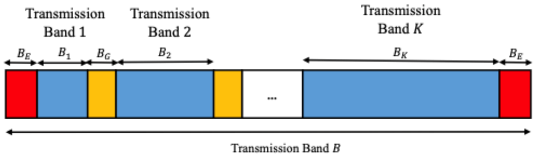


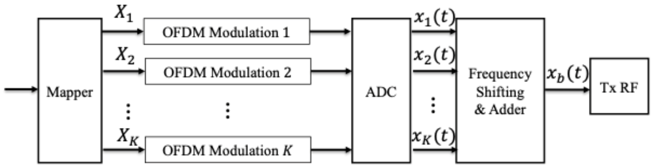
Yongzhi Wu, Filip Lemic, Chong Han, Zhi Chen, "A Non-Uniform Multi-Wideband OFDM System for Terahertz Joint Communication and Sensing", submitted for publication, 2020
Wu, Y., Lemic, F., Han, C., Chen, Z. "Sensing Integrated DFT-Spread OFDM Waveform and DNN-powered Detector Design for Terahertz Joint Communication and Sensing Systems", submitted for publication, 2021

6G PHY design

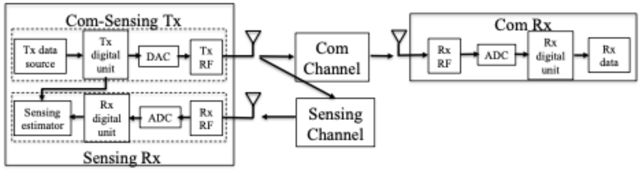
Taking into account sensing requirements from the start

- Non Uniform Multiband OFDM THz
  - Combine distance and sensing accuracy, using multiple OFDM waveforms
  - Non-uniform subcarrier spacing parameters
    - long detectable distance from the small subcarrier spacing
    - high sensing accuracy from the large subcarrier spacing.
  - 100 Gbps and sub-mm ranging





- SI-DFT-s-OFDM
  - Sensing integrated joint design allows for mm scale ranging and x10 better velocity accuracy.
  - Delay spread of sensing channel >> communication channel due to beamforming: different CPs are needed



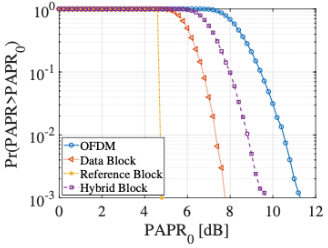


Fig. 4. Comparison of PAPR between OFDM and different blocks of SI-DFT-s-OFDM.

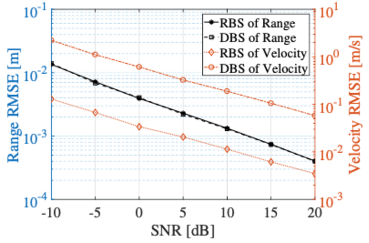
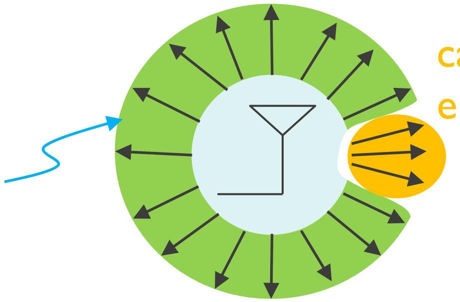


Fig. 5. RMSE of range and velocity estimation using RBS of SI-DFT-s-OFDM and DBS of OFDM.

Beamforming used to overcome large path loss

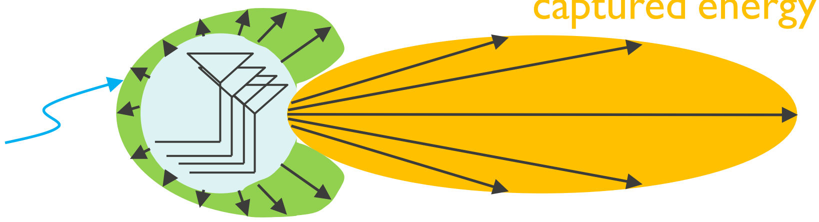
low-gain antenna

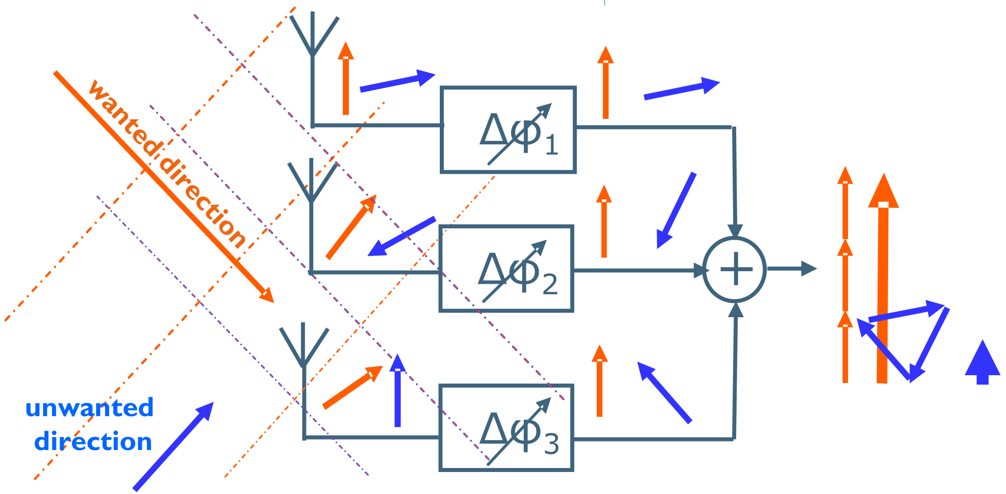
lots of
wasted energy



directional antenna array

much less
wasted
energy





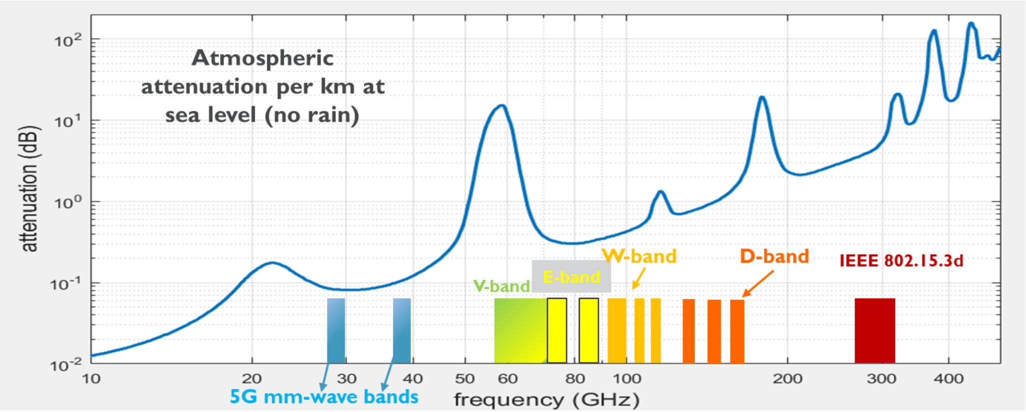
Beamforming circuitry:

