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THz Indium Phosphide Bipolar Transistor Technology

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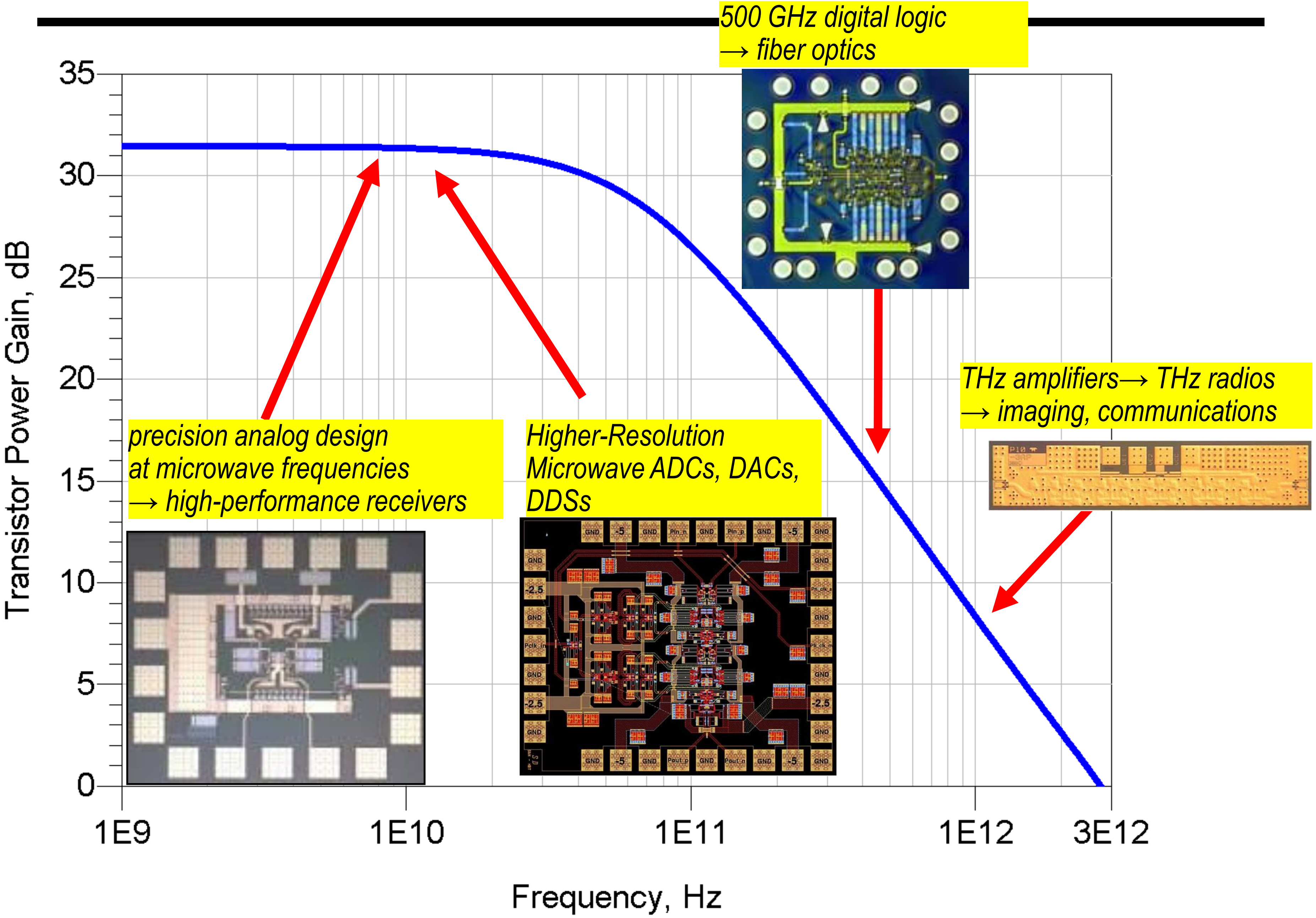
Why
THz Transistors ?

THz Transistors: Not Just For THz Circuits



500 GHz digital logic
→ fiber optics

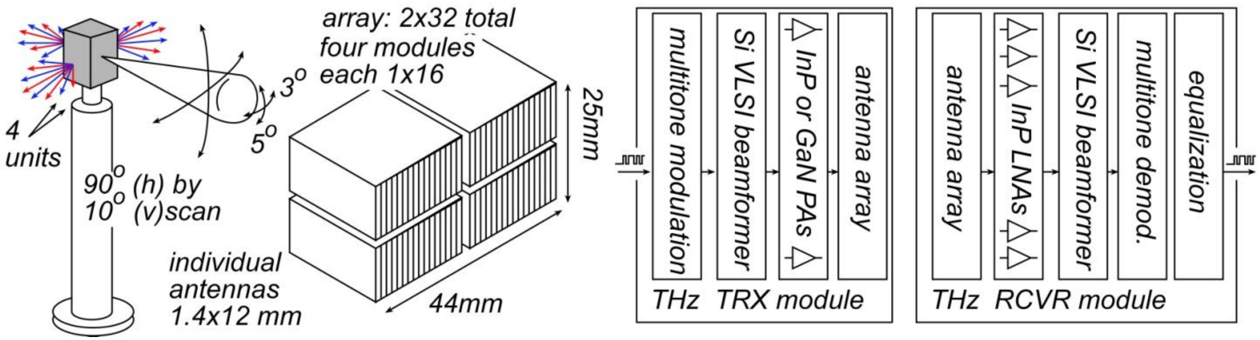
THz amplifiers→ THz radios
→ imaging, communications

precision analog design
at microwave frequencies
→ high-performance receivers

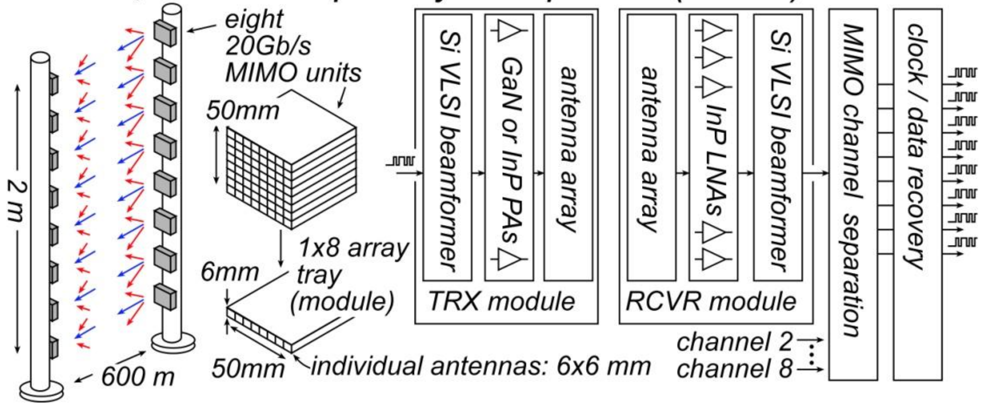
Higher-Resolution
Microwave ADCs, DACs,
DDSs

THz Communications Needs High Power, Low Noise

140 GHz, 10 Gb/s spatially scanned network node



340 GHz, 160Gb/s spatially multiplexed (MIMO) backhaul



Real systems with real-world weather & design margins, 500-1000m range:

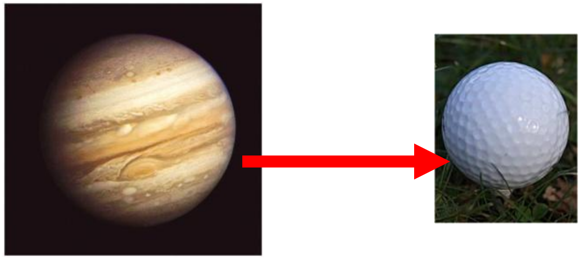
Will require:

3-7 dB Noise figure, 50-500 mW power/element, 64-256 element arrays
→ InP or GaN PAs and LNAs, Silicon beamformer ICs

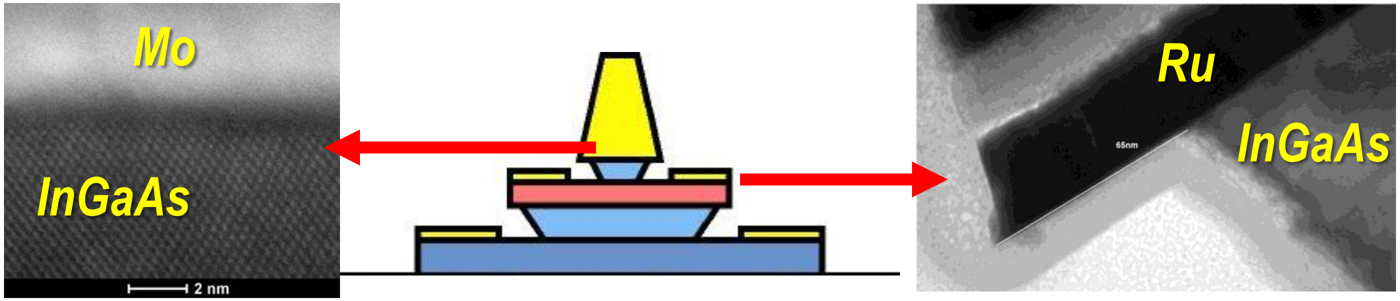
THz InP HBTs

THz & nm Transistors: what it's all about

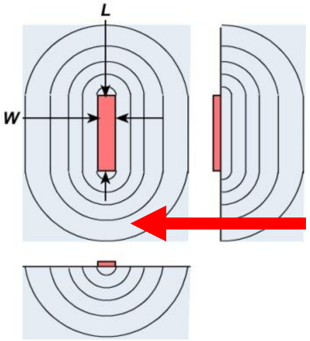
Metal-semiconductor interfaces (Ohmic contacts): <u>very low resistivity</u>
Dielectric-semiconductor interfaces (Gate dielectrics---FETs only): <u>thin !</u>



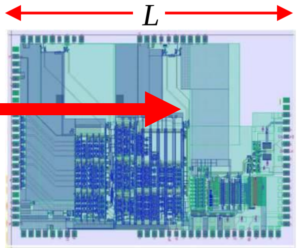
Ultra-low-resistivity (~0.25 Ω-μm^2), ultra shallow (1 nm), ultra-robust (0.2 A/μm^2) contacts



Heat

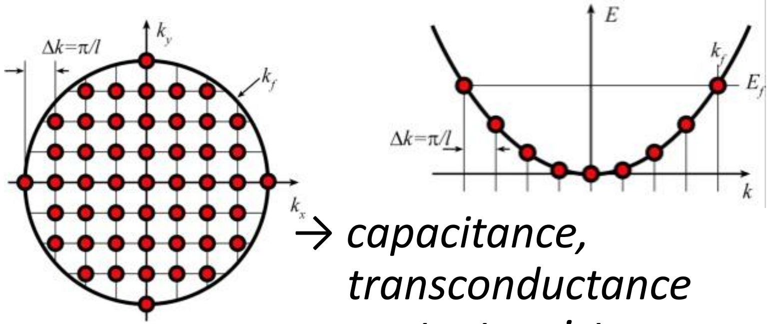


$$\Delta T_{IC} \propto \frac{P_{IC}}{K_{th} L}$$



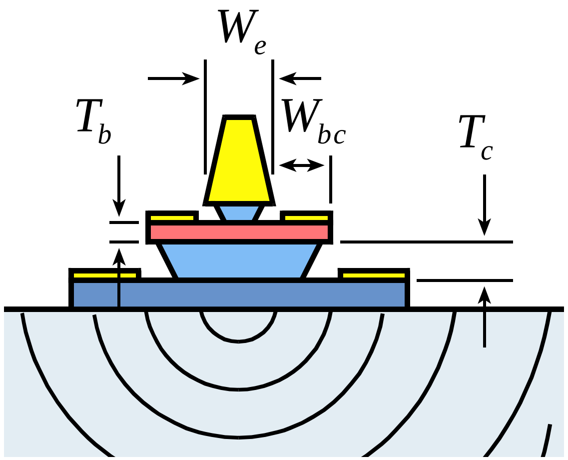
$$\Delta T_{\text{transistor}} \sim \frac{P}{\pi K_{th} L} \ln\left(\frac{L}{W}\right)$$

Available quantum states to carry current



→ *capacitance,*
transconductance
contact resistance

Bipolar Transistor Design



(emitter length L_E)

$$\tau_b \approx T_b^2 / 2D_n$$

$$\tau_c = T_c / 2v_{sat}$$

$$C_{cb} = \varepsilon A_c / T_c$$

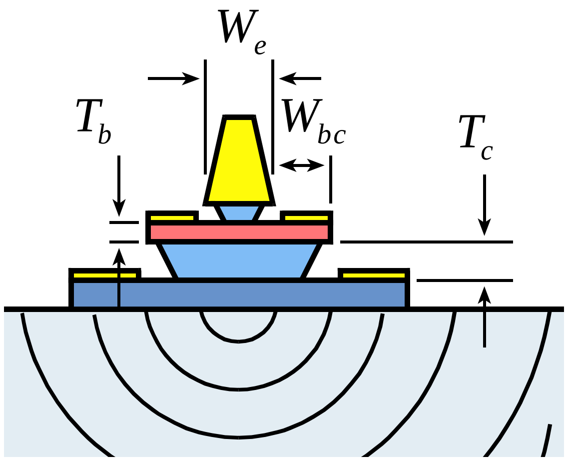
$$I_{c,\max} \propto v_{sat} A_e \left(V_{\text{ce,operating}} + V_{\text{ce,punch-through}}\right) / T_c^2$$

$$\Delta T \propto \frac{P}{L_E}\left[1+\ln\left(\frac{L_e}{W_e}\right)\right]$$

$$R_{ex} = \rho_{\text{contact}} / A_e$$

$$R_{bb} = \rho_{\text{sheet}}\left(\frac{W_e}{12L_e}+\frac{W_{bc}}{6L_e}\right)+\frac{\rho_{\text{contact}}}{A_{\text{contacts}}}$$

Bipolar Transistor Design: Scaling



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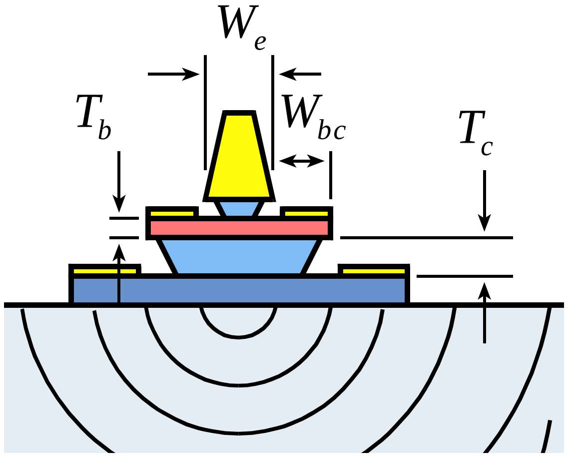
Scaling Laws, Scaling Roadmap

scaling laws: to double bandwidth

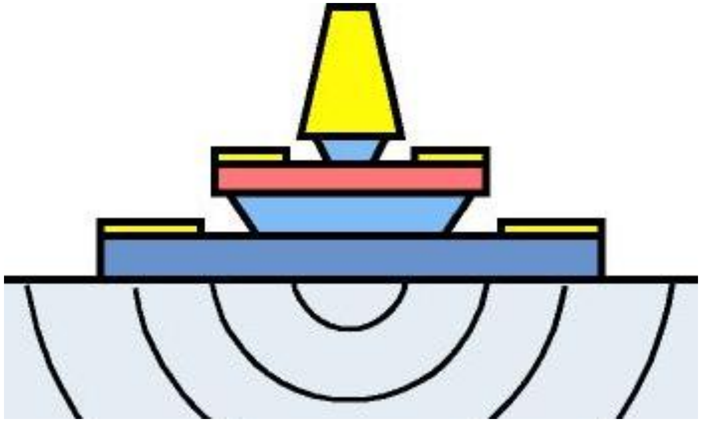
HBT parameter	change
emitter & collector junction widths	decrease 4:1
current density (mA/μm^2)	increase 4:1
current density (mA/μm)	constant
collector depletion thickness	decrease 2:1
base thickness	decrease 1.4:1
emitter & base contact resistivities	decrease 4:1



(emitter length L_E)

emitter	128	64	32 nm width
	4	2	1 Ω·μm^2 access ρ
base	120	60	30 nm contact width,
	5	2.5	1.25 Ω·μm^2 contact ρ
collector	75	53	37.5 nm thick,
	18	36	72 mA/μm^2 current density
	3.3	2.75	2-2.5 V, breakdown
f_τ	730	1000	1400 GHz
f_{max}	1300	2000	2800 GHz
RF-ICs	660	1000	1400 GHz
digital divider	330	480	660 GHz

HBT Fabrication Process Must Change... Greatly



32 nm width base & emitter contacts...self-aligned

32 nm width emitter semiconductor junctions

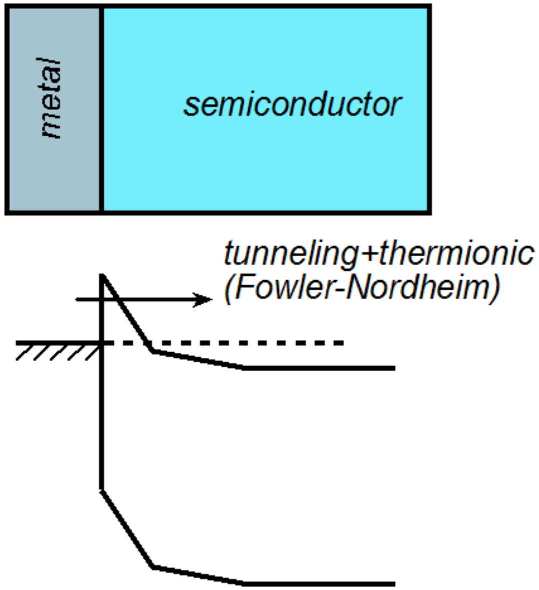
Contacts:

- ***1 Ω-μm^2 resistivities***
- ***70 mA/μm^2 current density***
- ***~1 nm penetration depths***
- ***→ refractory contacts***

