100-340GHz Systems: Transistors and Applications

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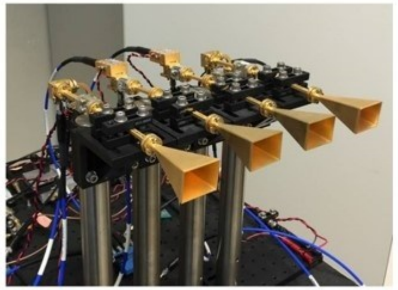
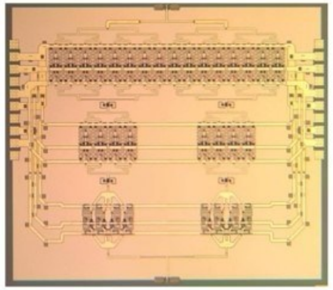
Why 100-340GHz Wireless ?

Services



Systems



ICs

Devices

Wireless networks: exploding demand.

Immediate industry response: 5G.

28, 38, 57-71(WiGig), 71-86GHz
increased spectrum, extensive beamforming

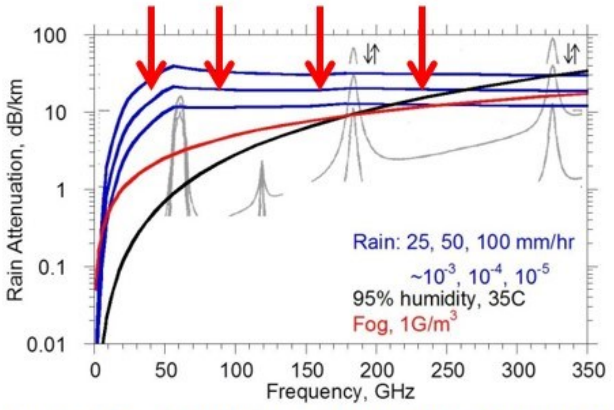
Next generation (6G ??): above 100GHz.

greatly increased spectrum, massive spectral multiplexing

Plus, TV-like imaging/sensing/radar: cars, airplanes, drones

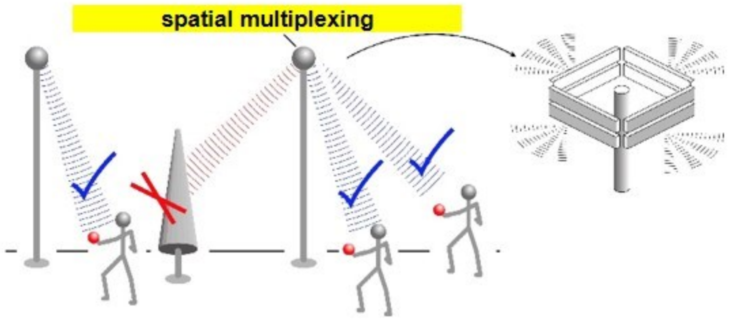
100-340GHz: Benefits & Challenges

Large available spectrum

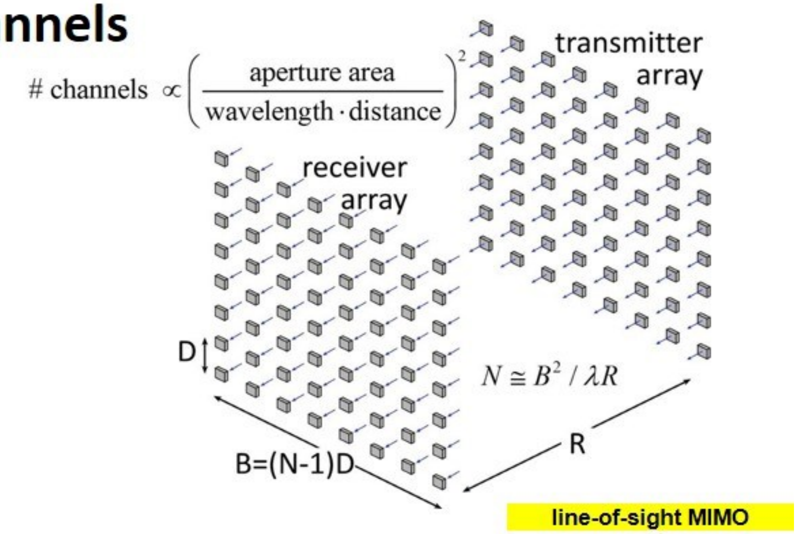


(note high attenuation in foul or humid weather)

Massive # parallel channels

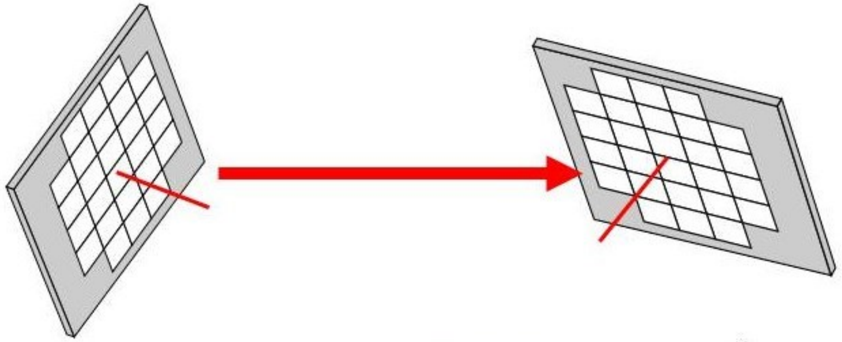


$$\text{angular resolution} = \frac{\text{wavelength}}{\text{array width}}$$



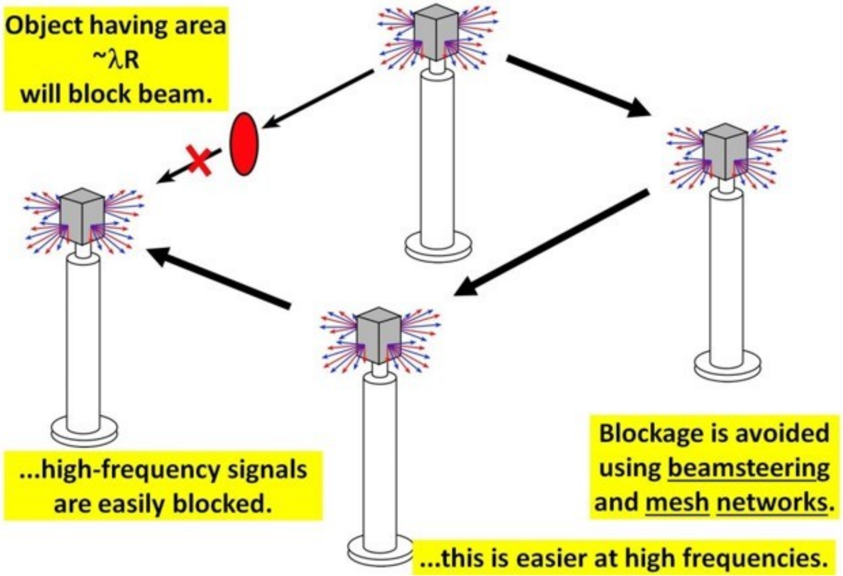
$$\#\ \text{channels} \propto \left(\frac{\text{aperture area}}{\text{wavelength} \cdot \text{distance}}\right)^2$$

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



Object having area ~λR will block beam.

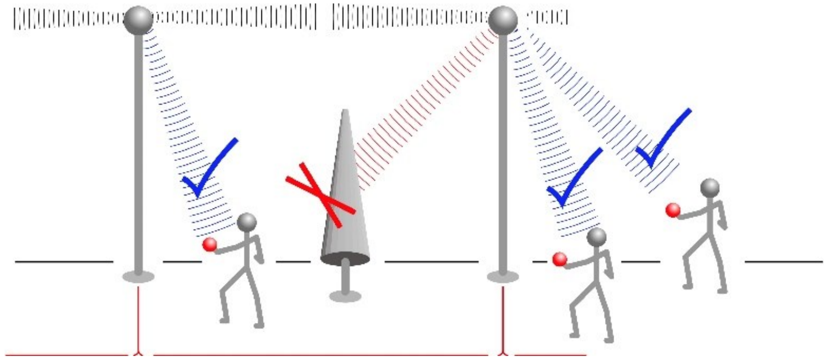
...high-frequency signals are easily blocked.

Blockage is avoided using beamsteering and mesh networks.

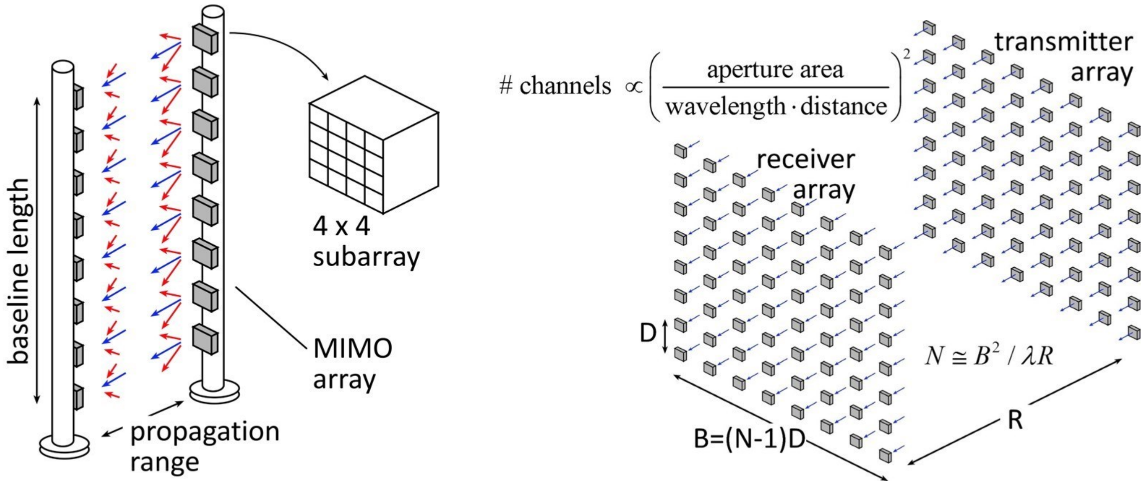
...this is easier at high frequencies.