- Phase shift $\Delta\varphi$
- Combiner ⊕
  splitter in transmit

Optimum antenna pitch:
half wavelength $\lambda/2$

Beamforming is here to stay

To overcome free space path loss and atmospheric attenuation



- TX side with N_{TX} antennas:

$$EIRP = P_{1TX} + \mathbf{20log_{10}N_{TX}} + G_{antenna}$$

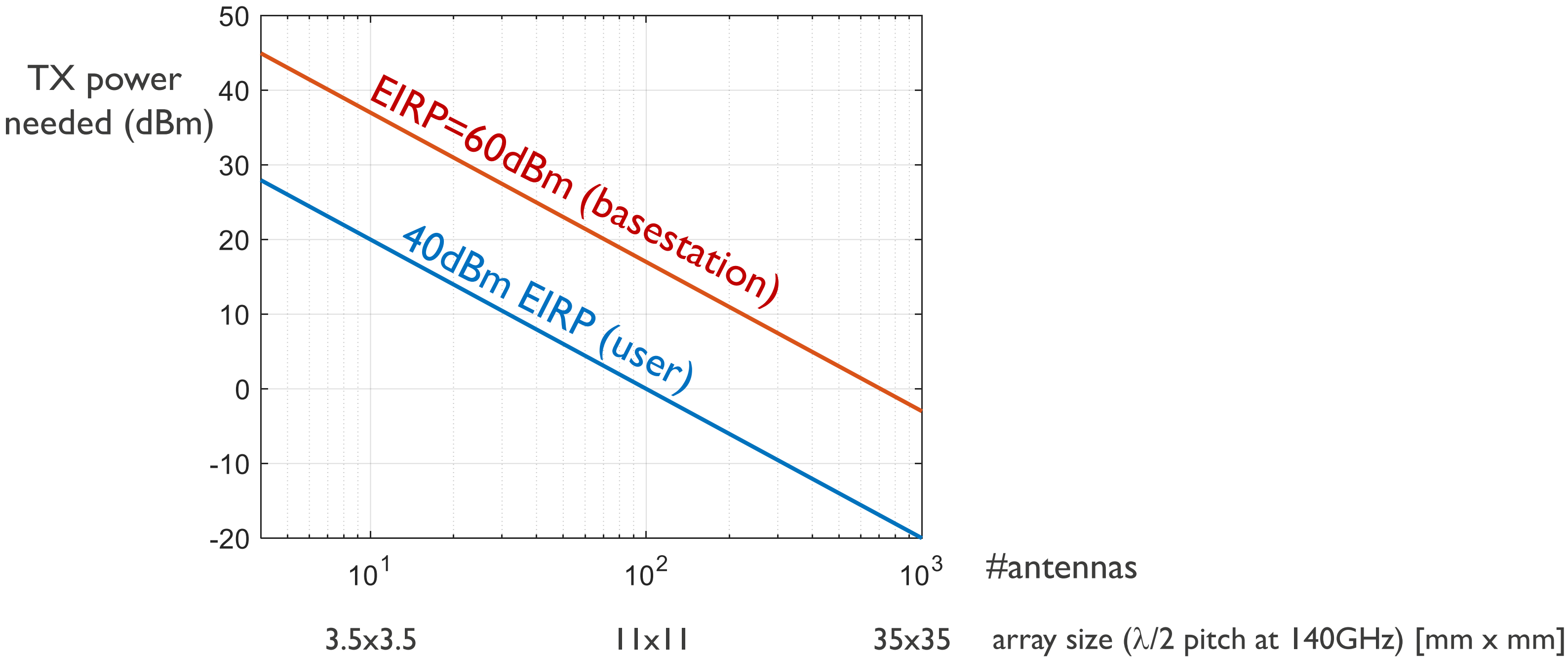
- RX side with N_{RX} antennas:

$$Sensitivity = -174dBm/Hz + NF + loss\ margin + 10log10BW + SNRmin \mathbf{- 10log_{10}N_{RX}}$$