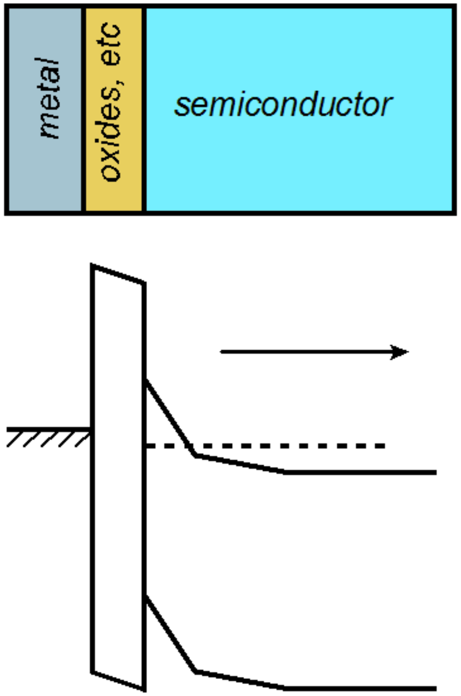
nm III-V FET, Si FET processes have similar requirements

Needed: Greatly Improved Ohmic Contacts

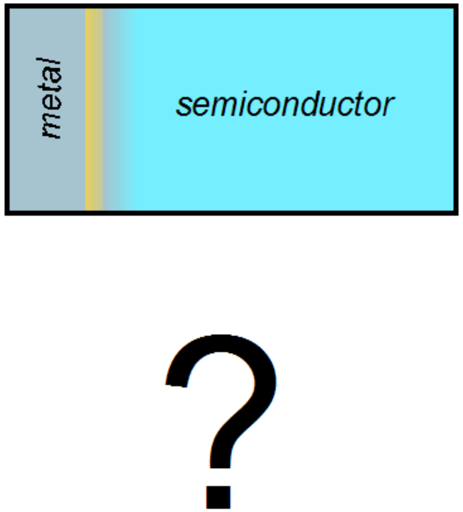
textbook



with surface oxide



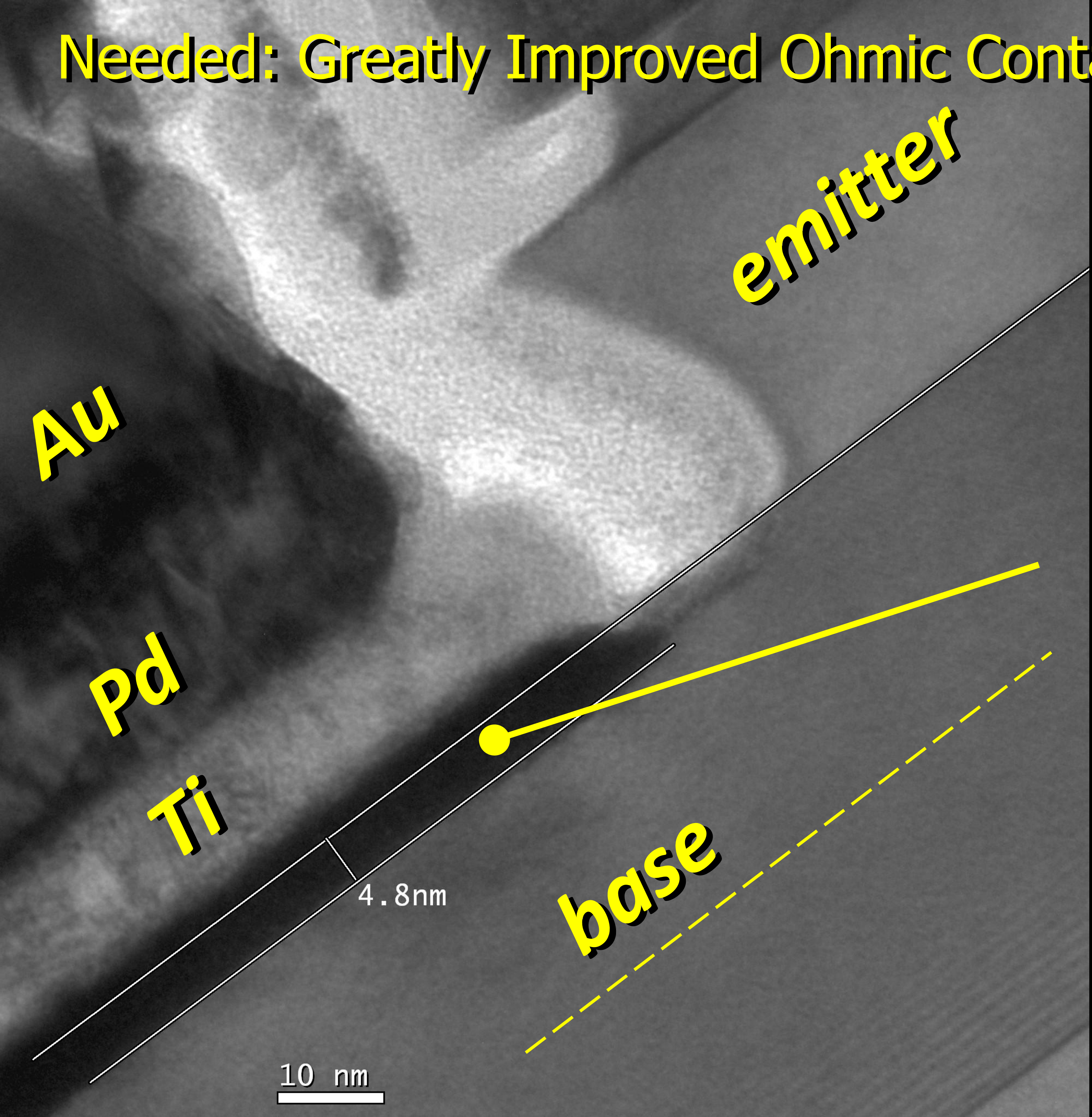
with metal penetration



Interface barrier → resistance

Further intermixing during high-current operation → degradation

Needed: Greatly Improved Ohmic Contacts

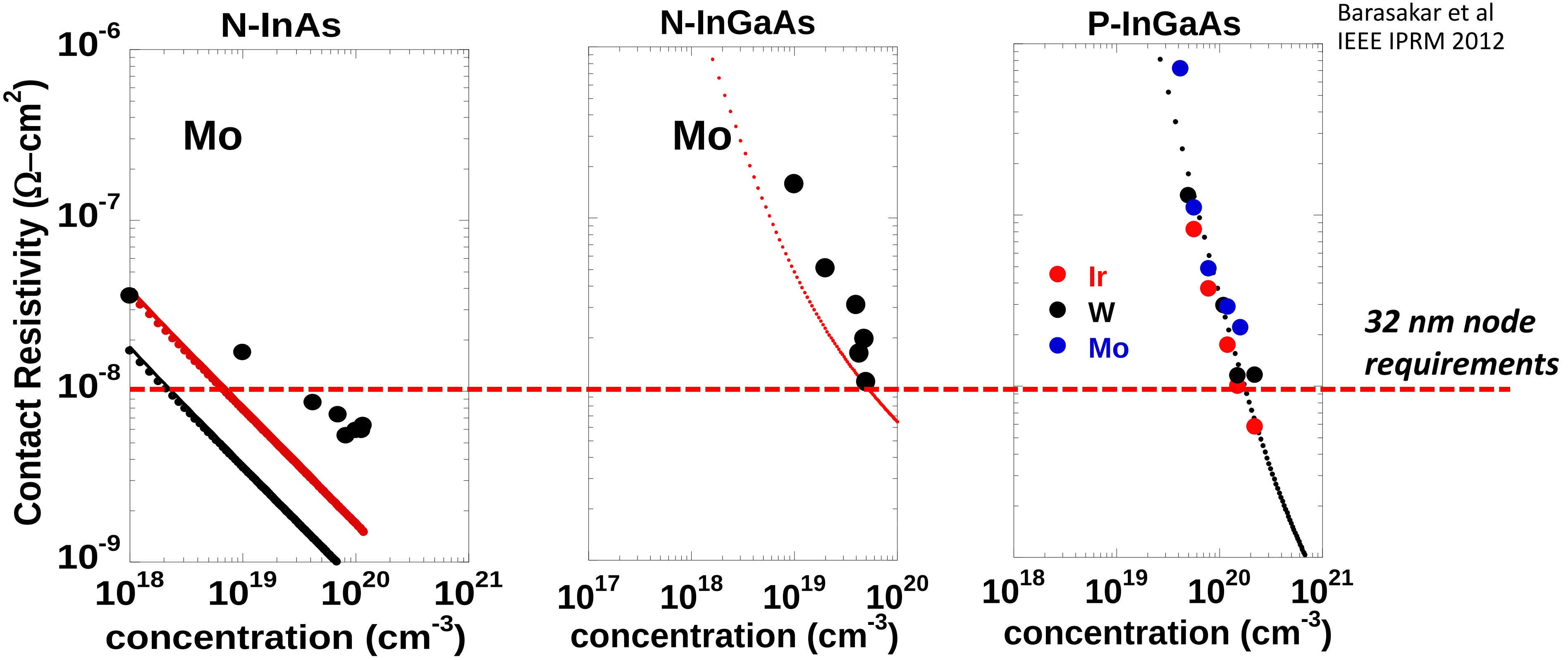


Pt/Ti/Pd/Au

~5 nm
Pt contact
penetration

(into 25 nm base)

Ultra Low-Resistivity Refractory *In-Situ* Contacts



Barasakar et al
IEEE IPRM 2012

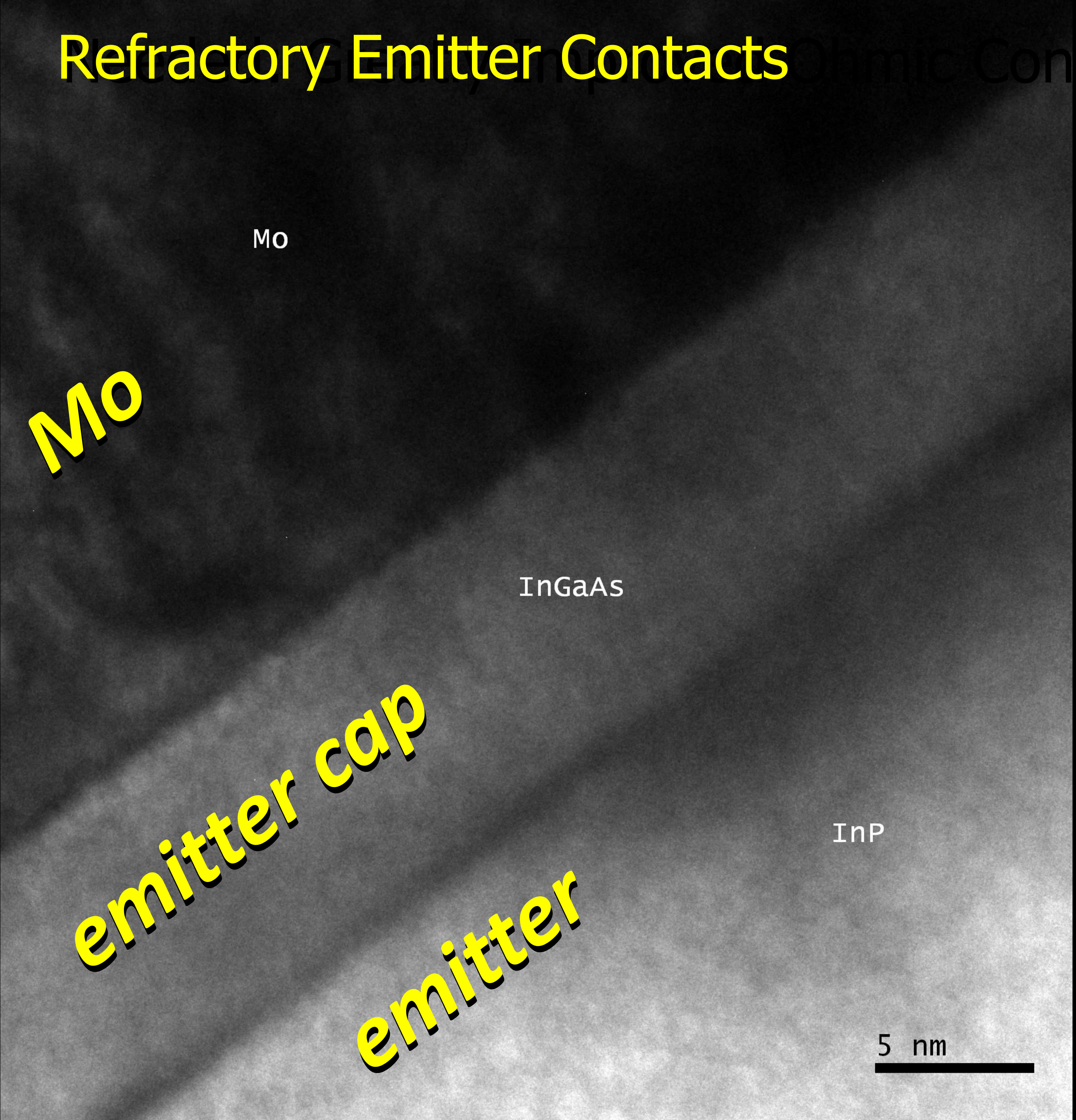
In-situ: avoids surface contaminants

Refractory: robust under high-current operation

Low penetration depth, ~ 1 nm

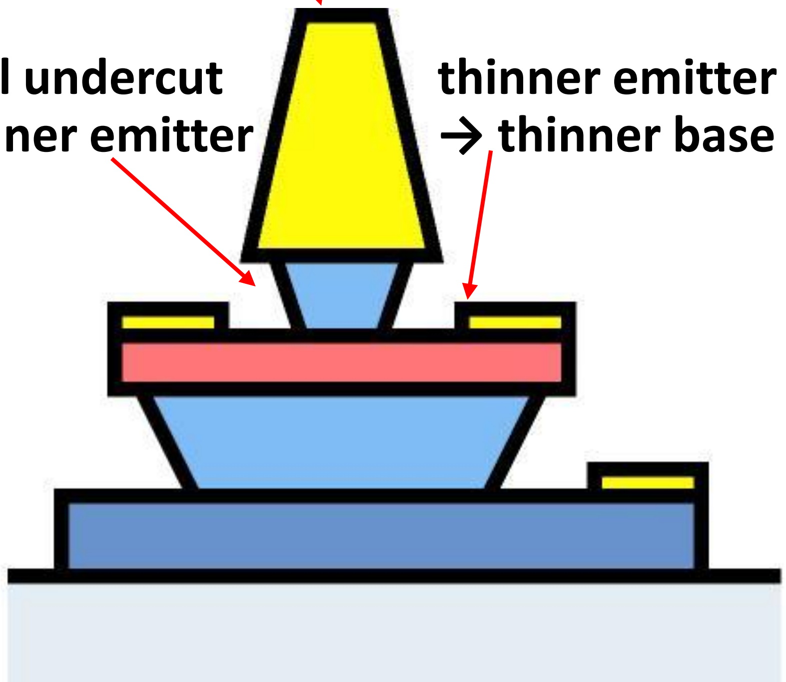
Contact performance sufficient for 32 nm /2.8 THz node.

Refractory Emitter Contacts



negligible penetration

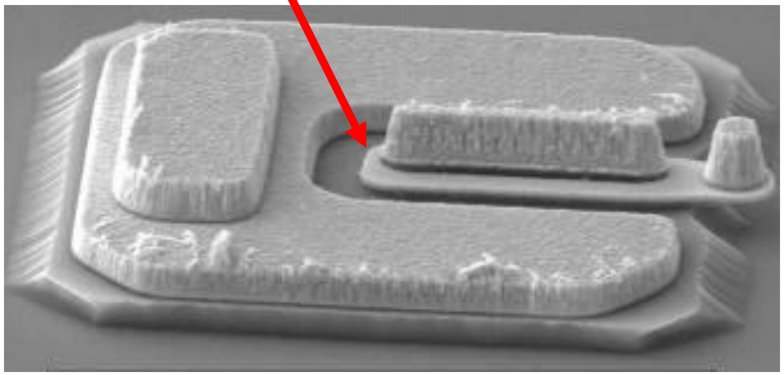
HBT Fabrication Process Must Change... Greatly



tall, narrow contacts: liftoff fails !