100-340GHz: Potential Applications

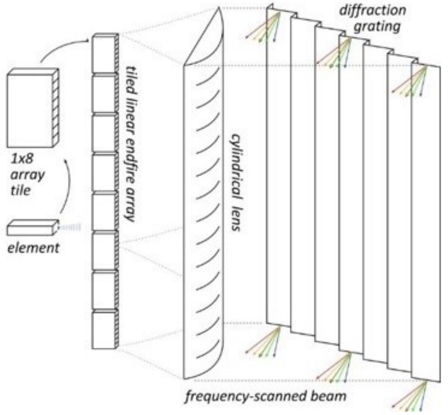
MIMO hub: 128 beams/face, 1Gb/s/user
140 GHz



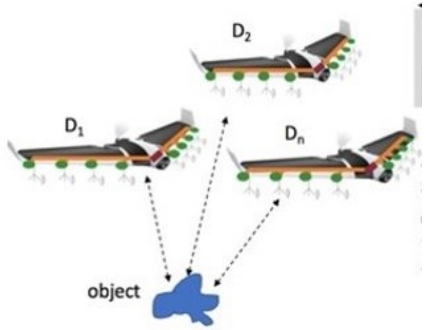
Point-point MIMO: 340GHz: Tb/s links
massive spatial multiplexing



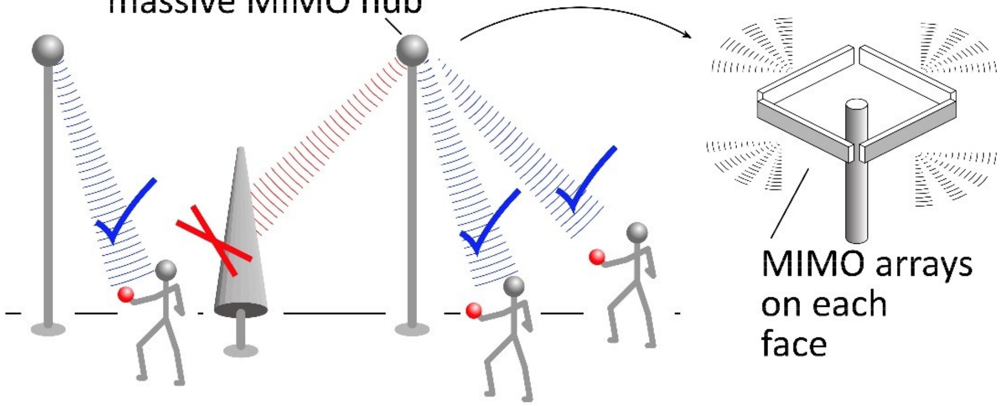
220, 340GHz imaging: drive/fly in fog/rain/snow
300m, 512×64 image, 60Hz, 15dB SNR

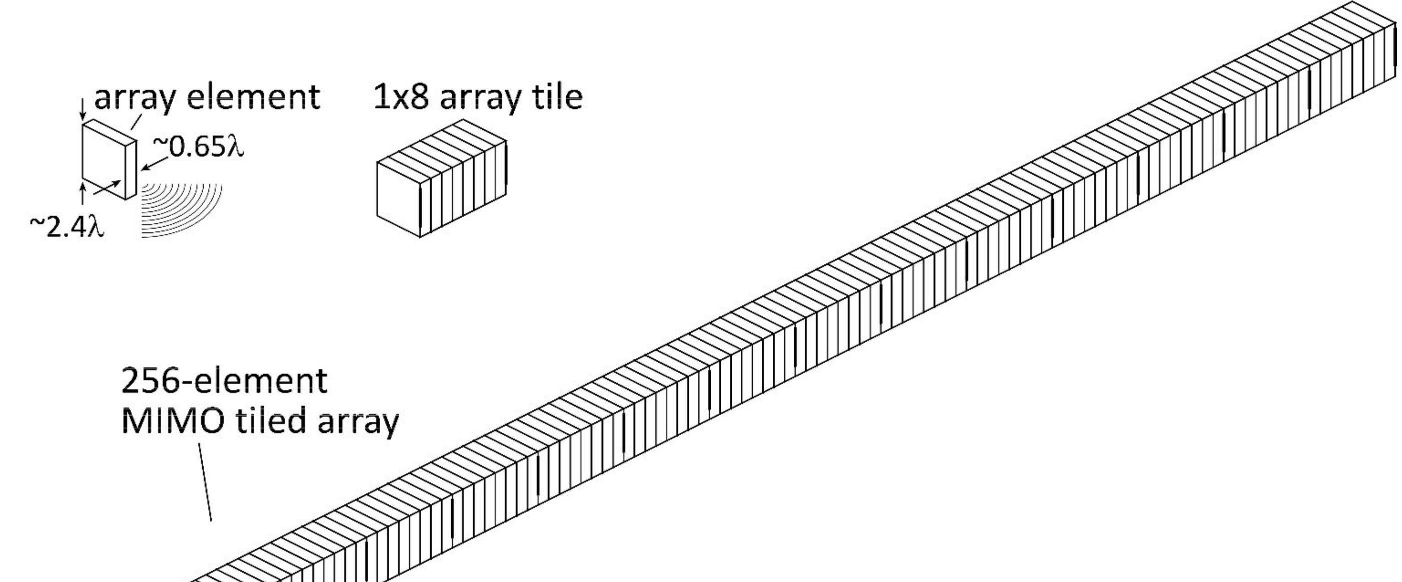


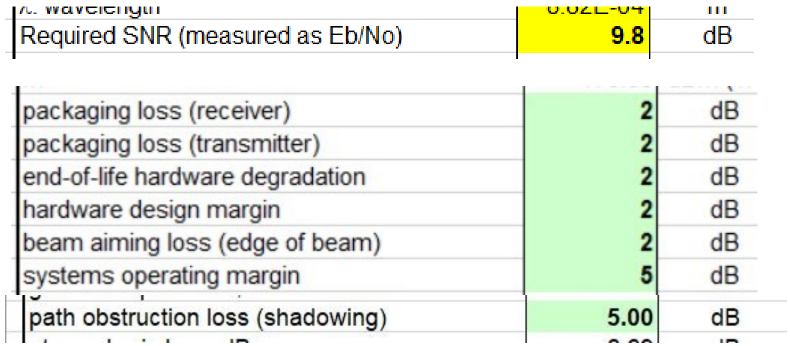
Ultra-compact imaging: drones
unlike visible: image through fog/smoke/rain



140 GHz Spatially Multiplexed Base Station







Required SNR (measured as Eb/No)	9.8	dB
packaging loss (receiver)	2	dB
packaging loss (transmitter)	2	dB
end-of-life hardware degradation	2	dB
hardware design margin	2	dB
beam aiming loss (edge of beam)	2	dB
systems operating margin	5	dB
path obstruction loss (shadowing)	5.00	dB

Each face supports 128 beams @ 1Gb/s/beam.

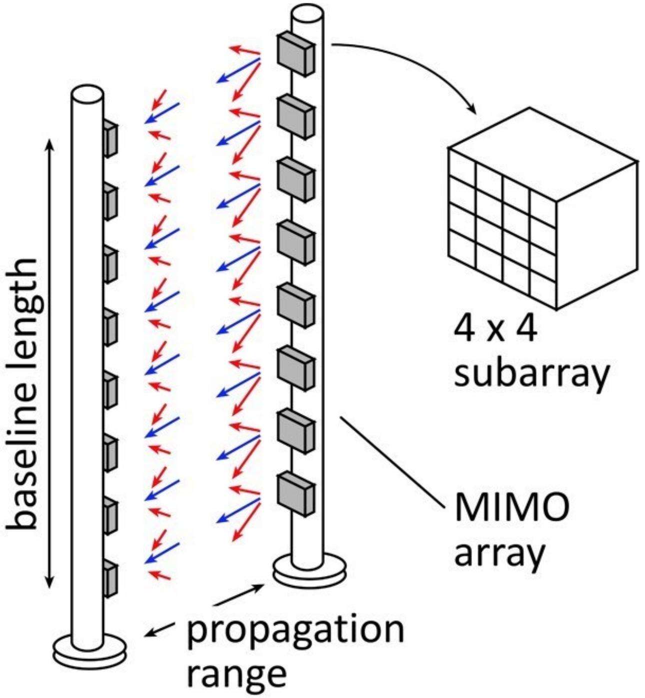
225 meters range in 50 mm/hr rain

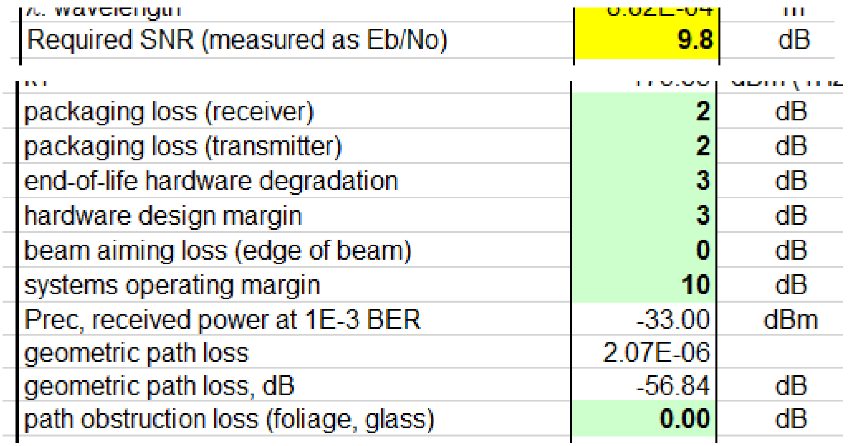
Realistic packaging loss, operating & design margins (20dB total)

PAs: 16 dBm P_{out} (per element)

LNAs: 3 dB noise figure

340 GHz 640 Gb/s MIMO Backhaul





Required SNR (measured as Eb/No)	**9.8**	dB
packaging loss (receiver)	**2**	dB
packaging loss (transmitter)	**2**	dB
end-of-life hardware degradation	**3**	dB
hardware design margin	**3**	dB
beam aiming loss (edge of beam)	**0**	dB
systems operating margin	**10**	dB
Prec, received power at 1E-3 BER	-33.00	dBm
geometric path loss	2.07E-06	
geometric path loss, dB	-56.84	dB
path obstruction loss (foliage, glass)	**0.00**	dB