- For $N_{TX} = N_{RX} = N$: link budget improves with $\mathbf{30log_{10}N}$

... and antenna area for a given gain ~ λ^2

Larger the antenna array → less power per power amplifier needed

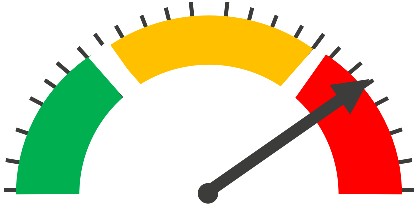


THz hardware: pressure on COST, power consumption and size

Base stations

User equipment

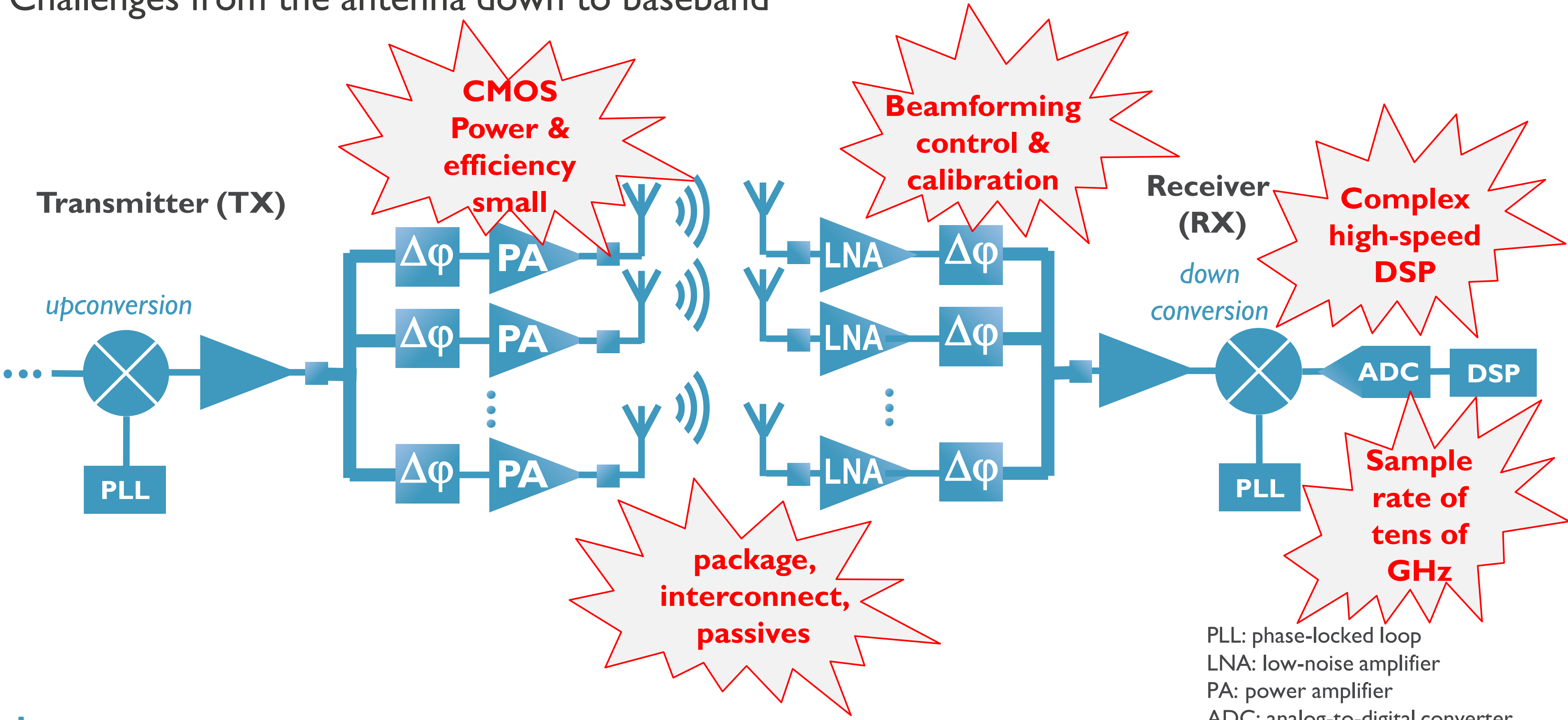
highest pressure



- Photonics ruled out (for the time being)
- High degree of integration needed
  → CMOS, as usual?
  “if it can be done in CMOS, it will be in CMOS”

Beamforming radio architecture for >100GHz connectivity

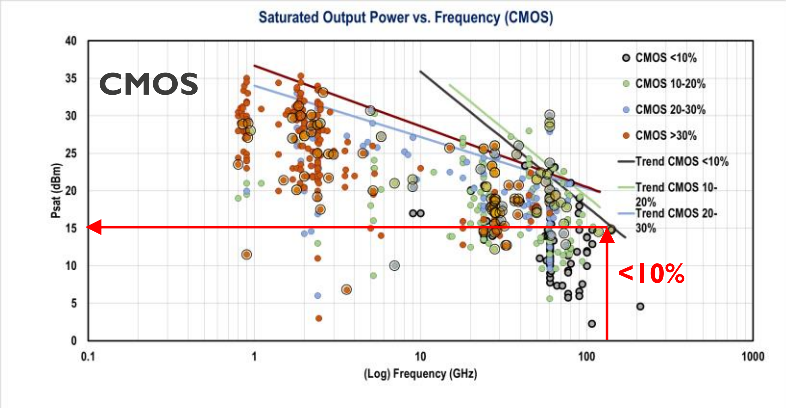
Challenges from the antenna down to baseband

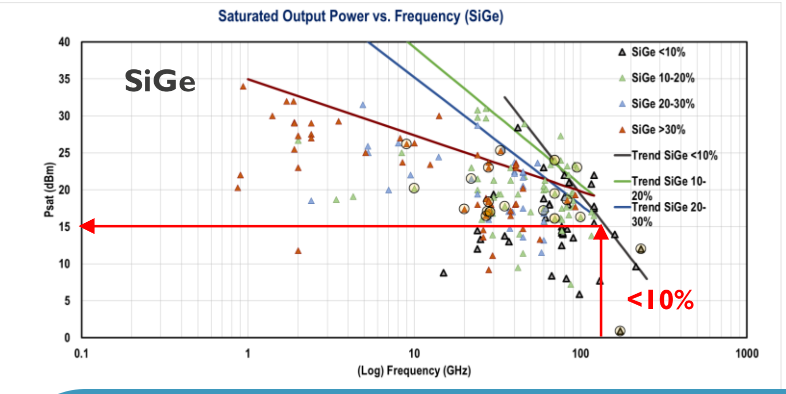


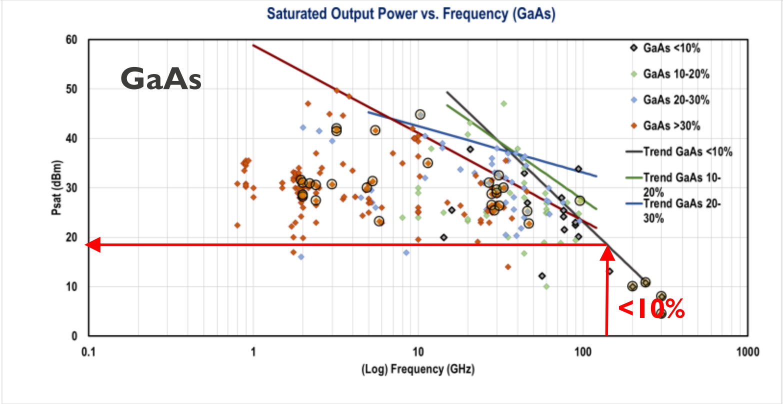
PLL: phase-locked loop
LNA: low-noise amplifier
PA: power amplifier
ADC: analog-to-digital converter
DSP: digital signal processing

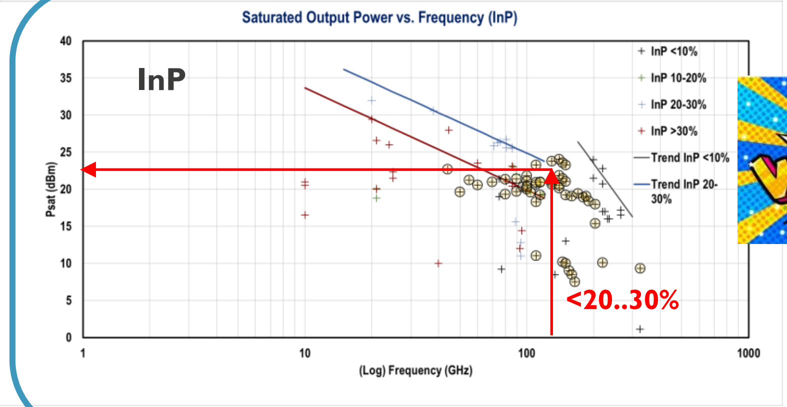
The BIG challenge: power generation above 100 GHz