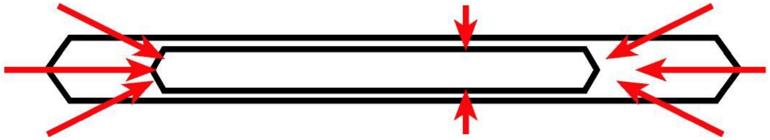
control undercut
→ thinner emitter

thinner emitter
→ thinner base metal



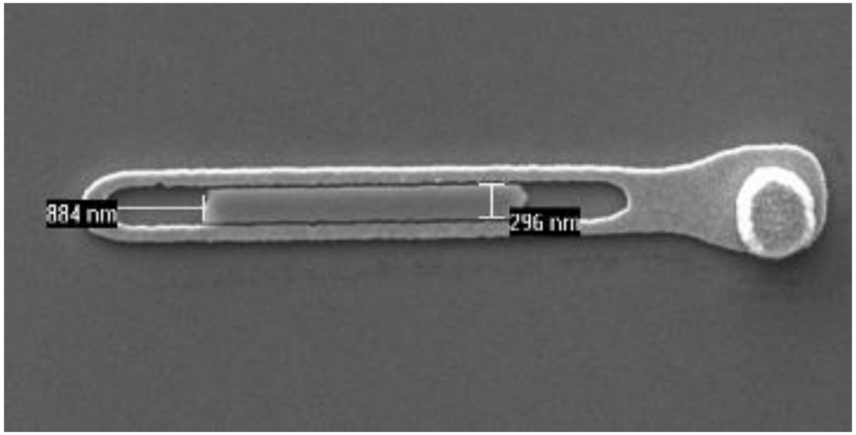
thinner base metal
→ excess base metal resistance

Undercutting of emitter ends



{101}A planes: fast

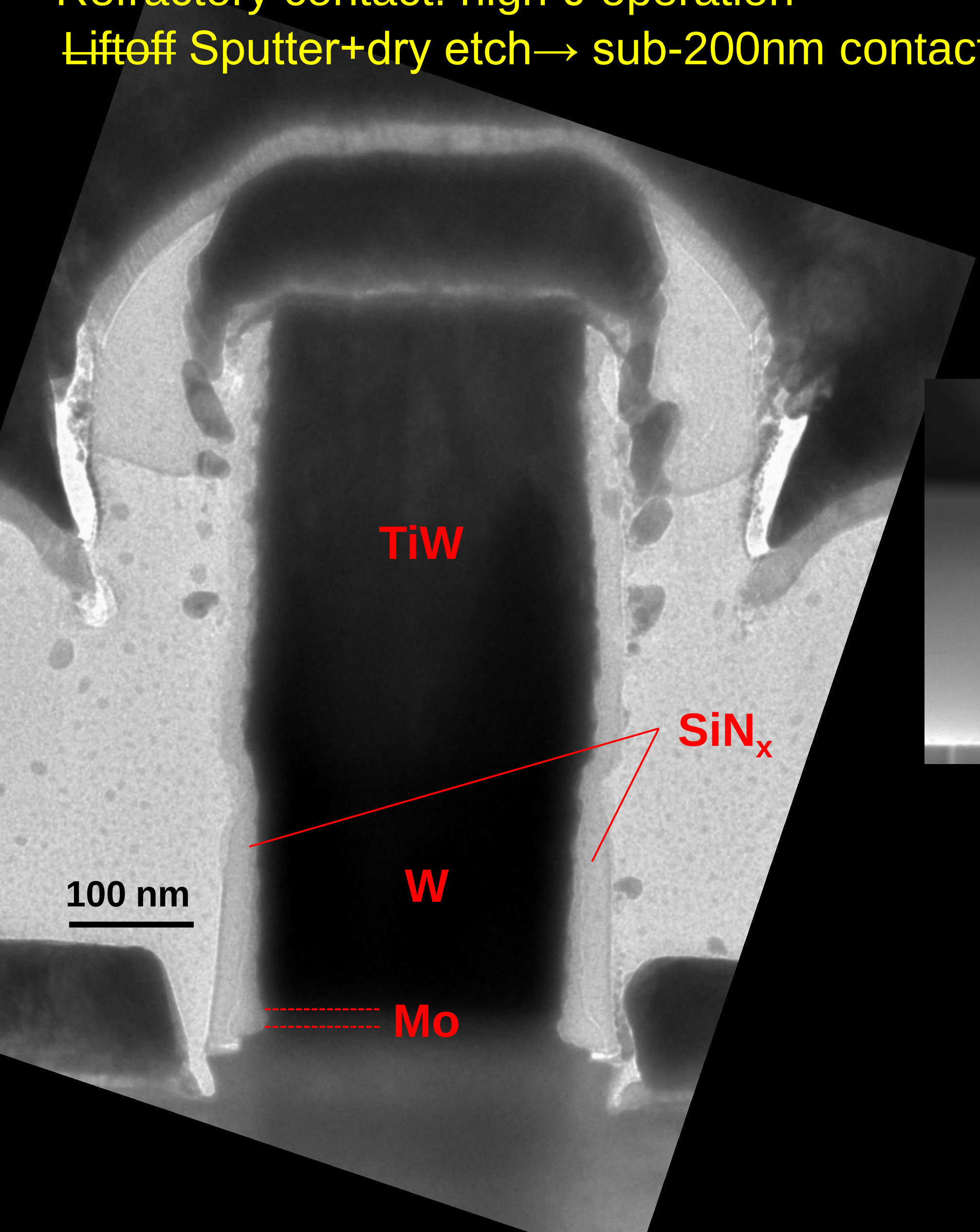
{111}A planes: slow

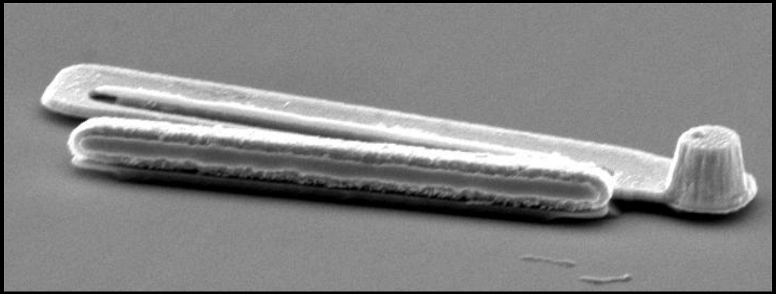


Sub-200-nm Emitter Anatomy

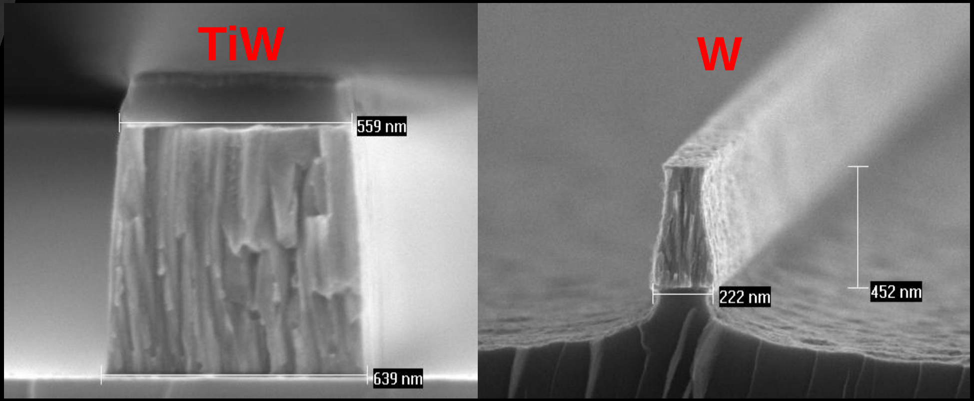
Refractory contact: high-J operation

~~Liftoff~~ Sputter+dry etch→ sub-200nm contacts





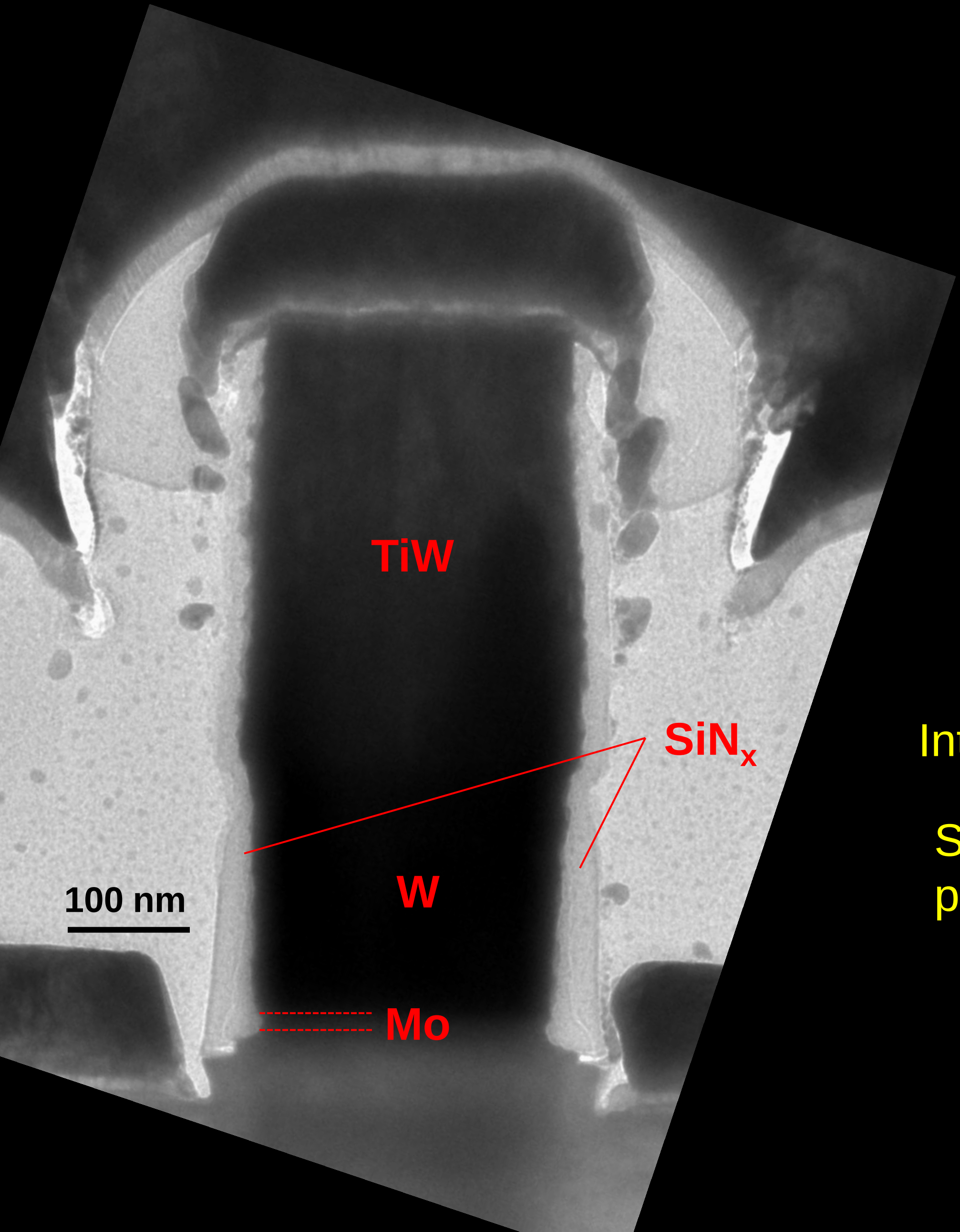
High-stress emitters fall off during subsequent lift-offs



Single sputtered metal has non-vertical etch profile

slide: E. Lobisser. HBT: V. Jain. Process: Jain & Lobisser

Sub-200-nm Emitter Anatomy



Hybrid sputtered metal stack for low-stress, vertical profile

W/TiW interfacial discontinuity enables base contact lift-off

Very thin emitter epitaxial layer for minimal undercut

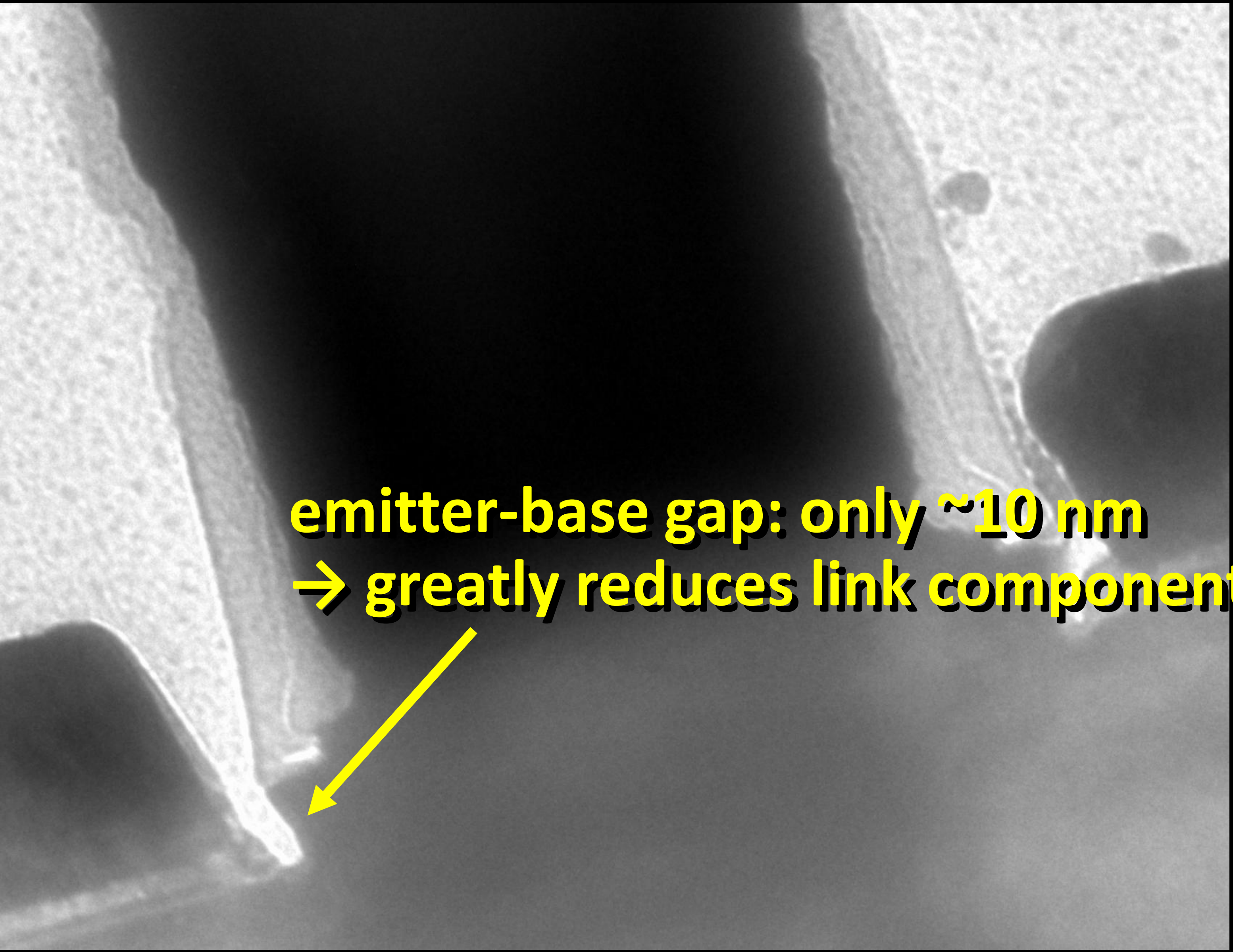
Semiconductor wet etch undercuts emitter contact

Interfacial Mo blanket-evaporated for low ρ_c

SiNx sidewalls protect emitter contact, prevent emitter-base shorts during liftoff