1.6m MIMO array: 8-elements, each 80 Gb/s QPSK; 640Gb/s total

4 × 4 sub-arrays → 8 degree beamsteering

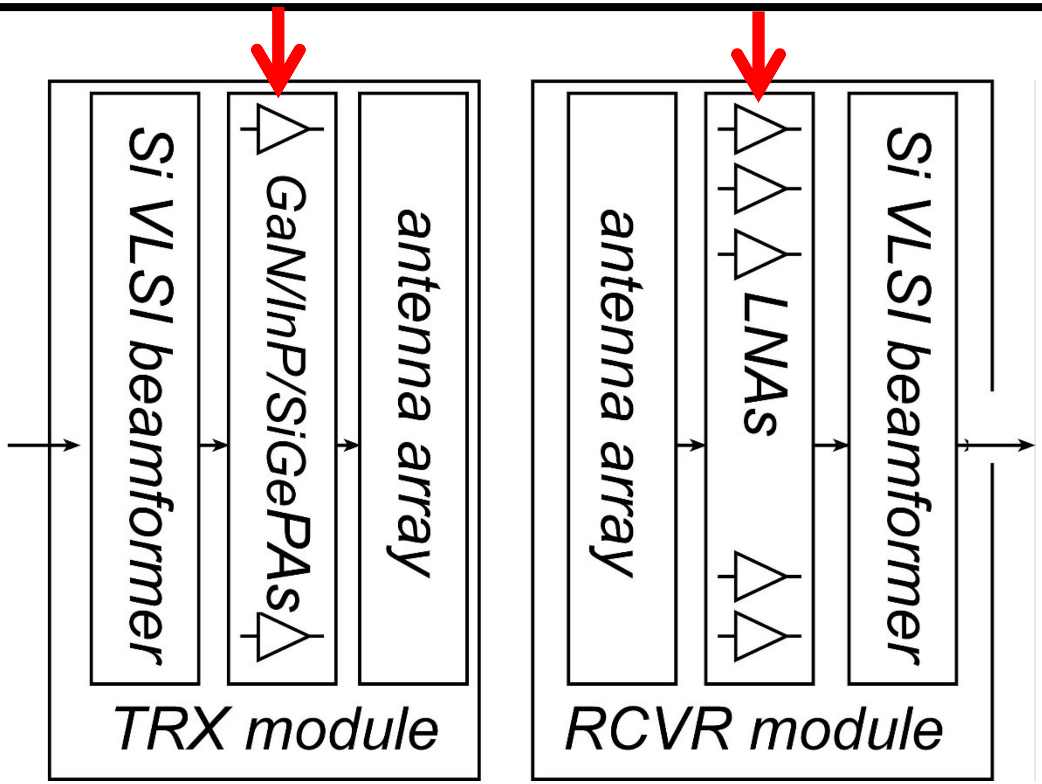
500 meters range in 50 mm/hr rain; 29 dB/km

Realistic packaging loss, operating & design margins

PAs: 82mW P_{out} (per element)

LNAs: 4 dB noise figure

Millimeter-Wave Wireless Transceiver Architecture



custom PAs, LNAs → power, efficiency, noise
Si CMOS beamformer→ integration scale

...similar to today's cell phones.

100-1000 GHz Transistors and ICs

	f_{max} GHz	Good ICs to (GHz)	complexity	LNAs	PAS	increased bandwidth ?
CMOS	350	150/200	transceivers	ok	poor: 1-5 mW	not easy
Production SiGe	300	200/250	transceivers	good	OK: 20-100 mW	depends on $$
R&D SiGe	700	300/500	transceivers	good	OK: 20-100 mW	2-3THz
R&D InP HBT	1150	400/650	PA, converters	poor	good: 100-200 mW	2-3THz
R&D InP HEMT	1500	500/1000	LNA	great	weak: 20-50 mW	2-3THz
R&D GaN	400	120/140	PAs	good	excellent: 0.1-1W	600GHz

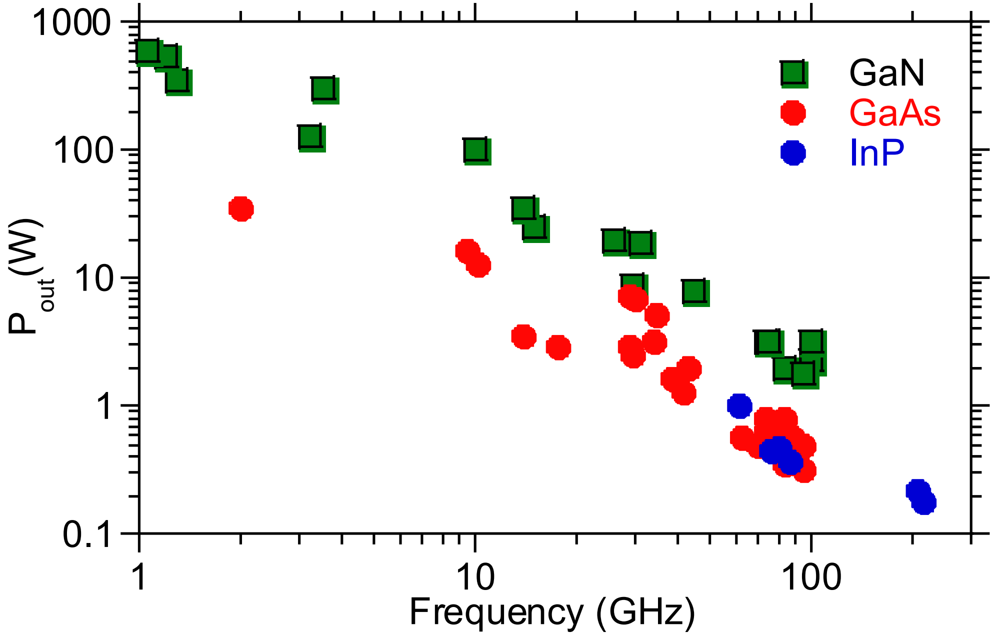
ICs with useful performance, hero experiments

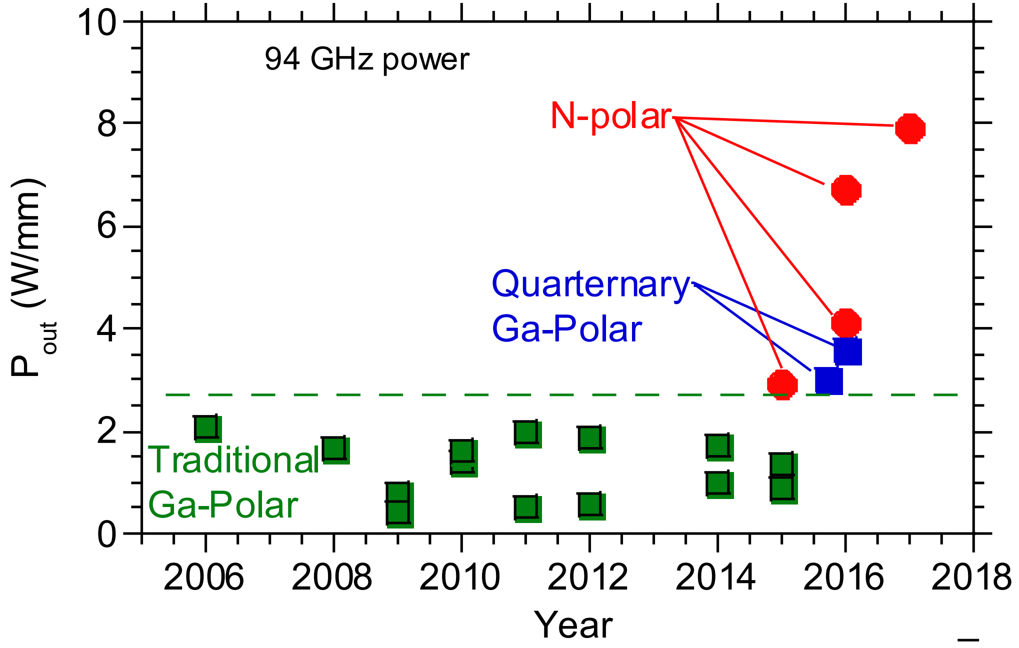
There are THz transistors today; their bandwidth will increase

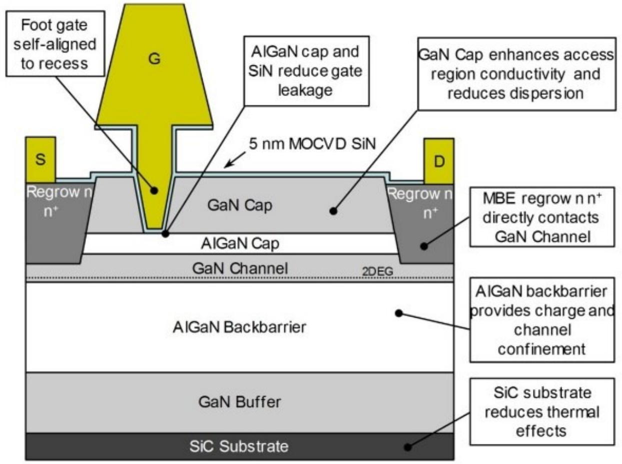
Challenge: reducing costs, increasing market size

Gallium Nitride Power Technologies

GaN is the leading high-frequency power technology







Foot gate self-aligned to recess

AlGaN cap and SiN reduce gate leakage

GaN Cap enhances access region conductivity and reduces dispersion

MBE regrow n n⁺ directly contacts GaN Channel

AlGaN backbarrier provides charge and channel confinement

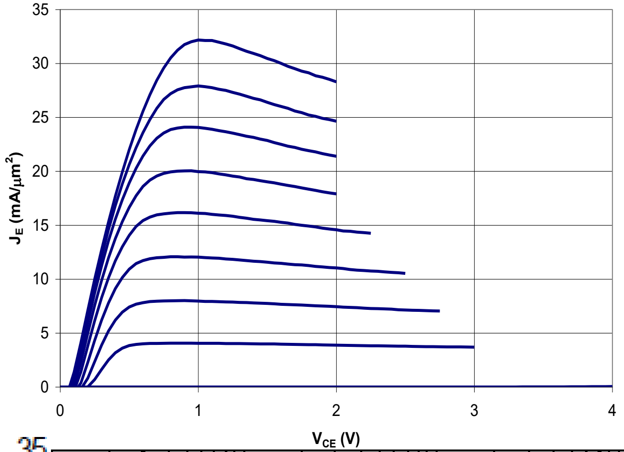
SiC substrate reduces thermal effects

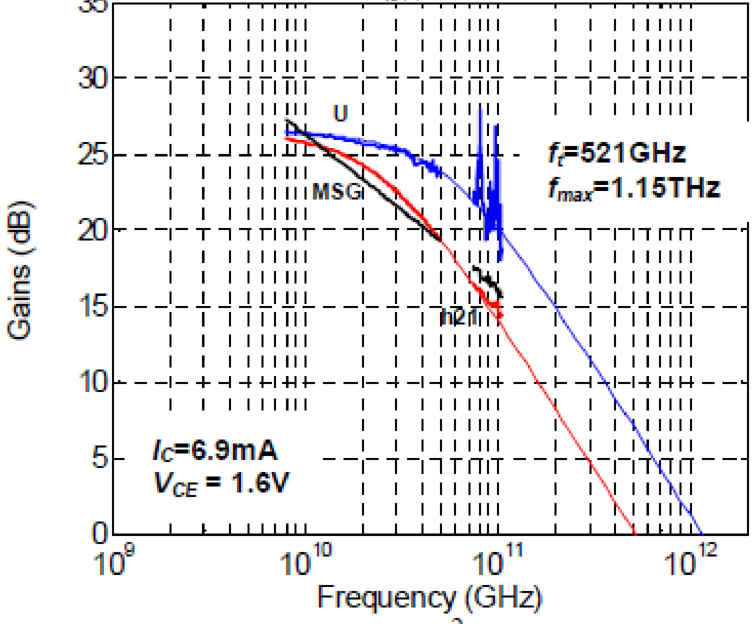
N-polar GaN: Mishra, UCSB

130nm / 1.1THz InP HBT Technology

1.1THz f_{max} HBT, 3.5 V breakdown

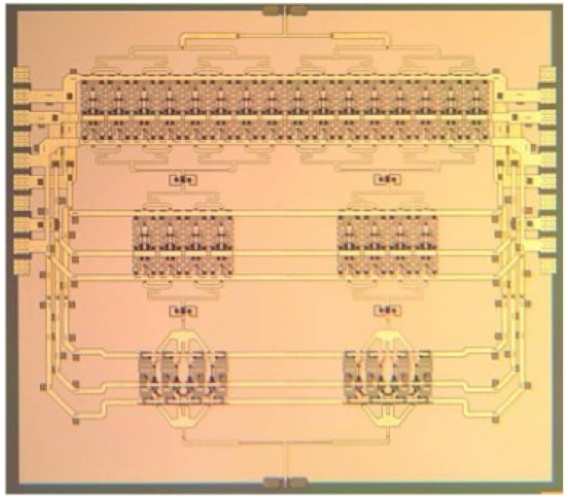
Teledyne/UCSB: M. Urteaga et al: 2011 DRC