InP PAs: higher power + higher efficiency







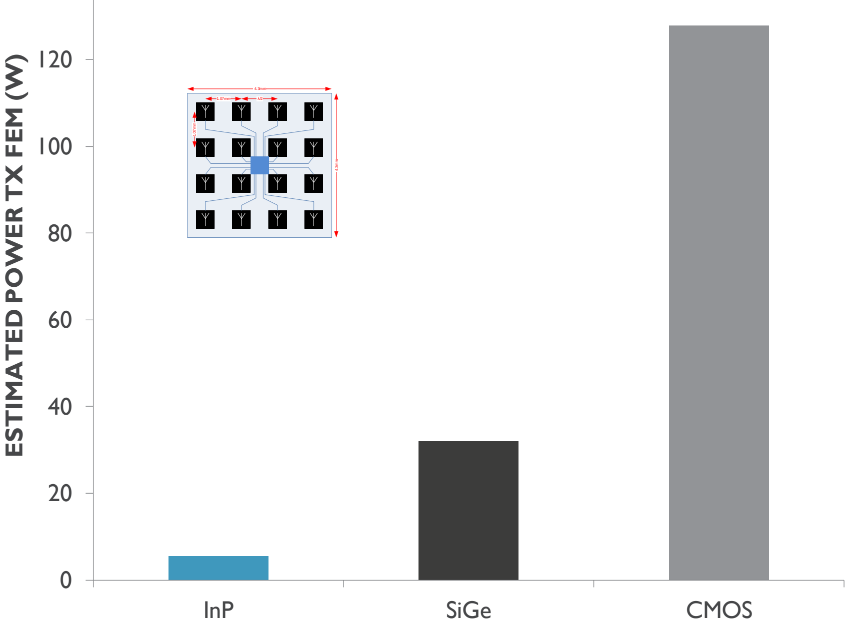


From H. Wang et al. , "Power Amplifiers Performance Survey 2000-Present," [Online]. Available: https://gems.ece.gatech.edu/PA_survey.html

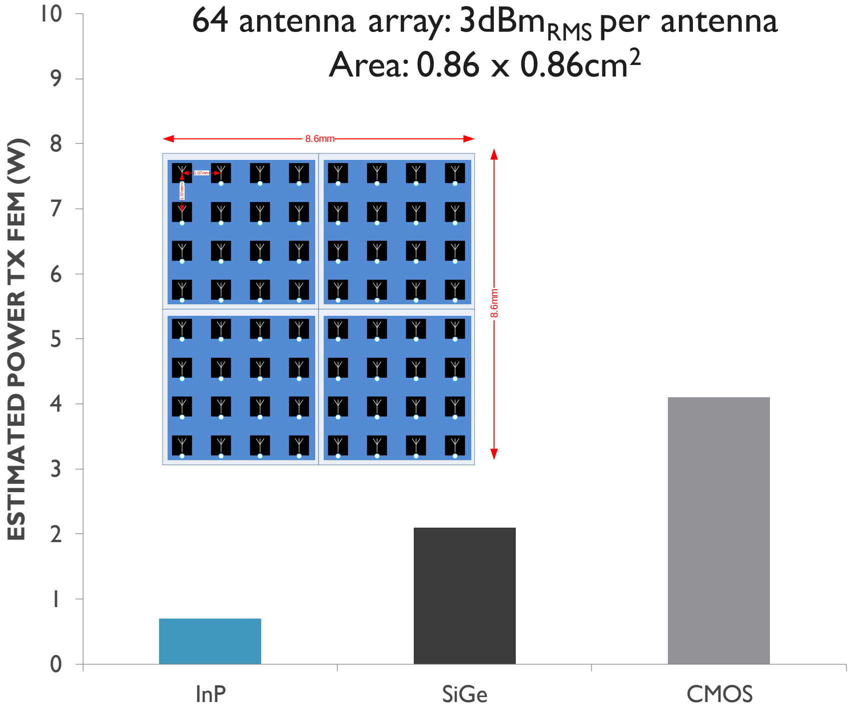
InP offers power advantages for medium to long ranges

Example: 140 GHz transmission of user equipment (UE) to hotspot

16 antenna array: 15dBm$_{RMS}$ per antenna
Area: 0.43 x 0.43cm^2

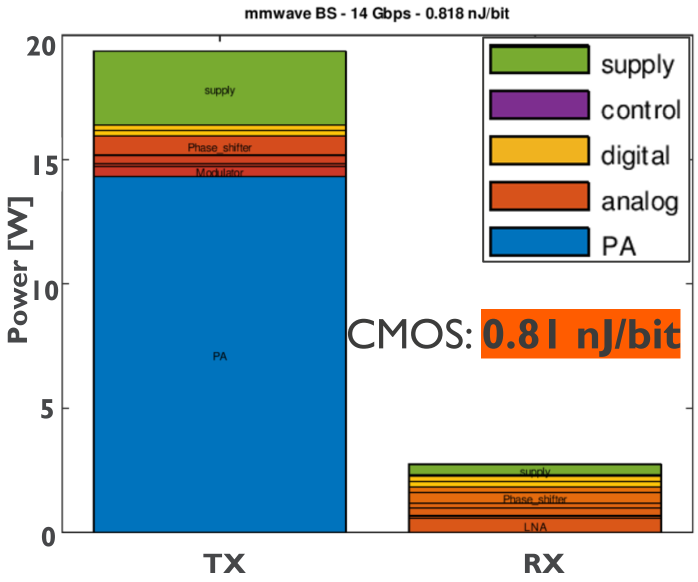


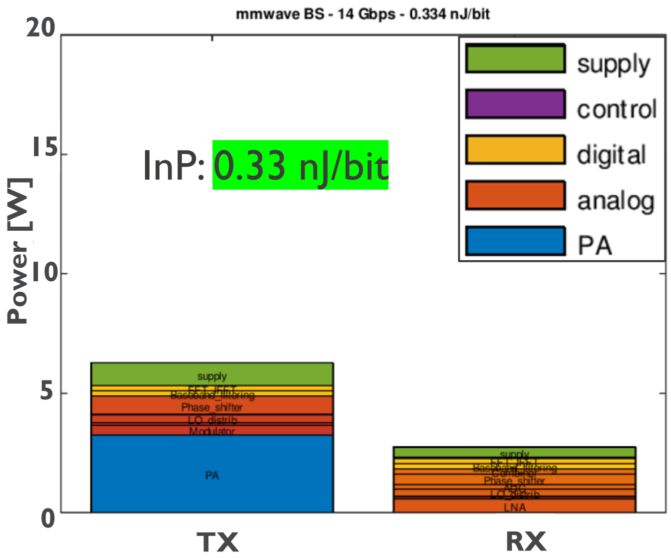
64 antenna array: 3dBm$_{RMS}$ per antenna
Area: 0.86 x 0.86cm^2