slide: E. Lobisser. HBT: V. Jain. Process: Jain & Lobisser

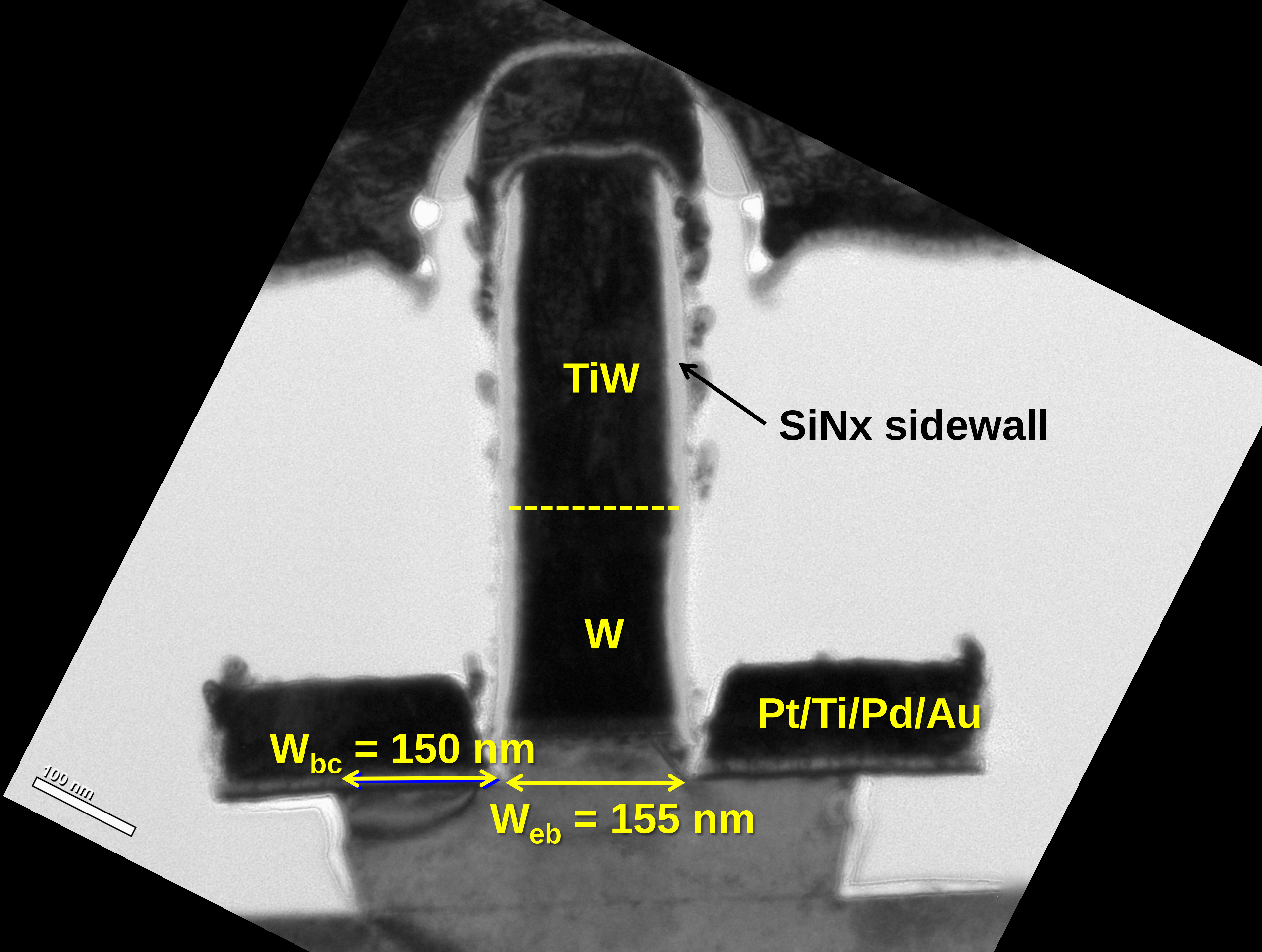
Sub-200-nm Emitter Anatomy



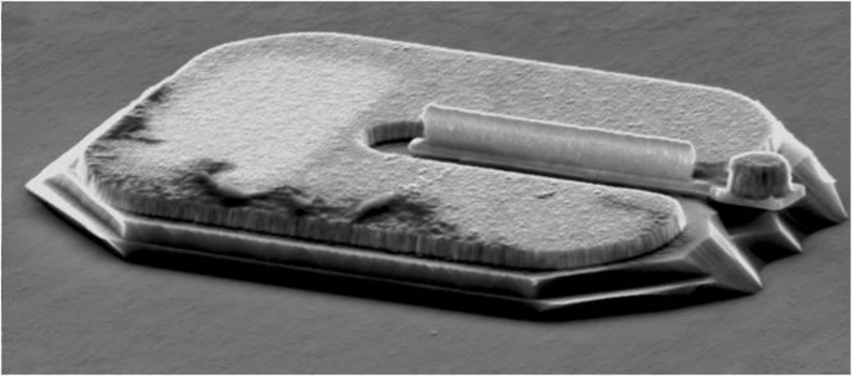
emitter-base gap: only ~10 nm

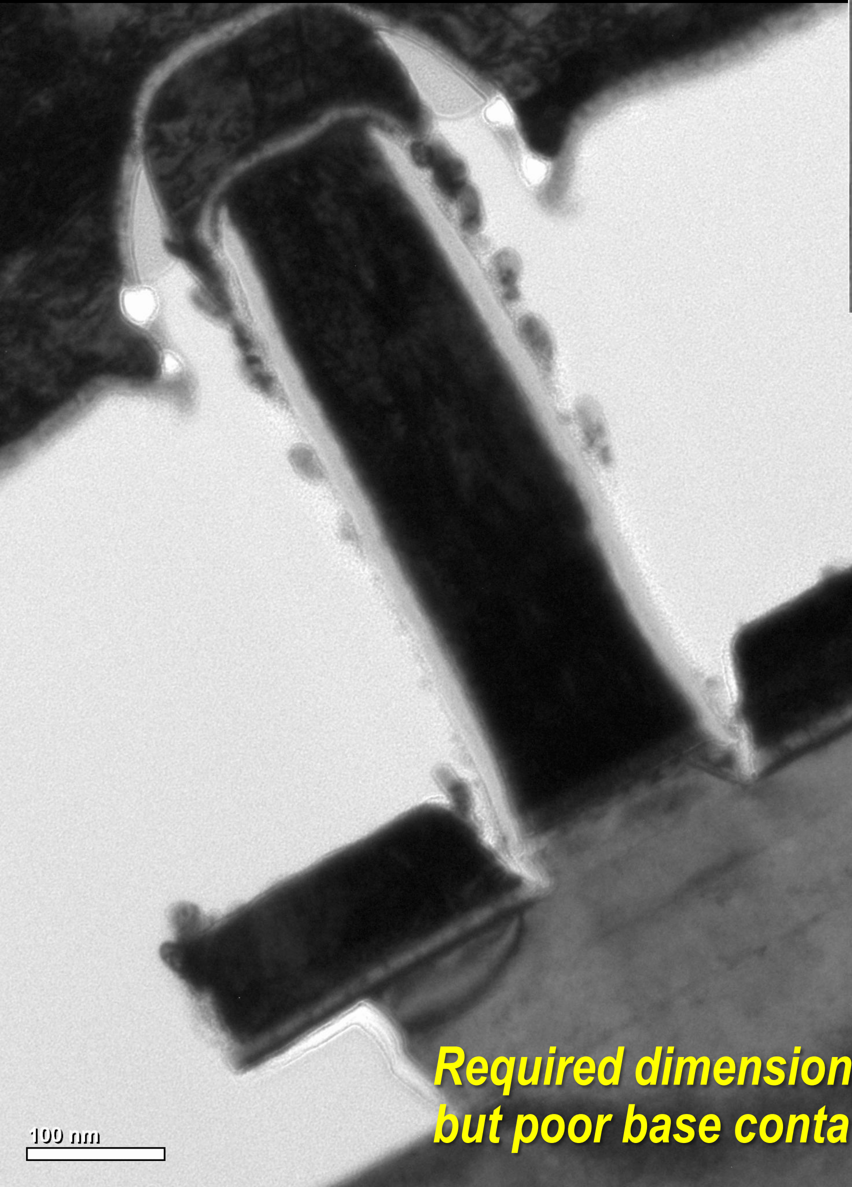
→ greatly reduces link component of R_{bb}

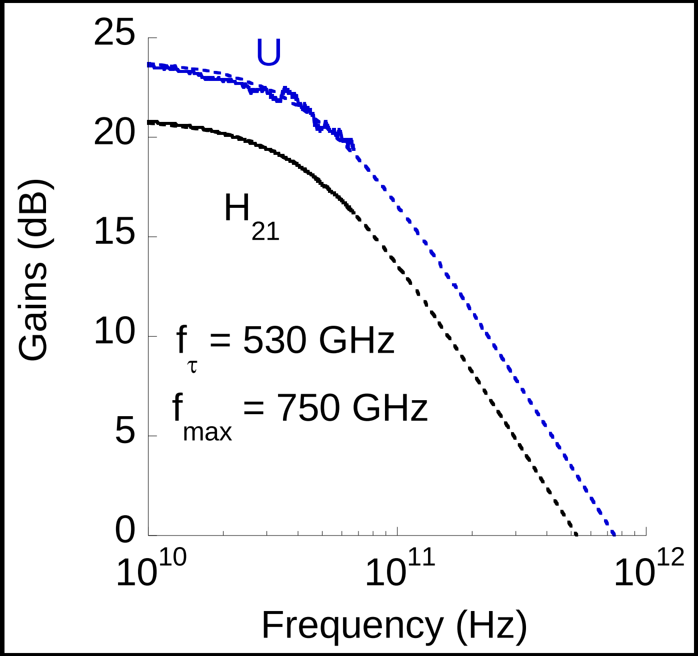
slide: E. Lobisser. HBT: V. Jain. Process: Jain & Lobisser


TiW
SiNx sidewall
W
Pt/Ti/Pd/Au
W_{bc} = 150 nm
W_{eb} = 155 nm
100 nm

RF Data: 25 nm thick base, 75 nm Thick Collector



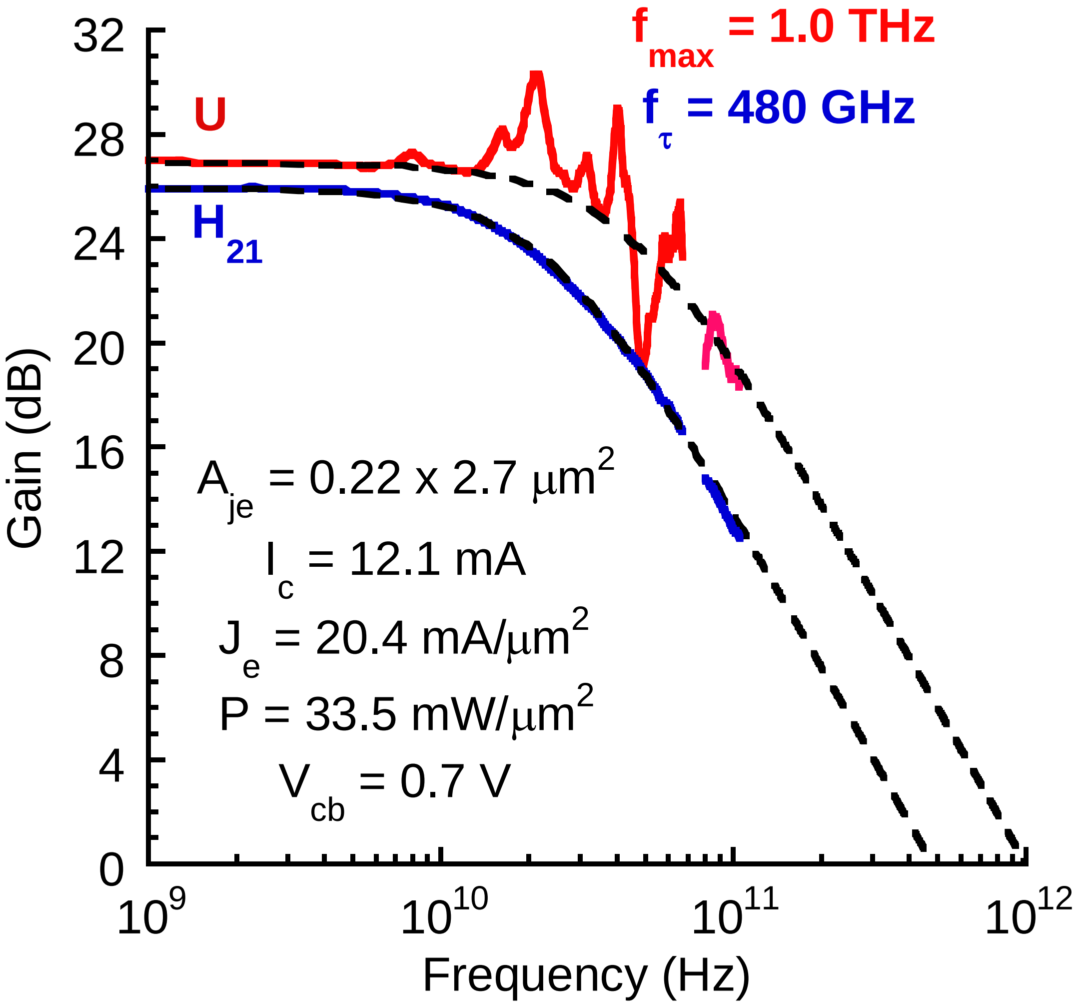




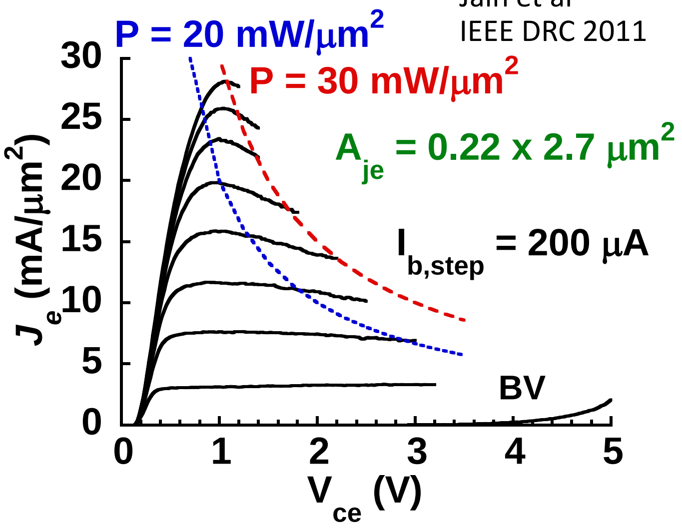
Required dimensions obtained but poor base contacts on this run

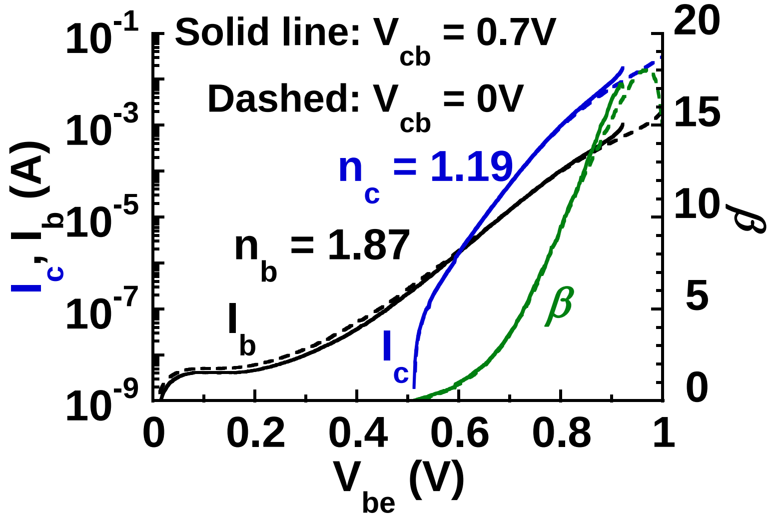
E. Lobisser, ISCS 2012, August, Santa Barbara

DC, RF Data: 100 nm Thick Collector



Jain et al
IEEE DRC 2011





THz InP HBTs From Teledyne

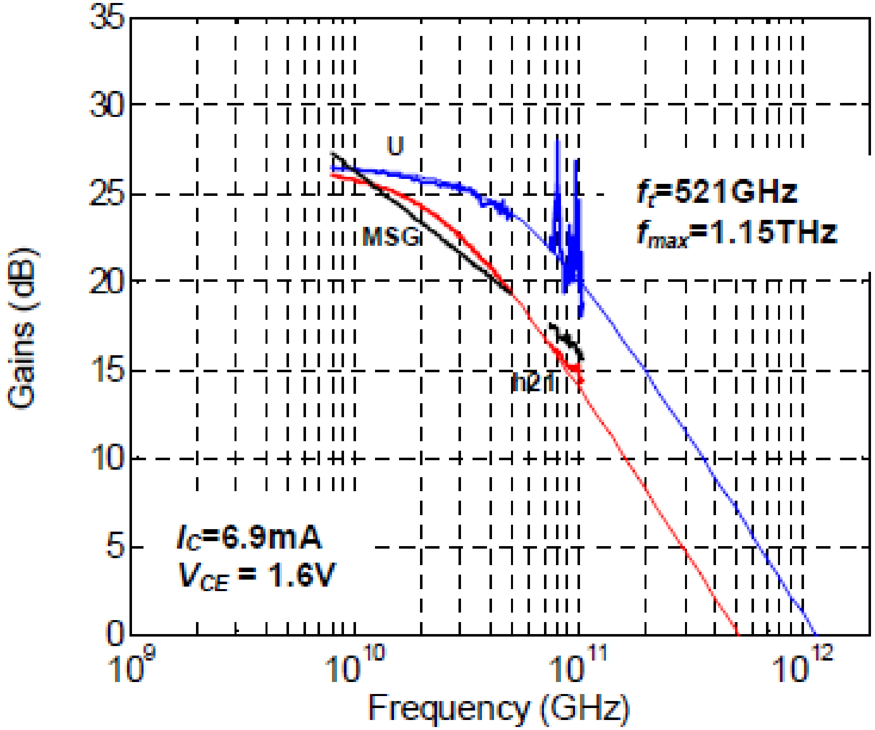


Fig. 3 RF gains of 0.13x2μm^2 HBT

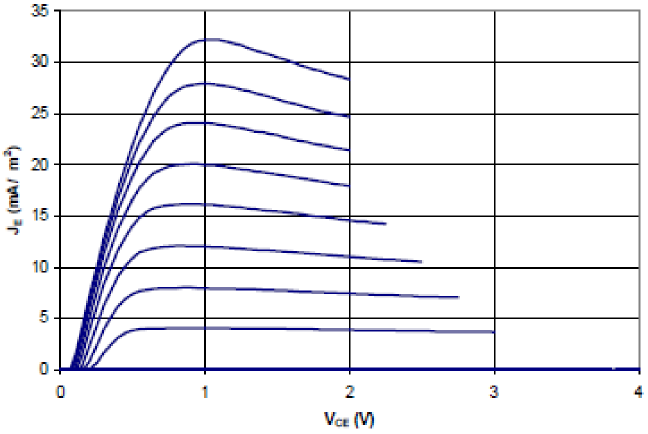


Fig. 2 Common-emitter IV characteristics of 130nm HBT normalized to emitter area

130nm InP DHBTs with f_t>0.52THz and f_{max} >1.1THz

M. Urteaga[1], R. Pierson[1], P. Rowell[1], V. Jain[2], E. Lobisser[2], M.J.W. Rodwell[2]
[1]Teledyne Scientific Company, Thousand Oaks, CA 93160. [2]Department of ECE, University of California, Santa Barbara, CA 93106. E-mail: murteaga@teledyne-si.com

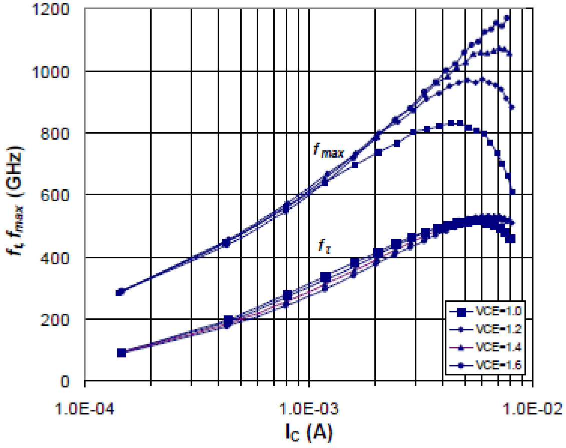


Fig. 4 f_t and f_{max} versus collector current at varying values of V_{CE} for 0.13x2μm^2 HBT

TELEDYNE
SCIENTIFIC COMPA
A Teledyne Technologies Comp

Urteaga et al, DRC 2011, June

Towards & Beyond the 32 nm /2.8 THz Node

Base contact process:

Present contacts too resistive (4Ω–μm^2)
Present contacts sink too deep (5 nm) for target 15 nm base

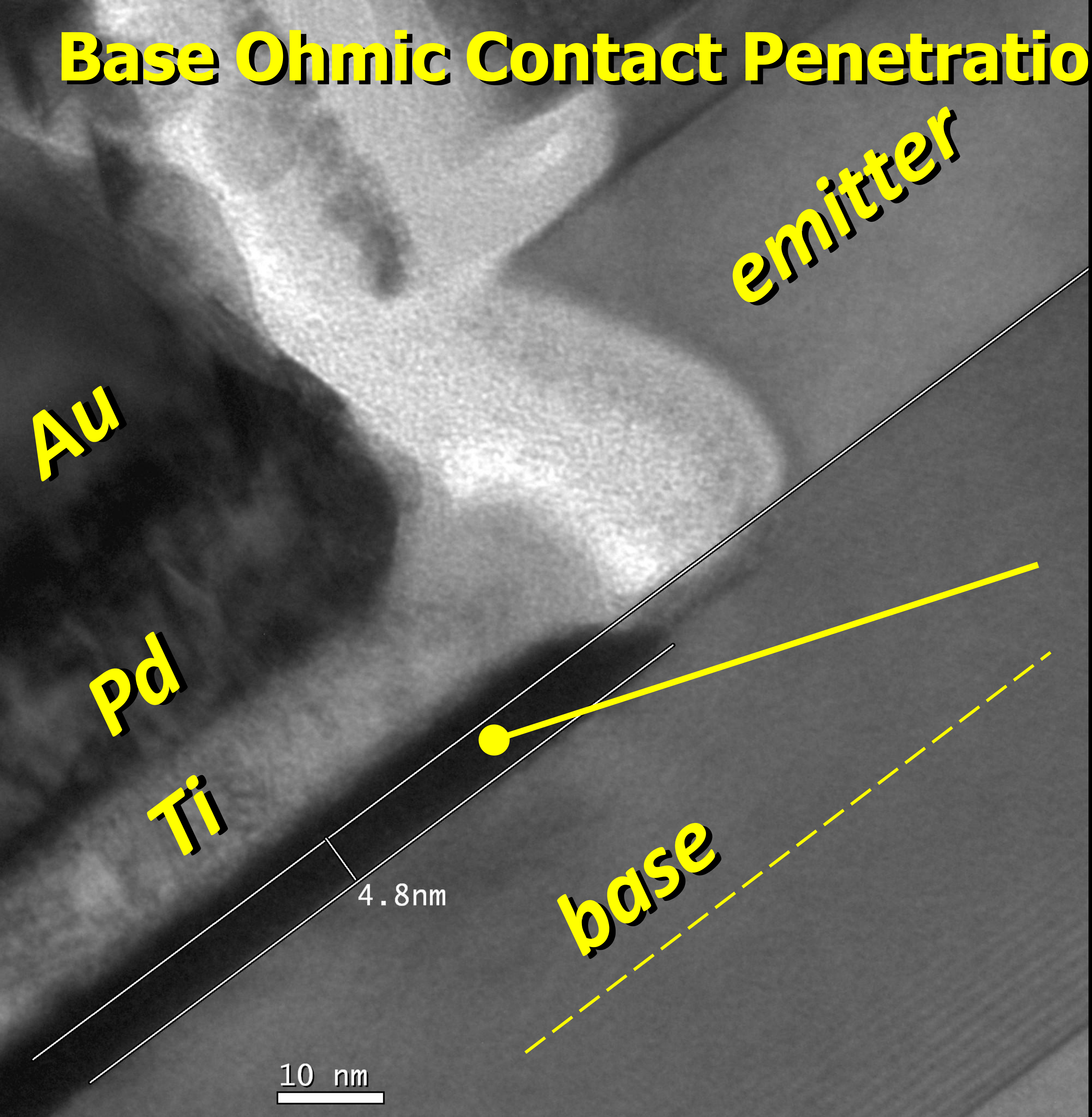
→ refractory base contacts

Emitter Degeneracy:

Target current density is almost 0.1 Amp/μm^2 (!)
Injected electron density becomes degenerate.
transconductance is reduced.