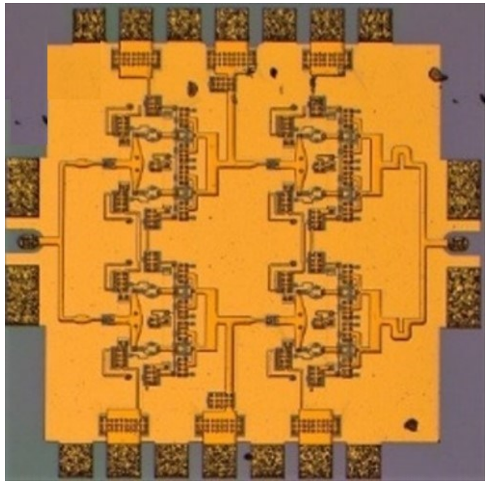
220 GHz, 0.18W power amplifier

UCSB/Teledyne: T. Reed *et al*: 2013 CSICS



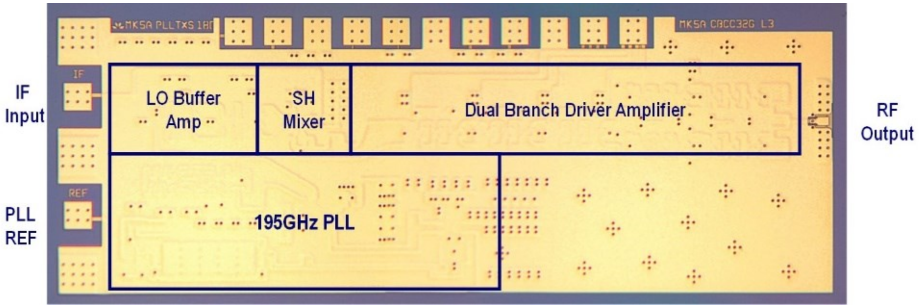
325 GHz, 16mW power amplifier

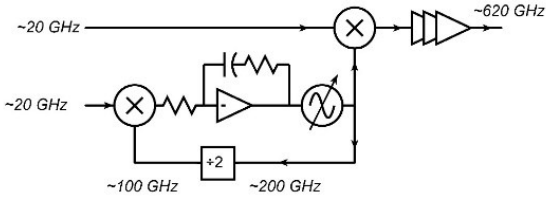
UCSB/Teledyne:
A. Ahmed, 2018 EuMIC Symp.