INP ADVANTAGE REMAINS WHEN BASEBAND IS INCLUDED

- Scenario of transmission from **UE to hotspot, 32 antennas** in UE (9dB$_{rms}$)
- Power estimates with digital downscaled to 2nm
  - assuming power reduction of 35% per new logic generation
- Total power consumption heavily PA-dominated





Link (Tx+Rx) efficiency: factor 2.5 difference between full CMOS and CMOS + InP

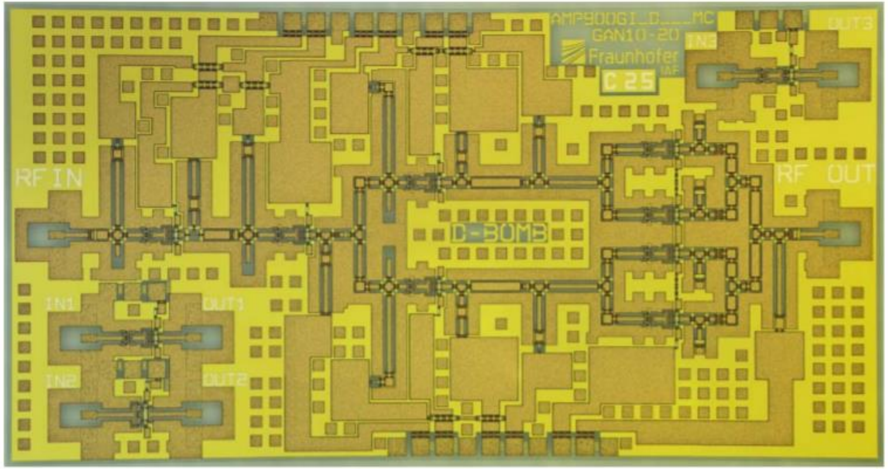
Grows with frequency, distance and smaller form factor.

umec

public

GaN: a game changer above 100 GHz?

Mobility similar to Si but much wider bandgap…

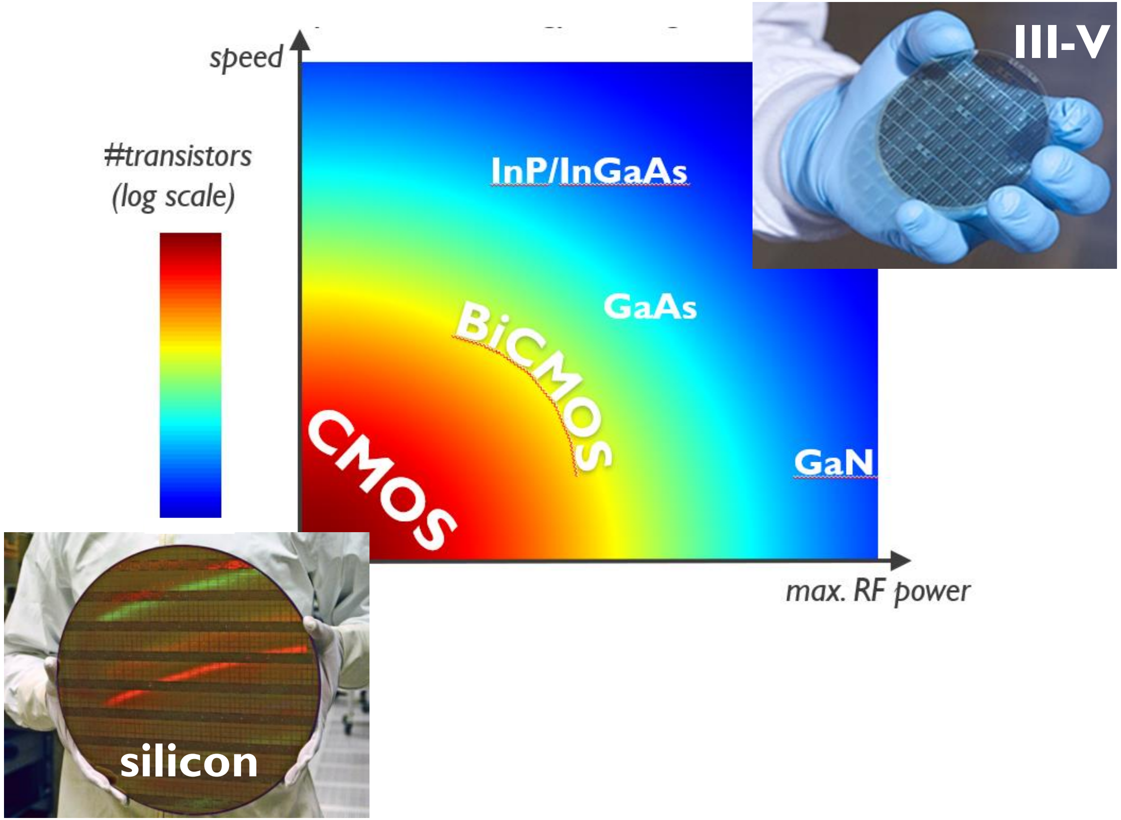


Cwiklinski et al., T-MTT 2019

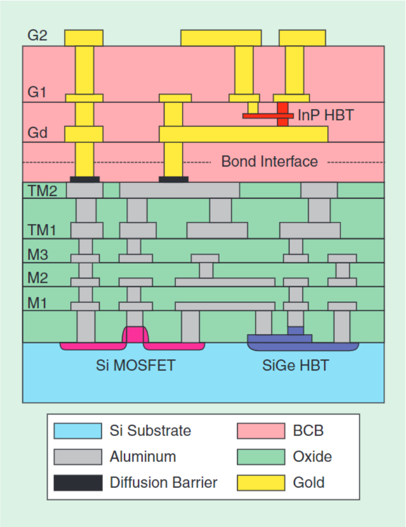
4-stage PA, 107-148 GHz
100nm GaN on SiC,
f_T/f_{MAX} = 100/300 GHz
VDD = 15V, Gain > 25 dB
Pout = 26.4 dBm, PAEmax = 16.5%

Is InP ready for the mass market?