→ Increased electron mass in emitter

Base Ohmic Contact Penetration

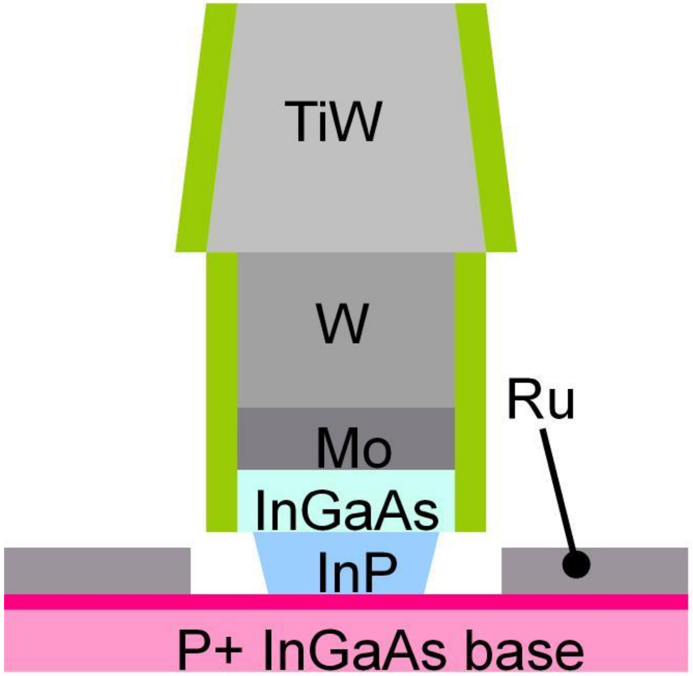


~5 nm
Pt contact
penetration

(into 25 nm base)

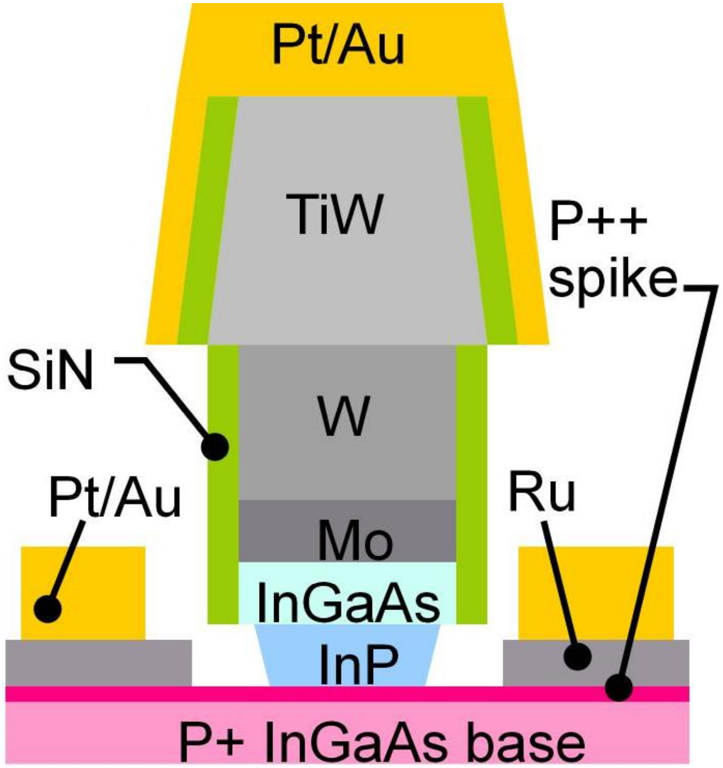
Refractory Base Process (1)

Blanket liftoff; refractory base metal



low contact resistivity
low penetration depth

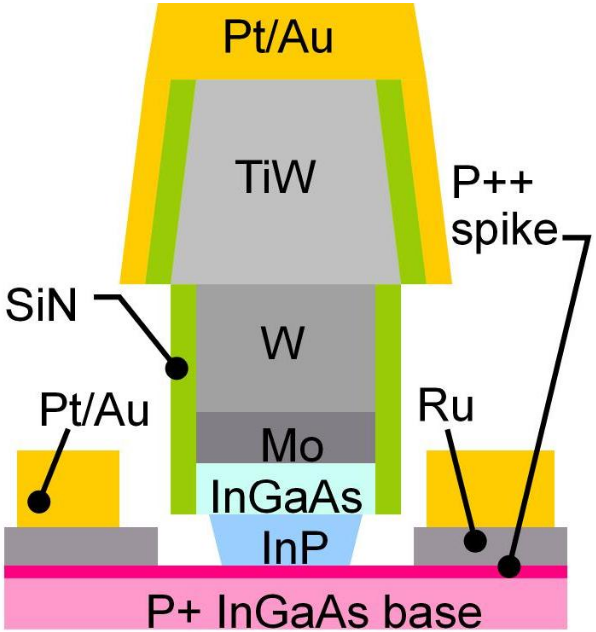
Patterned liftoff; Thick Ti/Au

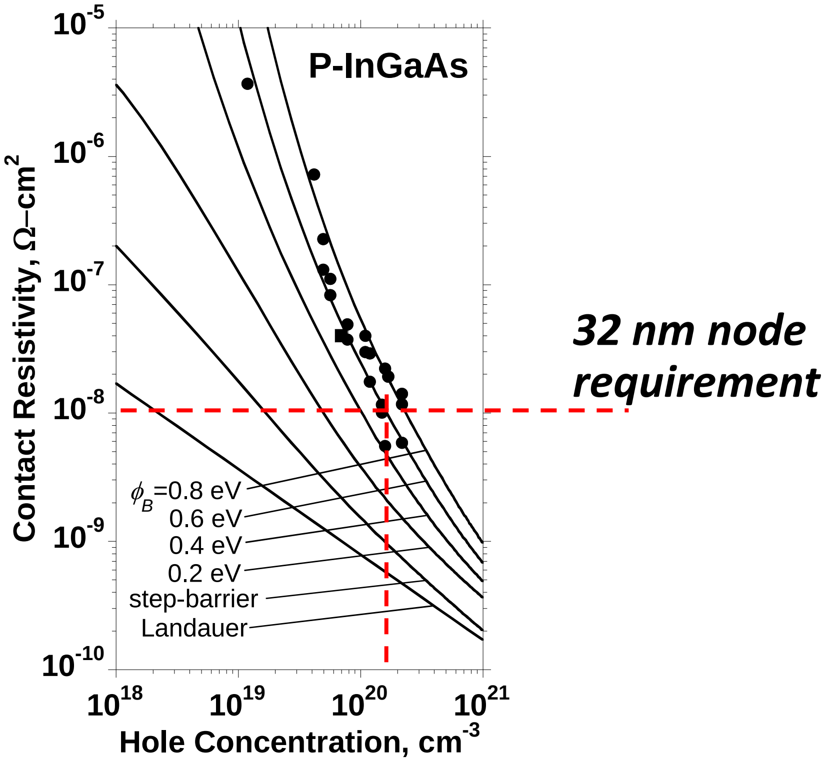


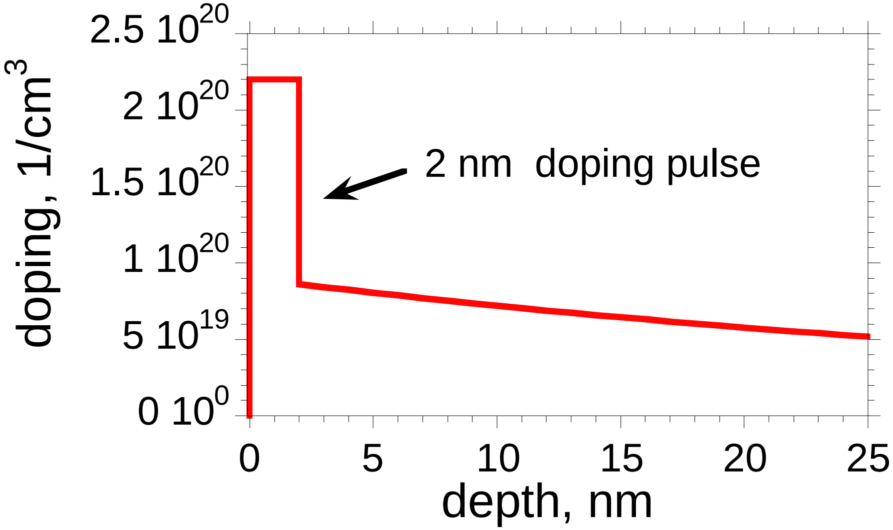
low bulk access resistivity

base surface not exposed to photoresist chemistry: no contamination
low contact resistivity, shallow contacts
low penetration depth allows thin base, pulsed-doped base contacts

Refractory Base Process (2)





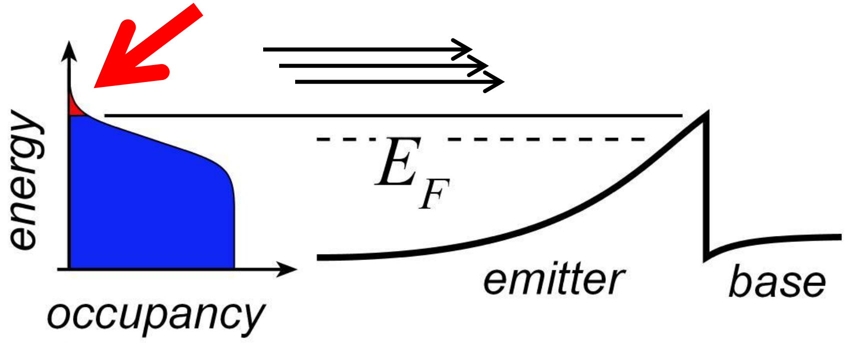


Increased surface doping:
reduced contact resistivity,
but increased Auger recombination.

→ Surface doping spike at most 2-5 thick.

Refractory contacts do not penetrate; compatible with pulse doping.

Degenerate Injection→ Reduced Transconductance

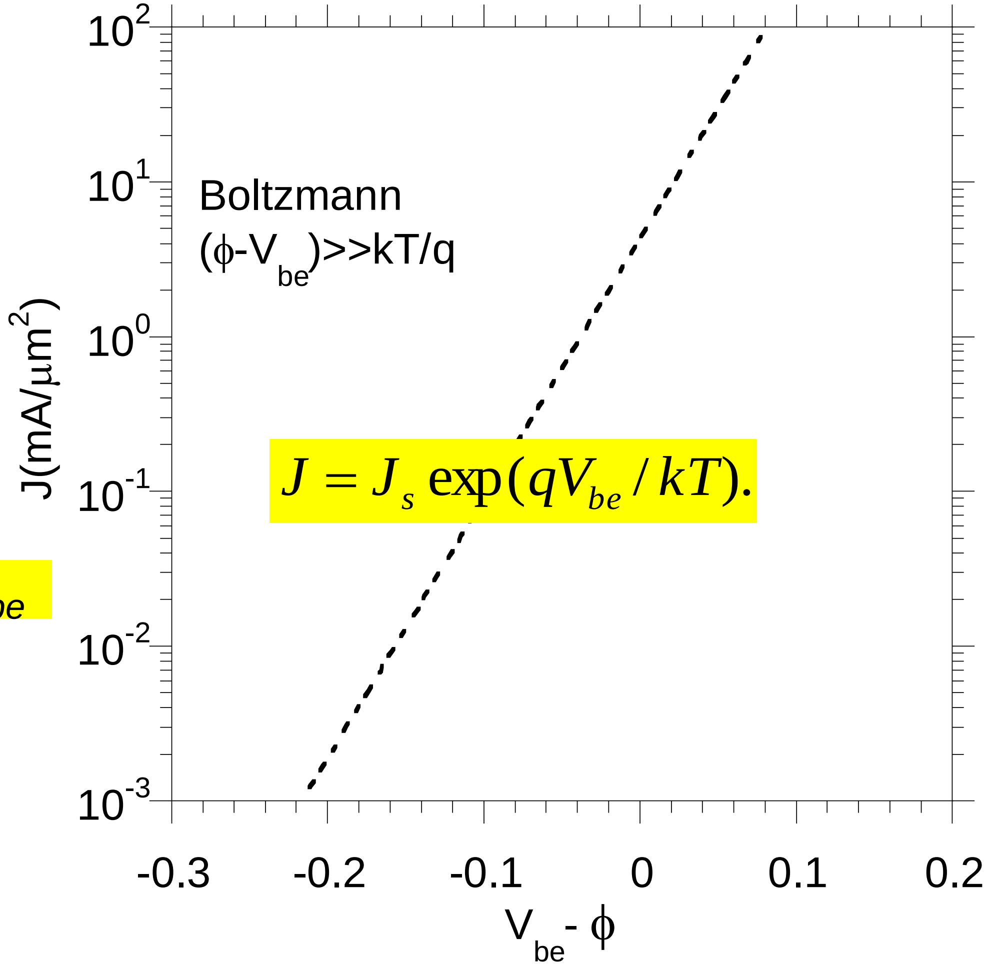


Current varies exponentially with V_{be}

$$J = J_s \exp(qV_{be}/kT).$$

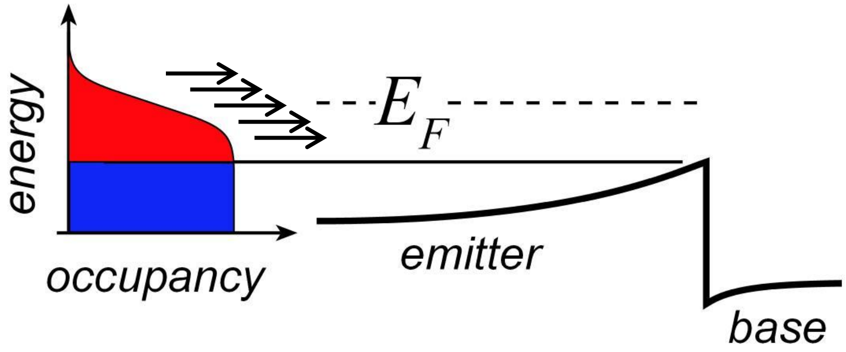
Transconductance is high

$$g_m / A_E \propto J$$


Boltzmann
$(\phi-V_{be}) >> kT/q$

$$J = J_s \exp(qV_{be}/kT).$$

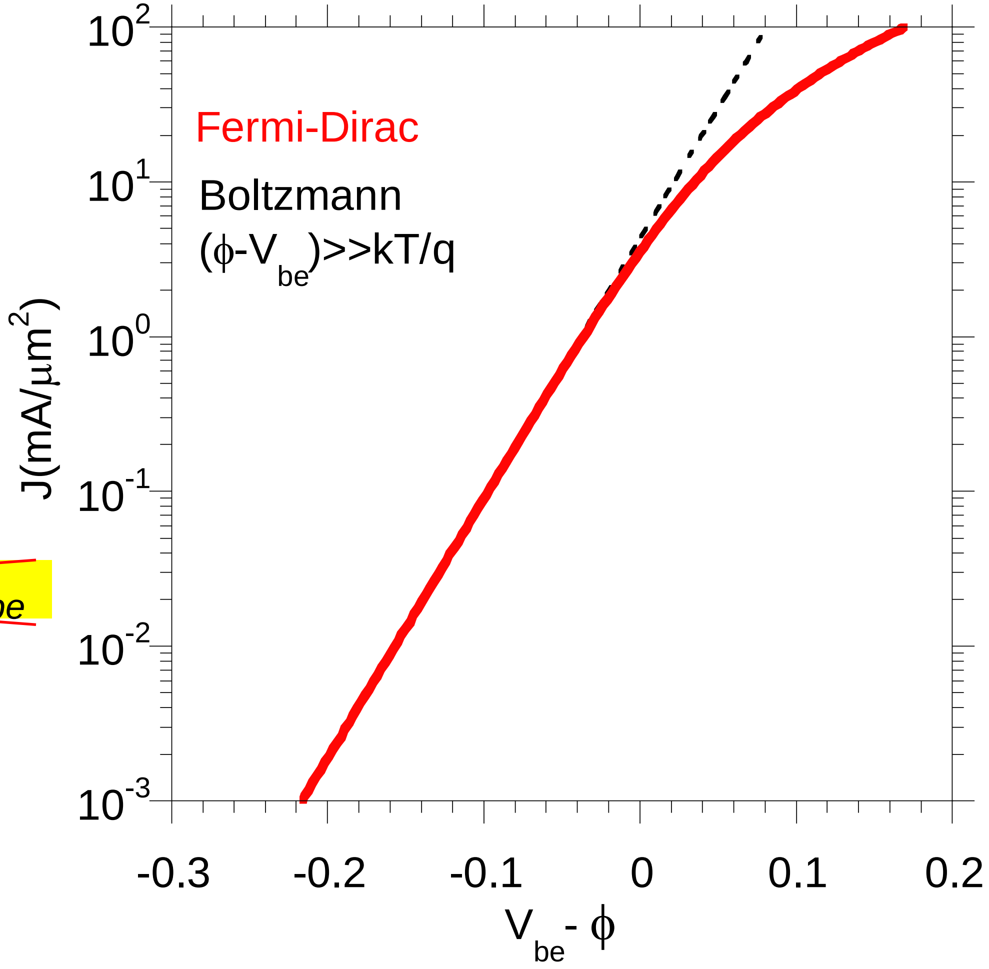
Degenerate Injection→ Reduced Transconductance