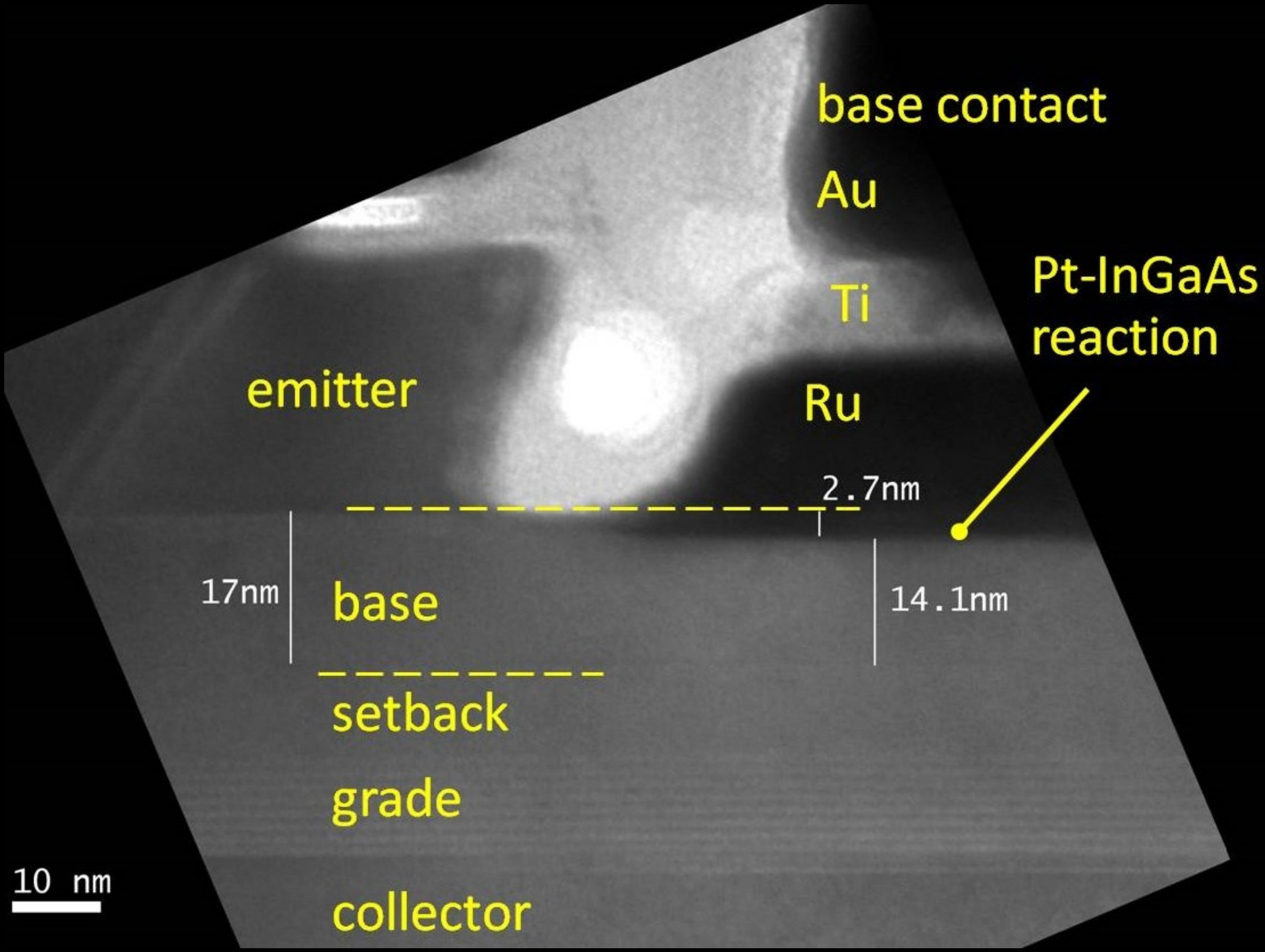
Integrated ~600GHz transmitter

Teledyne: M. Urteaga *et al*: 2017 IEEE Proceedings

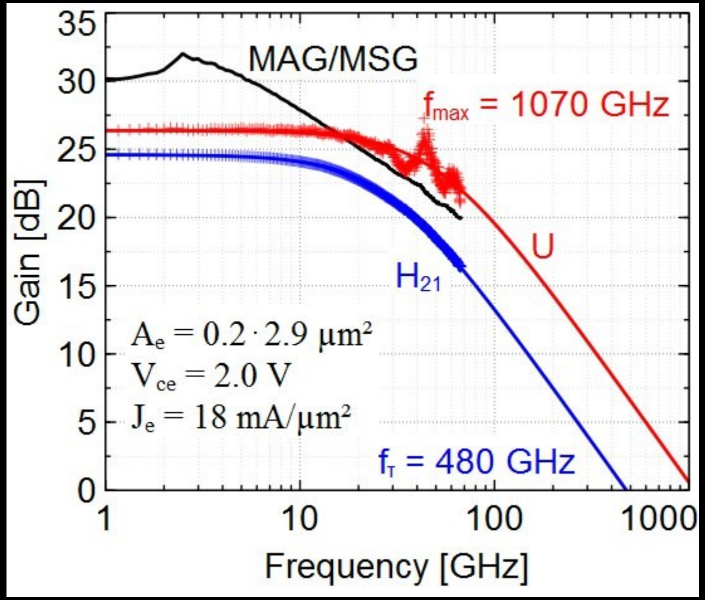


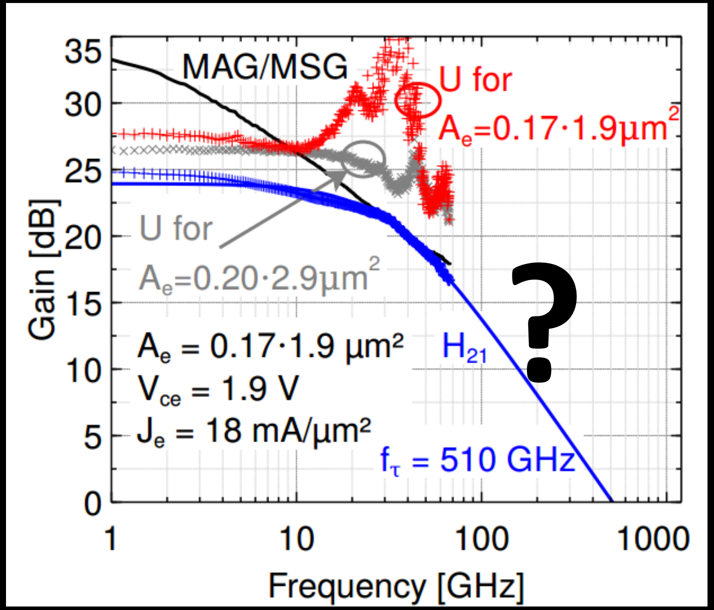


InP HBTs: 1.07 THz @200nm, ?? @ 130nm



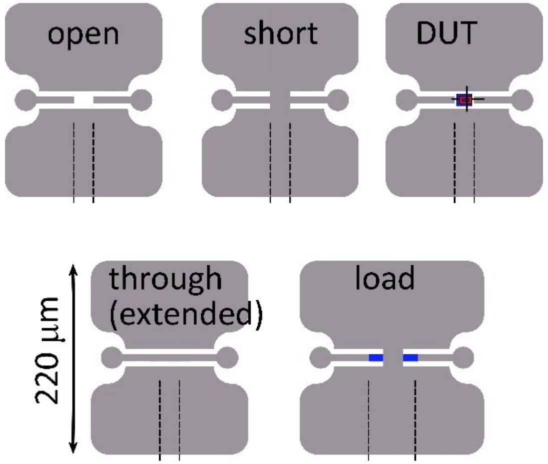
Rode et al., IEEE TED, Aug. 2015

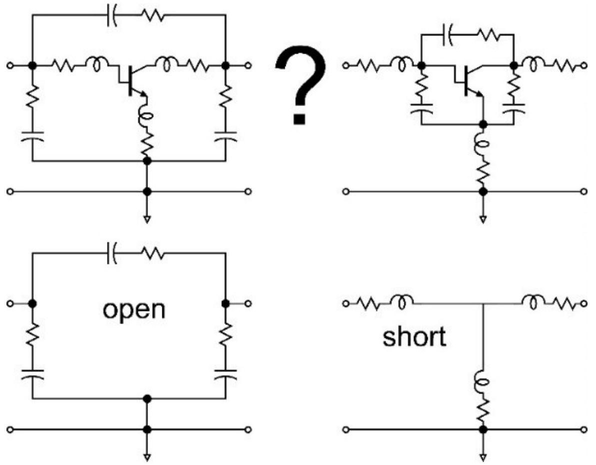




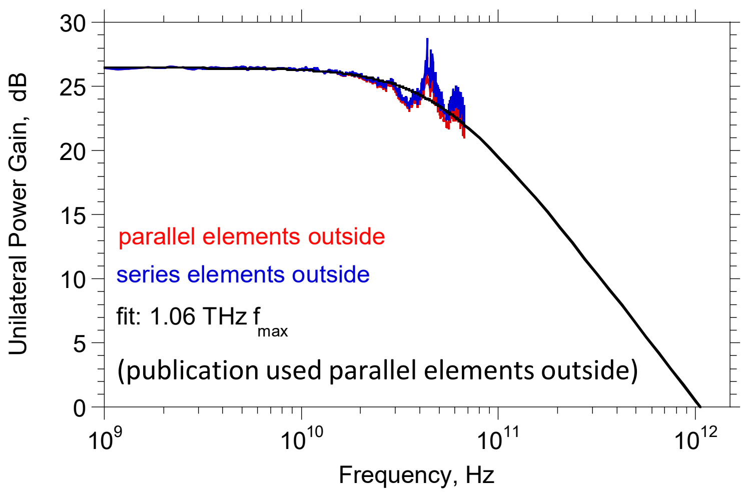
THz Transistor Measurements

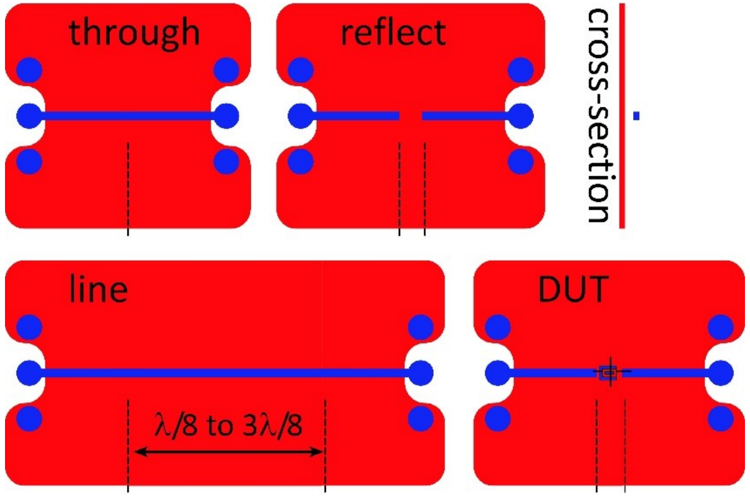
Simple pads:
Substrate coupling: need small pads, narrow CPW
Ambiguity in pad stripping order.
UCSB 130nm HBTs: order not important.
Add through & load to remove ambiguity



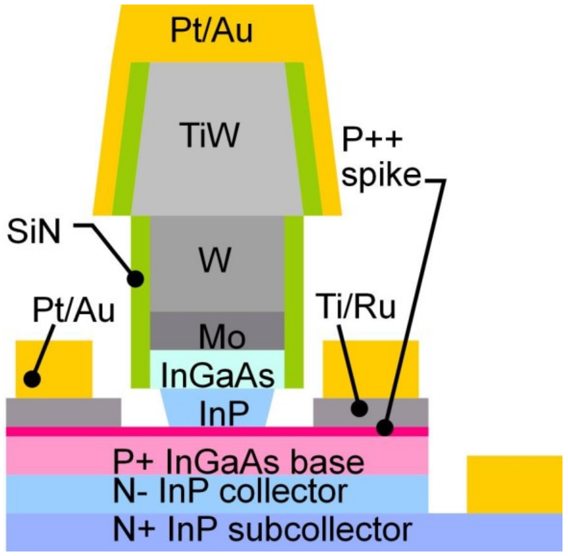


On-wafer through-reflect-line:
No ambiguity from pad stripping.
Calibration to line Zo
Still must avoid substrate resonances
  CPW does not work.
  needs thin-film microstrip
  or ~25 μm substrate with TSV's





Bipolar Transistor Scaling Laws



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

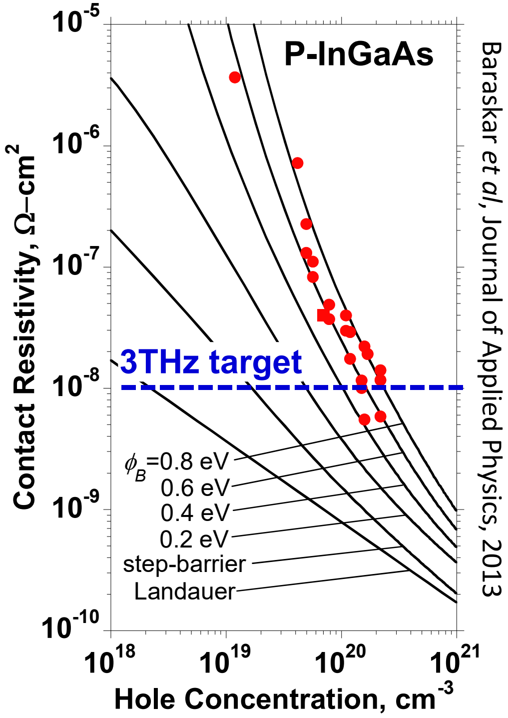
Ultra low resistivity contacts

Challenges at the 64nm/2THz & 32nm/3THz Nodes

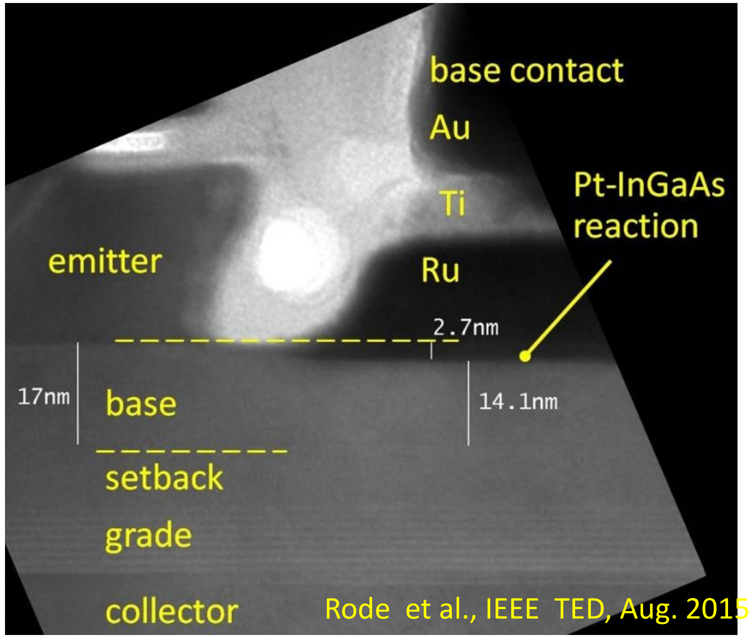
Need high base contact doping
$>10^{20}/\text{cm}^3$ for good contacts
high Auger recombination
very low β.

Need moderate contact penetration
Pd or Pt contacts
react with 3++ nm of base
penetrate surface contaminants
too deep for thin base

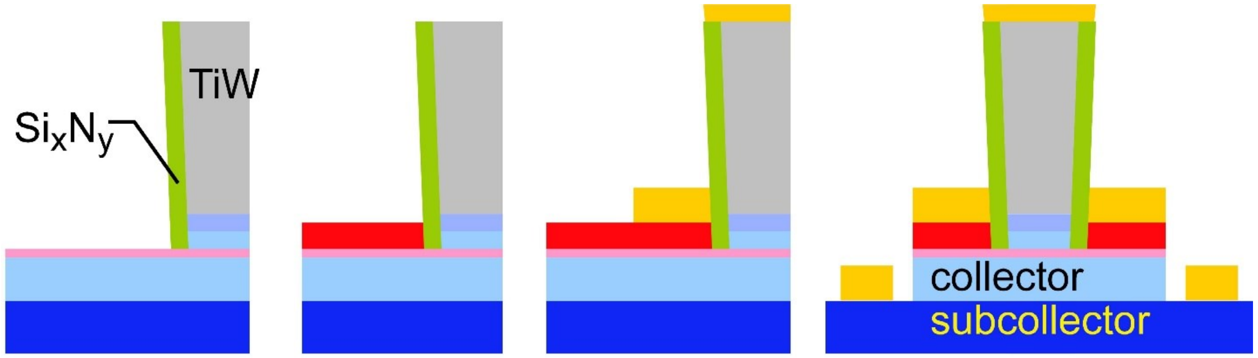
Solution: base regrowth:
thin, moderately-doped intrinsic base
thick, heavily-doped extrinsic base