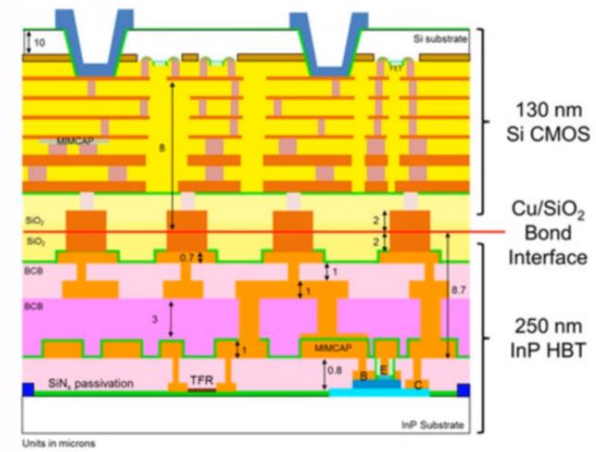
Today it is a niche process...



Can we combine CMOS high integration degree with III-V assets?



W. Heinrich et. al., *Connecting Chips With More Than 100 GHz Bandwidth*, IEEE Journal of Microwaves 2021



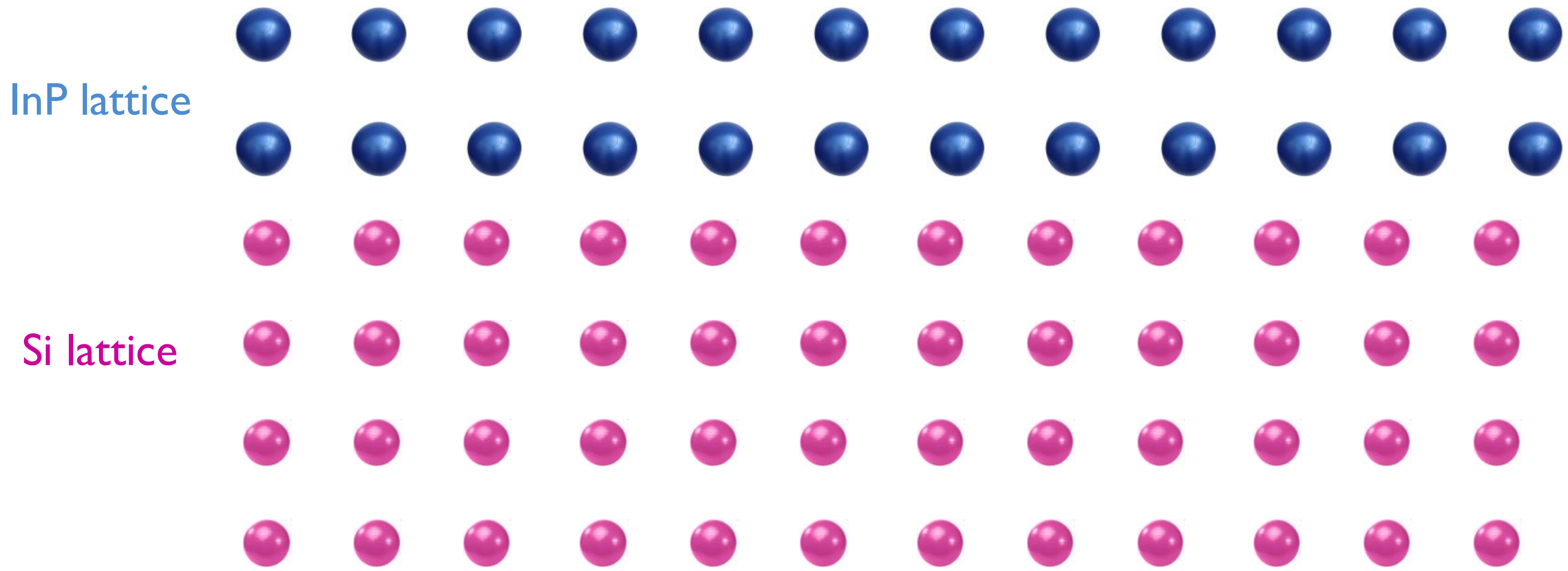
M. Urteaga et. al., *THz Bandwidth InP HBT Technologies and Heterogeneous Integration with Si CMOS*, IEEE BCTM 2016

Bonding III-V wafer on Si wafer

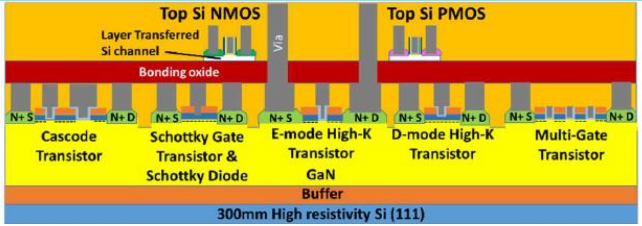
different wafer sizes!

Can we grow III-V on a 300 mm Si wafer?

Lattice mismatch → dislocations → disfunctional devices



GaN and InP on 300 mm Si wafer



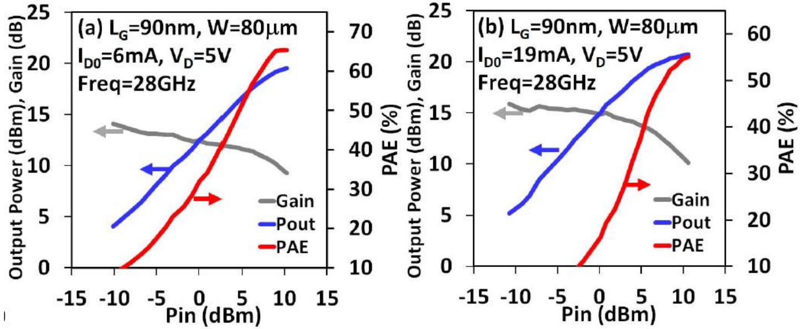
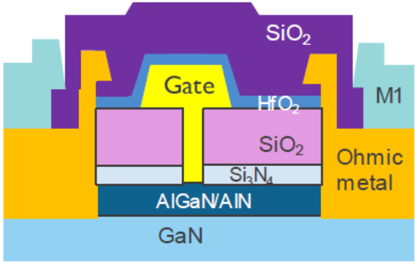


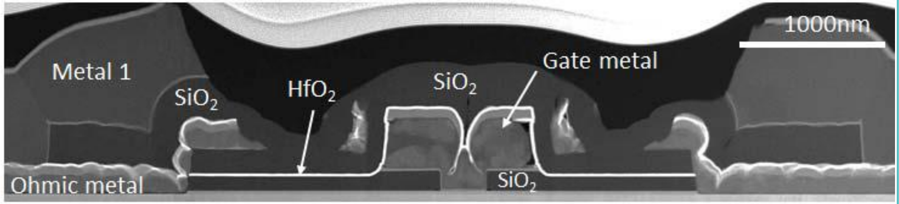
Fig. 8: Loadpull results show industry's best (a) peak PAE=65% with saturated power of 19.5dBm at 28GHz, (b) 20.7dBm of saturated power with peak PAE=55%.