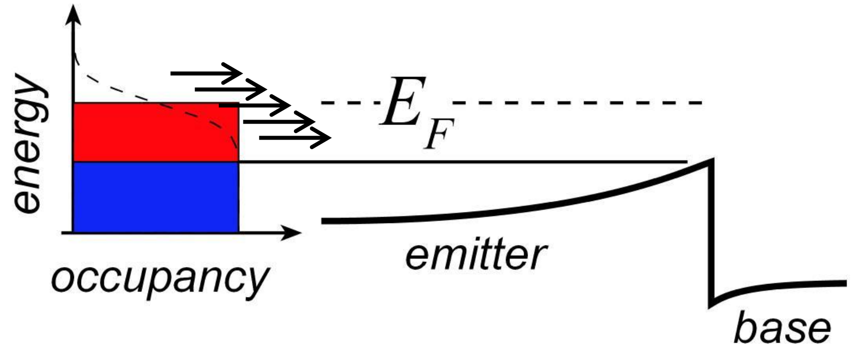
~~Current varies exponentially with V_{be}~~

$$\xcancel{J = J_s \exp(qV_{be}/kT).}$$

Transconductance is reduced



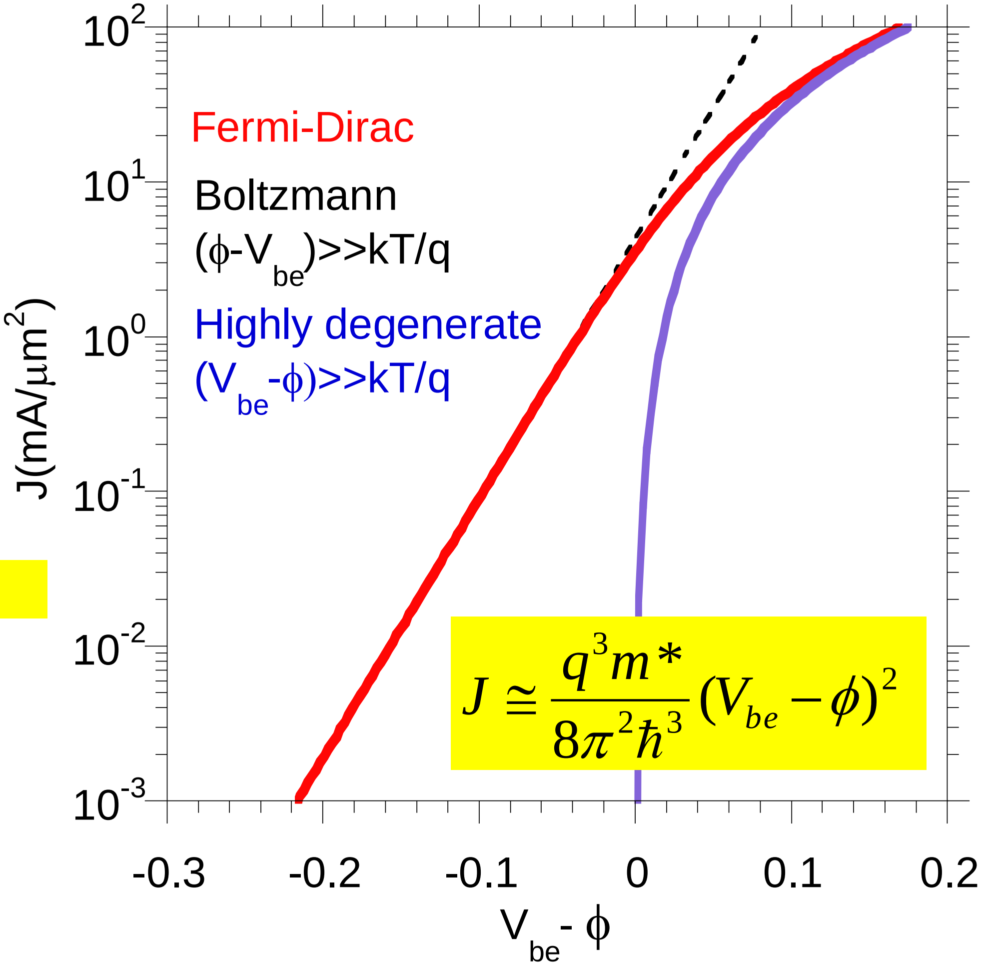
Degenerate Injection→ Reduced Transconductance



Highly degenerate limit:

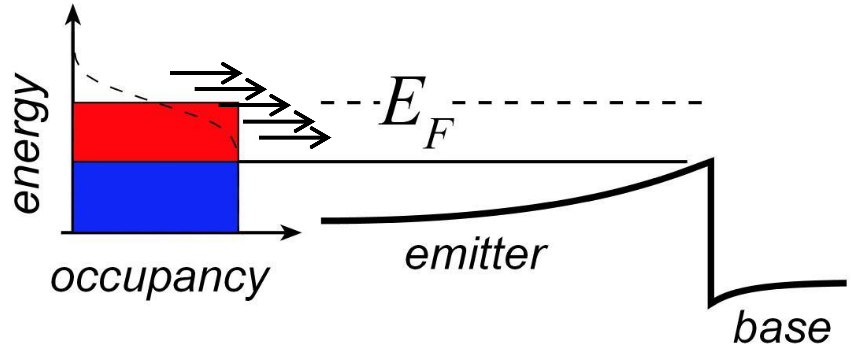
current varies as the square of bias

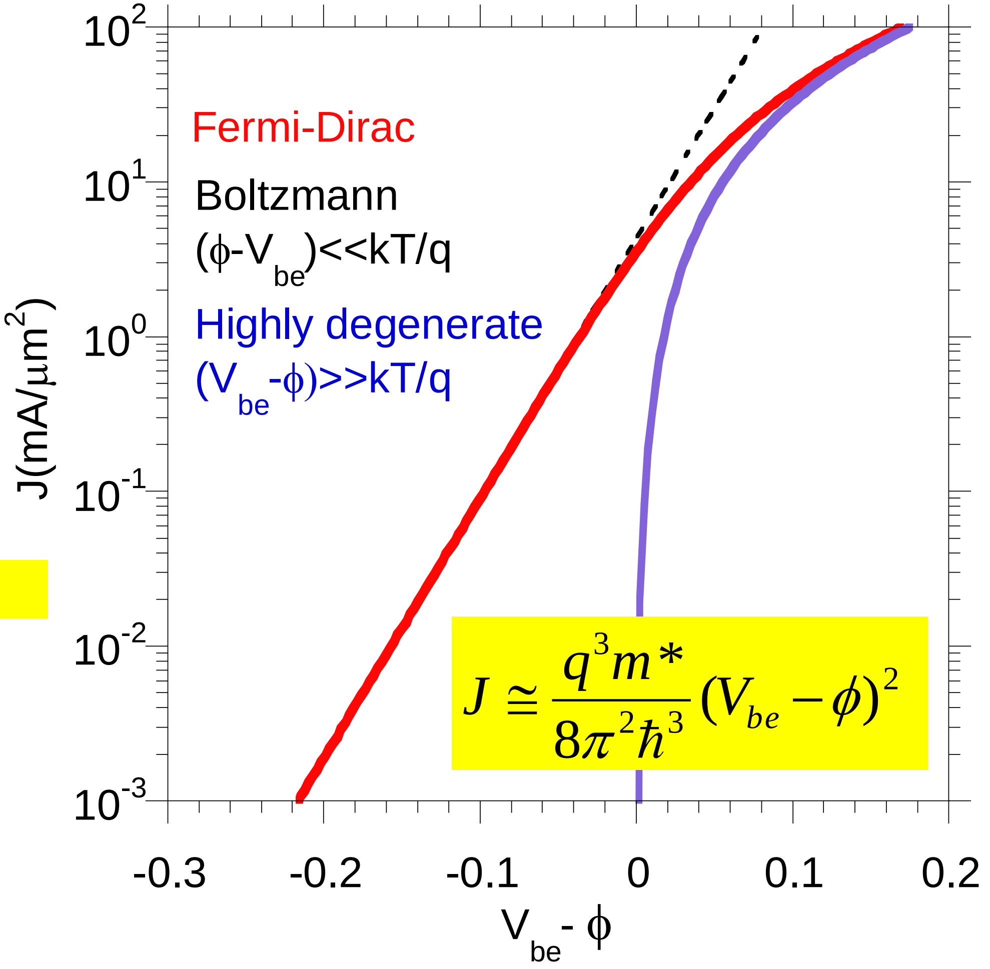
$$J \propto m_E^*(V_{be}-\phi)^2$$



$$J \cong \frac{q^3 m^*}{8\pi^2\hbar^3}(V_{be}-\phi)^2$$

Degenerate Injection→ Reduced Transconductance





$$J \cong \frac{q^3 m^*}{8\pi^2\hbar^3}(V_{be}-\phi)^2$$

Highly degenerate limit:

current varies as the square of bias

$$J \propto m_E^*(V_{be}-\phi)^2$$

Transconductance varies as $J^{1/2}$

$$g_m / A_E \propto \sqrt{m_E^* J}$$

...and as $(m^*)^{1/2}$

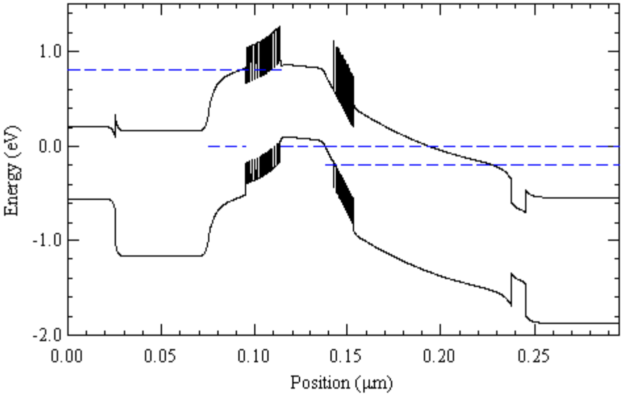
At & beyond 32 nm, we must increase the emitter effective mass.

Degenerate Injection→Solutions

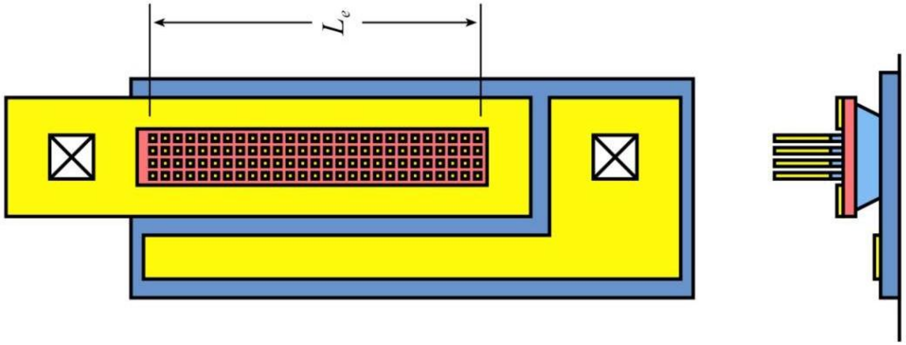
At & beyond 32 nm, we must <u>increase</u> the emitter (transverse) effective mass.

Other emitter semiconductors:
no obvious good choices (band offsets, etc.).

Emitter-base superlattice:
increases transverse mass in junction
evidence that InAlAs/InGaAs grades are beneficial



Extreme solution (10 years from now):
partition the emitter into small sub-junctions, ~ 5 nm x 5 nm.
parasitic resistivity is reduced progressively as sub-junction areas are reduced.

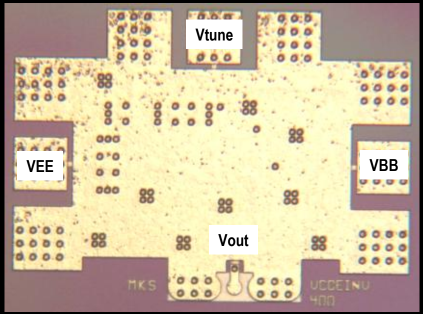


IC Results

InP HBT Integrated Circuits: 600 GHz & Beyond

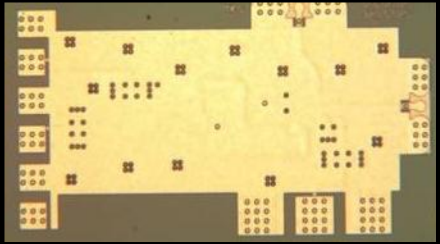
614 GHz fundamental VCO

M. Seo,



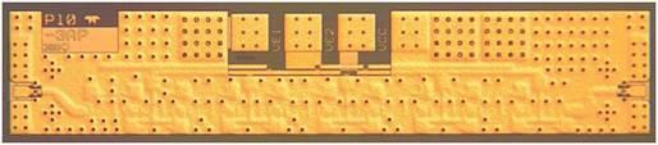
340 GHz dynamic frequency divider

M. Seo, UCSB/TSC
IMS 2010



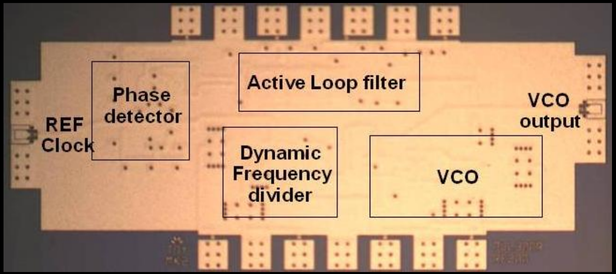
565 GHz, 34 dB, 0.4 mW output power amplifier

J. Hacker, TSC



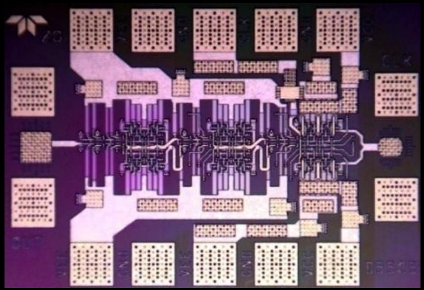
300 GHz fundamental PLL

M. Seo, TSC
IMS 2011



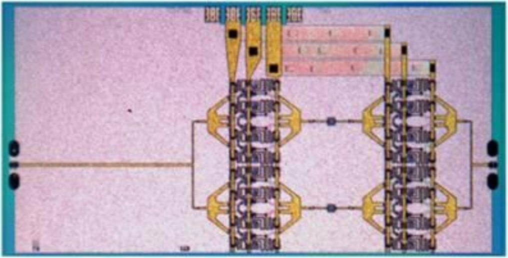
204 GHz static frequency divider (ECL master-slave latch)

Z. Griffith, TSC
CSIC 2010

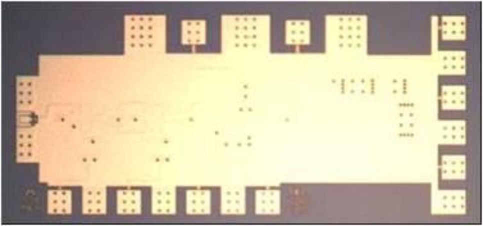


220 GHz 90 mW power amplifier

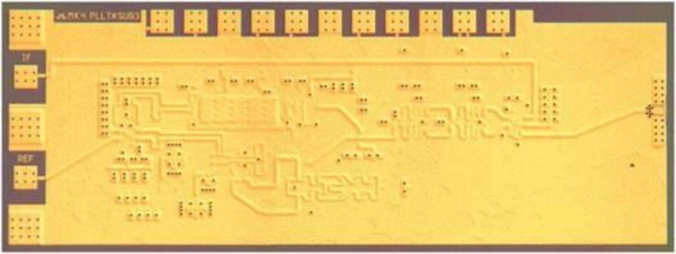
T. Reed, UCSB



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

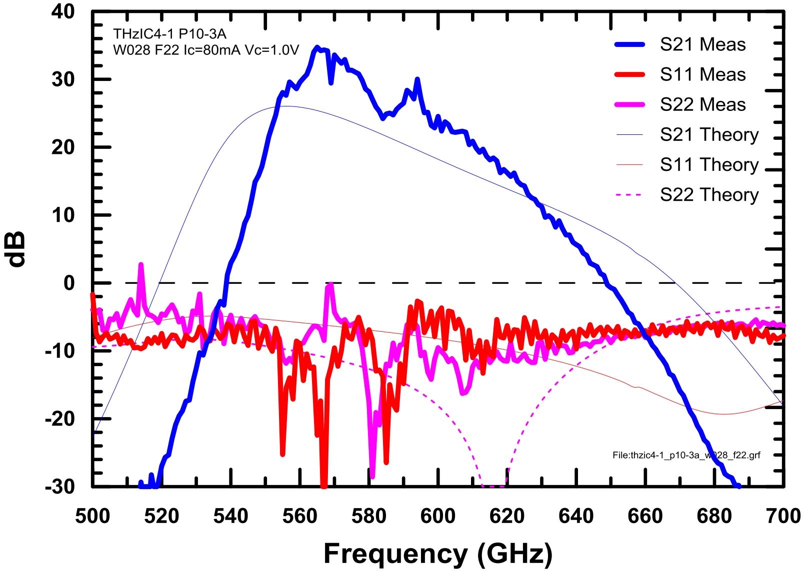


600 GHz Integrated Transmitter
PLL + Mixer
M. Seo

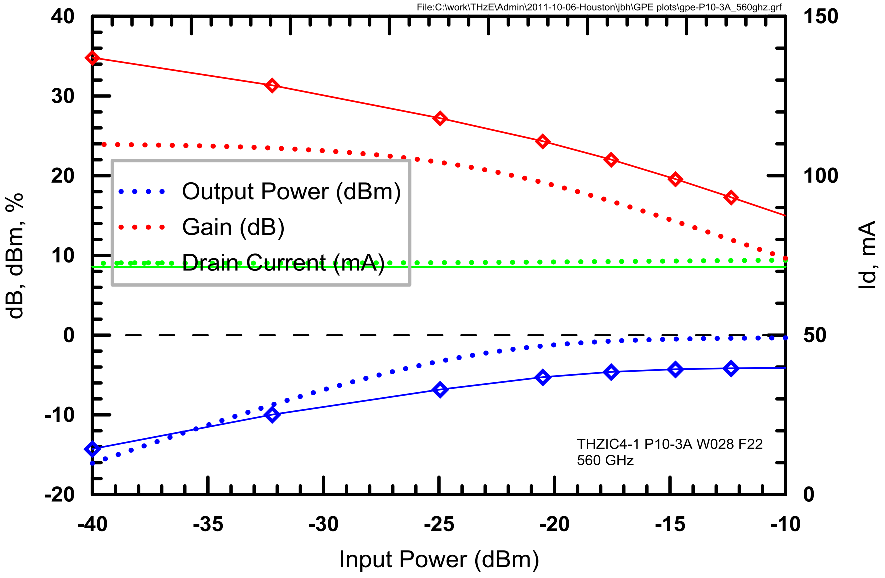


Teledyne: 560 GHz Common-Base Amplifier IC

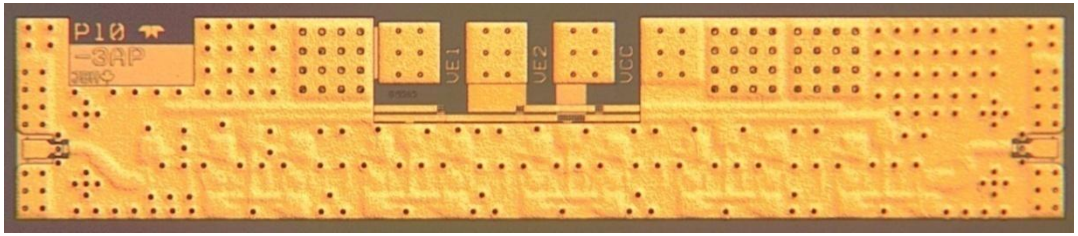
S-parameters



Output Power



- 10-Stage Common-base using inverted CPW-G architecture
- 34 dB at 565 GHz
- Psat -3.9 dBm at 560 GHz