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



Rode et al., IEEE TED, Aug. 2015



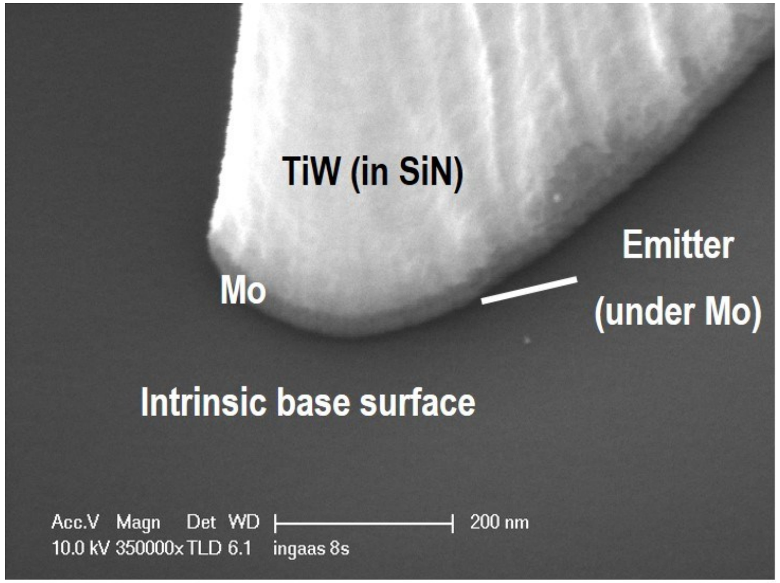
process e/b junction

MOCVD regrowth

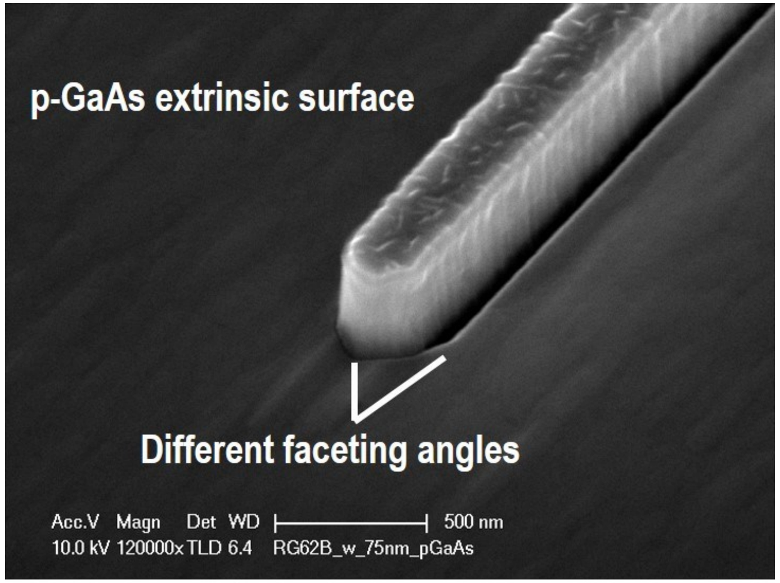
base contacts

collector mesa, contacts, etc.