Then et al., IEDM 2020

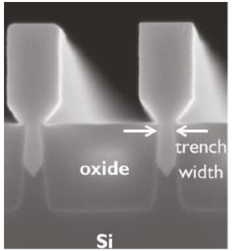
RF GaN on 200/300 mm wafers, processed with Si tools, Au free

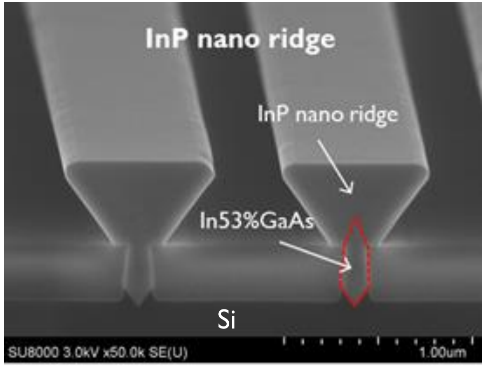


U. Peralagu et al., IEDM 2019



InP on 300mm Si wafers

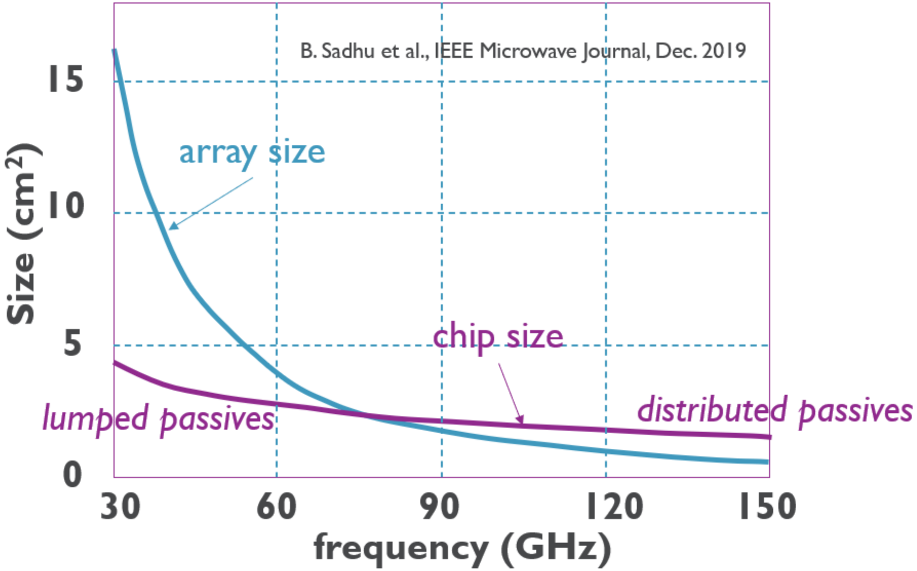




imec, 2018

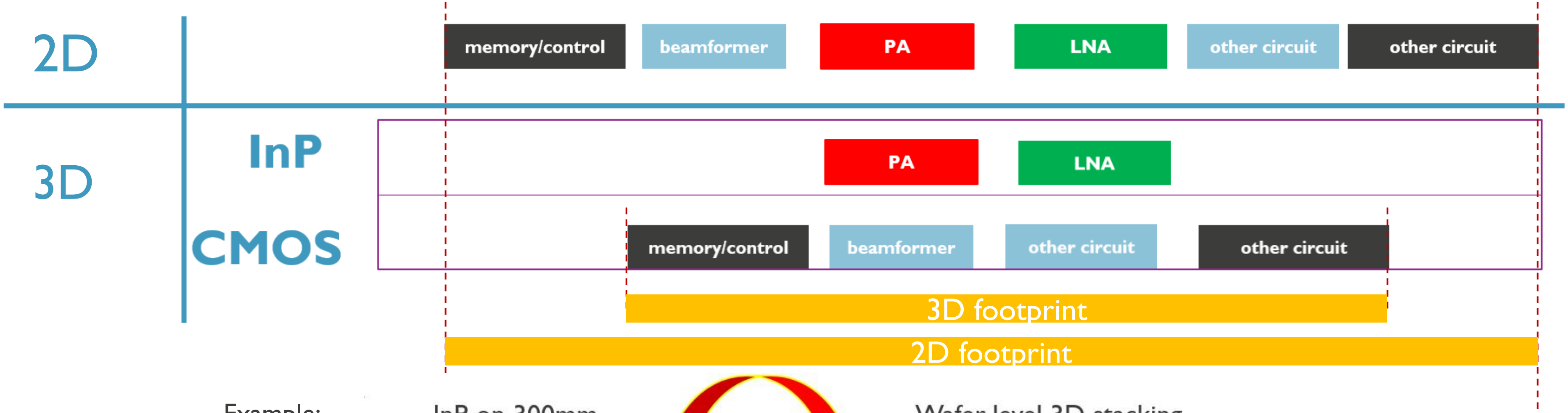
Above 100 GHz: antenna pitch < front-end circuit pitch

- Area of antenna array scales with λ^2
- Area of mm-wave chip hardly scales



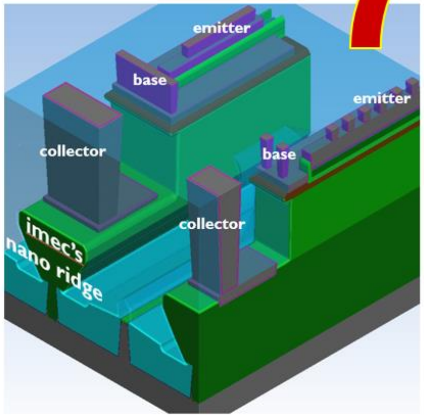
- Solution: exploit the third dimension

2D IC TECHNOLOGY VERSUS 3D: DIFFERENCE IN FOOTPRINT

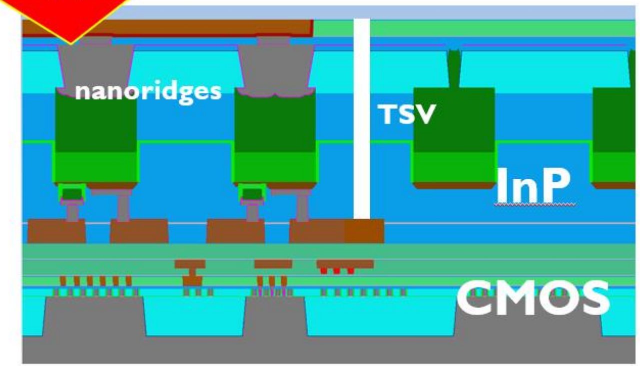


Example:

InP on 300mm



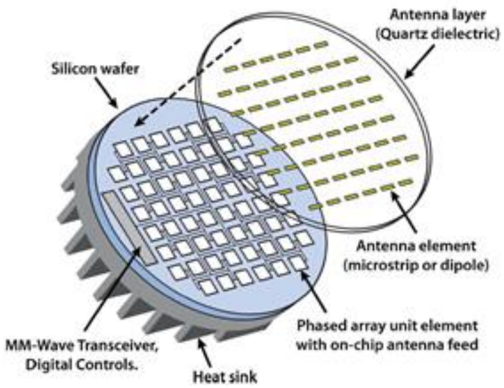
Wafer-level 3D stacking



Connection to the antennas

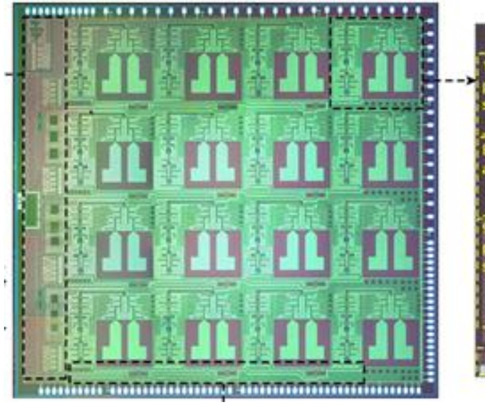
Example: CMOS + Antenna array

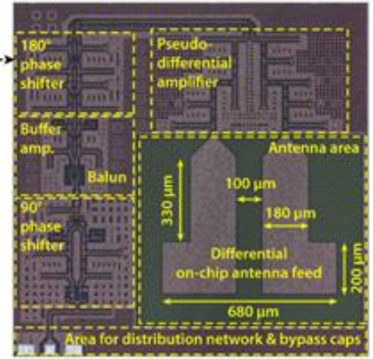
- Wafer to Wafer bonding
  - CMOS: Circuits + Antenna feed
  - Quartz superstrate antenna substrate
- Active circuits highly constrained by antenna feed
  - Reduced amplifier stages



W. Shin et. al., *A 108–114 GHz 4x4 Wafer-Scale Phased Array Transmitter With High-Efficiency On-Chip Antennas*, IEEE JSSC 2013

UC San Diego

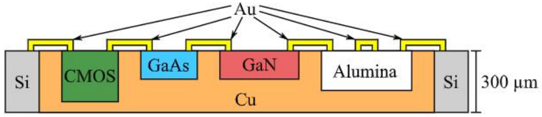




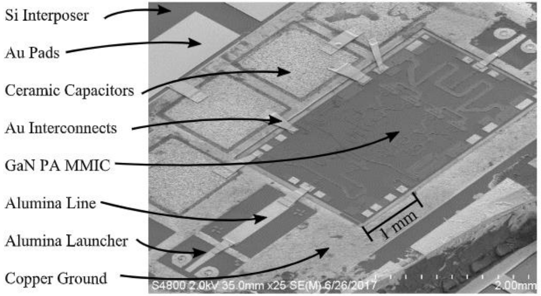
Packaging design with heat sinks

HRL LABORATORIES, USA

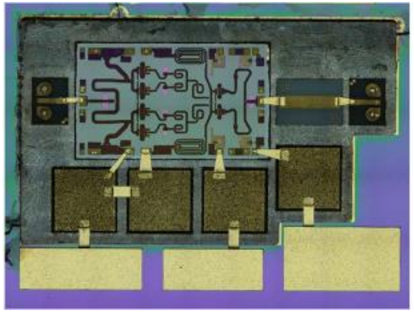
- Metal Embedded Chip Assembly (MECA)
- Embedding different chips in a copper carrier
  - Wirebond interconnects between different chips
  - Bandwidth issues: wirebonds



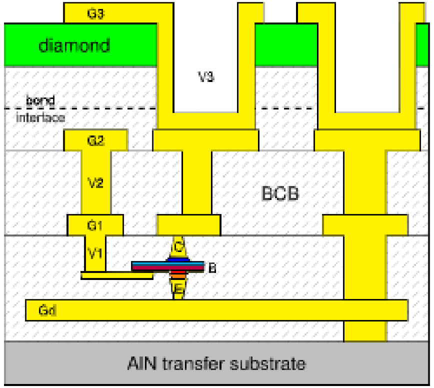
(a)



J. A. Estrada et. al., *Metal-Embedded Chip Assembly Processing for Enhanced RF Circuit Performance*, IEEE TMTT 2019

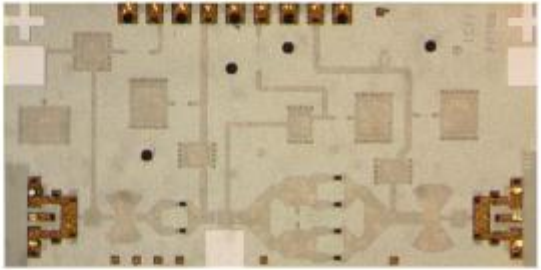


Ferdinand Braun Institute, Berlin



- Thin-film Amorphous diamond heat sink layer connected to HBT device using vias
  - Best thermal material
  - Cost may be high
- Power amplifier at 90 GHz
  - Pout: 20 dBm, PAE: 22 %

K. Nosaeva et. al., *Multifinger Indium Phosphide Double-Heterostructure Transistor Circuit Technology With Integrated Diamond Heat Sink Layer*, IEEE Trans. El. Devices 2016



Conclusions

- The lower part of the THz gap can be filled with a full electronic approach
  - IC technologies provide a cheaper path to products than optical approaches
- 6G convergence of communication and sensing
  - sensing with communication hardware is feasible
- Low-cost D-band transceivers for user equipment: CMOS + III-V most energy efficient
  - Cost effective processing technologies being explored
- Packaging strategy challenged by half-wavelength antenna pitch and by heat removal strategy
- Non-addressed challenges: testability, EDA tools for co-design of electrical, thermal, package, IC, antenna