1200x230 μm^2

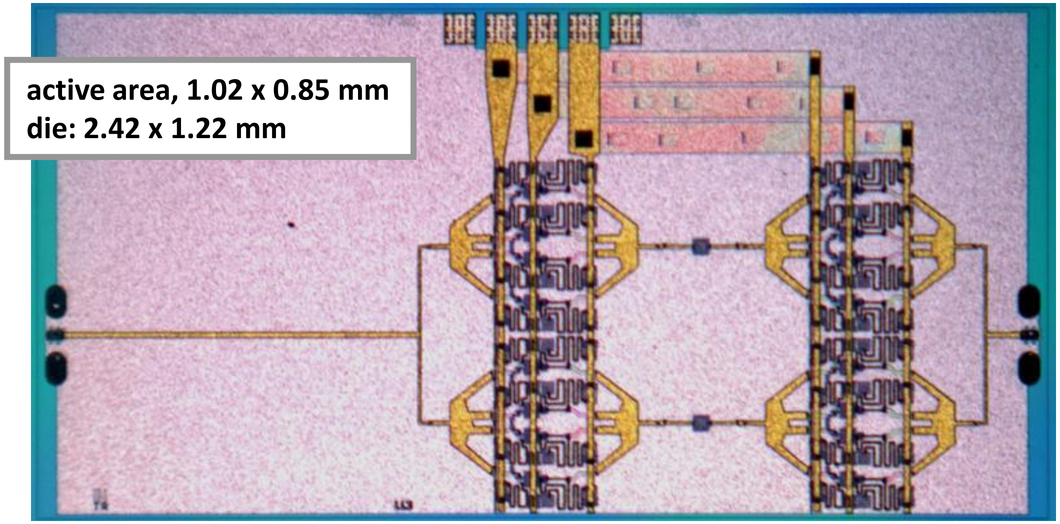
J Hacker et al, Teledyne Scientific

TELEDYNE SCIENTIFIC COMPANY
A Teledyne Technologies Company

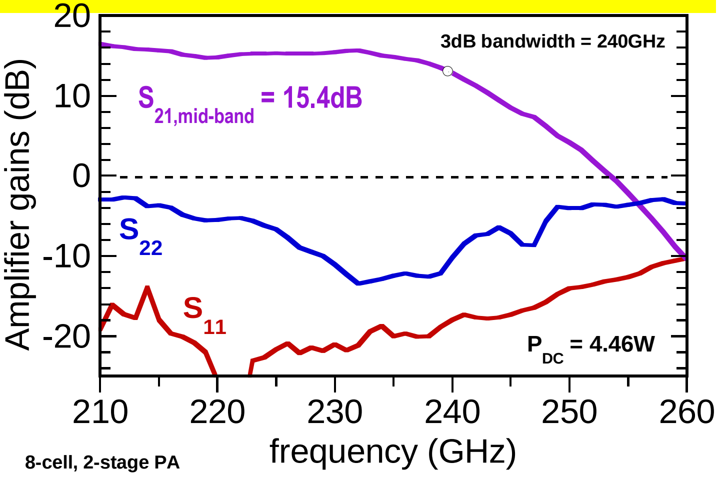
UCSB

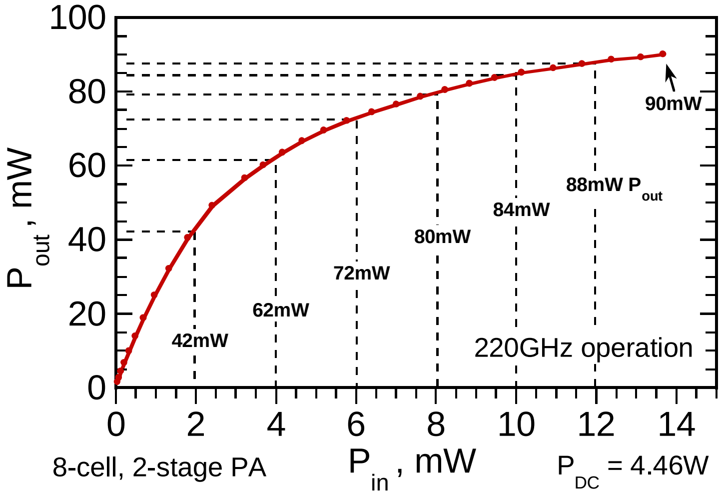
90 mW, 220 GHz Power Amplifier

Reed (UCSB) and Griffith (Teledyne): CSIC 2012
Teledyne 250 nm InP HBT



active area, 1.02 x 0.85 mm
die: 2.42 x 1.22 mm

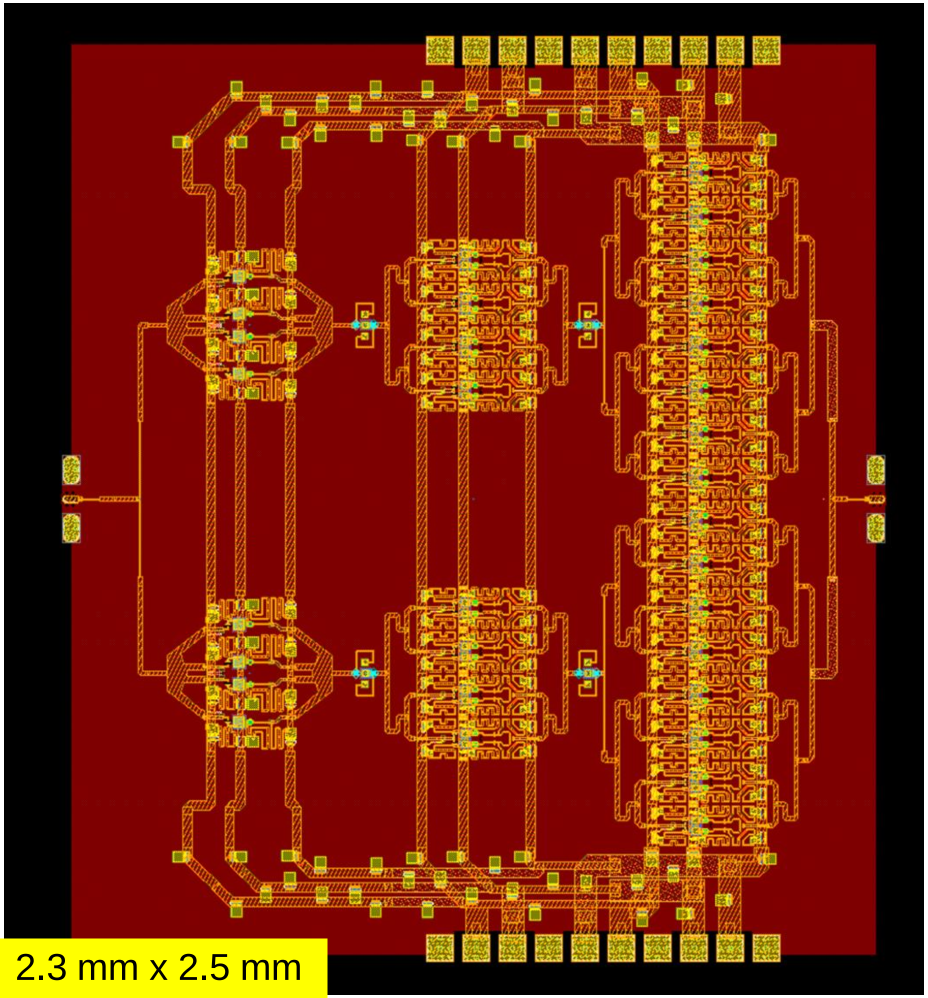




RF output power densities up to 0.5 W/mm @ 220 GHz.

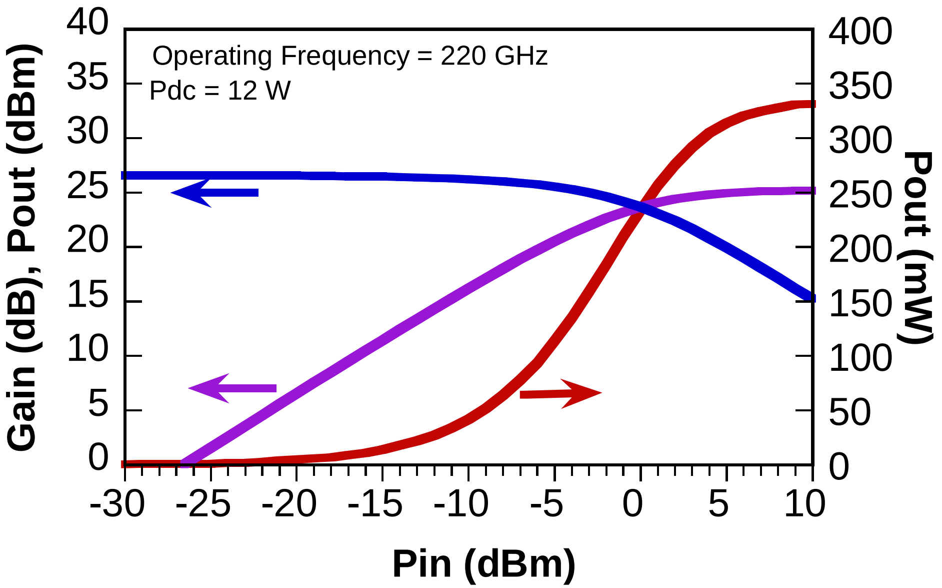
→ InP HBT is a competitive mm-wave / sub-mm-wave power technology.

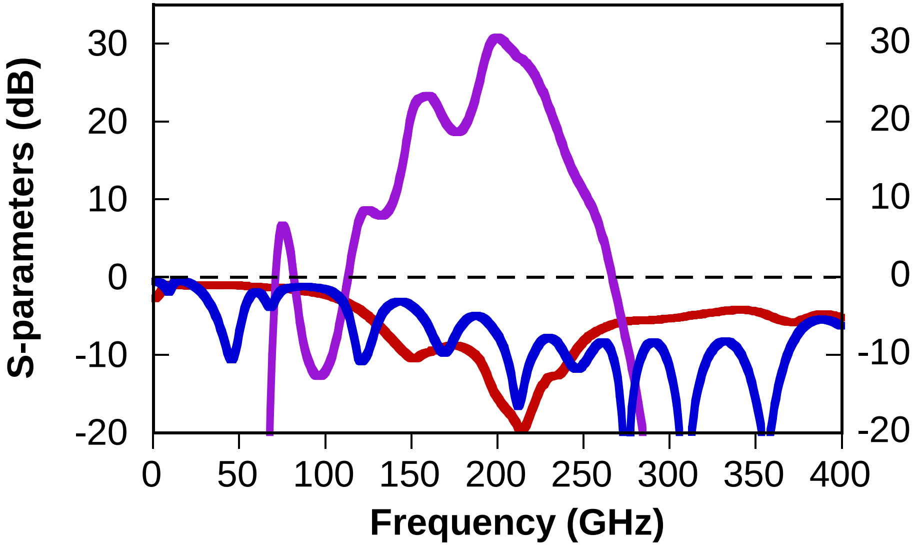
220 GHz 330mW Power Amplifier Design



2.3 mm x 2.5 mm

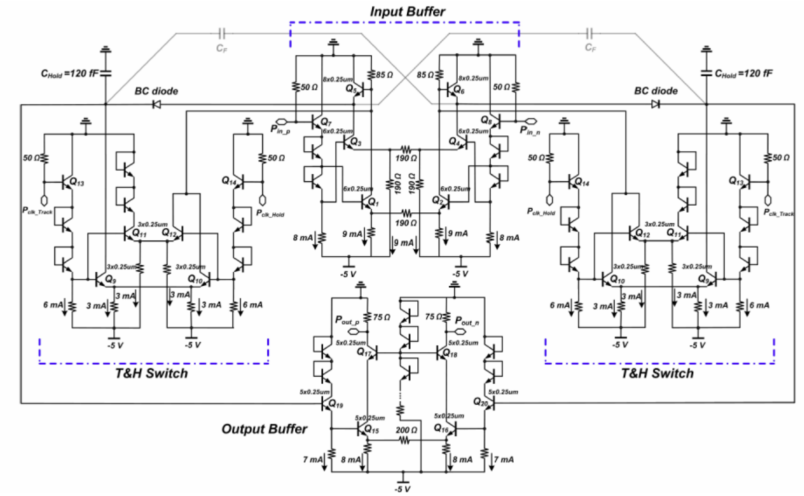
T. Reed, UCSB
Z. Griffith, Teledyne
Teledyne 250 nm InP HBT

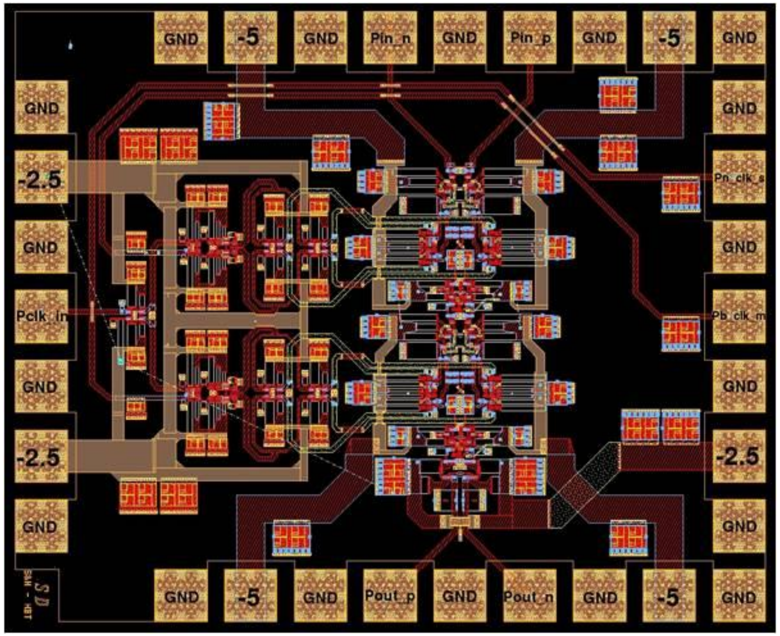


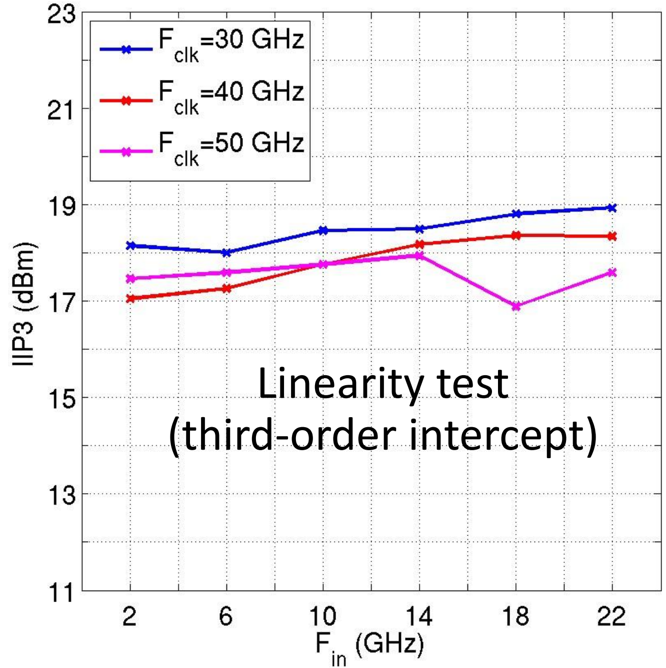


50-G/s Track/Hold Amplifier; 250 nm InP HBT

S. Daneshgar, this conference

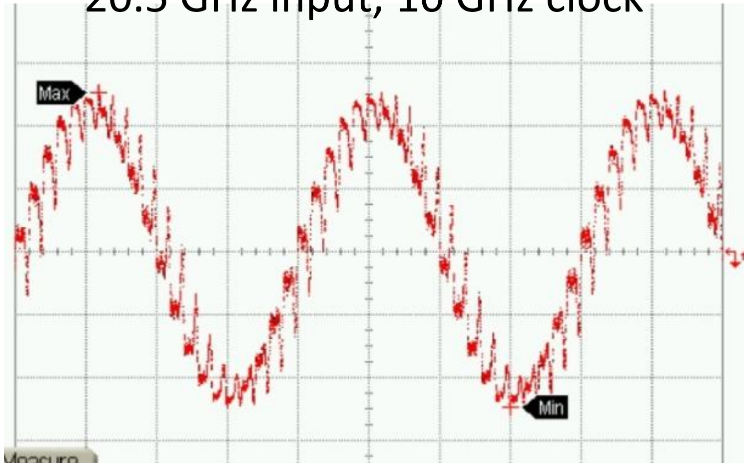






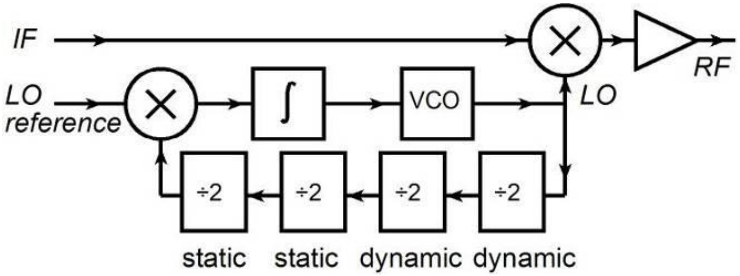
Linearity test
(third-order intercept)

20.5 GHz input, 10 GHz clock

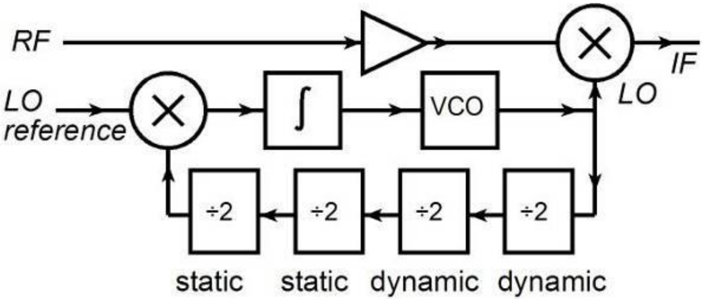


Where Next ? → 2 THz Transistors, 1 THz Radios.