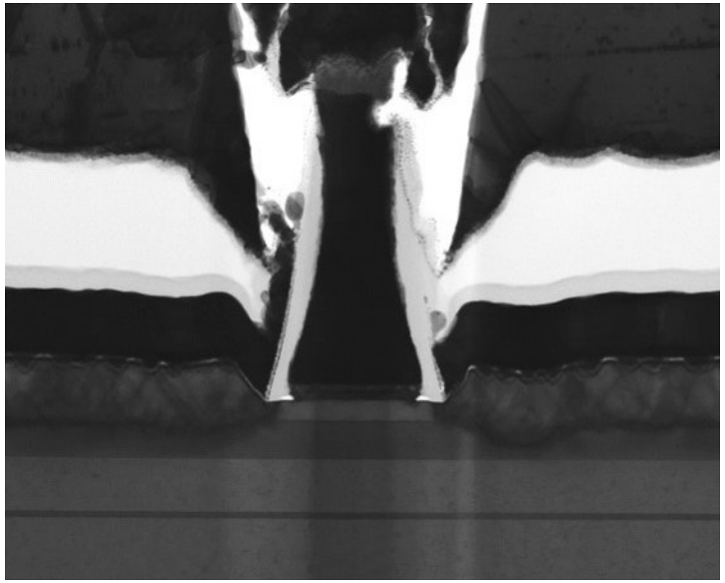
Regrown-Base InP HBTs: Images



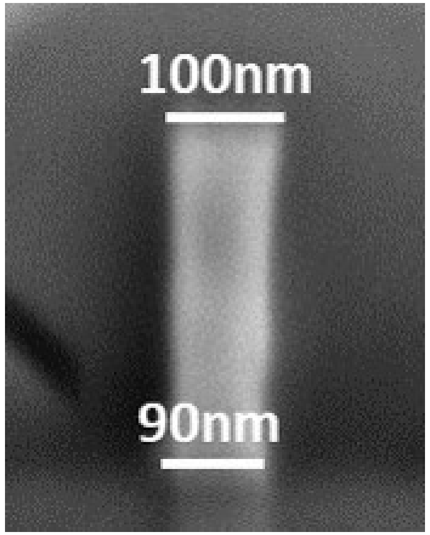
Before regrowth



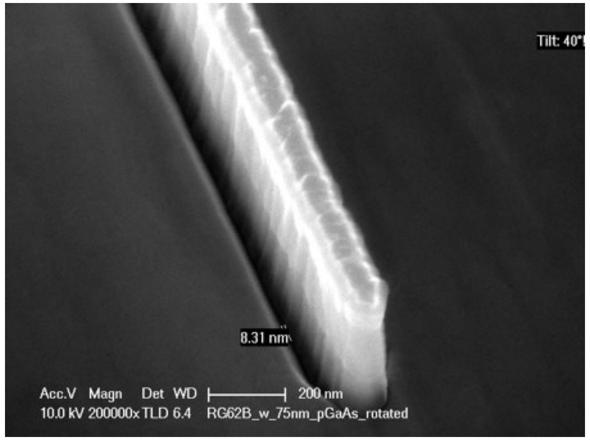
After 100nm p-GaAs regrowth



Cross-section



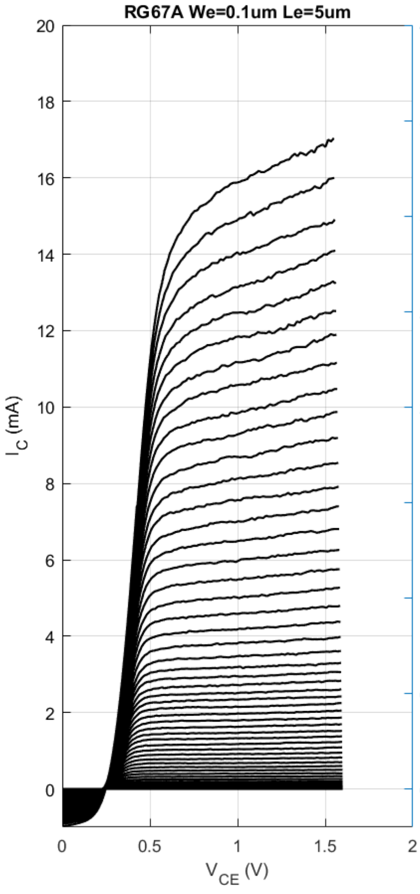
Dry-etched
TiW emitter contact



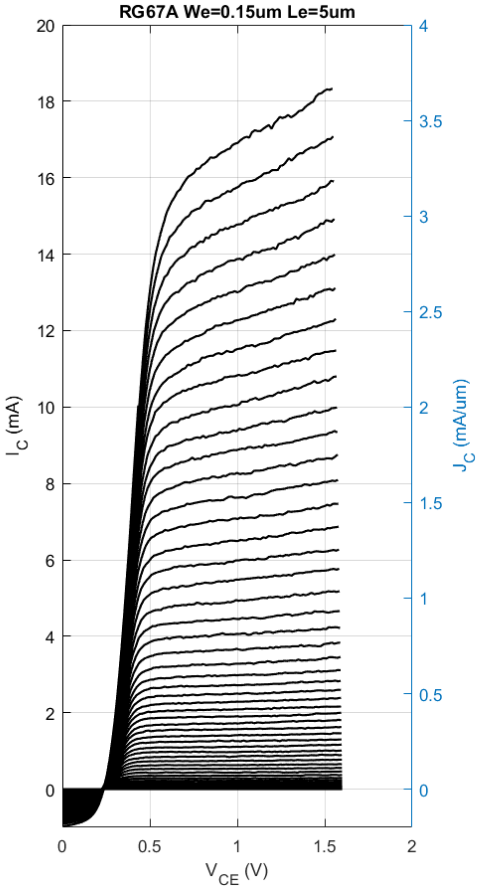
100nm emitter
after base regrowth

Regrown-Base InP HBTs: DC Data

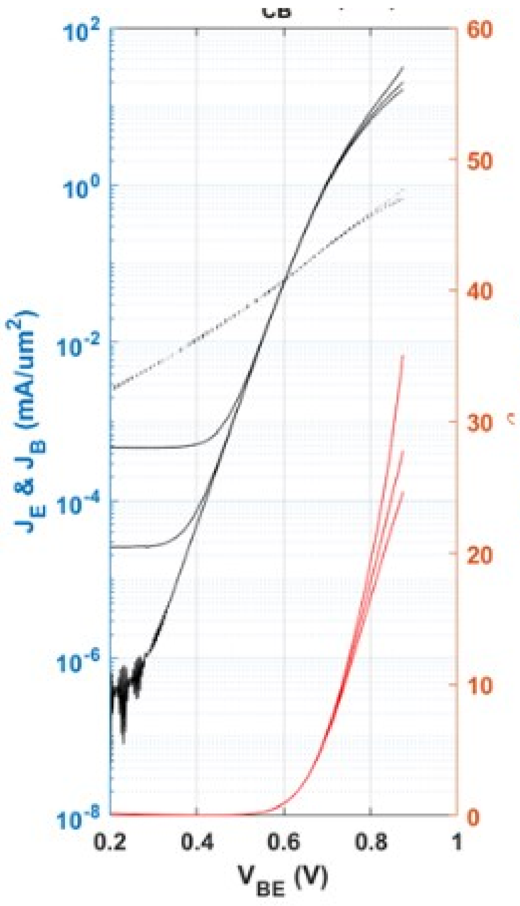
0.1× 5μm emitter



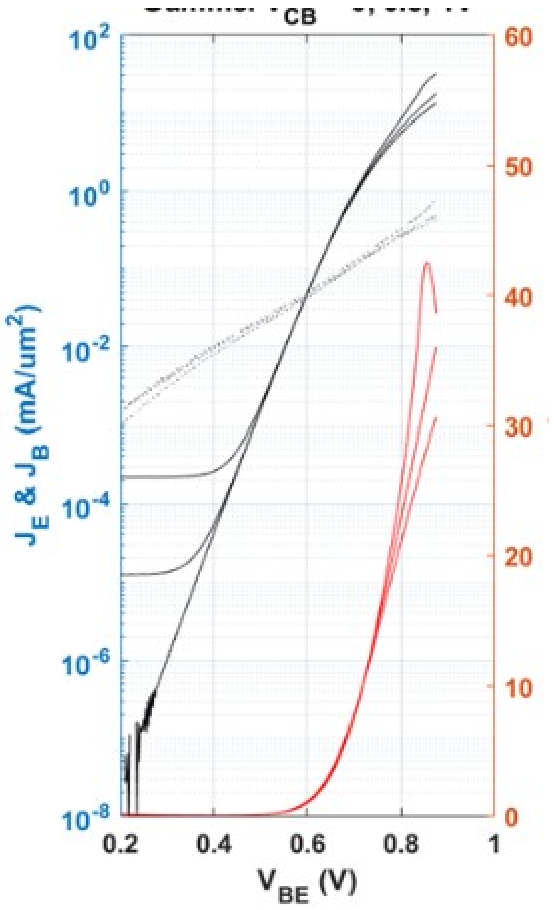
0.2× 5μm emitter



0.2× 5μm emitter



0.4× 5μm emitter

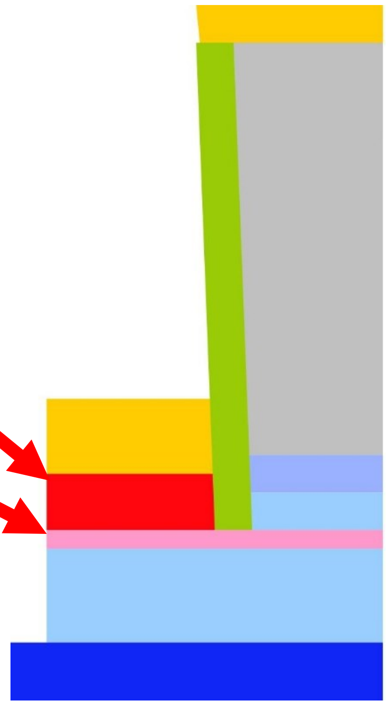


Good β, low R_{ex}, high-current operation

Regrown-Base InP HBTs: Base Resistance

0.9Ω–μm^2 resistivity for GaAs/metal contact ✓
294Ω sheet resistivity for regrown base ✓

1.0Ω–μm^2 resistivity for InGaAs/GaAs contact ✓
4300Ω/ sheet resistivity for intrinsic base ✗



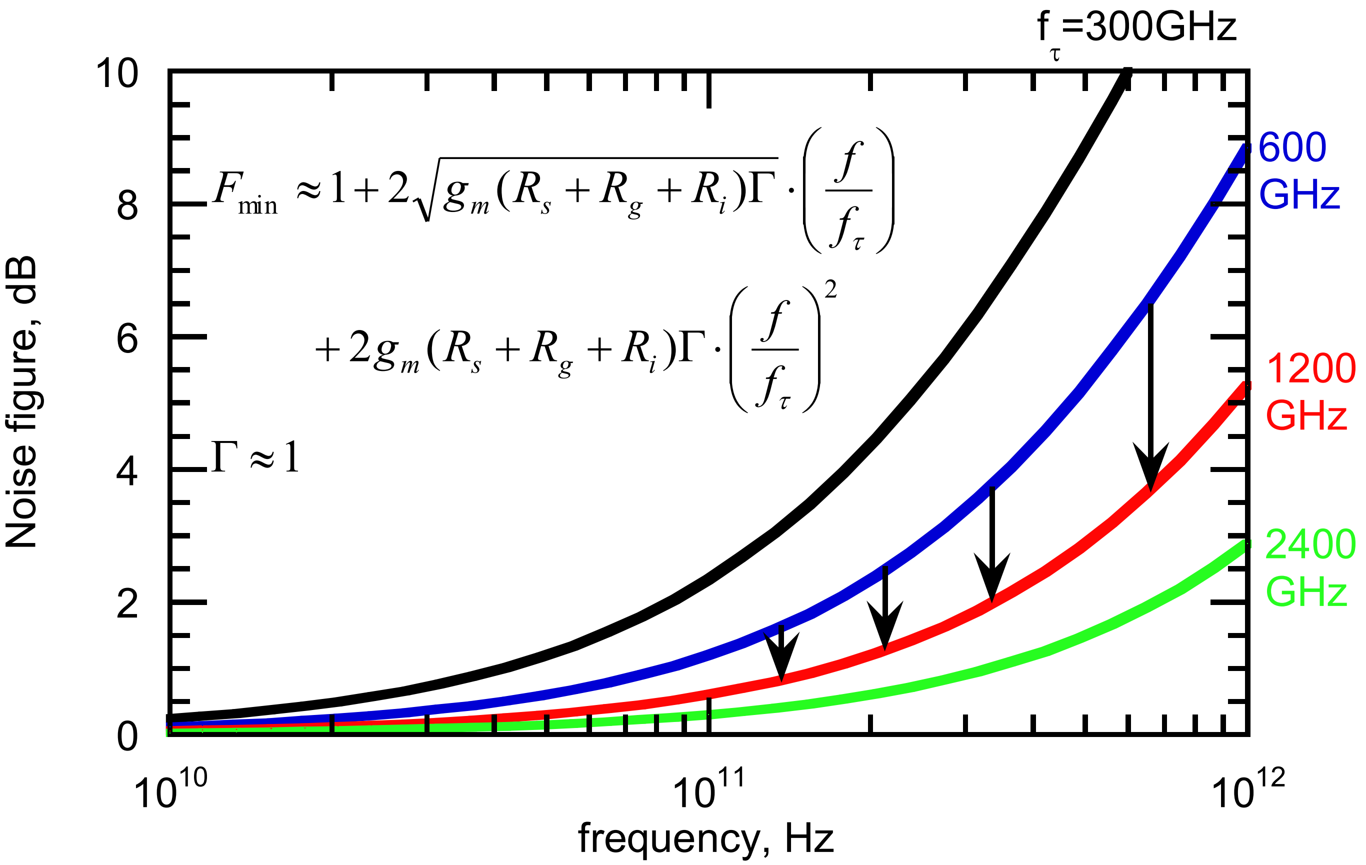
Base contact resistivity sufficient for 64nm/2THz node.
Improvements: anneal after regrowth, grade interface

Regrowth: base contacts suitable for 64nm/2THz & 32nm/3THz nodes

FETs (HEMTs): key for low noise

2:1 to 4:1 increase in f_τ:
  improved noise
  less required transmit power
  smaller PAs, less DC power

or higher-frequency systems



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)**

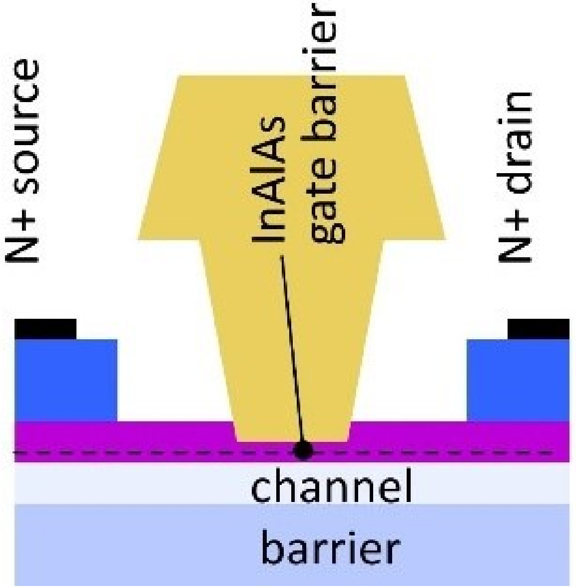
Towards faster HEMTs: MOS-HEMTs

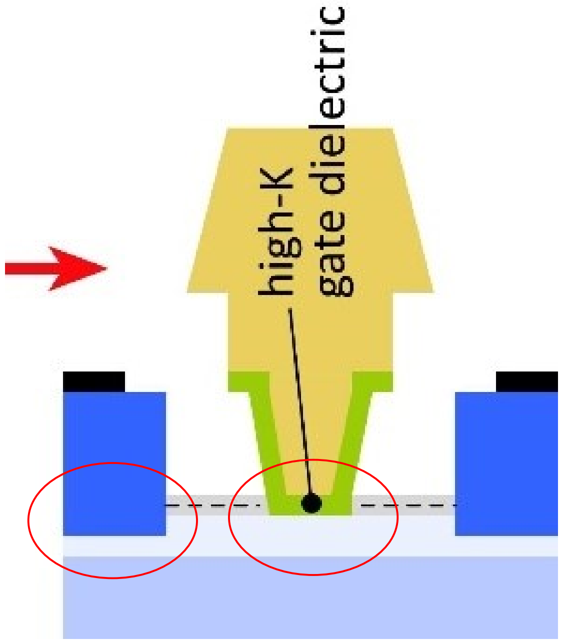
1st demonstration: Fraunhofer IAF

Scaling limit: gate insulator thickness
HEMT: InAlAs barrier: tunneling, thermionic leakage
solution: replace InAlAs with high-K dielectric
2nm ZrO_2 (ε_r=25): adequately low leakage

Scaling limit: source access resistance
HEMT: InAlAs barrier is under N+ source/drain
solution: regrowth, place N+ layer <u>on</u> InAs channel

Target ~10nm node
~0.3nm EOT, 3nm thick channel
1.2 to 1.5 THz f_τ.





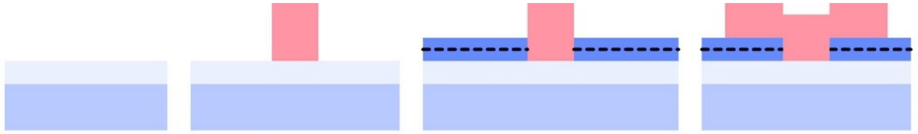
Towards Faster HEMTs: MOS-HEMTs

Jun Wu, UCSB, IEEE EDL, 2018

Double regrowth
modulation-doped access regions
N+ contacts

High-K gate dielectric: 3 nm ZrO2.