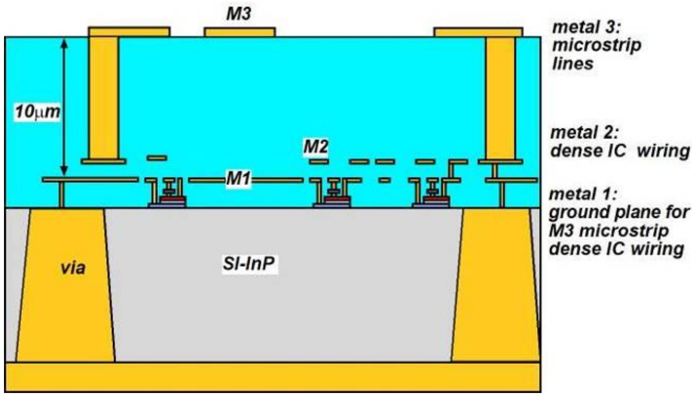
transmitter



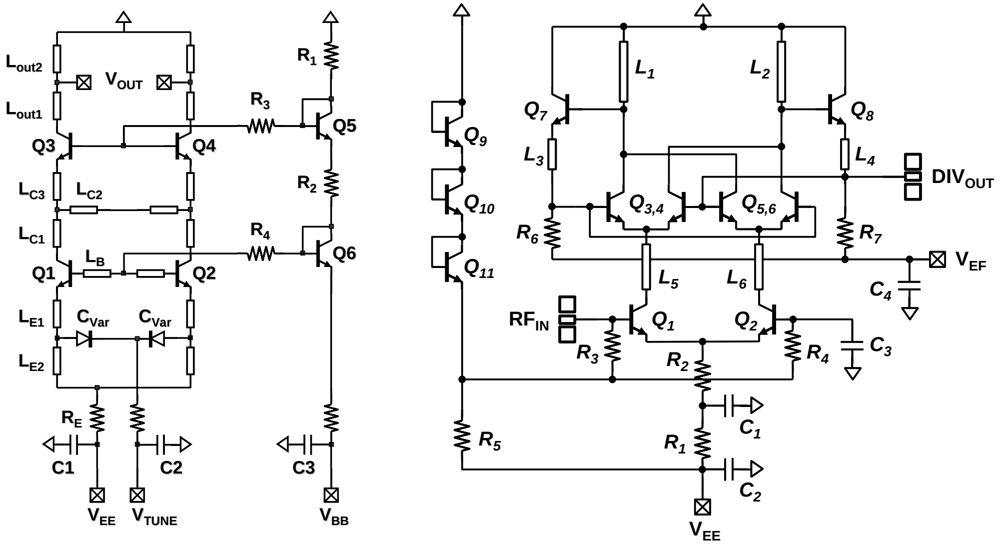
receiver



interconnects

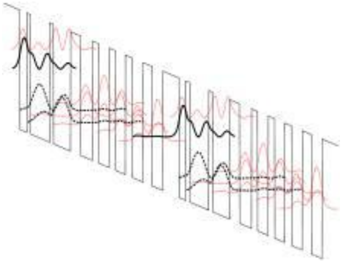


circuits

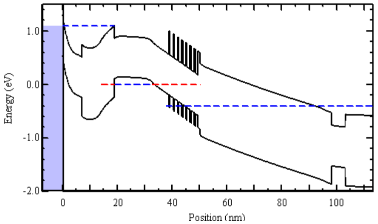


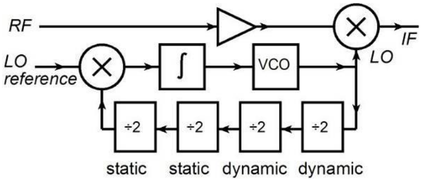
THz and Far-Infrared Electronics

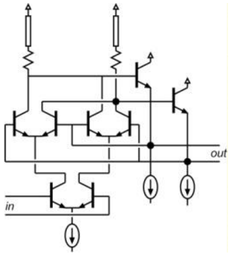
IR today→ lasers & bolometers → generate & detect

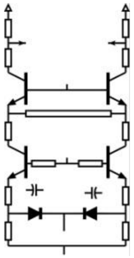


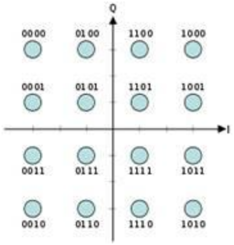
Far-infrared ICs: classic device physics, classic circuit design











It's all about classic scaling:
contact and gate dielectrics...

...wire resistance,...

...heat,...

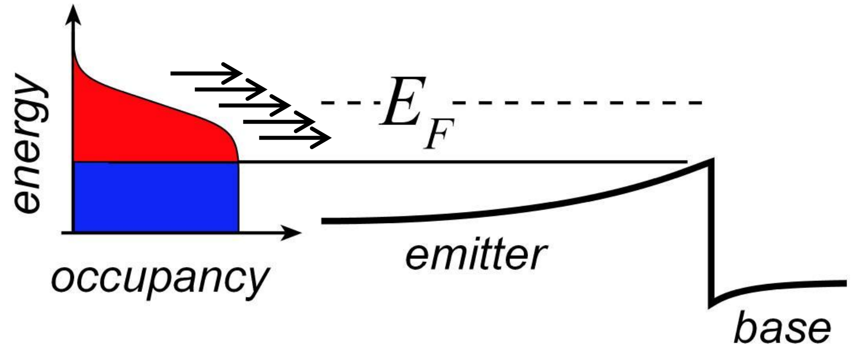
...& charge density.

band structure and
density of quantum states
(new!).

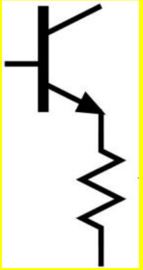
Even 1-3 THz ICs will be feasible

(backup slides follow)

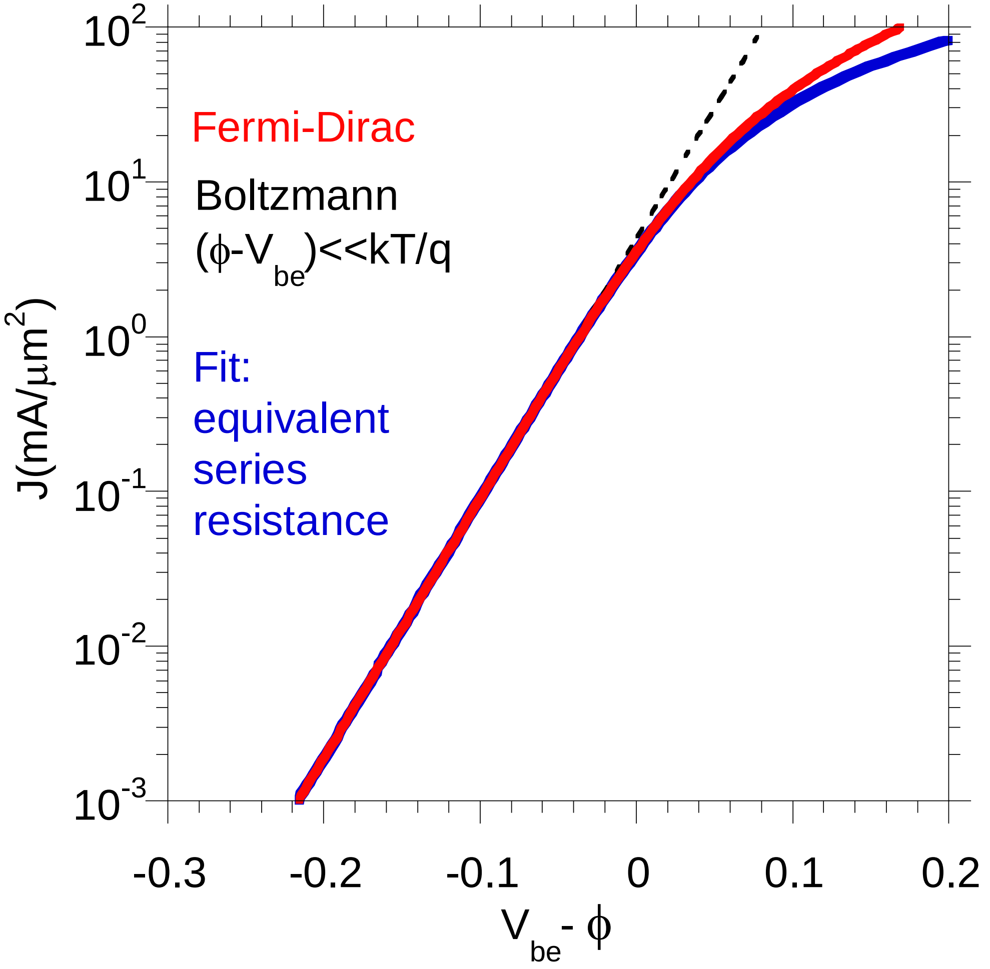
Weakly Degenerate→ Effective Added Resistance



$$V_{be} = (kT/q)\ln(I/I_s) + I\cdot R_{eq}$$



$$R_{eq} \propto 1/m_E^*$$

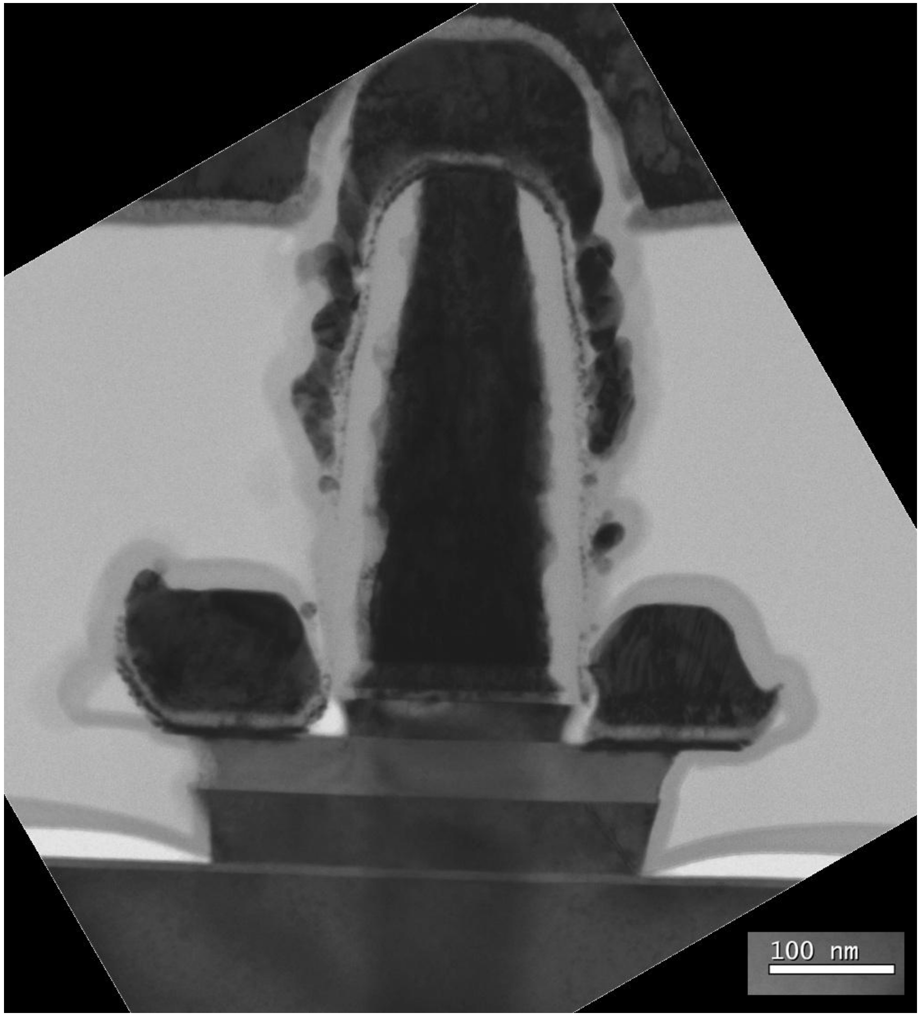


At & beyond 32 nm, we must increase the emitter effective mass.

HBT Scaling Roadmap

emitter	128	64	32 nm width
	4	2	$1\ \Omega\cdot\mu m^2$ access ρ
base	120	60	30 nm contact width,
	5	2.5	$1.25\ \Omega\cdot\mu m^2$ contact ρ
collector	75	53	37.5 nm thick,
	18	36	72 $mA/\mu m^2$ current density
	3.3	2.75	2-2.5 V, breakdown
f_τ	730	1000	1400 GHz
f_{max}	1300	2000	2800 GHz
RF-ICs	660	1000	1400 GHz
digital divider	330	480	660 GHz

140 nm Device: RF Results

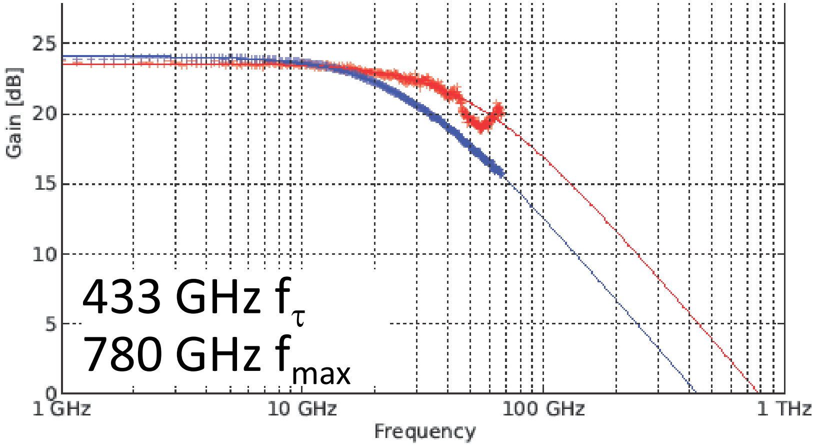


140 nm emitter junction

120 nm wide base contacts

75 nm thick collector
25 nm thick base

f_{max} impaired (780 GHz) : excessive contact penetration into base

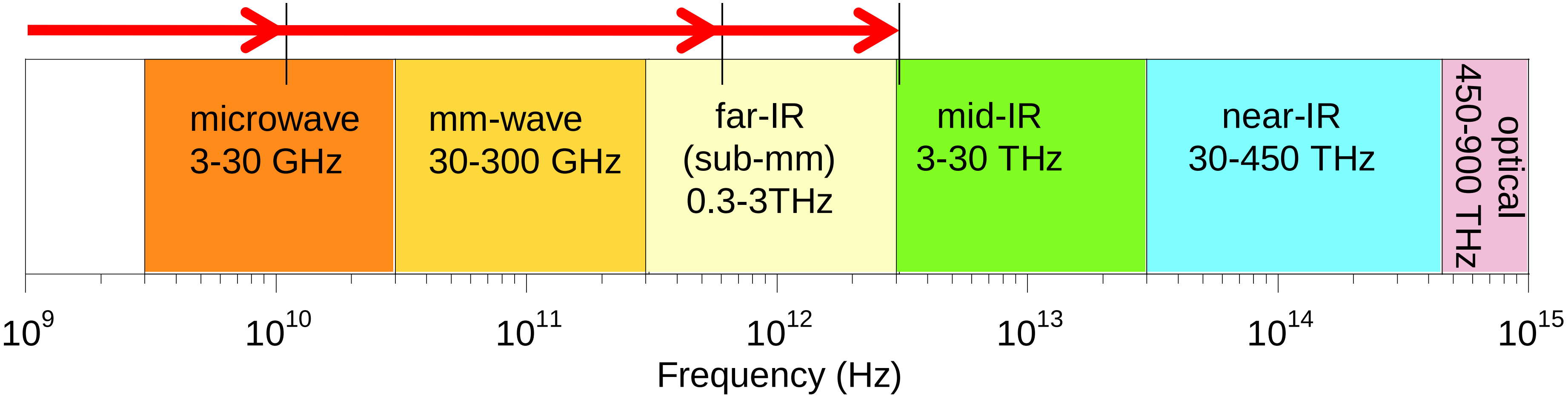


433 GHz f_τ
780 GHz f_{max}

Chiang & Rode
unpublished

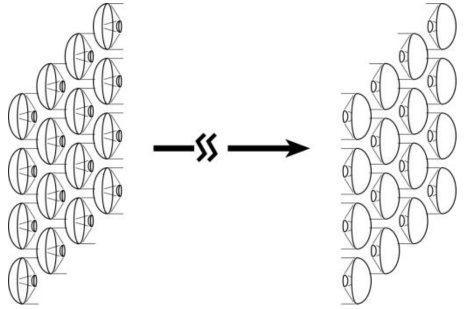
DC to Daylight.   Far-Infrared Electronics

How high in frequency can we push electronics ?



...and what would be do with it ?

0.3-3 THz radio: vast capacity bandwidth, # channels



0.1-0.4 THz imaging systems

0.1-1 Tb/s optical fiber links