Highly scaled
5nm InAs channel, 10-30nm gate lengths

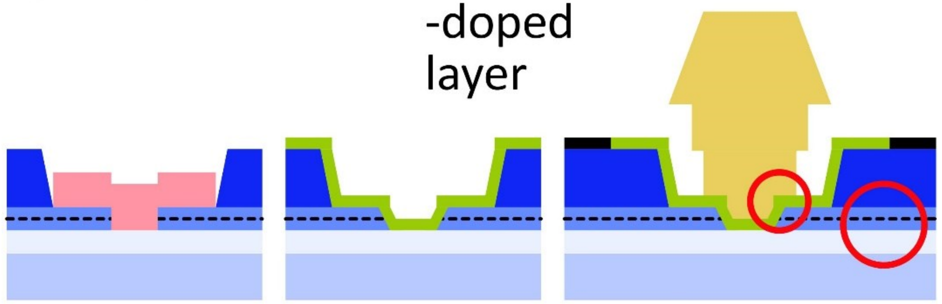


channel epitaxy

HSQ mask

regrowth: modulation -doped layer

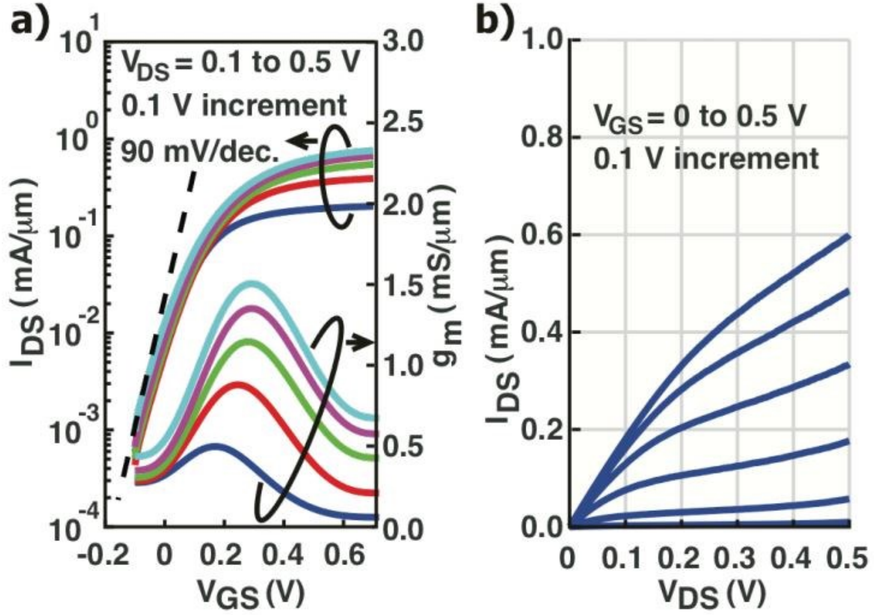
2nd HSQ mask

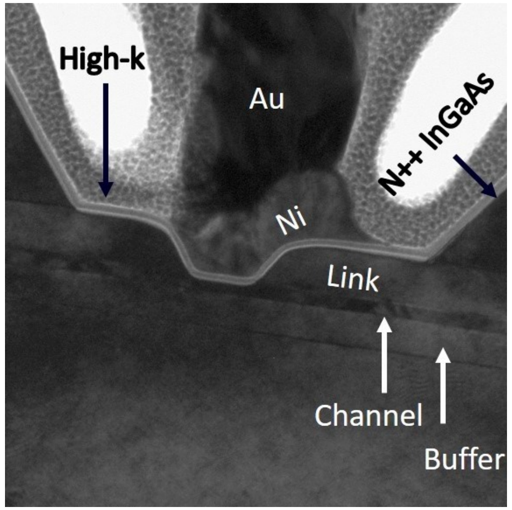


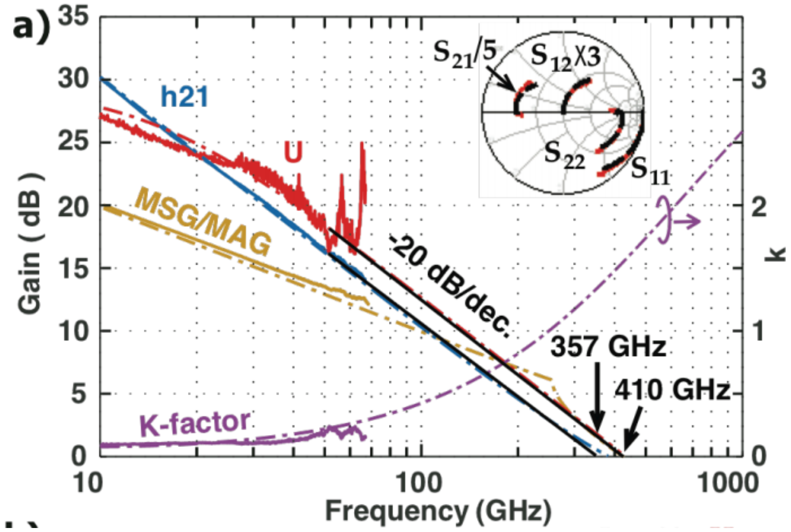
regrowth: N+ S/D

dielectric ALD

liftoff gate liftoff S/D







100-340GHz Wireless Systems:

100-340 GHz wireless systems
massive capacities via spatial multiplexing
compact, high-resolution imaging systems
short range: few 100 meters

Many challenges
spatial multiplexing: computational complexity, ~~dynamic range~~
packaging: fitting signal channels in very small areas

IC Technology
All-silicon for short ranges below 250 GHz.
III-V LNAs and PAs for longer-range links. Just like cell phones today
III-V frequency extenders for 340GHz and beyond

Device opportunity: better PAs, LNAs for 140, 220, 340GHz.

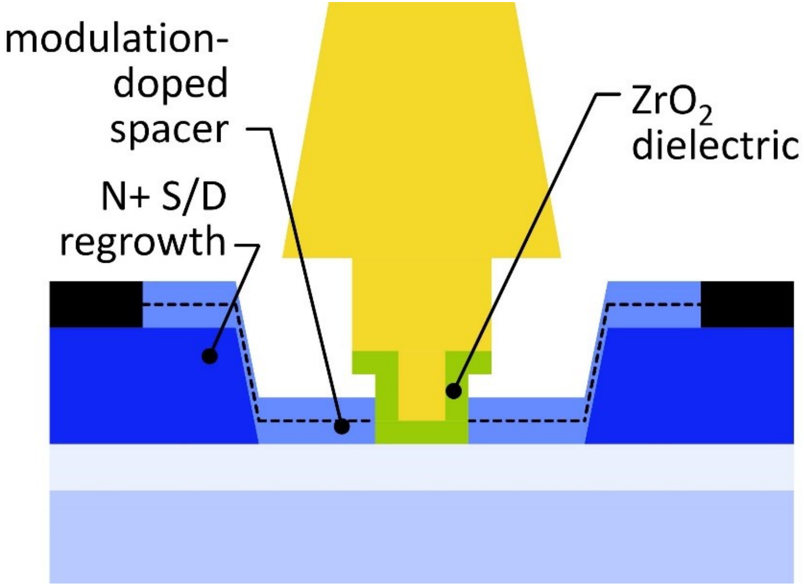
In case of questions

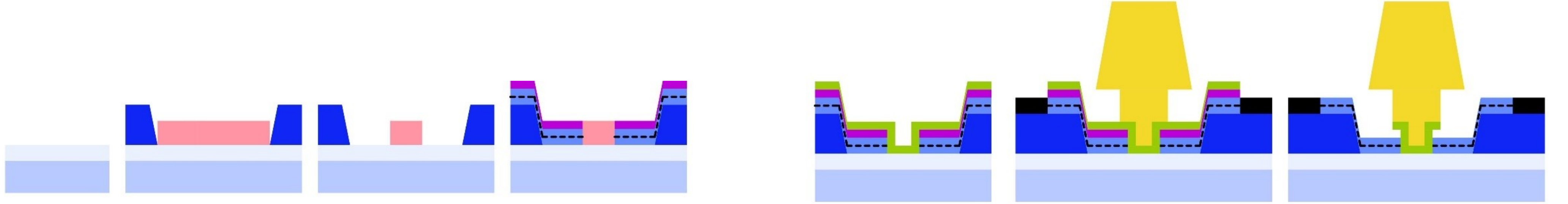
Towards faster HEMTs: next step

No N- material between channel and contacts
reduced source/drain access resistance

Sacrificial layer
reduces parasitic gate-channel overlap
less gate-source capacitance

2.5nm ZrO_2 dielectric, 3nm InAs channel
higher g_m , lower g_{ds}





channel epitaxy

HSQ mask, regrow N+ S/D

2nd HSQ mask

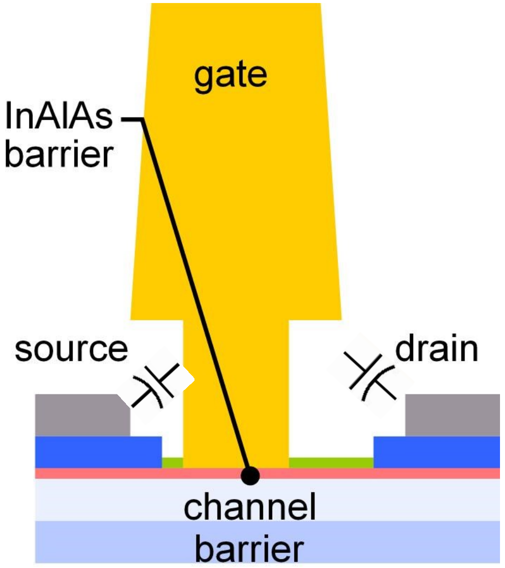
regrowth: modulation-doping, sacrificial layer

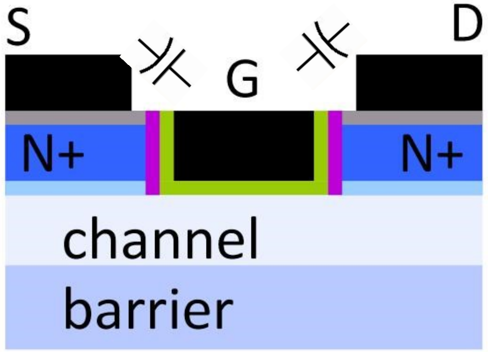
dielectric ALD

liftoff gate liftoff S/D

etch gate dielectric, etch sacrificical layer

FET Scaling Laws (these now broken)





🟦 vertical S/D spacer
🟪 low-K dielectric spacer
🟩 high-K gate dielectric

FET parameter	change
gate length	decrease 2:1
current density (mA/mm)	increase 2:1
specific transconductance (mS/mm)	increase 2:1
transport mass	constant
2DEG electron density	increase 2:1
gate-channel capacitance density	increase 2:1
dielectric equivalent thickness	decrease 2:1
channel thickness	decrease 2:1
channel state density	increase 2:1
contact resistivities	decrease 4:1

Gate dielectric can't be much further scaled.

g_m/W_g hard to increase→ C_{end} / g_m prevents f_τ scaling.

Shorter L_g→ poor electrostatics→ reduced g_m /G_{ds}

Towards faster HEMTs: MOS-HEMTs

1st demonstration: Fraunhofer IAF

Scaling limit: gate insulator thickness

HEMT: InAlAs barrier: tunneling, thermionic leakage
solution: replace InAlAs with high-K dielectric
2nm ZrO_2 (ε_r=25): adequately low leakage

Scaling limit: source access resistance

HEMT: InAlAs barrier is under N+ source/drain
solution: regrowth, place N+ layer <u>on</u> InAs channel

Target ~10nm node

~0.3nm EOT, 3nm thick channel
1.2 to 1.5 THz f_τ.